DIGITAL COMPRESSION OF TWO-TONE FACSIMILE SIGNALS

by

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ABSTRACT

In this thesis fixed-rate compression schemes for two-tone facsimile data are proposed which feature low implementation complexity, high resistance to transmission errors and compatibility with existing analogue apparatus. In the first part of the thesis the application of universal fixed-rate block-to-block coding is investigated. The method employs a variable codebook to approximate bit patterns of blocks of image data, the codebook entries being derived from local block statistics. The improvement over the use of a fixed codebook is however offset by the need to transmit codebook information. The compression ratios for a variety of test documents are obtained for variable and partially variable codebooks. The effects of transmission errors are also examined.

The major part of the thesis is concerned with the development of a proposed method of compression which encodes pairs of blocks of the image. In Sequential Block Interleave Coding (SBIC) distortionless coding is obtainable by a simple process of delaying lines of the image and sequentially interleaving nonwhite blocks into the spaces of white block-pairs. In the direct form of coding the coding field to give zero distortion is large which results in an increased vulnerability to transmission errors. To reduce the field size a pseudo-random mapping of blocks is carried out before coding. The subjective effects of the lossy outcome of this coding method are observed and a simple means of minimising the encoding distortion is suggested. A theoretical analysis for a memoryless block source is presented which is useful in predicting information-lossless performance from knowledge of the relevant block probabilities. A further advantage of the SBIC method is that it may be cascaded with fixed or universal block-to-block coding to give higher

levels of compression.

The practical viability of the SBIC method is demonstrated by incorporating the technique in a real-time compressor-expandor unit which was constructed for use with an analogue facsimile system specialising in the transmission of weathercharts. The unit employs the 8-bit Z-80 microprocessor to implement in software the compression and expansion processes as well as the essential transmission functions of modulation, channel equalisation and detection. The integrated software approach results in an extremely low-cost bolt-on unit which digitises the analogue facsimile signal, encodes the binary data and communicates the coded data stream over the telephone network.

An alternative form of block-pair coding called Coordinate Block Interleave Coding (CBIC) is also proposed where coordinates are used to identify positions of appropriate nonwhite blocks. Pseudo-random mapping of blocks is again useful to attain low distortion levels. Compared to block-to-block coding this technique achieves a higher compression ratio and does not require any codebook. The use of coordinates results in a highly-robust compression scheme so that the method is well-suited for transmission over very noisy channels.

CHAPTER 1

INTRODUCTION TO FACSIMILE SYSTEMS AND THEORETICAL ASPECTS OF DIGITAL CODING FOR COMPRESSION

1.1 Facsimile and its Merits

Facsimile refers to the transmission and copy of static images. In a facsimile system an electrical representation of the subject copy (or source image) is generated in a scanner and communicated to a remote recorder where a replicate or record copy of the source image is produced (Fig 1.1). In many aspects the facsimile system is similar to a television system. Both are picture communication systems which utilise the same principle of serial scanning and reconstruction of images. The television system, however, is designed for moving images and its bandwidth requirements are dictated by the rate of real-time movement. In a facsimile system the bandwidth for communication is that determined by the speed at which the image is required to be dispatched. This is influenced by the degree of fine detail in the image (which is typically higher than that in a television screen) but because of the stationarity of the image a much lower bandwidth is needed. The facsimile system is thus not constrained to wideband links but may utilise national and international telephone communication networks. As a consequence, through facsimile, a versatile exchange of graphical information within an increasingly wide section of the globe is made possible. Modern digital facsimile equipment which incorporates data compression and efficient modulation techniques, allows the transmission of documents in a matter of seconds.

Perhaps the most significant advantage of facsimile is the unrestricted content of images which may be transmitted. This is a feature not found in telex, an alternative system for text communication. Modern telex systems can transmit text and numerical data efficiently and speedily but the size and style of characters are restricted to fixed sets. With facsimile, text material irrespective of character fonts and sizes may be communicated and in addition signatures, diagrams, letterheads, etc may also be transmitted. The absence of restriction in the nature of transmitted text is also useful in some non-English text communication where the character set of the alphabet is much larger than that for English. An example is Chinese text which requires a set of at least 2,000 characters.

A traditional disadvantage of facsimile has been the relatively long transmission time for an image. With modern equipment incorporating compression techniques the gap in transmission time between facsimile and telex has considerably narrowed. When making a comparison in speed of communication, account should be taken of the keyboard transcription required in telex for messages which do not originate in printed form. The time required to 'keyboard-encode' the message by an adept telex-operator (who has to be paid and who may not be available at all hours) should also be taken into consideration. A further advantageous aspect of the facsimile system is the resistance to transmission errors. In telex the corruption of a transmitted digit results in an incorrect character being printed. The effect is hardly noticeable in a facsimile system because the raster-scan ensures a collection of picture elements represents each character. Although in data-compressed digital facsimile systems propagation effects do occur, these are usually limited to a line of image and the subjective effect is not serious.

The many benefits of modern facsimile units have resulted in their

widespread use today and their usage is fast increasing as more commercial and industrial establishments grasp the cost-effectiveness, speed and versatility of their use in the communication of pictorial matter including text. The penetration of facsimile into the home is also foreseeable in the very near future.

1.2 Historical Background

In this section an outline is given of the development of facsimile from its beginnings. An interesting historical account is described by Costigan in [1] and some factual aspects are reproduced in the following paragraphs.

Facsimile is one of the elderly electrical engineering systems. The first known facsimile transmission occured in 1842, about 30 years before the invention of the telephone by Bell, when the Scotsman Alexander Bain constructed a pendulum-driven mechanism, which registered electrically, by means of physical contact via a stylus, the metallic letters of the message to be transmitted (Fig.1.2a). The swinging motions of the electrical pendulum were used to provide the horizontal 'scanning' of the lettering, with on-off dc levels being generated corresponding to closure of eletrical circuit through the stylus and metallic lettering. The progression of the scan in the vertical direction was achieved by decrementing, after each pendulum cycle or scan, the height of the block on which the lettering were mounted, this being done by an advancing clockwork mechanism. The dc pulses were conveyed by wire to the receiving apparatus which was similar in construction to the 'scanner' except that in place of the metallic lettering a sheet of electrosensitive paper was used which turned dark at the application of dc pulses during sweeps across the paper. By this means a trace or facsimile of the lettering at the transmitter was produced. Synchronisation or 'phasing' between receiver and transmitter

was performed by electromagnetically holding one pendulum at the end of a cycle until both receiver and transmitter pendulums were spatially aligned.

A few years later in 1850 the familiar cylinder and screw arrangement for scanning was introduced by Bakewell (Fig.1.2b) which was to remain a dominant scanning method in facsimile equipment until the present day. In this system the subject copy (and receiver copy) is wrapped round a cylinder which rotates at a constant speed during scanning. The stylus (replaced by optical sensing unit later) is attached to a traversing carriage propelled by a slowly-rotating threaded screw positioned alongside the cylinder. As the carriage progresses down the length of the cylinder a continuous helical scan is described around the face of the cylinder and hence the subject copy. The fineness of thread of the screw fixes the scanning density of the apparatus.

The first commercial facsimile transmission system was established in Paris in 1865 and linked the capital with several other French cities. Generally, however, the development of facsimile was much in the shadow of that of the telegraph which could transmit printed information more speedily and reliably than the early facsimile machines. The beginning of this century saw the introduction of photo-electric scanning which could be used for the transmission of photographs. Facsimile links for this purpose were established as early as 1902 in Germany and a transatlantic connection came into operation in 1922. The use of facsimile for the transmission of meteorological information in the form of weathercharts and other weather data started in 1930. Then, the American company RCA pioneered the distribution of weather data to ships out at sea by means of radiofacsimile. In the following years the progress of facsimile remained steady although the pace of growth was slow compared with that of the telephone or television. The commercial concentration on the transmission of speech led to the development of an extensive network which was

specifically designed to carry voice signals and which was later to prove unsuited for the transmission of images. Facsimile however, continued to play a role in the telecommunications field. The major users of facsimile continued until only very recently to be newspaper houses, weather centres and military installations, although there were applications in other areas for e.g. crime prevention (transmission of fingerprints, photographs and details of suspects) and commerce (transmission of customer orders, stock-lists, bills, financial data). Throughout this period, as with all electrical equipment, new developments and latest technology were applied for the improvement of resolution, recording quality and transmission circuitry. Thus vacuum-tubes and mechanical relays which were prevalent in a few generations of facsimile equipment were eventually superceded by solid-state equivalents and, more recently, by LSI circuitry. Some elements of valve circuitry are still retained in present day analogue facsimile apparatus on account of their superior performances, e.g. photomultiplier tubes.

The arrival of the semiconductor changed significantly the role of facsimile in telecommunications. The introduction of a new generation of desktop facsimile equipment in the early 1960's brought about a shift from specialist applications towards a greater public recognition. These machines employed the telephone network for transmission, could record cleaner and clearer images, were automatic in their operation to some extent and therefore required little training for their use. The visionary concept of facsimile replacing the newstand as the prime provider of news in the home was revitalised. However, although more portable and speedier than their predecessors, this generation of analogue facsimile equipment, which is still widely used today, still required several minutes for the despatch of typical-sized documents. This situation was to change with the arrival of the latest generation of digital facsimile equipment which was more compact, more fully automated and speedier than ever before. This

equipment combines latest scanning and recording techniques with state-of-the art digital transmission. With the use of data compression techniques transmission speeds of tens of seconds for typical documents (A4 size) can be achieved. The relative low cost of these units have been made possible through the availability of low-cost LSI electronics and solid-state image-sensing devices. With increasingly powerful and cheap computing power becoming available for the implementation of sophisticated transmission techniques, plus the possibilities of custom-circuits for coding and other hardware, and continual improvement of solid-state image-sensing technology, better and cheaper facsimile machines can be expected in the next generation of facsimile equipment. Colour facsimile transmission is an interesting future prospect but this must await developments in low-cost colour-recording technology.

1.3 Present-Day Scanning and Recording Systems

The traditional raster-type scanning of the image almost invariably employ photo-electric devices in the facsimile equipment in use today. Usually a photocell or photomultiplier tube reads the light reflected from progressive areas on the subject copy, converting the intensity to an electric current but a transmitted light principle is also used on some scanners which require transparencies or negative films of subject copies (e.g. microfilm scanner). In the spot scanner (Fig 1.3a) a tiny spot of light moves along each line of scan and the reflected intensity is detected by the photoelectric device. Alternatively, in a floodlit system the general area of scan is illuminated and the elemental area whose intensity is read is pinpointed by a lens system located at the input to the transducer (Fig.1.3b). This has an advantage of a less sensitive transducer being needed but at the expense of a high-intensity illuminating lamp. The main difference between the photocell and the photomultiplier

tube is that the output of the former requires considerable amplification.

The physical mechanism of scanning may be electromechanical or electronic but the vast majority of existing facsimile systems employ electromechanical means. Here cylinder (or drum) scanning, or flatbed scanning may be used. In cylinder scanners the subject copy is wrapped round a cylinder which is then rotated at a constant speed (Fig.1.4) A moving carriage on which the scan head (including light source) is mounted slowly traverses alongside the cylinder propelled by a rotating threaded screw on which the carriage is mounted. A helical scan is traced out over the subject copy as the carriage progresses down the length of the copy. A disadvantage of the cylinder method of scanning is the need to wrap the copy round the drum before each scan. This is avoided in the flatbed scanner (Fig.1.5) where the copy is pulled slowly into a slit by a roller-feed mechanism and eventually exits through an output slit. Several techniques are used to achieve scanning action, one of which is shown in Fig.1.6 . Here a mirror is used to reflect the illuminated line of scan on to a slit aperture. Left-to-right scanning of the line is accomplished by the use of a rotating spiral slit. Eletronic scanning mechanisms require no moving parts but are generally expensive. However they are capable of extremely high speeds of scanning. The so-called flying spot scanner makes use of a cathode-ray tube (Fig.1.6) to produce the progressing light spot which is made incident on the subject copy through a lens-mirror combination. The reflected light is then read by a sensitive photo-transducer.

The laser is being increasingly used in high-resolution scanners as the illuminating light source. Its beam is sufficiently fine to define the elemental area of intensity without additional optics, often the beam is too fine and needs to be spread out by use of lenses. Some form of lens system however may be needed for correction of non-linearities.

Instead of a single photocell the photoelectric transducer may consist of an array of cells arranged in a straight line (linear array) or in a matrix. These may be embedded in a chip of silicon which may also contain extra facilities for amplification, clocking, etc. In its application a reduced image obtained via a condensing lens is made incident on the device whereupon idividual cells within it are activated. The Reticon linear array employs photodiodes which are internally connected to storage capacitors and MOS switches. The Fairchild CCD linear image sensor makes use of a silicon sensor array which accumulates charges depending on incident light flux. This is then transferred to an analogue shift register and subsequently clocked out. These devices are employed in the majority of modern facsimile scanners (e.g. digital Group 3 apparatus which stipulates 1728 array elements per scan line).

Recording is the reverse process of translating the electrical signal into a visual copy. Except for the actual recording much of the mechanisms for scanning may be applied in reverse at the recorder for the reconstitution of the image. Thus the cylinder and screw mechanism of Fig.1.2b can be used except that the intensity-reading optics is replaced by a 'writing' optical unit which marks elemental areas of a photoreceptive medium (e.g. film) which is wrapped round the drum. The laser is a useful means to this end. On more conventional recorders the image is displayed on paper which has usually been chemically treated. In electrosensitive paper a coating of electrically conducting carbon is covered by a second coating of all-white high-resistance zinc oxide. Marking is accomplished by a tungsten stylus which is fed with a high voltage. Above 50V the white coating is cratered to expose the black carbon, the width of the crater being dependent on the applied voltage. The ground plane is provided by the metallised drum or feed rollers. At higher scan-speeds larger voltages are required for cratering. Grey scale reproduction is possible with this

recording method. With thermal paper a dye-coating is used which is melted in the marking process by a temperature in the 110°C to 130°C range over 1 ms. The thermal print head which applies the heat consists of a length (of a scan-line) of a film resistive bar which is intersected at right angles along its length by fine conductors connected to a monolithic array of diodes. The elemental area on the resistive strip is supplied with current of typically 100mA by a single conductor when its diode is open, which then is rapidly heated up and melts the dye coat in contact with it. This method of recording is applicable to black-white images only. Another common recording medium is electrostatic paper in which an ionic salt has been added to make it slightly conducting. The surface of the paper is coated with a dieletric substance. The marking consists of a two-stage process. Initially a layer of charge is deposited by a stylus for elemental areas required to be marked. This is possible because of the slightly conducting paper, through which charges are attracted and deposited across the dieletric. A black toner is then applied to the surface of the charged surface and is fixed into the paper at points of deposited charge by heat or pressure. The recording method is widely used in modern facsimile recorders (e.g. Group 3 apparatus).

1.4. CCITT Standardisation of Facsimile Transmission

With the rapid growth in facsimile traffic it was recognised that some form of standardisation of transmission and receiving equipment and transmission techniques will be beneficial to users and suppliers and possibly encourage its further expansion. A goal of standardisation is to ensure that facsimile terminals may communicate with one another irrespective of manufacturing brands. To achieve this, recommendations on parameters of apparatus and methods of transmission were proposed by the international telecommunications body, the CCITT (Comite Consultatif

International Telegraphique et Telephonique) and have been largely adopted since their introduction. Three distinct groups of facsimile transmission are defined [2], based primarily on speed of transmission, and designated Groups 1, 2, 3 systems. The recommendations for a fourth group, Group 4, have been introduced recently. These recommendations do not preclude manufacturers from installing their own special features, for example extra-fast mode on Group 2 machines, which will work only when both transmitter and receiver are purchased from the same manufacturer.

Groups 1 and 2 facsimile are analogue systems which employ fixed-rate scanners. Group 1 apparatus enables transmission of a standard ISO A4 page (210 x 297mm or 8.3 x 11.7in) in 6 minutes. Frequency modulation is used for signal transmission and grey-scale reproduction is supported. The vertical density is 96 lines/inch and scanning time is 180 lines per minute. Group 2 apparatus achieves a transmission time of 3 minutes for an A4 page and employs vestigial-sideband amplitude-modulation(AM-VSB) with duobinary inversion to reduce the signal spectrum. A reduced grey-scale range is possible although many recorders use only black-white recording media. Some Group 2 apparatus feature a non-standard white-space skip facility which allows transmission of sparse text documents in less than 2 minutes. The majority of facsimile systems in existence which use the telephone network are Group 2 machines.

Group 3 apparatus contains a higher level of sophistication. Here the facsimile signal is digitised to two levels, black or white and coded for compression before transmitted via an in-built modem. The standard resolutions are 7.7 pels/mm (196 pels/inch) in the horizontal direction and 3.85 lines/mm (97.81ines/inch) in the vertical direction. An optional fine vertical resolution of 7.7 lines/mm (196 lines/inch) is available. Transmission rate is at 4800 bits per second conforming to the CCITT V27 specification (with fall-back to 2400 bits per second). An optional higher

speed transmission of 9600 bits per second (conforming to V29 specification)with fall-back to 7200, 4800 and 2400 bits per second) is allowed. At the standard rate of 4800 bits per second and for a normal resolution of 3.85 lines/mm the typical transmission time for an A4 document is 1 minute but the exact period varies depending on the amount of detail in the image.

Two compression methods are recommended for use at the normal or higher vertical resolutions. The standard code is that of the one-dimensional Modified Huffman code which encodes runlengths of the digitised output. Separate codebooks are to be employed for white and black runs. At the end of each line a 12-bit binary sequence of eleven zeros followed by a 1 is transmitted to indicate the end of line. At the receiver any sequence of seven consecutive zeros is regarded as an end of line (EOL) flag. A minimum transmission time of 20 ms is specified for a line in order to allow adequate time for the paper-feeding mechanism to advance a line. However options of 0, 5, 10 and 40 ms are possible for faster or slower apparatus. This implies that for a 20 ms minimum and transmission rate of 4800 bits per second a minimum number of 96 bits must be output per line, inclusive of 12 bit EOL sequence resulting in a maximum factor of compression of 20.6 per line. The two-dimensional modified READ code (for Relative Element Address Designate) is an optional scheme. In this code the current scan-line is encoded with reference to the previous line. To limit the propagation effects of transmission errors every kth line is encoded using the one-dimensional Huffman code. The value of K is 2 for normal resolutions and 4 for the higher resolution.

Group 4 facsimile apparatus is designed to link directly into digital data networks without the need for modems. In this case a very low if not zero error-rate of transmission is guaranteed in which case a value of K equal to the number of scan-lines in the image may be used for the modified READ coding method which is the recommended compression scheme. A

store-and-forward facility is also expected and total transmission time for an image is expected to be half of that for Group 3 apparatus.

1.5. Digital Facsimile

The original feature of facsimile transmission is the communication of the electrical signal which is output by the scanner and which represents the variations in intensity in elemental areas of the image to the remote receiver where it is directly applied to the recorder to produce the image copy. In digital facsimile this signal is sampled and quantised and usually encoded before transmission. At the receiver a decoding process is effected which recovers the digitised signal. An irreversible consequence of digitisation is the distortion arising from temporal and amplitude quantisation which is minimised by making the step size of quantisation sufficiently small so that subjectively the distortion is largely indiscernible. The digitised output sample is usually referred to as the pel (for picture element) or pixel. Each pel value is represented by a binary word whose length is determined by the number of grey levels regarded as adequate for an accurate reconstruction of the image. Practical image digitisers usually feature 5 or 6-bit output word lengths (giving 32 or 64 grey levels respectively) but a word length of 8 bits is often assumed in image-processing research.

The transmission of the digitised image as straight PCM requires a considerable bit rate which in turn requires more bandwidth than the analogue system if the image is to be transmitted in the same time. However the digitised image output now lends itself to elaborate processing techniques which can remove or reduce the redundancy intrinsic in the image and thereby achieve a considerable reduction in bit rate. The advent of low-cost digital computing and logic hardware makes this economical to implement in practice.

Digital facsimile also ties in with the present-day trend towards an integrated digital data network. Apart from the greater quality and reliability of transmission afforded by digital transmission systems, an all-digital telecommunications network allows common sharing of facilities and even more beneficially, integration with computer networks and facilities.

In the research reported in this thesis the class of images investigated is that of two-tone images. This includes a wide variety of image material, for example, text, line drawings and sketches. In such images tonal variations are unimportant and are removed by slicing the output of the scanner. Usually a fixed slicing threshold is employed which is manually adjustable but on some scanners a floating threshold is used which is determined by average levels of black and white. The two-level output is sampled at regular instants in time, the interval period of which defines the horizontal resolution, giving a clocked stream of binary data where a '1' usually denotes a black level and a '0' a white picture element. The vertical resolution is the density of lines along the vertical direction of the image where the horizontal direction is defined as the direction of the scan-line (along the shorter length of the A4 page) and the vertical direction is the orthogonal direction. The latter resolution is usually set by the scanning mechanism e.g. the pitch of the screw thread in the cylinder and screw scanner or the angular increment of the stepper motor drive in a flat-bed mechanism.

Resolution is an important consideration in the digitisation of the image. A large value obviously leads to an increased number of binary digits and an inadequate value results in poor image quality. The choice of resolution is determined by the fineness of lines and size of characters in the image. For line drawings at least two pels are required for a

vertical line's width. In the characters of text at least ten scan lines are required to dissect the character within its height[1]. As an example a typical height for elite typewritten characters is 1/16 inch which will require a resolution of 160 lines per inch for assured legibility. Fig.1.7 shows some examples of character heights and the corresponding vertical resolutions for independent character legibility.

A commonly observed effect in digitised black-white images is that of jitter. This appears as a saw-toothed approximation of edges such as vertical and oblique lines. The effect is illustrated in Fig.1.8. Because the sampling clock is not phase-locked to the line frequency the clocking instants gradually slip in phase on successive scan-lines, giving rise to the saw-toothed appearance. The effect is more pronounced on oblique lines and may be reduced by increasing the sampling density or synchronising the sampling clock to the line repetition frequency. The digitised output from the black-white facsimile image is a clocked binary stream which is communicated to the receiver by a normal digital transmission process for byexample by pulse signalling or by digital modulation of carrier. In its raw form the binary data contains a large measure of redundancy which can be reduced so that a smaller number of binary digits are needed. In the following paragraphs a review of the theoretical concepts involved in redundancy removal is given.

1.6 Theoretical Aspects of Data Compression

The purpose of a communication system is to communicate messages from a source over a medium to the receiver. A basic aim of the communications engineer is to design a system which does this as accurately and as economically as possible. Consider a discrete source which outputs symbols whose values belong to a set (alphabet) of size n. The output sequence may be transmitted directly using an n-valued signal, or each output symbol may

be first mapped into a different symbol or sequence of symbols whose alphabet size m may be different from n. A common alphabet size here is two so that each output symbol is mapped or encoded into a sequence of binary digits. In the straightforward case fixed length sequences or codewords are employed with the codeword length given by $\log_2 n$. Thus for a total of R output symbols from the source $R\log_2 n$ binary digits are transmitted over the channel. Clearly if this number of digits can be reduced some economy of transmission will have been achieved (for example saving in transmission time or reduction of transmission bandwidth). It is therefore of interest to the communications system designer to know what limits exist, if any, on the performance of such an encoding system for a given source. The process of mapping source symbols into an alternative symbol set in order to achieve greater efficiency in transmission is sometimes called source coding and the procurement of a reduced number of information digits to represent the source is known as data compression. Fig.1.9 shows the basic components of a communications system with source coding for data compression.

The theoretical bounds on data compression are entrenched in the field of information theory. A brief review of the more relevant aspects of information theory is given in this section. In the famous paper of Shannon [3] a measure of the information content of a source was introduced which is known as the entropy function. The entropy, which is a function of the statistical properties of the source, was shown to provide the bounds to compression for any encoder. The entropy of the source gives the average amount of information which is generated per symbol of output. The amount of information for a random event which has a probability of occurence p is quantified as $-\log p$. For a discrete independent(memoryless) source which features n possible outcomes the average of the information associated with each outcome is described as the entropy of the source and is given for a source X by:

$$H(X) = -\sum_{i=1}^{n} p_i \log p_i \qquad 1.1$$

where p_i is the probability of occurence of each output state and

$$\sum_{i=1}^{n} p_i = 1 \qquad 1.2$$

It is convenient to use logarithms to the base two thereby giving the entropy in bits per symbol. For digitised images the symbol corresponds to the pel (picture element).

With grey-level images quantised to r bits the pel may have one of 2^r possible values. Eqn. 1.1 may be used directly to obtain the entropy of the image source on the assumption it is statistically independent, that is,

$$H(X) = -\sum_{i=1}^{2^r} p_i \log p_i \text{ bits per pel} \qquad 1.3$$

The entropy has its maximum value when the state probabilities are equal. Then

$$H(X)_{max} = \log_2 2^r = r \text{ bits per pel} \qquad 1.4$$

where

$$p_i = \frac{1}{2^r} \quad \text{for all } i \qquad 1.5$$

The observation here is that the source outputs the largest amount of information of r bits per pel when all grey levels are equally probable. This is equal to the PCM codeword length at the output of the source, signifying that conventional PCM coding is most efficient when all grey levels are equiprobable. As it is unlikely in practice that the grey level probabilities will be equal, the source entropy will usually be less than r bits per pel and the use of fixed-length PCM words for transmission is therefore not efficient. It is thus useful to map the source states x_i to states y_i so that the new source Y, whose outputs are y_i, yield on average more information per symbol of its output than X. The scheme is illustrated in Fig.1.10. The binary alphabet will be assumed for the encoder Y so that each state y_i consists of a sequence of binary digits of length L_i. The average length of y_i is given by

$$\bar{L} = \sum_{i=1}^{n} p_i L_i \quad \text{bits where } n = 2^r \qquad 1.6$$

As $\bar{L}$ in effect is the average number of bits required to encode the output of X it is required to be as small as possible to minimise the total number of binary digits needed to convey the output sequence from X. The lower bound of $\bar{L}$ was shown by Shannon to be

$$\bar{L} \geq H(X) \quad \text{bits} \qquad 1.7$$

for a binary code alphabet and H(X) expressed in bits per symbol.

The above essentially means that in encoding a source it is not possible to devise a coder which produces codewords whose average word length is less than the source entropy. This is intuitively reasonable as a source which generates information at an average of H(X) bits per symbol will need a codeword whose average length is at least this number of bits

to convey the information without any loss. When the minimum number of bits is achieved the encoder is said to be 100% efficient. A figure of merit for efficiency can thus be defined as

$$\eta = \frac{\bar{L}}{H(X)} \qquad 1.8$$

Having known the lower bound of $\bar{L}$ or the upper bound of compression it would be useful to know the circumstances under which this can be achieved and how high efficiencies can generally be obtained. Before discussing these aspects some well-known concepts of coding are briefly presented.

For a code to be useful it must be uniquely decipherable i.e. any input sequence which is encoded by the coder must be reproduced exactly by the decoder without any alternative sequences being possible. A further useful feature of a code is that it be instantaneous i.e. it allows immediate detection of codewords once they have occured in the data stream. Instantaneous codes form a sub-set of uniquely decodable codes. A basic property of an instantaneous code is that no codeword is a prefix of any other codeword. A well-known test for the instantaneous code is the Kraft Inequality:

$$\sum_{i=1}^{n} \frac{1}{2^{L_i}} \leq 1 \qquad 1.9$$

stated here for binary codes.

To obtain an instantaneous code for a given source of n outcomes it is not an unreasonable approach to assign a codeword for each outcome of which length is sufficient to accomodate the amount of information associated with that outcome i.e. $-\log p_i$. Thus

$$-\log p_i \leq L_i \leq -\log p_i + 1 \qquad 1.10$$

where L_i is assigned to the integer nearest and greater than or equal to $-\log p_i$. It was shown by Shannon that for such a coding scheme an upper bound may be obtained on the average codeword length $\bar{L}$ which is equal to $H(X)+1$. Thus

$$H(X) \leq \bar{L} \leq H(X) + 1 \qquad 1.11$$

The average codeword length $\bar{L}$ takes on its minimum value of $H(X)$ when the probability distribution of the source symbols is given by

$$p_i = \frac{1}{2^{L_i}} \quad \text{for all } i=1,2,3,\ldots n \qquad 1.12$$

Even when the coding follows the condition of 1.10 there can exist more than one instantaneous code which gives average codeword lengths in the range given by Eqn.1.11. It is useful to know whether a code can be constructed which produces the minimum possible average wordlength always for a give arbitrary set of probabilities of source outcomes. Such a code, called a compact instantaneous code, is indeed possible and is attributable to Huffman [4]. The Huffman code produces a value of $\bar{L}$ which obviously satisfies Eqn.1.11 but which is the smallest compared to all other possible codes.

In practice the neat distribution of Eqn.1.12 is unlikely to occur so if it is required to approach the minimum limit of $\bar{L}$ with an arbitrary set of probabilities, then as Shannon showed one way of achieving this is to encode groups of N symbols. As N tends to infinity the efficiency of coding tends to 100% but the complexity of coding increases. The coding of source symbols taken N at a time is referred to as the encoding of the Nth extension of the source. The output of this extended source can be regarded as a new source denoted by X^N with increased alphabet size. The

entropy of this source is then

$$H(X^N) = -\sum_{j=1}^{n^N} p_j \log_2 p_j \text{ bits per symbol} \qquad 1.13$$

As $H(X^N)$ is the average information per N symbols of X, its average information per symbol is given by $\frac{H(X^N)}{N}$

For a statistically independent source the block entropy can be shown to be N times the per pel entropy [5], i.e.

$$H(X^N) = NH(X) \qquad 1.14$$

If the Huffman code was employed to encode the blocks the resultant average word length per block of X, $\bar{L}_N$, is constrained by the block entropy as

$$H(X^N) \leq \bar{L}_N \leq H(X^N) + 1 \qquad 1.15$$

The compression of X is reflected in the average word length per pel of X which is also known as the bit rate. The bounds of the bit rate, b, are stated in Shannon's First Theorem:

$$\frac{H(X^N)}{N \log D} \leq b = \frac{\bar{L}_N}{N} \leq \frac{H(X^N)}{N \log D} + \frac{1}{N} \qquad 1.16$$

stated here for an alphabet size D. The logarithm base is the same as that used in calculating the entropy. For a binary alphabet D=2 and if entropies are expressed in bits then the inequality 1.16 becomes

$$H(X) \leq b \leq H(X) + \frac{1}{N} \qquad 1.17$$

$$\lim_{N\to\infty} b = H(X) \qquad 1.18$$

i.e. the per symbol entropy may be approached by increasing the block size N.

In real life however the output samples of the digitised image are not statistically independent. This is apparent from the two-dimensional structure of the graphical content of images. An output of the image source is therefore likely to be influenced by others spatially close to it.

The entropy of the image source can be defined by the limiting value of the quotient of the block entropy $H(X^N)$ and the block size N as N tends to infinity i.e.

$$h(X) = \lim_{N\to\infty} \frac{H(X^N)}{N} \qquad 1.19$$

This is known as the absolute or true entropy of the source and takes into account all possible correlation between outputs of the source. Thus the output bit rate b of any compressor can never be smaller than this value. For a given finite N the value $\frac{H(X^N)}{N}$ is an upper bound to the true entropy of the source. A measure of the amount of compression achieved is the compression ratio (C.R.) which is defined as

$$\text{Compression Ratio} = \frac{\text{Total pels in uncoded image}}{\text{Total bits in encoded image}} \qquad 1.20$$

A source possessing finite memory may be modelled as an Mth order Markov source. In this model the current output sample X_0 is statistically dependent on M previous samples X_1 to X_M. For an image the latter samples will be located adjacent around the current pel. The Markov source is

completely described by a set of conditional probabilities which define the probability of the state of the current sample X_o given the states of the M samples on which it is statistically dependent. From these the entropy per symbol of the source may be found and is given, for an n-alphabet source, by

$$H(x) = -\sum_{j=1}^{2^M} \sum_{i=1}^{n} p_i(x_i, x_{j_1}, x_{j_2}, \ldots x_{j_M}) \log_2 p_i(x_i | x_{j_1}, x_{j_2}, \ldots x_{j_M})$$

bits per pel 1.21

where $p_i(x_i | x_{j_1}, x_{j_2}, \ldots x_{j_M})$ is the probability that the current output sample takes on the ith state given that the M previous outputs feature the jth state, and $p_i(x_i, x_{j_1}, x_{j_2}, \ldots x_{j_M})$ is the state probability of the M symbols joined with the current symbol. The state probabilities may be calculated from the conditional probabilities of the source.

When encoding the Nth extension of the Mth order Markov source the block entropy is, as with the memoryless case, N times the original entropy (proof given in [5])

$$\text{i.e. } H(X^N) = NH(X) \qquad 1.22$$

When the block size N exceeds the memory depth M, the extended source may be regarded as a first order Markov source. If N is smaller than M, the extended source is a new R-th order Markov source of alphabet size n^{M-R} where R is the alphabet size of the original Mth order Markov source.

The effect of correlation between output symbols of the source is to decrease the average information per symbol of the source over that in the memoryless case. This is evident in that the state of the M symbols for an M-memory source may be utilised to aid the prediction of the state of a current symbol with a consequent decrease in information required for the

purpose. The average information left which is needed to specify the outcome when a particular state of M symbols is known, is called the conditional entropy of the source, and is expressed as

$$H(X|X_1,X_2,\ldots X_M) = -\sum_{i=1}^{n} P(X_i|X_1,X_2,\ldots X_M)\log P(X_i|X_1,X_2,\ldots X_M) \qquad 1.23$$

The sum of the conditional entropies weighted by the (M+1) state probabilities gives the true entropy of the source.

Shannon's Coding Theorem for the ergodic Mth-order Markov source is expressed as follows:

$$\frac{(N-M)H(X) + \delta}{N} \leq b = \frac{L_N}{N} \leq \frac{(N-M)H(X) + \delta}{N} + \frac{1}{N} \qquad 1.24$$

where δ is a constant independent of N. In the limit as $N \to \infty$

$$b = H(X) \qquad 1.25$$

Here again the bit rate $\frac{L_N}{N}$ can be made to approach the source entropy H(X) by using larger blocks.

As stated earlier the research reported in this thesis is concerned with two-tone images. Binary images are particularly suitable for the application of source coding methods because the binary form of the source output allows reduced system complexity for their storage and manipulation and enables sophisticated coding methods to be applied. Further grey-level images lend themselves to a different approach to compression which is geared to exploitation of redundancy of amplitude samples (for example transform coding) and which can sustain relatively large levels of distortion introduced by the compression process. The binary image on the

other hand is a hard-limited copy of its original continuous form and as a consequence its amplitude information is exhausted. This type of image, whilst able to tolerate a small amount of distortion, is generally sensitive to encoding errors. The latter take the form of black dots appearing against a white background or loss of black elements in the image. In the former case a moderate amount of such distortion can occur without affecting the intelligibility of the image. The loss of black pels is more objectionable as although, in small amounts, do not destroy the legibility of graphic characters, can be irritating.

Up till now the source coding of image has been discussed for a lossless system i. e. one in which the source output is reproduced exactly after decoding. By allowing a small amount of distortion of the source outputs, increased levels of compression may be obtained. This type of encoding is known as lossy coding and is featured in the compression systems developed in this thesis. The entropy is effectively altered as a result of the distortion of the sources and is intuitively less in view of the potential for increased compression. As a consequence this coding approach is sometimes referred to as being entropy-reducing.

An inevitable consequence of compression is an increased susceptibility to transmission errors. Efficient variable-rate encoding schemes normally exhibit error propagation effects so that an entire image may be lost as a result of a single transmission error. In practice it is more often preferable to employ compression methods which exhibit lower compression ratios but are more robust in performance under noisy conditions.

In the next chapter a review of known techniques of achieving bit-rate reduction is given. In choosing a suitable method of digital compression the main considerations are unavoidably levels of attainable compression, complexity of implementation and effects of transmission errors.

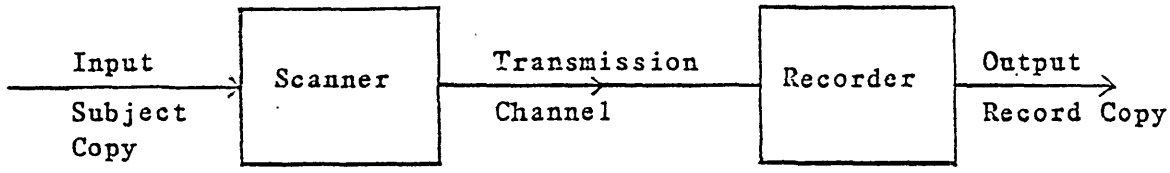
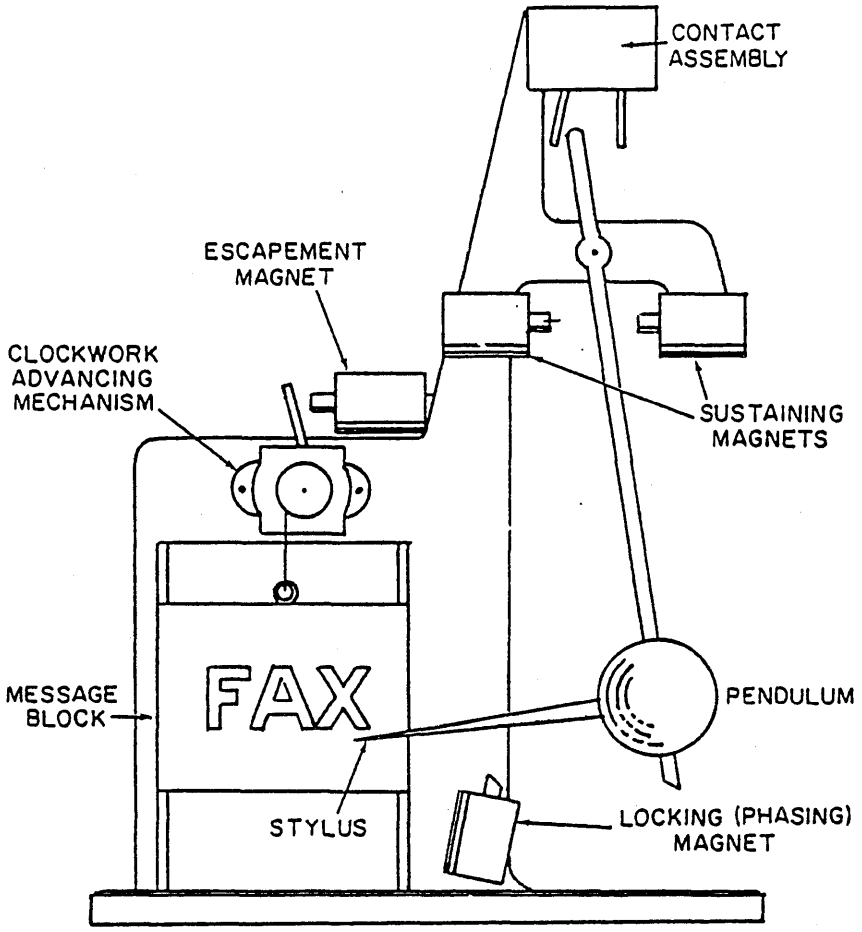
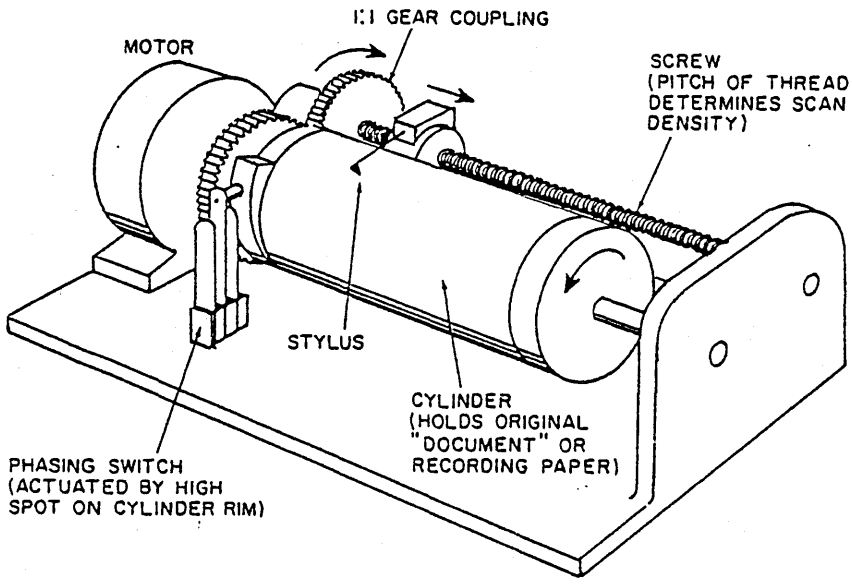


Fig.1.1. Components of a Facsimile System.

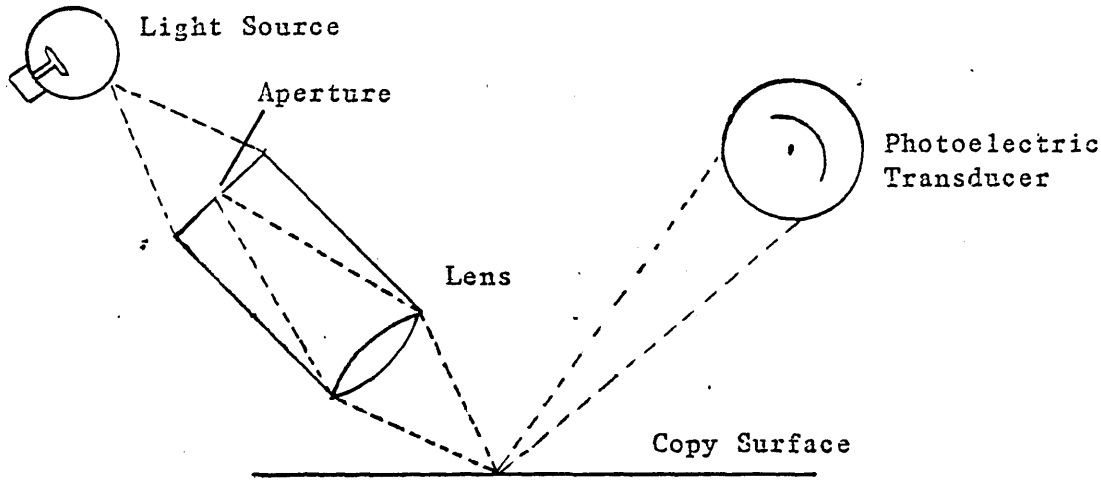


(a) Bain's Pendulum-driven Machine patented in 1843.

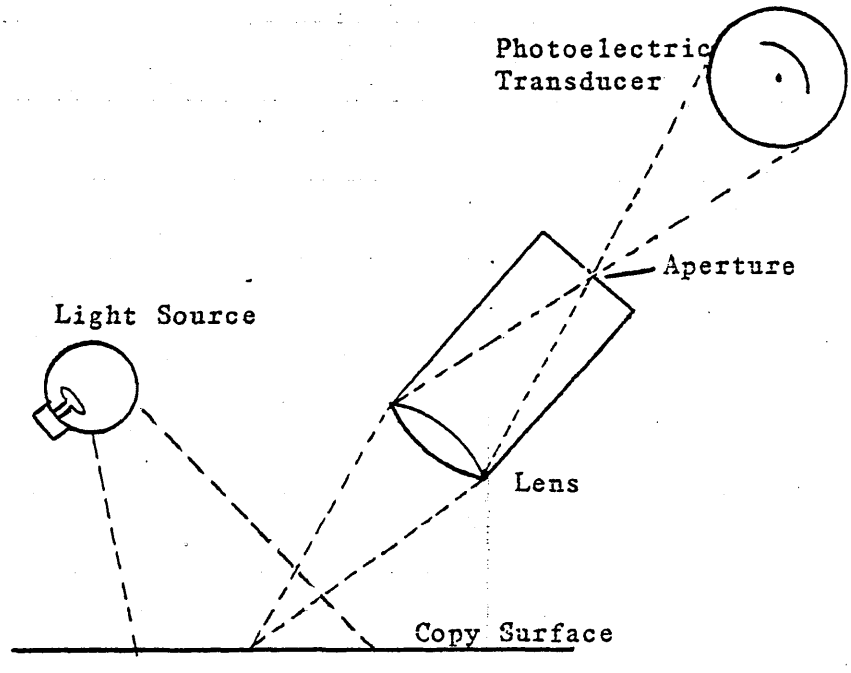


(b) Cylinder and Screw Scanner introduced in 1850.

Fig.1.2. Some Early Facsimile Apparatus (reproduced from Costigan).



(a) Spot Projection



(b) Flood Projection

Fig.1.3. Photoelectric Scanning of Subject Copy.

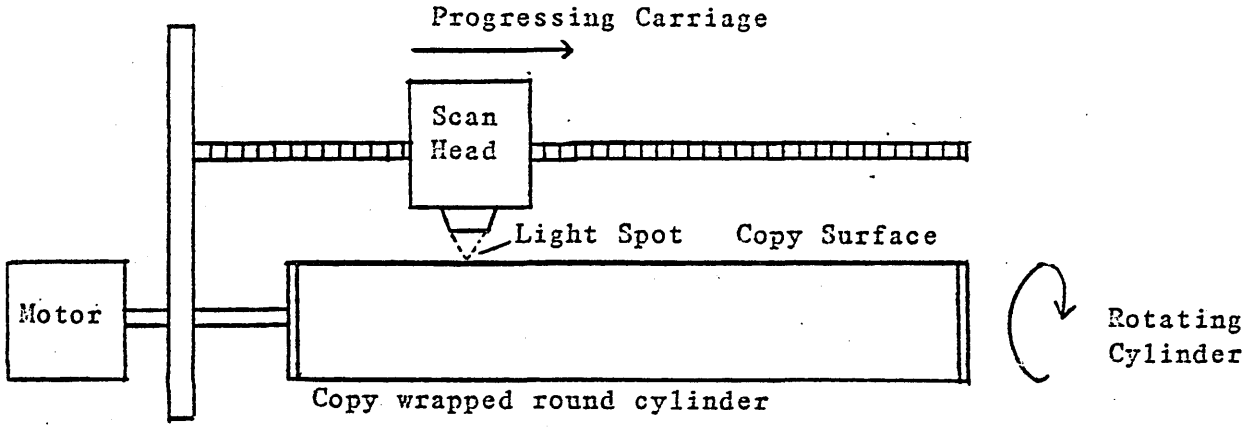


Fig.1.4. Cylinder and Screw Scanning Mechanism (plan view).

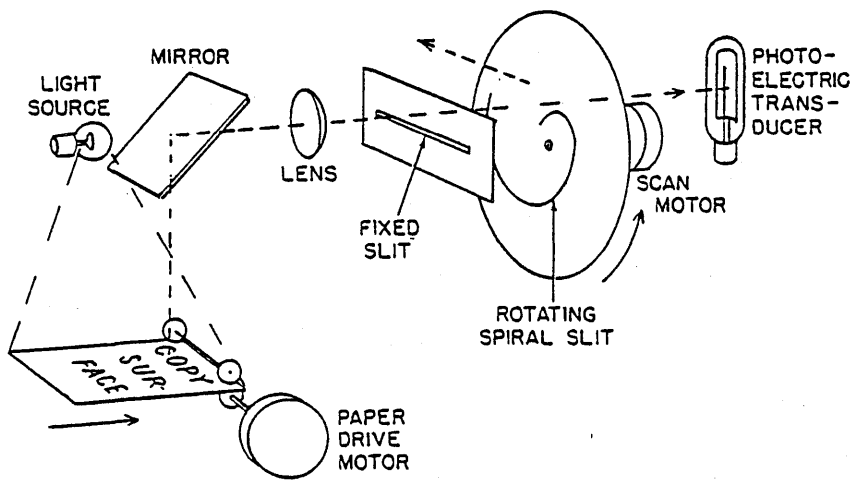


Fig.1.5. Flat-bed Scanning Using Spiral Slit Technique.

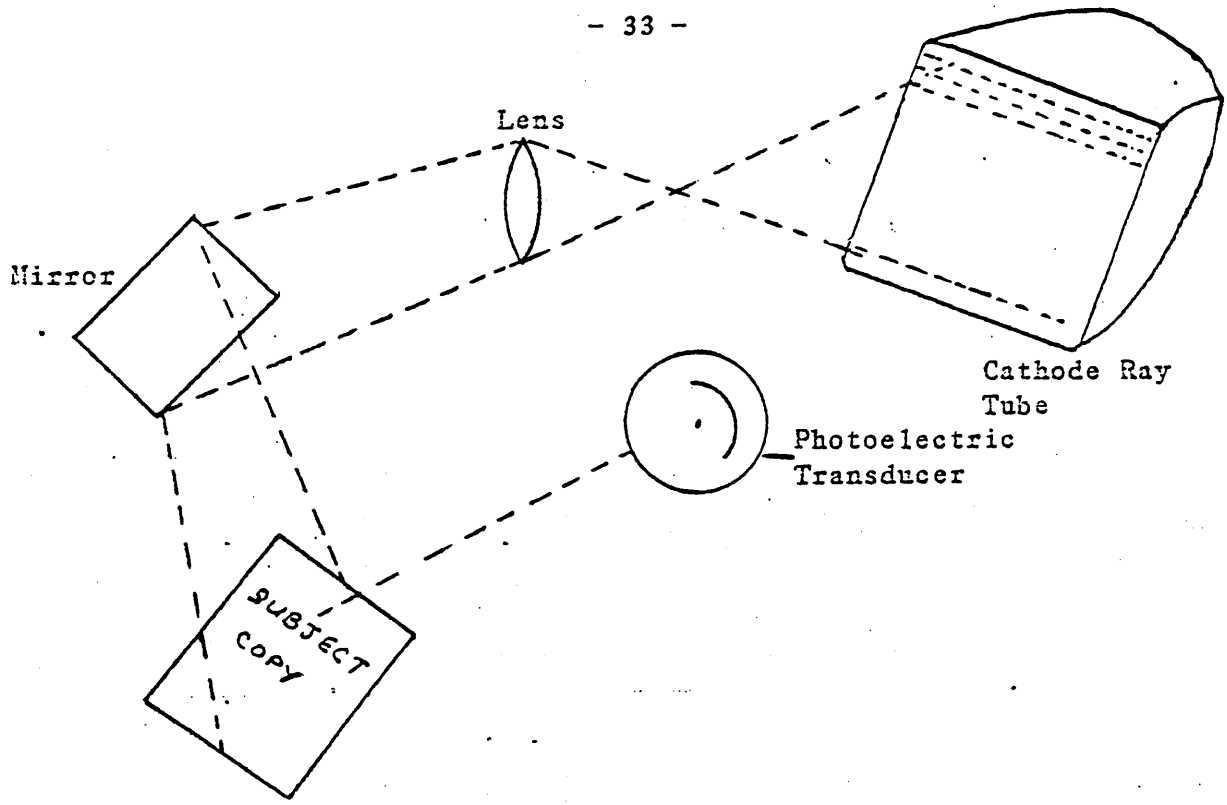


Fig.1.6. Electronic Scanning of Image.

	Minimum Character Height	Minimum Scan-line Density	Examples
1.	$\frac{3}{64}$ inch (1.2 mm)	214 lines/inch (8.43 lines/mm)	Footnotes, captions.
2.	$\frac{1}{16}$ inch (1.6 mm)	160 lines/inch (6.30 lines/mm)	Elite type font.
3.	$\frac{3}{32}$ inch (2.4 mm)	106 lines/inch (4.17 lines/mm)	Pica type font.
4.	$\frac{1}{8}$ inch (3.2 mm)	80 lines/inch (3.15 lines/mm)	Engineering drawings.
5.	$\frac{5}{32}$ inch (4.0 mm)	64 lines/inch (2.52 lines/mm)	Charts

Fig.1.7. Examples of Character Sizes and Corresponding Minimum Scan-line Densities for Assured Legibility (from Costigan).

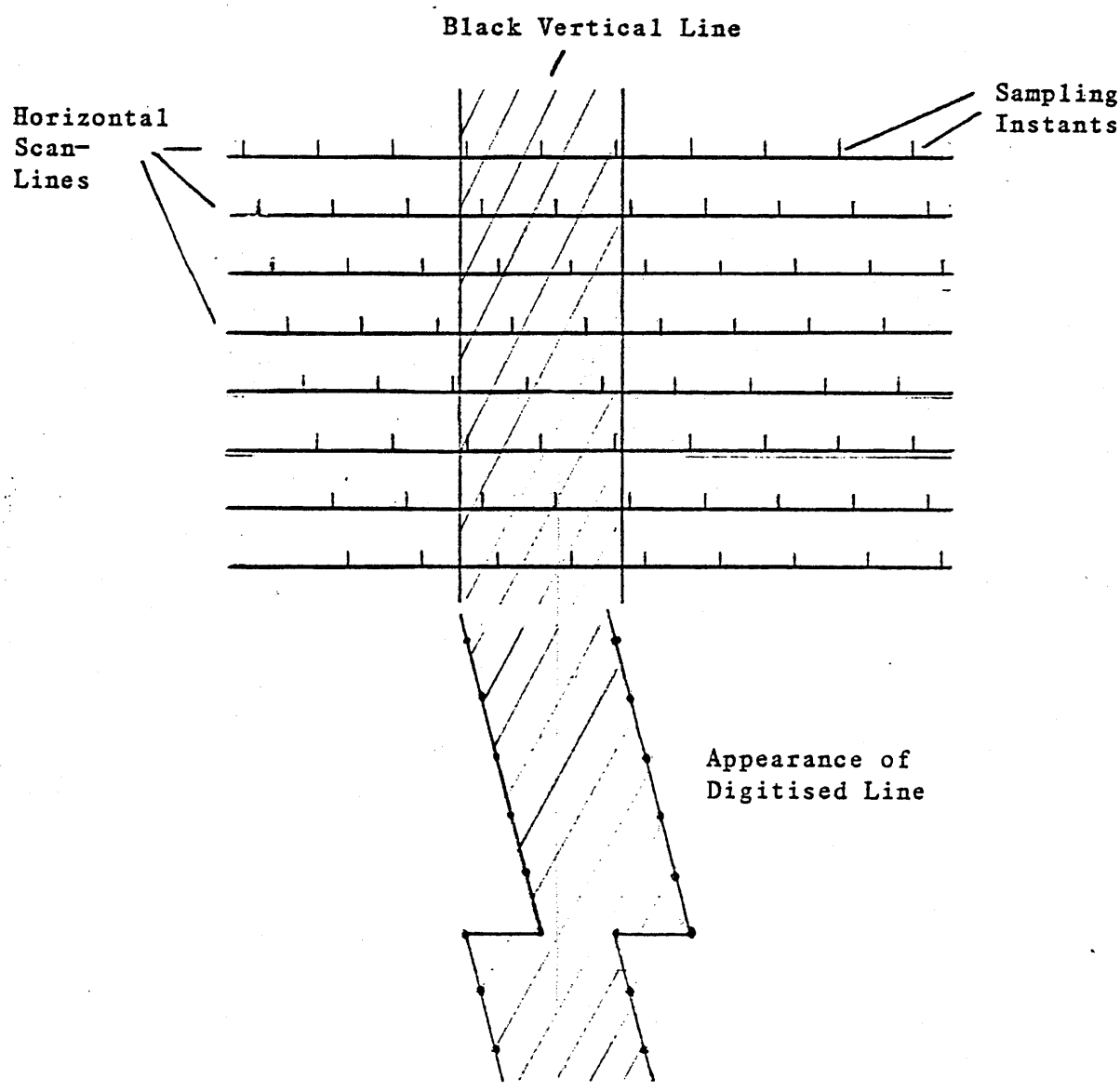


Fig.1.8. Showing the effect of jitter in Image Digitisation.



Fig.1.9. Elements of an Efficient Communication System.

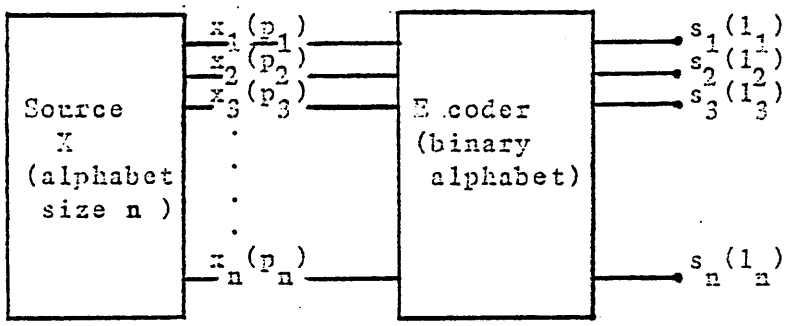


Fig.1.10. Encoding of discrete source X. Each possible outcome x_i has probability of occurence, p_i, and is mapped into a binary sequence s_i of length l_i.

CHAPTER 2

OVERVIEW OF COMPRESSION TECHNIQUES FOR BLACK-WHITE FACSIMILE DATA

2.1 Main Groups of Compression Methods

In the preceding chapter the theoretical limits to compression of a source were discussed and it was stated that it was possible to devise a code which produced the shortest average wordlength, or largest compression, for a source whose probability distribution of outcomes is known. It would appear that this might provide the universal solution to all compression problems. In principle if an image contains R pels, then encoding the Rth extension of the source using a Huffman code will take into account all possible correlation between pels within an image and will yield the optimum compressed sequence for all images. However such an implementation is impractical in view of the phenomenally large size of the source alphabet. Alternative strategies are needed which encode on a much less global basis. Much of the research into the compression of facsimile data is involved with the study of suitable models to approximate the real source and the development of coding methods to achieve the actual compression.

The three most well-known approaches to source encoding of binary facsimile data are runlength coding, predictive coding and block coding. A large number of techniques based on these premises have been described in the literature. The large majority of these are lossless methods concerned with obtaining as high a level of compression as is possible and are therefore inevitably variable-rate schemes. Fixed-rate coding schemes are intrinsically inflexible in that they are unable to exploit efficiently

redundancy in the image which is usually not uniformly distributed i.e.the degree of compression is constant irrespective of local content of image and is determined by the worst case local high-level activity likely to be encountered. For this reason fixed-rate schemes are more likely to be lossy in view of the need to obtain increased levels of compression. However fixed-rate schemes can have other advantages like simplicity of implementation and resistance to transmission errors.

2.2 Runlength Coding

Probably the most numerous of the coding methods for black-white facsimile are those which concentrate on encoding the image modelled as a runlength source. Here the lengths of the black and white runs in the output stream are encoded. A minimum-redundancy code based on the probabilities of runlengths may be used, for example the Huffman code, which is in fact the recommended scheme for use in CCITT Group 3 [2] facsimile apparatus although a modified form of Huffman coding is employed.

The theoretical limits of compression by encoding runs of pels can be ascertained from calculation of the entropy of the source. Assuming a single code is used to encode both white and black runs, the average information associated with a run of the runlength source X is given by:-

$$\text{Entropy per run, } H_r(X) = -\sum_{i=1}^{j} p_i \log p_i \qquad 2.1$$

where p_i is the probability of occurence of the ith run and j is the set of all possible runlengths.

To obtain a measure of compression potential the parameter of interest is the entropy per pel, H(X). This is given by $H_r(X)$ divided by the

average length of the output run i.e.

$$H(X) = \frac{H_r(X)}{\bar{r}} \qquad 2.2$$

where $\bar{r}$ is the average runlength.

In practice the probability distribution of white runs is quite different from that of black runs, so separate codes are used. The source is modelled as a pair of runlength sources X_w and X_b, and assuming white runs are independent of black runs the per pel entropy is given by

$$H(X) = \frac{\bar{r}_w}{\bar{r}_w + \bar{r}_b} H(X_w) + \frac{\bar{r}_b}{\bar{r}_w + \bar{r}_b} H(X_b) \qquad 2.3$$

where $H(X_w)$, $H(X_b)$ are the per pel entropies for white and black runlengths respectively, and $\bar{r}_w$, $\bar{r}_b$ are the average white and black runlengths. If a Huffman code is used for each of the sets of white and black runlengths the overall achievable bit rate b satisfies the relation

$$H(X) \leq b \leq H(X) + \frac{2}{\bar{r}_w + \bar{r}_b} \qquad 2.4$$

Whilst it is possible to calculate the entropy from the measured probabilities of runs it is often convenient and useful from an analytical point of view to obtain these in a less empirical fashion. To this purpose a first-order Markov model to the black-white facsimile source was developed by Capon [6] which has been used by many authors. In this source each output sample is statistically dependent only on its preceding sample. The probabilities of run lengths can be shown to exhibit a geometric distribution and successive runs are statistically independent (runs of the

real source have been found experimentally to be largely independent), i.e.

$$p(r_i) = p_i = 0 \qquad \text{for } i \leq 0$$
$$= \frac{1}{a-1} \exp^{-\left[\log \frac{a}{a-1}\right]i} \qquad \text{for } i=1,2,3,... \qquad 2.5$$

where a is the mean value of runlength.

From these a contour graph is obtained [17] from which the per pel entropy of the source may be read given only the average lengths of black and white runs. A further useful property of this model is that in view of the geometric distribution of the runlength probabilities and their statistical independence the calculated per pel entropy is an upper bound i.e.any other runlength distribution will not yield a larger value of entropy for the source.

The derivation of the Huffman code and the instrumentation of the encoder and decoder can be complex when the size of the source alphabet is large. Modifications to the Huffman coding procedure have been described in the literature, which sacrifice a small degree of optimality for ease of implementation. Probably the best known of these is the Modified Huffman code used in CCITT Group 3 apparatus. Here a runlength can range from one pel to one scan-line of 1728 pels. A Huffman codebook is formed for black and white runs respectively for run-lengths from 0 to 63. All run lengths greater than 64 are divided into multiples of 64 and any remainder is coded from the base codebook. Each multiple of 64 is assigned a Huffman codeword.

An alternative modification called the Truncated Huffman code [8] assigns Huffman codewords to run lengths up to 47 for white runs and 1 to 15 for black runs. Runs longer than these are coded using a prefix

codeword of 3 bits followed by the length of the run in binary (11 bits). A similar concept was discussed by Hankamer [9] where the procedure involved lumping together improbable source messages and treating the group as a single message with probability equal to the sum of the probabilities. The Huffman code found for this group is then used as a prefix when encoding the constituent messages and is followed by the uncoded message itself. For a large-alphabet source the amount of memory needed to hold the codebook is considerably reduced and if a large number of the messages are highly improbable the resultant decrease in coding efficiency is small. The performance of the Truncated Huffman code is found generally to be not as efficient as the Modified Huffman code in the compression of the CCITT test images [8] but the differences are not large.

Instead of employing the Huffman code other codes exist which achieve high levels of coding efficiency and are easier to implement. Two well-known codes are the linear and logarithmic codes. These are characterised by their wordlengths increasing approximately linearly or logarithmically through the message set. The use of one type of linear codes called the A_N codes (also known as Laemmel or L_N codes) and another of logarithmic codes, the B_N codes (also known as the Hasler or H_N codes), was studied by Meyr, Rosdolsky and Huang [10]. Both the A_N and B_N codes contain codewords whose lengths are multiples of fixed-length blocks. Examples for N=2 of the A code (A_2 code) and the B code (B_2) are shown in Fig.2.1. In the A_2 code runs of 1 to 3 are coded using a 2-bit binary word. The code 00 is reserved as a prefix to indicate runs greater than 3. Thus codes for runs 4 to 6 are simply the binary word extended by the 2-bit prefix code 00. For runs 7 to 9 the prefix is now two blocks of 00, and so on for longer runs. A run value may be obtained by adding the 2-bit blocks with a 00 in a block replaced by the maximum binary value of a block i.e.3. In general for an N-bit basic block a runlength is coded by a total of (n+1) N-bit blocks consisting of n N-bit prefix words if its value L lies

in the range

$$n(2^N-1) < L \leq (n + 1)\ (2^N - 1) \qquad 2.6$$

For a given size of alphabet r the maximum codeword length is that for r and may be found from

$$\frac{r}{2^N-1} - 1 \leq n < \frac{r}{2^N - 1} \qquad 2.7$$

The codeword length itself is (n+1)N bits.

For the B_2-code the first bit of each codeword is a continuation bit referred to as C in Fig.2.1b . This is followed by the 2-bit binary representation in all its possible combinations, giving 4 codewords. For runs greater than 4 a second block of 3 bits (including continuation bit) is appended. The 4 non-continuation bits in the codeword allow a further 16 values of runlength to be represented. For runs greater than 20 a third block of 3 bits is adjoined and so on. Within a codeword the continuation bit C is set to be the same, but alternates between succesive runs. The decoder thus needs to wait for the arrival of the next codeword to determine the end of the current codeword and the code is therefore not instantaneous. For n blocks of an N-bit code the total codeword length is n(N+1) bits inclusive of continuation bits, and the runlength L which may be coded is in the range

$$\frac{2^{nN} - 1}{2^N - 1} \leq L < \frac{2^{nN} - 1}{2^N - 1} + 2^{nN} \qquad 2.8$$

It was shown by Meyr et al that the A_N code is nearly optimum for a geometrical distribution of runlengths where the value of N is chosen to be the integer nearest to $(1+\log_2 a)$, where a is the mean of the distribution. The B_N code was similarly shown to be nearly optimum for a negative power

distribution i.e. of the form $P(L) \simeq L^{-\alpha}$ where α is a positive constant.

The results obtained by Meyr et al with the use of optimal A_N codes for separate coding of black and white runs of their set of test images showed that the redundancies in the original images may be reduced down to an average factor of 0.46 . Generally the coding of white runs was less efficient than that of black runs. The use of B_N codes resulted in improved compression and was also less sensitive to the choice of the basic block length N. The effectiveness of the use of the B_1 code on the coding of the CCITT test images may be observed from the comparison table given in the paper of Musmann and Preuss [8]. Here the B_1 code was used to encode both white and black runs. Compared with the use of the Modified Huffman code the compression ratios obtained were lower for all test images. However the implementation of the B_N codes is a great deal simpler. These can essentially be instrumented using presettable counters. An adaptive form of the A_N code was also carried out by Meyr et al in which a line was pre-scanned and the averages of black and white runs determined. These were then used to compute the optimum value of N to be used for the line using the relationship

$$N = 1 + \log_2(\bar{r} - 1) \qquad 2.9$$

where $\bar{r}$ is the average run length.

The results showed considerable improvement over the fixed optimum A_N codes with a factor of about 2 further decrease in redundancies. This is obtained at the expense of a delay of a scan-line and increased complexity of coder.

Other schemes for the encoding of runlengths have also been described. Golomb proposed a simple method for efficiently coding (and decoding) runs which are geometrically distributed and have an infinite number of

outcomes[11]. This method is ideally suited for coding runs of a memoryless binary source whose probabilities of '0' and '1' are p and (1-p) respectively. Another method for encoding runlengths was described by Ismail and Clarke [12]. The method here involves sectioning the scan-line into blocks of a size determined by the probability of black elements in the line and does not require knowledge of runlength statistics. A method for encoding runlengths in the derivative of the image was described by White, Lippman and Powers [13]. Here a single block-based code was used and its efficiency was found to be close to that of the Huffman code. Alternative runlength coding schemes have also been described by Takagi and Tsuda [14] and Rosenheck [15].

Runlength coding is basically a one-dimensional coding technique. In order to exploit the correlation between scanlines of the image, two-dimensional forms of runlength coding have been developed. The optional Modified READ (for Relative Element Address Designate) compression scheme recommended for use in the CCITT Group 3 apparatus for example attempts to obtain increased levels of compression by coding the differences between runs occurring in adjacent scan lines. The current scan line is coded with reference to the previous line. Run lengths in the current line are measured relative to selected reference points which are defined by certain conditions of distances between transmission pels in the current and previous lines in the immediate coding region. Different codes are used for the three identified states or modes. To restrict error propagation every 4th line is encoded normally (without reference to the previous line) using the Modified Huffman Code. A scheme which bears similarities to this was proposed by Huang [16]. Here the coding (called Predictive Differential Quantising or PDQ) references the current scan line to the previous but the coding is perhaps more straightforward. The difference between the position of the start of the current black run and the one above it, designated Δ_1 is encoded, and so is the difference

between the lengths of the black runs, Δ_2 (alternatively the difference between positions of black-white transitions may be transmitted instead of the latter). For new and final black runs special identifiers are used. Unlike the Modified Read code the distance between transmissions Δ_1 can take on a maximum of 1 scan line of pels with no option for alternative coding for large Δ_1. The calculated entropy values based on measured statistics were found to be generally lower for weathermaps but not for text compared with one-dimensional runlength coding. However the results for text improved over runlength coding when the resolution was increased. Another method which encodes blocks of two lines at a time has been developed by Kalle-Infotec U.K. Ltd. Here 'double-decker' runs of black or white are transmitted using adaptive run length codes which are block based. Transition regions at the edges of runs are classified and encoded separately. The results for CCITT images obtained with this code [8] showed improvements over one-dimensional runlength coding only for three of the eight test images at the standard resolution. At the higher vertical resolution this number increased to six. The relatively small improvements in performance of the code is compensated by the fact that in the event of transmissions errors propagation of decoded errors is confined to two lines of image.

2.3 2-Dimensional Predictive Coding

An important class of compression schemes which aims to exploit the two-dimensional redundancy prevalent in images is that which employs the prediction process. Here the current pel X_o is assumed to be statistically dependent on M previous pels which are located spatially in its immediate vicinity (Fig.2.2). The state of the current pel is predicted from a knowledge of the states of the M pels and compared with the true state. If the prediction is true a 0 is assigned, otherwise a 1 indicates a

prediction error. The one-to-one mapping of pels produces the 'prediction error' image which is then encoded using runlength codes e.g. Huffman. At the receiver the original image may be restored through the use of the same prediction tables. For an M-pel predictor the minimum probability of prediction errors, P_e, is stated to be [17]

$$P_e = \sum_{k=1}^{2^M} P(S_k) \text{ Min.}\{ P(1|S_x), 1 - P(1|S_k)\} \qquad 2.10$$

where $P(S_k)$ is the probability of the M-pel state and $P(1|S_k)$ is the conditional probability of the current pel state being 1, given the kth M-pel state.

This simply implies that the minimum errors as a result of the prediction process is determined by the lower value of the two conditional probabilities which may be obtained from measurement. Thus the use of tables formed from conditional histograms is the optimum form of predictor. The total prediction errors can only decrease as the prediction memory M increases. The use of adaptive prediction was also investigated by Kobayashi and Bahl [17] and the results for their test images showed lower levels of prediction errors than were obtained in the fixed predictors. The improvement however was not substantial.

The encoding of the prediction errors constitutes the actual compression stage. The above authors investigated the use of several codes including Huffman coding of blocks, straight binary runlength coding and Golomb's run length coding. A multimode version of Golomb's code was also proposed which was intended to compensate for non-geometric distribution of run lengths encountered in the image. This code was superior to the others and achieved about 80 to 90% of the calculated upper bounds for runlength coding.

Instead of encoding directly the prediction error patterns Preuss [18] encoded the runs of states of the M-pel patterns terminated by a prediction error (i.e. a 1 value) for the state. For each line the runs of all possible source states are transmitted one after another. The proposed technique ideally assigns an optimum code to encode runs of each state matched to its run statistics and was found to be optimum for encoding of the Mth order Markov source. However when M is large the use of individual codes for each state results in a high degree of complexity. A simplified alternative was suggested for practical coding which combined all states except for the all-zero pattern into a compound state, so that only two states were considered for encoding. The Laemmel and Hasler codes were used to encode the runs in the simulations with the simplified algorithm being used for larger prediction blocks. The results showed gains in compression ratio for all test images compared with one-dimensional coding especially when the non-simplified scheme was employed. The coding of the prediction pattern in this fashion is highly effective but is complex.

An interesting and very efficient compression method was described by Netravali et al [19]. By re-ordering the pels in the current scan-line using the previous line as a reference, a mapped image is obtained in which the average runlengths of white and black runs are increased. This yielded a lower runlength entropy than for the original image and hence promises an increase of amount of compression. The ordering procedure is quite simple - for each pel in the current scan line the pel above it in the previous line is examined and if it is white the current pel is stored in the left side of a line memory, if the previous pel is black the current pel is stored in the right side of the memory. As the ordering proceeds down the current scan line the line memory gradually fills. At the decoder the pels for a line are reinstated from knowledge of the states of corresponding pels in the previous line. Instead of ordering the pels of the scan line

the prediction errors may be used. The predictor used by the authors was a simple one-pel predictor using the previous line element. The entropy of the ordered image in this case was lower than that for ordered raw image pels. A further extension to larger predictors was proposed. Here instead of ordering being dependent on the previous line, the predictor state at each pel location is examined to establish if it is a 'good' or 'bad' state. 'Good' states are those which lead to a high probability of success of prediction i.e. their conditional probabilities are near to 1 or 0. If the state is a 'good' one the prediction error is placed on the left side of the memory, otherwise it is put on the right side. The entropy of the ordered result was found to be about 16 to 25% less than that for run length coding of unordered prediction errors using the same predictor. A simulation of Preuss's scheme was also carried out on the test images and the ordering technique registered a 10 to 18% gain of coding efficiency over this method. A similar ordering method has also been reported by Wah [20].

2.4 Block Coding

The coding of blocks of pels has the attraction of simplicity of coding hardware. Blocks of fixed size are easier to handle than variable entities like run length and are particularly suitable in byte or word-oriented computer systems whether in implementation or simulation. From Shannon's First Theorem the true entropy of the source can be approached by encoding increasingly large blocks of the output. For an image this will require the use of two-dimensional blocks which means that several lines of storage will be needed for a raster scanned image. If a Huffman code is employed the codebook size becomes excessive and decoding operations become complex. For a large majority of images however the all-white block has a very large probability of occurence in view of the

white background in the images. This suggests that a sub-optimal coding scheme may be effectively used which simply discriminates the all-white block and transmits the non all-white blocks without any coding. A flag bit is needed to identify the all-white or non-white state. Thus a block size of N pels will be coded with a single bit of 0 for an all-white state and a '1' followed by the block if the block is not all-white. The compression ratios for typical images using this white-block skipping (WBS) technique may be found in Huang and Hussain's paper [21]. Here a theoretical analysis was developed for Capon's model of the source. The bit rate for an image using a block size N is given by:-

$b_N = (1 - p_N + \frac{1}{N})$ bits per pel where p_N is the probability of an all-white block in the image. It is clear that the choice of N affects the obtainable bit rate and the best value for one image may not yield the best bit rate for another. Using optimum values of N the WBS method was found to be highly efficient for text. Huang and Hussain proposed a modification which skips whole lines of white. This resulted in compression which was comparable to Huffman run length coding of text but there was no improvement for the weathermaps or line drawings.

The idea of skipping white was further applied in an adaptive scheme proposed by Coulon and Johnsen [22]. The block size N was sub-divided into sections which are examined for all-white states. When each sub-division was not all-white, a further division is made until some minimum block-size is left. At each stage of division a prefix flag bit is assigned to indicate an all-white or non-white state. The results obtained were compared with non-adaptive WBS coding and coding using Laemmel and Hasler codes. When a two-dimensional adaptive block code (N=16x16) was used the result was superior to that of the other codes.

2.5 Other Lossless Compression Techniques

Apart from the runlength, predictive and block models adopted for the encoding of the facsimile source, other strategies have also been proposed. A number of these employ principles based on pattern recognition. The automated recognition of letters and numerals is a wide field in itself. Its use in facsimile compression is restricted to typewritten and printed image material. Even within these the characters are restricted to a small set of types and fonts. However even these may be adequate for some applications for example the transmission of weather numeric information and newspaper text. A more flexibile pattern-encoding scheme was described by Arena [23]. In the one-dimensional version block runs were transmitted by specifying the positions of the starts of the runs using co-ordinates. The positions of block runs of length 1 followed by 2, 3 and so on were transmitted with transition from one length to the next indicated by a special code word. In the two-dimensional case, rectangular patterns replaced runs. The results showed an improvement in compression (which is more than double) over optimum runlength coding only for the two-dimensional version. The complexity of coding however is high, requiring storage of a whole page and elaborate pattern identification procedures. Arena also investigated the transmission of individual black elements content. Another flexible scheme which uses the idea of pattern recognition has been described by Ascher and Nagy [24]. Pratt et al[25] proposed a self-learning symbol recognition scheme called combined symbol matching (CSM) in which a table of symbols is formed from commonly recurring characters or binary patterns in the image. Each character, or symbol, which is isolated is compared with the existing symbols in the table and if a match is found the code for the symbol is transmitted. Nonisolated symbols are coded using a two-dimensional runlength coding technique. Tests with CCITT documents showed a substantial improvement for text material but for graphics the performance was similar to that

achievable with two-dimensional runlength coding.

2.6 Fixed Rate Compression Methods

The compression methods discussed previously are variable-rate techniques, producing codewords whose lengths vary depending on local image content. To enable continuous transmission over a constant-rate channel buffering is required if the image source is fixed-rate , or alternatively, a variable velocity scanner is required. The design and implementation of a buffer to achieve a smooth data rate without underflow or overflow can be complicated. The difficulty may be overcome by the use of fixed rate compression techniques in which a constant length of output codewords is issued for a given length of input symbols. The compression ratio is therefore fixed for all images. Constant rate methods of compression generally yield lower values of compression ratio than variable-rate techniques and usually are lossy coding schemes. However, they are simple to implement, readily applicable to fixed-rate scanning apparatus still in wide use, and generally are more immune to transmission errors.

A straightforward and extremely low-cost compression method is that of block-to-block coding. Here blocks of N pels of the image output are taken and for each block an M-bit codeword is assigned where M is less than N. This yields a compression ratio of N/M. The coding involves allocating codewords to the 2^M most probable patterns of N-pel blocks, but because M is smaller than N some patterns are unassigned. These are simply approximated to the most similar assigned patterns thus introducing distortion of the image. This distortion is subjectively acceptable to some extent and the smallest value of M which is applicable is determined by the worst case resultant distortion that is deemed tolerable. The encoding itself is trivial involving simply reading the memory storing the

codewords with addressing by the input pattern. For large N the memory size of 2^N x M bits becomes excessive and a search-and-compare method may be employed which is time-consuming and requires more complex hardware. Present-day memory technology allows the direct lookup method to be economically implemented for block sizes up to 16 pels. The investigation into this method of compression has been carried out by Tindall [26] who used one-dimensional blocks and Preuss [27] who employed two-dimensional blocks. Tindall employed primarily 8-pel blocks and used a codebook which is derived from the combined statistics of a wide variety of images sampled at 150 pels/inch. With the use of two-dimensional blocks which requires delays of several scan lines, Preuss reported higher compression ratios using larger block sizes up to 36 pels (6x6). The percentage encoding errors indicated that compression ratios of 2 and 3 may be obtained with block sizes of 5x5 and 6x6 for the two test images employed. However no mention was made as to whether the codebooks used were derived from individual image statistics. For large blocks the coding performance has been observed [26] to be sensitive to block statistics and moreover each image may not yield sufficient number of block samples to provide adequately accurate statistics. The block-to-block compression scheme was demonstrated by Tindall to be capable of withstanding transmission errors up to an average rate of about 1 in 100. At this rate most variable rate compression methods including those using re-synchronisation sequences, will have failed.

A different form of block-to-block encoding which does not require a priori statistics of the image was described by Tindall [26]. Prior to encoding sections of the data stream are delayed and stored. Then using a pseudo-random address generator the pels of the section are accessed for block coding. The randomisation of the pels results in block patterns which ideally obey the probability distribution for groups of N pels of statistically independent pels, which is a binominal distribution. A

codebook is derived based on this distribution which assigns M-bit words to the most probable patterns and for non-assigned patterns the pattern having the most number of coincident black elements is used for approximation. In this way distortion takes the form entirely of a loss of black elements but because these are randomly distributed the subjective effects should not be too severe. The results obtained generally showed that the maximum compression ratio attainable which is subjectively acceptable is about 1.33 using an 8-pel coding block and scrambling section size of 1024 pels. The random loss of black elements results in overall drop in contrast of the image and individual pels losses could be discerned by the naked eye in black regions. An adaptive form of this method of compression was also proposed which led to a variable-rate output but yielded higher compression and was quite resistant to transmission errors.

A method of compression aimed at bit rate reduction of a multiplexed multi-channel facsimile system was described by Seitzer et al [28]. The synchronous digitised samples from N scanners were presented to the multiplexer but only one channel is connected to the output and the outputs of the others are lost. To identify which channel has been selected an address word of length $\log_2(N+1)$ bits is transmitted thereby giving a compression ratio of $N/\log_2(N+1)$. The strategy here aims to exploit the fact that the probability of N outputs simultaneously registering more than 1 black element is small in view of the normally small black element probability of each image. The statistical distribution of the N-tuple patterns was reported to be nearly binomial thereby suggesting that the instantaneous signal samples at the input to the multiplexer are largely independent of one another. The limits of performance were studied by Stucki [29]. The practical maximum value of N was stated to be 12 which gives a maximum compression ratio of 3.7.

A fixed-rate compression method proposed by Stucki [30] sub-samples

the image and offsets the sub-sampling instants by half the pitch between picture elements in alternate lines. Consider an image originally sampled at 200 pels an inch . The equivalent action of sub-sampling by a factor of two in the horizontal direction only is to transmit alternate pels in the horizontal direction, which immediately gives a compression ratio of two. To compensate for the subjective effects of this sub-sampling, at every other line the transmitted horizontal pels are staggered as shown in Fig.2.3a. Tindall simulated this scheme as a comparison with the block-to-block technique and reported that sub-sampling with an element offset on alternate lines showed raggedness of lines in line drawings but was less noticeable in text material. Sub-sampling by factors greater than 2 are also viable, as shown in Fig.2.3b for a factor of 3, with staggering on succeeding lines, but a worsening of image quality can be expected. Post-processing operations can be carried out at the receiver to restore the untransmitted elements. Stucki proposed the use of a fixed set of polymino rules for establishing the colours of missing elements. Preuss in [27] adopted a statistical approach where a priori tables based on conditional probabilities are used to predict the colour of the untransmitted element from the states of surrounding transmitted elements. Fig.2.4 shows the patterns for 4-pel and 12-pel predictors. For prediction states which are unreliable additional information to indicate these are transmitted in the line interval. In the interpolative method of Stern [31], one data bit is transmitted for every block of NxN pels thereby giving a compression ratio of N^2. The transmitted bit is not an image pel but its state is dependent on the states of adjacent pels. At the receiver the N^2 adjacent bits are made the same colour as the transmitted bit. A ragged appearance of the reconstructed image was obtained for text material, for N=2, but strokes of characters were preserved. In [32] Ismail and Clarke desribed a method of sub-sampling which transmits alternate elements in both horizontal and vertical directions thereby

achieving a compression of 4. Prior to this sub-sampling doubling of single-element runs was performed which improved the connectivity of characters in the sub-sampled image. At the receiver restoration masks and interpolation functions were employed to improved the subjective quality of the reconstructed image.

2.7 Effects of Transmission Errors

An inevitable consequence of compression is increased sensitivity to transmission errors. In the variable-rate schemes ivolving the coding of runlengths or blocks of the image output the effect of a single transmission error is to generally cause erroneous decoding from that point onwards with consequent false reinstatement of subsequent blocks or runs. To restrict such propagation of errors practical coding schemes usually incorporate re-synchronisation sequences at regular intervals in the image - normally at the end of each scan-line or a multiple of scan-lines.

A study of the effects of transmission errors on the CCITT coding schemes was made by Bodson and Schaphorst [33]. Tape recordings of transmission error sequences encountered on actual telephone line connections over the German switched network using a 4800 bps modem were used in the computer simulation. The types of errors are usually of the burst variety arising from switching equipment in the exchanges. Similar recordings were used by Mussman and Preuss [8] in their comparison of noise effects on several one and two-dimensional compression schemes. In these recordings each lasting minutes the average rate of error was in the range 1 in 10^3 to 1 in 10^6. In order to reduce the subjective effects of errors several actions may be taken at the receiver. The presence of an error in a scan-line may be assumed when the decoded scan-line length does not equal the known length. When this is detected the previous line may be repeated

for the present line or the present line can be simply blanked. For the two-dimensional scheme several error processing options involving repetition and blanking were simulated by Bodson and Schaphorst [33]. The results obtained by these authors generally indicate that when operating over the switched network the loss of intelligibility of characters can occur especially when several adjacent scan-lines are corrupted by an error burst. The effect is, as may be expected, worse for two-dimensional coding schemes where a group of scan-lines may be incorrectly interpreted as a result of a single transmission error. By including error processing techniques the subjective effects of errors may be reduced to a limited extent at the expense of increased complexity of the receiver. Apart from errors occuring in the coded lines the synnchronisation sequences are also susceptible to errors. The corruption of these inevitably lead to loss of scan-lines in the decoded image.

Fixed-rate compression methods whose compression ratios are generally lower than variable-rate schemes and are independent of the image, are usually more resistant to transmission errors. In the N/M block-to- block coding method for example the effect of a single error is to cause at most N pels to be wrongly reinstated. Resynchronisation sequences are unnecessary although code-word framing has to be established at the start of transmission. In the interpolating schemes of Preuss, Stucki and Stern the effects of incorrectly received colours of trasmitted elements may result in false reconstruction of missing elements but because the interpolation process makes use only of transmitted elements and not the reconstituted pels, error propagation does not occur.

2.8 Conclusion

The encoding of the black-white facsimile source based on runlength,

predictive and block models constitute the bulk of compression methods which have been developed. Many of these have been successfully implemented and incorporated into working apparatus. The encoding of runlength for example has become almost a standard approach in practical facsimile compression. The majority of these compression schemes are information-preserving and variable-rate which imply that they may not be readily compatible with existing constant-rate facsimile equipment. Further they are sensitive to transmission errors and require high-performance channels for satisfactory operation. For some situations a sacrfice of the amount of compression may be acceptable for the benefits of noise immunity, low cost and image-invariant compression. This thesis is devoted to the development of such compression systems.

Runlength	Codeword
1	01
2	10
3	11
4	00 01
5	00 10
6	00 11
7	00 00 01
8	00 00 10
9	00 00 11
10	00 00 00 01
11	00 00 00 10
12	00 00 00 11
13	00 00 00 00 01

A_2 - Code

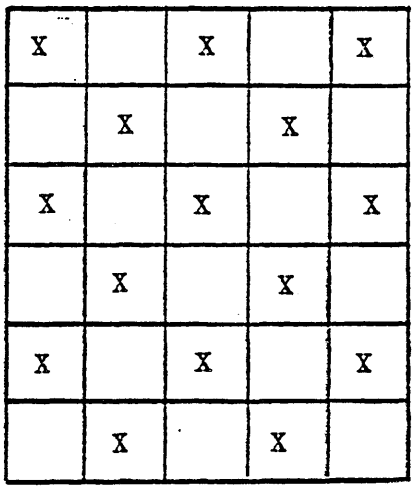
Runlength	Codeword
1	C00
2	C01
3	C10
4	C11
5	C00 C00
6	C00 C01
7	C00 C10
8	C00 C11
9	C01 C00
10	C01 C01
11	C01 C10
12	C01 C11
13	C10 C00

B_2 - Code

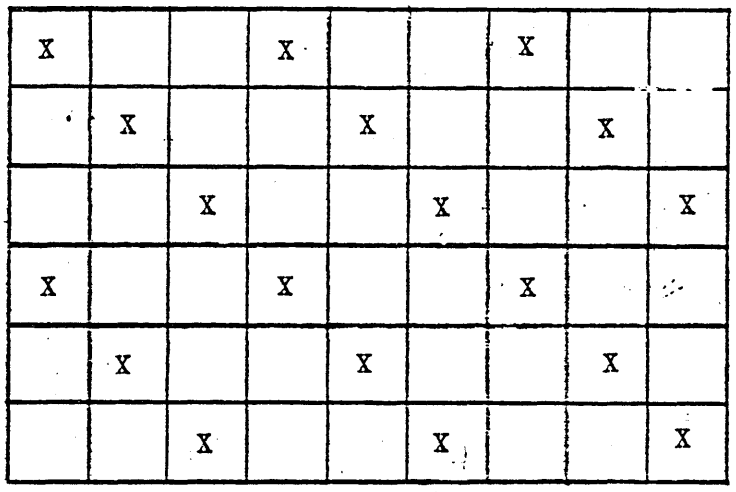
Fig.2.1. Codeword Assignments for Runlengths up to 13 in the A_2 and B_2 Codes.

X_{13}	X_{12}	X_{11}	X_{10}
X_9	X_8	X_7	X_6
X_5	X_4	X_3	X_2
X_1	X_0		

Fig.2.2. A 13-pel Predictor. The state of X_0 is predicted from the states of X_1 to X_{13}.



(a) N = 2



(b) N = 3

Fig.2.3. Examples of Horizontal Sub-sampling.

	X_1		X_2	
		X_0		
	X_3		X_4	

4-pel Predictor

	X_1		X_2	
X_3		X_4		X_5
	X_6	X_0	X_7	
X_8		X_9		X_{10}
	X_{11}		X_{12}	

12-pel Predictor

Fig.2.4. Typical Prediction Patterns for Preuss's Interpolation Algorithm. X_0 is the pel to be reconstructed, all other X_i are transmitted pels used for prediction.

CHAPTER 3

PROGRAMME OF RESEARCH AND DESCRIPTION OF SYSTEM HARDWARE

3.1 Relevance of the Research

In this research the aim is to develop low-cost compression systems for two-tone digital facsimile images which can perform well over noisy transmission links. In the presence of transmission errors at average rates of worse than 1 in 1000 the more established variable-rate compression schemes are likely to fail. The trade-off for noise immunity is lower amounts of compression than can be obtained with the variable-rate methods. Possible areas where such robust compression systems may have application include HF links as used for example for maritime facsimile transmissions, narrowband VHF channels, aircraft communication channels, underwater data links and poor-grade telephone channels.

The low cost and fixed rate feature of this type of compression system makes it also suitable for economical digitisation of existing analogue facsimile systems which usually employ constant-rate scanners and recorders. Digitisation is attractive nowadays as it offers the prospect of integration with other digital facilities including link-up with computer systems. The inclusion of a compression system results in a lower transmission bit rate requirement for the facsimile channel thus enabling cheaper lower-speed modems to be used, or multiplexing with other digital services e.g. telex. For a constant-rate transmission channel a fixed-rate compressor avoids the neccesity for buffering or changes to the scanning equipment. An example is the conversion to digital facsimile of CCITT

Group 2 apparatus which at the present time constitutes the majority of facsimile machines utilising the telephone network. This achieves a transmission time of 3 minutes for an A4 page compared with the nominal 1 minute for Group 3 apparatus, but is simpler and less expensive. For non high-volume document transmissions the Group 2 speed may be adequate and digitisation, incorporating compression, can be performed economically by means of a special digitisation unit external to the equipment.

A further possible reason for digitisation is that satisfactory performance may not be achievable with the analogue apparatus over some links, for example due to excessive group delay or poor attenuation response of the channel. In this case the more powerful equalisation techniques featured in modern modems may overcome such difficulties and provide for better-quality received images.

The cost of digitisation can be expensive especially if additional digital facilities are not available for sharing the modems required at each end of the transmission line. A possible solution is to avoid the use of commercial modems and include digital transmission facilities within the facsimile digitisation unit thereby making it a complete self-contained module. In order for such an approach to be successful the coding and transmission functions should be implemented by a common processor so that the hardware costs are minimised. In this thesis such a system has been developed making available a low-cost 'bolt-on' unit for the digitisation of fixed-rate facsimile apparatus.

3.2. Organisation of Thesis and Originality of Research

In this thesis three methods of fixed-rate compression of the black-white facsimile image are presented. Chapter 4 describes the investigations into a block-to-block compression scheme which does not require any a priori codebook and as such is a 'universal' coding scheme directly applicable to all images without previous knowledge of its statistics. The principle of universal coding is known in the literature e.g. [34] but to the author's knowledge a study of the application of this technique to two-level images is as yet unreported. Specifically the research here examines the levels of compression ratio attainable by a universal approach to block-to-block encoding compared with a fixed-codebook scheme as researched by Tindall [26] and reported by Preuss [27]. The quantitative results of computer simulation of this lossy coding scheme are presented and the qualities of reconstructed images are assessed. The performance in the presence of transmission errors is evaluated. The use of partially adaptive codebooks is also investigated.

In Chapter 5 a new method of compression is proposed which basically interleaves non-white blocks into the white background. To this end pairs of blocks of the image are taken and are assigned header bits representing their white or non-white states, and interleaving of non-white blocks is subsequently carried out on a sequential basis. This form of compression is thus called Sequential Block Interleave Coding (SBIC) and its development constitutes the main work of the research. For the method to be loss-free the block-pair states must show a favourable probability distribution, otherwise errors are introduced which take the form of lost black elements. To reduce this distortion a simple but effective procedure is introduced for selecting the blocks to be deleted. In general though by delaying a sufficient number of lines lossless coding can be achieved.

However the use of a large coding field produces a greater vulnerability to transmission errors. To avoid this a pseudo-random mapping of blocks is proposed which can give virtually error-free results for all the test images at considerably-reduced field sizes. Consequently a strong resistance to transmission errors is achieved. The compression ratio obtainable with this scheme is higher than that for block-to-block compression by 20% for 8-bit blocks. A powerful feature of the coding method is that it may be cascaded with block-to-block coding (fixed or universal schemes) to yield higher compression ratios with little increase in complexity. The sensitivity to transmission errors is also examined.

The implementation of the SBIC scheme in hardware is described in Chapter 6. Here a codec was constructed which effectively converts an analogue facsimile system used for the transmission of meteorological charts, to a digital system without changes to the scanning or recording apparatus. To avoid the need for dedicated commercial modems the codec was designed to be self-contained i.e. it includes its own transmission facilities. Details of the hardware and software design are presented. In particular an integrated software approach allows a low-cost complete unit to be successfully developed. The performance of the system is described in Chapter 7.

In Chapter 8 a different strategy of interleaving non-white blocks into white intervals is proposed. By using co-ordinates a sequential method is avoided which results in an extremely noise-resistant compression method. The compression ratio obtainable by this Coordinate Block Interleave Coding (CBIC) scheme is 9% higher than block-to-block coding for 8-bit blocks.

The main conclusions of the research are given in Chapter 9 and some suggestions for further work are also presented.

3.3. Description of System Hardware

3.3.1 Computer Simulation of Compression Systems

The main investigation of the compression method was performed through simulation on a DEC PDP-15 computer. Fig.3.1 shows a diagram of the system configuration. The images were scanned using a Muirhead D-901 facsimile transmitter which is an analogue machine featuring a cylinder and screw scanning mechanism. The facsimile signal is presented to the input interface where it is sliced and sampled at a frequency which can be adjusted (for control of sampling density). The parallel output from this interface is then transferred to the PDP-15 minicomputer where it is stored permanently on magnetic tape. Processing is performed on the stored images which are retrieved from tape and held on magnetic disks at each processing stage. The processed image is subsequently fed to a Muirhead K-441 facsimile recorder via the output interface where it is printed out for subjective evaluation. This recorder employs an eletrostatic principle with dry toner, and has a roller-feed mechanism. Control signals for start, phasing etc are obtained by direct link with the transmitter which is also started up at each image output. Image data is stored as eight-bit bytes with two bytes packed into a computer word which is 18 bits. The total storage for each image varies from 68000 to 119000 bytes. The binary signal from the output interface is fed directly into the writing amplifiers, bypassing the front end circuitry for demodulation, filtering etc. A software interface was written to allow individual lines and bytes to be accessed from the unclassified contiguous image elements on disk. The main simulation of compression systems was performed by programs written in Fortran. However most of the software interfacing to the stored image, input-output drivers and time-consuming data manipulation operations were written in the machine's assembler language, MACRO-15. These were usually in the form of subroutines called from Fortran master programs.

3.3.2 Development of Compression System for Real-time Operation

In the implementation phase of the research a self-contained codec was constructed for use with an analogue facsimile system specialising in the transmission of weathercharts. The drum-type Muirhead K-150-TR4 transmitter can accommodate a maximum chart size of 22 x 18 inches. A choice of 4 drum speeds is available giving a range of transmission times of 10 to 40 minutes for a full-sized chart. The scan-line density is fixed at 96.5 lines per inch. Transmission is by means of amplitude modulation at the lower speeds and vestigal-sideband modulation at the highest drum speed of 240 RPM. Following transmission of the start signal a period of about 30 seconds is used to phase up the receiver for correct alignment of the received image. The Muirhead K-649-TR4 recorder employs a roller-fed chemically-soaked recording paper for its image output. Marking of the paper is carried out by a helix arrangement of styli which rotate in synchronism with the scanning cylinder. Both transmitter and receiver are of heavy construction designed perhaps to withstand rough environmental conditions as may be encountered, for example, in a ship's room.

In the development of the codec a North Star Horizon microcomputer was used to develop the programs for the Z-80B microprocessors located at the transmitter and receiver ends. This was written in the microsystem's MAKRO Z-80 assembler language and stored on floppy disk. The binary program is subsequently downloaded via an RS-232 connection, to an EP 4000 EPROM emulator/programmer which emulates the program section of memory in the microprocessor circuitry at either transmit or receive end. When a program has been found to be satisfactory it is programmed into an EPROM (type 2732) on the same device which may then be used to emulate the other EPROM in the codec. To this end a stock of EPROMS was available which was constantly being re-erased by a low-cost ultra violet erasing unit. This approach allows a highly flexible and fast means of hardware development

for a system which is primarily dependent on real-time software. In-situ debugging of the prototype was performed using a Hewlett-Packard 1630 logic analyser.

3.4 Description of Test Images Used in Research

3.4.1 Choice of Images in Document Compression

It is clear that in any study of compression systems for images it is not possible to investigate every single type of image which may be transmitted. In a computer simulation, computing resources usually dictate the number of different images which may be processed. Whilst an excessive number of images imposes heavy computational demands and may not produce any more useful or spectacular results, on the other hand the use of just one or two test images may not yield results which are conclusive for the wide range of facsimile documents encountered in practice. The performance of compression schemes vary to a large extent according to the image material, so for meaningful comparisons to be made it is preferable that the same test images be employed where possible.

In this research a set of six test images is used which is regarded as being representative of the black-white images normally transmitted in document facsimile systems. These have previously been used by Tindall [26] in his study of two tone compression methods which include lossy fixed-rate techniques. Thus accurate comparisons can be made as to the performance of the fixed-rate methods developed in this thesis. The images were originally selected to correspond with the classification of F. de Coulon (images displayed in [7]). The set of test images are:-

(1) A1 - Business Letter

(2) A2 - Dense Typing

(3) A3 - Circuit Diagram

(4) A4 - Handwritten Letter

(5) A5 - Weathermap

(6) A6 - Computer-drawn Weathermap

The images were sampled at a density of 150 pels/inch (5.9 pels/mm). The vertical resolution was fixed at 90 lines/inch (3.5 lines/mm). At this sampling resolution it is arguable that some of the images may be over-sampled. An efficient compression system should in principle exploit the intrinsic two-dimensional redundancy of image structure and not simply the amount of oversampling. In order to observe the effects of lowering of resolution an additional image A5b was included in the set. This image is the weathermap sampled at a density of 75 pels/inch.

3.4.2 Physical Description of Test Images

Figures 3.2 to 3.8 show the set of test images. For the main group of six images sampled at 150 pels/inch, each scan-line consists of 1128 pels except for A2 which is 904 pels. The reduced line width for A2 is deliberate, in order to omit excessive white margin areas so that the image consists exclusively of dense typing apart from the heading. This image thus represents highly compact text material which is more difficult to compress than less closely packed typewritten text. A common example of the latter is the 'business letter' A1 which includes letterhead and signature. The ample amount of white in this image should produce high levels of compression with variable-rate schemes. The height of the character type here is about .09 inch (2mm). The sampling density of 150 pels/inch is judged to be just about adequate. Test image A3 is a circuit diagram of one of the interface cards in the system apparatus. Image A4 is a handwritten passage which describes the operation of the facsimile link to the minicomputer. The images A5 and A6 are typical of those produced at a meteorological centre. Image A5 is a contour weather chart in which

contours are plotted against a background of an outline of continents and a grid of latitude and longitude. This gives a three-dimensional picture of the atmosphere which is helpful to forecasters. The image A6 is an example of an output from a computer forecast of the weather which is regarded to be superior to human efforts and is gradually becoming the norm. In practice the sizes of the weathercharts which are transmitted are much larger than those displayed in A5 and A6. It is clear that at the present time facsimile plays a vital role in the distribution of meteorological information.

3.4.3 Statistical Properties of Test Images

The bounds of lossless compression are determined by the entropies of the image sources which may be evaluated for specific statistical models of the source. Table 3.1 shows a comparison of the theoretical limits to compression and some useful statistical parameters of the test images are given. In the fifth column the entropies are calculated for the independent pel source in which each picture element is assumed uncorrelated with any previous element. The per pel entropy in this case is given by:-

$$H_{pel} = -p\log_2 p-(1-p)\log_2(1-p) \quad \text{bits per pel} \qquad 3.1$$

where p is the measured probability (percentage) of black elements.

In the sixth column the theoretical limits to block coding are obtained for 8-pel blocks using measured probabilities of 8-pel states. The practical bounds of compression are shown in the next two columns where the Huffman code has been used for source encoding. All other codes cannot attain better performance. The Huffman code in this case has been constructed from the individual block statistics of the images.

The variations in the attainable compression in 8-pel block coding of the test images is a reflection of the levels of redundancy in the images. The densely typed page of A2 is least amenable to compression (max CR=2.8) whereas the more sparse image of A1 may be compressed by up to a factor of 7.6. The good compression potential of the latter is attributable to the very high probability of all-white block, as shown in the third column. The more homogeneous images of A5 and A6 show relatively modest compression bounds of 3.7 and 3.5 respectively. The effect of lowering the resolution is demonstrated in the maximum compression ratio for A5b of 2.8. For a halving of the horizontal resolution the compression limit has decreased by 25%. This suggests that it may be more efficient to sample at a lower resolution and obtain a compression ratio of say x, than double the resolution and hope for a compresion ratio of 2x which is unlikely. However the subjective consequence of operating at a lower resolution may be undesirable.

3.5 Results of Block-to-Block Coding of Test Images

3.5.1 Block-to-Block (N/M) Coding Principles

Block-to-block coding is a simple method of achieving compression which features a fixed-rate output and is resistant to transmission errors. For smaller blocks the implementation is trivial, requiring only a serial-to-parallel shift register and a read-only-memory(ROM). In this research the fixed-rate methods of compression developed will be compared with this technique. Block-to-block coding will also form an integral part of these compression systems. In particular 8-pel blocks are employed which is convenient and efficient from a hardware point of view - many digital IC packages feature 8-bit word lengths and if a microprocessor is to be used, standard 8-bit commercial microprocessors can be employed. In

view of its importance to this research the rest of this chapter is devoted to a discussion of this technique and the results of its application to the test images are presented.

Block-to-block coding is based on the fact that when N-pel blocks of the image output are taken some of the 2^N possible binary patterns have low probabilities of occurence. Thus only the most frequent 2^M N-pel patterns are assigned M-bit codewords. Where an input pattern does not have a valid codeword it is approximated to the nearest pattern in the assigned set and the codeword for that is transmitted. The approximation is irreversible and leads to errors in the reconstructed image. However the effects of this type of approximation may not be too noticable by the human eye so that a level of distortion can be tolerated. Even if the encoding distortion is visible the intelligibility of content is usually unaffected and therefore the primary criterion for acceptability is the impairment of the aesthetic quality of the reproduced image. In some situations a visible degradation of the reproduced image without loss of legibility can be an acceptable sacrifice for reduced bandwidth or transmission time for example in transmission over hostile channels.

A quantitative measure of the distortion arising from block-to-block coding is the percentage reconstruction errors (PRE) which is defined as:-

$$PRE = \frac{\text{Total Number of Erroneous Pels in Image After Coding}}{\text{Total Number of Pels in Image}} \times 100 \qquad 3.2$$

This simply gives the total count of additional or lost black pels due to approximation, expressed as a percentage of the total number of picture elements. A further useful parameter is the percentage number of blocks in the image which have unassigned patterns called the percentage unassigned block (PUB). This is expressed as:-

$$PUB = \frac{\text{Total Number of Blocks with Unassigned Patterns}}{\text{Total Number of Blocks in Image}} \times 100 \qquad 3.3$$

A straightforward method for deciding upon the choice of codebook pattern to approximate an invalid pattern is that which finds the maximum of the similarity factor S where S is the number of pel coincidences between the input pattern and an assigned pattern. Thus:-

$$S = \sum_{i=1}^{N} \overline{[x_i \oplus y_i]} \qquad 3.4$$

for $x_i, y_i = 0$ or $1 \; \forall \; i$

where $\oplus$ denotes the exclusive or operation and the overhead bar indicates logical inversion of the result (exclusive-NOR operation), x_i and y_i are the binary values of each bit of the N-bit input and assigned patterns respectively. Fig.3.9 shows a possible hardware derivation of S (N=8). The shift registers holding the input pattern and an assigned pattern are clocked on positive-going edges whilst the 3-bit counter is negative-edge triggered. The output of the Exclusive-NOR gate feeds into an inhibit input of the counter which is not advanced when this level is low. At the end of 8 clock pulses the contents of the shift registers are back in their original positions and the value of S is available at the output of the counter. In finding the maximum value of S for the set of assigned patterns, a separate register may be used to hold the current maximum which is updated by comparing with the current value of S as it is obtained for each assigned pattern.

The above approximation method, whilst relatively simple, does not always produce the pattern which is subjectively preferable. For example, in Fig.3.10 the input pattern may be approximated by pattern A instead of pattern B which is subjectively closer, because the similarity factor is 6 in both cases. Note that in both cases the resulting distortion (encoding

errors) will be the same, implying that the PRE cannot be relied on too heavily as a measure of acceptability for the reconstructed image quality.

To improve on the selection process the cross-correlation between the input pattern and each possible candidate pattern may be used. This essentially involves for each pair, obtaining a set of (2N-1) values of S in which each S value is obtained by successive shifting at one bit a time the candidate patterns and for each shift the value of S is found. This is done for both left and right shifts. At each shifted position only the remaining bits in the register are used for evaluating S (shifting is not circular here). The sum of the N values of S after (2N-1) shifts (first value of S is for unshifted patterns) is the crosscorrelation measure and the maximum value for the set of 2^M assigned patterns identifies the selected pattern for transmission. The derivation of the cross-correlation measure however is time-consuming if not complicated. To simplify the procedure a truncated cross-correlation measure may be used in which only three shift states of a pattern are contemplated. These are zero shift, right shift and left shift of a bit. The states are illustrated in Fig.3.11. For the right or left shift state the maximum value of S is (N-1). The value of the truncated cross-correlation measure T is obtained as

$$T = \sum_{i=1}^{N} \overline{[x_i \oplus y_i]} + \sum_{i=1}^{N-1} \overline{[x_{i+1} \oplus y_i]} + \sum_{i=1}^{N-1} \overline{[x_i \oplus y_{i+1}]} \qquad 3.5$$

for $x_i, y_i = 0$ or $1 \; \forall \; i$

With two-dimensional blocks the value of T may be found for each row and the sum of the T values constitutes the measure of similarity.

Where the block size N is small the simplest method of implementation of block-to-block coding is the lookup method where all approximations have been performed a priori and only the codewords for transmission are stored

in a ROM (Fig.3.12). As memory capacities of ROM chips continue to increase the method may be economically used for increasingly higher values of N. At the present time block sizes of up to 16 bits which require up to 2^{16} words of storage may be thus implemented. Decoding is fairly straightforward involving a lookup of a ROM of size 2^M x N bits. For larger blocks the alternative scheme shown in Fig.3.13 may be used for encoding. The 2^M N-bit assigned patterns are stored in memory and for each input block the stored patterns are scanned for a match with the input pattern. During this sequential scan the approximation algorithm may also operate to find the closest pattern so that if a match is not found the nearest pattern is immediately available after the last pattern has been compared. The binary address of the input pattern in the memory or its nearest approximation is transmitted. It is clear that the coding process here is quite time-consuming. To reduce the coding complexity the straightforward approximation method of finding the maximum of S, instead of T, may be employed. Also by working in parallel using K memory stores each holding $(2^M)/K$ assigned patterns the encoding time may be reduced by a factor of about K.

3.5.2 Results of 8/M Coding of Test Images

The results of block-to-block coding of the set of test images are given in Table 3.2 for a block size of 8 pels. The codebook is derived from the combined statistics of all the test images. The reconstructed images are shown in Figs.3.14 to 3.34. For image A1 8/6 coding yields a result (Fig.3.14) which is hardly distinguishable from the original shown in Fig.3.2 . The percentage errors here is 0.1%. With 8/5 coding however the distortion is perceptible although intelligibility of characters is largely unaffected. When M is reduced further to 4, the distortion becomes severe (0.82%) and is unacceptable. Image A5 can be encoded up to 8/5 with

undetectable difference in image quality (PRE = 0.27%). The reconstructed image with 8/4 coding is acceptable (PRE=1.34%) although the quality of line edges is slightly degraded and aberrations of a few characters are visible. The better performance of this image may be attributed to its oversampled nature. When the sampling density is reduced to 75 pels/inch the reconstructed images may be examined in in Figs.3.32 to 3.34 . Here the level of acceptable distortion is that for 8/6 coding as 8/5 and 8/4 coded images are clearly inferior to their original. From the point of view of total number of coded bits for the weathermap, higher savings are obtained by sampling at the lower resolution of 75 pels/inch and applying 8/6 coding, than sampling at 150 pels/inch and achieving 8/5 compression. The results for the test images as a whole show that 8/6 coding can be satisfactorily applied to all the test images. This corresponds to a saving of 25% in transmission time.

3.6 Conclusion

In the first part of this chapter a summary was given of the programme of research which is reported in this thesis. Some possible areas of application of the compression methods which are developed were outlined. The originality aspects of the research work were also stated. A description of the system in which the research was conducted was given. The set of test images used in the research were presented and their statistical properties evaluated. Finally the compression method of block-to-block coding was discussed. This technique is significant to the compression systems developed in this thesis. The results for 8/M coding of the test images were given which will be referred to later in the thesis.

	Black Element Probability	Independent Pel Entropy	White Block Probability	Theoretical Limits		Huffman Coding	
				Per Pel Entropy	Maximum Compression Ratio (8-pel blocks)	Bit Rate	Compression Ratio
A1	0.040	0.243	0.902	0.132	7.60	0.199	5.03
A2	0.156	0.624	0.662	0.358	2.80	0.368	2.72
A3	0.073	0.377	0.831	0.190	5.26	0.234	4.28
A4	0.092	0.442	0.821	0.198	5.05	0.239	4.19
A5	0.115	0.515	0.730	0.269	3.71	0.290	3.45
A6	0.097	0.458	0.732	0.285	3.51	0.306	3.27
A5b	0.099	0.547	0.638	0.360	2.78	0.368	2.72

Table.3.1. Bounds of Compression for Test Images.

Image	8/3		8/4		8/5		8/6	
	PRE	PUB	PRE	PUB	PRE	PUB	PRE	PUB
A1	1.84	7.07	0.81	4.63	0.37	2.40	0.10	0.73
A2	6.78	24.81	3.13	17.52	1.72	10.22	0.15	1.12
A3	2.33	8.49	0.82	4.96	0.26	1.66	0.11	0.75
A4	2.56	10.10	1.34	7.70	0.42	2.66	0.07	0.58
A5	3.55	13.51	1.45	8.68	0.27	1.87	0.04	0.28
A6	4.17	15.79	1.67	10.05	0.50	3.42	0.13	0.96
A5b	6.08	23.15	2.49	15.18	0.91	6.66	0.32	2.39

Table 3.2. Results of 8/M Coding of Test Images.

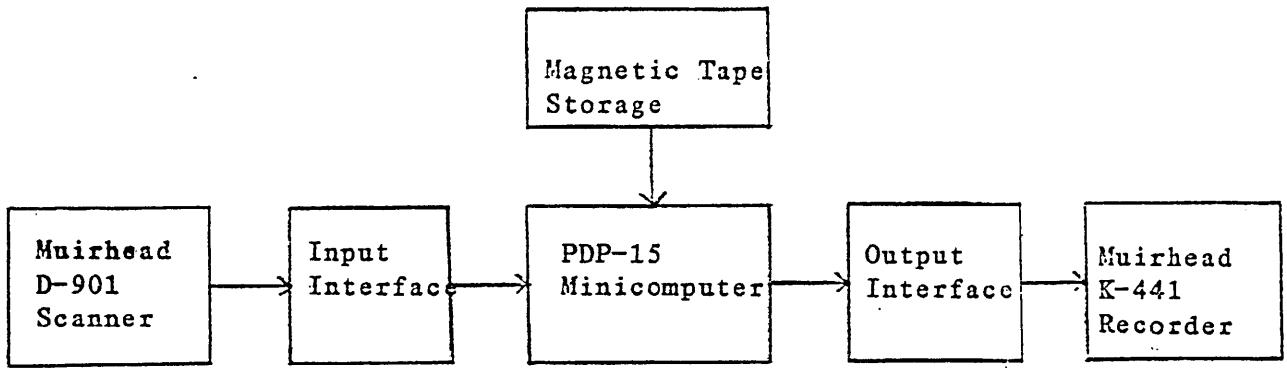


Fig.3.1. System Apparatus for Simulation of Compression Methods.

Fig.3.2. Test Image A1.

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P.S. If this letter did better your knowledge or understanding in any way, please let me know how.

Fig.3.3. Test Image A2.

A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably fuller employment — depend on this. They show that higher exports and import substitution go together — the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

Fig.3.4. Test Image A3.

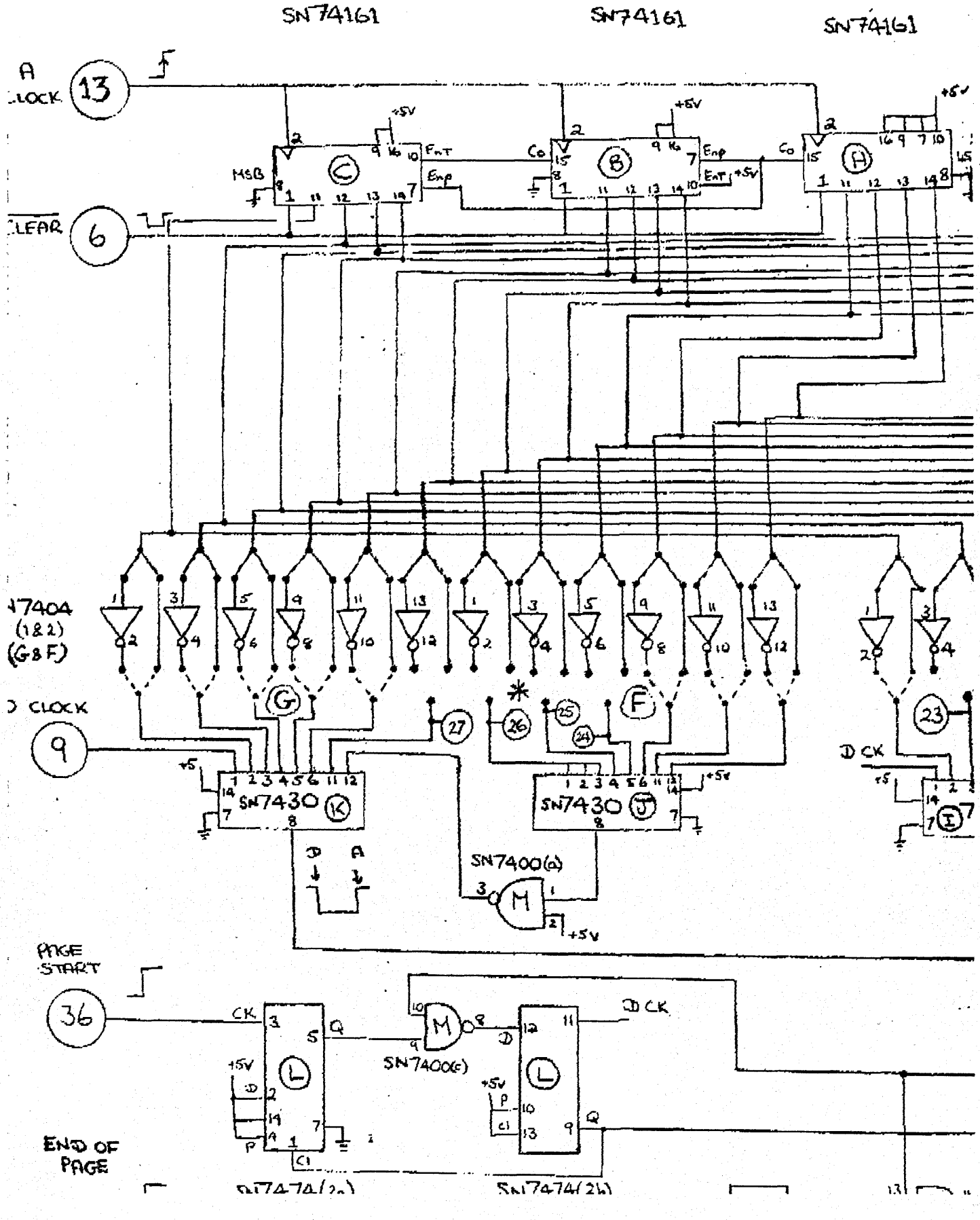


Fig.3.5. Test Image A4.

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be amassed to

Fig.3.6. Test Image A5.

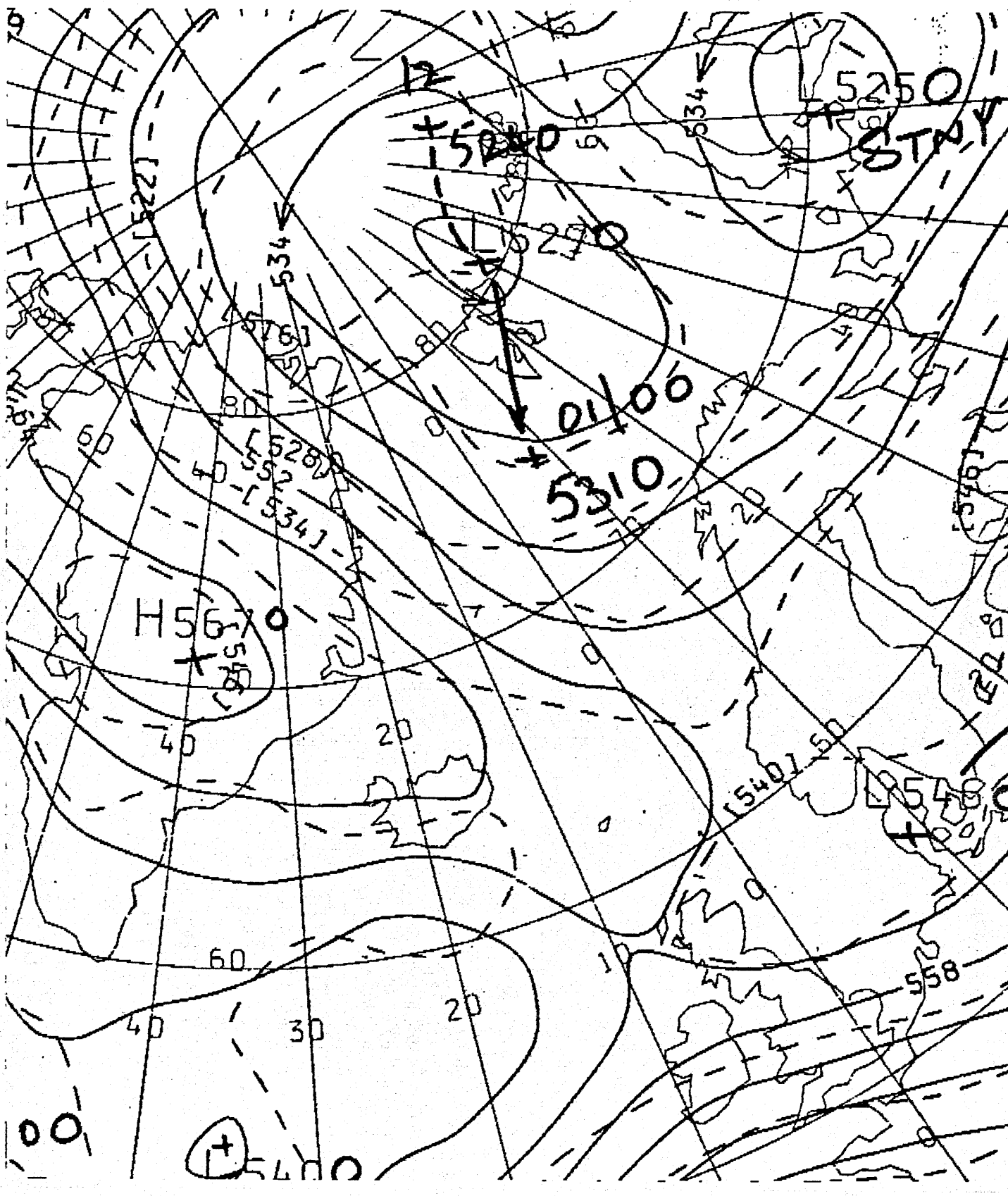


Fig.3.7. Test Image A6. - 81 -

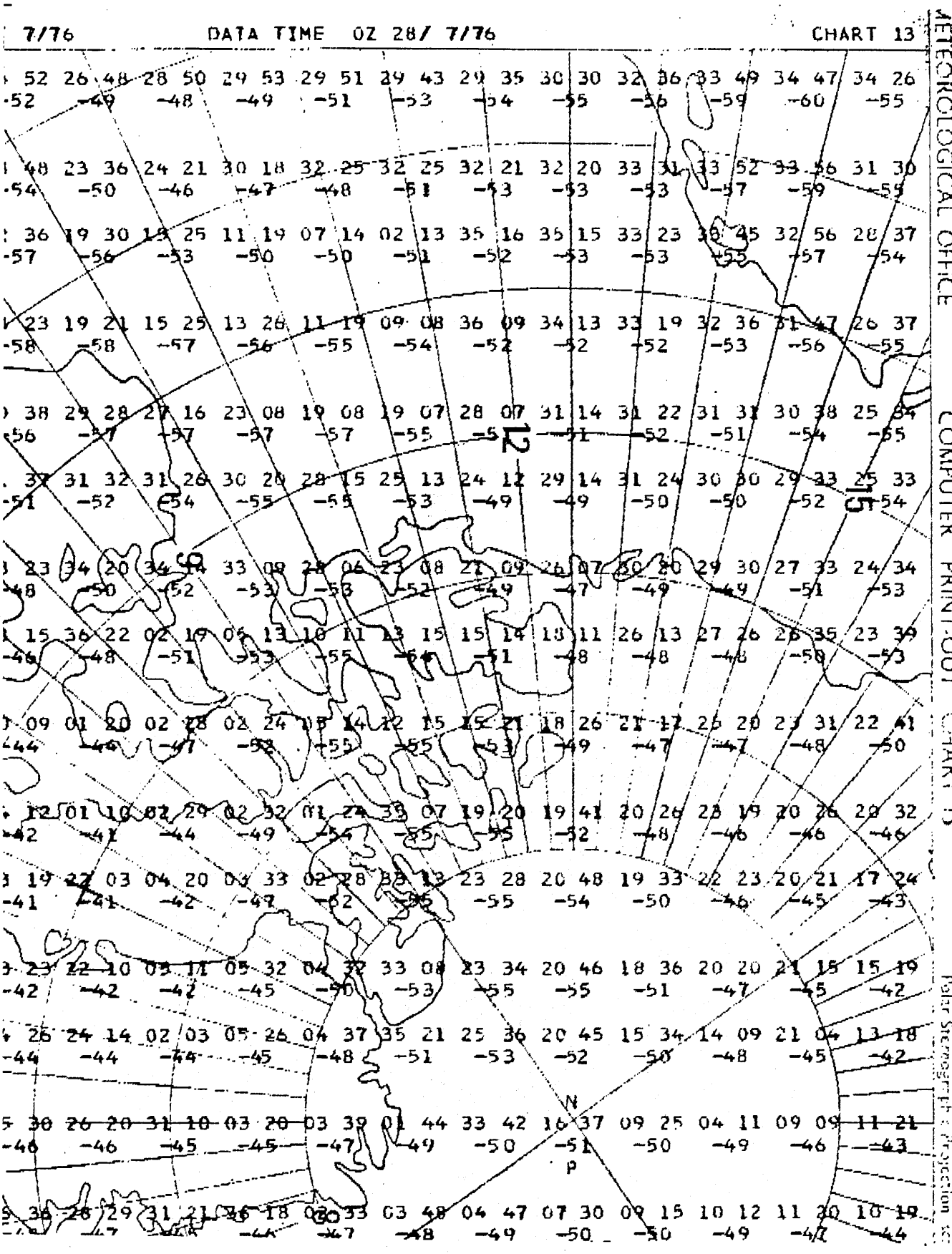
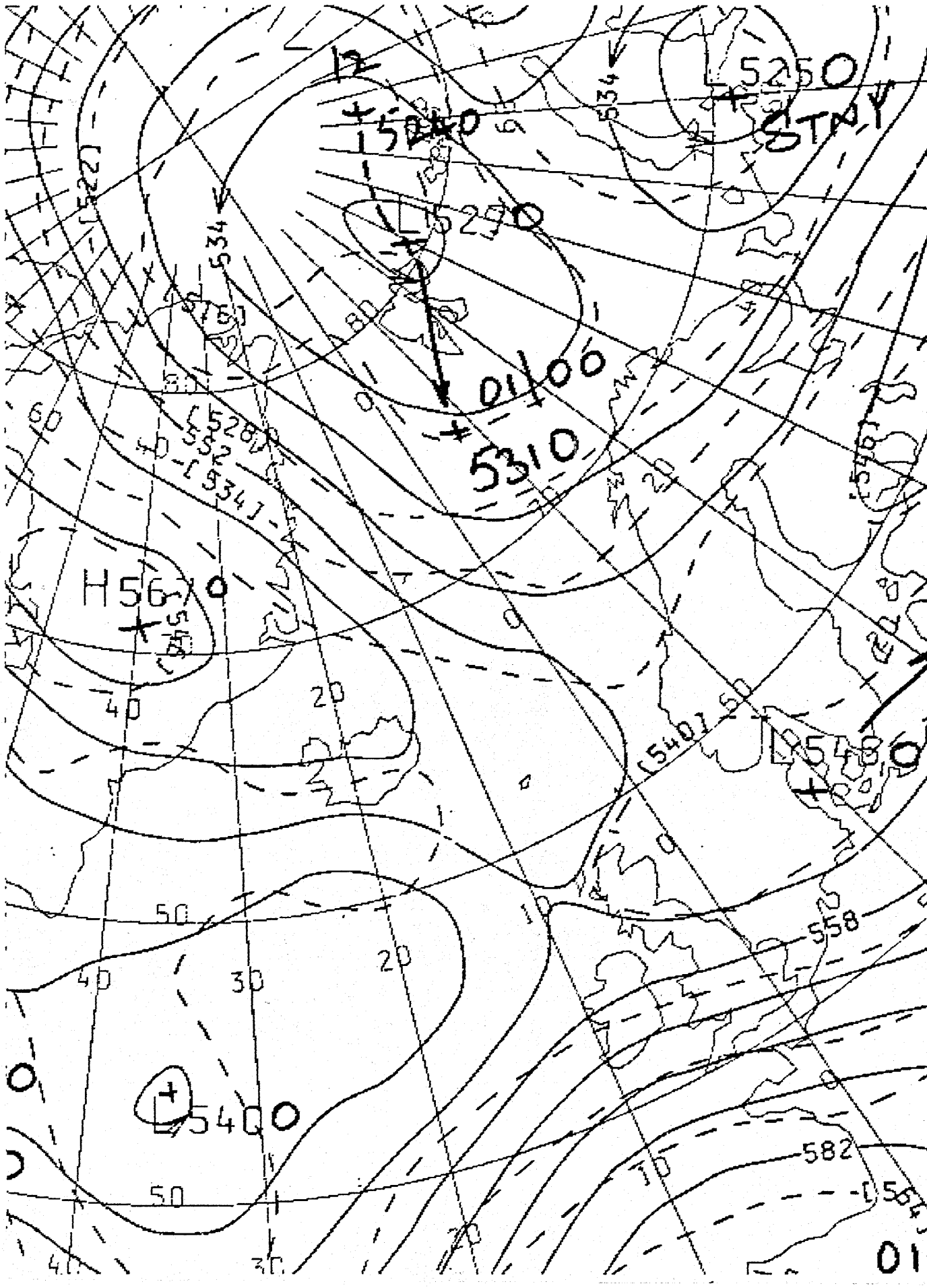


Fig.3.8. Test Image A5b.



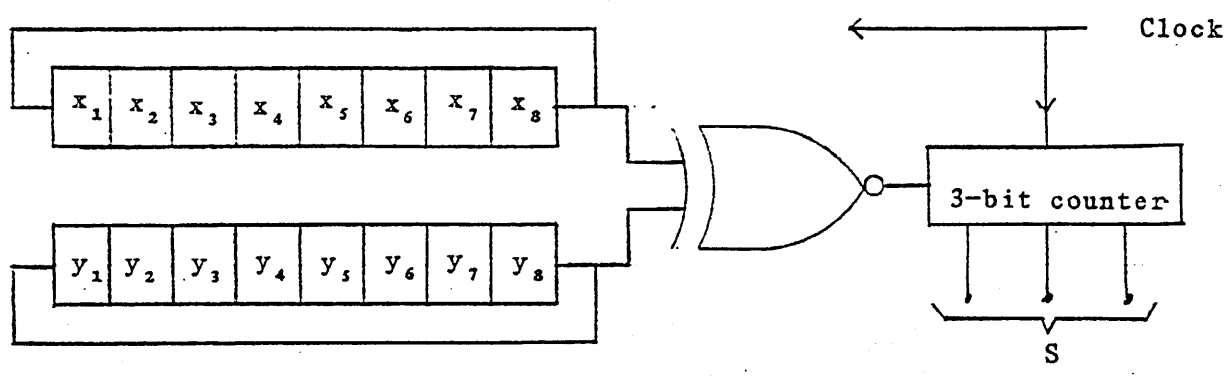


Fig.3.9. Derivation of Similarity Factor S for N = 8.

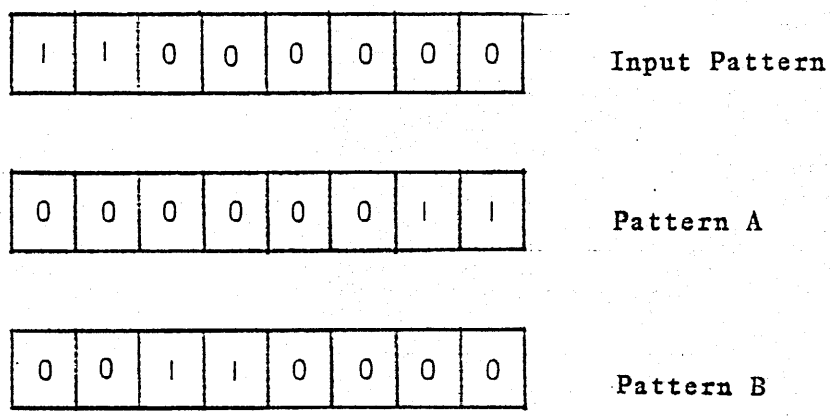


Fig.3.10. Showing possible misapproximation of input pattern.

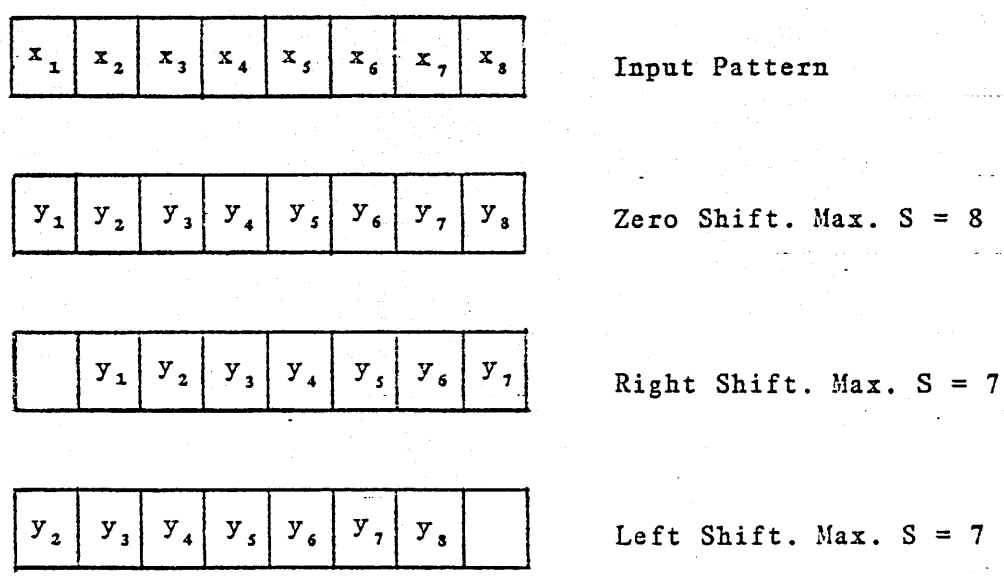


Fig.3.11. Shift States of Candidate Pattern in Obtaining Truncated Cross-Correlation Measure (N = 8).

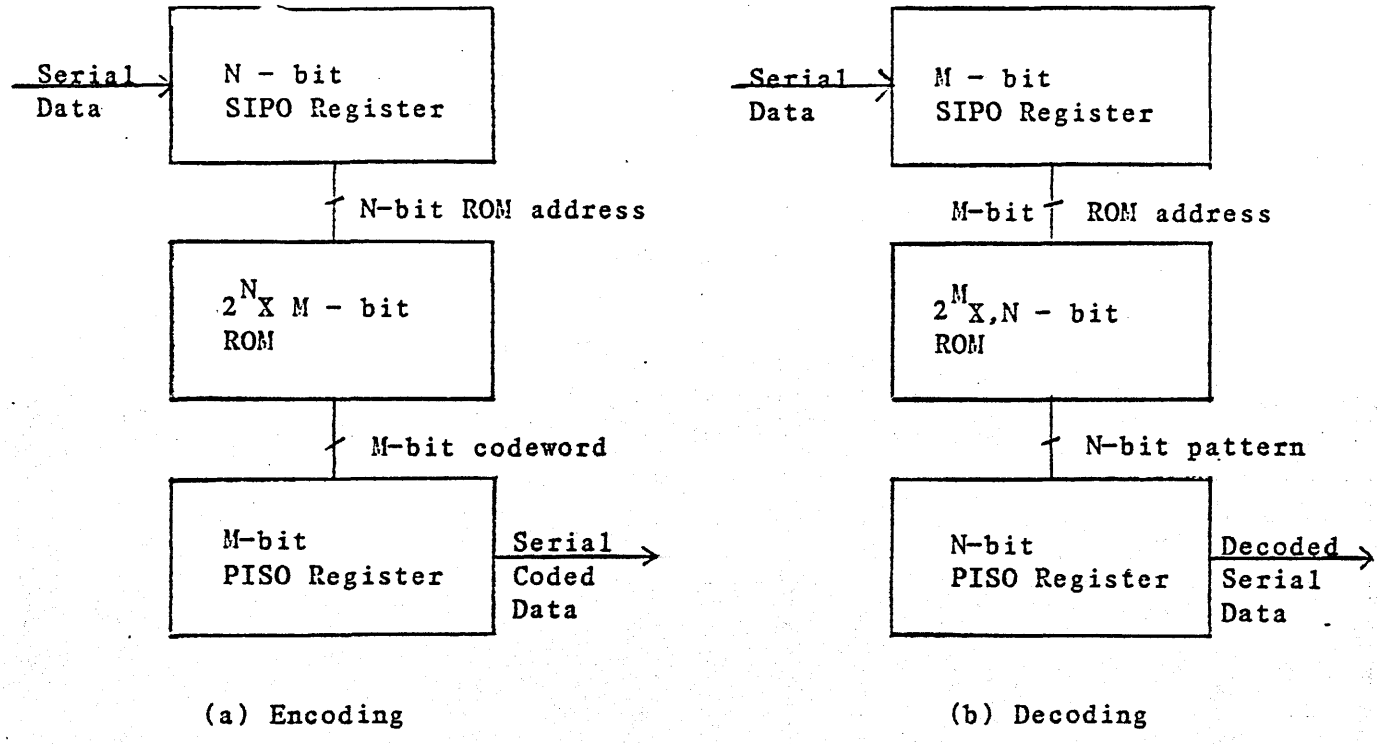


Fig.3.12. ROM-lookup Implementation of Block-to-block Compression.

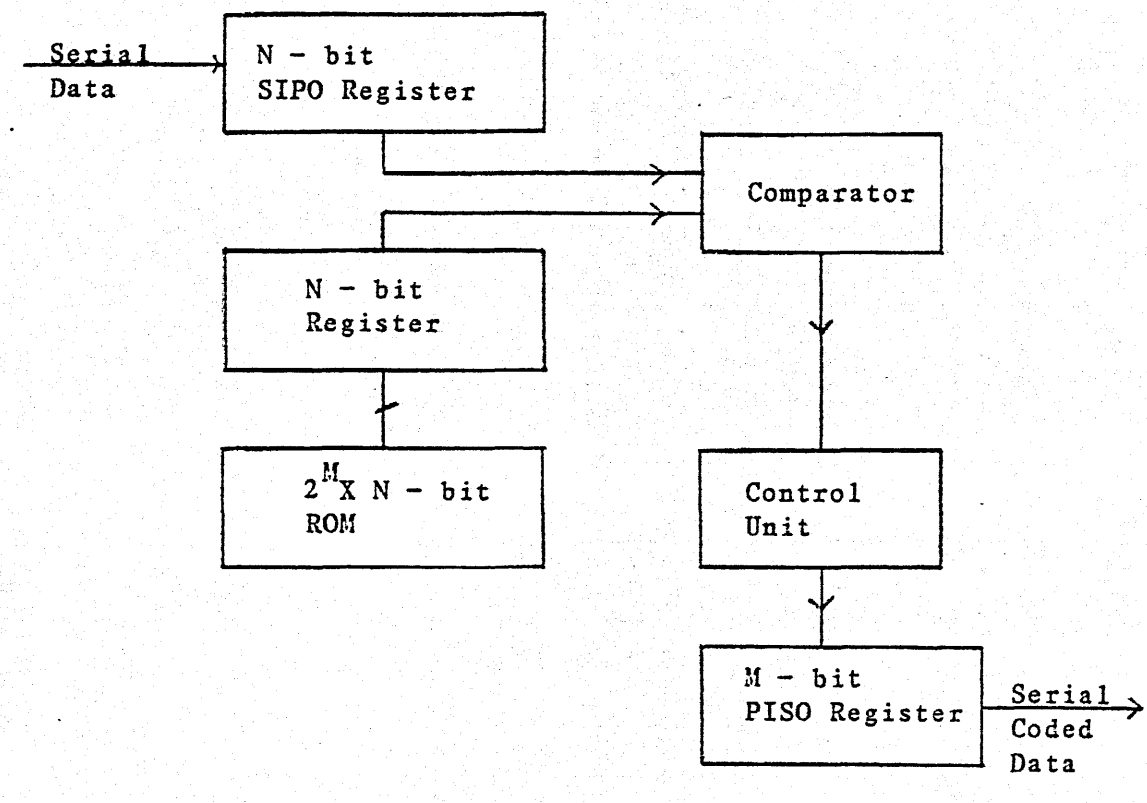


Fig.3.13. Search Method of N/M Encoding.

Fig.3.14. Reconstructed Image A1 After 8/6 Compression.
Compression Ratio = 1.33 .

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Fig.3.15. Reconstructed Image A1 After 8/5 Compression.
Compression Ratio = 1.60 .

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Fig.3.16. Reconstructed Image A1 After 8/4 Compression.
Compression Ratio = 2.00 .

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Fig.3.17. Reconstructed Image A2 After 8/6 Compression.
Compression Ratio = 1.33 .

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The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

Fig.3.18. Reconstructed Image A2 After 8/5 Compression.
Compression Ratio = 1.60 .

A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably fuller employment — depend on this. They show that higher exports and import substitution go together — the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

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Fig.3.19. Reconstructed Image A2 After 8/4 Compression.
Compression Ratio = 2.00 .

A constructive starting point

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Fig.3.20. Reconstructed Image A3 After 8/6 Compression.
Compression Ratio = 1.33 .

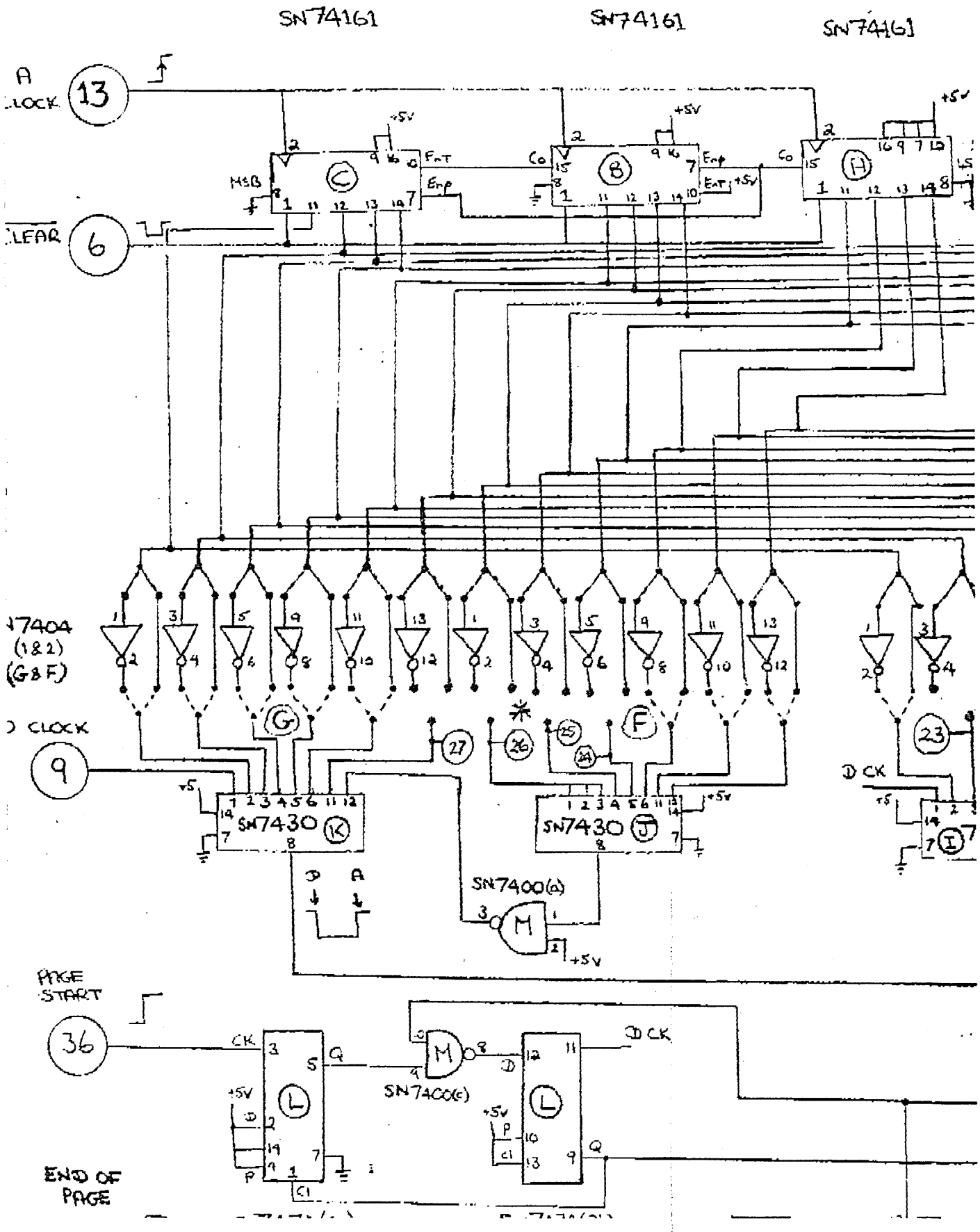


Fig.3.21. Reconstructed Image A3 After 8/5 Compression.
Compression Ratio = 1.60 .

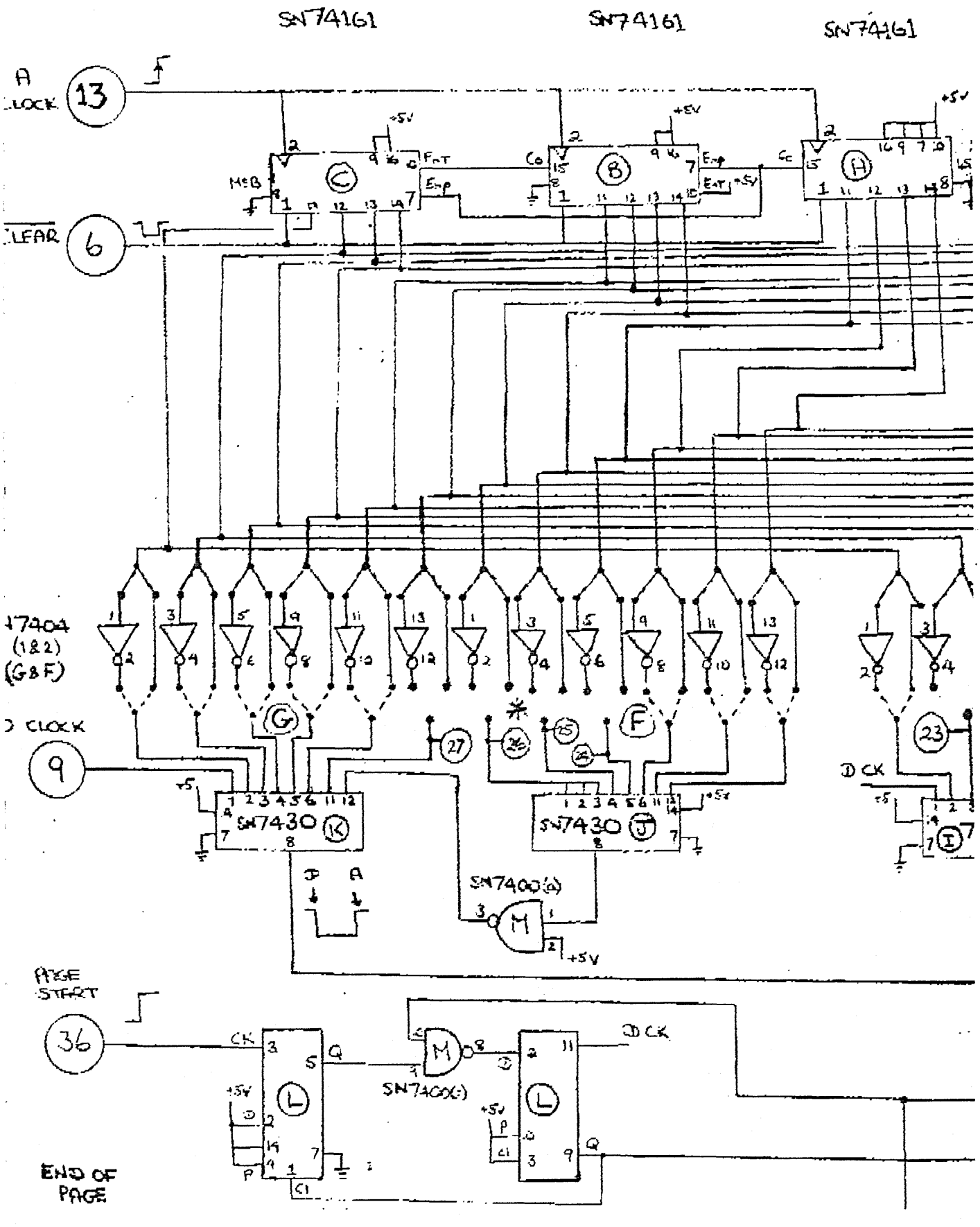


Fig.3.22. Reconstructed Image A3 After 8/4 Compression.
Compression Ratio = 2.00 .

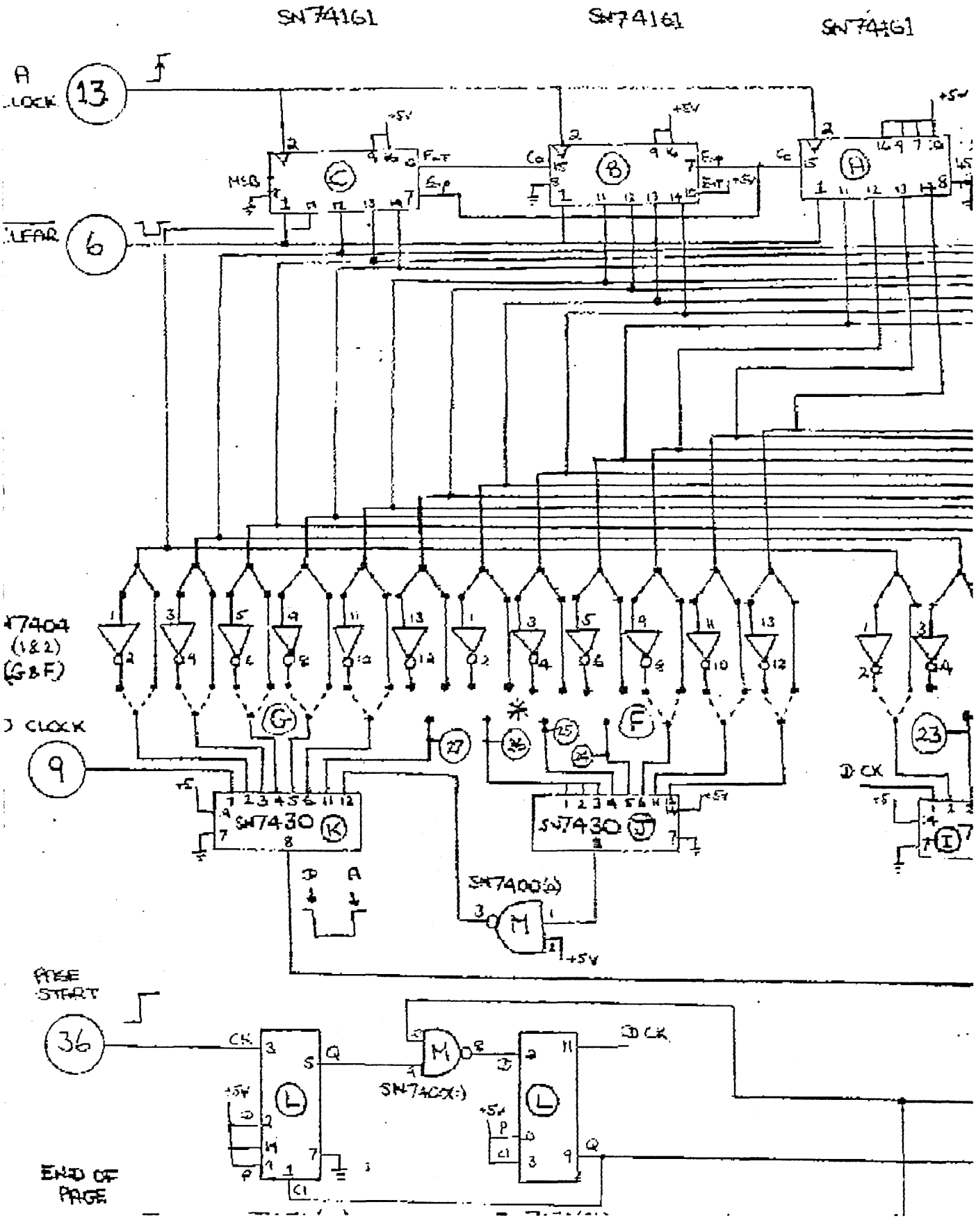


Fig.3.23. Reconstructed Image A4 After 8/6 Compression.
Compression Ratio = 1.33 .

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be amassed for

Fig.3.24. Reconstructed Image A4 After 8/5 Compression.
Compression Ratio = 1.60 .

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be amassed to

Fig.3.25. Reconstructed Image A4 After 8/4 Compression.
Compression Ratio = 2.00 .

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/16 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface & the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC-tape. Thus a set of "standard" digitised documents and drawings can be amassed to

Fig.3.26. Reconstructed Image A5 After 8/6 Compression.
Compression Ratio = 1.33 .

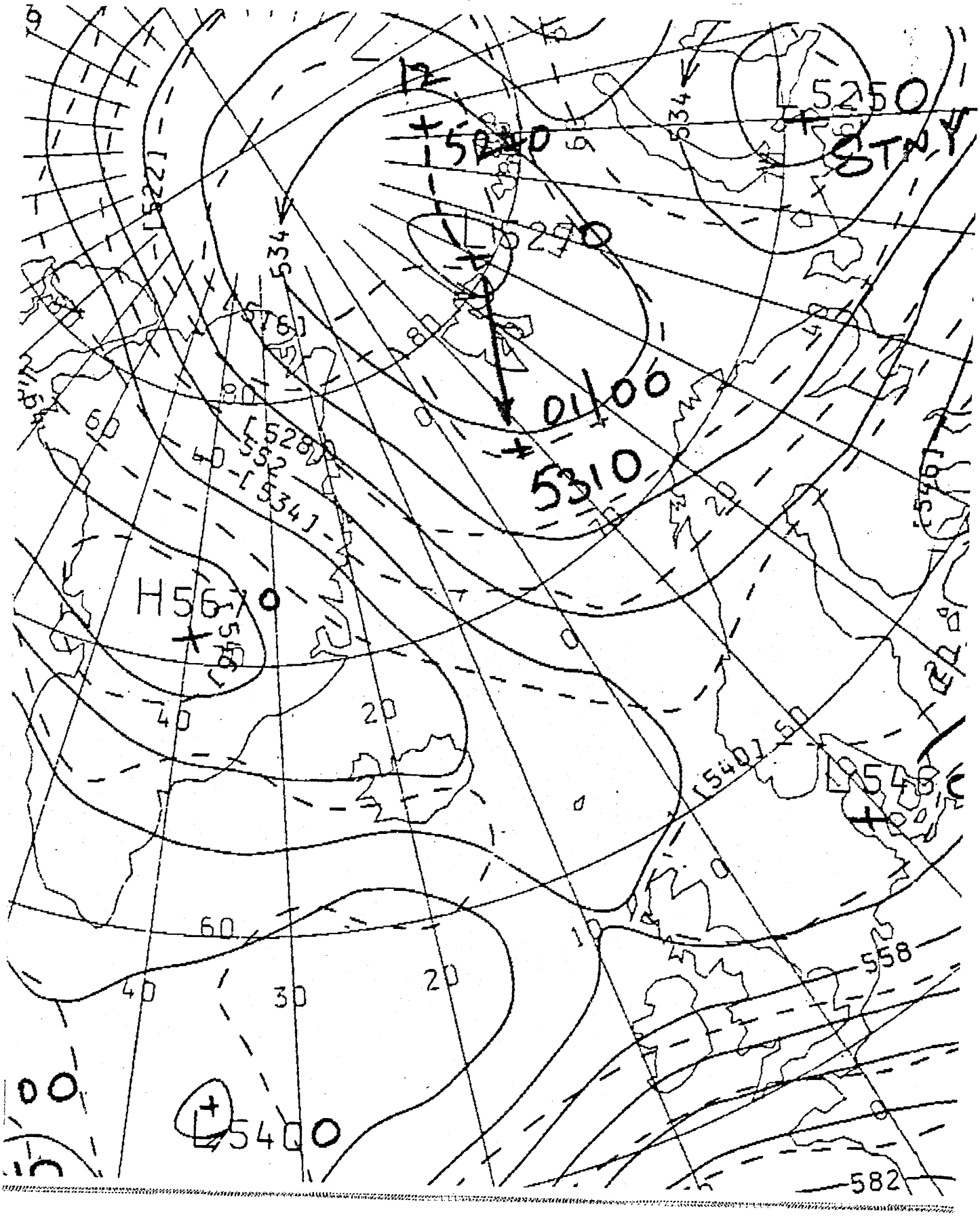


Fig.3.27. Reconstructed Image A5 After 8/5 Compression.
Compression Ratio = 1.60 .

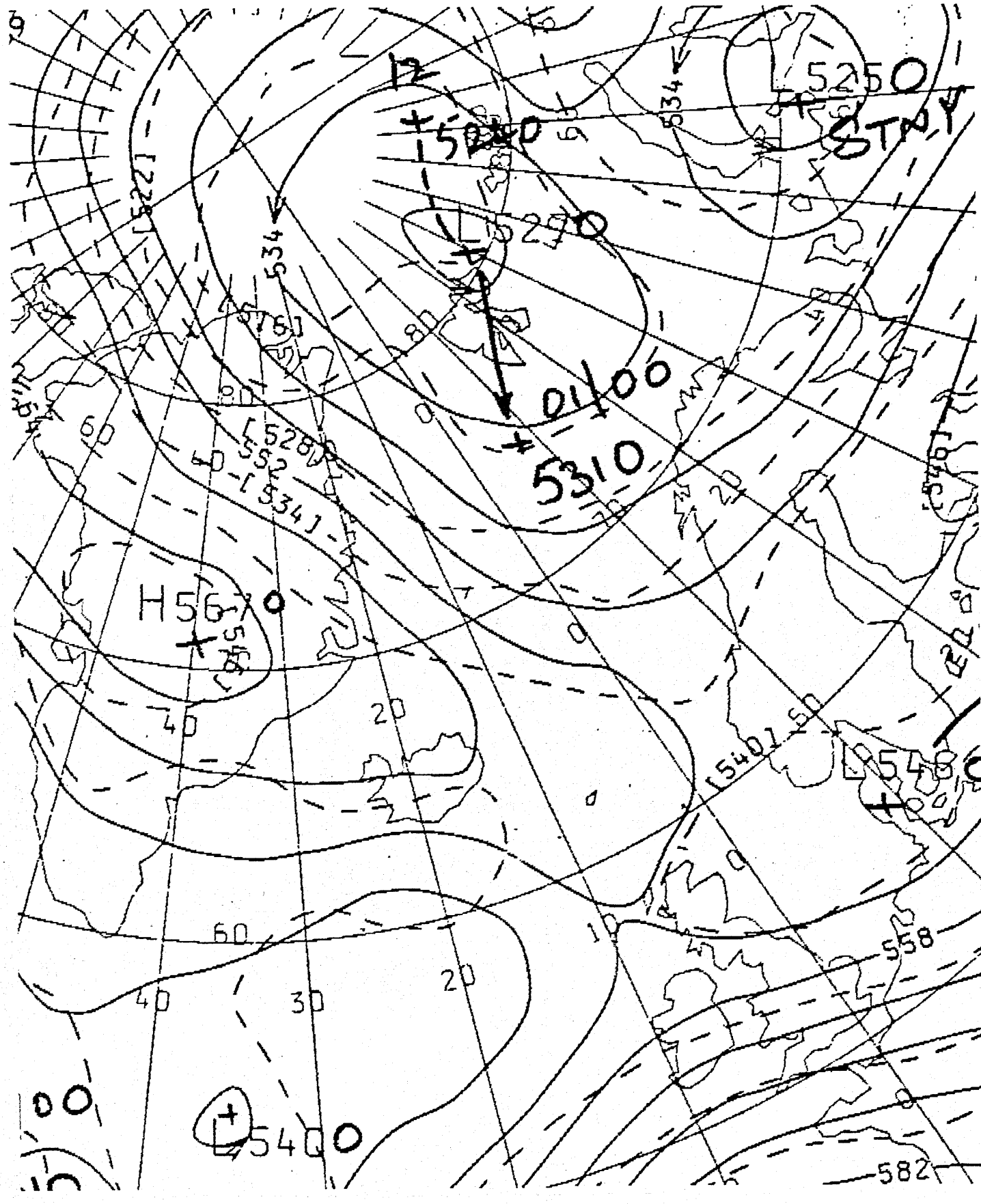


Fig.3.28. Reconstructed Image A5 After 8/4 Compression.
Compression Ratio = 2.00 .

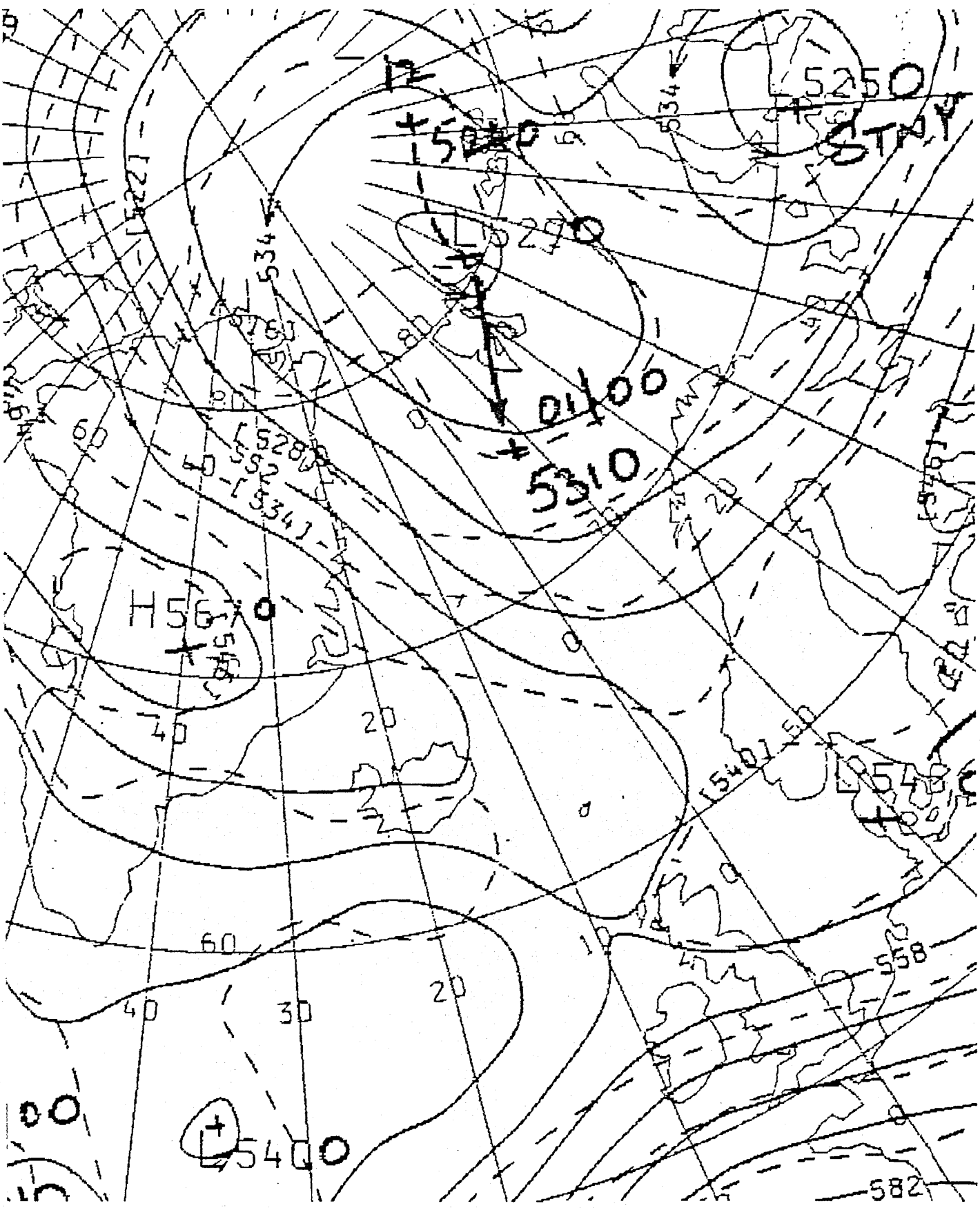


Fig.3.29. Reconstructed Image A6 After 8/6 Compression.
Compression Ratio = 1.33 .

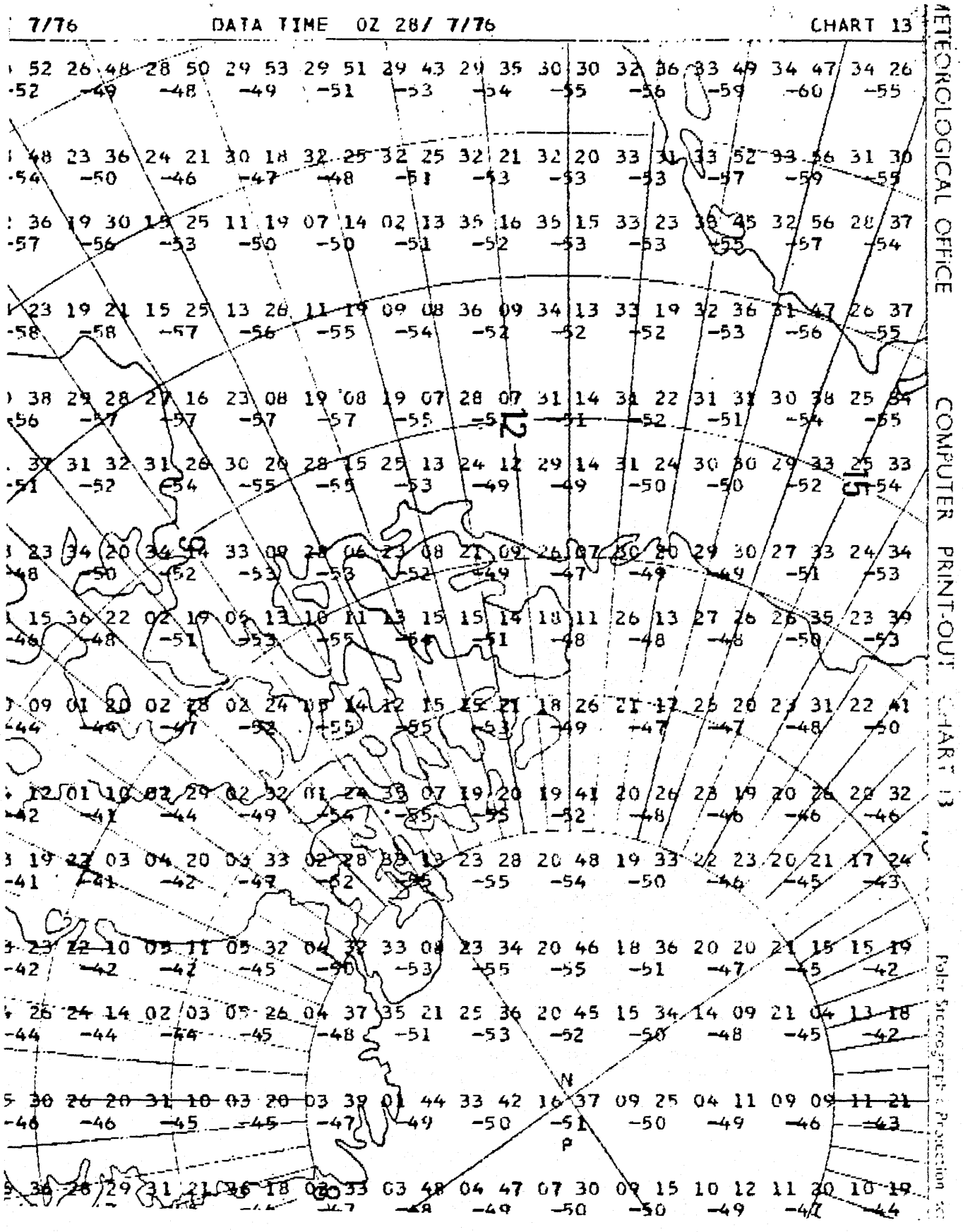


Fig.3.30. Reconstructed Image A6 After 8/5 Compression.
Compression Ratio = 1.60 .

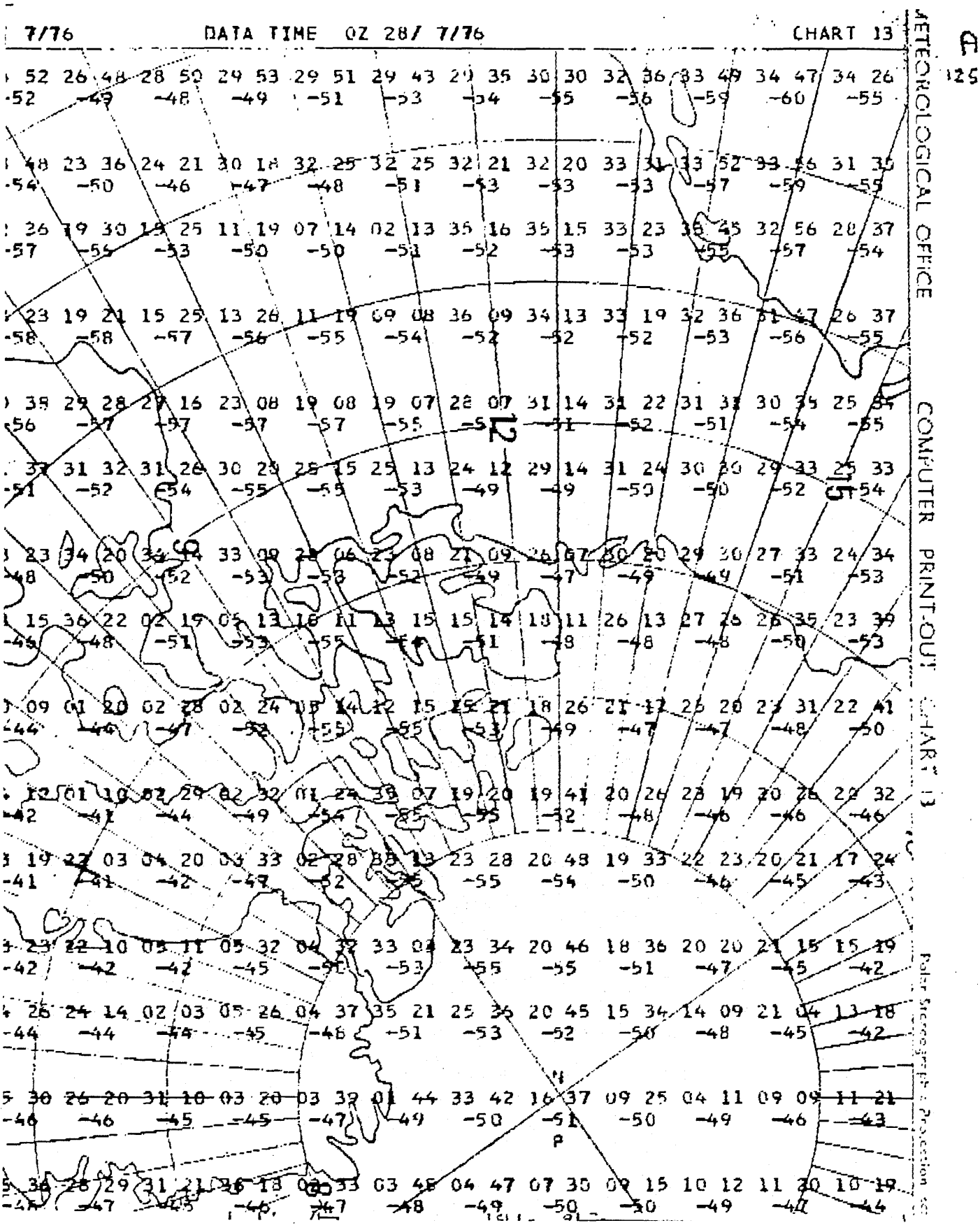


Fig.3.31. Reconstructed Image A6 After 8/4 Compression.
Compression Ratio = 2.00 .

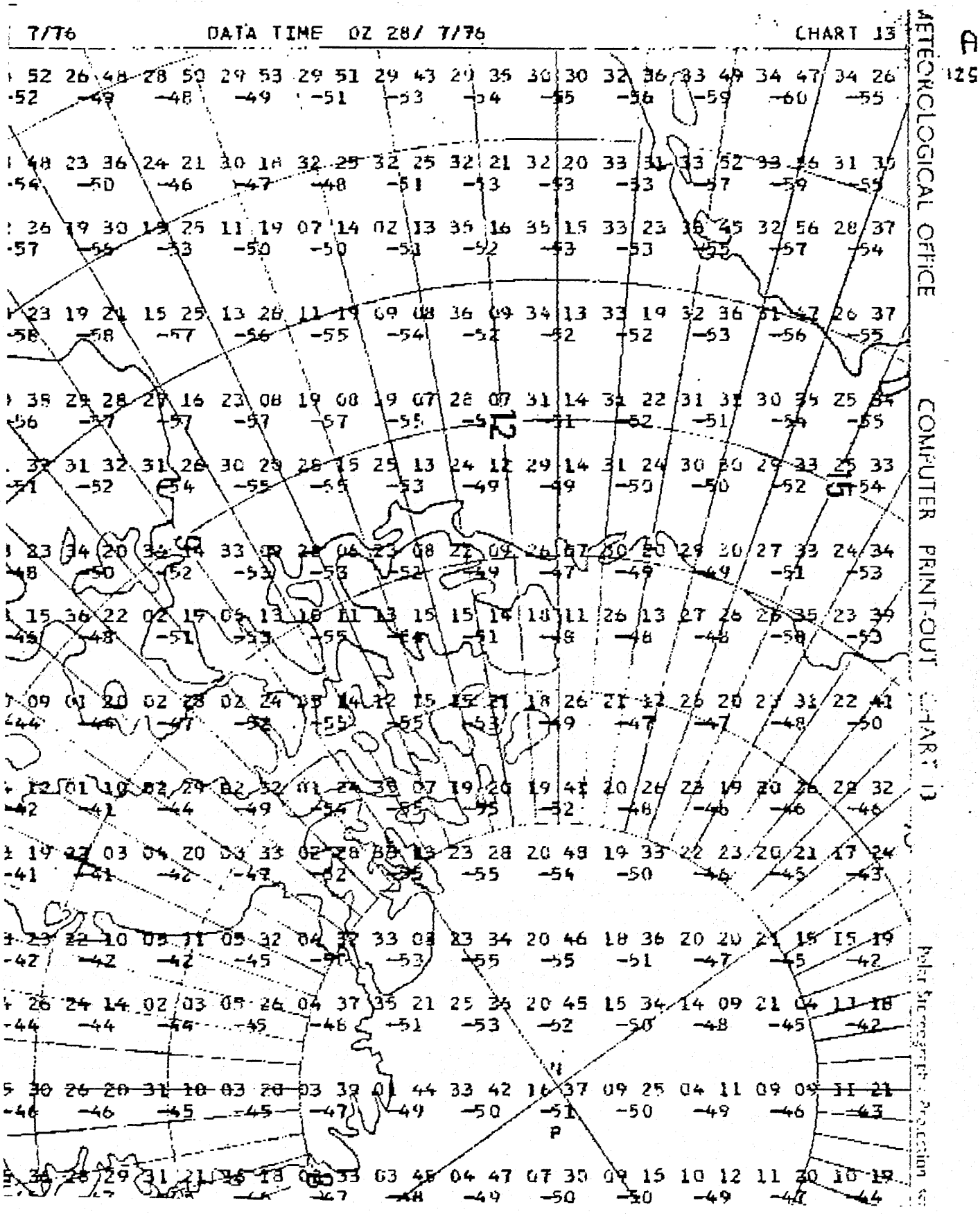


Fig.3.32. Reconstructed Image A5b After 8/6 Compression.
Compression Ratio = 1.33

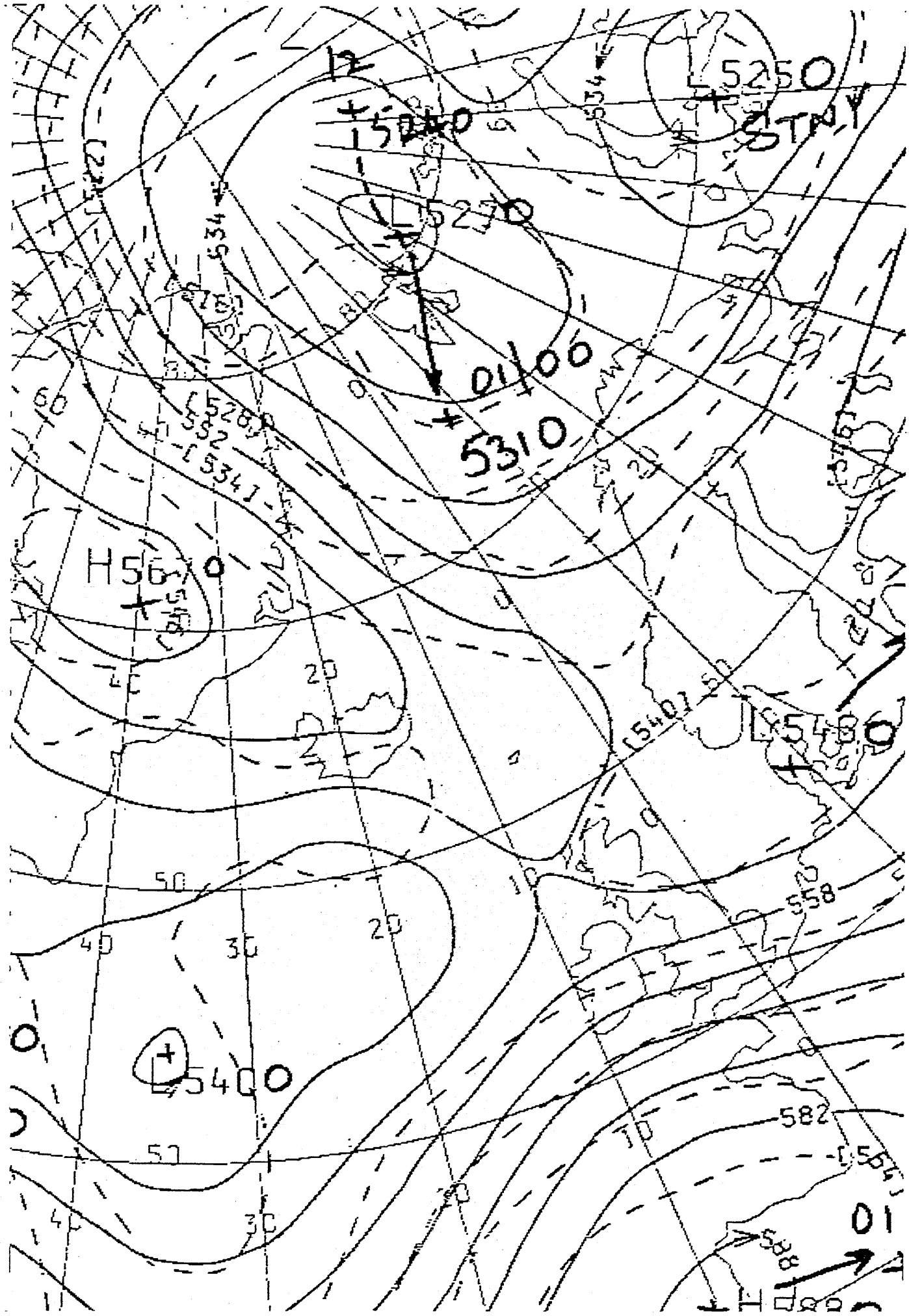


Fig.3.33. Reconstructed Image A5b After 8/5 Compression.
Compression Ratio = 1.60 .

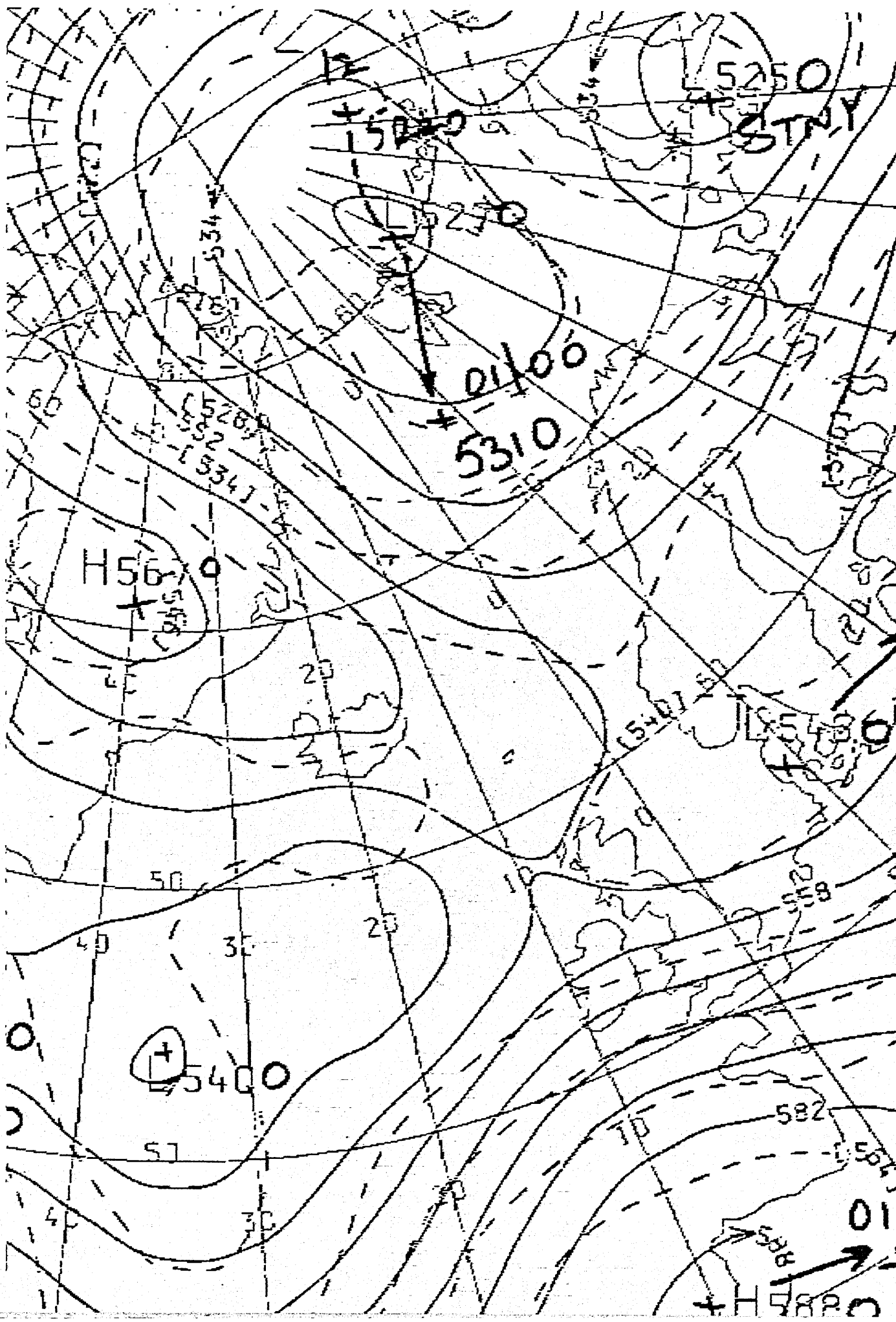
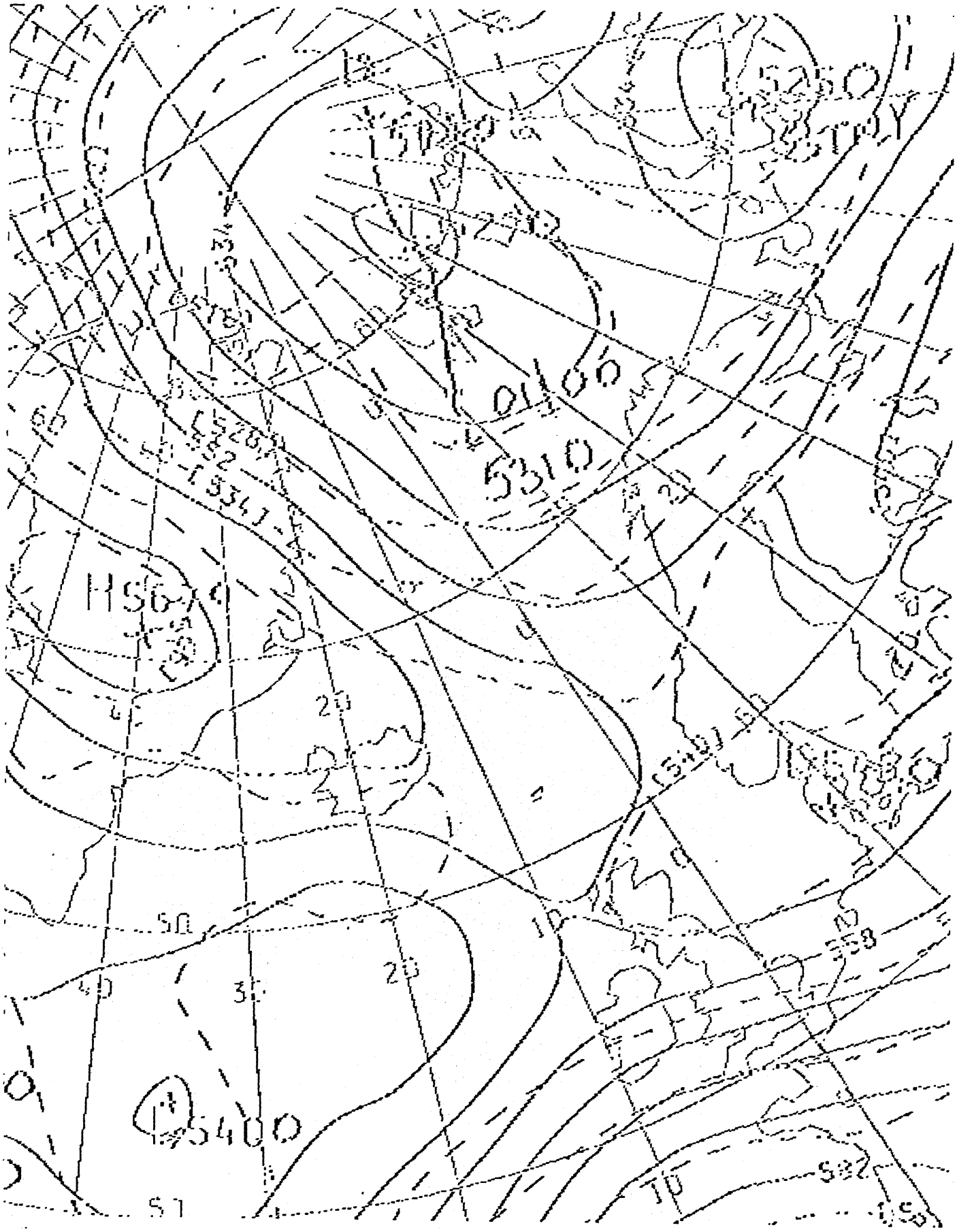


Fig.3.34. Reconstructed Image A5b After 8/4 Compression.
Compression Ratio = 2.00



CHAPTER 4

UNIVERSAL FIXED RATE BLOCK-TO-BLOCK CODING OF THE BLACK-WHITE FACSIMILE SOURCE

4.1 Universal Fixed Rate Block-to-Block Coding and its Merits

In the basic block-to-block (N/M) method of compression blocks of N pels of the binary facsimile data are taken and for each block an M-bit codeword is transmitted which identifies the N-bit binary pattern of the block or an approximated version of the pattern. This compression scheme whilst featuring good noise immunity and low implementation complexity suffers from several disadvantages. A major shortcoming is the fixed nature of the codebook used for encoding blocks of picture elements. This codebook is normally derived empirically from the combined statistics of a wide variety of images likely to be encountered on a practical facsimile system. This means that individual documents whose image statistics are not matched to those upon which the codebook is based will suffer large levels of distortion as a result of the encoding. Local variations in image statistics will produce similar distortion. The latter localised distortion often determines the subjective acceptability of a reconstructed image - loss or distortion of characters in isolated areas although occuring infrequently can often lead to unacceptability. A second disadvantage of an a priori codebook is the derivation of the codebook itself. This would require access to a mainframe or minicomputer (or nowadays, a microcomputer) having a large memory capacity and a facsimile scanning peripheral unit. The use of standard codebooks may not be

suitable for facsimile equipment specialising in certain classes of images or operating in different resolution ranges. A further disadvantage of a fixed codebook based on combined statistics of images is that the use of larger blocks for achieving lower distortion levels results in increased sensitivity to the codebook derivation. Tindall [26] observed that the use of a larger block (16-pels) gave rise to decreased levels of distortion compared to a block of 8-pels for a fixed compression ratio but the improvement was not obtained for a codebook derived from another image's statistics.

The above shortcomings are significantly reduced in a block-to-block compression scheme which is independent of the nature and stationarity of the source statistics. A method which may achieve this objective is to retain the N/M coding method but in addition to divide the image data into segments and derive a codebook from the block statistics of each segment. The segment codebook is transmitted along with the coded data bits at the output of each segment. At the receiver the codebook is extracted from the data stream and decoding subsequently effected on the coded segment. The compression ratio will be that of the basic N/M scheme reduced by the additional bits required for transmission of the codebook information. For a codebook containing a fixed number of entries (2^M), for each segment the output of the coder will thus consist of a fixed number of bits per segment which can be released into the transmission channel at uniform rate without the need for buffering. In view of the universal applicability of this type of compression without prior knowledge of the source statistics it is designated Universal Fixed-Rate Block-to-Block Coding or Universal N/M Coding for short.

In this chapter the results of a study of Universal N/M Coding of the binary facsimile image are presented. The adopted approach is to view the

method as a codebook-adaptive form of block-to-block coding earlier researched by Tindall for the set of test images [26]. The performance resulting from adaptation of the codebook is directly weighed against that of the non-adaptive fixed-codebook scheme. The limits of performance of the universal method in the compression of actual binary images are established. Later in the chapter the effects of transmission errors are investigated by simulation. Before a discussion of the simulation results the parameters for a universal N/M scheme are first introduced.

4.2 System Parameters

The compression ratio in a universal N/M block-to-block compression scheme may be defined as the ratio of the total bits (or pels) present in the uncompressed image to the total of coded data bits and codebook information bits. Let the image be divided into y segments and let each segment contain z picture elements. The total transmitted bits for each segment is the sum of coded data and codebook bits i.e.

$$B_{seg} = rM + I \qquad 4.1$$

where r is the number of N-bit blocks per segment (rN=z) and I is the number of bits used to represent the segment codebook. For each segment

$$I = N.2^{M} \qquad 4.2$$

The compression ratio (CR) is given by

$$CR = \frac{yz}{yB_{seg}} \qquad 4.3$$

$$= \frac{rN}{rM + N2^M} \qquad 4.4$$

$$= \frac{\frac{N}{M}}{1 + \frac{N}{M}.\frac{2^M}{r}} \qquad 4.5$$

It is readily apparent that the compression ratio tends to that of the basic scheme ie. $\frac{N}{M}$ as the segment size increases ($r \to \infty$). In general as long as $r >> 2^M$ i.e. the number of blocks in the segment far exceeds the number of entries in the codebook, the compression ratio does not deviate much from that of the basic scheme. Table 4.1 shows some compression ratios attainable for 8-pel blocks at various segment sizes. Figure 4.1 shows the relationships between compression ratios and segment sizes for block sizes of 8, 10 and 12 pels.

In view of the correlation existing between pels in successive lines of the image and the line format of scanning it is a natural choice for the segment to consist of an integer number of lines. It may be feasible for the segment to consist of a portion of a line but unless the scan length is very long the resulting compression ratio will be poor because of the relatively few number of blocks in each segment. The choice of how many lines to constitute a segment is influenced by two main conflicting factors. As Eqn.4.5 shows a large segment will give rise to a higher compression ratio but the degree of adaptivity to line-by-line changes in block statistics deteriorates. For images whose statistics are not likely to change over several lines a larger segment will permit a large enough number of samples to derive a codebook more accurately matched to the

statistics of the segment. This is perhaps more applicable to homogeneous image material like weathercharts. The use of large segments would also require a larger amount of storage for the lines of data constituting each segment and consequently a longer time delay is introduced.

The block size N is an important parameter in determining the performance of the compression scheme. A large N will provide a wider range of values of N/M so that a larger choice of compression ratios is available. When larger blocks are used lower distortion levels are possible as the correlation between samples exist over several elements. However there is an obvious limit to further improvement when N becomes too large as correlation vanishes between pels too distant apart. The practical bound is, however, usually determined more from the amount of memory required to store the codebook which increases exponentially with N. For example a 20-pel block will require 2^{20} ie. about 1 million 20-bit words of storage if a ROM method of encoding is employed. For a codebook-adaptive scheme the number of codebook information bits therefore increases exponentially with N for a constant value of N/M and the compression ratio rapidly decreases. As Eqn.4.5 shows the compression ratio can remain constant if the segment size increases in a correspondingly rapid manner. The resulting disadvantages due to a large segment size have been cited earlier. A further disadvantage of using large N is a decreased immunity to transmission errors. For the same probability of transmission error the probability of codeword corruption exists if the block size is increased. A larger block size also implies that a contaminated block codeword will give rise to a larger average number of errors after decoding. Individual blocks incorrectly decoded may also become more visible compared to smaller-sized blocks.

4.3 Simulation of a Universal Fixed-Rate Scheme for Noise-Free Transmission

The computer program designed for simulation of the universal block-to-block compression method incorporated the following features:

i) the capability to process the assortment of test images of varying line widths and resolutions

ii) the facility for easy adjustment of system parameters e.g. block size and codebook length

iii) the ready analysis of performance criteria eg. percentage reconstruction errors, percentage unassigned patterns at line and segment levels. Codebooks and pattern histograms including cumulative probability distributions may also be accessed at these levels.

The image to be processed is first transferred to magnetic disk from permanent storage on magnetic tape. In view of the block mode of storage of the data an elaborate indexing routine was devised which allowed individual image lines to be directly accessed from block storage. Groups of these lines constituting a segment are transferred to the limited amount of core available and processing then commences on the segment blocks. When the processing is completed the segment is returned to disk and the procedure is repeated for the next segment. When all segments in the image data have been processed in this way the image is transmitted to the Muirhead K-441 receiver where it is printed out for subjective evaluation.

In the encoding process the first step is to obtain a count of the frequency of occurence of block patterns in each segment. This is followed by a sorting of the frequency histogram in order of decreasing frequency. The sorted histogram is finally truncated to the first 2^M entries to form

the segment codebook. An M-bit pure binary code is used to code the segment blocks in association with the derived codebook. The decoding procedure simply consists of decoding the data bit stream using the segment codebook. The detailed generation of the segment codebook is now described.

4.4 Codebook Derivation

4.4.1 Operations Procedure

The derivation of the codebook for an image segment may be accomplished in two stages. These are:

i)the formation of the frequency histogram of block patterns

ii)the obtaining of the Z most frequent block patterns, where $Z = 2^M$.

The first stage is most speedily performed by use of a 2^N-word count store where the word length must be capable of accumulating the maximum count for a block pattern. As N increases this count store increases exponentially in capacity but practical restrictions for N will allow a store capacity which is not excessively large (eg $N < 10$). The store contents are zeroed at the start of an image segment and for each input block the binary pattern is used to address the store whose enabled location is then incremented. At the end of a segment the histogram is available in the store. On a microprocessor this operation is readily executed and a single instruction may be all that is required.

The second stage of the codebook derivation requires a sorting of the accummulated counts for the block patterns. Numerous sorting algorithms are available and two of these which are highly suitable for the present

application are now described. The first involves a straightforward search for the maximum value of an array of elements, removing this value from the array and repeating the process for the reduced array. A full descending-order sort of an array of J elements ($J=2^N$ in this application) will therefore require (J-1) such searches (the last search is for a set of size 1 which is omitted). Each search involves successively comparing array elements with a running maximum and updating it if a larger value is found. Associated with the maximum count is the block pattern which is also updated. The block pattern is the binary address of the count store. It is not necessary to use a second array to hold the maximum values as they are being obtained. As each maximum is found it can be placed at the top of the array whose content is then placed in the location of the maximum. A main advantage of this 'shrinking set' sorting algorithm is that a truncated sort of Z stages will yield, in order, the Z largest values of the array and its associated block patterns which is all that is required for the codebook derivation.

4.4.2 Merge Sorting

An alternative method of sorting known as Merge Sorting[44] has the advantage of superior computational speed but requires an extra array in its operation. In view of the declining cost of memory, the latter may not be a serious disadvantage. The operation of the algorithm for a descending order sort is shown in Fig.4.2 for an input array size which is a power of two. In the first stage pairs of elements of the input array L1 are examined and the elements of the pair are reordered with the larger value located first, and transferred to an array L2. In the next stage the array L2 is divided now into groups of four, and within each set of four elements

the elements are again ordered and transferred to a new array L3. Now groups of 8 elements (in this case only one group) are ordered and transferred to a further array L4. Here the desired sorted array is obtained in L4, and is obtained after 3 stages of ordering and transferring (known as merging). For an original input array of J elements where J is a power of 2 there will be $\log_2 J$ stages of merging. This is a great improvement over the J stages required of the full shrinking sort described earlier (albeit the cycle time decreases linearly with shrinkage in the latter case). The primary operation which achieves this high-speed sort is the merging operation at each stage. The principle is illustrated in Fig.4.3. Here a group of eight elements is being transferred or merged to a new group which resides in C. The input group is divided into two halves A and B and a pointer is available for each half (IA and IB respectively) which addresses the two elements being compared for a transfer to the location IC of the array C. In the transfer operation A(IA) is compared with B(IB). If A(IA) is greater than B(IB) it is transferred to location C(IC) and IB is incremented. When IA or IB reaches its upper bound of 4 the merge operation is complete. The flow diagram for this operation is shown in Fig.4.4. For each merge operation there is a total of J comparisons, giving a total of $J\log_2 J$ comparisons for the entire sort operation.

Compared with the shrinking sort routine, apart from the additional memory required the merge algorithm cannot be used for a truncated sort. However the time for a full sort is only proportional to $J\log_2 J$ comparisons. In the shrinking sort, a total of Z stages is needed with each stage requiring successively J-1, J-2, J-3 ..J-Z comparisons. If Z is small or if speed is not critical the truncated shrinking sort routine is advantageous. Otherwise the merge algorithm is to be preferred at the

expense of increased memory requirements. It is emphasised that in both methods a parallel procedure for shuffling the block patterns associated with the count values is required. To achieve this a parallel array storing the associated block patterns may be used and the contents are ordered along with ordering of the count array. For the merge algorithm a further holding array is therefore needed in addition to the input pattern array. For such an associative sort the block patterns may be treated as extensions of the count values being sorted, and are merged in parallel with the count values at each stage. Two arrays are therefore involved in the parallel merge operation for the block patterns. At each stage no actual comparison of block patterns is obviously carried out but a transfer of J patterns is required. If a transfer operation is regarded as equivalent to a comparison then the associated sort will require $J\log_2 J$ compare operations.

A comparison of the times of execution for some typical values of Z and J are shown in Table 4.1. The programs used were written in high-level Fortran language. The superior performance of the merge algorithm for large arrays is clearly evident.

The method of aproximation of invalid block patterns involves finding maximum value of the truncated cross-correlation function, as described in chapter 3 for the fixed N/M scheme. In a practical implementation though, it may be preferable to employ the simpler process based on maximum bit-coincidence count.

4.5 Simulation Results for 8-pel Blocks

4.5.1 Discussion of Results for 1-line Segment

The initial tests carried out on Universal N/M compression of binary images made use of 8-pel blocks. This was compatible with earlier simulation of fixed N/M schemes which predominantly used blocks comprising of the same number of elements. Thus more accurate comparisons can be made and meaningful conclusions drawn as to the relative merits of the transmission of codebook information. Images A1 and A5 which share the same resolutions and line-width were used in the initial tests. The segment size was set at 1 line which meant a storage requirement of only 1 scan-line of the image. Table 4.3 shows the percentage reconstruction errors (PRE) and the percentage of blocks whose patterns require approximation (percentage unassigned blocks, PUB). Figures for the fixed-codebook scheme have also been included for comparison. For data A1 it is seen that the use of a variable codebook in the 8/4 compression mode resulted in almost 50% fewer reconstruction errors over that for the fixed codebook. The price paid is a decrease in compression ratio from 2.0 to 1.63. The reconstructed image displayed in Fig.4.5 shows a distinct improvement over that of the fixed-codebook scheme (Fig.3.16) but the level of distortion is still objectionable. Tests for 8/5 and 8/6 compression modes were omitted for the single-line segment because of the poor compression ratios exhibited by these modes (see Table 4.1). For data A5 a decrease in PRE of 63% was obtained when a universal approach was adopted for the 8/4 mode. The subjective improvement in image quality is apparent (Fig.4.6, compared with Fig.3.28 for fixed scheme). When comparing on the basis of compression ratio it is found that for data A1 the fixed 8/5 scheme produced a similar quantitative amount of distortion as the

line-adaptive 8/4 scheme and yielded an approximately similar value of compression ratio (1.60). For data A5 the fixed 8/5 scheme produced half as many errors as the codebook-adaptive 8/4 method. One of the possible reasons for the limited performance of the universal method for a single-line segment is the lack of correlation between blocks in the horizontal direction of scan-line. This is reflected in the percentage of unassigned blocks which was 2.26% in image A1 for the universal 8/4 scheme. The fixed 8/5 scheme had 2.60% of approximated blocks whilst producing about the same level of distortion indicating that the invalid blocks, whilst being fewer in number, produced more encoding errors after approximation in the universal case. This could be in part due to the smaller codebook choice in the 8/4 mode of the universal scheme. A further possible reason is a mismatch of unassigned patterns with codebook patterns within the segment. In general for the block-to-block method of compression to work well, i.e. yield low levels of PRE, the probability distribution of block patterns in the segment should show a strong bias towards towards some patterns, and the lower-probability patterns which are excluded from the codebook should have a measure of similarity to the codebook patterns. Assuming successive blocks are statistically independent, which for large blocks is likely to be true, the latter effect is less likely to occur. However if blocks of image are correlated to some extent within the segment the likelihood of some resemblance of excluded patterns to codebook patterns increases. For image data this kind of correlation does exist across lines of image as a result of two-dimensional redundancy of the image. However if only a single line of image is taken redundancy in the vertical dimension is not exploited. To examine this aspect further a test was carried out in which the unassigned blocks of each line were approximated using the codebook patterns of the previous

line rather than those of its own line. Table 4.4 shows the resulting percentage reconstruction errors and the change from the normal universal 8/M scheme. For both A1 and A5 a drop of PRE is recorded when the previous line's codebook was used. The change for A1 is small but a significant reduction of 28% was found for A5. This demonstrates a better matching of invalid patterns of the current line to the codebook patterns of the previous line than those of its own line, and suggests a strong line-to-line correlation which overshadows any possible correlation of blocks within the same line. The above method of approximation cannot be practically implemented because it is not possible to discriminate, after the approximation process, between invalid blocks approximated using the previous line's codebook, and valid blocks coded using the codebook of the current line.

In the course of the simulation it was observed that the all-white pattern was a consistent member of all segment codebooks and almost always remained the most probable pattern. As a consequence no loss of information will occur if the pattern is omitted from the transmitted codebook. At the receiver the pattern will be assumed to be the first codebook pattern of every segment. This practice was carried out in all further tests reported on and the compression ratio calculated using the slightly modified expression

$$CR = \frac{\frac{N}{M}}{1 + \frac{N}{M}.\frac{(2^M-1)}{r}} \qquad 4.6$$

An additional advantage of the omission of the all-white codebook pattern apart from the obvious decrease of transmitted codebook size is

that in the event of this pattern being corrupted by transmission noise, had it been transmitted, a large number of errors will occur as a result of the very large frequency of the pattern in the segment.

4.5.2 Results for Multi-line Segments for Images A1 and A5

The effect on percentage reconstruction errors and invalid or unassigned blocks when the segment consists of more than one line is shown in Table 4.5, with figures for the fixed N/M scheme also included in the table. For both A1 and A5 the percentage reconstruction error in the 8/4 mode registered a sharp increase when the segment size was increased from one to two lines. For further increments in the segment size the error count increases more gradually. At a size of 6 lines the percentage error for A5 is still considerably less than that of the basic 8/4 scheme while the number of errors for A1 approaches the figure for the fixed method. The reconstructed images for segments consisting of 2, 4 and 6 lines are shown in Figs.4.7 to 4.9 for A1 and of 6, 8 and 10 lines in Figs.4.10 to 4.12 for A5. For A1 gradual deterioration in subjective quality is apparent as the segment size increases. Generally the image quality tends to that of the basic 8/4 scheme with increasing number of lines in a segment. For A5 the increase in distortion is very gradual and not very noticeable. The quality of A5 at 10 lines per segment (CR = 1.96) appears to be acceptable. The reproduced images for 8/5 universal coding are given in Figs.4.13, 4.14(for A1, segment sizes = 4 and 6 lines) and Fig.4.15(for A5, segment size = 6 lines). The image A1 at 6 lines per segment is very readable and is roughly similar to that obtained in the basic 8/6 compression method (Fig.4.14). The compression ratio of 1.51 obtained here may be regarded as the limit for subjectively acceptable levels of

reconstruction distortion in the compression of A1 using the universal fixed rate method. This is an increase of 13% over the value for the basic method (8/6 mode or 1.33 compression ratio). For the weatherchart A5 a compression ratio close to 2 is attainable using the 10-line 8/4 mode mentioned earlier (Fig.4.12, CR = 1.96).

For both the 8/4 and 8/5 modes the results for the case when the segment size consists of the entire image are included in the tables of results. This corresponds to the derivation of the codebook from the individual image statistics. Storage of the whole image is required which is not an attractive practical proposition but for facsimile systems which specialise in transmitting specific types of image material eg. weathermaps and where the image statistics do not vary from one image to another it may not be necessary to rederive the codebook for each image. This then becomes a fixed-codebook system which is dependent on the stationarity of the block statistics of the transmitted images.

4.5.3 Results for Other Test Images

The results for 8/M universal coding of the other test images are given in Tables 4.6 and 4.7. Table 4.6 shows the distortion figures for the test images sampled at 150 pels/ inch and containing 1128 pels per line, as with A1 and A5. In these cases the compression ratio is constant for each segment size made equal to a multiple of lines. The results for the remaining test images which have different resolutions and/or line widths are given in Table 4.7. In all cases a fall in the number of encoding errors is recorded when an adaptive codebook is employed instead of an average fixed codebook for the same mode of compression. The decrease in number of errors gradually reduces as the segment size

increases, while the compression ratio also increases. A graphical form of the results is given in Fig.4.16. From Table 4.6 it is clear that of all the test images the circuit diagram A3 and handwritten letter A4 showed the largest drops in number of encoding errors when the universal approach was adopted (about 65% for 8/4 1-line segment and excess of 78% for 8/5 2-line segment for both images). For the images sampled at 150 pels/inch the smallest changes are shown by the densely typed image A2 which registered a decrease of 41% for the 8/4 1-line segment, and the computer-printed weatherchart A6 which showed a drop of 60% for the 8/5 2-line segment. The results for A5b demonstrate the effect on a lower-resolution version of the weathermap. When compared with the results for A5 in Table 4.5, for approximately similar values of r, the segment size in blocks, the decrease in encoding distortion is seen generally to be smaller for the lower-resolution version. This might be expected because the performance of A5 is the best of all the test images that were coded and the results for A5b are more similar to the other images. The oversampled nature of A5 gives rise to block statistics which are relatively different from the average statistics used to form the fixed codebook and a universal scheme clearly adapts to the oversampling yielding much greater levels of improvement.

A selection of reconstructed images is shown in Figs.4.17 to 4.32. For each test image the result for single-line 8/4 coding (CR=1.65) is displayed and except for A5b the result for 8/5 coding is also given for a segment size of 2 lines (CR=1.33) and 8 lines (CR=1.55). The quality of these images may be compared with those in Figs.3.17 to 3.34 for the fixed codebook scheme. For the universal 8/5-coded images the use of a 2-line segment does not generally produce perceptible image degradation. When the segment is increased to 8 lines it was still difficult to make out the

increased amount of distortion especially for the images containing diagrams and drawings. The compression ratio here is 1.55 which is 16% higher than that for the 8/6 fixed-codebook method. However, if very high quality of reproduction is required it may be better to restrict the segment size to 2 lines. The compression ratio then is similar to that of 8/6 coding using a fixed codebook but no a priori knowledge of image statistics is needed.

4.5.4 Use of Squarer Segments

The performance of universal block-to-block coding is further investigated for segments which are not an integer number of lines but cover 'squarer' portions of the image. For an implementation in a raster-scan system the use of a multiple-line segment was convenient and provides for minimum storage required for a given r (where r is a line of blocks or greater). However the lack of correlation between blocks along a line of scan has been earlier noted and a more two-dimensional segment can perhaps produce better results. The results of simulation are shown in Tables 4.8 and 4.9 for a selection of segment sizes. Percentage changes from the figures for equal or nearest values of r (given here as axb where a is the number of 8-pel blocks in the horizontal direction and b is the number of lines) are included beside the PRE and PUB columns. The segment size in terms of the number of lines and the proportion of the line width is given in the second column. For all the images used in the simulation the 8/4 mode of coding performed better when the segment size of 141 blocks is configured from 8 lines vertically and 1/2 line horizontally instead of a whole line, but the improvement is slight for some of the images (A1, A4 and A6). For these images it is clearly not worth the storage of 8 lines

needed to encode this segment. The image A2 showed the best result, achieving a 64% reduction of reconstruction errors when the 8 x 1/8 configuration was employed instead of an entire line. Nevertheless the distortion level of 1.86% is still excessive for subjective acceptability of the approximated image. For the oversampled weathermap A5 (not shown in tables) a decrease of 20% in PRE was recorded. The resultant value of 0.43% reconstructed error yields an image which is quite acceptable subjectively so that a compression ratio of 1.65 may be obtained for this image with the universal scheme. The results for 8/5 universal coding with the more two-dimensional segments however do not show significant change from the use of multiple-line segments. As noted from Tables 4.8 and 4.9 a segment size which spans 32 lines vertically and an eighth of a line horizontally shows a slight or unchanged PRE level over the same-sized segment made up of 4 horizontal lines. For segments which cover larger portions of the line width the improvement is even less and in some cases slight increases in distortion levels are obtained. It is likely that the improvement will be more marked when the segment becomes a square ie. the number of pels in each direction is the same, but this calls for an even greater number of lines of storage (for example if r = 560 blocks = 4480 pels the corresponding square matrix dimensions is 67 x 67). It is unlikely that the amount of improvement will justify the additional storage capacity required.

Examples of reconstructed images with the use of two-dimensional segments are given in Figs.4.33 to 4.38. Here the results for 8/4 mode are displayed. The segment size in all these examples covers approximately 64 pels in the horizontal direction and 8 pels in the vertical direction and for all cases improvements in PRE over a single-line segment have been obtained. For the business letter A1 the image degradation is visible but

not disturbing. A more pronounced improvement is apparent for the image A2 over a single-line segment (Fig.4.17) but the quality is not likely to be acceptable in commercial facsimile systems. This is not the case for the weathermap A5 where high quality of image is retained. Image denigration is also visible in the low-resolution version of the weathermap, A5b where the relative coarseness of sampling makes it difficult to conceal the effects of approximation of patterns.

4.6 Coding with Vertical Blocks

In both the fixed and universal N/M compression methods the serial output of the scanner is taken N pels at a time and suitably coded. For each block the probability of a binary pattern is determined by the statistics of the source and a block is normally assumed to be independent of all other blocks. In practice the correlation between picture elements along a line of scan usually exist over several elements and is influenced by the degree of oversampling. However if N is large relative to the depth of correlation the blocks may be treated as being statistically independent. In a real image the redundancy is intrinsically two-dimensional so that blocks which occur in the next scan-line may be influenced by those above them in the current line. For the test images A1 and A5 the correlation between scan-lines was earlier demonstrated in the single-line universal 8/4 scheme when the unassigned blocks of the current line were approximated with fewer errors using the codebook derived from the blocks of the previous line than its own line. The use of segments which are more uniformly two-dimensional results in excessive storage requirement. In an attempt to capture further the correlation between blocks a vertical coding block is introduced which requires a storage of N

lines. The configuration is shown in Fig.4.39. A coding block consists of N vertical pels and the segment comprises r such adjacent blocks. The value of r is constrained, for equal-sized segments throughout the image, to be a fraction of the number of pels in a line but obviously the compression ratio diminishes for smaller values of r. The following considerations may be noted for this method of coding:

i) The adjacency of the vertical blocks in the segment provides the main motive for this choice of block configuration. A larger proportion of correlated block patterns is expected than for the case of the original serial block configuration in view of the increased mutual proximity of blocks. However with serial blocks, when the segment consists of several lines of image, the line-to-line correlation may also be captured. A comparison of the performances for the two configurations should therefore indicate the relative dominance of this correlation in relation to format of coding block.

ii) The main test images exhibit a lower resolution in the vertical dimension (100 pels/inch) compared with the horizontal dimension (150 pels/inch). This means that patterns for a vertically-configured block will reflect the lower sampling density and hence the image source will exhibit a higher entropy in view of the reduced amount of redundancy. The consequence is an offset in possible gains due to better correlation between blocks. Apart from difference in resolutions the natural redundancy of the image may also have unequal components in the horizontal and vertical dimensions. This is difficult to quantify but intuitively the disparity where it exists is not terribly large.

The results of computer simulation for 8-pel blocks are given in Tables 4.10 and 4.11. Segment sizes were chosen to span 1/8, 1/4, 1/2 and

1 line width and be equal to earlier simulated schemes. Percentage changes from the conventional serial format of blocks are included for segments of equivalent size. On the whole the results show a mix of improvement and worsening of performance depending on image type. The images A1, A2 and A5b yielded lower levels of distortion whilst A4, A5 and A6 showed increased amounts of encoding errors. The remaining image A3 exhibited a varied performance depending on compression mode and segment size. The use of vertical blocks appears to be quite suitable for typed material. Figs.4.40 to 4.45 show the reconstructed images for A1 and A2 for various segment sizes and modes. From the tables the percentage decreases in reconstructed errors are substantial, in most cases the number of errors was half of less of that obtained with the use of horizontal coding blocks. Generally the percentage improvement increased with smaller segment values. This seems to suggest that the correlation between the vertical block patterns is exceptionally strong in typed material and is exploited more fully by smaller-sized segments. As the segment size increases the performance becomes comparable with that for serial blocks which over several lines may also capture the vertical component of image redundancy. The reconstructed image of A1 shown in Fig.4.40 is clearly superior to that of Fig.4.5 where a serial coding block was employed. For this 8/4 coded image the quality tends close to that of acceptable commercial quality. The same observation is made for the image A2 shown in Fig.4.43. On inspection of both 8/4 and 8/5 coded images it appears that the results of approximation of vertical blocks is more visible than for serial coding blocks despite the smaller number of reconstruction errors. This may be attributable to the lower vertical resolution which is two-thirds of the horizontal resolution in these images.

The unfavourable performances of the other test images reflect their

sensitivity to the change to a vertical block format and indicate their dependence on the strong horizontal component of redundancy for good 8/M coding generally. Image A5 for example is over-sampled primarily in the horizontal dimension. A horizontal coding block therefore exploits the abundant horizontal redundancy in an adaptive universal coding scheme and therefore yields lower amounts of distortion, whereas a vertically-configured block captures mainly the smaller amount of vertical redundancy. Thus for the image A5b where the horizontal resolution has been reduced to 75 pels/inch the use of horizontal blocks is no longer as beneficial and a vertical block produced better results. For images which contain a large number of horizontal lines eg. A3 a change to a vertical block obviously eliminates the concentration of all-black patterns that may otherwise be found in a segment which are conducive to good performance.

4.7 Results of Simulation for Other Block Sizes

The study of universal fixed-rate coding has hitherto been carried out for a block size of 8 pels. This value of N allowed ready comparison with fixed codebook techniques and is a very convenient choice for implementation especially if microprocessors are employed. The block size also yields good performance generally for block-to-block coding schemes. In this section the results of using block sizes other than 8 are reported. In particular, attention is given to the usage of larger block sizes with the aim of achieving higher compression ratios than can be obtained by a block size of 8 pels.

As discussed earlier in section 4.2 higher compression ratios can be obtained by the use of larger blocks but the segment size must also increase at the expense of increased storage and loss of fine adaptivity to

changes in image statistics. To observe the effects of different block sizes a simulation of the coding method using horizontal coding blocks was carried out on the images A1, A5 and A5b. Table 4.13 shows the levels of PUB and PRE obtained for various block sizes and segments. Referring to the table, it is clear from the PRE values for A1 that a block size of 7 pels will not be capable of giving compression ratios greater than 1.5, the approximate value obtainable with 8-pel blocks. Bearing in mind that the maximum value of PRE at which good image quality is preserved is about 0.2%, the simulated 7/4 modes yield unacceptably large amounts of distortion. With a 7/5 mode a PRE value of 0.1% is obtained which is below the margin of acceptable image quality (CR=1.35). At a block size of 9 pels a 16-entry codebook fails to produce a satisfactory image even for a single-line segment, which is to be expected as the simulation for 8-pel blocks had earlier shown an inadequate performance. When the codebook size is increased to 32 patterns the distortion is still above acceptable levels and it does not appear to be possible to obtain increased compression ratio values over 8-pel blocks without incurring an inferior image quality. For a block size of 10 pels a wider range of compression modes is available. Use of small codebooks as in 10/4 coding resulted in unacceptable PRE levels even when the segment size is reduced to 1 line. With 10/5 coding good performance does not appear to be obtainable with the simulated segment sizes of 2 to 10 lines. A simulation for 10/6 coding employing a segment size of 8 lines (CR=1.49) produced a PRE which is just below the acceptable limit. Finally, the results from the use of 12-pel blocks do not suggest that appreciably large gains in compression ratio are possible mainly because for this large block size the segment size must be large to reduce the proportion of codebook bits to codeword bits. Assuming that no codebook is transmitted it is interesting to note that for the same number

of lines in a segment ie 8 a change from 10/4 to 10/5 and 12/6 (CR=2.0 in each case) yields values of PRE of 0.72%, 0.52% and 0.33% respectively, showing that as the block size increases for a given size of segment, lower levels of distortion are obtained. In pratice the need to transmit larger codebooks swamps the benefits that may arise from the use of bigger blocks.

For the image A5 the threshold of PRE for good image quality is about 0.5% but PRE levels of up to 1.0% are often tolerable. It is apparent that reasonable-quality images may be obtained from the majority of modes and segment sizes shown in Table 4.13. With 8-pel blocks acceptable image quality was earlier obtained for a segment consisting of 1 line of coding using the 8/4 mode (CR=1.65). When the block size was increased to 9 pels the resultant PRE of 0.73% is not intolerable (reconstructed image shown in Fig.4.46) but the fine quality of characters has been eroded. The degradation becomes more visible as the segment size increases (Figs.4.47 and 4.48). For the 6-line segment the value of compression ratio is 1.93. Two examples of compressed images which exhibit a compression ratio of about 2 are shown in Figs.4.49 and 4.50 where 11/5 coding has been performed for segment sizes of 6 and 8 lines respectively (CR=1.98 and 2.03). The image in the former case is visibly slightly better (PRE=0.7%) but for both cases the quality is reasonably good.

The image A5b is able to accommodate a level of PRE of about 0.4% without much noticeable degradation. From Table 4.13 this level is exceeded by most of the simulated cases for block sizes up to 11 pels. Fig.4.51 shows the result for 9/5 coding with a segment of 6 lines (CR=1.57). The image distortion, although slight may be generally detected. A better quality of image is obtained with 11/6 coding employing a 10-line segment (Fig.4.52, CR=1.49). THe PRE of 0.33% is probably just

about acceptable. The reduced resolution of this image means that more lines are needed to form a segment of resonable size which adversely affects the degree of adaptivity.

The results obtained with the use of larger block sizes indicate the difficulty of attaining higher compression ratios by increase of the block size. Small increases were indeed obtained but it is doubtful if the additional complexity and cost will justify a recourse to use of these larger blocks. The results demonstrate the value of the choice of 8 pels as block size for obtaining relatively good compression ratios without too much complexity of implementation.

4.8 Vertical Block Coding of A1 for Various N

The favourable results obtained from universal 8/M coding which employed vertical blocks, for typed image material, prompted an investigation to see if it was possible to obtain a compression ratio of 2.0 for the image A1 with a different value of N. The percentage reconstructed errors obtained in this simulation are shown in Table 4.14. Decreasing the block size to 7 pels and using a codebook of 8 entries failed to produce an image of acceptable quality (Fig.4.53, CR=2.09). The result for 9/4 coding featuring a segment which spans an eighth of a line (CR=1.82) is shown in Fig.4.54. The image is probably just barely acceptable. Two results for the use of 10-pel blocks are shown in Figs.4.55 and 4.56. The compression ratios here are respectively 1.97 and 2.21. The quality of the former case is very similar to that of Figs.4.54 for 9/4 coding. In the latter case the PRE of 0.36% is outside the limit of acceptability of about 0.2% and this is evident in the displayed image of Fig.4.56. Further results for 11 and 12-pel blocks are exhibited in

Figs.4.57 to 4.59. The quality of these images is indeed good and indicate that a compression ratio of 2.0 is attainable through the use of these block sizes. The lowest level of PRE is showed by the 12/5 coded image (0.18%) featuring a segment size of 1/3 line (CR=2.00).

4.9 Effects of Transmission Errors on Universal Fixed-Rate Coded Images

The preceding discussion has assumed an error-free transmission channel where the received codewords are always identical with those transmitted. A practical channel will introduce errors in the transmitted bit stream at a rate and in a manner determined by the nature of the channel. The errors may be fairly random and isolated or may occur in bursts. Over a telephone channel for example errors are more likely to occur in bursts. The effect of errors is to cause erroneous decoding at the receiver. In this section the consequence of transmission errors, of both random and burst nature, on the universal block-to-block coded images is investigated by simulation.

It is clear that when a received binary digit is in error the consequence depends on whether a codebook bit or codeword bit has been corrupted. If the error occurs in a codebook pattern the effect is a reproduction of the corrupted pattern wherever it occurs in the segment. The total errors therefore depends on the frequency of the pattern in the segment. For random isolated errors the subjective effects should not be serious as these do not usually destroy intelligibility of the image but appear as sporadic black dots against a white background or isolated specks of white in black regions. If the transmission error coincides with a codeword bit the effect is similar to that of fixed N/M coding ie. a false reinstatement of a pattern occurs. The propagatory effects of a single

transmission error therefore do not extend outside the block size of N pels which makes this scheme relatively noise-tolerant. As the percentage of codeword bits is large compared with those of codebook bits the effects of transmission errors should not be drastically different from the fixed-codebook scheme.

The probability of an M-bit header being corrupted can be calculated for random transmission errors. If the probability of a transmission bit error is p, then the probability that a header word is corrupted is

$$P_c = 1 - (1 - p)^M \qquad 4.7$$

Table 4.15 shows the values of P_c for various M. With larger M the probability P_c increases, signifying that if larger coding blocks are used in the compression scheme with correspondingly bigger values of M the likelihood of a codeword being corrupted increases. Assuming that an image contains J codewords the expected number of corrupted codewords is P_cJ and if on average each corrupted codeword results in x reconstructed errors the expected total reconstructed errors due to codeword corruption is xP_cJ. With larger blocks the value of J decreases but x increases. Additional errors will be introduced as a result of codebook contamination.

Before presenting the results of computer simulation for transmission over a noisy channel, the method of simulation is described. For binary transmission the corruption of transmitted digits corresponds to inversion of the states of bits of the coded output from the universal block-to-block encoder. This is readily performed by EX-OR ing the transmitted bit stream with the output from a binary noise source. Two noise sources are simulated in this investigation. The first is a memoryless random source whose probabilities of outputs of '1' and '0' states are p and (1-p)

respectively. A '1' state results in a bit error in the transmitted bit sequence. The simulation of a memoryless binary source is readily achieved by partitioning into two the range of output from an integer random number generator. For example the output set of an integer random variable which lies in the range of 0 to 2^n-1 and exhibits equal probability of occurence over this range can be grouped into two such that the sum of the output probabilities in the two sets equal p and (1-p) respectively. Then one group is taken as being the '1' state of the binary source and the other the '0' state. For equiprobable random integer outputs this corresponds to the numbers 0 to r-1 as representing the '1' state where $p = r2^{-n}$. (2^{-n} is the equal probability of occurence of each number in the range 0 to 2^n-1). By changing r the value of p can be made to be variable. In most high-level languages a real random number generator is available as an intrinsic function. The random output, which is usually in the range 0 to 1.0 is readily converted to an integer variable by scaling of a factor 2^n and truncating the fractional part of the product.

The second noise source is based on the Gilbert model [35], and simulates the effects of burst transmission errors. This employs a first-order Markov source in which the state of the current output is dependent on the state of the previous output. The state diagram is shown in Fig.4.60. An output state is described as a 'good' state in which the Gilbert source always outputs a '0' signifying an error-free transmission bit, or a 'bad' state when a 'coin-tossing' or random-decision operation is performed and the outcome of it determines if a '0' or '1' is the output from the Gilbert source. In the case of the latter an inversion of the transmitted bit is performed. As shown in Fig.4.60 the probability of a change to a bad state from a good state is p, and the probability of no change when in the good state, is 1-p. When in the bad state a third

probability h is introduced which decides if the Gilbert source outputs a '1'. When in the bad state the probability of a transition to a good state is p_2 and the probability that it stays in the bad state is the complement probability $(1-p_2)$. On the whole the probability of a bad state is given by

$$P_B = \frac{p_1}{p_1 + p_2} \qquad 4.8$$

and the average probability of a transmission bit error is

$$p = hP_B = \frac{hp_1}{p_1 + p_2} \qquad 4.9$$

By a suitable choice of the three parameters h, p_1 and p_2 the value of p can therefore be varied. Fig.4.61 shows the values of these parameters for the value of p used in the tests. The Gilbert noise source is readily implemented through use of three simulated random binary sources.

The simulation of noise effects was found to make heavy demands on the available processing resources, in particular computational time. As a consequence it was not possible to carry out tests on too many images. It was decided to perform tests for one selected image and compare this with those for fixed-codebook block-to-block coding. The latter have already been performed by Tindall [26] for the images A1 and A5 and so these were avoided. (the subjective effects of noise were anticipated to be similar to those of the fixed scheme and so a different test image would be desirable). The image A5b was chosen as this was the most difficult to compress and because of its lower resolution, should show out more clearly the effects of transmission errors than the more densely sampled images

which can subjectively mask these out to some extent. The coding mode used was 8/5 with a segment size of 8 lines (CR=1.47). The PRE value of the encoded image for noiseless transmission is 0.45%. Figs.4.62 to 4.64 show the decoded images when random errors are injected into the transmitted bit stream at the error rates an average of 1 in 1000, 1 in 100 and 1 in 32. At the rate of 1 in 1000 the effect of transmission errors is negligible. As the number of errors increases to 1 in 100 on average, the number of short black streaks resulting from false reinstatements is increased but the intelligibility of the image is preserved. Increasing the average number of errors to 1 in 32 results in a reconstructed image in which contour lines and some characters can be correctly interpreted but a large amount of detail is beyond recognition. In assessing the quality of reproduced image it should be borne in mind that in the uncompressed case the reconstructed image after transmission over a noisy channel is corrupted anyway and so the quality should be judged against the contaminated image rather than a noise-free version of it. Logically therefore the main criterion when evaluating the decoded image is its relative intelligibility rather than high fidelity of reproduction.

The results for burst errors whose number total on average 1 in every 100 bits and 1 every 32 bits are shown in Figs.4.65 and 4.66. The improved quality of the image over random errors at the same rate is evident. This is of course attributable to the error burst coinciding with a codeword which will have been corrupted anyway by a single error. In Fig.4.66 the image content has been preserved to a large extent despite the average number of transmission errors of 1 in 32. This error rate is exceedingly large and the robustness of the compression technique is clearly demonstrated.

The quantitative results for the simulation of transmission error effects are shown in Table 4.16. The propagation factor K is calculated as the number of reconstructed errors divided by the number of transmission errors which occured for the image. This indicates the average number of reconstructed errors generated per transmission error but should not be interpreted too precisely as it does not take into account the PRE due to universal N/M coding. The decrease in number of errors in the reconstructed image when a burst mode is employed over a random mode is also evident.

In order to determine the rough threshold of average error rate which the coded image is capable of withstanding a further test was performed with the average error rate at 1 in 50. The reconstructed image for this amount of random transmission errors is displayed in Fig.4.67. Although quite heavily contaminated most of the characters in the image are just readable and this level of transmission errors appears to be the approximate limit where these occur at random.

As a comparison with fixed block-to-block compression a simulation was carried out for an 8/5 mode and the results are compared in Table 4.17. A high average error rate of 1 in 32 was used in the test which should minimise the proportion of contributions of encoding distortion to the percentage reconstructed errors. It is seen that fewer reconstructed errors were obtained in the case of fixed 8/5 coding which may be attributable to the contamination of transmitted codebook patterns in the universal case. The reconstructed image of the 8/5 coded image is shown in Fig.4.68. Comparing with that of Fig.4.64 it appears that the decoded image is subjectively worse than that of the universal scheme. A much

greater number of black horizontal dashes is evident. A possible reason for this effect is the variation of codebook patterns from segment to segment in the universal method. In the fixed N/M system one of a constant set of 32 patterns is reinstated when a codeword is corrupted, generally therefore for a large number of corrupted codewords a superimposition of these patterns at random occurs on the image. In the universal scheme a different set of patterns is obtained for each segment and a more diverse range of patterns is reinstated giving a less harsh appearance (due primarily to the all-black pattern being reinstated by corrupted codewords in the fixed 8/5 case).

4.10 Instrumentation Considerations for Universal N/M Coding

The system block diagram for a universal block-to-block compression scheme is shown in Fig.4.69. The input is taken a segment at a time and a codebook is derived from the block statistics of the segment. For each segment the codebook consisting of 2^M-1 N-bit binary patterns (excluding all-white pattern) is transmitted in addition to the coded data bits. S_1 indicates the multiplexing of the codebook bits on to the transmitted bit stream. At the receiver the switch S_2 selects the codebook from the data stream and this is then used to decode the codewords of the segment. The decoded output is finally fed serially to the printing unit.

In order to maintain continuous real-time transmission a dual-buffer technique may be employed at the transmitter and receiver. In this case two identical memory buffers, each capable of holding a segment of input data, are used alternately for holding successive segments of input image data at the transmitter. Whilst the contents of one memory are being processed the next segment is being loaded into the other memory. At the

receiver similarly decoding is carried out on the contents of one buffer whilst the other is being filled with the next segment. A delay of two segments is introduced at the transmitter if a time period of one segment is allocated for processing ie. the processed output is despatched to line when the other buffer has been filled. A similar delay of 2 segments will be incurred at the receiver. This method, whilst introducing a greater delay than is strictly necessary, is straightforward to implement, eases timing considerations and relaxes processing speed requirements. If an extended delay cannot be tolerated than the processed output may be despatched as soon as the codebook has been derived at the transmitter and the total delay here becomes the delay of one segment plus the time taken to derive the codebook which is dependent on processor speed. At the receiver decoding can commence as soon as the codebook has been received and a delay of one segment may be all that is incurred if the processor is fast enough. This is only possible if the codebook is transmitted ahead of the codeword bits i.e. if interleaving of codebook bits with codewords is adopted in order to protect against error bursts destroying consecutive codebook patterns, the dual-buffer technique is more appropriate. Normally delays of several lines are tolerable in facsimile transmission where communication proceeds in one direction only.

The varied tasks at the transmitter are best performed by a microprocessor. For transmission over the telephone network commercial 8-bit microprocessors should be capable of performing the coding operations within the time of a segment. The use of 8-bit coding blocks will greatly facilitate operations and maximise throughput rate. In deriving the codebook sorting and comparing procedures are called for, as discussed in section 4.4 which are readily implemented by a microprocessor. The storage of input data and output of codewords can also be performed in parallel with

the processing, via interrupt service routines. This greatly reduces the amount of hardware with the result that the system can be realised at relatively low cost. Fig.4.70 shows the recommended configuration for the implementation of the universal N/M encoder.

The hardware requirements of the receiver are relatively straight forward. Extraction of the codebook is readily performed by a ganged switch S_1 (Fig.4.71) which is then written into a RAM. During this time addressing of the RAM is from an M-bit counter. The RAM is then addressed by the M-bit codewords of the segment to furnish the binary patterns. which are stored in the FIFO buffer (capacity of 2 segments). At the end of the segment the decoded patterns are clocked out from the buffer of the segment to furnish the binary patterns. A parallel-to-serial converter is used to output the decoded data serially to the printing unit.

4.11 Interleaving of Codebook Bits in Line Intervals

The difficulty of obtaining higher yields of compression ratio in universal N/M coding has been seen to be largely due to the additional bits required for transmission of the codebook. In most constant-rate scanners a small period exists between lines in which no image data is present. This is the inactive region of the scan line, referred to as 'lost time'. If the codebook entries are transmitted during this period the compression ratio is effectively increased to N/M as no additional time is required to transmit the codebook information. The question which arises is can the entire codebook be transmitted within the number of line intervals in the segment.

Obviously the length of the 'lost time' period is crucial. For CCITT

Groups 1 and 2 apparatus, a typical length of an inactive region is 5% of the scan line. In practice, in transmission of many documents a white margin is present on both edges of the page and if these are included, up to 10% of the scan-line may be used for transmitting codebook information.

Let the scan-length be resolved into L pels and let L=kN where N is the coding block size. Let q be the proportion of inactive region to the total scan-line length. Then the number of pels in the inactive region is qL or $\frac{qL}{N}$ blocks. For a segment size of w lines the space of qLw pels is available which can accomodate $\frac{qLwM}{N}$ = qkwM output bits where the output bit rate is assumed to be $\frac{M}{N}$ times the input rate. i.e. a CR of $\frac{N}{M}$ is assumed. This corresponds to $\frac{qkwM}{N}$ codebook patterns. For a 9-inch scan-line, k = 168 for a sampling density of 150 pels/inch. For a universal 8/5 coding scheme with a segment size of 8 lines, a total of 42 patterns is allowed to be transmitted if the inactive region is 5% of the scan line. This number of patterns exceeds the 31 entries of the codebook for this mode and the amount of lost time is therefore adequate for transmission of the entire segment codebook. The segment size can be reduced to 6 lines when 31 entries can just be squeezed into the 6 5% line intervals. Below this number of lines the length of the line interval must rise, for example a 10% line interval will permit transmission of codebook in a segment of 4 lines but not less. This coding mode has been found to be on the edge of subjective acceptibility. For larger blocks the value of k is decreased and one or more of the parameters q, w and $\frac{N}{M}$ should rise to compensate for this. For example if the block size is 12 pels, k=112 for the same resolution and scan-line length. Then if 12/6 compression is employed and r=0.1 the number of lines in a segment must be at least 12 to accomodate the 63 12-bit codebook patterns. This segment size is quite large and will not lead to acceptable image quality with the 12/6 coding

mode. Reducing the compression ratio to 1.7 by employing the 12/7 mode does not necessarily result in fewer lines as the number of codebook entries is now doubled. It is therefore preferable to use smaller coding blocks if codebook patterns are to be transmitted within the line intervals.

4.12 Block-to-Block-Coding With Partial Codebook Transmission

The need to transmit the codebook in a universal fixed-rate coding scheme reduces the amount of compression especially for smaller-sized segments. On the other hand if a fixed codebook is employed the mismatch of statistics can result in larger amounts of encoding errors. A compromise solution is to transmit a portion of the segment codebook with the remaining portion predetermined. For example in an 8/5 coding scheme the first 16 entries of the 32-entry codebook are assumed to be constant for all segments and the remaining patterns are derived from the segment statistics and are transmitted. At first sight this might seem to restrict heavily the number and choice of patterns in the segment codebook but a survey of segment codebook patterns has shown the presence of several 'common' patterns which occur with a very high frequency in all the segment codebooks. If these are predetermined the codebook size can be reduced without severely affecting the performance of the compression technique.

The transmission of partial codebooks implies the loss of universality in that some knowledge of the block statistics is required in order to ascertain the predetermined codebook entries. The latter will correspond to the most common patterns featured in the average codebook employed in fixed N/M coding. Fig.4.72 shows the 64 most frequent patterns for 8-pel blocks as obtained from the combined statistics of the test images. The

first 16 patterns contain isolated runs of mainly 2 and 3 black elements. It may be possible to construct these patterns without having to obtain them statistically from a wide variety of images.

The levels in compression ratio as a result of predetermining codebook entries are shown in Table 4.18 for 8/4 and 8/5 coding schemes. For comparison the compression ratios for the universal scheme without predetermination are given in a separate table. It will be interesting to observe whether predetermination will give a better performance for a fixed compression ratio than a fully-adaptive universal coding scheme. For example, a compression ratio of 1.33 may be obtained by either predetermining 16 entries of an 8/5 1-line coding scheme, or employing a 2-line segment without any predetermination.

The simulation of a block-to-block compression scheme with partial codebook transmission was performed using the images A5, A5b, A6 and a truncated version of A2, denoted A2a, which is the image A2 without its heading. This represents more closely worst-case text material in which words and lines of text are packed close together with few all-white lines present. The values of PRE and PUB are shown in Tables 4.18 to 4.22 for 8/4 and 8/5 coding. The results of the unpredetermined case are also included in the tables for easy comparison. For the image A5 a fully-adaptive scheme was earlier shown to produce an acceptable quality of reconstructed image when a 1-line 8/4 mode was used. The resultants images when half the codebook entries are predetermined, are displayed in Figs.4.73 and 4.74. Good quality is maintained and a similarly acceptable quality is observed when the segment size is increased to 2 lines (Fig.4.74). The compression ratios in these two cases are 1.80 and 1.89 respectivly. With 8/5 coding the predetermination of up to 24 entries of

the 32-entry codebook appear to have little effect on the level of encoding errors. A compression ratio of 1.58 is easily obtained from 8/5 coding with 24-entry predetermination and a segment of 6 lines. The results of the lower resolution version of the weathermap show practically error-free coding for 8/5 1-line mode when the number of predetermined entries is 16. For larger segments the PRE levels also increase very slowly for up to 16 entries of predetermined codebook. Assuming a threshold of acceptability of 0.3% a compression ratio of 1.53 may be obtained using a 4-line segment with 8/5 mode and predetermination of half the codebook. The reconstructed images for three modes of coding are displayed in Figs.4.75 to 4.77. The quality of the first of these is clearly unacceptable. With the 8/5 mode predetermination of half the codebook results in an acceptable quality of image for a 2-line segment(Fig.4.76). When the segment size increases to 6 lines(Fig.4.77) degradation of the image becomes visible. For the densely-typed material of A2 the results for 8/5 coding show increases in distortion which are larger for smaller segments as the number of preset entries increases. The reconstructed images with predetermination of 8 and 16 entries are shown in Figs. 4.78 to 4.81 for both 2-line and 4-line segments. Of the four displayed images the quality of the one yielding the highest compression ratio (C.R = 1.51, Fig.4.81) is not objectionable although aberrations of individual characters are occasionally visible. The text material is in general quite difficult to compress.

On the whole the results clearly show a significant advantage in predetermining a proportion of the segment codebook. For equal compression ratios, inspection of the tables of results show that lower levels of encoding errors are usually obtained when predetermination is employed for a small segment compared with use of larger segments without predetermination. On a subjective basis the increase in encoding

distortion when a partial codebook is transmitted is not serious when the number of predetermined entries extends to half the codebook size. From experience with earlier simulation work the maximum compression obtainable is usually determined by the performance obtained for the densely typed material of A2 and the low-resolution image A5b although in the latter case the difference in resolution may not be too representative of performance at the main resolution of 150 pels/inch. The limit of compression ratio for A2 as judged by subjective assessment of the reconstructed image appears to be about 1.5 with a partially-adaptive scheme. This compares with 1.33 obtainable with a fully universal 8/5 coding scheme.

In the previous section a method of increasing the compression ratio was proposed which inserts codebook patterns into the line intervals which commonly occur in fixed-rate scanning. With a partialy-adaptive block-to-block scheme the decreased size of codebooks imply fewer line intervals are required for the codebook transmission and smaller segments may therefore be implemented. For the example of 8/5 coding described in the previous section, a 5% line interval now enables a 50% predetermined codebook to be transmitted in 3 lines of image. Alternatively a 75% predetermined codebook (8 entries) may be slotted into 2 line intervals. The reduction of the segments size in this way provides a further incentive for predetermination of the segment codebook.

4.13 Conclusions and Comments

The results reported in this chapter are now summarised. The investigation into an adaptive form of block-to-block coding in which codebook information is conveyed to the receiver on a segment basis, has shown that compared with the use of a fixed average codebook, lower levels

of encoding distortion are obtained for a given N/M mode of coding. However the possible benefits of increased compression ratio are stifled by the additional transmission time for the codebook. As a result in terms of compression ratio a resort to a universal scheme does not produce appreciably much gain in compression ratio over a fixed-codebook scheme but the dispensing of an a priori codebook means that no statistical knowledge of the source is required and the method is immediately applicable to all images. On an individual image basis, significant gains are possible, especially where the resolutions and image content are quite different from the average. An envisaged system which exploits this situation is one in which a set of values of M is made switch-selectable and the operator can simply choose a lower value of M for a higher-resolution image. A corresponding system for a fixed-codebook implementation will require an availability of several codebooks which again may not be well-matched to the particular image being transmitted.

The universal coding scheme offers a more diverse choice of compression ratios than a fixed system. The user is thus able to decide upon a system which strikes a suitable balance between image quality and amount of compression. Higher compression ratios are generally obtained by increasing the segment size at the expense of increased storage requirements, greater time delay between image input and decoded output and a lower degree of adaptivity to local image statistics resulting in higher levels of encoding errors. The segment is most conveniently made equal to an integer number of physical lines of image. A simulation was performed to investigate the benefits of using more two-dimensional segments but the large number of additional lines of storage required to implement such segments do not justify the slight improvements in performance. In an attempt to capture further redundancy within the segment an alternative

vertical configuration of coding block was proposed. A mixed set of results was obtained in which both improvement and worsening of performance was recorded depending on image content and resolution. The results for typed image material however were outstanding with decreases of half or more of encoding distortion observed. The lower levels of encoding errors obtained here were partly offset by the increased visibility of pattern approximations because of lower resolution in the vertical dimension.

The effect of varying the coding block size N was studied. The general conclusion here is that an excessive number of image lines is needed if improvements in image quality or compression ratio are to be obtained through employing a larger block size. The amount of improvement is unlikely to justify the increased complexity of the system. A special simulation employing the image A1 with the use of vertical coding blocks showed the feasibility of obtaining a 2:1 compression for this image when a block size of 12 pels was used (12/6 coding, segment size = 1/3 line).

The consequence of transmission errors in the universal fixed-rate coding scheme was observed. Both random and burst errors were injected into the simulated bit stream at various average rates of bit error. At an average of 1 in 1000 the effect of transmission errors is negligible. At a rate of 1 in 100 the reconstructed images preserved their intelligibility. The decoded image is generally obscured by errors when the average transmission error rate increases to 1 in 32 but contour lines and some larger characters could still be made out. Generally for the same average error rate burst transmission errors produced fewer reconstructed errors in the image.

The implementation of the encoder in the universal N/M scheme is more involved than for the fixed-codebook system. However the varied tasks are

readily performed by a microprocessor which considerably reduces the hardware complexity and cost. Decoding is more straightforward and requires a relatively small amount of hardware. With ever-decreasing cost of memory and microprocessor circuitry the cost of implementation should not be a major disadvantage for this type of coding.

In the final section of the chapter an attractive compression method was investigated which compromised between a fully-adaptive universal N/M scheme and a fixed N/M system. Here only a portion of the codebook of a segment is transmitted, the other codebook entries being established a priori. Knowledge of source statistics is therefore required but extra gains in compression ratio may be obtained because of the smaller codebook that is transmitted. The level of encoding distortion however increases on account of the reduced scope for adaptability in each segment. The results of simulation for 8/M coding showed a low sensitivity to the effect of predetermining up to half the number of entries in the codebook. As a consequence it is generally preferable to employ predetermination with a small segment size then universal coding with a large segment size in order to achieve the same compression ratio. A further advantage of partial codebook transmission is the feasibility of fitting the segment codebook within line intervals of the segment. For example it is expected that a compression ratio of 1.6 may be obtained for a system in which lines of image constitute the segment and the 50%-predetermined codebook is transmitted in the line intervals.

Overall the universal block-to-block compression system is capable of yielding a compression ratio of 1.33 with very good image quality, with the use of 8-pel blocks. Slightly higher levels of compression ratio up to about 1.5 are possible if a small and often unnoticeable increase in

distortion can be tolerated. A fixed-codebook system on the other hand gives a maximum compression ratio of 1.33 (8/6 coding). If a compromised partial codebook is employed, a compression ratio of 1.6 may be obtained if the codebook is interleaved in the inactive periods of the scan-lines. The compression techniques in these cases feature fixed-rate output, high resistance to transmission errors and low hardware complexity of implementation.

COMPRESSION MODE	SEGMENT SIZE 1 line	2 lines	4 lines	6 lines	8 lines	10 lines	N/M
8/3	2.32	2.45	2.57	2.60	2.62	2.63	2.67
8/4	1.63	1.77	1.89	1.93	1.94	1.96	2.00
8/5	1.17	1.32	1.47	1.51	1.53	1.54	1.60
8/6	0.83	0.99	1.16	1.21	1.24	1.26	1.33

1 line consists of 141 8-pel blocks.

Table.4.1. Showing some Compression Ratios Attainable in Universal N/M Coding with 8-pel Blocks.

Array Size	Shrinking Set Algorithm (Full Sort)	Merge Algorithm
32	0.621	0.742
64	1.148	1.127
128	3.175	2.247
256	10.562	4.149
512	39.010	9.372
1024	152.141	18.493
2048	595.411	41.721
4096	2362.230	85.992

Units in CP(Computational) Seconds.

Table 4.2. Comparison of Execution Times for Shrinking Set and Merge Sorting (with association) Algorithms.

Image	Compression Mode	Compression Ratio	% Reconstruction Errors			% Unassigned Blocks		
			Universal Coding Scheme	Fixed Codebook Scheme	% Dec.	Universal Coding Scheme	Fixed Codebook Scheme	% Dec.
A1	8/3	2.32	1.08	1.84	41.3	4.66	7.07	34.1
	8/4	1.60	0.42	0.81	48.1	2.26	4.63	51.2
A5	8/3	2.32	2.43	3.55	31.5	10.79	13.51	20.1
	8/4	1.60	0.54	1.45	62.8	3.26	8.68	62.4

Table 4.3. Results of Universal 8/M Coding of Images A1 and A5 with Segment Size Equal to 1 Line of Image.

Compression Mode	A1	A5
8/3	1.05 (-2.8%)	1.98 (-18.5%)
8/4	0.39 (-7.1%)	0.39 (-27.8%)

Figures in brackets are percentage decreases from values in Table 4.3.

Table 4.4. Percentage Reconstruction Errors Obtainable With Previous Line Codebook Approximation of Unassigned Patterns.

Fixed 8/M Scheme

Compression Mode	Compression Ratio	% Reconstruction Errors		% Unassigned Blocks	
		A1	A5	A1	A5
8/4	2.0	0.81	1.45	4.63	8.68
8/5	1.6	0.42	0.27	2.40	1.87
8/6	1.33	0.10	0.04	0.73	0.28

Universal N/M Scheme

Segment Size	r	Compression Ratio	Mode	PRE				PUB			
				A1	%Δ	A5	%Δ	A1	%Δ	A5	%Δ
1 line	141	1.65	8/4	0.42	-48.1	0.54	-62.8	2.26	-51.1	3.26	-62.4
2 lines	282	1.78	8/4	0.55	-32.1	0.73	-49.7	2.97	-35.9	4.58	-47.2
4 lines	564	1.90	8/4	0.65	-19.8	0.86	-40.7	3.49	-24.6	5.43	-37.4
6 lines	846	1.93	8/4	0.69	-14.8	0.90	-37.9	3.70	-20.1	5.77	-33.5
8 lines	1128	1.95	8/4	0.72	-11.1	0.93	-35.9	3.82	-17.3	5.98	-31.1
10 lines	1410	1.96	8/4	0.73	- 9.9	0.95	-34.5	3.90	-15.8	6.11	-29.6
Whole Image	117171	2.00	8/4	0.79	- 2.5	1.05	-27.6	4.60	- 0.6	6.97	-19.6
2 lines	282	1.33	8/5	0.15	-64.3	0.01	-96.3	0.96	-60.0	0.10	-94.7
4 lines	564	1.47	8/5	0.20	-52.3	0.08	-70.4	1.31	-45.4	0.52	-72.2
6 lines	846	1.51	8/5	0.23	-45.2	0.11	-59.3	1.53	-36.3	0.73	-61.0
8 lines	1128	1.55	8/5	0.24	-42.9	0.13	-51.9	1.58	-34.2	0.86	-54.0
10 lines	1410	1.55	8/5	0.25	-40.5	0.14	-48.1	1.69	-29.6	0.93	-50.3
Whole Image	117171	1.60	8/5	0.34	-19.0	0.18	-33.3	2.34	- 2.5	1.18	-36.9

%Δ = Percentage Change from Fixed N/M Method for Same Mode.
PRE = Percentage Reconstruction Errors
PUB = Percentage Unassigned Blocks

Table 4.5. Results of Universal Fixed-Rate 8/M Coding of Images A1 and A5.

Mode	Segment Size	r	CR	A3				A4				A5			
				PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ
8/4	1 line	141	1.65	0.29	-64.6	1.51	-69.6	0.46	-65.7	2.82	-63.4	0.87	-47.9	4.90	-51.2
8/4	2 lines	282	1.78	0.36	-56.1	2.27	-54.2	0.57	-57.5	3.59	-53.4	1.13	-32.3	6.39	-36.4
8/4	4 lines	564	1.90	0.44	-46.3	2.88	-41.9	0.65	-51.5	4.08	-47.0	1.32	-21.0	7.44	-26.0
8/4	6 lines	846	1.93	0.49	-40.2	3.18	-35.9	0.68	-49.3	4.27	-44.5	1.39	-16.8	7.90	-21.4
8/4	8 lines	1128	1.95	0.58	-29.3	3.33	-32.9	0.70	-47.8	4.40	-42.9	1.42	-15.0	8.15	-18.9
8/4	10 lines	1410	1.96	0.61	-25.6	3.47	-30.0	0.71	-47.0	4.44	-42.3	1.50	-10.2	8.41	-16.3
8/4	Whole Image	117171	2.00	0.82	0.0	4.68	- 5.6	0.75	-44.0	4.82	-37.4	1.67	0.0	10.05	0.0
8/5	2 lines	282	1.33	0.03	-88.5	0.21	-87.3	0.09	-78.6	0.65	-75.6	0.20	-60.0	1.28	-62.6
8/5	4 lines	564	1.47	0.09	-65.4	0.54	-67.5	0.13	-69.0	0.94	-64.7	0.29	-42.0	1.91	-44.2
8/5	6 lines	846	1.51	0.12	-53.8	0.17	-53.6	0.15	-64.3	1.09	-59.0	0.34	-32.0	2.23	-34.8
8/5	8 lines	1128	1.55	0.14	-46.2	0.91	-45.2	0.16	-61.9	1.17	-56.0	0.37	-26.0	2.40	-29.8
8/5	10 lines	1410	1.55	0.16	-38.5	1.02	-38.6	0.18	-57.1	1.25	-53.0	0.38	-24.0	2.50	-26.9
8/5	Whole Image	117171	1.60	0.26	0.0	1.63	- 1.8	0.24	-42.9	1.71	-35.7	0.46	- 8.0	3.04	-11.1

%Δ = Percentage Change from Fixed N/M Method for Same Mode.

Table 4.6. Results of Universal 8/M Coding of Images A3, A4 and A5.

Mode	Segment Size	A2						A5b					
		r	CR	PRE	%Δ	PUB	%Δ	r	CR	PRE	%Δ	PUB	%Δ
8/4	1 line	113	1.58	1.86	-40.6	9.84	-43.8	70	1.40	0.74	-70.3	3.51	-76.9
8/4	2 lines	226	1.77	2.11	-32.6	11.39	-35.0	140	1.65	1.31	-47.4	6.71	-55.8
8/4	4 lines	452	1.88	2.39	-23.6	12.70	-27.5	280	1.81	1.62	-34.9	8.50	-44.0
8/4	6 lines	678	1.91	2.52	-19.5	13.25	-24.4	420	1.87	1.77	-28.9	9.22	-39.3
8/4	8 lines	904	1.93	2.61	-16.6	13.68	-21.9	560	1.90	1.89	-24.1	9.64	-36.5
8/4	10 lines	1130	1.95	2.69	-14.1	13.95	-20.4	700	1.92	1.97	-20.9	9.91	-34.7
8/4	Whole Image	93903	2.00	3.00	- 4.2	16.43	- 6.2	65590	2.00	2.72	- 9.2	11.46	-24.5
8/5	2 lines	226	1.31	0.55	-68.0	3.70	-63.8	140	1.18	0.04	-95.6	0.20	-97.0
8/5	4 lines	452	1.44	0.69	-59.9	4.68	-54.2	280	1.36	0.26	-71.4	1.57	-76.4
8/5	6 lines	678	1.49	0.76	-55.8	5.20	-49.1	420	1.43	0.38	-58.2	2.36	-64.6
8/5	8 lines	904	1.52	0.79	-54.1	5.53	-45.9	560	1.47	0.45	-50.5	2.82	-57.7
8/5	10 lines	1130	1.53	0.82	-52.3	5.76	-43.6	700	1.49	0.48	-47.3	3.06	-54.1
8/5	Whole Image	93903	1.60	0.96	-44.2	6.88	-32.7	65590	1.60	0.65	-28.6	4.40	-33.9

%Δ = Percentage Change from Fixed N/M Method for Same Mode.

Table 4.7. Results of Universal 8/M Coding of Images A2 and A5b.

Mode	Segment Size	r	CR	A1				A3				A4				A6			
				PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ
8/4	8 lines x $\frac{1}{8}$ line	8x17 =136	1.64	0.39	- 7.1	2.15	-11.0	0.22	-24.1	1.19	-20.1	0.45	- 2.2	2.80	- 0.7	0.81	- 6.9	4.48	- 8.6
8/5	8 lines x $\frac{1}{2}$ line	8x70 =560	1.47	0.20	0.0	1.33	+ 1.6	0.09	0.0	0.54	0.0	0.13	0.0	0.91	- 3.2	0.29	0.0	1.88	- 1.6
8/5	32 lines x $\frac{1}{8}$ line	32x17 =544	1.47	0.20	0.0	1.29	- 1.6	0.08	-11.1	0.49	- 9.3	0.11	-15.4	0.79	-16.0	0.29	0.0	1.85	- 3.1
8/5	16 lines x $\frac{1}{2}$ line	16x70 =1120	1.53	0.24	0.0	1.59	+ 0.6	0.14	0.0	0.87	- 4.4	0.16	0.0	1.16	- 0.9	0.37	0.0	2.40	0.0
8/5	32 lines x $\frac{1}{4}$ line	32x35 =1120	1.53	0.24	0.0	1.58	0.0	0.14	0.0	0.87	- 4.4	0.16	0.0	1.14	- 2.6	0.37	0.0	2.41	+ 0.4

%Δ = Percentage Change from Equivalent Multiple-line Segment.

Table 4.8. Results of Universal 8/M Coding of Images A1, A3, A3, A4 and A6 Using 2-Dimensional Segments.

A2								A5b							
Mode	Segment Size	r	CR	PRE	%Δ	PUB	%Δ	Mode	Segment Size	r	CR	PRE	%Δ	PUB	%Δ
8/4	8 lines x $\frac{1}{8}$ line	8x14 =112	1.58	1.41	-63.3	7.51	-23.7	8/4	8 lines x $\frac{1}{8}$ line	8x8 =64	1.36	0.52	-29.7	2.59	-26.2
8/5	32 lines x $\frac{1}{8}$ line	32x14 =448	1.44	0.65	- 5.8	4.43	- 5.3	8/5	8 lines x $\frac{1}{2}$ line	8x35 =280	1.36	0.27	+ 3.8	1.62	+ 3.2
8/5	32 lines x $\frac{1}{4}$ line	32x28 =896	1.52	0.78	- 1.3	5.46	- 1.3	8/5	32 lines x $\frac{1}{8}$ line	32x8 =256	1.34	0.25	- 3.8	1.54	- 1.9
8/5	16 lines x $\frac{1}{2}$ line	16x56 =896	1.52	0.78	- 1.3	5.47	- 1.1	8/5	32 lines x $\frac{1}{2}$ line	32x35 =8960	1.57	0.53	- 1.9	3.46	- 1.7

%Δ = Percentage Change from Equivalent Multiple-line Segment.

Table 4.9. Results of Universal 8/M Coding for Images A2, A5b Using Two-Dimensional Segments.

Mode	Segment Size	r	CR	A1				A3				A4			
				PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ
8/4	1 line	1128	1.95	0.39	-45.8	2.10	-45.0	0.61	+ 5.2	3.31	+ 0.6	1.17	+67.1	2.16	+45.7
8/4	$\frac{1}{2}$ line	564	1.90	0.31	-52.3	1.76	-49.6	0.44	0.0	2.43	+15.6	0.98	+50.8	5.34	+30.9
8/4	$\frac{1}{4}$ line	282	1.78	0.26	-52.7	1.42	-52.2	0.31	-13.9	1.66	-26.9	0.77	+35.1	4.25	+18.4
8/4	$\frac{1}{8}$ line	141	1.65	0.21	-50.0	1.13	-50.0	0.19	-34.5	1.02	-32.5	0.55	+19.6	3.10	+10.0
8/5	1 line	1128	1.55	0.13	-13.3	0.74	-22.9	0.17	+21.4	1.08	+18.7	0.39	+14.4	2.52	+11.5
8/5	$\frac{1}{2}$ line	564	1.47	0.09	-55.0	0.53	-59.5	0.10	+11.1	0.62	+14.8	0.28	+11.5	1.86	+97.9
8/5	$\frac{1}{4}$ line	282	1.33	0.06	-60.0	0.32	-66.7	0.05	+66.7	0.30	+42.9	0.17	+88.9	1.13	+73.8

%Δ = Percentage Change from Equivalent Serial Scheme.

Table 4.10. Results of Universal 8/M Coding for Images A1, A3, A4 Using Vertical Coding Blocks.

Mode	Segment Size	r	CR	A5				A6			
				PRE	%Δ	PUB	%Δ	PRE	%Δ	PUB	%Δ
8/4	1 line	1128	1.95	1.95	+110.	10.17	+70.1	1.87	+24.1	9.69	+18.9
8/4	$\frac{1}{2}$ line	564	1.90	1.72	+100.	9.03	+66.3	1.61	+22.0	8.41	+13.0
8/4	$\frac{1}{4}$ line	282	1.78	1.45	+98.6	7.55	+64.8	1.28	+13.3	6.72	+ 5.2
8/4	$\frac{1}{8}$ line	141	1.65	0.98	+81.5	5.12	+57.1	0.92	+ 5.7	4.74	- 8.5
8/5	1 line	1128	1.55	0.50	+285.	3.32	+286.	0.72	+94.6	4.52	+88.3
8/5	$\frac{1}{2}$ line	564	1.47	0.39	+38.8	2.50	+381.	0.55	+89.7	3.39	+77.5
8/5	$\frac{1}{4}$ line	282	1.33	0.22	+2100	1.38	+1280	0.34	+70.0	2.05	+60.2

%Δ = Percentage Change from Equivalent Serial Scheme.

Table 4.11. Results of Universal 8/M Coding for Images A5, A6 Using Vertical Coding Blocks.

A2								A5b							
Mode	Segment Size	r	CR	PRE	%Δ	PUB	%Δ	Mode	Segment Size	r	CR	PRE	%Δ	PUB	%Δ
8/4	1 line	904	1.93	1.52	-43.5	8.10	-40.8	8/4	1 line	560	1.90	1.75	- 7.4	8.84	- 8.3
8/4	$\frac{1}{2}$ line	452	1.88	1.00	-58.2	5.55	-56.3	8/4	$\frac{1}{2}$ line	280	1.81	1.43	-11.7	7.47	-12.1
8/4	$\frac{1}{4}$ line	226	1.77	0.67	-68.2	3.82	-75.2	8/4	$\frac{1}{4}$ line	140	1.65	1.06	-19.1	5.39	-19.7
8/4	$\frac{1}{8}$ line	113	1.58	0.37	-80.1	2.20	-77.6	8/4	$\frac{1}{8}$ line	70	1.40	0.49	-33.8	2.42	-31.1
8/5	1 line	904	1.52	0.53	-32.9	3.05	-44.8	8/5	1 line	560	1.47	0.38	-15.6	2.39	-15.2
8/5	$\frac{1}{2}$ line	452	1.44	0.23	-66.7	1.39	-70.3	8/5	$\frac{1}{2}$ line	280	1.36	0.22	-15.4	1.37	-14.6
8/5	$\frac{1}{4}$ line	226	1.31	0.10	-81.8	0.62	-83.2	8/5	$\frac{1}{4}$ line	140	1.18	0.05	+25.0	0.28	+40.0

%Δ = Percentage Change from Equivalent Serial Scheme.

Table 4.12. Results of Universal 8/M Coding for Images A2, A5b Using Vertical Coding Blocks.

Mode	Segment Size	r	CR	A1		A5	
				PRE	PUB	PRE	PUB
7/4	1 line	161	1.50	0.26	1.45	0.26	1.62
7/4	2 lines	322	1.62	0.36	1.98	0.41	2.49
7/4	4 lines	644	1.68	0.43	2.40	0.50	3.05
7/3	1 line	161	2.12	0.86	3.83	1.84	8.51
7/5	2 lines	322	1.23	0.05	0.35	0.00	0.00
7/5	4 lines	644	1.31	0.08	0.54	0.01	0.04
7/5	6 lines	966	1.34	0.10	0.63	0.02	0.10
7/5	8 lines	1128	1.35	0.10	0.67	0.02	0.15
9/4	1 line	125	1.77	0.52	2.92	0.73	4.31
9/4	2 lines	250	1.98	0.69	3.77	1.01	6.50
9/4	4 lines	375	2.06	0.81	4.41	1.20	7.61
9/5	1 line	125	1.24	0.13	0.93	0.00	0.01
9/5	2 lines	250	1.47	0.25	1.68	0.08	0.60
9/5	4 lines	500	1.62	0.32	2.18	0.22	1.67
9/5	6 lines	750	1.68	0.37	2.49	0.28	2.05
9/5	8 lines	1000	1.70	0.39	2.62	0.31	2.26
10/4	1 line	112	1.87	0.60	3.42	0.95	6.18
10/4	2 lines	224	2.14	0.82	4.39	1.34	8.39
10/5	1 line	112	1.29	0.18	1.29	0.00	0.02
10/5	2 lines	224	1.57	0.32	2.22	0.16	1.30
10/5	4 lines	448	1.76	0.44	2.88	0.39	3.02
10/5	6 lines	672	1.83	0.49	3.27	0.47	3.57
10/5	8 lines	896	1.87	0.52	3.45	0.52	3.91
10/5	10 lines	1120	1.90	0.54	3.63		
10/6	8 lines	896	1.49	0.18	1.44		
12/6	8 lines	752	1.71	0.33	2.59		
12/6	12 lines	1128	1.80	0.38	2.99		

Mode	Segment Size	r	CR	A5b	
				PRE	PUB
9/4	1 line	70	1.52	0.80	4.81
9/4	2 lines	124	1.77	1.56	4.81
9/5	6 lines	373	1.57	0.62	4.24
9/5	8 lines	497	1.62	0.72	4.88
10/5	6 lines	312	1.67	0.90	6.21
10/5	10 lines	560	1.80	1.08	7.39
10/5	20 lines	1120	1.90	1.24	8.33
11/5	6 lines	283	1.77	1.19	8.36
11/6	10 lines	509	1.49	0.33	2.77
11/6	20 lines	672	1.65	0.59	4.84

Table 4.13. Results of Universal N/M Coding of Images A1, A5 and A5b With Various Block Sizes.

Mode	Segment Size	CR	PRE
7/3	$\frac{1}{8}$ line	2.09	0.48
9/4	$\frac{1}{8}$ line	1.82	0.25
9/4	$\frac{1}{4}$ line	2.01	0.31
9/4	$\frac{1}{2}$ line	2.12	0.37
10/4	$\frac{1}{8}$ line	1.97	0.29
10/4	$\frac{1}{4}$ line	2.21	0.36
10/5	1 line	1.90	0.22
11/5	$\frac{1}{4}$ line	1.77	0.12
11/5	1 line	2.06	0.26
12/5	$\frac{1}{3}$ line	2.00	0.18

Table 4.14. Universal N/M Coding of A1 Using Vertical Coding Blocks of Various Sizes.

Probability of Transmission Error, p	Probability of Codeword Corruption, P_c			
	M = 3	M = 4	M = 5	M = 6
0.0001	3×10^{-4}	4×10^{-4}	5×10^{-5}	6×10^{-6}
0.001	3×10^{-3}	4×10^{-3}	5×10^{-3}	6×10^{-3}
0.01	3×10^{-2}	4×10^{-2}	5×10^{-2}	6×10^{-2}
0.1	0.27	0.34	0.41	0.47

$$P_c = 1 - (1 - p)^M$$

Table 4.15. Values of Probability of Codeword Corruption for Various Probabilities of Random Transmission Bit Error and Codeword Length M.

Average Error Rate	Nature of Noise	% Transmitted Bits in Error	% Reconstruction Errors	Propagation Factor, K
1 in 1000	Random	0.01	0.82	82
1 in 100	Random	0.1	2.77	28
1 in 50	Random	2.0	5.14	2.6
1 in 32	Random	3.16	7.43	2.4
1 in 100	Burst	0.1	2.46	25
1 in 32	Burst	3.16	6.34	2.0

Table 4.16. Percentage Reconstruction Errors for Image A5b After Exposure to Simulated Transmission Errors (8/5 Compression, 8-line Segment).

	% Reconstruction Errors	Propagation Factor, K
Universal 8/M	7.43	2.4
Fixed N/M	6.85	2.2
Percentage Difference	7.8%	

Table 4.17. Comparison of Percentage Reconstruction Errors Between Fixed and Universal 8/M Coding (8-line Segment) of Image A5b in the Presence of Random Transmission Errors (Average Error Rate = 1 in 32).

8/4 Mode

Segment Size	r	Compression Ratio			
		No. of Predetermined Entries:			
		0(Universal Coding)	4	8	12
1 line	141	1.63	1.71	1.80	1.89
2 lines	282	1.77	1.84	1.89	1.94
4 lines	564	1.89	1.92	1.94	1.97
6 lines	846	1.93	1.94	1.96	1.98

8/5 Mode

Segment Size	r	Compression Ratio					
		No. of Predetermined Entries:					
		0(Universal Coding)	4	8	12	16	24
1 line	141	1.17	1.21	1.26	1.30	1.35	1.47
2 lines	282	1.32	1.38	1.41	1.44	1.47	1.53
4 lines	564	1.47	1.48	1.50	1.51	1.53	1.56
6 lines	846	1.51	1.52	1.53	1.54	1.55	1.58

Table 4.18. Values of Compression Ratio for 8/M Coding With Predetermination.

Mode	Segment Size	r	Unpredetermined			4-entry			8-entry			12-entry					
			CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB
8/4	1 line	70	1.40	0.74	3.51	1.49	0.78	4.45	1.63	1.12	6.20	1.79	1.64	9.43			
8/4	2 lines	140	1.65	1.31	6.71	1.71	1.29	7.34	1.79	1.44	8.15	1.89	1.76	10.37			
8/4	4 lines	280	1.81	1.62	8.50	1.84	1.59	9.02	1.89	1.66	9.48	1.94	1.91	11.27			
8/4	6 lines	420	1.87	1.77	9.22	1.89	1.71	9.71	1.93	1.75	10.07	1.96	1.97	11.71			
												16-entry			24-entry		
8/5	1 line	70	0.94	0.00	0.00	0.98	0.00	0.00	1.03	0.00	0.00	1.17	0.00	0.01	1.35	0.11	0.74
8/5	2 lines	140	1.18	0.04	0.20	1.21	0.04	0.25	1.26	0.05	0.30	1.35	0.09	0.56	1.47	0.32	2.11
8/5	4 lines	280	1.36	0.26	1.57	1.41	0.25	1.67	1.26	0.27	1.70	1.47	0.29	1.91	1.53	0.47	3.17
8/5	6 lines	420	1.43	0.38	2.36	1.45	0.37	2.46	1.47	0.38	2.47	1.51	0.40	2.62	1.55	0.52	3.56

Table 4.19. Results of Universal 8/M Coding With Predetermination of Image A5b.

Mode	Segment Size	r	Unpredetermined			4-entry			8-entry			12-entry					
			CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB
8/4	1 line	141	1.65	0.54	3.26	1.71	0.53	3.43	1.80	0.58	3.60	1.89	0.78	4.90			
8/4	2 lines	282	1.78	0.73	4.58	1.84	0.73	4.65	1.89	0.74	4.69	1.94	0.89	5.65			
8/4	4 lines	564	1.90	0.86	5.43	1.92	0.85	5.47	1.94	0.86	5.48	1.97	0.97	6.24			
8/4	6 lines	846	1.93	0.90	5.77	1.94	0.89	5.80	1.96	0.89	5.80	1.98	0.99	6.46			
												16-entry			24-entry		
8/5	1 line	141	1.18	0.00	0.00	1.21	0.00	0.00	1.26	0.00	0.00	1.35	0.00	0.00	1.47	0.01	0.05
8/5	2 lines	282	1.36	0.01	0.10	1.38	0.01	0.10	1.41	0.01	0.10	1.47	0.03	0.23	1.53	0.05	0.34
8/5	4 lines	564	1.47	0.08	0.52	1.48	0.08	0.52	1.50	0.08	0.52	1.53	0.10	0.63	1.56	0.11	0.69
8/5	6 lines	846	1.51	0.11	0.73	1.52	0.11	0.73	1.53	0.11	0.73	1.55	0.13	0.83	1.58	0.13	0.86

Table 4.20. Results of Universal 8/M Coding With Predetermination of Image A5.

Mode	Segment Size	r	Unpredetermined			4-entry			8-entry			12-entry					
			CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB
8/4	1 line	113	1.58	2.40	12.70	1.65	2.43	13.73	1.75	2.64	14.98	1.89	3.06	17.48			
8/4	2 lines	226	1.77	2.71	14.60	1.81	2.70	15.46	1.87	2.88	16.41	1.93	3.22	18.46			
8/4	4 lines	452	1.88	3,02	16.28	1.90	2.97	17.00	1.93	3.10	17.64	1.97	3.36	19.24			
8/4	6 lines	678	1.91	3.25	17.09	1.93	3.09	17.66	1.95	3.19	18.16	1.98	3.40	19.58			
												16-entry			24-entry		
8/5	1 line	113	1.11	0.47	3.02	1.15	0.50	3.29	1.19	0.53	3.49	1.30	0.62	4.17	1.44	0.78	5.37
8/5	2 lines	226	1.31	0.70	4.65	1.34	0.71	4.82	1.37	0.73	4.94	1.44	0.79	5.42	1.51	0.90	6.32
8/5	4 lines	452	1.44	0.89	6.01	1.46	0.90	6.12	1.47	0.91	6.18	1.51	0.94	6.49	1.56	0.99	7.07
8/5	6 lines	678	1.49	0.97	6.69	1.50	0.98	6.76	1.51	0.99	6.80	1.54	1.01	7.00	1.57	1.05	7.46

Table 4.21. Results of Universal 8/M Coding With Predetermination of Image A2a.

Mode	Segment Size	r	Unpredetermined			4-entry			8-entry			12-entry					
			CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB	CR	PRE	PUB
8/4	1 line	141	1.65	0.87	4.90	1.71	0.89	5.15	1.80	0.96	5.58	1.89	1.17	7.02			
8/4	2 lines	282	1.78	1.13	6.39	1.84	1.12	6.58	1.89	1.16	6.80	1.94	1.29	7.82			
8/4	4 lines	564	1.90	1.32	7.44	1.92	1.28	7.57	1.94	1.29	7.68	1.97	1.39	8.43			
8/4	6 lines	846	1.93	1.39	7.90	1.94	1.35	8.00	1.96	1.36	8.09	1.98	1.43	8.70			
												16-entry			24-entry		
8/5	1 line	141	1.18	0.06	0.37	1.21	0.06	0.39	1.26	0.06	0.40	1.35	0.10	0.66	1.47	0.17	1.06
8/5	2 lines	282	1.33	0.20	1.28	1.38	0.20	1.29	1.41	0.20	1.29	1.47	0.22	1.43	1.53	0.26	1.70
8/5	4 lines	564	1.47	0.29	1.91	1.48	0.29	1.91	1.50	0.29	1.92	1.53	0.30	1.99	1.56	0.33	2.20
8/5	6 lines	846	1.51	0.34	2.23	1.52	0.34	2.24	1.53	0.34	2.24	1.55	0.34	2.27	1.58	0.37	2.41

Table 4.22. Results of Universal 8/M Coding With Predetermination of Image A6.

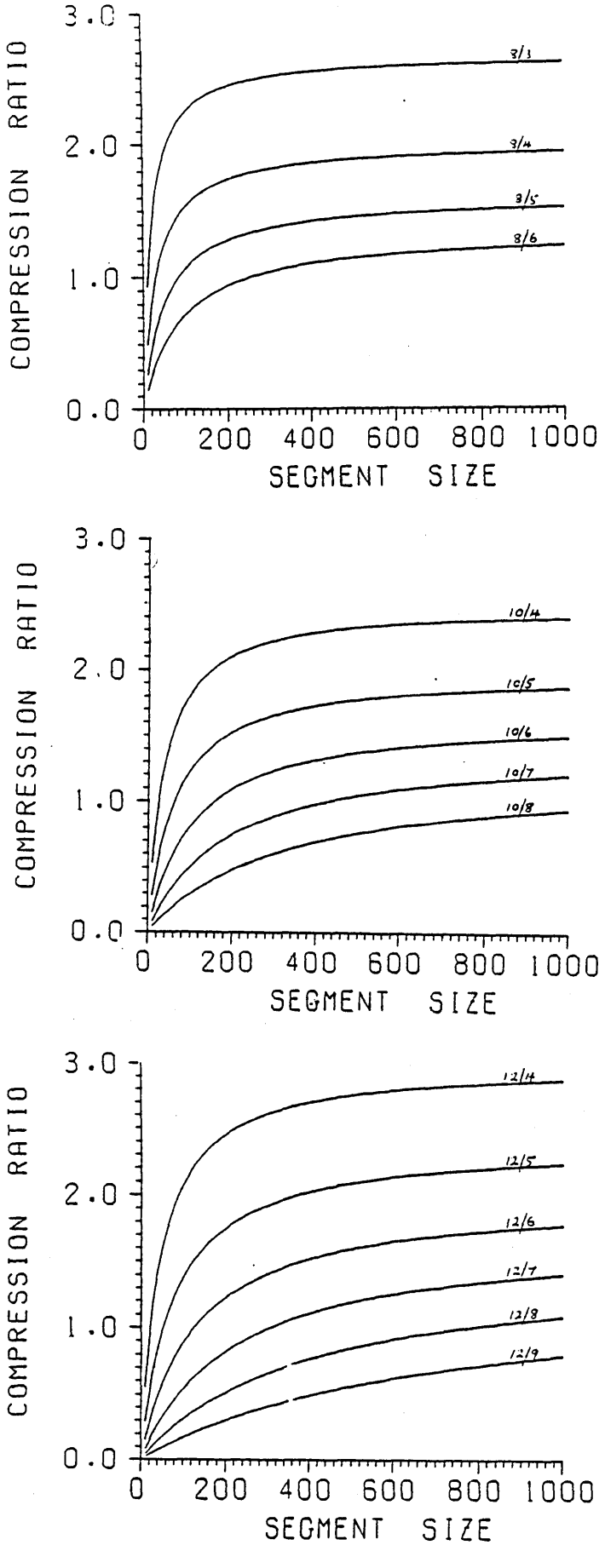


Fig.4.1. Compression Ratio versus Segment Size in Universal N/M Compression for Block Size = 8, 10, and 12 pels.

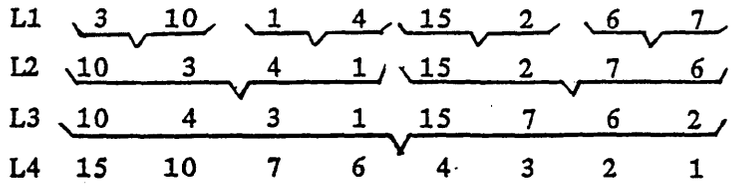


Fig.4.2. Operation of Merge Sorting.

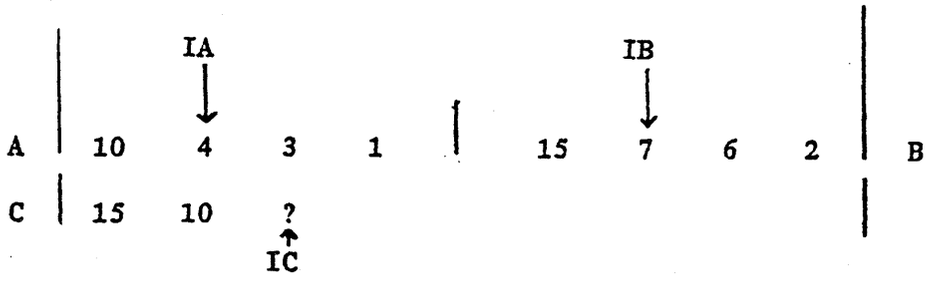


Fig.4.3. Merging of Two Halves of a Group.

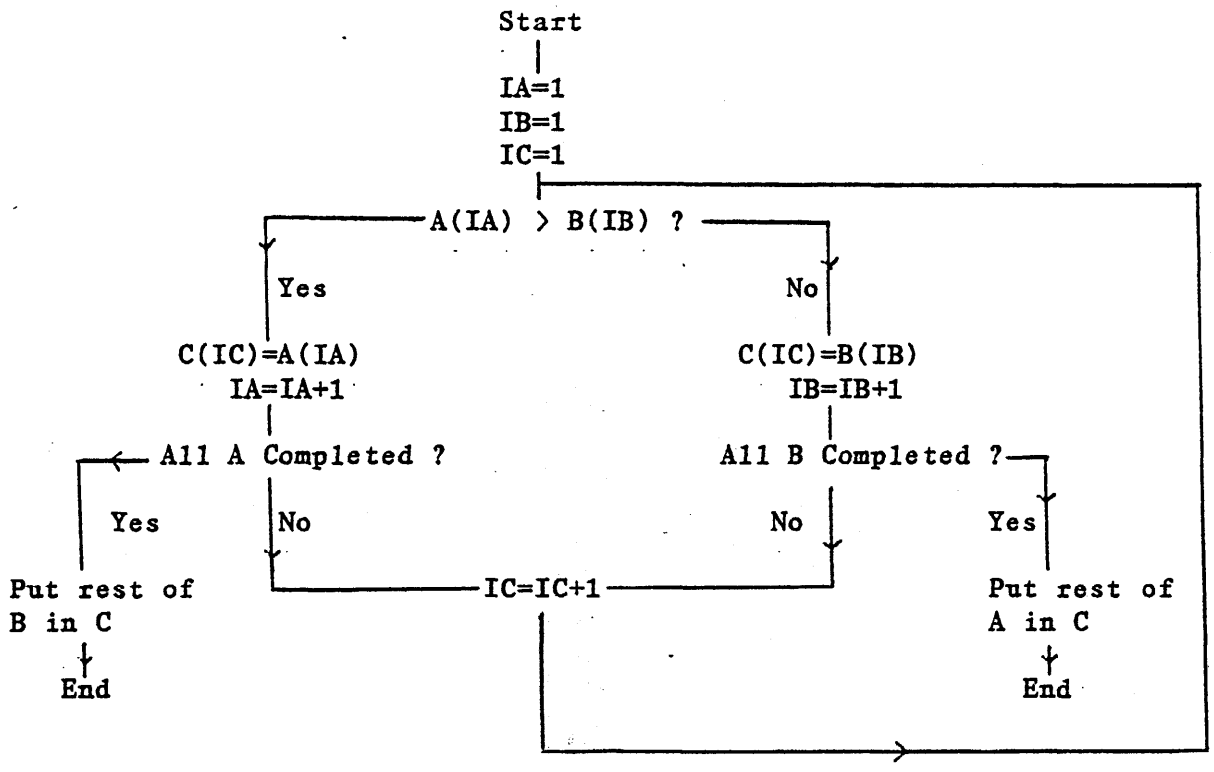


Fig.4.4. Flow Diagram of Merge Operation.

Fig.4.5. Data A1, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.65).

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Our ref. ABC/DE/FG Your ref.

Dear Mr. One,

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Yours sincerely,

D.W. Tindall

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Fig.4.6. Data A5, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.65).

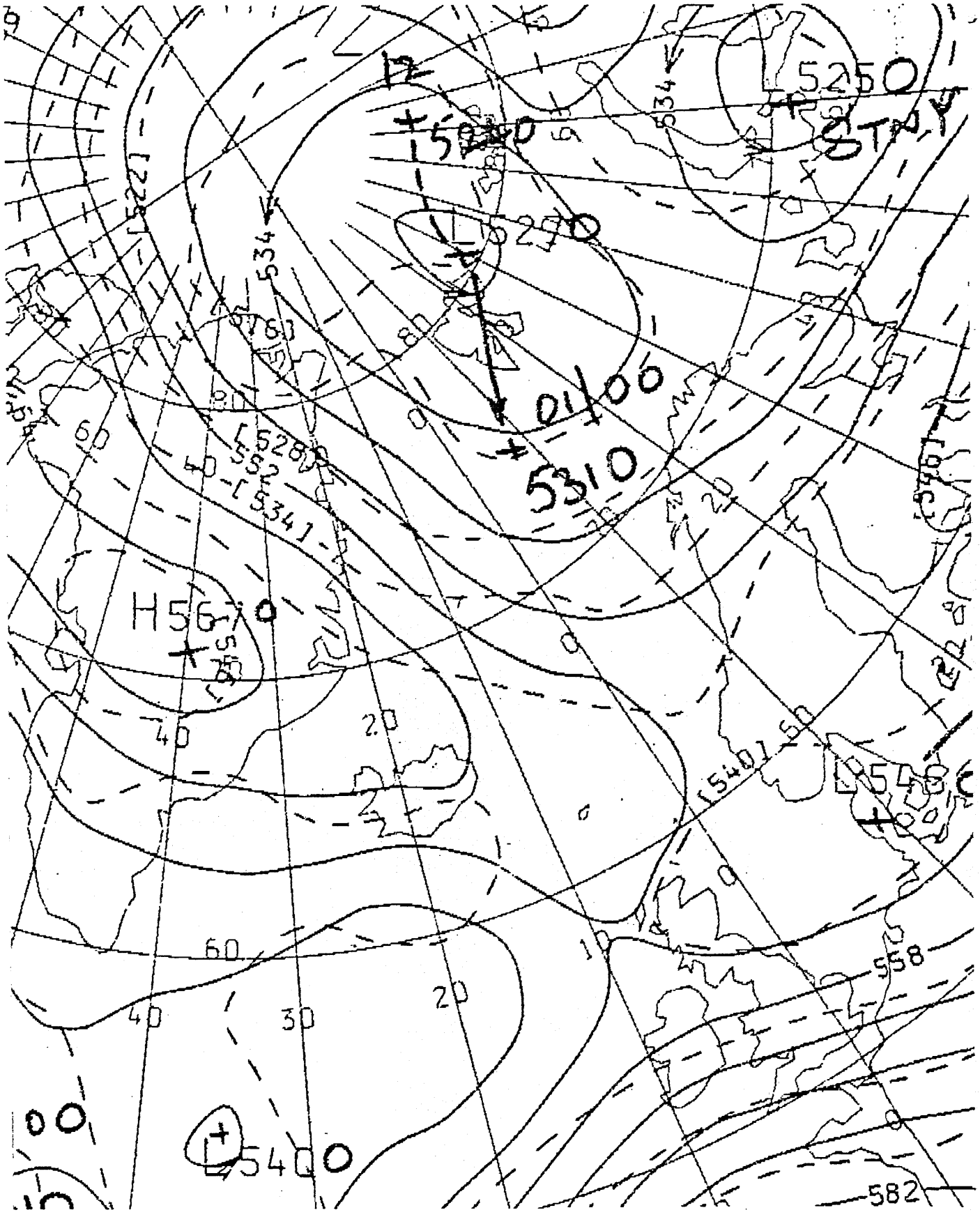


Fig.4.7. Data A1, Universal 8/4 Compression, Segment Size = 2 lines. (CR=1.78).

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
EXHIBITION ROAD LONDON SW7 2BT
Telephone: 01-589 5111 Telex: 261503
Ext. 1406

Mr. N. E. One
1 Somewhere Rd.,
Newtown,
Berks,
RG1 8LD.

23/9/76

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Fig.4.8. Data A1, Universal 8/4 Compression, Segment Size = 4 lines. (CR=1.90).

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Fig.4.9. Data A1, Universal 8/4 Compression, Segment Size = 6 lines. (CR=1.93).

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Fig.4.10. Data A5, Universal 8/4 Compression, Segment Size = 6 lines. (CR=1.93).

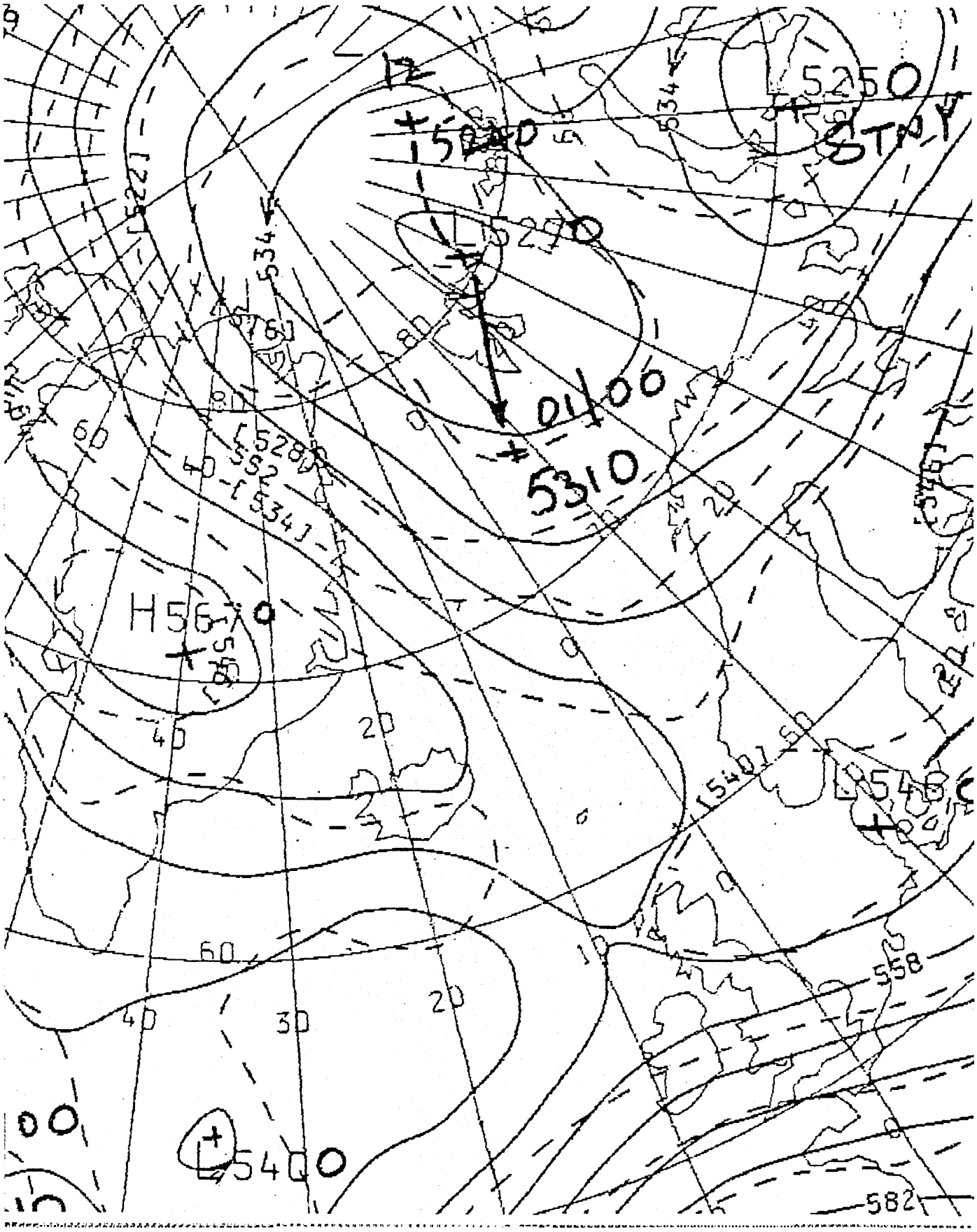


Fig.4.11. Data A5, Universal 8/4 Compression, Segment Size = 8 lines. (CR=1.95).

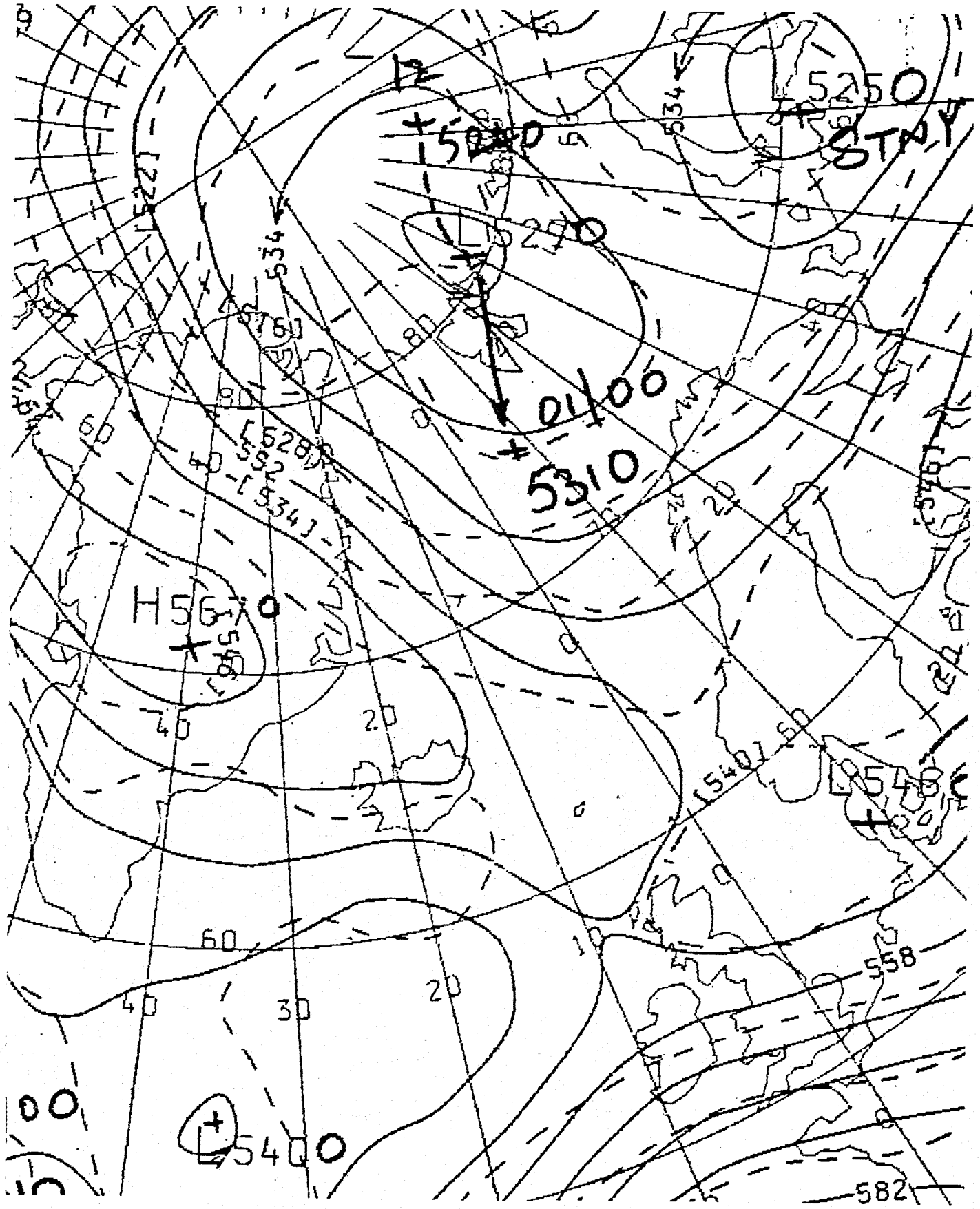


Fig.4.12. Data A5, Universal 8/4 Compression, Segment Size = 10 lines. (CR=1.96).

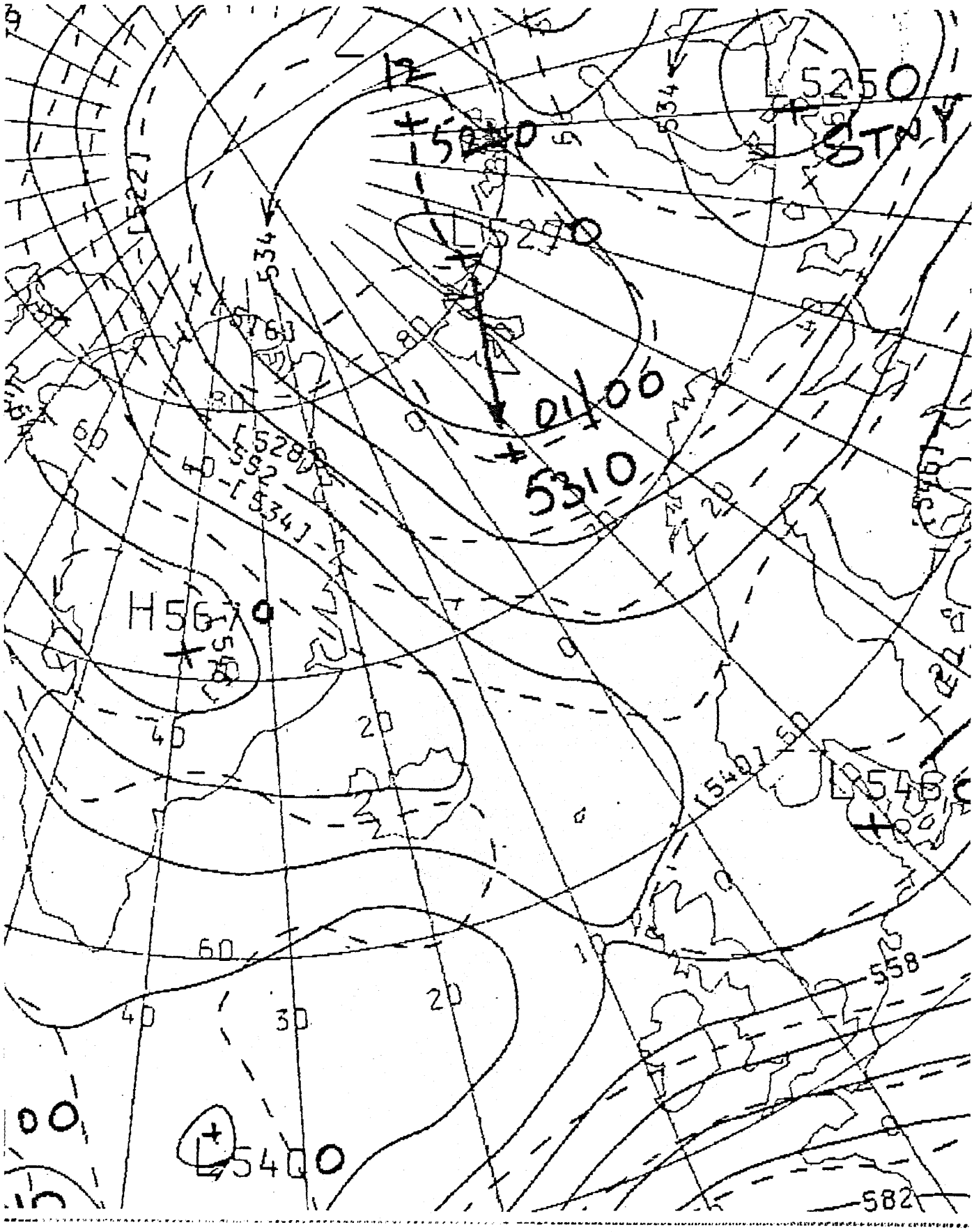


Fig.4.13. Data A1, Universal 8/5 Compression, Segment Size = 4 lines. (CR=1.47).

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Fig.4.14. Data A1, Universal 8/5 Compression, Segment Size = 6 lines. (CR=1.51).

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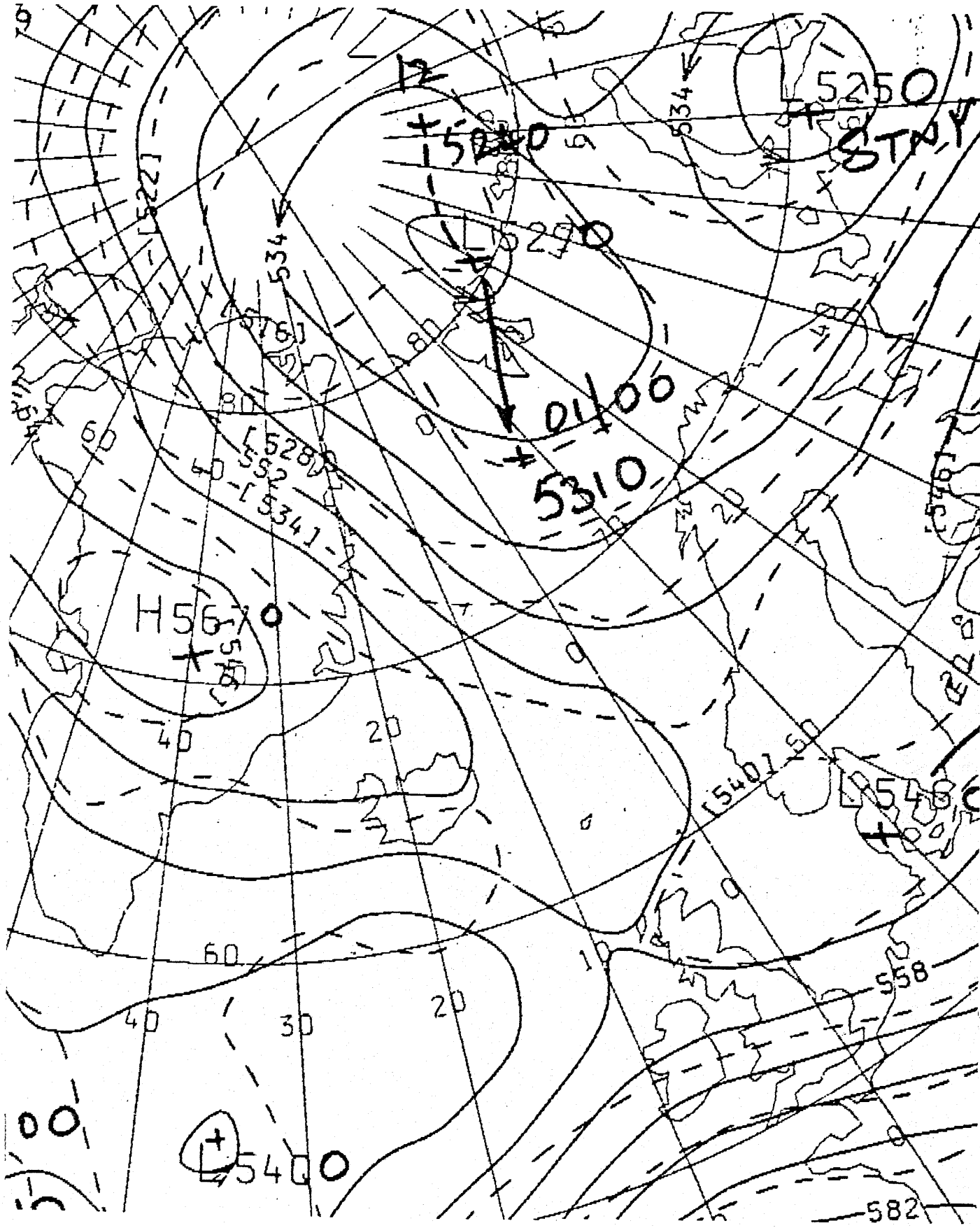
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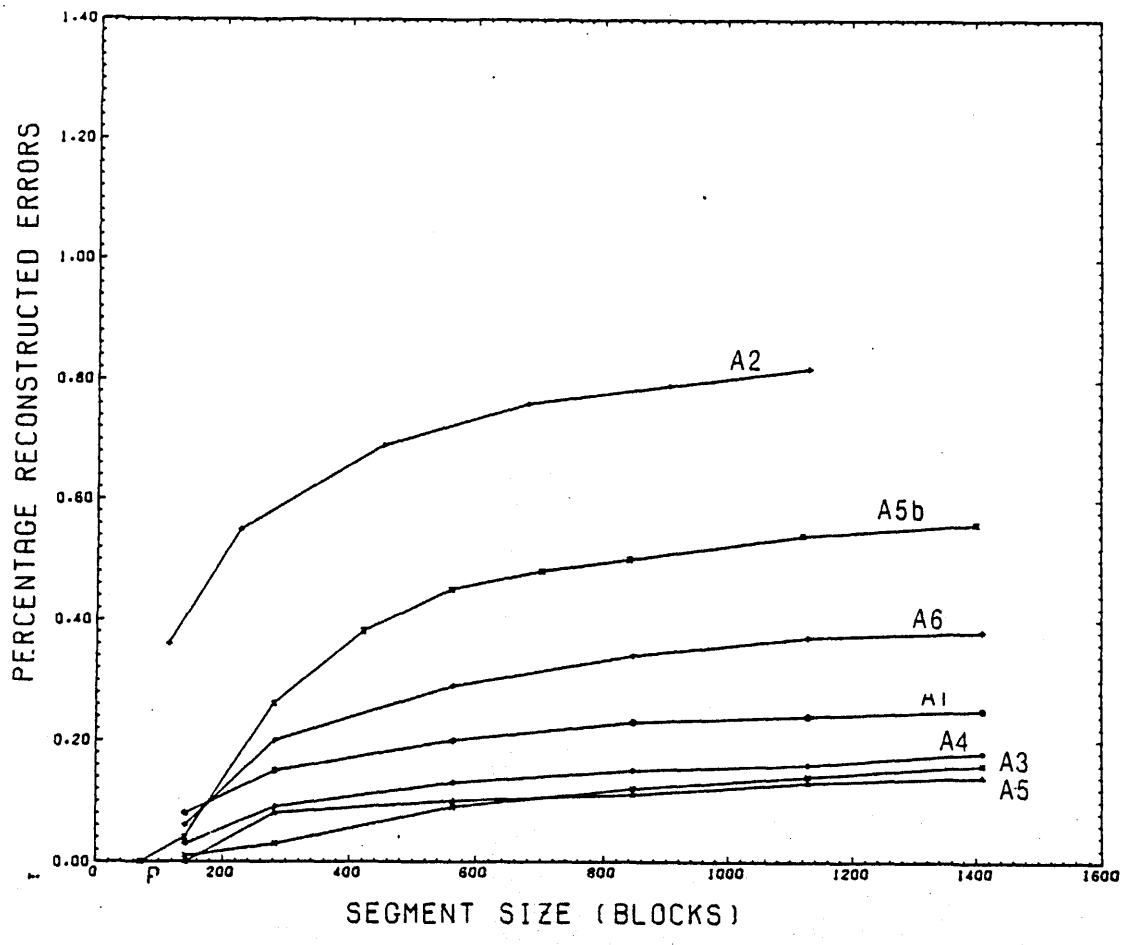
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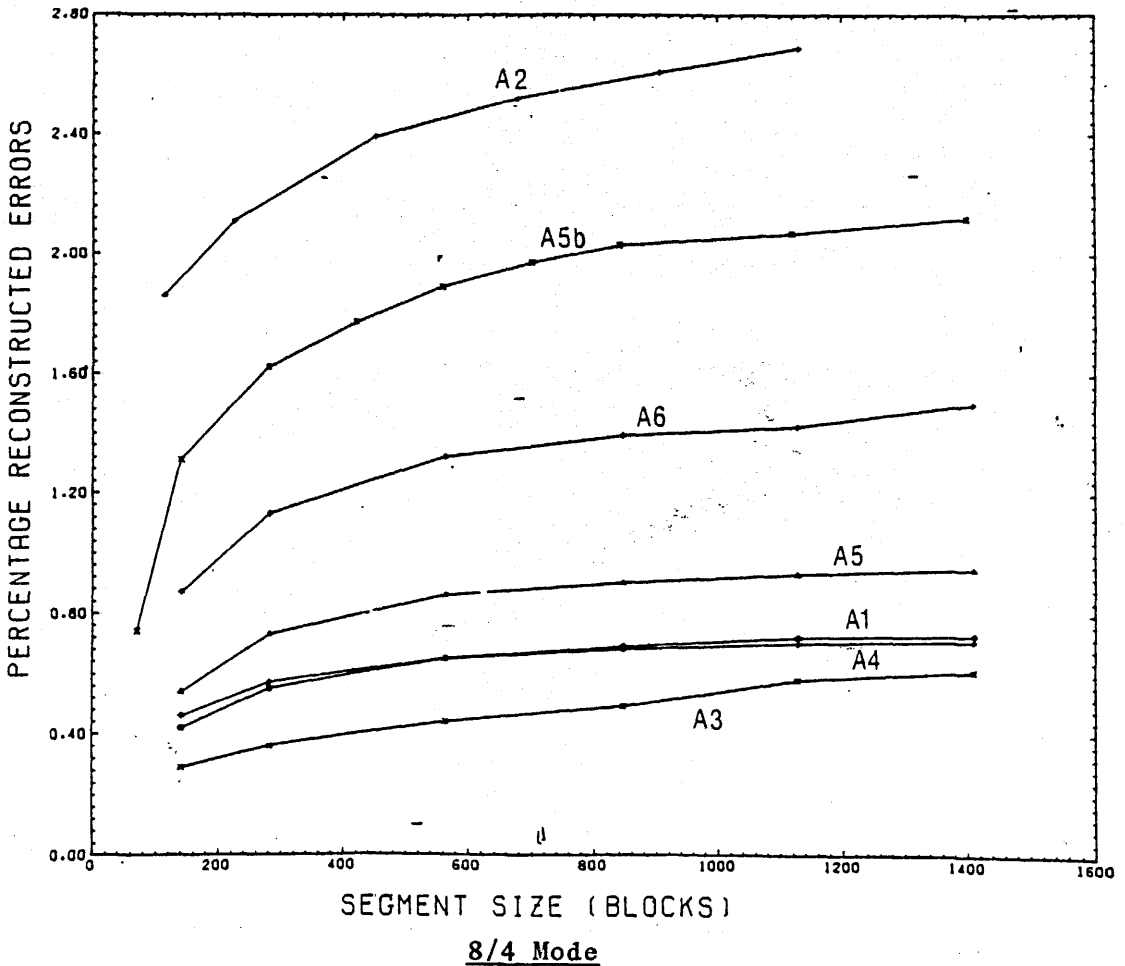
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Fig.4.15. Data A5, Universal 8/5 Compression, Segment Size = 6 lines. (CR=1.51).





8/5 Mode



8/4 Mode

Fig.4.16. Plots of PRE versus Segment Size for Test Images.

Fig.4.17. Data A2, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.58).

A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives --- notably fuller employment — depend on this. They show that higher exports and import substitution go together --- the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

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Fig.4.19. Data A2, Universal 8/5 Compression, Segment Size = 8 lines. (CR=1.52).

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Fig.4.20. Data A3, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.65).

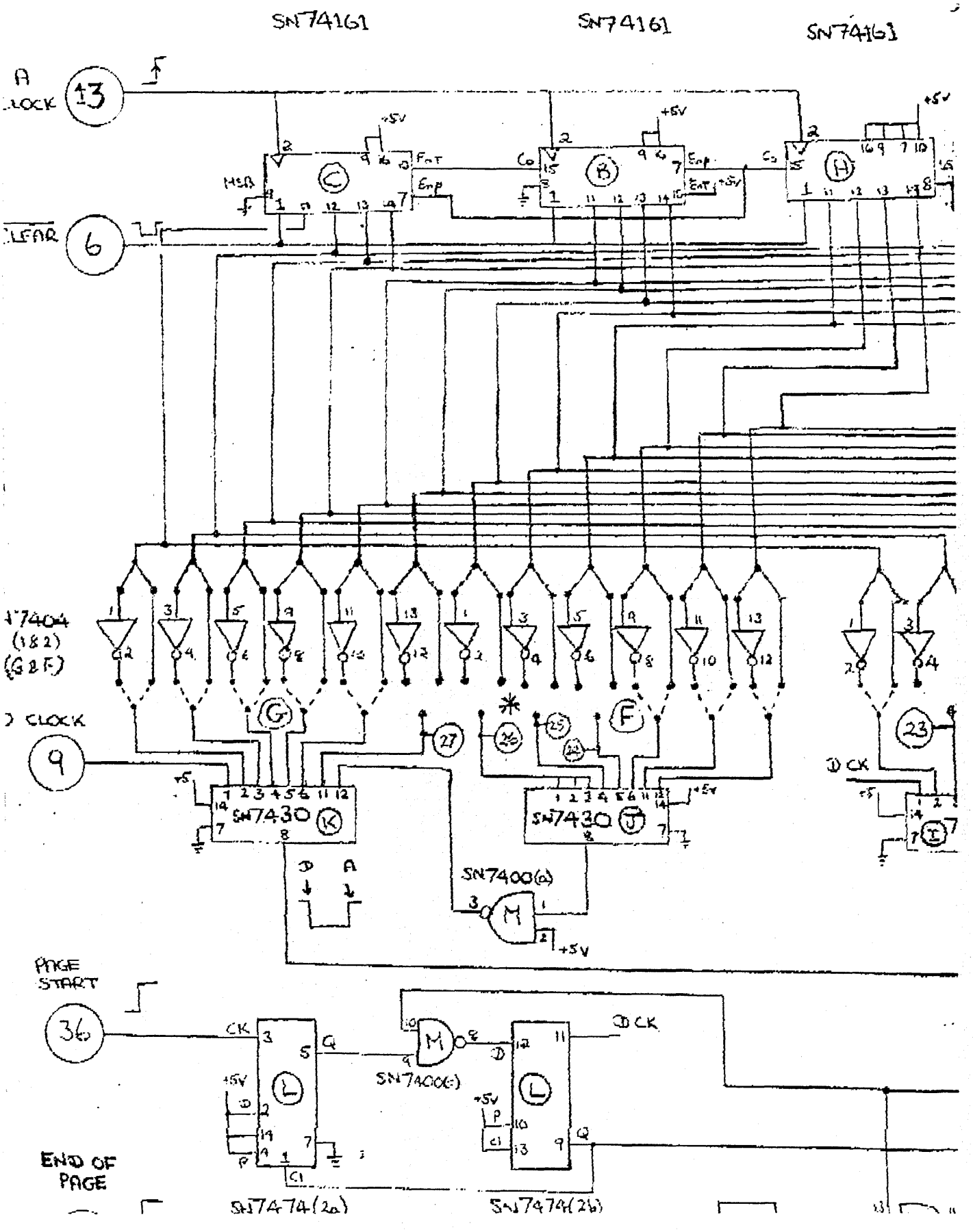


Fig.4.21. Data A3, Universal 8/5 Compression, Segment Size = 2 lines. (CR=1.33).

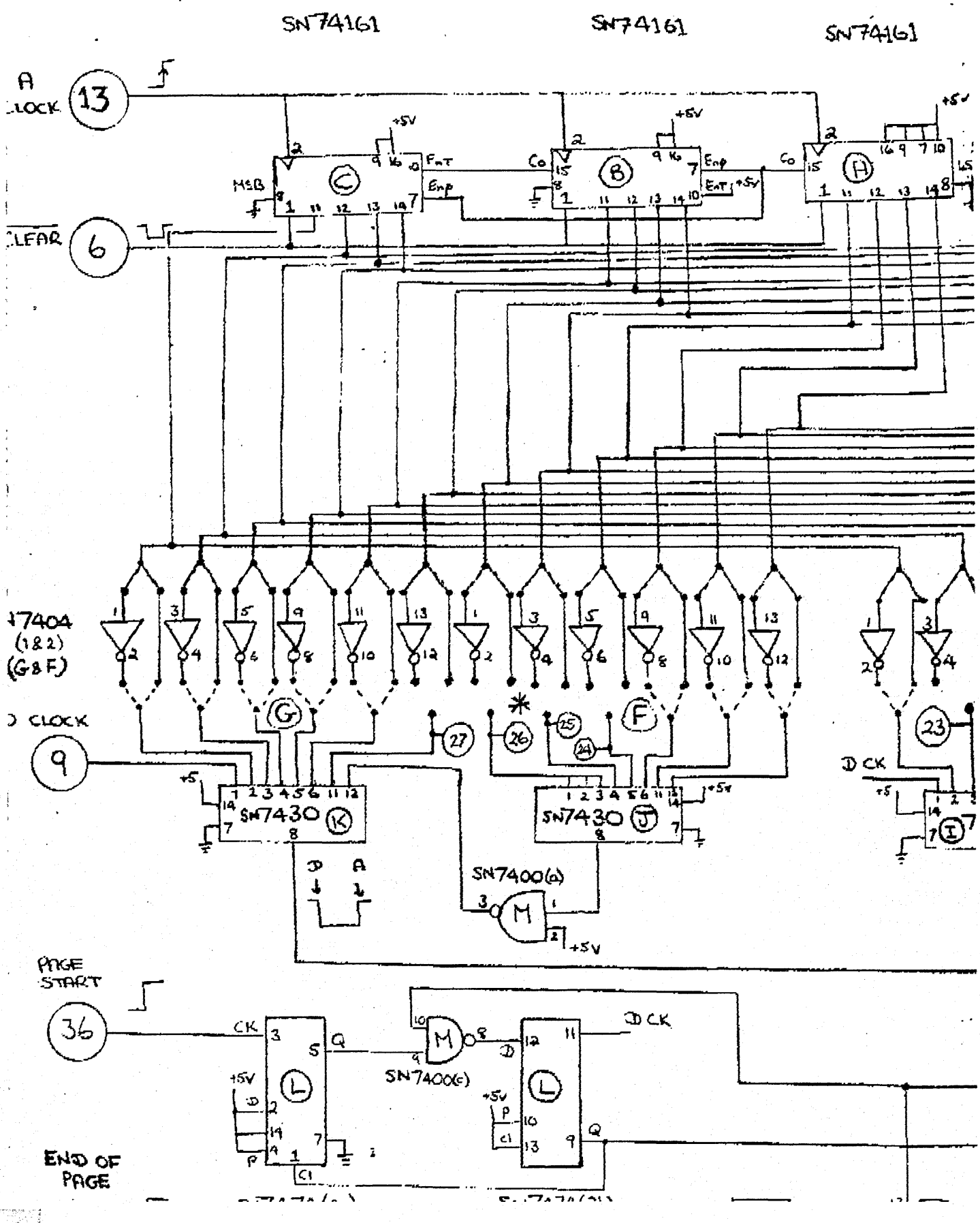


Fig.4.22. Data A3, Universal 8/5 Compression, Segment Size = 8 lines. (CR=1.55).

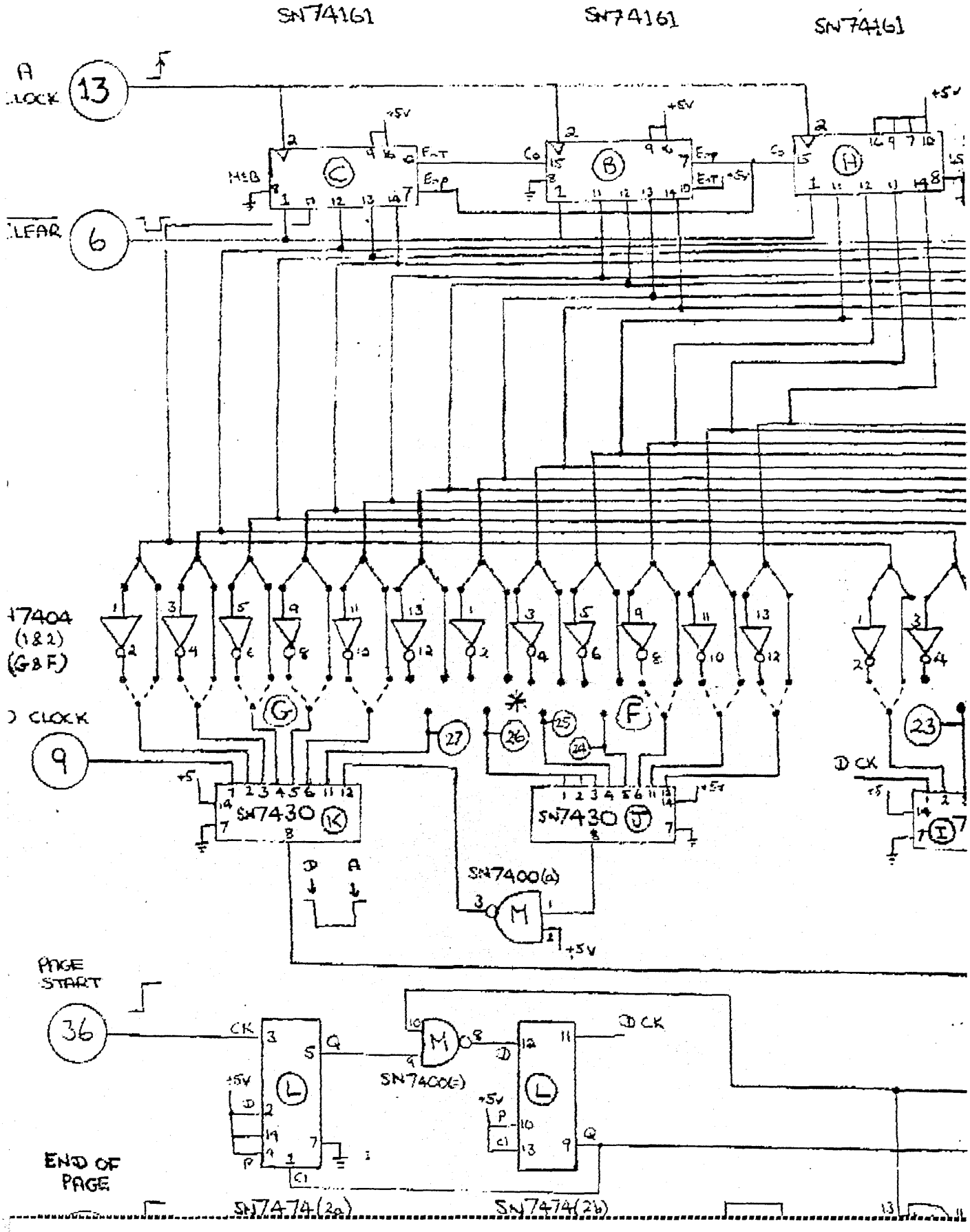


Fig.4.23. Data A4, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.65).

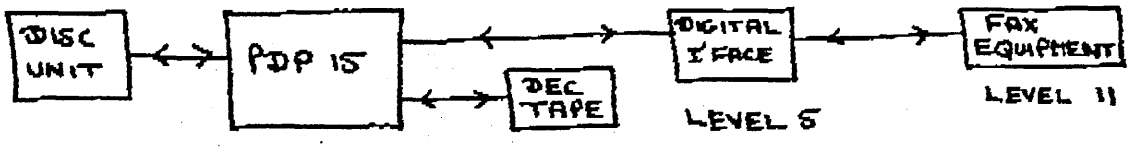
DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be amassed to

Fig.4.24. Data A4, Universal 8/5 Compression, Segment Size = 2 lines. (CR=1.33).

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Fig.4.25. Data A4, Universal 8/5 Compression, Segment Size = 8 lines. (CR=1.55).

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Fig.4.20. Data A6, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.65).

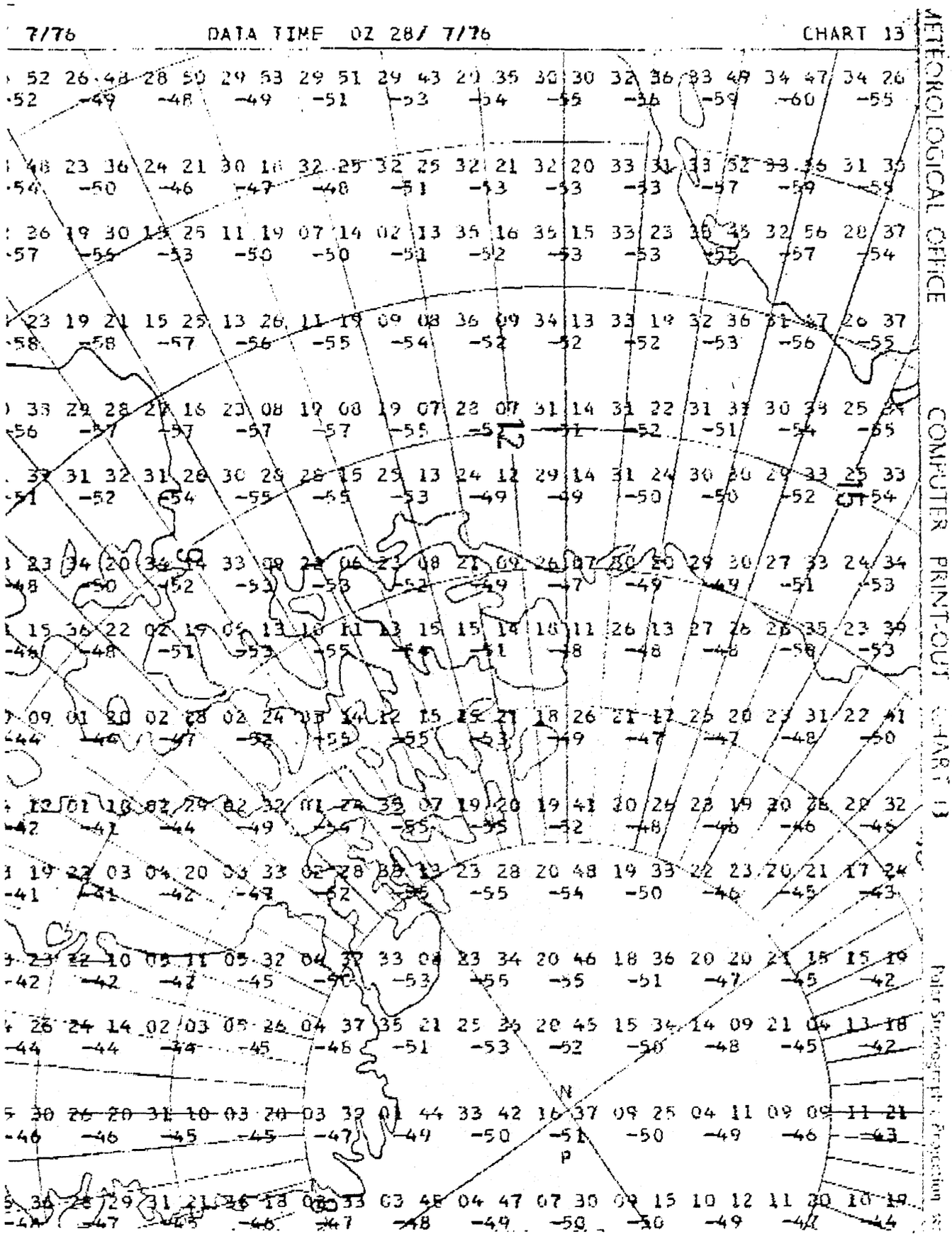


Fig.4.27. Data A6, Universal 8/5 Compression, Segment Size = 2 lines. (CR=1.33).

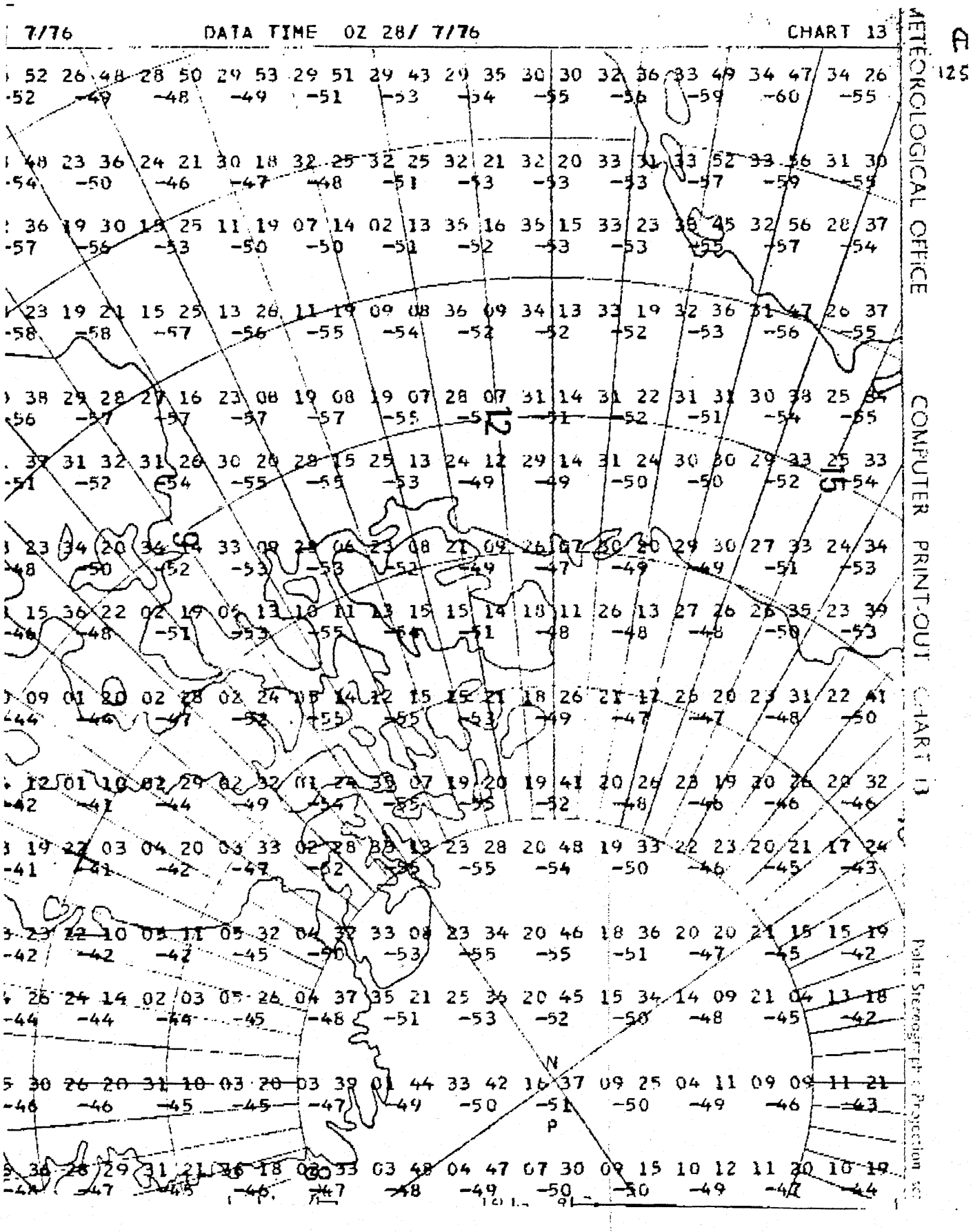


Fig.4.28. Data A6, Universal 8/5 Compression, Segment Size = 8 lines. (CR=1.55).

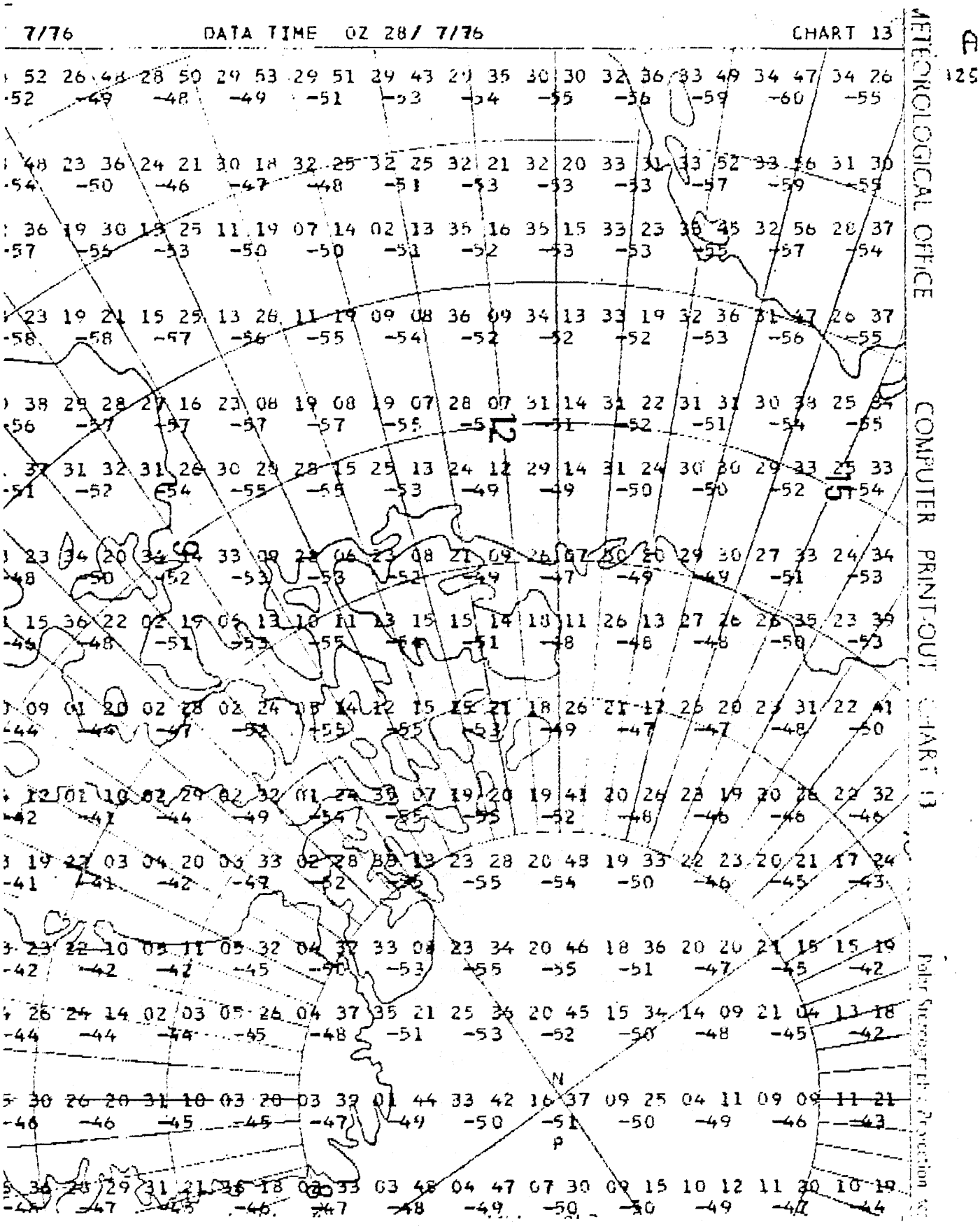


Fig.4.29. Data A5b, Universal 8/4 Compression, Segment Size = 1 line. (CR=1.40).

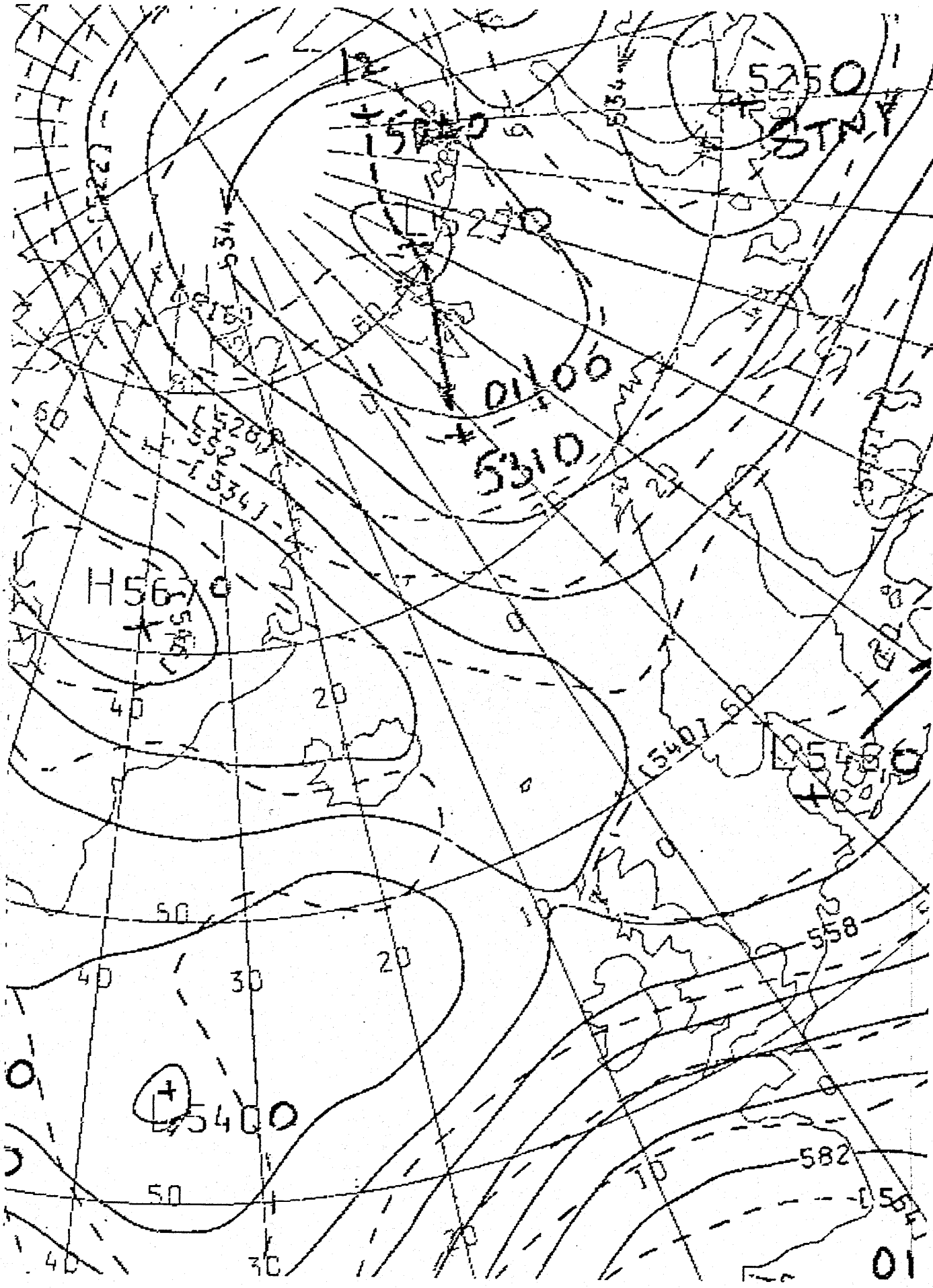


Fig.4.30. Data A5b, Universal 8/4 Compression, Segment Size = 4 lines. (CR=1.81).

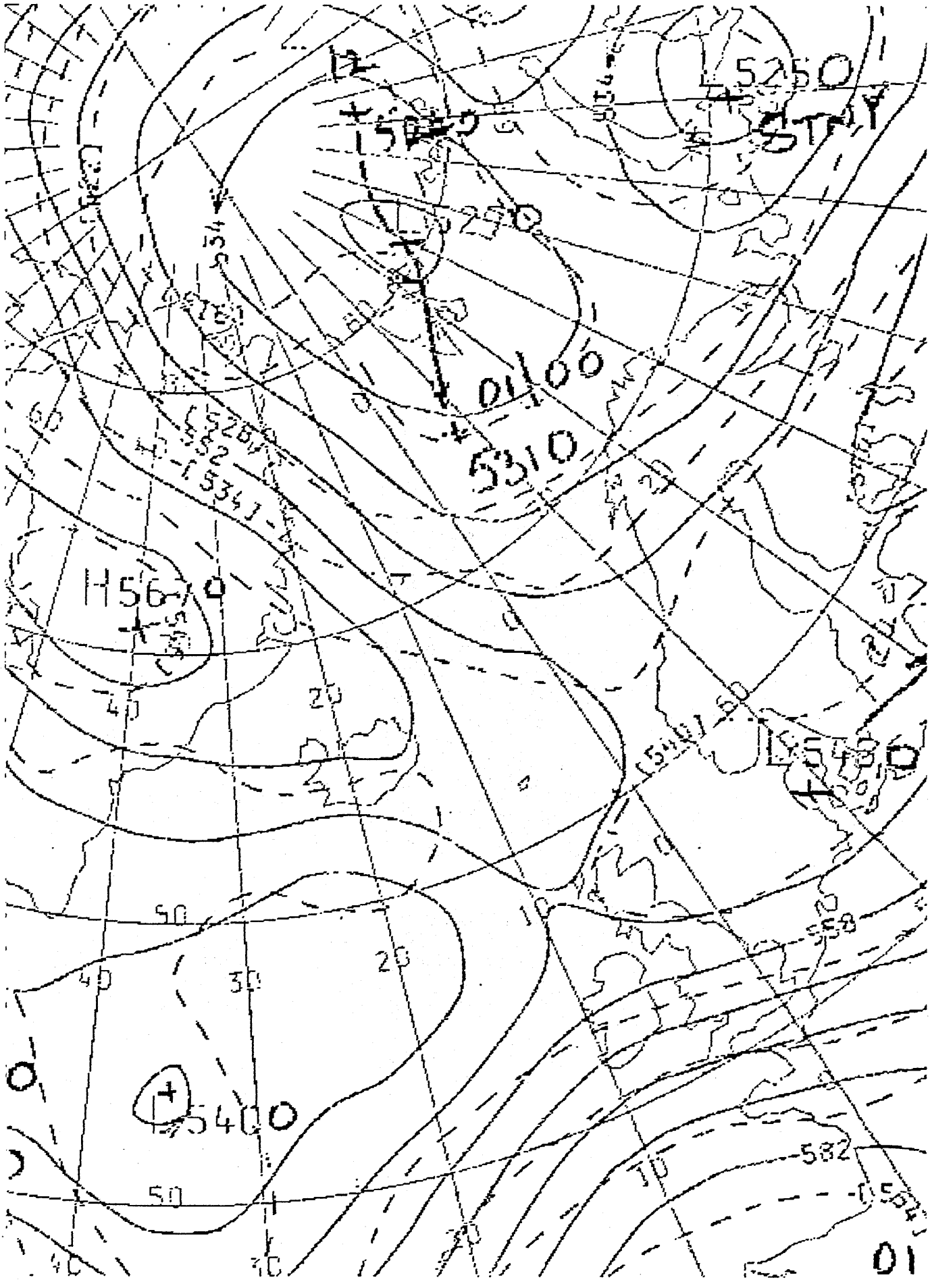


Fig.4.31. Data A5b, Universal 8/5 Compression, Segment Size = 6 lines. (CR=1.43).

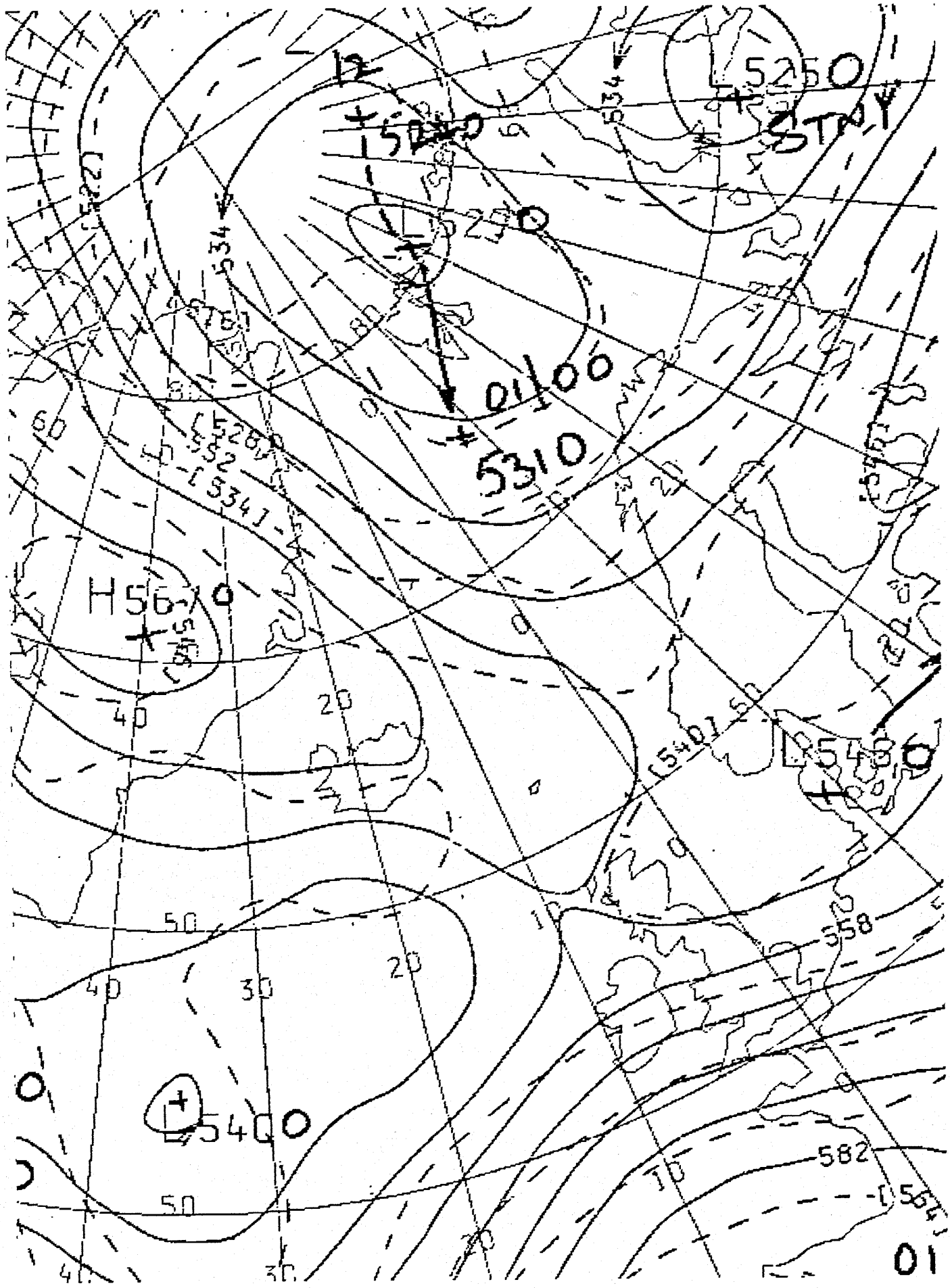
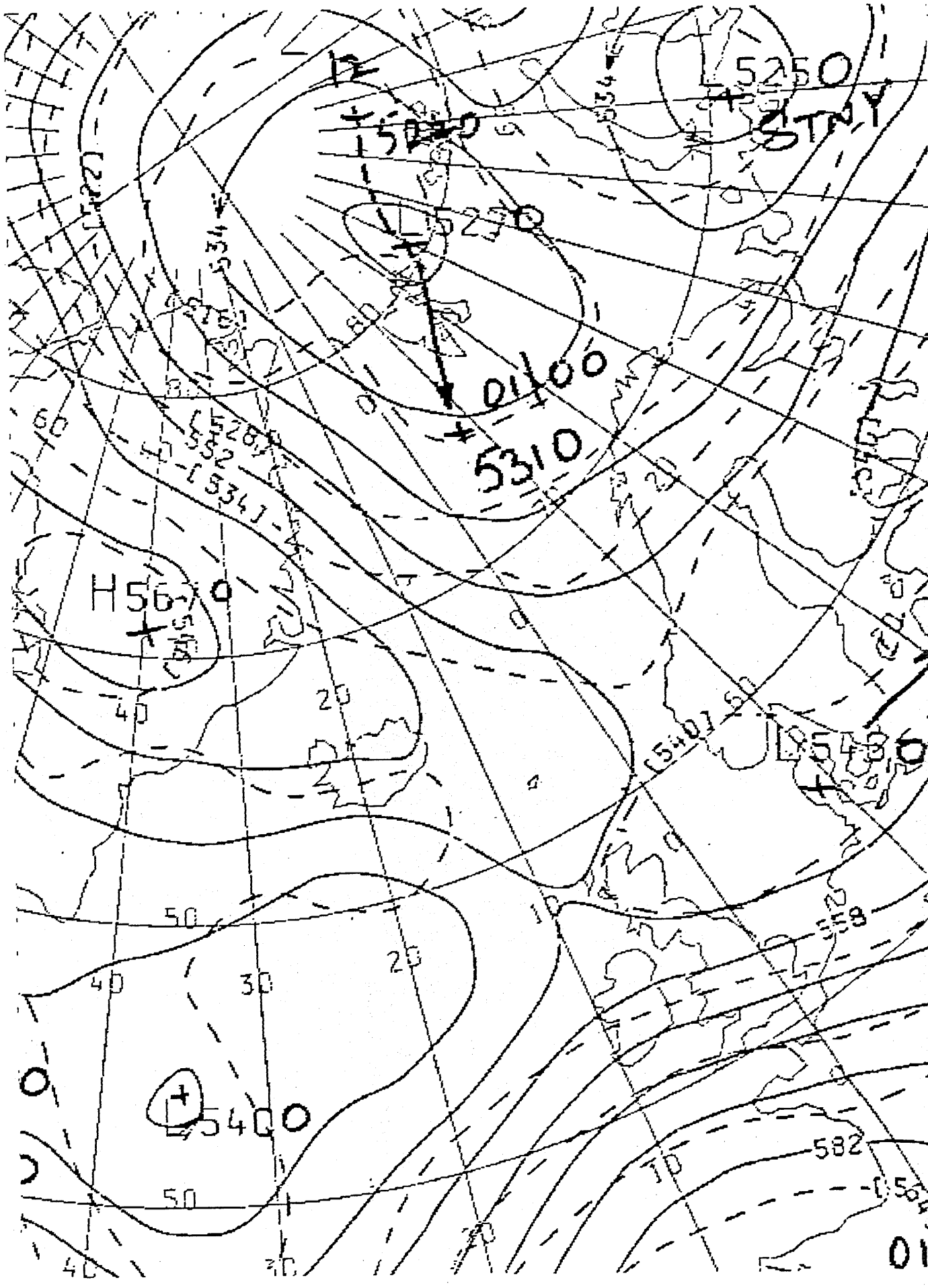


Fig.4.32. Data A5b, Universal 8/5 Compression, Segment Size = 20 lines. (CR=1.55).



...g.1.3.3. Data AI, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.64).

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Fig.4.34. Data A2, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.58).

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Fig.4.35. Data A3, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.64).

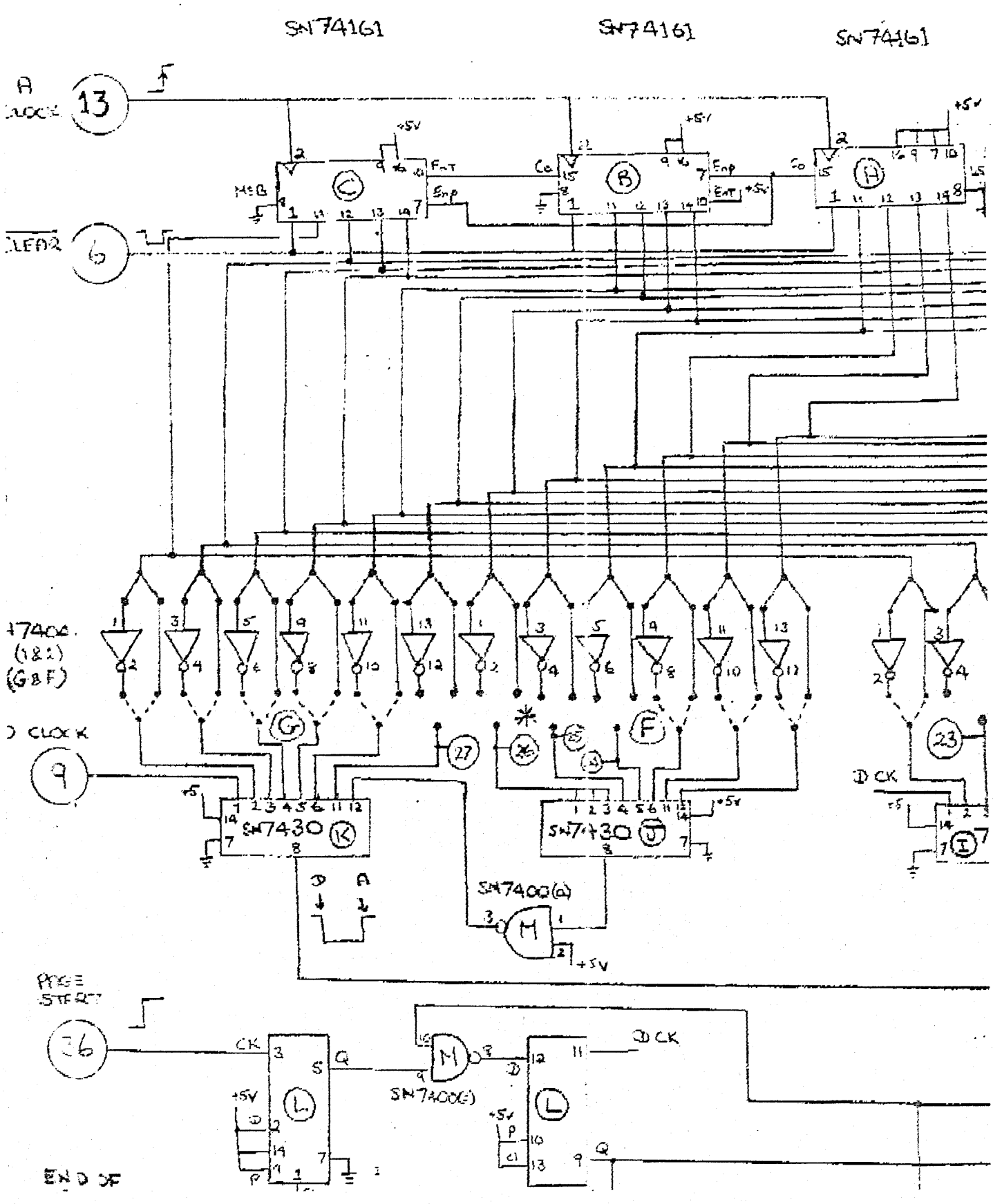


Fig.4.36. Data A5, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.64).

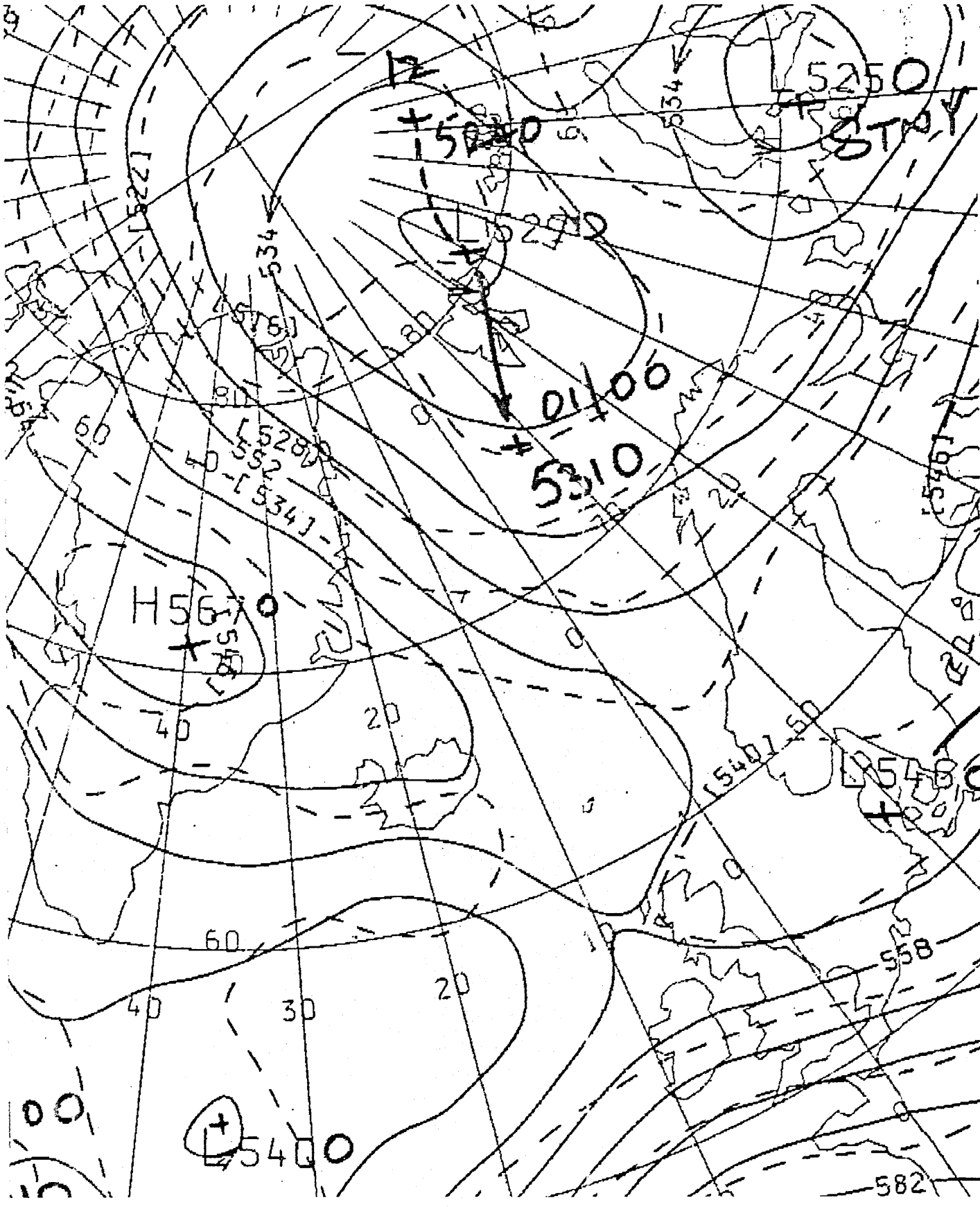


Fig.4.37. Data A6, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.64).

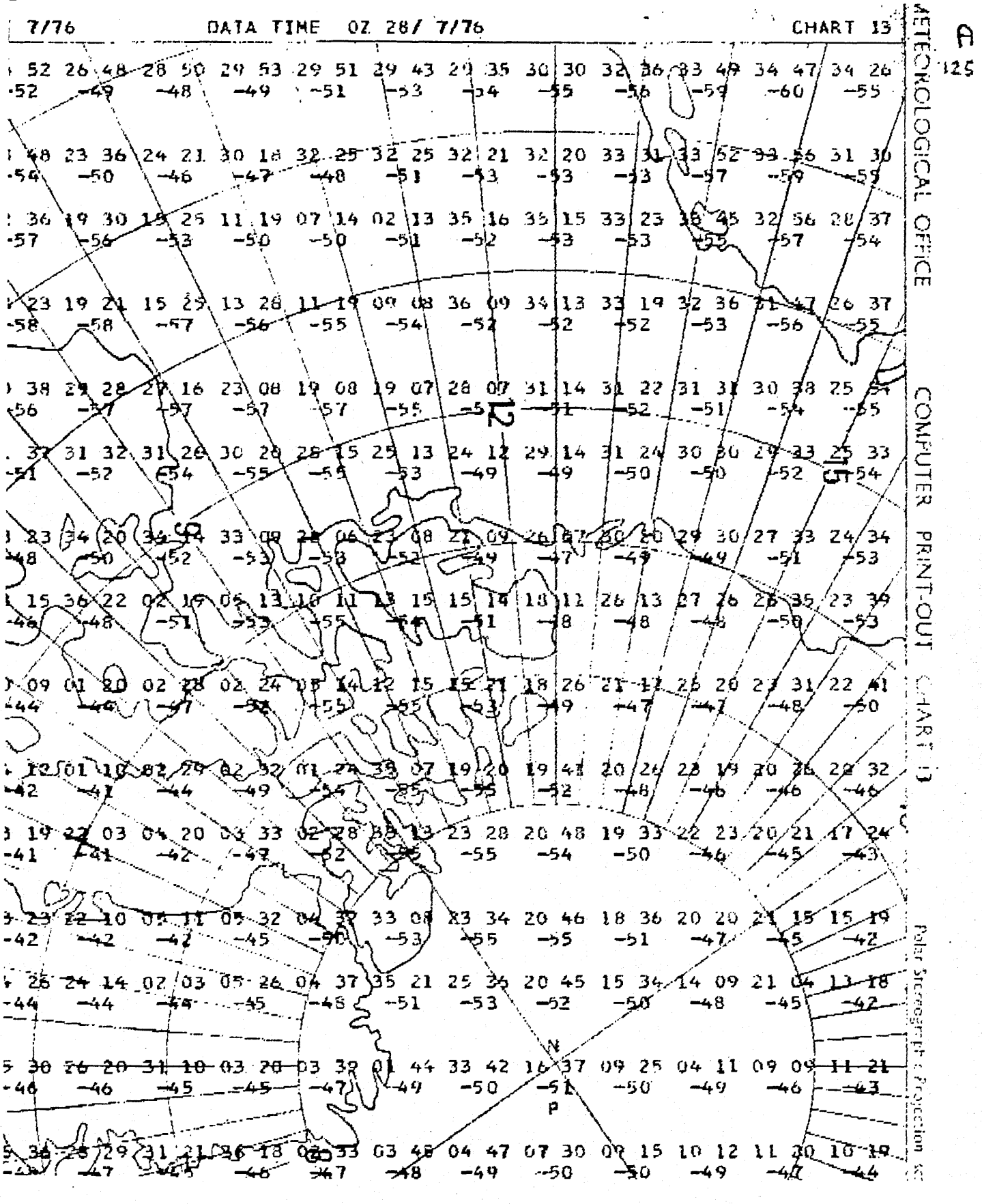
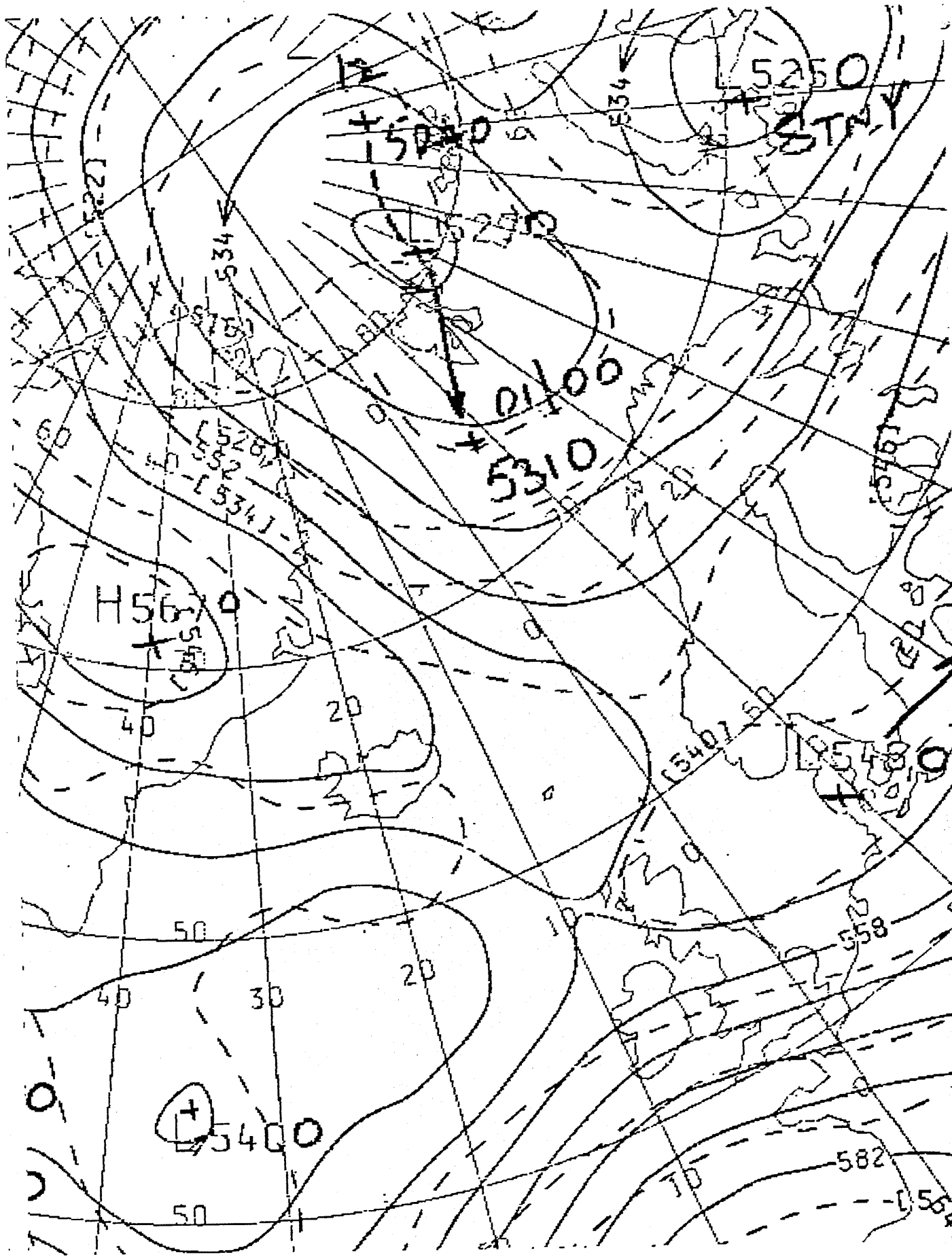


Fig.4.38. Data A5b, Universal 8/4 Compression,

Segment Size = 8 lines x $\frac{1}{8}$ line width. (CR=1.36).



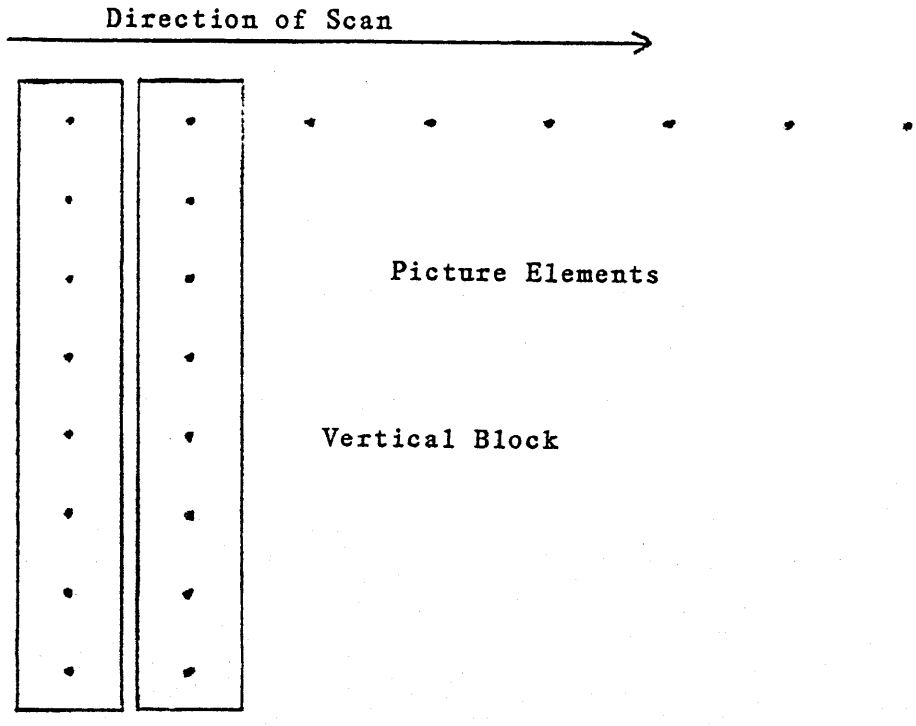


Fig.4.39. Vertical Block Configuration.

Fig.4.40. Data A1, Universal 8/4 Coding With Vertical Blocks,

Segment Size = $\frac{1}{8}$ line width. (CR=1.65).

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Fig.4.41. Data A1, Universal 8/4 Coding With Vertical Blocks,
Segment Size = $\frac{1}{2}$ line width. (CR=1.90).

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Fig.4.42. Data A1, Universal 8/5 Coding With Vertical Blocks,

Segment Size = 1 line width. (CR=1.53).

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Fig.4.43. Data A2, Universal 8/4 Coding With Vertical Blocks,

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A constructive starting point

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Fig.4.46. Data A5, Universal 9/4 Compression, Segment Size = 1 line. (CR=1.77).

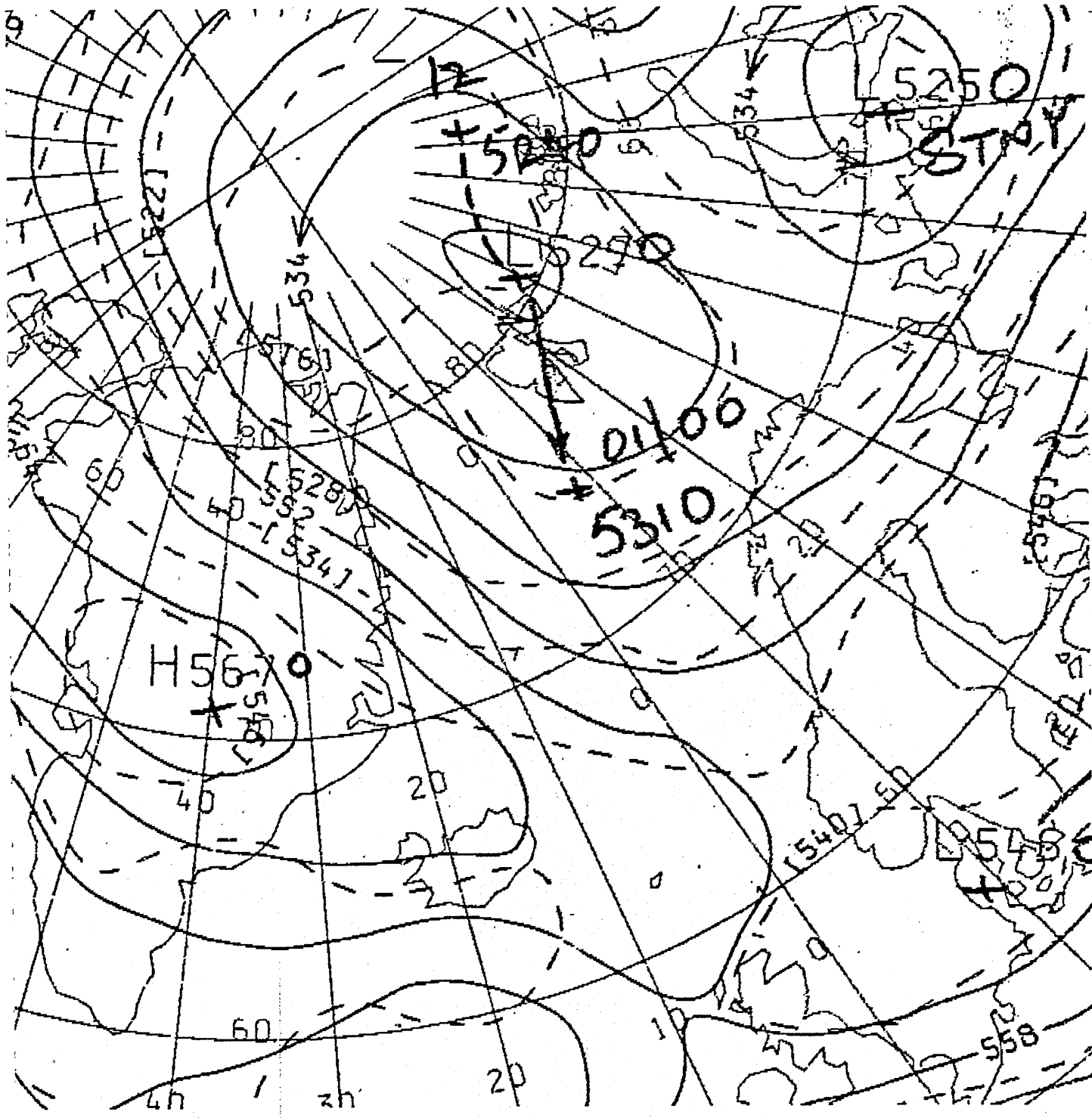


Fig.4.47. Data A5, Universal 9/4 Compression, Segment Size = 2 lines. (CR=1.98).

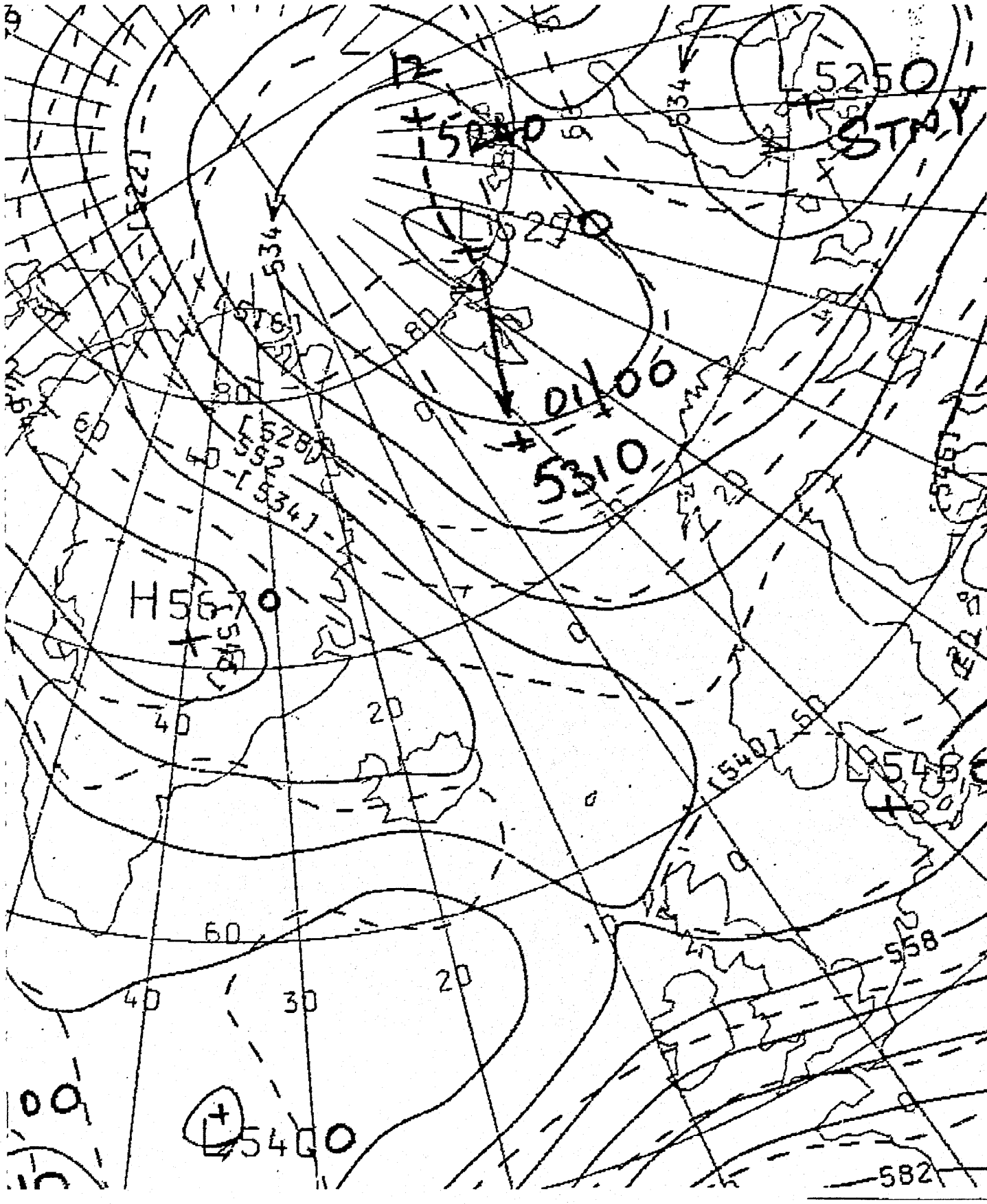


Fig.4.48. Data A5, Universal 9/4 Compression, Segment Size = 6 lines. (CR=1.93).

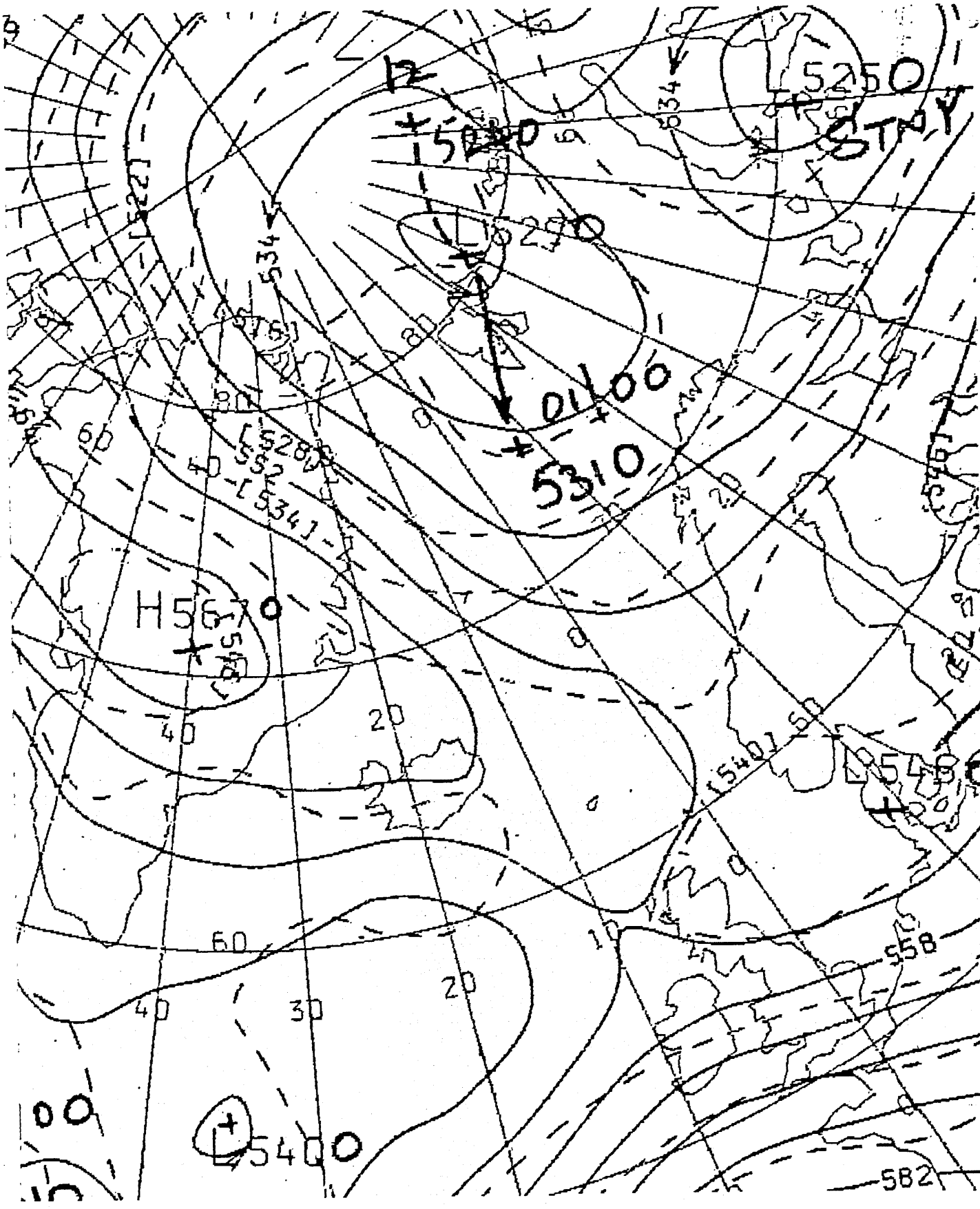


Fig.4.49. Data A5, Universal 11/5 Compression, Segment Size = 6 lines. (CR=1.98). -214-

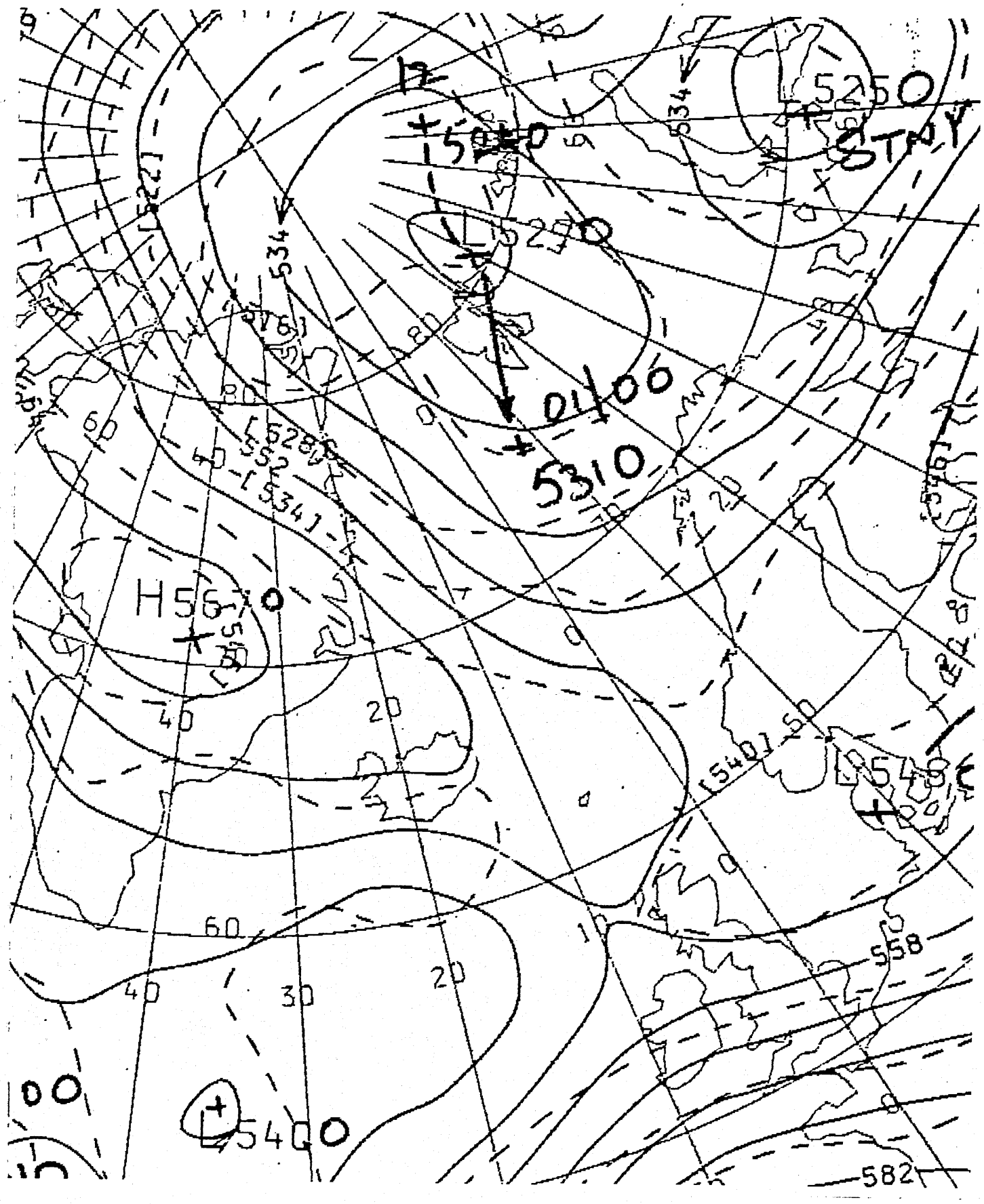


Fig.4.50. Data A5, Universal 11/5 Compression, Segment Size = 8 lines. (CR=2.03).

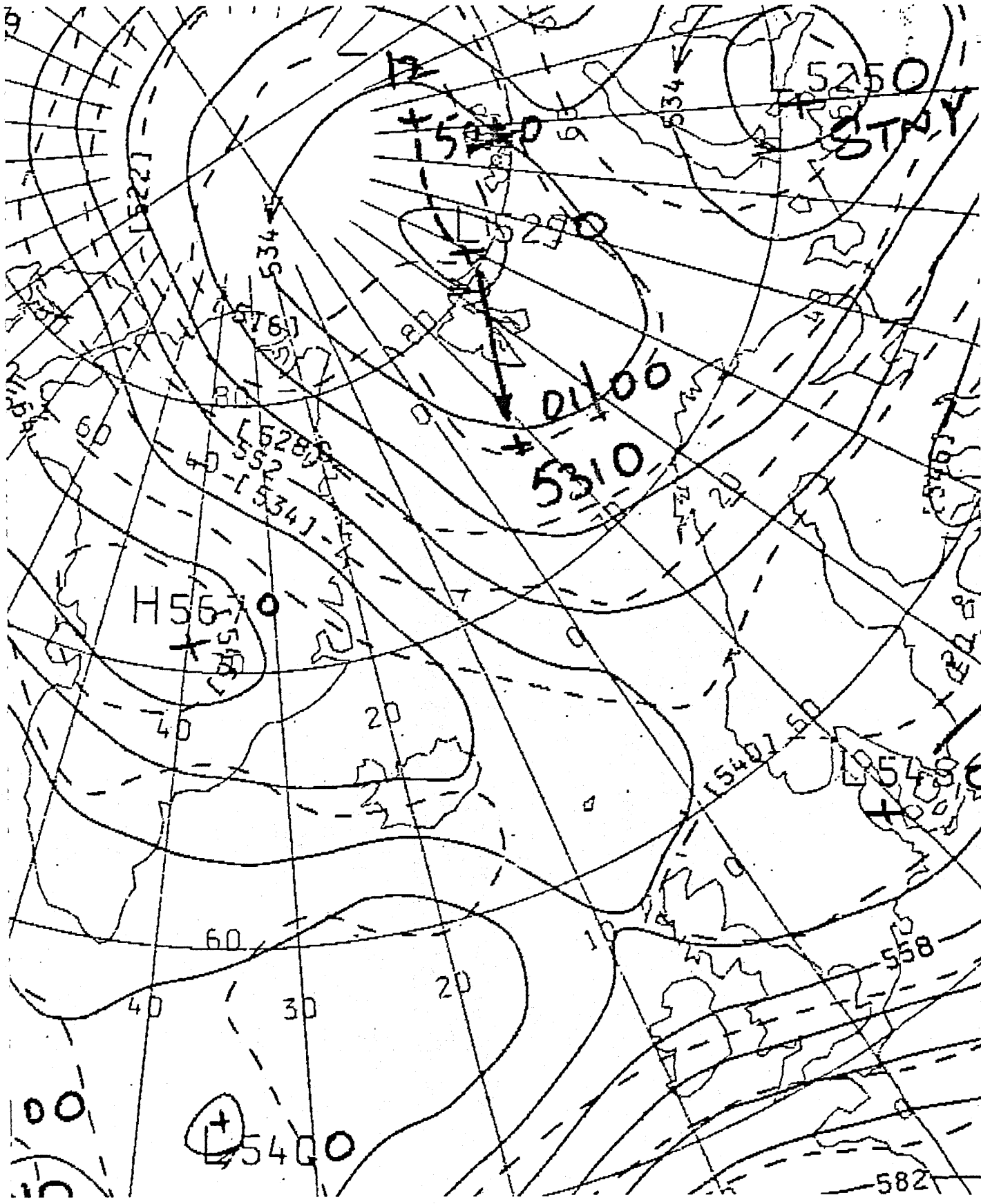


Fig.4.51. Data A5b, Universal 9/5 Compression, Segment Size = 26lines. (CR=1.57).

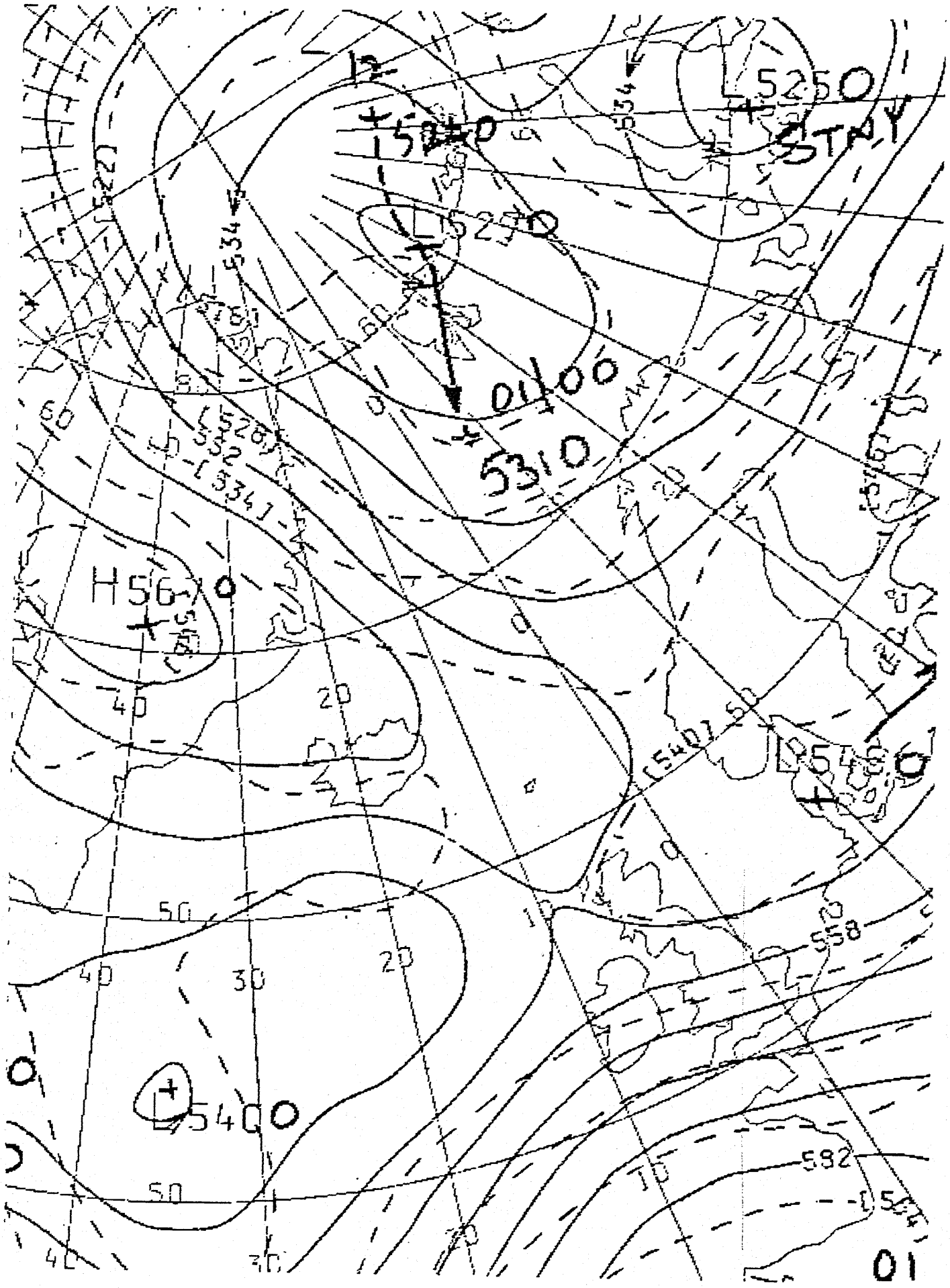


Fig.4.52. Data A5b, Universal 11/6 Compression, Segment Size = 10 lines. (CR=1.49).

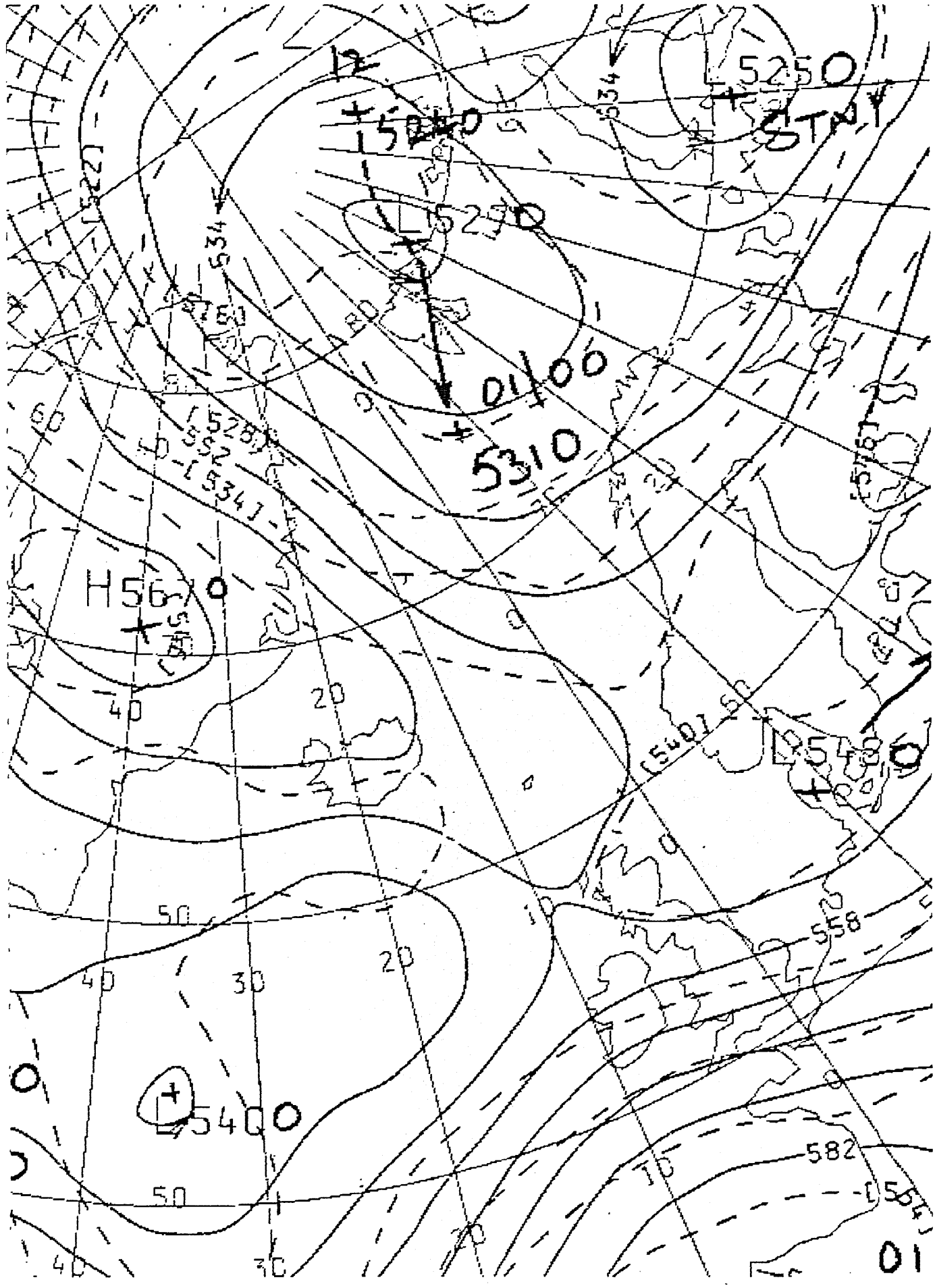


Fig.4.53. Data A1, Universal 7/3 Coding With Vertical Blocks,

Segment Size = $\frac{1}{8}$ line width. (CR=2.09).

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Fig.4.54. Data A1, Universal 9/4 Coding With Vertical Blocks,

Segment Size = $\frac{1}{8}$ line width. (CR=1.82).

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Fig.4.55. Data A1, Universal 10/4 Coding With Vertical Blocks, Segment Size = $\frac{1}{8}$ line width. (CR=1.97).

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Fig.4.56. Data A1, Universal 10/4 Coding With Vertical Blocks, Segment Size = $\frac{1}{4}$ line width. (CR=2.21).

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Fig.4.57. Data A1, Universal 11/5 Coding With Vertical Blocks,

Segment Size = 1 line width. (CR=2.07).

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Fig.4.58. Data A1, Universal 11/5 Coding With Vertical Blocks,
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Fig.4.59. Data A1, Universal 12/5 Coding With Vertical Blocks,
Segment Size = $\frac{1}{3}$ line width. (CR=2.00).

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Our ref. ABC/DE/FG Your ref.

Dear Mr. One,

This letter has been written purely for the purpose of filling a part of the sheet of paper you see in front of you. I doubt very much whether you will be any wiser having read it, but I think you will agree that, from a distance, it looks like a very ordinary business letter, in fact, the sort of document which millions of people throughout the world receive every day. If I have succeeded in producing a "typical" letter, then I hope that the statistics I derive from it, and the processing which I perform on it, will also yield typical results for this class of document. In turn, such work may lead to a better understanding of the extent to which data compression techniques may be used. Please forgive me for wasting your time while you read this nonsense.

Yours sincerely,

D. W. TINDALL

P.S. If this letter did better your knowledge or understanding in any way, please let me know how.

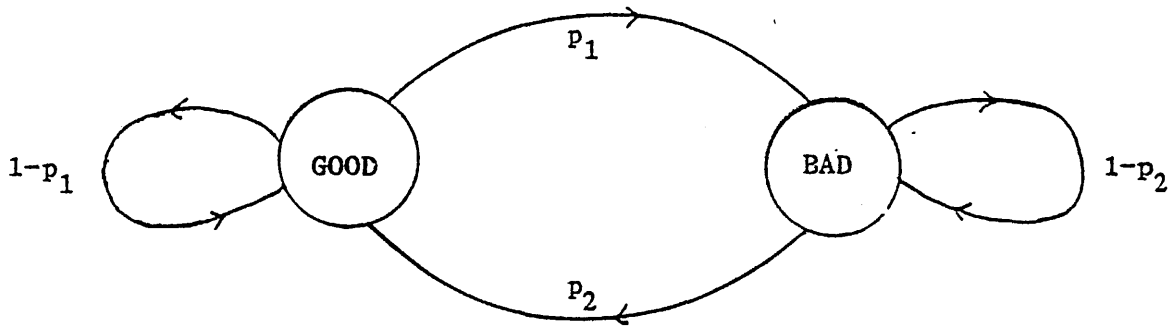


Fig.4.60. First Order Markov Source Used in Gilbert Burst Noise Model.

Probability of Bit Error, p	Average Bit Error Rate	p_1	p_2	h
0.1	1 in 10	0.0625	0.25	0.5
0.0316	1 in 32	0.01688	0.25	0.5
0.01	1 in 100	0.00510	0.25	0.5
0.00316	1 in 320	0.00159	0.25	0.5
0.001	1 in 1000	0.00050	0.25	0.5
0.000316	1 in 3200	0.00016	0.25	0.5
0.0001	1 in 10000	0.00005	0.25	0.5

Fig.4.61. Parameter Values for Various Probabilities of Bit Errors in Simulated Gilbert Noise Source.

Fig.4.62. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed to 1 in 1000 Random Errors.

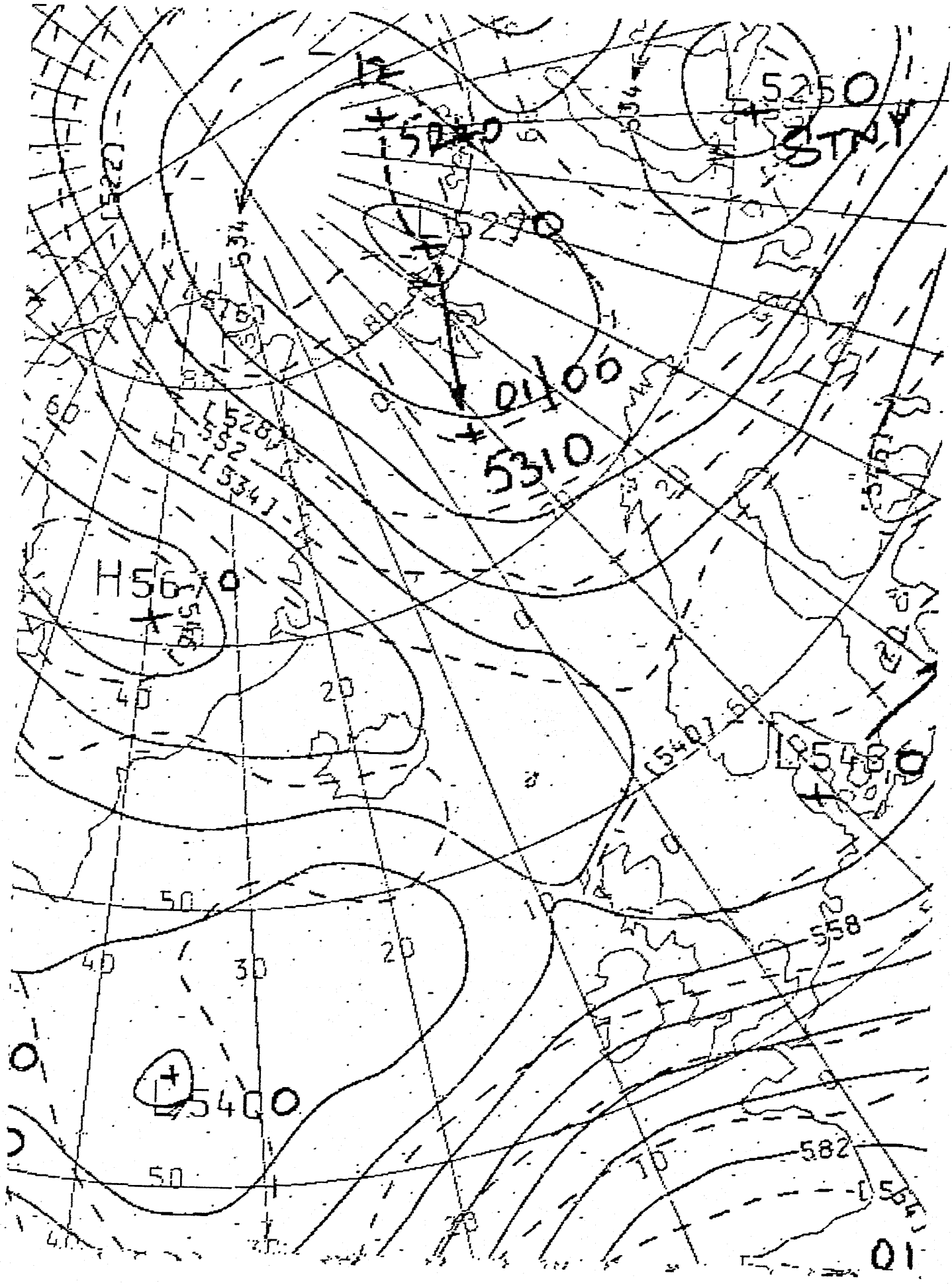


Fig.4.63. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed to 1 in 100 Random Errors.

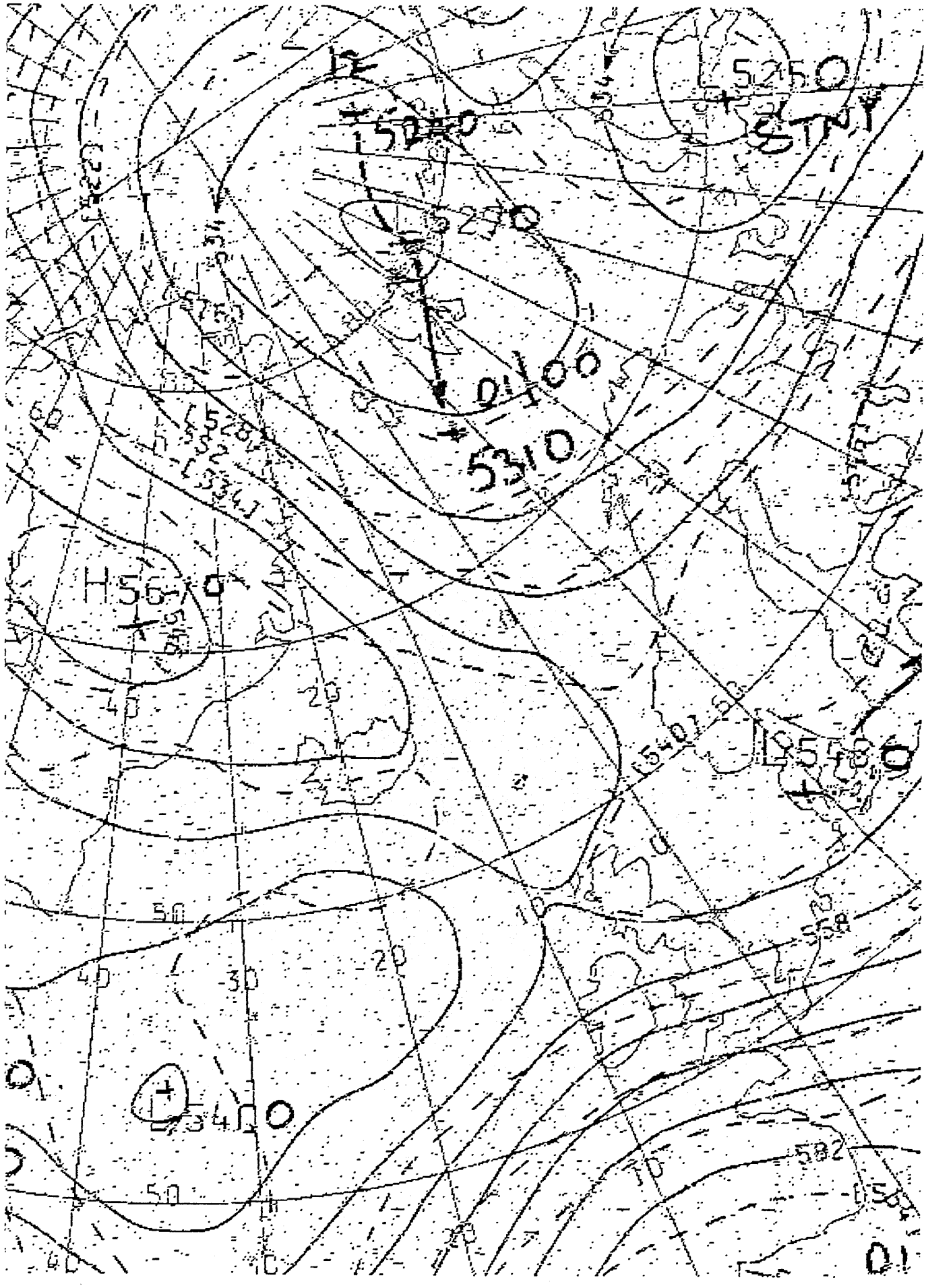


Fig.4.64. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed to 1 in 32 Random Errors.

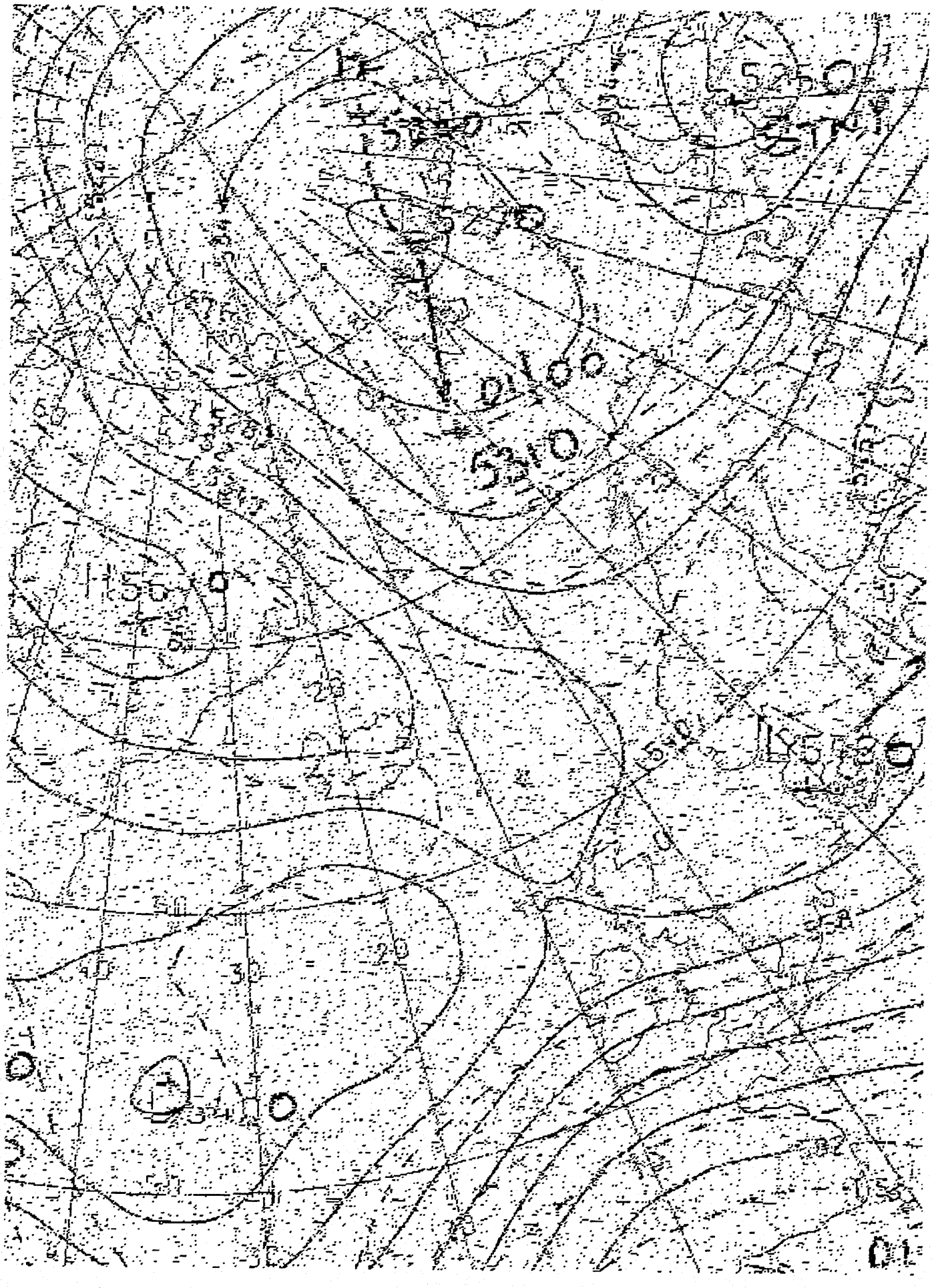


Fig.4.65. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed to 1 in 100 Burst Errors.

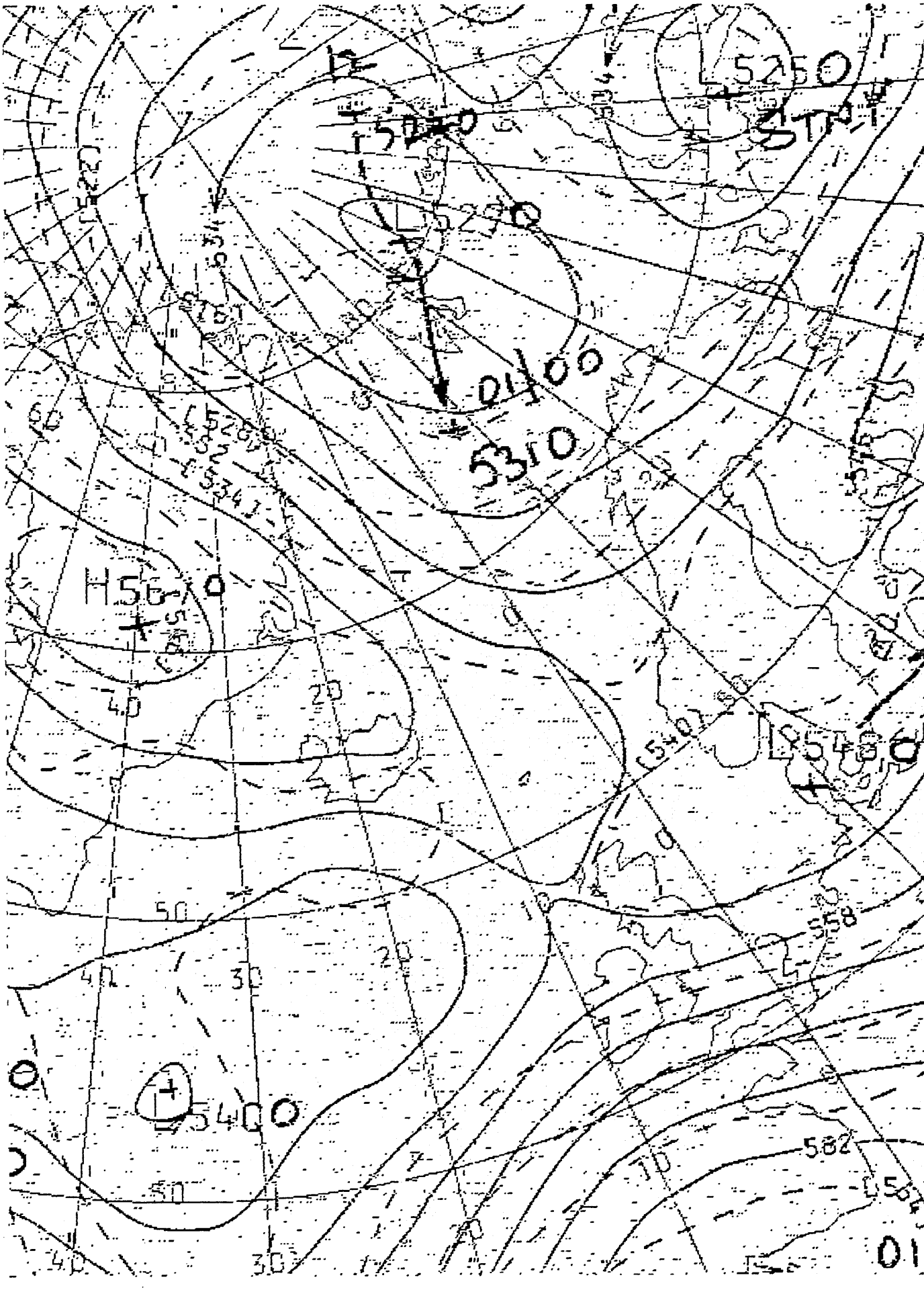


Fig.4.66. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed to 1 in 32 Burst Errors.

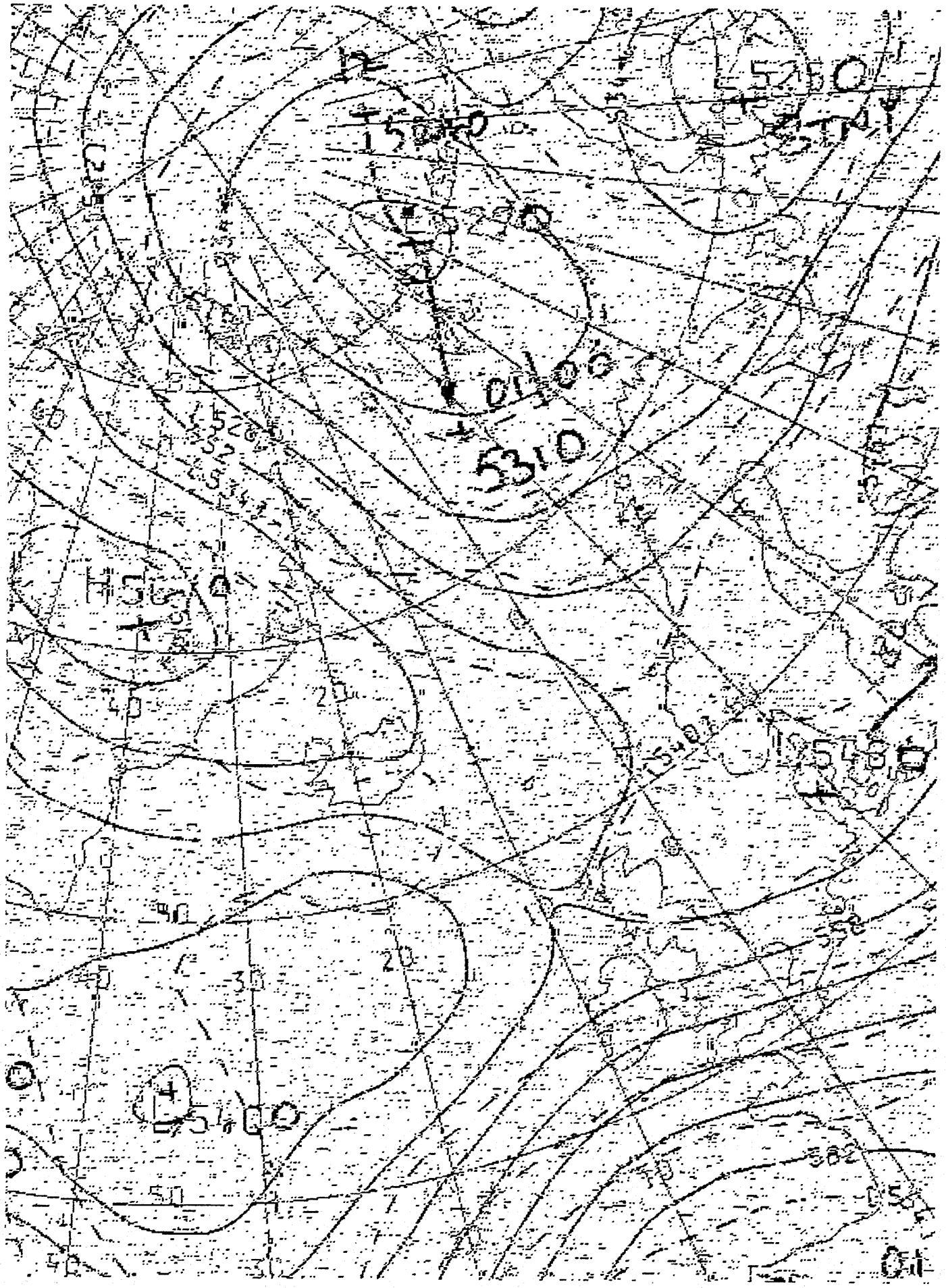


Fig.4.67. Data A5b, Universal 8/5 Coded (8-line Segment), Exposed 1 in 50 Random Errors.

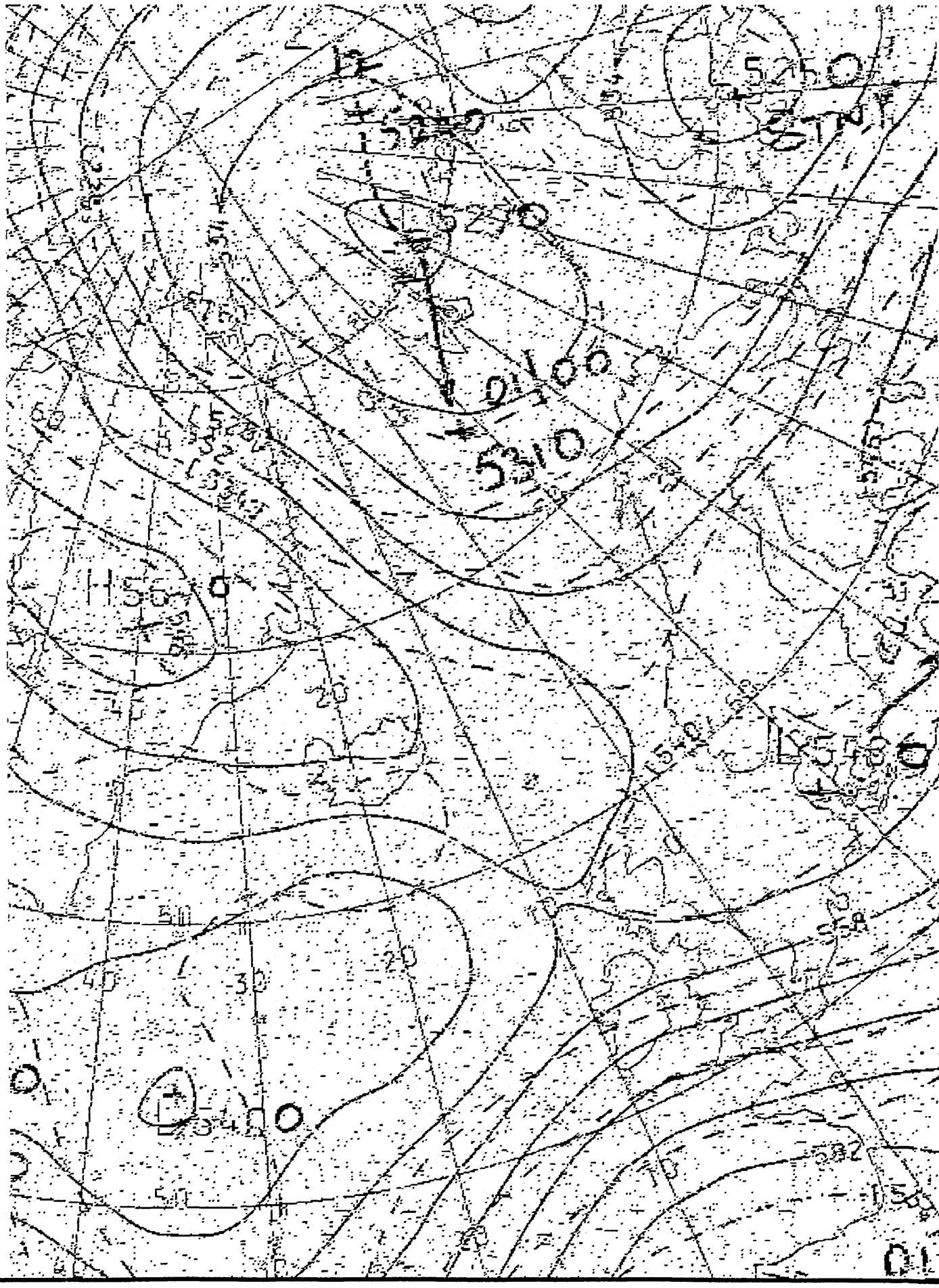
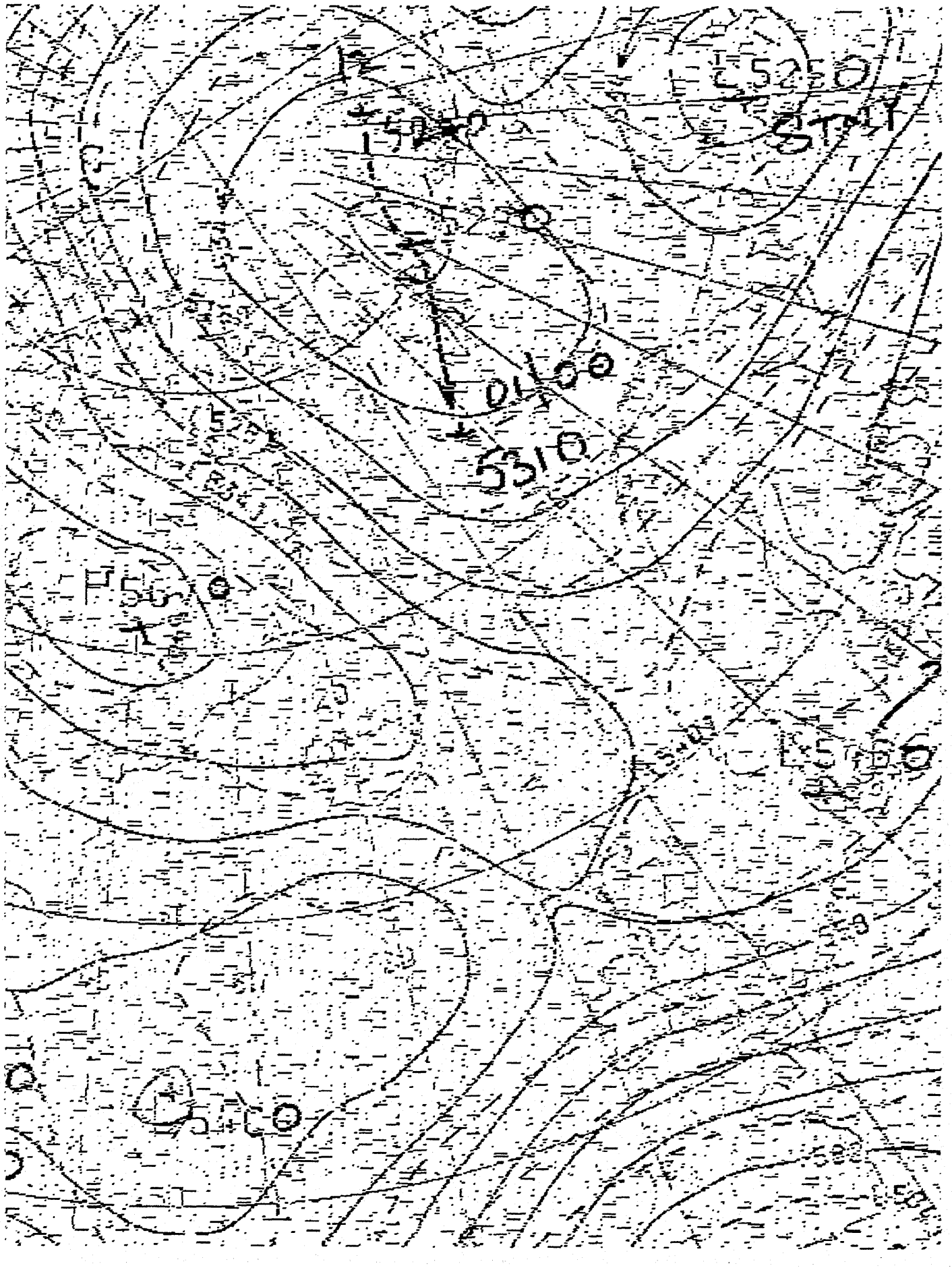
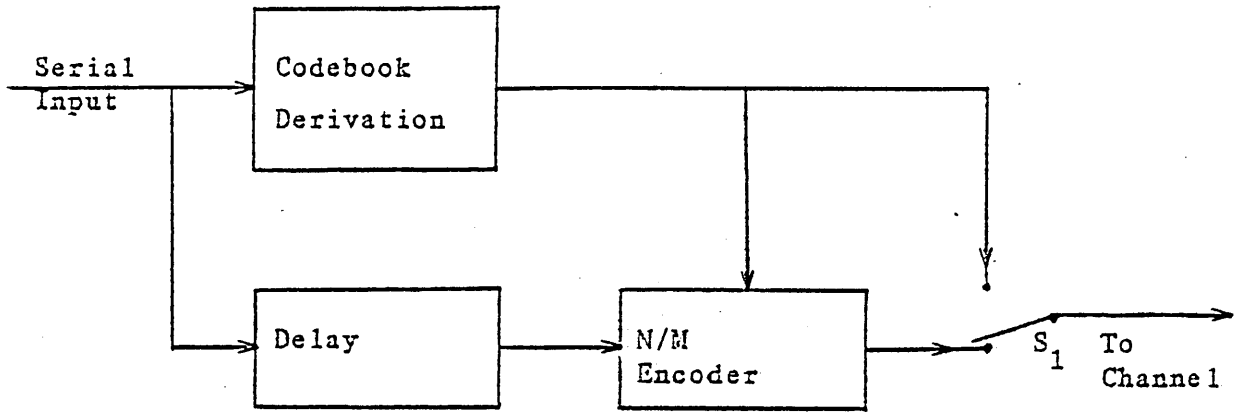
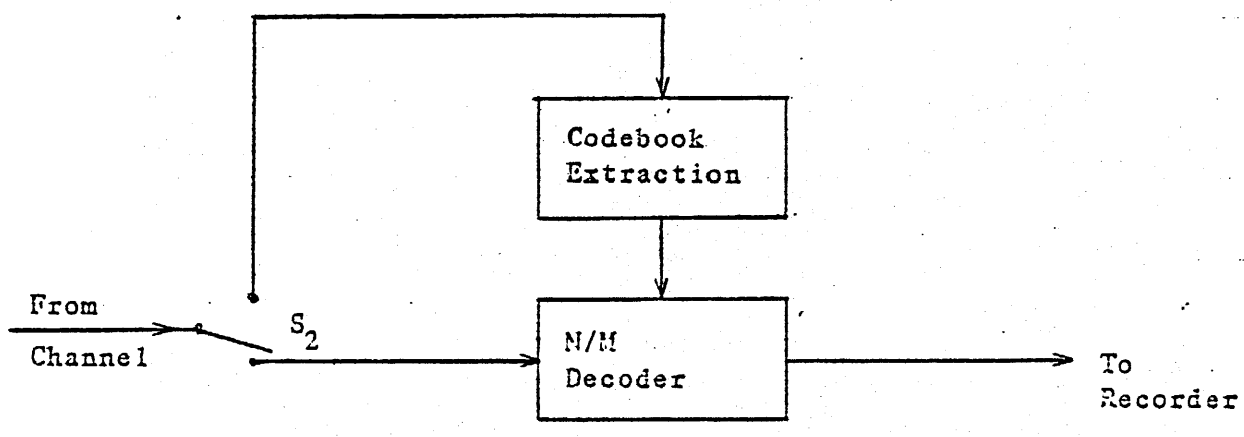


Fig.4.68. Data A5b, 8/5 Coded Using Fixed Codebook,
Exposed to 1 in 32 Random Errors.





(a) Encoder



(b) Decoder

Fig.4.69. System Block Diagram of Universal N/M Compression System.

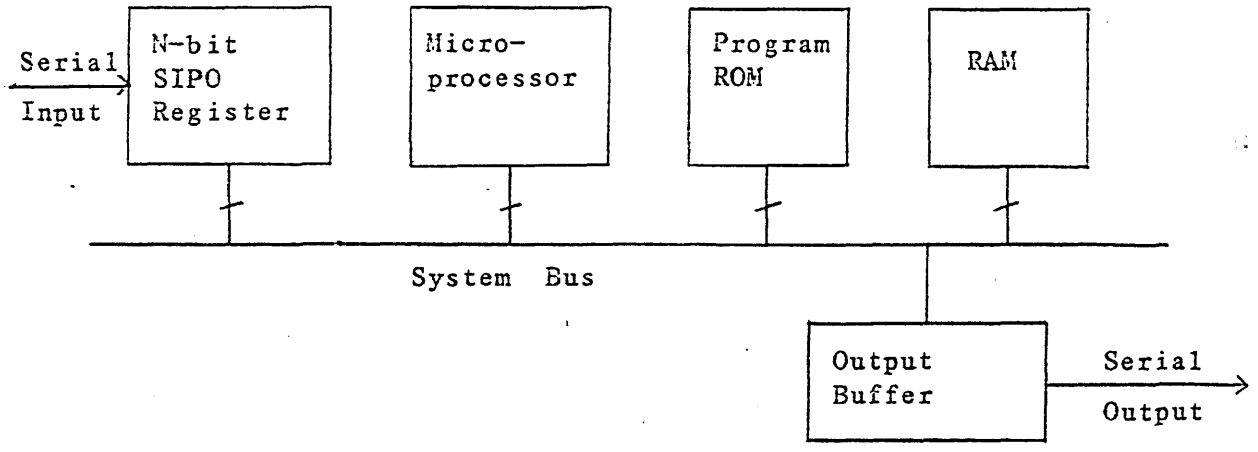


Fig.4.70. Microprocessor Implementation of Universal N/M Encoder.

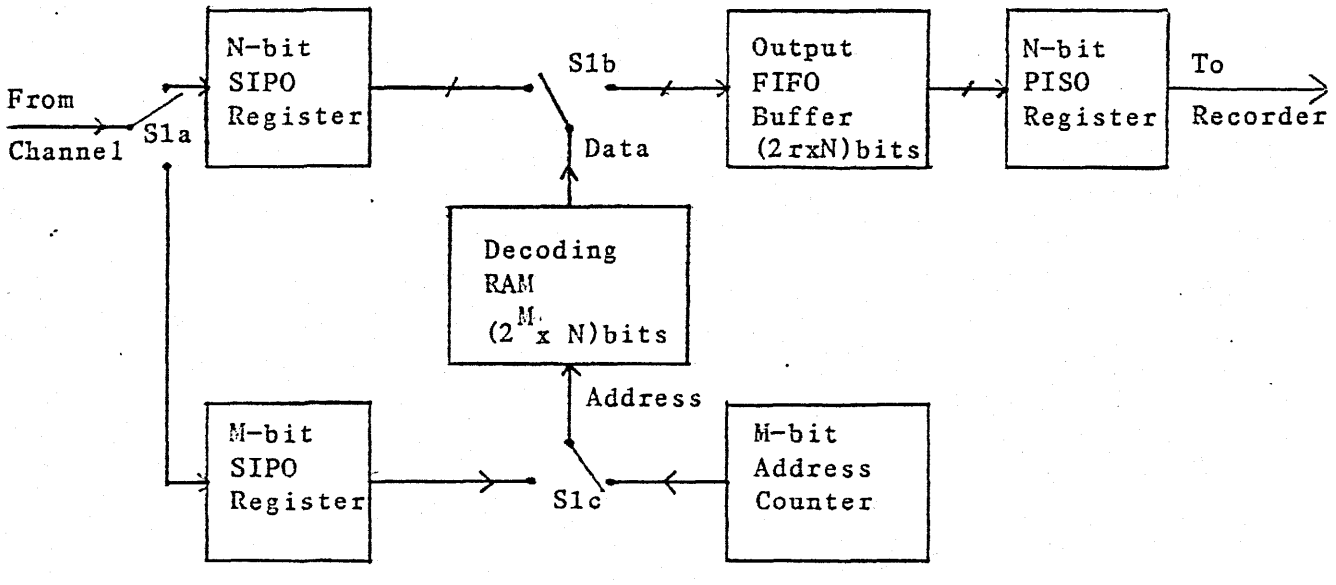


Fig.4.71. Instrumentation of Universal N/M Decoder.

No.	Decimal Value	Binary Pattern
1	0	00000000
2	1	00000001
3	128	10000000
4	192	11000000
5	255	11111111
6	3	00000011
7	224	11100000
8	7	00000111
9	24	00011000
10	15	00001111
11	240	11110000
12	12	00001100
13	48	00110000
14	96	01100000
15	6	00000110
16	56	00111000
17	28	00011100
18	112	01110000
19	248	11111000
20	31	00011111
21	14	00001110
22	63	00111111
23	252	11111100
24	254	11111110
25	127	01111111
26	60	00111100
27	32	00100000
28	120	01111000
29	30	00011110
30	64	01000000
31	8	00001000
32	2	00000010
33	4	00000100
34	16	00001000
35	195	11000011
36	193	11000001
37	131	10000011
38	62	00111110
39	124	01111100
40	227	11100011
41	135	10000111
42	199	11000111
43	225	11100001
44	129	10000001
45	126	01111110

46	142	10001110
47	231	11100111
48	97	01100001
49	113	01110001
50	140	10001100
51	241	11110001
52	143	10001111
53	49	00110001
54	198	11000110
55	99	01100011
56	134	10000110
57	156	10011100
58	243	11110011
59	207	11001111
60	206	11001110
61	115	01110011
62	57	00111001
63	159	10011111
64	25	00011001

Fig.4.72. The 64 Most Common Patterns for 8-pel Blocks, of the Test Images.

Fig.4.73. Data A5, Universal 8/4 Compression, Segment Size = 1 line, 8 Entries Predetermined. (CR=1.80).

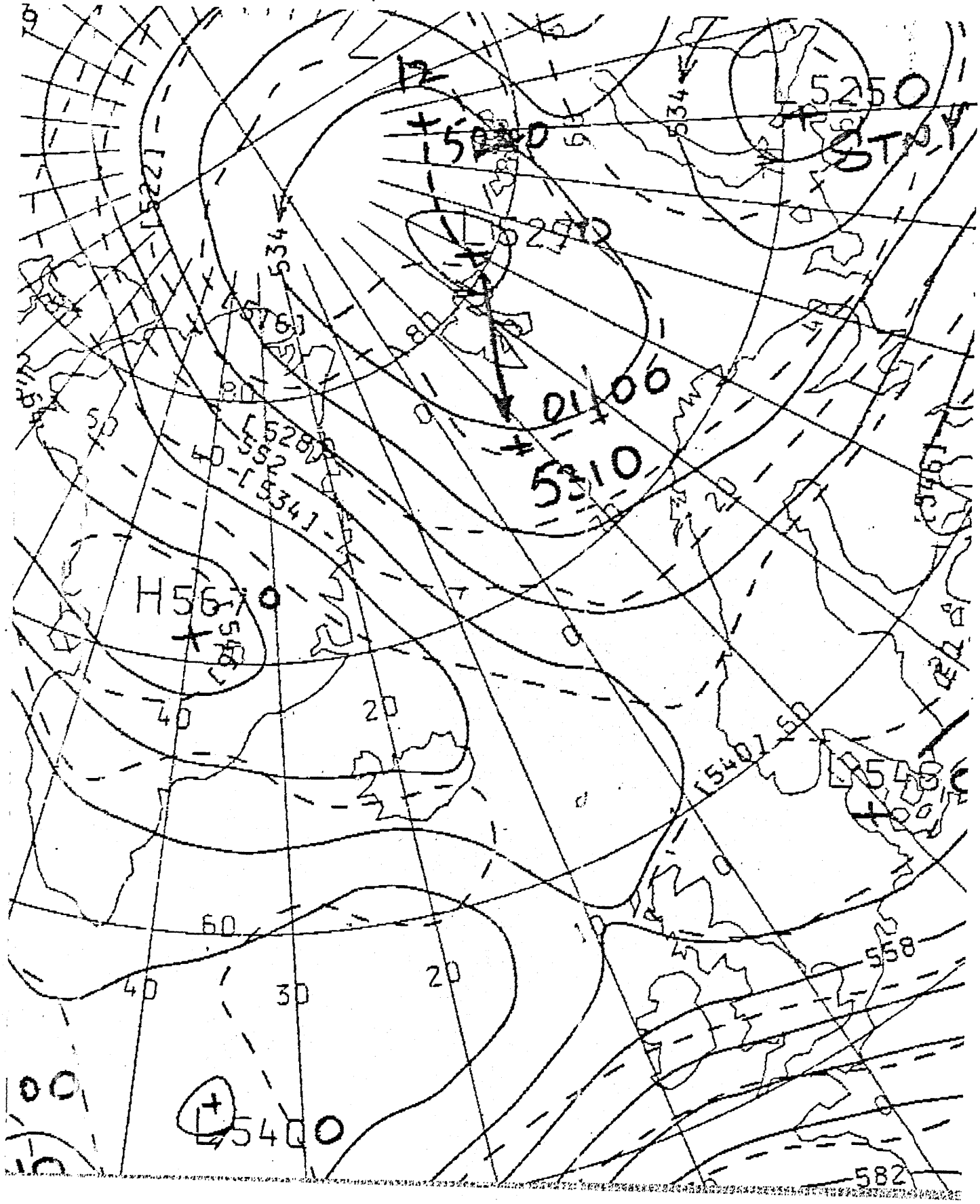


Fig.4.74. Data A5, Universal 8/4 Compression, Segment Size = 2 lines, 8 Entries Predetermined. (CR=1.89).

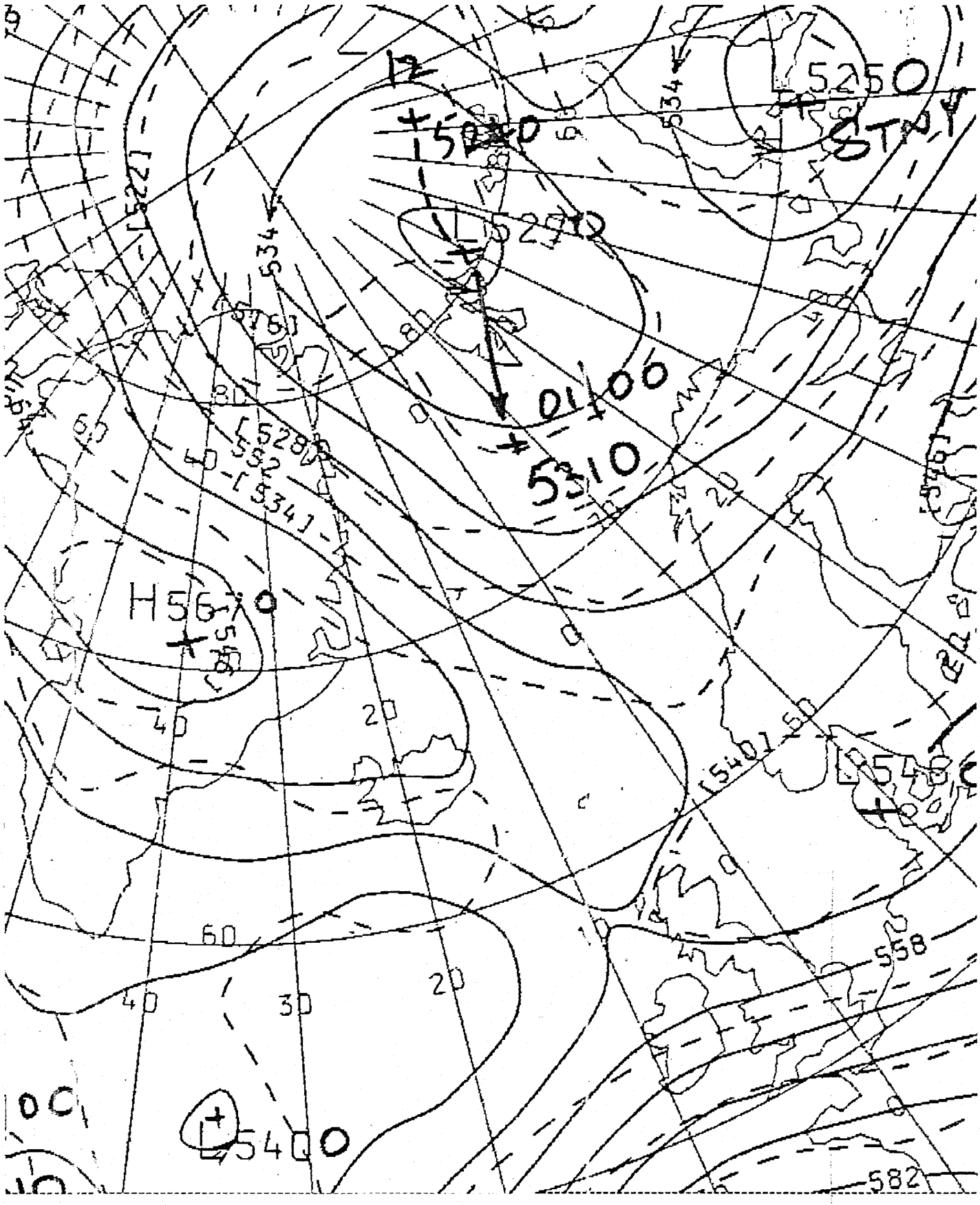


Fig.4.75. Data A5b, Universal 8/4 Compression, Segment Size = 1 line, 8 Entries Predetermined. (CR=1.63).

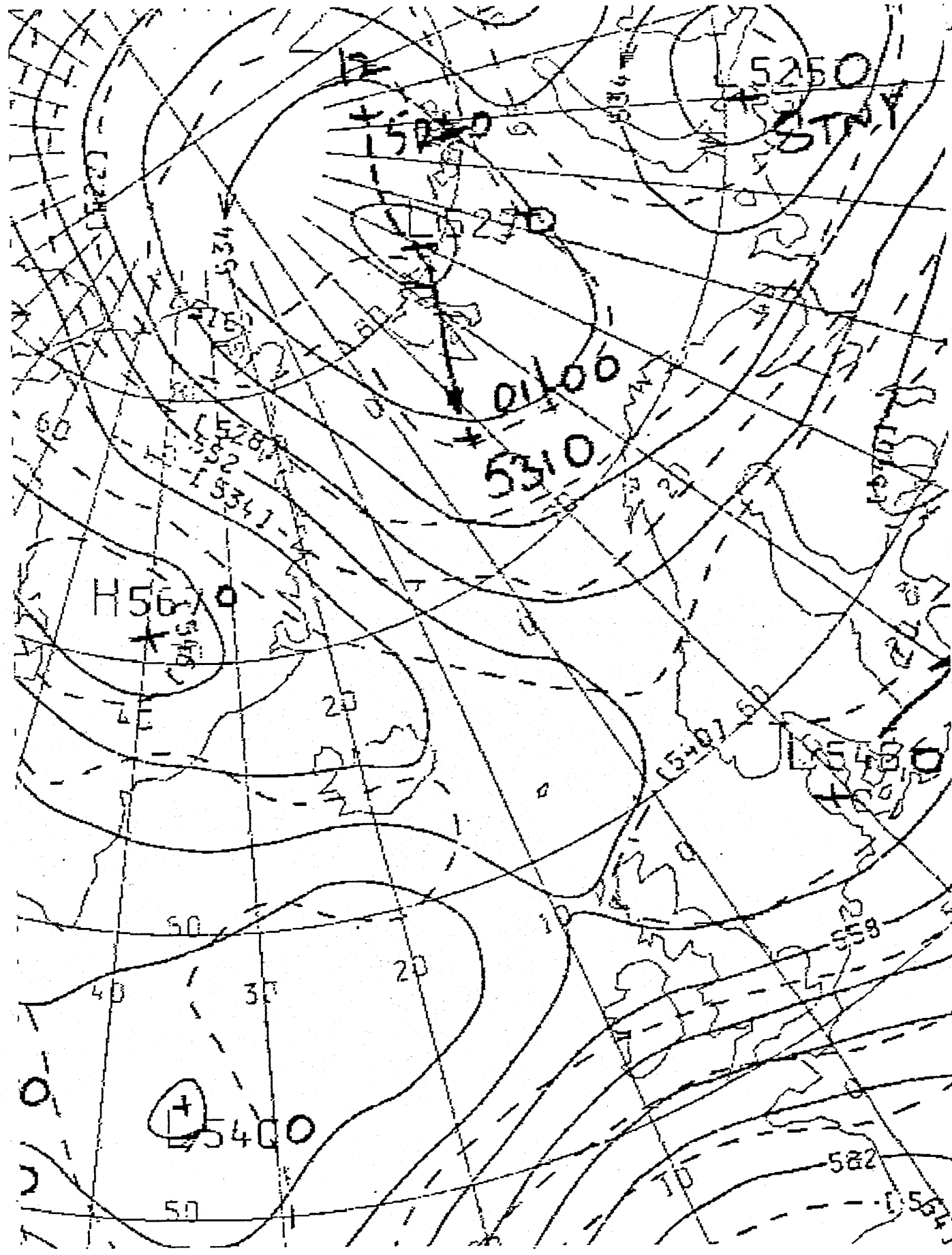


Fig.4.76. Data A5b, Universal 8/5 Compression, Segment Size = 2 lines, 16 Entries Predetermined. (CR=1.35).

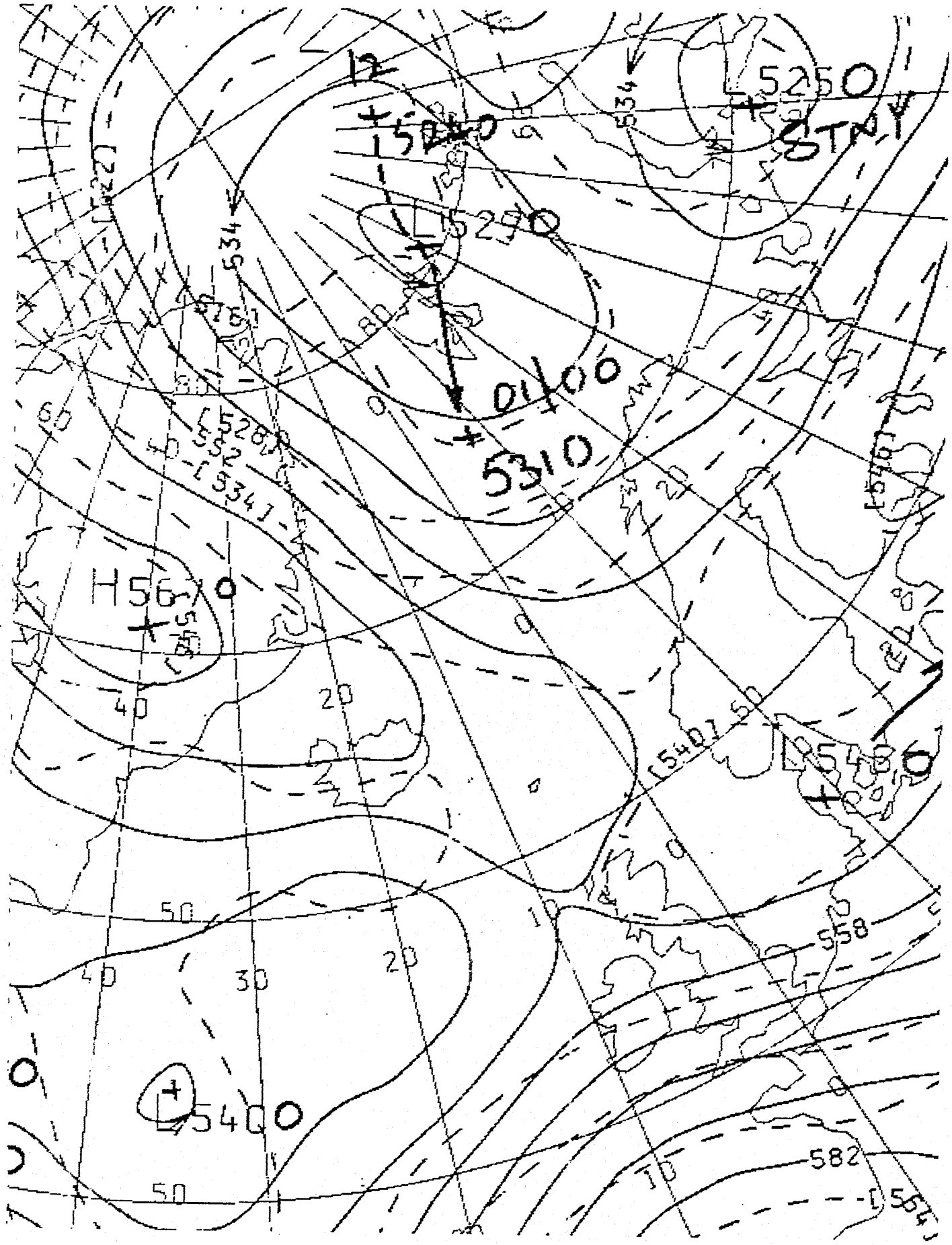


Fig.4,77. Data A5b, Universal 8/5 Compression, Segment Size = 6 lines, 16 Entries Predetermined. (CR=1.51).

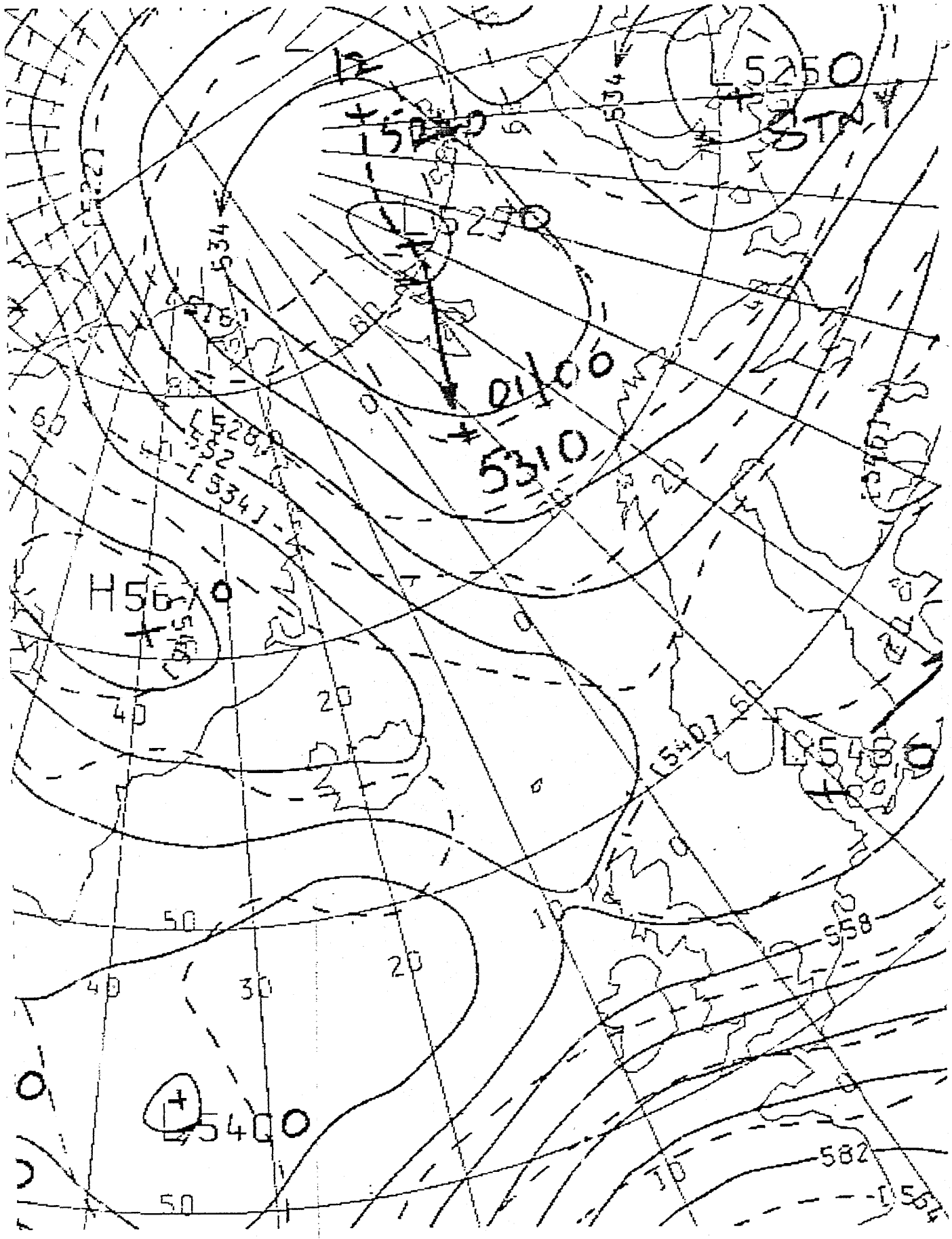


Fig.4.78. Data A2a, Universal 8/5 Compression, Segment Size = 2 lines, 8 Entries Predetermined. (CR=1.37).

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably fuller employment — depend on this. They show that higher exports and import substitution go together — the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

Fig.4.79. Data A2a, Universal 8/5 Compression, Segment Size = 2 lines, 16 Entries Predetermined. (CR=1.44).

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Fig.4.80. Data A2a, Universal 8/5 Compression, Segment Size = 4 lines, 8 Entries Predetermined. (CR=1.47).

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CHAPTER 5

SEQUENTIAL BLOCK INTERLEAVE CODING (SBIC)

5.1 The Sequential Block Interleave Coding (SBIC) Method

In a typical black-white image the large dominance of white is apparent. If by some means the black element content can be rearranged to occupy the white spaces the total number of transmitted elements may be reduced. In this chapter a new method of compression is proposed which encodes blocks of image pels and effectively interleaves non-white blocks into the white background. A distinguishing feature of the method is the utilisation of states of pairs of blocks with the coding operation dependent on the particular block-pair state. For each pair of blocks a codeword of fixed length is transmitted thereby achieving a fixed rate of output. This method is therefore directly compatible with constant-rate scanners and synchronous transmission over digital channels.

In the proposed method the image output is encoded on a segment basis where each segment consists of a fixed number of blocks. This segment is called the coding field. Within the coding field the blocks of image are examined in pairs and four states may be defined according to the presence of all-white block states in the pair. These are:

i) Double-White (DW) in which both left and right blocks of the block-pair are all-white.

ii) Left-White (LW) in which the left block only of the block-pair is

all-white. The right block is nonwhite, i.e. it contains one or more black elements.

iii) Right-White (RW) in which the right block only of the block-pair is all-white. The left block is therefore non-white.

iv) Double-Nonwhite (DNW) in which both blocks are nonwhite.

The coding procedure consists of two stages. The first stage involves a scan of the block-pairs of the coding field for the presence of the DNW (Double-Nonwhite) states. The scan proceeds from the leftmost to rightmost block-pair of the field. When a DNW block-pair is detected, its right nonwhite block pattern is fed into a first-in first-out (FIFO) buffer. When the scan is completed the encoding stage commences. Here the block-pairs of the field are encoded beginning from the leftmost block-pair. For each block-pair a two-bit header word is assigned which identifies one of the four states of the block-pair. This header is followed by an N-bit block pattern if the block is assumed to consist of N pels. The block pattern is dependent on the state of the block-pair. If the block-pair exhibits a LW (Left-White) or RW (Right-White) state, the block pattern is the nonwhite block of the pair. If the state of the block-pair is DNW (Double-Nonwhite), the left nonwhite block pattern is chosen. Finally if the state of the current block-pair is all-white (DW), the transmitted block pattern is taken from the FIFO buffer. If the FIFO buffer is empty an all-white pattern is transmitted. Thus in this way right nonwhite members of DNW block-pairs in the field are slotted into the output spaces of DW block-pairs. At the receiver a reverse two-stage process is implemented. First the input header words are examined for a DW state. When this occurs the adjoining N-bit pattern is fed into a FIFO buffer. At the end of the scan for a field, decoding proper commences when the block-pair patterns are reconstructed from the header word and its

adjoined N-bit pattern. For a DNW block-pair the right nonwhite member is taken from the FIFO buffer. Because these patterns have been originally transmitted in the order in which they occured in the field, their reinstatement is similarly effected on a sequential basis. In view of the interleaving nature of the compression technique, performed in a sequential manner, the method has been designated Sequential Block Interleave Coding (SBIC). Fig.5.1 shows the block diagram of this compression system. In the encoder the auxiliary FIFO store holds the right nonwhite members of DNW block-pairs in the field. The main store implements the field delay. At the end of a field the FIFO contents are inserted into the output via S2 when DW patterns occur. For each block-pair the header and block pattern are adjoined and released serially into the transmission channel. At the receiver the header and block pattern components of the codeword are separated and for DW states the block pattern is pushed into the FIFO buffer. At the end of a field the contents of the latter are reinserted into the DNW block-pairs as identified by the delayed header words, and the reconstructed block-pair is fed serially to the recording unit.

Two difficulties quickly become evident in the above SBIC scheme. The first problem occurs when the total number of double-nonwhite block-pairs exceeds the total double-white block-pairs in the field i.e. the contents of the FIFO buffer are not all transmitted at the end of the field. When this happens the field is said to be in a state of overflow and the simplest strategy is one of non-action i.e. the excess blocks are not transmitted resulting in their being substituted by the all-white pattern at the receiver. This process is referred to as blanking, or deletion, of excess or 'surplus' nonwhite blocks. The consequent loss of black elements is treated as an encoding distortion which may be minimised by a selective procedure described later. The second difficulty has to do with the

excessive occurence of all-black block-pairs which can occur in regions of horizontal black lines of the image leading to a large number of surplus blocks in the coding field. The effect of blanking will give rise to visible breaks in the reinstated lines which is clearly unacceptable. The problem may be overcome by introducing a fifth state to the total possible states of the block-pair, which is the double-black (DB) state where all elements in both blocks are black. Instead of increasing the size of the header word to identify this additional state use is made of the fact that in the original four-state arrangement three combinations of header and appended block patterns will never occur. Assuming a header bit of 0 and 1 denotes a white and nonwhite block respectively the headers 00, 01, 10, 11 may be used to represent the DW, RW, LW , DNW states respectively. Then the following combinations of header and adjoined block patterns will never occur:

a) Header word 01 followed by block pattern of all 0's

b) Header word 10 followed by block pattern of all 0's

c) Header word 11 followed by block pattern of all 0's

One of these may be used to identify an all-black block-pair state thus avoiding the need to extend the header word length.

For a block size of N pels the compression ratio is given by

$$CR = \frac{2N}{N+2} \qquad 5.1$$

$$= \frac{2}{1+\frac{2}{N}} \qquad 5.2$$

As $N \rightarrow \infty$, $CR \rightarrow 2$, i.e. the compression ratio tends to 2 when the block size grows to infinity. A plot of CR as a function of N is given in

Fig.5.2. From this it is apparent that there is little additional compression to be gained by increasing the block size N beyond about 8. The use of a larger block also has the disadvantage that a longer delay line is required for the same number of blocks in a coding field. A method for obtaining compression ratios greater than 2 is presented later in the chapter.

5.2 Implementation Considerations

A more detailed description of the SBIC compression system is now given. Fig.5.3 shows a block diagram for the SBIC encoder for a block size of N pels and a field size of F block pairs (2F blocks). The serial input data is clocked into two N-bit registers which have parallel outputs. The header logic circuitry detects the five states of the block-pair and controls the subsequent routing of the register contents to either the main storage buffer or the auxiliary FIFO buffer which stores the right nonwhite blocks of DNW blockpairs. A 2-bit header is also furnished which is stored in a shift register of capacity Fx2 bits. This arrangement is slightly different from that of Fig.5.2(a) where the main buffer stores block-pairs. Here the main store holds only one block of the block-pair thereby halving the storage capacity, but in order to direct which block of the pair to be stored it is necessary to determine the five states of the block-pair. Thus state identification is performed at the input end of the delay line and the header word is also delayed with the block patterns. After a field of blocks has been fed in, the output from the header store is used to route the outputs of the buffers to the multiplexer which transmits a block following a 2-bit header word. The encoding process is therefore quite straightforward requiring only shift registers, buffer stores and logic

circuitry.

The block diagram of the decoding operation is shown in Fig.5.4. The header words are separated from block patterns by the demultiplexer. Where a DW header is prefixed the block pattern is stored in the auxiliary FIFO buffer instead of the main buffer. At the end of a field the contents of the main buffers are accessed according to the header states and the block-pairs are reconstructed in the two N-bit registers. When ready the contents of the registers are clocked out in a serial manner.

In a practical implementation it is necessary to design for continuity of data flow. A major advantage of the SBIC compression method is the fixed relationship between the output and data clock rates, greatly easing timing and buffering considerations. Fig.5.5 shows a hardware realisation of the SBIC encoder. The all-black block-pair is indicated by a header state followed by a block pattern of N zeros. At the start of operation the registers are cleared and the first 2N bits of the data are clocked into the two input registers at the input bit rate f_i. Then the states of the two blocks are determined by the logic gates G1-G3. G1 and G3 produce a low output only when its N inputs are all white and the NAND gate gives a high output only when its 2N input lines are all black. The outputs of the gates are sampled at the end of each block-pair by the three one-bit latches. The switch positions S1 and S2 are selected by the header word state appearing at the latch outputs. The next 2N pulses of the input clock push out the current block-pair and clocks in the next pair of blocks. In the first half of these pulses the main and auxiliary FIFO buffers are enabled to clock in the emerging data from the shift registers. Two FIFO buffers are deployed which alternate between successive fields. After F block-pairs have been input the header and block pattern(s) are

available at the output ends of the stores. The 2-bit header is first output from the serial-out register. During this time the block pattern in the main store is being shifted into the output FIFO buffer at the input rate f_i. The function of the latter buffer is to enable readout of the stored blocks at the output rate f_o. After the header bits have been transmitted, at the output rate f_o, the block pattern of the codeword is clocked out either from the output buffer or the auxiliary buffer depending on the state of the header. When the auxiliary buffer is empty its output is maintained at a low level so that the transmitted block pattern is all-white. The codeword for the all-black(DB) pattern has been determined at the input end when a high level at the latched output of G2 cancels the high output of G1 by clearing its latch thereby generating the header state 01, and at the same time the left input register is cleared so that an all-white pattern is clocked into the main storage buffer.

The decoding hardware shown in Fig.5.6 is quite similar to that of the encoder. The serial input codeword is separated by the switch S1 into its header and block pattern components. The individual bits of the header are obtained at the output of the 2-bit serial-in parallel-out register and are used to direct the serial block pattern into either the main storage buffer or the auxiliary FIFO buffer. As at the encoder two FIFO buffers are employed to ensure no 'bunching up' of right nonwhite patterns from adjacent fields. The input clock to these buffers and the main store is derived from the line bit rate, f_i. At the end of a coded field the block patterns and 2-bit header are available at the outputs of the buffer stores. The output of the main store is routed by the header state to either the left or right register whilst for each DNW state a block pattern is accessed from the FIFO buffer and clocked into the right register. At the start of each block-pair the two registers are of course cleared. The

gate G4 detects the double-black pattern and its latched output forces a black level via the gate G5. The reconstructed block-pair is latched into a parallel-to-serial register which outputs the decoded data serially to the recording unit.

From the above implementation it is evident that the SBIC compression system may be realised at little cost of hardware. The serial means of storage employed in the described encoding and decoding schemes reduces component cost and wiring complexity. The speed at which the system can operate depends only on the speed of logic of the handful of logic gates, switches and serial storage elements, thus making it suitable for use in very high-speed facsimile systems e.g. newspaper facsimile systems. The fixed-rate nature of the coder output avoids large unwieldy smoothing buffers or start-stop drives which are difficult to control with precision especially with the larger high-speed scanners.

5.3 Application of SBIC to Test Images

The results of computer simulation of the SBIC method of compression applied to the test images are presented in this section. In order to examine clearly the effect of resolution a further two images are introduced which are the two images A4 and A6 sampled at the lower resolution of 100 and 125 pels/inch respectively. These will be labelled A4b and A6b. Three measures of performance are employed in the study. These are the percentage, P_F, of fields in the image which have overflowed, the percentage, P_B, of blocks in the image which have been blanked as a result of field overflow, and the percentage, P_L, of lost black elements resulting from blanking. A block size of 8 pels is used throughout the simulation which is a good choice in terms of compression yield,

convenience of implementation and simulation. The compression ratio is therefore fixed at 1.60 which corresponds to a 37% reduction of image transmission time.

The measured probabilities of the block-pair states for the test images are shown in Table 5.1. As expected the business letter A1 has the largest number of double-white patterns (88% of all block-pair patterns). The dense packing of the typed material in A2 restricts its percentage of DW states to 61%. The weathermap A5b which is sampled at 75 pels/inch has the smallest number of DW block-pairs at 43%. This compares with 59% for the same image sampled at 150 pels/inch. Tables 5.2 to 5.4 show the results obtained for the test images with various values of the coding field size F. It is clear that overflow-free, or information-lossless coding, is obtainable for all the test images when the field size is sufficiently large (4096 block-pairs). For all the images sampled at 150 pels/inch a field size of 2048 block-pairs is adequate for distortionless coding. As may be expected, structured images like A1 and A2 required considerably larger coding fields before zero distortion is achieved, than was the case with more homogeneous image material as in A5. This is due to the necessity for inclusion of the white spaces between lines of characters to ensure enough numbers of double-white block-pairs in the coding field. Inter-word and inter-letter white spaces are obviously by themselves unable to furnish enough double-white pairs of blocks to convey the abundant right blocks of double-nonwhite block-pairs in the field. The required field size for error-free coding therefore is dependent on the height of characters. With the densely-typed image of A2 distortionless coding was achieved at a field size of 2048 block-pairs which necessitates a storage of 36 scan-lines. This corresponds to 0.36 inch of the vertical axis which is 3.6 times the average character

height of 0.1 inch. The image A1 which contains smaller characters attained lossless coding at a field size of 1024 block-pairs. The more homogeneous images of A3 and A5 required even lower field sizes (256 and 64 block-pairs respectively). The excellent result for A5 indicated that better performance may be expected when the image is slightly oversampled. For the images A4b and A6b the effect of lower resolutions did not result in a larger coding field for error-free coding than their higher resolution versions but it has to be noted that the physical area covered by a fixed size of field is greater at the lower resolution so that a wider section of image is available for contribution of double-white block-pairs. Finally the low-resolution weathermap A5b was found to demand the largest of all field sizes, 4096 block-pairs, in order to give deletion-free performance. This corresponded to about 1.1 inches of the vertical axis of the image. This image is generally difficult to compress which might be expected from its relatively high entropy value of 0.36 (see Table 3.1).

The subjective effects of blanking of blocks in overflowed fields may be examined in Figs.5.7 to 5.12 for selected values of field sizes. The deletion of excess non-white blocks of DNW block-pairs which occur last in the field gives rise to a clustering of the distortion to the right end of the field. For the image A2 shown in Fig.5.8 the percentage of blocks deleted is 5% and the loss of black elements is 2.3%. It is evident, especially from this figure that the intelligibility of characters is mainly unaffected by this kind of distortion. This is due to the fact that in the event of blanking, double-nonwhite pairs will always have only its right block deleted with the left block intact and for a series of such double nonwhite block-pairs in an active region, left nonwhite blocks remain which are sufficient to preserve the form and legibility of characters if the block size is not very large. Thus even in the worst

situation when all the DNW block-pairs in the field have their right blocks deleted intelligibilty will largely be preserved due to retention of left nonwhite blocks. Generally the loss of blocks is quite visible even though the percentage of such losses over the total number of blocks in the image may be very small. The human eye appears to be quite sensitive to loss of black elements in the image.

5.4 Selective Deletion of Blocks in Overflowed Fields

The action of deleting the right blocks of excess double-nonwhite pairs in overflowed fields results in distortion which is polarised to the right end of the field and although it does not destroy the intelligibility of image material it is starkly visible. Instead of simply blanking the blocks of last-occuring double-nonwhite pairs an alternative strategy is proposed in which the blocks to be deleted are selected from a pool of prospective blocks in the field based on a suitable criterion. The optimum and fortunately simple basis for selection is the set of blocks which result in minimum distortion i.e. least black element loss. To this end, assuming U blocks are required to be deleted, the U blocks having the least black elements are selected for deletion. For this purpose the black element count, or Hamming weight W_i, of each candidate block is ascertained and the blocks corresponding to the U least values are deleted. Apart from minimising the black element loss the choice of blocks allows a more uniform distribution of deleted blocks over the coding field instead of the clustered nature featured in the straight deletion strategy. This will hopefully produce a subjectively greater masking effect on deleted blocks.

The detailed procedure for obtaining the blocks to be deleted is as follows. For each double-nonwhite block-pair in an overflowed field the

constituent blocks are examined and the Hamming weights obtained for both blocks. The lower Hamming weight values and its address identification is placed in a 'pool'. The operation is repeated for all double-nonwhite pairs in the field. When this is completed the U least values of Hamming weights and their address identifications are found after an ascending order sort of the pool contents (U, the number of blocks blanked, is equal to the difference betwen total double-nonwhite and double-white block-pairs in the field). The sorting algorithms described in section 4.3 may be used here except that an ascending-order sort (with association) is performed instead of a descending-order sort. This is readily achieved by comparing for less than instead of greater than, in each of the compare operations undertaken. The block-pairs whose contributions to the pool are the U least values selected are identified and the blocks deleted. The assignment of codewords to all block-pairs in the field can now proceed. Note that unlike the original strategy where only the right blocks of double-nonwhite pairs may be deleted, here either right or left block may be deleted here. This choice is designed to reduce the loss of black elements further, as now only the block with the lower Hamming weight of the double-nonwhite block-pair may be deleted.

The selection of blocks for deletion as described above was implemented on the computer and the results of the simulation are shown in Table 5.5. Figures for the original straight deletion strategy are also shown for purposes of comparison and percentage decrease in distortion levels indicated. The percentage decrease observed ranges from 20% to 80% with larger decreases generally obtained at larger field sizes where distortion from straight deletion was low.

Figs.5.13 to 5.15 show the resultant images when selective deletion

was applied. For image A2 shown in Fig.5.13 the amount of black element loss is reduced by 41% compared to that in Fig.5.10 for straight deletion. The more uniform spread of the distortion is apparent but it is not certain if the subjective effect is better over that of Fig.5.10. For the weathermap of A5 shown in Fig.5.14 the consequence of selective deletion is to reduce the black element loss by 62% which makes it difficult to detect the distortion.

The physical realisation of the SBIC encoder with selective deletion is readily accomplished using a microprocessor. Most of the tasks of sorting and maneouvring of data blocks may be speedily executed by relatively low power microprocessors. A dedicated microprocessor implementation of the SBIC compression system has many advantages. By organising the data as bytes or computer words the coding procedure is easily effected using the computer's memory for storage and buffering. Much switching and logic circuitry may be avoided and flexibility of operation is achieved.

The implementation of the selective deletion process may be achieved at high speed using an alternative non-sorting technique which stores candidate blocks according to their Hamming weight i.e. each store holds blocks of the same Hamming weight. For each input DNW block-pair the nonwhite member with the lower Hamming weight is kept in the store of its Hamming weight value. At the end of a field of block-pairs the blocks with the least Hamming weight value i.e. 1, which are now immediately available, are deleted first followed by those having increasingly larger Hamming weight values i.e. 2, 3, 4....N. For a block size of N bits, N stores are needed to hold blocks or their address identifications and each store obviously needs to be able to hold the largest expected number of blocks in

the field with the same Hamming weight. A considerable saving of time otherwise used for sorting is achieved. This technique is suitable both for hardware implementation and software realisation.

5.5 Theoretical Performance of SBIC Scheme

It is useful to estimate the performance of the SBIC compression method from a statistical description of the source. In this section the probability that a field overflows as the field size F varies is calculated from a knowledge of the block statistics of the image source. Using the measured statistics from the set of test images the probabilities of overflow are computed and compared with the experimental results obtained from the simulation of the scheme.

5.5.1 Probability of Field Overflow for a Memoryless Block Source

In the following analysis the probability of overflow occuring in a coding field is determined as a function of the field size F. The image source is assumed to be an independent block source model in which the output can take on one of 2^N states where N is the number of pels in the block. This source is therefore characterised by the set of probabilities

$$P_i \quad , \quad 0 \leq i \leq 2^N - 1$$

where P_i is the probability of occurence of the binary pattern i and

$$\sum_{i=0}^{2^N-1} P_i = 1$$

When a pair of blocks is taken the probabilities of block-pair states are given by:

$$P(\text{Double-White}) = P_{DW} = P_0^2 \tag{5.3}$$

$$P(\text{Left-White}) = P_{LW} = P_0(1-P_0) \tag{5.4}$$

$$P(\text{Right-White}) = P_{RW} = (1-P_0)P_0 \tag{5.5}$$

$$P(\text{Double-Black}) = P_{DB} = P_{2^N-1}^2 \tag{5.6}$$

$$P(\text{Double-Nonwhite}) = P_{DNW} = (1-P_0)^2 - P_{2^N-1}^2 \tag{5.7}$$

and also

$$P_{DW} + P_{LW} + P_{RW} + P_{DB} + P_{DNW} = 1 \tag{5.8}$$

It is noted that the left-white and right-white states may include the all-black block pattern as its nonwhite block. The double-nonwhite state probability is given by the total probability of all nonwhite patterns, $(1-P_0)^2$, less the probability of the double-black block-pair state, $P_{2^N-1}^2$.

When F block-pairs are taken, if F is large the expected number of double-white(DW) states and double-nonwhite(DNW) states are $P_{DW}F$ and $P_{DNW}F$ respectively. Field overflow therefore occurs when $P_{DW}F < P_{DNW}F$ i.e. $P_{DW} < P_{DNW}$.

For finite F the probability of a field overflowing, P_F, can be obtained from the total probability of the field outcomes in which the total DW states is less than the total DNW states. The probability distribution of field outcomes is given by the multinomial distribution with the total number of state combinations equal to 5^F. To find the configurations for which overflow occurs the following conditions apply:

i) overflow can occur only when a DNW state is present in the field so that all field outcomes without a DNW state can be excluded

ii) overflow always occurs when the total DNW states exceeds half the field size ($\frac{F}{2}$ for even F, $\frac{F-1}{2}$ for odd F), irrespective of

the states of the other block-pairs in the field

iii) when y, the number of DNW states is less than or equal to $\frac{F}{2}$ or $\frac{F-1}{2}$ depending on even or odd F, overflow occurs only when y>x where x is the total DW states in the field

From the above considerations the overflowing field configurations are those in which the total DNW states, y, exceed INT($\frac{F}{2}$) where INT denotes the integer value, and those in which y is less than or equal to INT($\frac{F}{2}$) but greater than x, the total DW states. The total probability of these outcomes is therefore given by

$$P_F = P(y=F) + P(y=F-1) + P(y=F-2) \ldots\ldots + P(y=\tfrac{F}{2}+1) + P(y=1,x=0) + P(y=2,x<2) + P(y=3,x<3)\ldots\ldots + P(y=\tfrac{F}{2},x<\tfrac{F}{2}) \quad 5.9$$

stated here for F even.

Each of the probabilities P(y=a) where $\frac{F}{2} + 1 \leq a \leq F$, can be evaluated using the binomial theorem as

$$P(y=a) = {}^{F}C_{a}(P_{DNW})^{a}\ (1 - P_{DNW})^{(F-a)} \quad 5.10$$

Each of the remaining probabilities P(y=a,x<a) , a=1 to $\frac{F}{2}$ may be evaluated as

$$P(y=a,x<a) = P(y=a,x=0) + P(y=a,x=1)\ldots\ldots + P(y=a,x=a-1)$$

$$= \sum_{i=0}^{a-1} P(y=a,x=i) \quad 5.11$$

Each summation term can be evaluated using the trinomial distribution giving

$$P(y=a,x=i) = \frac{F!}{a!i!(F-a-i)!} (P_{DNW})^a (P_{DW})^i (1 - P_{DNW} - P_{DW})^{(F-a-i)} \qquad 5.12$$

so that Eqn.5.11 becomes

$$P(x=a,x<a) = \sum_{i=0}^{a-1} \frac{F!}{a!i!(F-a-i)!} (P_{DNW})^a (P_{DW})^i (1 - P_{DNW} - P_{DW})^{(F-a-i)} \qquad 5.13$$

Using these relations,

$$P_F = \sum_{y=\frac{F}{2}+1}^{F} {}^{F}C_y (P_{DNW})^y (1 - P_{DNW})^{(F-y)}$$

$$+ \sum_{y=1}^{\frac{F}{2}} \sum_{i=0}^{y-1} \frac{F!}{y!i!(F-y-i)!} (P_{DNW})^y (P_{DW})^i (1 - P_{DNW} - P_{DW})^{(F-y-i)} \qquad 5.14$$

for F even. For odd F, $\frac{F}{2}$ is replaced by $\frac{F-1}{2}$.

By substituting Eqns.5.3, 5.7 into 5.14 the probability of overflow may be calculated from a knowledge of only the two probabilities P_0 and P_{2^N-1} which are of the N-bit white and all-black patterns respectively.

In general for real images the all-black block probability P_{2^N-1} is very small. Then the probability P_{DNW} may be approximated by $(1 - P_0)^2$. In this case

$$P_F = \sum_{y=\frac{F}{2}+1}^{F} {}^{F}C_y (1-P_0)^{2y} \left(2P_0 - P_0^2 \right)^{(F-y)}$$

$$+ \sum_{y=1}^{\frac{F}{2}} \sum_{i=0}^{y-1} \frac{F!}{y!\,i!\,(F-y-i)!} (1-P_0)^{2y} (P_0)^{2i} \left(2P_0 - 2P_0^2 \right)^{(F-y-i)} \qquad 5.15$$

The rightmost term can be factorised to give

$$P_F = \sum_{y=\frac{F}{2}+1}^{F} {}^{F}C_y (1-P_0)^{2y} \left(2P_0 - P_0^2 \right)^{(F-y)}$$

$$+ \sum_{y=1}^{\frac{F}{2}} \sum_{i=0}^{y-1} \frac{F!}{y!\,i!\,(F-y-i)!} (1-P_0)^{(F+y-i)} (P_0)^{(F-y+i)}\, 2^{(F-y-i)} \qquad 5.16$$

A plot of P_F against F for various values of P_0 is shown in Fig.5.16. A table of values is also given in Table 5.6 for a selection of field sizes. When the all-white block probability is 0.9 a field size of 16 block-pairs is adequate to yield a probability of overflow which is negligible (0.128×10^{-8} or 1 in 8×10^8 fields). In a practical coding scheme a target of 10^{-6} for the value of P_F is sufficiently small to almost ensure lossless encoding (the number of fields in an image depends on the field size, block size, scanning resolution, etc. For the test images the number of block-pairs do not exceed 10^5 so that if the field size is 10 or more block-pairs the total fields per image is no greater than 10^4. A target of 10^{-6} for the value of P_F is intuitively reasonable for prediction of deletion-free coding). From Fig.5.16 field sizes at which P_F becomes less

than 10^{-6} may be observed. These are listed in Table 5.7. When the white block probability is 0.9 a field size of only 10 block-pairs is sufficient to reach this value 10^{-6}. As P_0 reduces to 0.8 the field size increases to 24 and further to 64 when P_0 is 0.7. At P_0= 0.6 the field size is outside the range of 160 block-pairs capable of being simulated by the computer. For P_0= 0.5 it is seen that no distinct decrease of P_F occurs for increasing field size. At this value of P_0 the double-white and double-nonwhite block-pair states become equiprobable (equal to 0.25) and overflow is also very likely to occur in the larger fields.

5.5.2 Application of Results to Test Images

Using the measured values of P_0 and P_{255}(all-black probability for 8-pel blocks) for the test images, shown in Table 5.8, the results for P_F as calculated from Eqn.5.12 are plotted in Fig.5.17 and tabulated in Table 5.9. Table 5.10 shows the values of F when the probability of field overflow becomes less than 10^{-6}. It is seen that for the worst case image of A5b a field size of 140 block-pairs is required to give this arbitrary level of overflow probability. At the other extreme the largely-white image of A1 required only 10 block-pairs to achieve this value of P_F. For the images sampled at 150 pels/inch the typed image A2 demanded the largest field size of 98 block-pairs to give an overflow probability of 10^{-6}. In a practical compression scheme the system must be designed to cater for the worst-case image. It is clear that for this set of test images error-free coding is likely to be obtained with field sizes in excess of 140 block-pairs.

A comparison between the calculated overflow probabilities and those obtained experimentally is given in Table 5.11. The field overflow

probability is measured as a percentage of overflowed fields over the total fields coded in the image normalised to unity. For field sizes above 16 the total number of fields in an image is too small to provide statistically accurate results. The disparity between theoretical and experimental figures is evident and reflects the deviation of the real image source from the stationary independent block model employed in the analysis. This is especially marked in the structured images of A1, A2 and A4 where the width of a field usually encompasses a section of the image which does not bear the statistics of the image as a whole. In order to alleviate this difficulty a scrambling of blocks may be performed before encoding which results in delay of a segment of the image. The size of the segment has to be significantly large in order for the scrambling to be effective. Details of this scheme are described in the following section.

5.6 Scrambled SBIC Compression

The theoretical results obtained in the previous section suggested that field sizes upward of about 140 block-pairs were likely to be adequate for deletion-free performance of all the test images. The results of simulation discussed in section 5.3 however showed much larger field sizes, for example 4096 block-pairs, are actually needed. In a practical implementation it is desirable to keep the field size as small as possible for two main reasons. The first is one of system cost and complexity. A larger field size demands increased amount of storage and additional hardware complexity as longer wordlengths, higher-capacity counters, etc. are required. The second and more important reason is the effect of transmission errors. In the event of a transmission error the effects of propagation are contained within a field so that a smaller field is

advantageous if corruption of image is not to be too severe. The simulation of the SBIC method in the presence of transmission errors is described later.

In order to reduce the field size requirement for lossless compression a pseudo-scrambling of blocks prior to coding is attempted. At the transmitter this is a pre-processing operation in which a section of image blocks is taken and the blocks mapped into a memory buffer which is then encoded using the SBIC technique. After decoding at the receiver a reverse mapping procedure is performed which restores the blocks to their original locations. The size of this memory store is equal to the scrambling segment size, S, and a delay of this section of blocks is introduced. For values of S which are a power of two the mapping source is readily realised from the parallel outputs of a shift register wired as a maximal-length sequence generator. This generates a pseudo-random set of integers in the range 1 to 2^n-1 where $n=\log_2 S$. The tapping points from this shift register (shown in Fig.5.18) are given in Fig.5.19 for values of n from 2 to 16. As the register is clocked each integer occurs once in a period of 2^n-1 integers after which the sequence is repeated. It may be more convenient to employ a ROM containing the pre-derived sequence especially in a microprocessor realisation of the coder. The descrambling process at the receiver is a reverse procedure, making use of the same set of integers to reinstate blocks in a buffer store. At the end of a de-mapping of S blocks the original sequence is available in the buffer store, after an incurred time delay of S blocks.

The choice of scrambling segment size S is mainly limited by the delay which is acceptable and cost of storage. Ideally the value of S is that of the total number of blocks in the image ie. storage of the entire image

but this is obviously not desirable in practice. A value of S which is too small will however be inadequate to smooth out local variations of block statistics from the average statistics of the image as a whole which is the objective. For structured images containing text it is unlikely that a value of S which physically covers only a few lines of image is sufficient and it is intuitively expected that the scrambling segment should span the white intervals between lines of text. The correct choice of S then is influenced by the height of the text characters.

The simulation of the scrambled SBIC scheme was carried out for various values of the scrambling block size S on the set of test images. The effect of scrambling on the block-pair statistics is shown in Table 5.12. The probabilities as calculated from the measured block probabilities P_0 and P_{255} for each image are given in the first column of results. The second column shows the actual measured block-pair state probabilities (obtained as percentages of occurence in the image). The disparity between these two columns of results reflect the deviation of the real image source from the memoryless block model. The difference between the measured and calculated values of the double-nonwhite probability, P_{DNW}, is significant in most of the images. For the set of images sampled at 150 pels/inch even the more homogeneous images like A3 and A5 show large differences in P_{DNW}. The image A5b has the closest set of probabilities to the calculated values.

The effect of scrambling dramatically narrows the deviations from the calculated probabilities. As the scrambling segment size increases the block-pair statistics approach those predicted from the independent block source. At the scrambling segment size of 8192 blocks the differences are small, especially for P_{DW}, P_{LW}, and P_{RW}. The convergence of P_{DNW} is more

gradual and appears to demand very large scrambling segment sizes which may be difficult to implement in practice. This is especially true of the structured images. The weathermaps A5, A5b and A6 exhibit very good correspondence with the calculated results.

The results of encoding the scrambled blocks of image data are presented in Tables 5.13 to 5.15. Selective deletion is employed where field overflow is encountered. Generally the use of larger scrambling segments enable smaller values of field sizes for lossless SBIC compression. At a scrambling block size of 1024 blocks, deletion- free operation is not possible for the range of field sizes up to 512 block-pairs for some images eg. A1 and A2. Increasing the value of S to 2048 blocks results in error-free coding of A1 for a value of F larger than or equal to 32 but A2, A6, A5b and A6b still suffered encoding distortion up to a field of 512 block-pairs. When the scrambling segment size was 4096 blocks only A5b experienced black element loss at a field size of 512 block-pairs. Zero distortion for this image is however achieved at the same field size when the scrambling segment size was increased to 8192 blocks. Fig.5.20 shows the result of pseudo-scrambling of 8-bit blocks of the image A2 with S=4096 blocks. Although generally well-randomised the separation between the heading and text in the original image was still present and the differing block statistics between the area of the heading and the text are clearly visible.

Comparing with the results given in Tables 5.2 to 5.5 for unscrambled SBIC, the decrease in field size required for distortionless coding is considerable. The worst-case image, weathermap A5b, now can be encoded without error at a field size of 512 block-pairs compared with 4096 block-pairs previously. The typed material of A1 and A2 does not suffer

deletion when field sizes of 32 and 128 block-pairs are employed (S=8192 blocks) respectively. This compares with 512 and 1024 block-pairs in the unscrambled case.

The subjective effects of distortion when block scrambling is applied may be examined in Figs.5.21 to 5.27. A scrambling segment size of 4096 blocks is employed which is a reasonable compromise between delay and scrambling effectiveness. The sensitivity of the human eye to the encoding distortion may also be ascertained from viewing of the images with reference to the percentage distortion levels given in Table 5.15. For image A1 the loss of black elements for a field size of 4 is only 0.05% but the distortion is easily detected in the reconstructed image shown in Fig.5.21. This distortion level compares with the 0.1% which is acceptable in the approximation of block patterns in block-to-block compression. When the field size is increased to 16 block-pairs the registered amount of distortion is 0.001% which is virtually undetectable in the reconstructed image of Fig.5.22. A range of field sizes is also displayed for the densely-typed image A2 in Figs.5.23 to 5.26 with levels of distortion from 0.7 % at F=4 to 0.03% at F=32. Here again the visibility of the encoding distortion is high in Fig.5.23 for F=4. At F=16 the amount of distortion of 0.12% is barely perceptible, and when F=32 the image is practically indistinguishable from its original. As a comparison the PRE for fixed 8/6 coding of this image is 0.15%. The result for the handwritten image A4 is shown in Fig.5.27 for F=4. The distortion level here is 0.06% and the black element loss can be detected on close scrutiny. For all the displayed images the intelligibility of the image content is unaffected by the encoding distortion. The acceptability of the distortion is therefore a matter of subjective preference. Commercial facsimile is unlikely to tolerate a level of distortion which is largely visible but in other

specialised applications for example weatherchart transmission, the gains in bit rate reduction and low cost of implementation may justify a small amount of black loss of some characters in the reproduced images.

5.7 SBIC Performance Based on a Memoryless Block-Pair Source Model

In the preceding discussion a block model was assumed for the facsimile source and an analysis was given of the expected performance of this source when pairs of blocks were encoded in the SBIC scheme. In order to homogenise the statistics for real images a scrambling of blocks was adopted which was found to be effective. It is just as feasible to have scrambled block-pairs instead of blocks prior to encoding. If scrambling is perfect and block-pairs are totally decorrelated the image source may be represented by an independent block-pair source characterised by the set of three probabilities P_{DW}, P_{DNW} and P_E where P_E is equal to $P_{LW} + P_{RW} + P_{BB}$ and the sum $P_{DW} + P_{DNW} + P_E$ equals unity.

From Eqn.5.14 the probability of field overflow of this trinary source is

$$P_F = \sum_{y=\frac{F}{2}+1}^{F} {}^{F}C_y (P_{DNW})^y \, (1 - P_{DNW})^{(F-y)}$$

$$+ \sum_{y=1}^{\frac{F}{2}} \sum_{i=0}^{y-1} \frac{F!}{y!\,i!\,(F-y-i)!} (P_{DNW})^y (P_{DW})^i (P_E)^{(F-y-i)} \qquad 5.17$$

for F even. For odd F, $\frac{F}{2}$ is replaced by $\frac{F-1}{2}$.

A table of values of P_F is given in Table 5.16 for various settings of P_{DNW} and P_{DW}. The selection of field sizes is again chosen to be powers of 2 as these are convenient for implementation. The most pronounced observation from the results is the sensitivity of the probability of overflow to the double-nonwhite probability P_{DNW}. For all the values of P_{DW} and P_{DNW} in the table the double-nonwhite block-pair probability is less than the double-white probability which means that for very large field sizes overflow-free performance is expected. However for the set of field sizes up to 128 block-pairs successful operation (ie deletion-free coding) is dependent on the relative smallness of the doule nonwhite probability. This is especially apparent for the lower values of P_{DW}. As an example when $P_{DW}= 0.5$ a value of P_{DNW} which is a quarter of P_{DW} ie 0.125, gives an adequately low level of P_F equal to 0.2×10^{-8} at a field size of 128 block-pairs, but when $P_{DW}= 0.1$ the value of P_F for $P_{DNW}= 0.025$ which is also a quarter of P_{DW} is much higher (0.4×10^{-2}) for the same field size. The observation here is that as the double-white probability drops the double-nonwhite probability must decrease quite rapidly in order to attain low levels of P_F. For larger values of P_{DW} (greater than 0.6) the value of P_{DNW} is naturally constrained to be small as $P_{DW}+ P_{DNW} < 1$ and very low values of P_F are easier to achieve.

Using measured values of P_{DW} and P_{DNW} for 8-bit blocks from the test images (given in Table 5.1) the probability of overflow is calculated for various F and the results are plotted in Fig.5.28. A table of values is given in Table 5.17. Comparing the figures in Table 5.17 with those of Table 5.11 higher probabilities of overflow are almost invariably obtained with usage of the block-pair probabilities rather than block probabilities.

Referring back to Table 5.12 the differences between block-pair probabilities calculated for an independent block model and the measured values may be studied. Although the measured double-white probability is higher than the calculated value for all the images the double-nonwhite probability is also consistently greater, which offsets the advantage of the increased double-white probability. Comparing the two plots of Figs.5.28 and 5.17 it is interesting that the image A2 is the most difficult to compress when the block-pair model is assumed whereas the image A5b was the case for the memoryless block source. This may be attributable to the large measured value of P_{DNW} found for A2. The order of difficulty in attaining error-free coding for the remaining test images is unaltered.

The results of scrambling segment-pairs of image prior to coding were examined for the test images A1, A2, A5 and A5b with the scrambling block-size set at 4096 blocks (2048 block-pairs). The resultant values of the percentage of deleted blocks are given in Table 5.18 and corresponding results for the scrambling of blocks (S=4096) are included for comparison. An increased number of deleted blocks is obtained for all the four images when scrambling is performed on block-pairs instead of blocks for a fixed length of delay line. For the structured images A1 and A2 larger differences are recorded and this may be partly due to the enhanced double-nonwhite probabilities of these sources. For the weathermaps A5 and A5b the differences are smaller which is in accord with the smaller differences between the measured block-pair statistics and those for the independent block model. These simulation results indicate that for 8-bit blocks an approach to SBIC compression based on encoding a block-pair source does not produce better results over those for an independent block source. An indication to the performance with larger blocks may be found

by comparing the measured block and block-pair statistics of the test images. Table 5.19 shows the relevant probabilities obtained for larger blocks with the images A2 and A5b. Consider the case when N=2x8=16 bits. For image A2 the value of P_0 of 0.6 suggests, from Table 5.6 that deletion-free coding is possible at some value of field size in excess of 160 block-pairs if the source was a memoryless block source. The corresponding result for a memoryless block-pair source with P_{DW}= 0.56 and P_{DNW}= 0.37, as interpolated from Table 5.16, is less encouraging and suggests a field size of much larger value for error-free coding. A similar outcome is predicted for the block size of 2x8 for image A5b. With larger block sizes the value of P_0 falls below 0.5 which is unsuitable for the coding system, whilst with the block-pair statistics the value of P_{DNW} rapidly catches up on P_{DW} and exceeds it making the encoding method unfeasible even with very large field sizes. However as a matter of interest if storage of the entire image is acceptable and a field size equal to the image area is utilised error-free coding is possible with larger block sizes for the block-pair source than for the block source as long as the value of P_{DNW} is less than or equal to P_{DW}. In this case scrambling is unnecessary. A possible application here is the reduction of storage capacity for the image.

5.8 Comparison with Block-to-block Compression

In the preceding sections it was shown that a compression ratio of 1.6 was obtainable for all the test images when pairs of 8-pel blocks were encoded using the SBIC method. This compares with 1.33 attainable by block-to-block compression using the 8/6 mode in the fixed-codebook scheme and 8/5 in the universal scheme although in the latter case a slightly

larger value may be obtained if image quality is not critical. The SBIC method has the advantage therefore of a 20% gain in compression ratio for 8-pel blocks. A major difference between SBIC and block-to-block coding is the possibility for lossless coding in the former case. It is possible to get error-free coding with the N/M method but this is obtained usually at not inconsiderable sacrifice of compression ratio. Alternatively very large blocks may be used in a fixed-codebook scheme where the codebook size becomes excessively large. In the SBIC method information-lossless coding is obtained by simply delaying a sufficient number of scan-lines of image. A further important difference between the SBIC method and block-to-block coding is that the former does not require a codebook. In the loss-free system or one in which no selective deletion of blocks is carried out the encoding and decoding procedures are probably easier to implement than the search-method of N/M implementation, or universal N/M coding in general. If a selective deletion process is used then a sorting procedure is required but this may be circumvented by utilising Hamming-weight stores, as described in section 5.4. A further difference which has been observed is the subjective effect of the distortion that is introduced by the SBIC scheme in a lossy implementation. Compared with the distortion arising from approximation of patterns in the block-to-block method the loss of black pels is readily noticeable so that from an aesthetic point of view much smaller values of percentage reconstruction errors can be tolerated. With the SBIC scheme a high resistance to loss of intelligibilty is intrinsically present due to the nature of block deletion which ensures no loss of a series of adjacent nonwhite blocks.

5.9 Use of Reserved Block Patterns

In the preceding discussion the block-pair could assume one of 5 five states which were labelled by a 2-bit header or in the special case of the double-black state, a 2-bit header code followed by an N-bit white pattern. It is feasible to increase the number of block-pair states further without extending the header wordlength. This is achieved by noting that some block patterns never or are extremely unlikely to occur and may be therefore used to represent the additional block-pair states. As an example the 8-bit patterns 01010101 and 10101010 are rarely found in the image data stream. Each such pattern can be used in adjoinment with the two-bit header so that 4 states may be represented per pattern. Additional block-pair states can be used to convey useful information which can help reduce the number of DNW states in the field thereby reducing the possibilities of field overflow. It may also be used, as described later, to restrict the effects of transmission errors. An example of the former application is in the representation of certain black-dominant block-pair patterns(not block-patterns) as special block-pair states. For example the seven patterns 0000000111111111, 0000001111111111, 0000011111111111, 0000111111111111, 0001111111111111, 0011111111111111, 0111111111111111 may be thus specially encoded which excludes them as DNW patterns, thereby reducing the total DNW count in the field. Such black-dominant patterns can occur in localised areas of images for example in areas of headings, horizontal bars, solid diagrams, etc. and can otherwise lead to large field size requirements for deletion-free performance. Commonly-occuring DNW patterns which are not necessarily black-dominant may also be specially encoded using reserved block patterns for the purpose of reducing the number of DNW states in the field.

5.9 Cascaded SBIC and Block-to-Block Coding

The SBIC compression method is limited in its range of compression ratios which tends to 2 as the block size N tends to infinity. In order to obtain higher levels of the block pattern which forms part of the codeword at the output of each block-pair may be encoded using the block-to-block technique. This is equivalent to a cascade of the SBIC scheme with the block-to-block coding method. The block-to-block encoder may employ a fixed-codebook, or be of the universal type described in Chapter 4. In the fixed-codebook case the block-to-block encoding operation is trivial if a pre-programmed ROM is used - a memory-read operation is all that is required, using the block pattern contained in each SBIC codeword to address the ROM. At the decoder a read operation is also performed to recover the block pattern or its approximated pattern, before SBIC decoding is carried out.

For a fixed N/M block-to-block encoder the compression ratio of the cascaded system is given by

$$CR = \frac{2N}{2 + M} \qquad 5.18$$

The values of compression ratio are tabulated in Table 5.20 for various N and M. It is seen that for 8-bit blocks a compression ratio of 2.0 is immediately feasible using 8/6 mode of block-to-block coding. This is an increase of 50% and 25% respectively over 8/6 coding and SBIC compression by themselves.

Eqn.5.18 may be rewritten as

$$CR = \frac{\frac{N}{M}}{\frac{1}{M} + 0.5} \qquad 5.19$$

The significance of this result is that for a fixed value of the block-to-block compression ratio N/M a higher value of the combined compression ratio is obtainable for higher values of M which is only possible with larger values of N itself. As an example, for the same value of compression ratio of 1.33 of the block-to-block coder, the mode 8/6 gives a combined compression ratio of 2.0 whereas the modes 16/12 and 32/24 result in ratios of 2.29 and 2.46 respectively.

It is clear that higher levels of compression ratio are achievable when the block size N increases for the cascaded compression system. When larger blocks are used the block-to-block encoder by itself can yield higher compression ratios and when cascaded with the SBIC scheme the overall compression ratio is also enhanced by the larger value of M. However the effect of using larger blocks in the SBIC encoder is to increase the probability of field overflow. A small amount of distortion is of course tolerable and the total encoding distortion in the image is the sum of the distortion levels due to both forms of coding.

The cascaded compression system was simulated for 8-pel blocks using a fixed codebook derived from the combined statistics of the set of test images. The images A4b and A6b were excluded from these tests. In the case where the SBIC section is distortionless the resultant distortion is due entirely to block-to-block coding and the images will be similar to those already displayed in Figs.3.14 to 3.34. For lossy SBIC samples of images after cascading with 8/6 coding are displayed in Figs.5.29 to 5.32.

In each case the combined compression ratio was 2.0 and a selective deletion of blocks was performed for overflowed fields. Image blocks were scrambled in sizes of 4096 blocks before encoding. The reconstructed images for three different field sizes in the cascaded coding of image A2 are shown in Figs.5.29 to 5.31. The percentage reconstructed errors are given in Table 5.22. Compared with the resultant images for the uncascaded system shown in Figs.5.24 to 5.26 the additional distortion due to block-to-block coding is difficult to detect visually. The quality of image shown in Fig.5.31 for the field size of 32 block-pairs is exceedingly good despite the percentage reconstructed errors of 0.17%. The result for the image A4 is depicted in Fig.5.32. Here the field size of 4 block-pairs produced a rather high-quality result at a compression ratio of 2.0. To avoid excessive numbers of displayed images the results for the other test images have been omitted. In general the image quality will be identical to those for fixed 8/6 coding shown in Chapter 3. Where the selected field size ensures no deletion of blocks. Otherwise the subjective effect is very similar to those featuring a small level of block element loss as obtained from the use of smaller field sizes. To the compression system designer the choice of field size is a matter of fine quality of image which is desired by the user.

It is of course equally feasible to cascade the SBIC method with a universal block-to-block compression system. This will give a scheme which does not require any prior knowledge of block statistics but more elaborate operations are involved especially at the encoding stage. The combined combpression ratio is calculated as follows. The segment size of r blocks in the adaptive scheme will usually be less than the scrambling segment size S of the SBIC compressor eg. S=4096 whereas r is typically less than 1500 in the 8-bit system. For this reason the universal block-to-block

coding has to be performed before the scrambled SBIC operations. If this were not the case the universal block-to-block coder will be operating on scrambled image blocks originating from a wider physical area of image than its segment size and block-to-block correlation is no longer exploited. It is also convenient to let the scrambling segment size S be a multiple of the segment r. If S=Kr where K is an integer then in the cascade implementation Kr blocks are N/M encoded using the derived segment codebooks and the M-bit codewords may be subsequently scrambled and operated upon by the SBIC encoder. The transmitted codebook bits are kept separate and are unaffected by the SBIC stage. For a segment of r blocks of N-bits, the total output bits is $rM + N.2^M$ where $N.2^M$ is the total number of codebook bits. The r M-bit codewords are scrambled and subsequently output as 2-bit header plus M-bit word for each input block-pair. The total output bits is therefore equal to $N.2^M + \frac{r}{2}(2+M)$ and the combined compression ratio is given by

$$CR = \frac{rN}{N.2^M + r + \frac{rM}{2}} \qquad 5.20$$

Dividing by rM,

$$CR = \frac{\frac{N}{M}}{\frac{N}{M}\frac{2^M}{r} + \frac{1}{M} + 0.5} \qquad 5.21$$

A selection of values of CR is given in Table 5.22 for 8/5 coding with segment sizes equal to various number of lines of the image A1. It is seen that a segment size of 4 lines will give a compression ratio of 2, the image quality for this segment size has been found to be acceptable in Chapter 4. A further increase in the segment size does not produce a large

increase in the compression ratio but results in poorer quality of image.

5.11 Effects of Transmission Errors

The performance of SBIC method has been hitherto described on the assumption of error-free transmission conditions. In a real channel the received codewords may be corrupted with the consequence that erroneous decoding may follow. The effects of transmission errors is now considered.

In the uncascaded SBIC compression system each output codeword consists of a 2-bit header followed by a block pattern. If the bits of the block pattern are corrupted by transmission noise the reconstructed pattern shows out the errors on a pel-by-pel basis ie. a single corrupted bit produces a single reconstructed pel error. The facsimile image can tolerate a substantial number of this type of errors without loss of intelligibility, especially if they are sufficiently isolated from one another. The effect of a header bit being corrupted is more serious. A false report on the status of the current block-pair is the direct result. The exact consequence is complex and depends on what the header state is before and after corruption. The most serious effect occurs when a DW or DNW state is corrupted or generated as a result of a transmission error. Then an incorrect block will be placed in the FIFO buffer, or a valid block block may be omitted. Because the reinstatement of the FIFO buffer contents works on a sequential basis the result can be the incorrect placement of all the blocks in the buffer. However there is no total failure of the decoding process and this is where the SBIC system is superior to many variable-rate compression techniques in its noise performance. Left-white, right-white and all-white block-pairs may still be correctly reinstated. The left halves of double-nonwhite block-pairs

will also be recovered without error for uncorrupted header states in the field. This aspect is of importance as it ensures that a large proportion of the image material is successfully reconstructed even if the sequential reinstatement of right blocks of double-nonwhite pairs has been adversely affected. This allows the SBIC compression scheme to withstand large levels of transmission errors which are not possible with standard variable-rate techniques.

It is clear that the propagatory effects of transmission errors may be reduced by restricting the size of the field as the corruption of a header word does not have any effect outside its field. The improved noise performance obtained from reducing the field size F has to be weighed against the increased probability of field overflow and black element loss resulting from a reduced field size. Over hostile transmission channels the small degradation of image quality due to encoding may be acceptable as a trade-off for immunity against more serious degradation resulting from transmission errors.

Assuming that a single corrupted header word is responsible for a failure of the sequential reinstatement of right blocks of double-nonwhite block-pairs the probability of such a failure may be calculated for the case of random transmission errors whose probability of occurence is p. In a field of F block-pairs, the output contains F 2-bit header words. The probability of a header word being corrupted is $1-(1-p)^2$. The probability of one or more header words in error in a field is

$$\begin{aligned} P_E &= 1 - P(\text{all } 2F \text{ header bits uncorrupted}) \\ &= 1 - (1 - p)^{2F} \end{aligned} \qquad 5.22$$

Table 5.23 shows some values of P_E for various values of p and 2F.

From these figures an indication of the noise performance is obtainable. For $p=10^{-4}$ very low levels of probability header word corruption within a field are obtained. The average error rate here is that which may be found on telephone circuits. At an average rate of 1 in 1000 the likelihood of contaminated header words remains low for smaller values of field size. For a value of p equal to 0.01 significant proportions of fields are likely to experience sequential reinstatement failure especially for the larger field sizes of 32 and 64 block-pairs. The probability of failure increases sharply as the error rate worsens to 1 in 10. At this rate more than half the fields are expected to fail at the field size of 4 block-pairs. This proportion is reduced to about a fifth for the same block-pair size at the error rate of 1 in 32. It is reminded that the failure here is not catastrophic, its primary effect is to cause a false reinstatement of one half of double-nonwhite block-pairs, the number of which vary from field to field.

In a cascaded SBIC with N/M compression system the corruption of an M-bit codeword causes a false reinstatement of that block pattern and the subjective effect is similar to that observed for block-to-block coding. Roughly the result of transmission errors is the sum of the effects of errors individually on the SBIC and N/M schemes. The increased sensitivity of the combined system to transmission errors is a price to pay for the extra yields of compression ratio which are obtained.

The effects of transmission errors is probably best ascertained by visual inspection of the reconstructed images. To this purpose random errors and burst errors derived from the Gilbert model were injected into the simulated output of the coder in a similar manner to that described in Chapter 4 for the universal block-to-block compression scheme. Two sets of

trials were conducted. The first simulated the system for an uncascaded SBIC system with scrambling, whilst the second examined the noise performance for a cascaded system. The image A2 was chosen for the tests as it contains a great deal of text thus providing a good amount of material for subjective assessment. The reconstructed images for the uncascaded scheme in the presence of random transmission errors whose average error rate are 1 in 100 and 1 in 32 are shown in Figs.5.33 and 5.34. The field size was set at 16 block-pairs. It is seen that at the rate of 1 in 100 the text is totally readable and intelligibility is unimpaired. When the average error rate is increased to 1 in 32 the quality is degraded to some extent but it is still possible to read and understand the text. Certain individual characters are no doubt unrecognisable but words and sentences can be made out from context. The effect of increasing the field size to 32 block-pairs is shown in Fig.5.35. The total reconstructed errors here has been increased compared that for the field size of 16 block-pairs. Error counts expressed as percentages are given in Table 5.24. Figs.5.36 and 5.37 show the effects of burst transmission errors on field sizes of 16 and 32 block-pairs respectively. The resulting error counts shown in Table 5.24 clearly confirm that for the same average error rate burst errors give rise to fewer reconstructed errors than random errors. This is because a header word is corrupted just as thoroughly by a single transmission error whether it occurs in isolation or in a burst. In the latter case an error burst is responsible for a single false header word which results in a smaller total of corrupted header words for the same total count of transmission errors.

The subjective effects of transmission errors on a cascaded SBIC with 8/6 compression system may be observed in Figs.5.38 to 5.45 with error counts given in Table 5.25. The compression ratio of 2.0 is obtained for

all these images. In Figs.5.38 to 5.40 a field size of 32 block-pairs is featured and in Figs.5.41. to 5.44 this has been reduced to 16 block-pairs. At the average rate of 1 in 1000 (Fig.5.38) the effect of transmission errors is inconsequential which bears out the noise advantage of the SBIC compression scheme over many variable-rate compression systems. At an average rate of 1 in 100 for random errors (Fig.5.39) good intelligibility was maintained. The total errors here is nearly twice the number incurred in the uncascaded scheme for the same field size of 32 block-pairs (Fig.5.33). For burst errors at the same average error rate the total reconstructed errors was reduced by about 25%. The performance at an average error rate of 1 in 32 was generally unacceptable for both random (Fig.5.42) and burst errors (Fig.5.44). In order to observe the effects of even smaller field size usage a test was carried out on image A1 wherein a field size of 4 block-pairs was employed in a cascaded scrambled SBIC (S=4096 blocks) with 8/6 compression scheme. The resultant image displayed in Fig.5.45 showed a strong resistance to transmission errors. Although much of the image quality has deteriorated words could still be made out with some difficulty, and the contents of the letter could still be fathomed.

5.12 Suggested Technique for Limiting the Effects of Transmission Errors

The concept of reserving block patterns for representing extra block-pair states was described in section 5.9. A possible method for restricting the propagation of errors is to use a reserved block pattern as a synchronisation sequence. This is particularly suitable for large field size realisations. The field is divided into records of equal length and at the end of each record a reserved block pattern is pushed into the FIFO

store during the scanning of DNW patterns in the encoding procedure. At the receiver when the pattern is detected the reinstatement of the FIFO contents resynchronises to the start of the next record. The space taken up by the end-of-record pattern is a DW output space implying a sacrifice of a number of these states in the coding field but as the number of records is small this should not lead to any large increase in field overflow. Instead of using a single end-of-record pattern several patterns may be used to uniquely identify records of the field so that in the event of an end-of record pattern being corrupted the effect does not propagate to other records. Here a means of error detection is possible if a check is made of the correct order of arrival of the end-of-record sequences and/or the overlapping of reinstated patterns into wrong records. Some suitable response may then be initiated in the event of an error being detected, for example repetition of block-pairs from previous line.

5.13 Conclusions

In this chapter a method of fixed-rate compression has been presented in which the input image data is delayed and pairs of blocks are encoded according to their white states. By providing a sufficient length of delay a lossless form of coding is possible. The employment of a large coding field however increases the system's vulnerability to transmission errors so that this approach is more suitable for low-noise transmission channels. By pseudo-scrambling the blocks before encoding the field size for lossless coding can be reduced considerably. This field size can be decreased further if a small amount of distortion is introduced which corresponds to a loss of black picture elements. The level of this distortion and its subjective effect can be improved by a process of selective deletion based

on a minimum Hamming weight criterion. The operations involved are well-suited for a microprocessor implementation which will enable the system to be realised at very low cost. A theoretical assessment of the probability of field overflow was given for a memoryless block model of the image source. A comparison was also made for a memoryless trinary block-pair model. The results of simulation showed a poorer performance than that for a memoryless block source.

The SBIC technique of compression achieves its maximum compression ratio of 2 when the block size tends to infinity. In order to obtain higher levels of compression a cascade with N/M block-to-block coding was proposed. The combined compression ratio is much higher when the block size is large but this has to be weighed against the increase in field size for deletion-free operation and greater complexity of the N/M coder especially if the ROM-lookup method is not feasible. The results of simulation carried out for 8-bit blocks shows that a combined compression ratio of 2.0 is possible for all the test images. This amount of compression exceeds that obtainable by fixed block-to-block encoding alone by 50%.

Finally the effects of transmission errors were examined for uncascaded and cascaded SBIC systems. In the uncascaded case the chief effect of transmission errors is the failure of correct reinstatement of one half of double-nonwhite block-pairs. The subjective effects of this type of errors is not catastrophic and a high degree of intelligibility is maintained for average error rates worse than 1 in 100 if the field size is kept small. In the cascaded system additional reconstructed errors are incurred from corruption of codewords of block patterns. Even so the reproduced image is quite intelligible at an average error rate of 1 in 100 of transmission errors.

Image	P_{DW}	P_{DB}	P_{LW}	P_{RW}	P_{DNW}
A1	87.82	0.05	2.40	2.37	7.37
A2	61.19	1.15	5.04	4.97	27.65
A3	74.68	1.86	8.43	8.48	6.54
A4	76.07	0.62	6.04	6.00	11.27
A5	58.79	0.46	14.19	14.24	12.32
A6	59.70	0.19	13.48	13.42	13.20
A4b	74.10	0.13	7.87	7.49	10.40
A5b	43.16	0.05	20.39	20.84	15.57
A6b	51.16	0.34	15.36	15.43	17.70

Table 5.1. Block-pair Statistics of Test Images for Block Size of 8 pels. Probabilities are expressed as percentages.

Test Image	Field Size, F											
	2	4	8	16	32	64	128	256	512	1024	2048	4096
A1	8.53	9.49	9.35	8.53	7.58	7.59	6.74	7.42	3.54	0.00	0.00	0.00
A2	30.80	31.20	31.30	30.00	31.40	32.20	33.50	28.30	16.50	2.27	0.00	0.00
A3	6.61	6.10	4.78	2.49	1.23	0.51	0.82	0.00	0.00	0.00	0.00	0.00
A4	11.24	12.19	12.20	10.73	9.78	10.50	10.30	8.81	3.57	0.00	0.00	0.00
A5	10.70	8.27	5.79	2.81	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A6	14.35	14.90	15.90	15.50	14.40	14.00	13.16	12.30	9.82	1.82	0.00	0.00
A4b	11.20	12.10	11.50	10.90	11.90	11.90	11.80	10.70	1.15	0.00	0.00	0.00
A5b	16.30	15.20	13.10	10.30	6.31	6.60	6.06	6.11	6.25	6.45	7.14	0.00
A6b	20.40	21.30	21.90	22.00	22.20	22.10	21.00	18.50	15.40	9.80	0.00	0.00

Table 5.2. Percentage Overflowed Fields, P_F, obtained for Test Images After SBIC.

Test Image	Field Size, F											
	2	4	8	16	32	64	128	256	512	1024	2048	4096
A1	3.20	2.85	2.45	1.97	1.41	0.99	0.81	0.57	0.11	0.00	0.00	0.00
A2	13.11	12.48	11.56	9.85	6.94	5.33	4.95	3.77	0.64	0.03	0.00	0.00
A3	2.14	1.35	0.71	0.28	0.10	0.05	0.04	0.00	0.00	0.00	0.00	0.00
A4	4.11	3.32	2.77	2.23	1.58	1.08	1.04	0.76	0.12	0.00	0.00	0.00
A5	3.22	1.52	0.66	0.19	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A6	4.52	3.00	2.36	1.86	1.41	1.14	1.07	0.91	0.54	0.03	0.00	0.00
A4b	3.97	3.37	2.85	2.35	2.05	1.94	1.74	1.06	0.01	0.00	0.00	0.00
A5b	4.95	2.94	1.59	0.81	0.30	0.26	0.23	0.21	0.21	0.16	0.05	0.00
A6b	6.33	4.67	3.97	3.48	3.22	3.04	2.78	2.34	0.90	0.22	0.00	0.00

Table 5.3. Percentage Deleted Blocks, P_B, obtained for Test Images After SBIC.

Test Image	Field Size, F											
	2	4	8	16	32	64	128	256	512	1024	2048	4096
A1	1.40	1.26	1.07	0.86	0.62	0.42	0.31	0.21	0.05	0.00	0.00	0.00
A2	5.97	5.69	5.26	4.52	3.11	2.31	2.15	1.57	0.27	0.02	0.00	0.00
A3	1.02	0.68	0.38	0.17	0.06	0.02	0.02	0.00	0.00	0.00	0.00	0.00
A4	2.32	1.88	1.59	1.30	0.92	0.63	0.59	0.45	0.07	0.00	0.00	0.00
A5	1.42	0.68	0.30	0.083	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A6	1.86	1.23	0.98	0.77	0.56	0.45	0.42	0.36	0.22	0.01	0.00	0.00
A4b	1.69	1.47	1.25	1.04	0.91	0.87	0.79	0.47	0.003	0.00	0.00	0.00
A5b	1.48	0.89	0.48	0.25	0.09	0.08	0.07	0.06	0.06	0.04	0.01	0.00
A6b	2.69	1.98	1.73	1.53	1.43	1.34	1.21	1.00	0.38	0.10	0.00	0.00

Table 5.4. Percentage Black Elements Lost, P_L, obtained for Test Images after SBIC.

Image \ Field Size F		2	4	8	16	32	64	128	256	512	1024	2048	4096
A1	P_L	1.06	0.92	0.76	0.60	0.40	0.24	0.17	0.11	0.014	0.00	0.00	0.00
	P_L*	1.40	1.26	1.07	0.86	0.62	0.42	0.31	0.21	0.05	0.00	0.00	0.00
	% Δ	24.30	27.00	29.00	30.20	35.50	42.90	45.20	47.60	72.00	0.00	0.00	0.00
A2	P_L	4.53	4.30	3.93	3.29	2.09	1.36	1.23	0.91	0.11	0.0039	0.00	0.00
	P_L*	5.97	5.69	5.26	4.52	3.11	2.31	2.15	1.57	0.27	0.02	0.00	0.00
	% Δ	24.10	24.40	25.30	27.20	32.80	41.10	42.80	42.00	59.30	80.50	0.00	0.00
A3	P_L	0.76	0.50	0.27	0.12	0.04	0.016	0.008	0.00	0.00	0.00	0.00	0.00
	P_L*	1.02	0.68	0.38	0.17	0.06	0.02	0.02	0.00	0.00	0.00	0.00	0.00
	% Δ	25.50	26.50	28.90	29.40	33.30	20.00	60.00	0.00	0.00	0.00	0.00	0.00
A4	P_L	1.70	1.34	1.07	0.83	0.55	0.30	0.28	0.19	0.02	0.00	0.00	0.00
	P_L*	2.32	1.88	1.59	1.30	0.92	0.63	0.59	0.45	0.07	0.00	0.00	0.00
	% Δ	26.70	28.70	32.70	36.20	40.20	52.40	52.50	57.80	71.40	0.00	0.00	0.00
A5	P_L	0.95	0.41	0.15	0.03	0.004	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P_L*	1.42	0.68	0.30	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	% Δ	33.10	39.70	50.00	62.50	60.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A6	P_L	1.28	0.78	0.56	0.40	0.27	0.20	0.18	0.15	0.08	0.003	0.00	0.00
	P_L*	1.86	1.23	0.98	0.77	0.56	0.45	0.42	0.36	0.22	0.01	0.00	0.00
	% Δ	31.20	36.60	42.90	48.10	51.80	55.60	57.10	58.30	63.60	70.00	0.00	0.00
A4b	P_L	1.24	1.05	0.86	0.68	0.54	0.49	0.42	0.22	0.0007	0.00	0.00	0.00
	P_L*	1.69	1.47	1.25	1.04	0.91	0.87	0.79	0.47	0.003	0.00	0.00	0.00
	% Δ	26.60	28.60	31.20	34.60	40.70	43.70	46.80	53.20	76.70	0.00	0.00	0.00
A5b	P_L	1.02	0.57	0.26	0.12	0.039	0.034	0.03	0.029	0.027	0.020	0.006	0.00
	P_L*	1.48	0.89	0.48	0.25	0.09	0.08	0.07	0.06	0.06	0.04	0.01	0.00
	% Δ	31.10	36.00	45.80	52.00	56.70	57.50	57.10	51.70	55.00	50.00	40.00	0.00
A6b	P_L	1.87	1.33	1.10	0.91	0.80	0.71	0.63	0.52	0.16	0.03	0.00	0.00
	P_L*	2.69	1.98	1.73	1.53	1.43	1.34	1.21	1.00	0.38	0.10	0.00	0.00
	% Δ	30.50	32.80	36.40	40.50	44.10	47.00	47.50	48.00	57.90	70.00	0.00	0.00

P_L* = Percentage Discortion with Scraight Deletion %Δ = Percentage Decrease of P_L from P_L*

P_o \ F	2	4	8	16	32	64	128
0.5	0.31	0.36	0.40	0.43	0.45	0.46	0.48
0.6	0.18	0.17	0.09	0.04	0.0095	0.0086	0.00049
0.7	0.084	0.058	0.026	0.0052	0.00025	0.7×10^{-6}	0.73×10^{-11}
0.8	0.027	0.01	0.0015	0.33×10^{-4}	0.19×10^{-7}	0.89×10^{-14}	0.25×10^{-26}
0.9	0.0037	0.00043	0.59×10^{-5}	0.13×10^{-8}	0.75×10^{-16}	0.35×10^{-30}	0.99×10^{-59}

Table 5.6. Approximated values of Field Probability Overflow P_F for various P_o and F.

P_o	F
0.6	>160
0.7	64
0.8	24
0.9	10

Table 5.7. Values of Field Size at which P_F reaches 10^{-6} or less.

Test Image	Measured All-white Probability P_o	Measured All-black Probability P_{255}	Calculated Block-Pair State Probabilities: P_{DW}	P_{DB}	P_{LW}	P_{RW}	P_{DNW}
A1	0.9020	0.0030	0.8136	0.0000	0.0884	0.0884	0.0096
A2	0.6620	0.0243	0.4382	0.0006	0.2238	0.2238	0.1137
A3	0.8314	0.0248	0.6912	0.0006	0.1402	0.1402	0.0278
A4	0.8209	0.0193	0.6739	0.0004	0.1470	0.1470	0.0317
A5	0.7301	0.0175	0.5330	0.0003	0.1971	0.1971	0.0725
A6	0.7315	0.0103	0.5351	0.0001	0.1964	0.1964	0.0720
A4b	0.8179	0.0044	0.6690	0.0000	0.1489	0.1489	0.0331
A5b	0.6377	0.0046	0.4067	0.0000	0.2310	0.2310	0.1312
A6b	0.6655	0.0137	0.4429	0.0002	0.2226	0.2226	0.1117

Table 5.8. Measured values of P_o and P_{255} for Test Images and Calculated Probabilities of Block-Pair States Assuming a Memoryless Block Source.

Image \ F	2	4	8	16	32	64	128
A1	0.0035	0.00039	0.5×10^{-5}	0.93×10^{-9}	0.41×10^{-16}	0.11×10^{-30}	0.94×10^{-60}
A2	0.11	0.092	0.054	0.019	0.0025	0.53×10^{-4}	0.31×10^{-7}
A3	0.016	0.0047	0.00038	0.28×10^{-5}	0.19×10^{-9}	0.11×10^{-17}	0.49×10^{-34}
A4	0.020	0.0063	0.00062	0.69×10^{-5}	0.10×10^{-8}	0.29×10^{-16}	0.31×10^{-31}
A5	0.062	0.037	0.013	0.0015	0.25×10^{-4}	0.91×10^{-8}	0.15×10^{-14}
A6	0.062	0.037	0.012	0.0014	0.23×10^{-4}	0.75×10^{-8}	0.11×10^{-14}
A4b	0.021	0.0069	0.00072	0.90×10^{-5}	0.17×10^{-8}	0.78×10^{-16}	0.22×10^{-30}
A5b	0.14	0.12	0.082	0.038	0.0086	0.00053	0.25×10^{-5}
A6b	0.11	0.089	0.051	0.017	0.0021	0.38×10^{-4}	0.17×10^{-7}

Table 5.9. Calculated Probabilities of Field Overflow from Measured P_o and P_{255} of Test Images.

Image	F
A1	10
A2	98
A3	18
A4	20
A5	46
A6	46
A4b	22
A5b	140
A6b	94

Table 5.10. Approximate Values of Field Size at which P_F reached 10^{-6} for the Test Images.

Image \ F		2	4	8	16
A1	1	0.0853	0.095	0.094	0.085
	2	0.0035	0.39×10^{-3}	0.5×10^{-5}	0.93×10^{-9}
A2	1	0.31	0.31	0.31	0.30
	2	0.11	0.092	0.054	0.019
A3	1	0.066	0.061	0.048	0.025
	2	0.016	0.0047	0.38×10^{-3}	0.28×10^{-5}
A4	1	0.11	0.12	0.12	0.11
	2	0.020	0.0063	0.62×10^{-3}	0.69×10^{-5}
A5	1	0.11	0.083	0.058	0.029
	2	0.062	0.037	0.013	0.0015
A6	1	0.14	0.15	0.16	0.16
	2	0.062	0.037	0.012	0.0014
A4b	1	0.11	0.12	0.12	0.11
	2	0.021	0.0069	0.72×10^{-3}	0.9×10^{-5}
A5b	1	0.16	0.15	0.13	0.10
	2	0.138	0.121	0.082	0.038
A6b	1	0.20	0.21	0.22	0.22
	2	0.112	0.089	0.051	0.017

Row 1 - Experimental Probabilities; Row 2 - Calculated Probabilities

Table 5.11. Comparison of Experimental Probabilities of Field Overflow with Calculated Probabilities for Independent Block Model.

Test Image		Independent Block Model	Measured Values	Scrambling Segment Size in Blocks: 1024	2048	4096	8192
A1	P_{DW}	0.8136	0.8782	0.8381	0.8291	0.8243	0.8202
	P_{DB}	0.0000	0.0005	0.0000	0.0000	0.0000	0.0001
	P_{LW}	0.0884	0.0240	0.0635	0.0709	0.0770	0.0823
	P_{RW}	0.0884	0.0237	0.0635	0.0724	0.0747	0.0776
	P_{DNW}	0.0096	0.0737	0.0349	0.0276	0.0240	0.0199
A2	P_{DW}	0.4382	0.6119	0.4788	0.4440	0.4531	0.4485
	P_{DB}	0.0006	0.0115	0.0081	0.0049	0.0044	0.0020
	P_{LW}	0.2238	0.0504	0.1826	0.2152	0.2056	0.2154
	P_{RW}	0.2238	0.0497	0.1837	0.2157	0.2070	0.2133
	P_{DNW}	0.1137	0.2765	0.1468	0.1202	0.1298	0.1209
A3	P_{DW}	0.6912	0.7468	0.7026	0.7003	0.7007	0.7006
	P_{DB}	0.0006	0.0186	0.0021	0.0017	0.0013	0.0016
	P_{LW}	0.1402	0.0843	0.1290	0.1311	0.1313	0.1306
	P_{RW}	0.1402	0.0848	0.1287	0.1311	0.1314	0.1322
	P_{DNW}	0.0278	0.0654	0.0377	0.0358	0.0353	0.0350
A4	P_{DW}	0.6739	0.7607	0.7026	0.6938	0.6867	0.6853
	P_{DB}	0.0004	0.0062	0.0012	0.0006	0.0003	0.0003
	P_{LW}	0.1470	0.0604	0.1191	0.1277	0.1404	0.1391
	P_{RW}	0.1470	0.0600	0.1170	0.1261	0.1354	0.1396
	P_{DNW}	0.0317	0.1127	0.0600	0.0517	0.0371	0.0357
A5	P_{DW}	0.5330	0.5879	0.5380	0.5378	0.5364	0.5351
	P_{DB}	0.0003	0.0046	0.0004	0.0004	0.0003	0.0003
	P_{LW}	0.1971	0.1419	0.1910	0.1918	0.1965	0.1932
	P_{RW}	0.1971	0.1424	0.1932	0.1929	0.1892	0.1950
	P_{DNW}	0.0725	0.1232	0.0774	0.0771	0.0776	0.0764

Table 5.12. Block-Pair Statistics of Test Images After Scrambling of Blocks.

Test Image		Independent Block Model	Measured Values	Scrambling Segment Size in Blocks: 1024	2048	4096	8192
A6	P_{DW}	0.5351	0.5970	0.5595	0.5512	0.5445	0.5374
	P_{DB}	0.0001	0.0019	0.0003	0.0003	0.0002	0.0001
	P_{LW}	0.1964	0.1348	0.1732	0.1811	0.1881	0.1971
	P_{RW}	0.1964	0.1342	0.1715	0.1801	0.1900	0.1952
	P_{DNW}	0.0720	0.1320	0.0955	0.0873	0.0772	0.0702
A4b	P_{DW}	0.6690	0.7410	0.6974	0.6788	0.6695	0.6642
	P_{DB}	0.0000	0.0013	0.0001	0.0000	0.0000	0.0000
	P_{LW}	0.1489	0.0787	0.1201	0.1363	0.1447	0.1496
	P_{RW}	0.1489	0.0749	0.1189	0.1356	0.1459	0.1514
	P_{DNW}	0.0331	0.1040	0.0636	0.0493	0.0400	0.0347
A5b	P_{DW}	0.4067	0.4316	0.4116	0.4148	0.4062	0.4031
	P_{DB}	0.0000	0.0005	0.0000	0.0000	0.0001	0.0000
	P_{LW}	0.2310	0.2039	0.2247	0.2236	0.2277	0.2332
	P_{RW}	0.2310	0.2084	0.2269	0.2216	0.2296	0.2303
	P_{DNW}	0.1312	0.1557	0.1368	0.1399	0.1364	0.1333
A6b	P_{DW}	0.4429	0.5116	0.4704	0.4569	0.4588	0.4509
	P_{DB}	0.0002	0.0034	0.0008	0.0003	0.0002	0.0003
	P_{LW}	0.2226	0.1536	0.1957	0.2107	0.2141	0.2180
	P_{RW}	0.2226	0.1543	0.1968	0.2087	0.2105	0.2225
	P_{DNW}	0.1117	0.1770	0.1363	0.1233	0.1165	0.1084

Table 5.12. Block-Pair Statistics of Test Images After Scrambling of Blocks. (Cont'd)

Test Image	S	Field Size, F								
		2	4	8	16	32	64	128	256	512
A1	1024	3.80	3.57	3.75	3.45	3.37	3.26	3.48	3.48	3.48
	2048	2.40	1.57	0.71	0.36	0.22	0.11	0.00	0.00	0.00
	4096	2.09	1.40	0.53	0.14	0.00	0.00	0.00	0.00	0.00
	8192	1.66	1.14	0.57	0.14	0.00	0.00	0.00	0.00	0.00
A2	1024	16.78	17.38	17.12	17.24	17.20	15.32	16.13	15.59	16.13
	2048	13.70	13.58	11.65	9.54	7.47	5.57	6.79	4.35	3.26
	4096	14.22	13.70	11.50	8.02	4.55	1.77	0.82	0.00	0.00
	8192	13.16	11.72	9.23	5.65	2.91	0.57	0.00	0.00	0.00
A3	1024	3.17	2.01	1.28	0.69	0.46	0.10	0.00	0.00	0.00
	2048	2.94	2.11	1.17	0.77	0.36	0.10	0.20	0.00	0.00
	4096	2.90	1.87	1.13	0.44	0.31	0.00	0.00	0.00	0.00
	8192	2.73	1.70	0.83	0.18	0.10	0.00	0.00	0.00	0.00
A4	1024	6.70	6.65	6.37	5.73	5.92	5.70	5.26	5.26	4.39
	2048	4.87	3.78	2.29	1.01	0.22	0.00	0.00	0.00	0.00
	4096	2.70	1.30	0.18	0.06	0.00	0.00	0.00	0.00	0.00
	8192	2.64	1.29	0.24	0.00	0.00	0.00	0.00	0.00	0.00
A5	1024	7.16	5.29	3.11	1.59	0.44	0.00	0.00	0.00	0.00
	2048	7.12	5.11	2.65	1.07	0.44	0.00	0.00	0.00	0.00
	4096	7.10	5.07	2.65	1.03	0.39	0.00	0.00	0.00	0.00
	8192	6.91	5.07	2.54	0.84	0.22	0.00	0.00	0.00	0.00

Table 5.13. Percentage Overflowed Fields, P_F, after SBIC with Pseudo-Scrambling of Blocks.

Test Image	S	Field Size, F 2	4	8	16	32	64	128	256	512
	1024	10.66	10.42	10.16	9.98	9.65	9.65	9.87	9.65	9.65
	2048	9.06	7.83	6.36	4.88	3.18	2.41	0.88	1.32	0.88
A6	4096	7.27	5.26	3.00	1.42	0.28	0.00	0.00	0.00	0.00
	8192	6.19	3.82	1.62	0.25	0.00	0.00	0.00	0.00	0.00
	1024	6.77	6.07	5.13	4.04	2.81	1.69	1.69	0.56	1.12
	2048	4.42	2.81	1.21	0.43	0.00	0.00	0.00	0.00	0.00
A4b	4096	3.24	1.66	0.69	0.00	0.00	0.00	0.00	0.00	0.00
	8192	2.55	1.05	0.34	0.00	0.00	0.00	0.00	0.00	0.00
	1024	15.37	15.13	13.00	10.98	8.90	6.82	7.20	6.06	6.06
	2048	15.19	14.63	12.52	10.75	8.52	7.01	6.82	3.03	4.55
A5b	4096	15.19	14.53	11.57	9.38	6.93	4.30	3.91	4.69	4.69
	8192	14.36	13.66	10.96	8.45	5.86	4.49	1.95	1.56	0.00
	1024	15.60	15.80	15.55	15.60	15.63	14.98	15.57	17.45	16.04
	2048	13.72	13.39	12.13	10.88	9.73	8.96	8.96	9.91	9.43
A6b	4096	12.03	11.04	8.29	5.77	3.19	2.04	1.44	1.92	0.00
	8192	11.01	9.44	6.78	3.97	2.10	1.20	0.00	0.00	0.00

Table 5.13. Percentage Overflowed Fields, P_F, after SBIC with Pseudo-Scrambling of Blocks. (Cont'd)

Test Image	S	Field Size, F								
		2	4	8	16	32	64	128	256	512
A1	1024	1.13	0.68	0.44	0.29	0.20	0.14	0.13	0.11	0.11
	2048	0.67	0.25	0.07	0.02	0.01	0.01	0.00	0.00	0.00
	4096	0.59	0.21	0.05	0.01	0.00	0.00	0.00	0.00	0.00
	8192	0.47	0.17	0.05	0.01	0.00	0.00	0.00	0.00	0.00
A2	1024	5.03	3.29	2.19	1.52	1.08	0.81	0.72	0.67	0.62
	2048	3.79	2.22	1.19	0.63	0.32	0.20	0.13	0.07	0.04
	4096	4.10	2.35	1.23	0.51	0.17	0.04	0.01	0.00	0.00
	8192	3.69	1.95	0.89	0.33	0.10	0.01	0.00	0.00	0.00
A3	1024	0.87	0.32	0.13	0.05	0.02	0.00	0.00	0.00	0.00
	2048	0.81	0.34	0.12	0.05	0.02	0.01	0.00	0.00	0.00
	4096	0.81	0.30	0.11	0.03	0.01	0.00	0.00	0.00	0.00
	8192	0.76	0.27	0.07	0.01	0.00	0.00	0.00	0.00	0.00
A4	1024	1.99	1.26	0.82	0.56	0.42	0.30	0.26	0.24	0.22
	2048	1.37	0.61	0.20	0.06	0.01	0.00	0.00	0.00	0.00
	4096	0.71	0.18	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	8192	0.70	0.19	0.02	0.00	0.00	0.00	0.00	0.00	0.00
A5	1024	1.97	0.83	0.29	0.09	0.02	0.00	0.00	0.00	0.00
	2048	1.97	0.80	0.26	0.06	0.01	0.00	0.00	0.00	0.00
	4096	1.96	0.80	0.23	0.06	0.01	0.00	0.00	0.00	0.00
	8192	1.92	0.79	0.23	0.05	0.01	0.00	0.00	0.00	0.00

Table 5.14. Percentage Blocks Deleted, P_L, after SBIC with Pseudo-Scrambling of Blocks.

Test Image	S	Field Size, F 2	4	8	16	32	64	128	256	512
	1024	3.11	1.96	1.32	0.93	0.73	0.63	0.58	0.56	0.54
	2048	2.57	1.31	0.63	0.31	0.13	0.07	0.03	0.03	0.03
A6	4096	1.99	0.82	0.26	0.07	0.01	0.00	0.00	0.00	0.00
	8192	1.69	0.57	0.13	0.01	0.00	0.00	0.00	0.00	0.00
	1024	1.95	1.05	0.55	0.27	0.12	0.05	0.02	0.01	0.01
	2048	1.21	0.43	0.10	0.02	0.00	0.00	0.00	0.00	0.00
A4b	4096	0.86	0.24	0.06	0.00	0.00	0.00	0.00	0.00	0.00
	8192	0.66	0.15	0.02	0.00	0.00	0.00	0.00	0.00	0.00
	1024	4.42	2.60	1.46	0.82	0.51	0.31	0.24	0.21	0.21
	2048	4.38	2.50	1.38	0.73	0.41	0.27	0.20	0.16	0.16
A5b	4096	4.33	2.47	1.27	0.68	0.34	0.13	0.10	0.06	0.04
	8192	4.08	2.31	1.17	0.56	0.26	0.12	0.05	0.01	0.00
	1024	4.69	3.11	2.18	1.71	1.45	1.23	1.18	1.15	1.12
	2048	3.96	2.41	1.42	0.89	0.62	0.48	0.42	0.38	0.36
A6b	4096	3.44	1.87	0.87	0.40	0.14	0.06	0.03	0.02	0.00
	8192	3.08	1.53	0.68	0.27	0.08	0.02	0.00	0.00	0.00

Table 5.14. Percentage Blocks Deleted, P_L, after SBIC with Pseudo-Scrambling of Blocks. (Cont'd)

Test Image	S	Field Size, F 2	4	8	16	32	64	128	256	512
A1	1024	0.31	0.180	0.106	0.063	0.037	0.024	0.020	0.017	0.014
	2048	0.194	0.071	0.018	0.005	0.002	0.002	0.000	0.000	0.000
	4096	0.163	0.052	0.009	0.001	0.000	0.000	0.000	0.000	0.000
	8192	0.129	0.040	0.010	0.002	0.000	0.000	0.000	0.000	0.000
A2	1024	1.653	1.040	0.620	0.390	0.250	0.180	0.150	0.130	0.120
	2048	1.220	0.670	0.320	0.150	0.070	0.040	0.020	0.010	0.007
	4096	1.320	0.700	0.320	0.120	0.030	0.006	0.005	0.000	0.000
	8192	1.180	0.590	0.240	0.080	0.020	0.002	0.000	0.000	0.000
A3	1024	0.232	0.079	0.026	0.007	0.003	0.0001	0.000	0.000	0.000
	2048	0.208	0.083	0.024	0.008	0.003	0.0009	0.000	0.000	0.000
	4096	0.212	0.074	0.022	0.007	0.002	0.000	0.000	0.000	0.000
	8192	0.195	0.062	0.015	0.002	0.000	0.000	0.000	0.000	0.000
A4	1024	0.783	0.477	0.286	0.177	0.120	0.075	0.060	0.050	0.050
	2048	0.517	0.216	0.056	0.015	0.002	0.000	0.000	0.000	0.000
	4096	0.243	0.058	0.004	0.0002	0.000	0.000	0.000	0.000	0.000
	8192	0.240	0.058	0.005	0.000	0.000	0.000	0.000	0.000	0.000
A5	1024	0.569	0.222	0.064	0.017	0.0028	0.000	0.000	0.000	0.000
	2048	0.582	0.208	0.057	0.011	0.0019	0.000	0.000	0.000	0.000
	4096	0.571	0.212	0.051	0.011	0.0015	0.000	0.000	0.000	0.000
	8192	0.571	0.220	0.054	0.009	0.0009	0.000	0.000	0.000	0.000

Table 5.15. Percentage Black Elements Lost, P_L, after SBIC with Pseudo-Scrambling of Blocks.

Test Image	S	Field Size, F 2	4	8	16	32	64	128	256	512
	1024	0.818	0.498	0.302	0.185	0.133	0.107	0.094	0.087	0.084
	2048	0.651	0.305	0.128	0.054	0.019	0.0096	0.0043	0.0039	0.003
A6	4096	0.481	0.182	0.047	0.011	0.001	0.000	0.000	0.000	0.000
	8192	0.407	0.121	0.022	0.002	0.000	0.000	0.000	0.000	0.000
	1024	0.537	0.275	0.129	0.054	0.019	0.008	0.0026	0.0011	0.008
	2048	0.320	0.102	0.020	0.004	0.000	0.000	0.000	0.000	0.000
A4b	4096	0.213	0.057	0.011	0.000	0.000	0.000	0.000	0.000	0.000
	8192	0.155	0.031	0.004	0.000	0.000	0.000	0.000	0.000	0.000
	1024	0.823	0.460	0.236	0.119	0.070	0.041	0.032	0.028	0.026
	2048	0.810	0.431	0.219	0.105	0.053	0.034	0.025	0.020	0.019
A5b	4096	0.804	0.441	0.208	0.102	0.047	0.016	0.012	0.007	0.0055
	8192	0.770	0.412	0.182	0.078	0.033	0.015	0.0067	0.001	0.000
	1024	1.290	0.836	0.544	0.400	0.320	0.260	0.250	0.240	0.230
	2048	1.050	0.610	0.320	0.180	0.120	0.084	0.069	0.061	0.056
A6b	4096	0.877	0.437	0.178	0.070	0.021	0.0083	0.0036	0.0019	0.000
	8192	0.757	0.351	0.137	0.049	0.0126	0.0027	0.000	0.000	0.000

Table 5.15. Percentage Black Elements Lost, P_L, after SBIC with Pseudo-Scrambling of Blocks. (Cont'd)

P_{DW}	P_{DNW}	Field Size 2	4	8	16	32	64	128
0.1	0.025	0.044	0.071	0.093	0.090	0.059	0.023	0.0036
0.1	0.050	0.087	0.140	0.180	0.190	0.160	0.110	0.0540
0.1	0.075	0.130	0.200	0.260	0.290	0.290	0.260	0.2200
0.2	0.050	0.077	0.098	0.091	0.058	0.022	0.0034	0.0098
0.2	0.100	0.150	0.190	0.190	0.160	0.110	0.054	0.0140
0.2	0.150	0.220	0.270	0.290	0.290	0.260	0.220	0.1500
0.3	0.075	0.099	0.100	0.073	0.035	0.0082	0.5×10^{-3}	0.3×10^{-5}
0.3	0.150	0.190	0.200	0.180	0.130	0.076	0.027	0.0400
0.3	0.225	0.260	0.290	0.290	0.280	0.240	0.180	0.1100
0.4	0.100	0.110	0.093	0.056	0.021	0.0031	0.8×10^{-4}	0.7×10^{-7}
0.4	0.200	0.200	0.190	0.160	0.110	0.053	0.014	0.0011
0.4	0.300	0.270	0.290	0.290	0.260	0.220	0.150	0.0790
0.5	0.125	0.110	0.082	0.043	0.012	0.0011	0.1×10^{-4}	0.2×10^{-8}
0.5	0.250	0.190	0.180	0.150	0.090	0.037	0.0072	0.3×10^{-3}
0.5	0.375	0.230	0.270	0.280	0.250	0.200	0.130	0.0580
0.6	0.100	0.070	0.042	0.014	0.0017	0.3×10^{-4}	0.1×10^{-7}	0.2×10^{-14}
0.6	0.200	0.120	0.100	0.058	0.020	0.0025	0.5×10^{-4}	0.3×10^{-7}
0.6	0.300	0.150	0.160	0.130	0.074	0.026	0.0038	0.1×10^{-3}
0.7	0.100	0.050	0.026	0.0063	0.4×10^{-3}	0.2×10^{-5}	0.6×10^{-10}	0.7×10^{-19}
0.7	0.200	0.080	0.064	0.032	0.0072	0.4×10^{-3}	0.2×10^{-5}	0.3×10^{-10}
0.8	0.050	0.017	0.0051	0.4×10^{-3}	0.2×10^{-5}	0.1×10^{-9}	0.5×10^{-18}	0.8×10^{-35}
0.8	0.100	0.030	0.014	0.0026	0.8×10^{-4}	0.9×10^{-7}	0.1×10^{-12}	0.5×10^{-24}
0.9	0.050	0.0075	0.019	0.9×10^{-4}	0.2×10^{-6}	0.9×10^{-12}	0.3×10^{-22}	0.4×10^{-43}

Table 5.16. Probability of Overflow P_F Against Field Size F for various P_{DW} and P_{DNW} of Block-Pair Source.

Note $P_{DW} + P_{DNW} < 1.0$

Image \ F	2	4	8	16	32	64	128
A1	0.013	0.0044	0.00041	0.32×10^{-5}	0.21×10^{-9}	0.11×10^{-17}	0.43×10^{-34}
A2	0.138	0.137	0.103	0.052	0.014	0.0013	0.12×10^{-4}
A3	0.029	0.011	0.001	0.27×10^{-4}	0.13×10^{-7}	0.34×10^{-14}	0.35×10^{-27}
A4	0.041	0.022	0.0051	0.00026	0.87×10^{-6}	0.12×10^{-10}	0.32×10^{-20}
A5	0.086	0.057	0.023	0.0041	0.00015	0.26×10^{-6}	0.10×10^{-11}
A6	0.089	0.060	0.025	0.0047	0.00019	0.41×10^{-6}	0.23×10^{-11}
A4b	0.043	0.022	0.0049	0.00025	0.78×10^{-6}	0.10×10^{-10}	0.22×10^{-20}
A5b	0.153	0.134	0.093	0.045	0.012	0.00093	0.72×10^{-5}
A6b	0.142	0.119	0.075	0.031	0.0057	0.00024	0.53×10^{-6}

Table 5.17. Calculated Probabilities of Field Overflow for Independent Block-Pair Source Model.

Image \ F		4	8	16	32	64	128	256
A1	1	0.40	0.12	0.02	0.002	0.00	0.00	0.00
	2	0.21	0.05	0.01	0.00	0.00	0.00	0.00
A2	1	3.82	2.08	1.02	0.46	0.22	0.13	0.12
	2	2.35	1.23	0.51	0.01	0.04	0.01	0.00
A5	1	1.22	0.39	0.09	0.01	0.003	0.00	0.00
	2	0.80	0.23	0.06	0.01	0.00	0.00	0.00
A5b	1	2.62	1.40	0.70	0.36	0.20	0.11	0.07
	2	2.47	1.27	0.68	0.34	0.13	0.10	0.06

Table 5.18. Percentage Deleted Blocks for Coding with Scrambled Block-Pairs.

Image \ N(axb)		1 x 8	3 x 4	2 x 8	3 x 8	4 x 8	6 x 8
A2	P_o	0.6620	0.6261	0.6050	0.5590	0.5112	0.4403
	P_{DW}	0.6119	0.5590	0.5567	0.5117	0.4632	0.4040
	P_{DNW}	0.2765	0.2875	0.3237	0.3729	0.4239	0.5158
A5b	P_o	0.6377	0.7023	0.6011	0.5701	0.5409	0.4894
	P_{DW}	0.4316	0.5701	0.4017	0.3788	0.3562	0.3191
	P_{DNW}	0.1557	0.1631	0.1972	0.2375	0.2731	0.3388

axb $\triangleq$ no. of vertical pels x no. of horizontal pels of block

Table 5.19. Showing the Effects of Larger Block Sizes on Block and and Block-Pair Statistics.

N	M	CR
8	4	2.67
8	5	2.29
8	6	2.00
12	6	3.00
12	8	2.40
12	9	2.18
12	10	2.00
16	8	3.20
16	9	2.91
16	10	2.67
16	11	2.46
16	12	2.29

N	M	CR
20	10	3.33
20	11	3.08
20	12	2.86
20	13	2.67
20	14	2.50
24	12	3.43
24	13	3.20
24	14	3.00
24	15	2.82
24	16	2.67
24	17	2.53
24	18	2.40

N	M	CR
32	16	3.56
32	17	3.37
32	18	3.20
32	19	3.05
32	20	2.91
32	21	2.78
40	16	4.44
40	18	4.00
40	20	3.64
40	22	3.33
40	24	3.08
40	26	2.86

Table 5.20. Compression Ratios Obtained From SBIC Cascaded with Fixed N/M Coding.

r	No. of lines of image A1	CR	C_{UN}
141	1	1.51	1.17
282	2	1.81	1.32
423	3	1.95	1.43
564	4	2.02	1.47
705	5	2.07	1.49
846	6	2.10	1.51
987	7	2.13	1.52
1128	8	2.15	1.53
1269	9	2.16	1.54
1410	10	2.17	1.54

C_{UN} = Compression Ratio for 8/5 Universal Block to Block Coding alone.

Table 5.21. Compression Ratios Obtained from Cascaded 8/5 Universal Block to Block Coding with SBIC.

Image	F	N/M	SBIC Distortion	N/M Distortion	Total Distortion
A2	8	8/6	0.31%	0.15%	0.46%
A2	16	8/6	0.11%	0.15%	0.26%
A2	32	8/6	0.02%	0.15%	0.17%
A4	4	8/6	0.072	0.07%	0.14%

Table 5.22. Distortion Levels for Cascaded SBIC with 8/6 Coding.

p \ F	4	8	16	32	64
0.1 (1 in 10)	0.5695	0.81469	0.9656	0.9988	0.9999
0.03 (1 in 32)	0.2265	0.4018	0.6421	0.8719	0.9836
0.01 (1 in 100)	0.0773	0.1485	0.2750	0.4744	0.7237
0.001 (1 in 1000)	0.0080	0.0159	0.0315	0.0620	0.1202
0.0001 (1 in 10^4)	0.0008	0.0016	0.0032	0.0064	0.0127

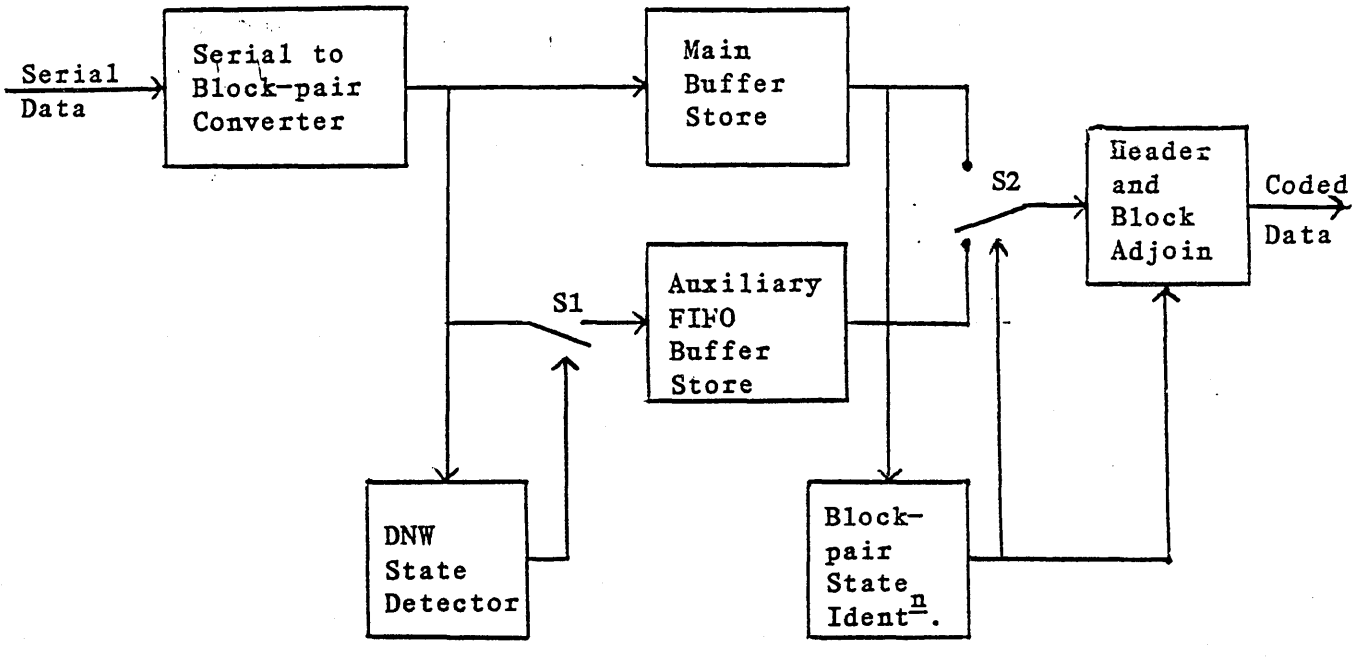
Table 5.23. Probability of Header Word Corruption P_E as a Function of Field Size F and Probability of Random Transmission Errors p. Average Error Rates are Given in Brackets.

F	Error Type	Average Rate	Percentage Received Bits in Error	Percentage Reconstruction Errors
16	Random	1 in 100	0.01	1.519
16	Random	1 in 32	0.0316	3.921
32	Random	1 in 100	0.01	1.608
32	Random	1 in 32	0.0316	4.342
16	Burst	1 in 32	0.0316	3.672
32	Burst	1 in 32	0.0316	4.097

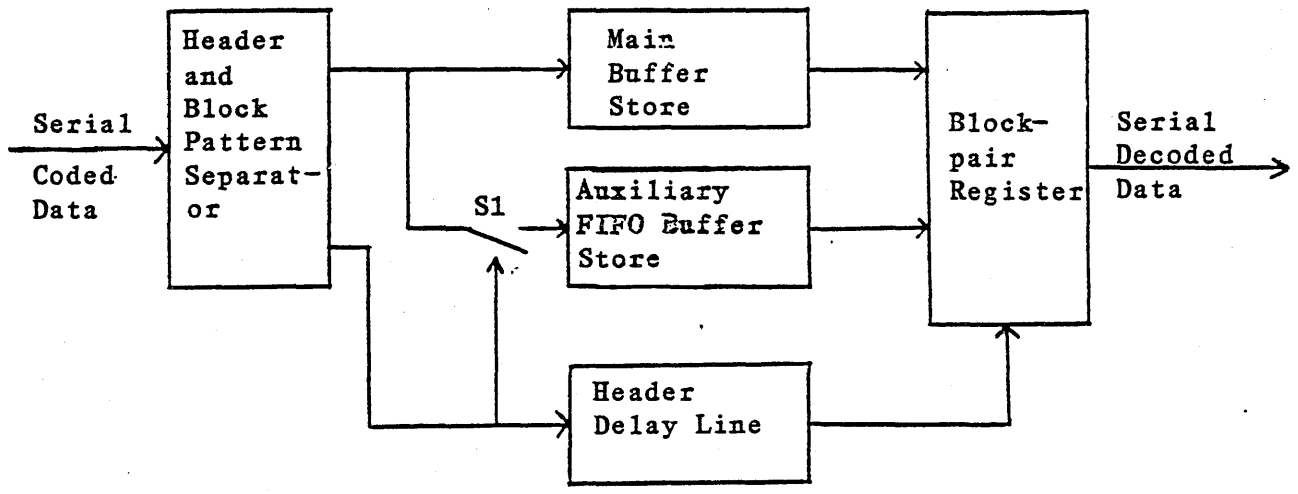
Table 5.24. A Selection of Percentage Reconstruction Errors in Noise Performance Trials for Uncascaded Scrambled SBIC Compression of Image A2 (S = 4096 blocks).

F	Error Type	Average Rate	Percentage Received Bits in Error	Percentage Reconstruction Errors
32	Random	1 in 1000	0.001	0.527
32	Random	1 in 100	0.01	2.954
32	Random	1 in 32	0.0316	7.709
16	Random	1 in 100	0.01	2.889
32	Burst	1 in 100	0.01	2.176
32	Burst	1 in 32	0.0316	5.888

Table 5.25. Percentage Reconstruction Errors in Noise Performance Trials for Cascaded Scrambled SBIC Compression (S = 4096 blocks) with 8/6 Block-to-Block Coding of Image A2.



(a) Encoding



(b) Decoding

Fig.5.1. The Sequential Block Interleave Coding Scheme.

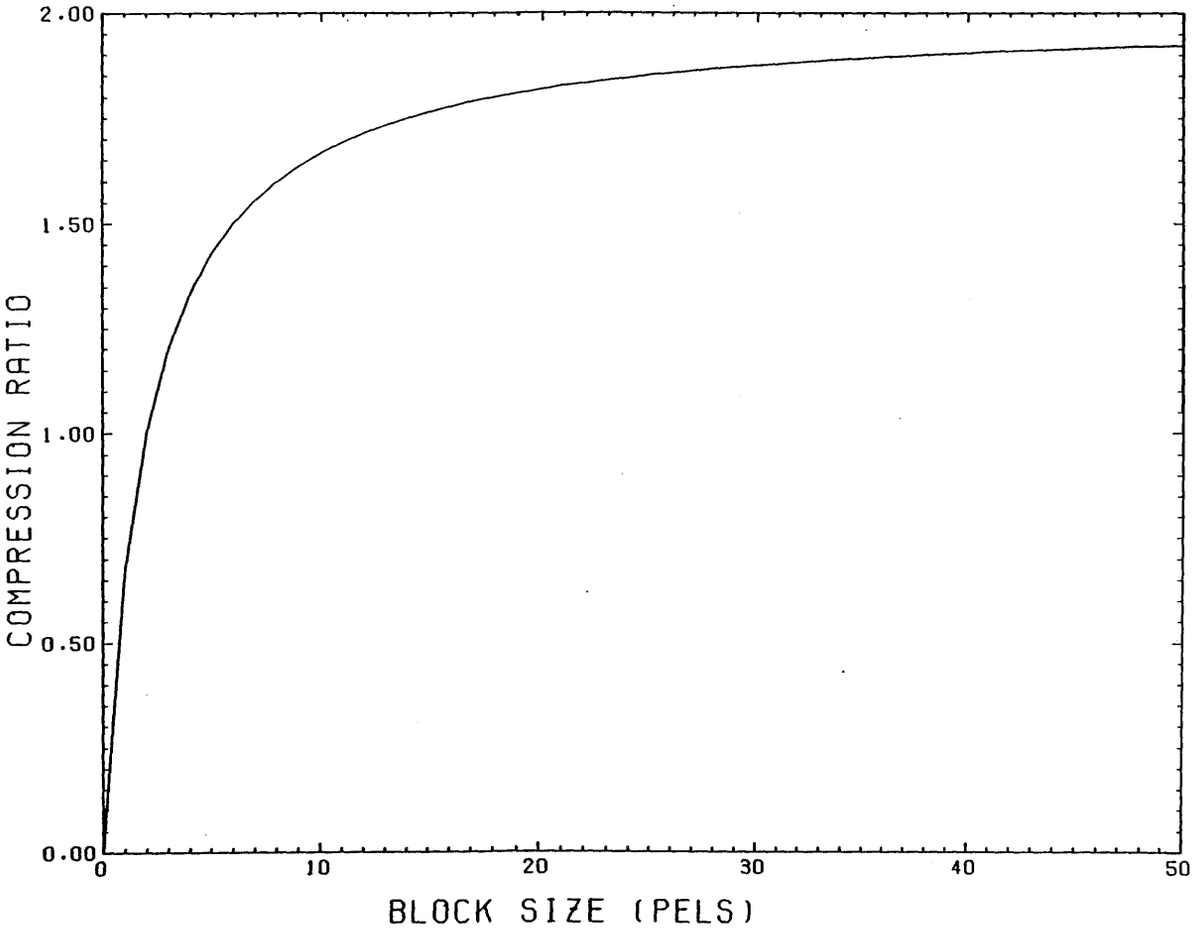


Fig.5.2. Compression Ratio as a Function of Block Size in SBIC Scheme.

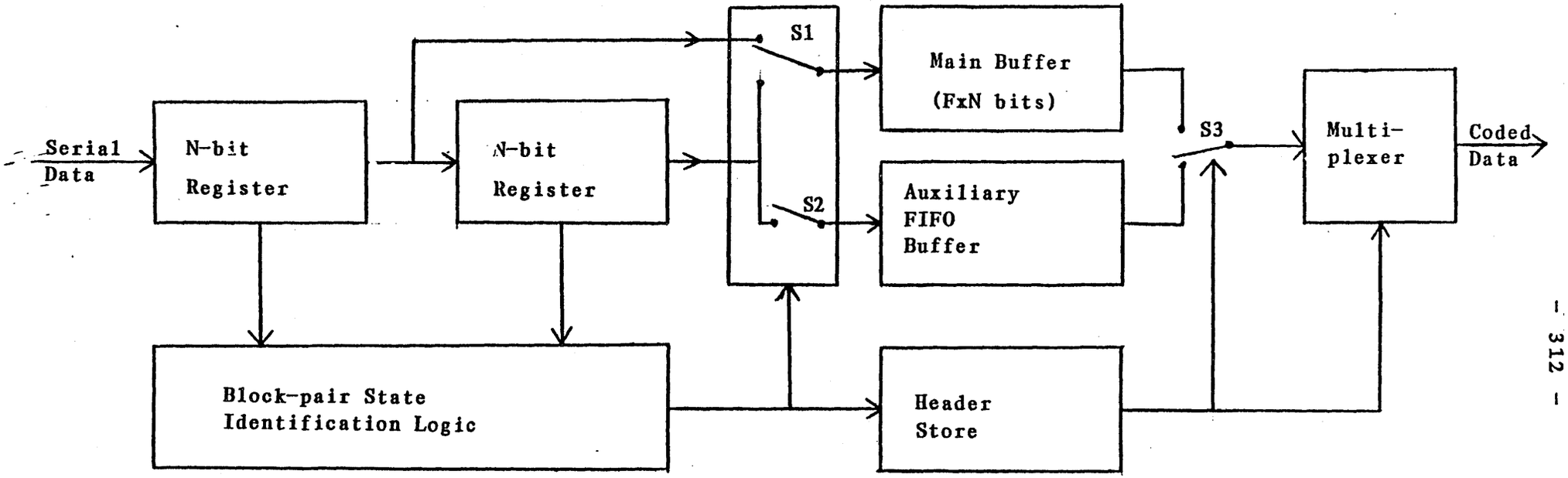


Fig.5.3. Block Diagram of Implementation of SBIC Encoder.

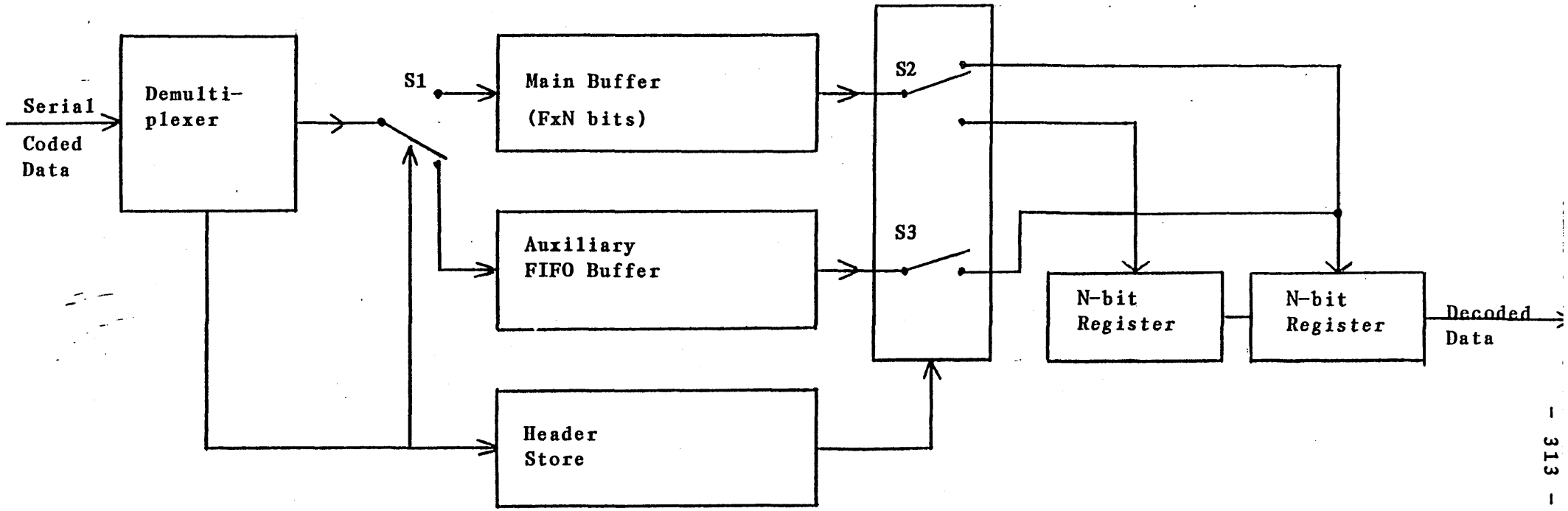


Fig.5.4. Block Diagram of Implementation of SBIC Decoder.

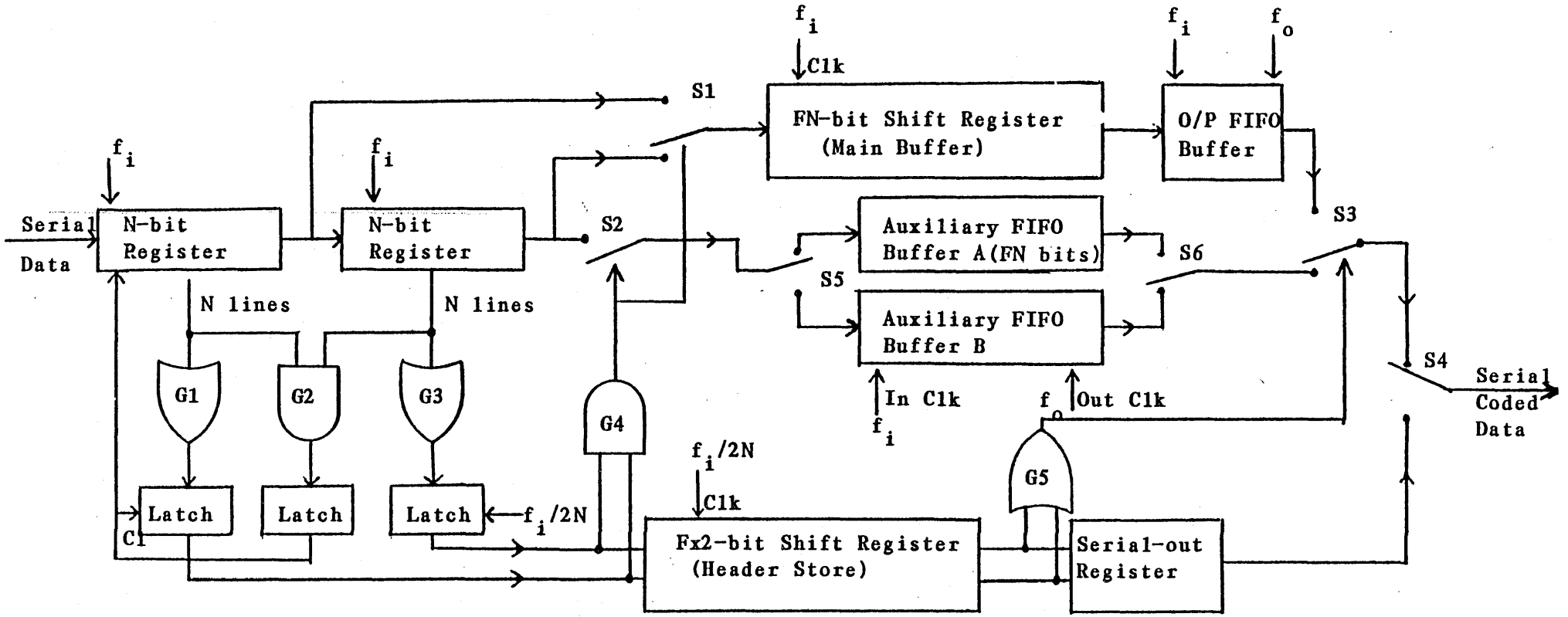


Fig.5.5. A Practical Realisation of the SBIC Encoder.

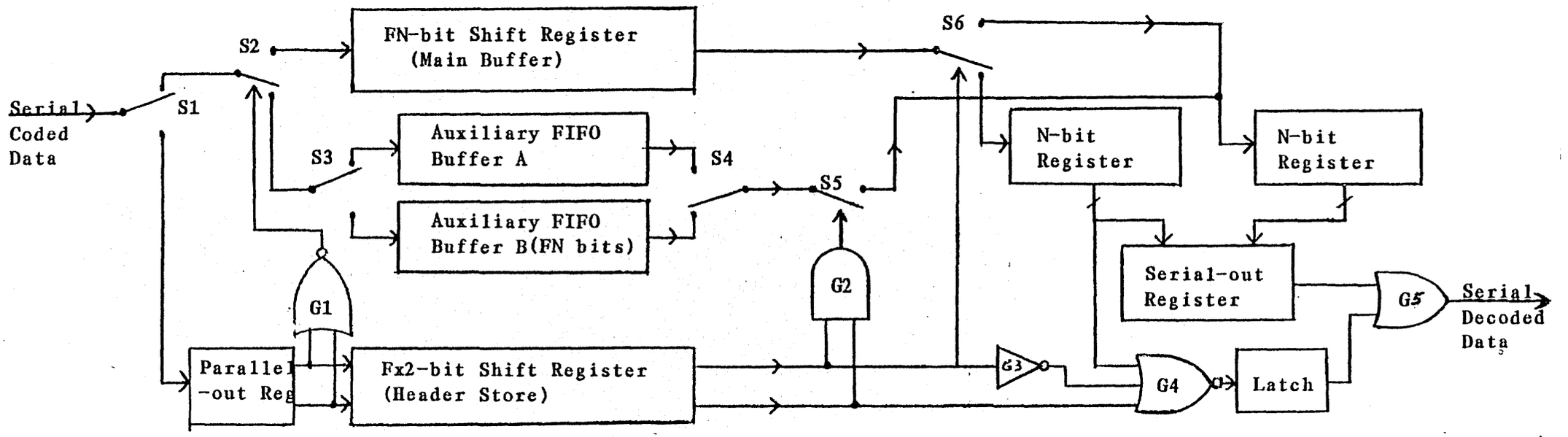


Fig.5.6. A Practical Realisation of the SBIC Decoder.

Fig.5.7. Data A1, SBIC with Field Size = 256 block-pairs.

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23/9/76

Our ref. ABC/DE/FG Your ref.

Dear Mr. One,

This letter has been written purely for the purpose of filling a part of the sheet of paper you see in front of you. I doubt very much whether you will be any wiser having read it, but I think you will agree that, from a distance, it looks like a very ordinary business letter, in fact, the sort of document which millions of people throughout the world receive every day. If I have succeeded in producing a "typical" letter, then I hope that the statistics I derive from it, and the processing which I perform on it, will also yield typical results for this class of document. In turn, such work may lead to a better understanding of the extent to which data compression techniques may be used. Please forgive me for wasting your time while you read this nonsense.

Yours sincerely,

D. W. TINDALL

P.S. If this letter did better your knowledge or understanding in any way, please let me know how.

Fig.5.8. Data A1, SBIC with Field Size = 512 block-pairs.

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IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
EXHIBITION ROAD LONDON SW7 2BT
Telephone: 01-589 5111 Telex: 261503
Ext. 1406

Mr. N. E. One
1 Somewhere Rd.,
Newtown,
Berks,
RG1 8LD.

23/9/76

Our ref. ABC/DE/FG Your ref.

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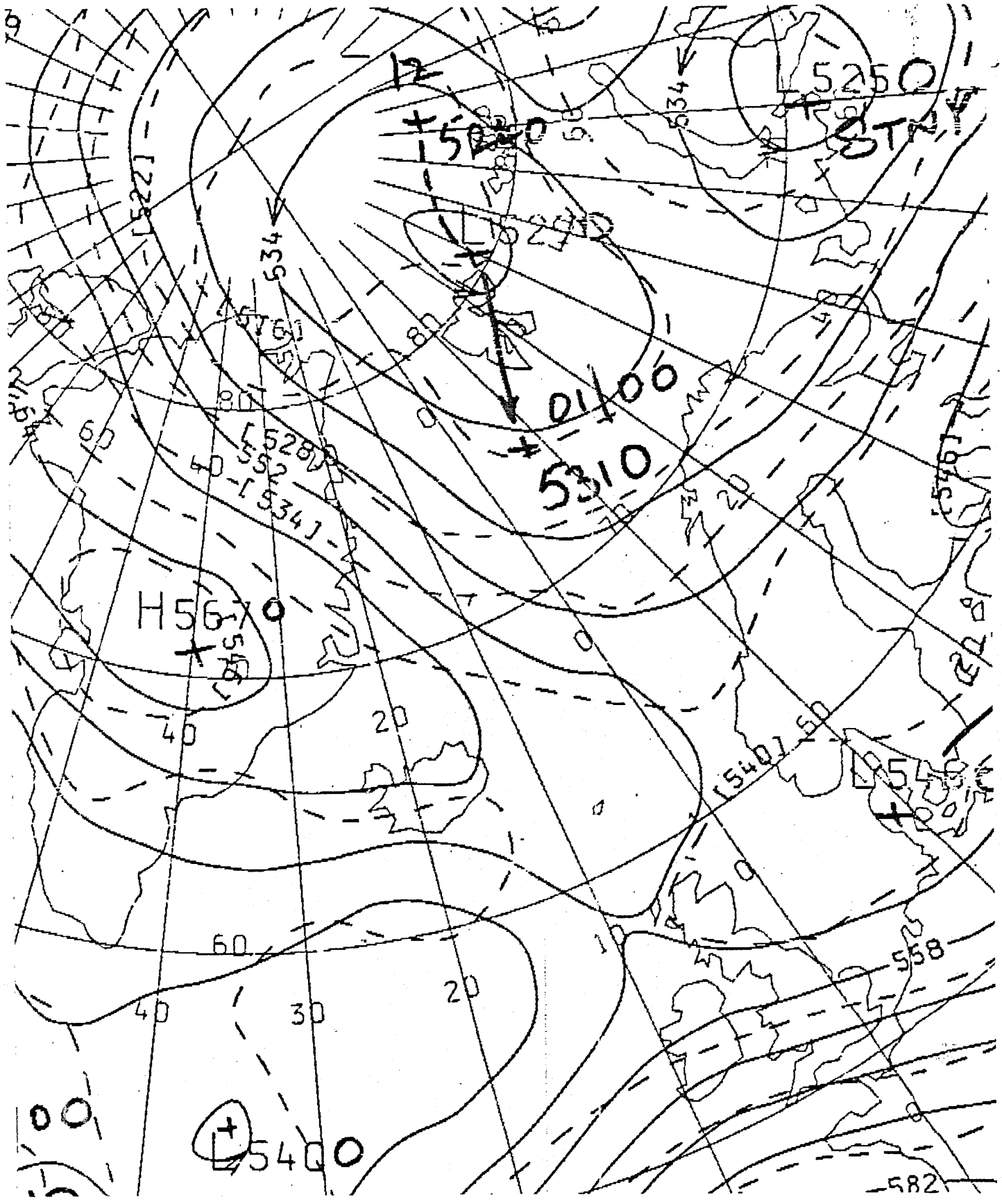
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Fig.5.12. Data A5, SBIC with Field Size = 16 block-pairs.



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Fig.5.14. Data A5a, SBIC with Field Size = 16 block-pairs.
Selective Deletion of Blocks Performed.

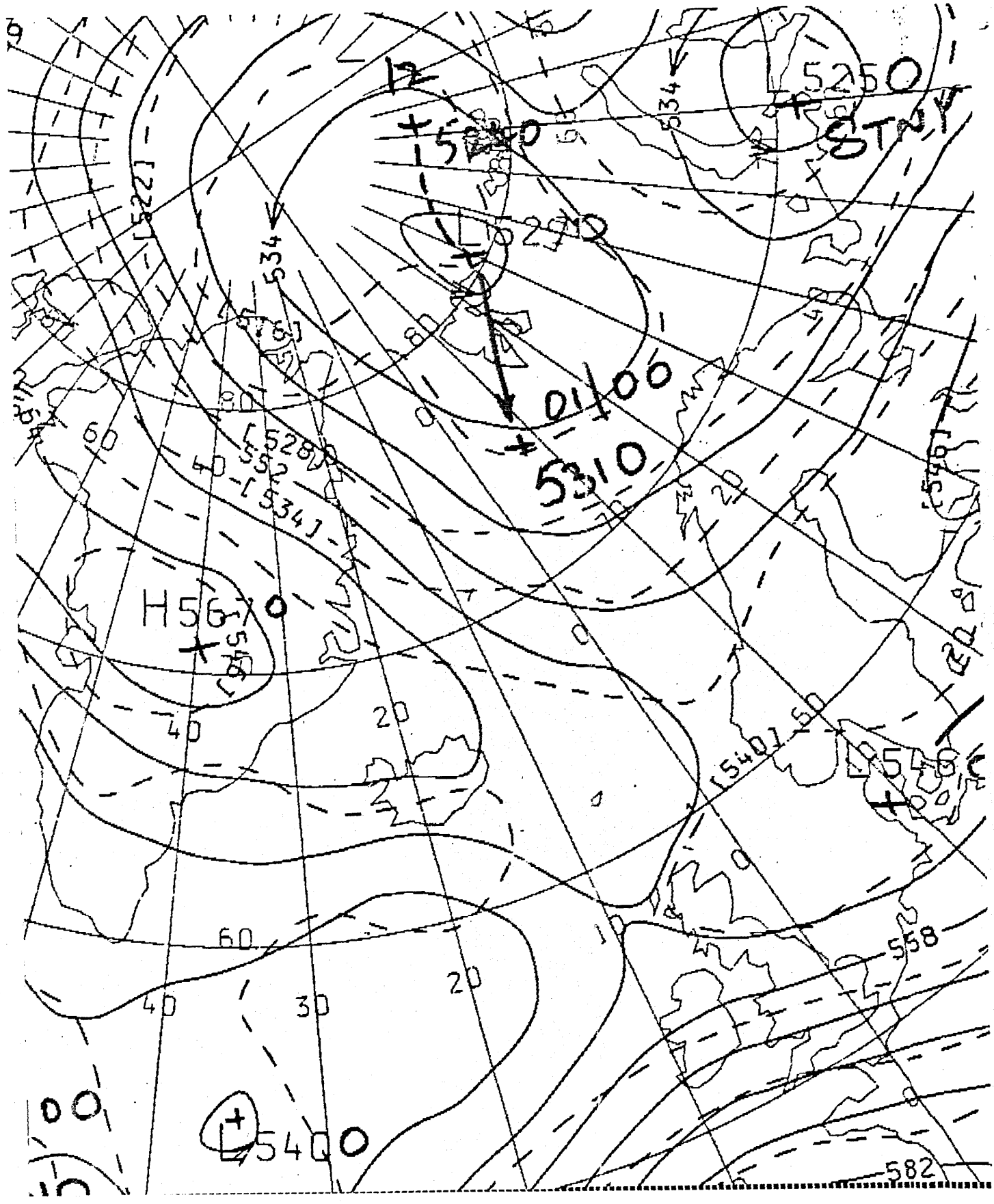
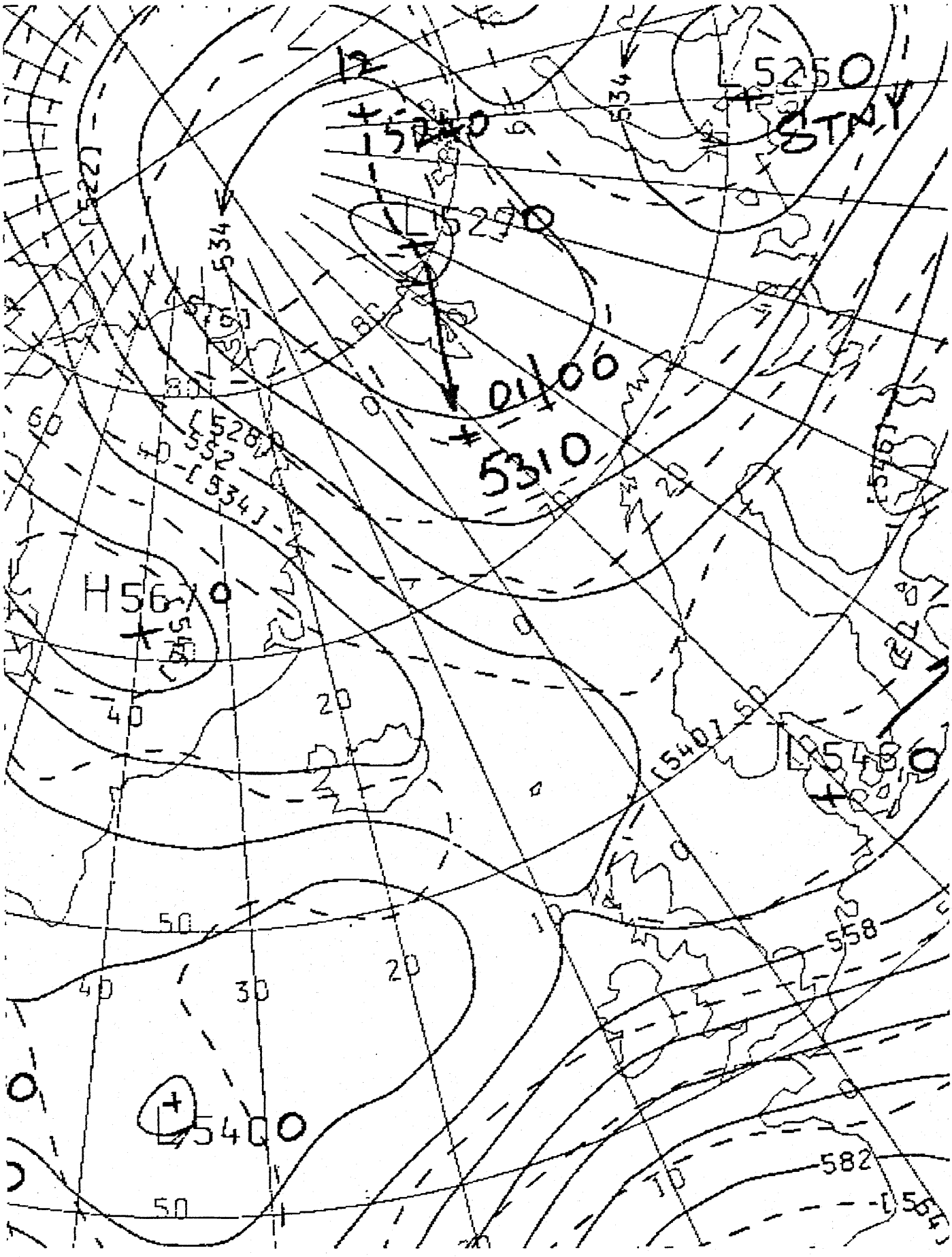


Fig.5.15. Data A5b, SBIC with Field Size = 35 block-pairs.
Selective Deletion of Blocks Performed.



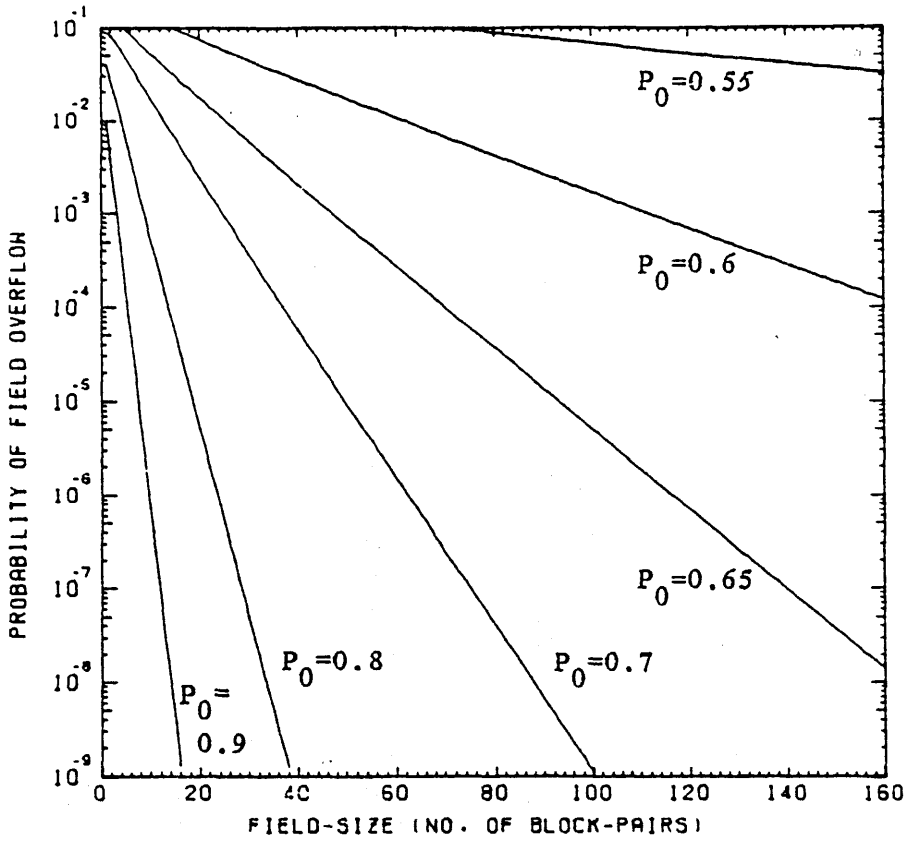


Fig.5.16. Probability of Field Overflow, P_F against Field Size, F for Various Probability of White Block Pattern, P_0.

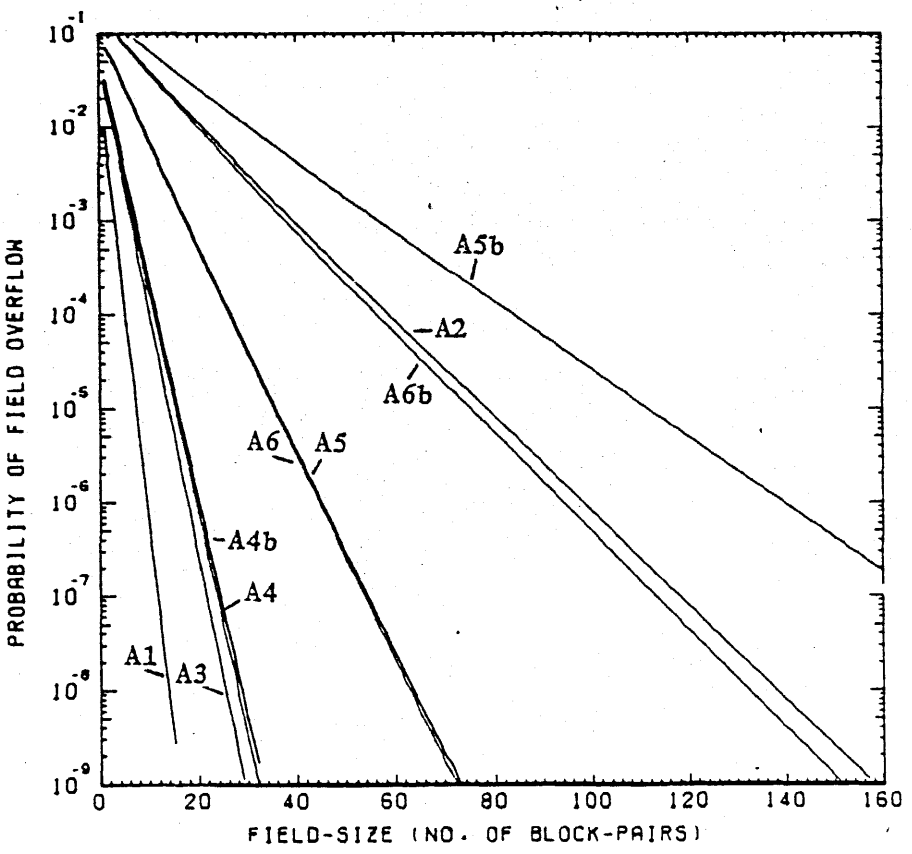


Fig.5.17. Probability of Overflow, P_F, against Field Size, F, for Test Images Assuming a Memoryless Block Source.

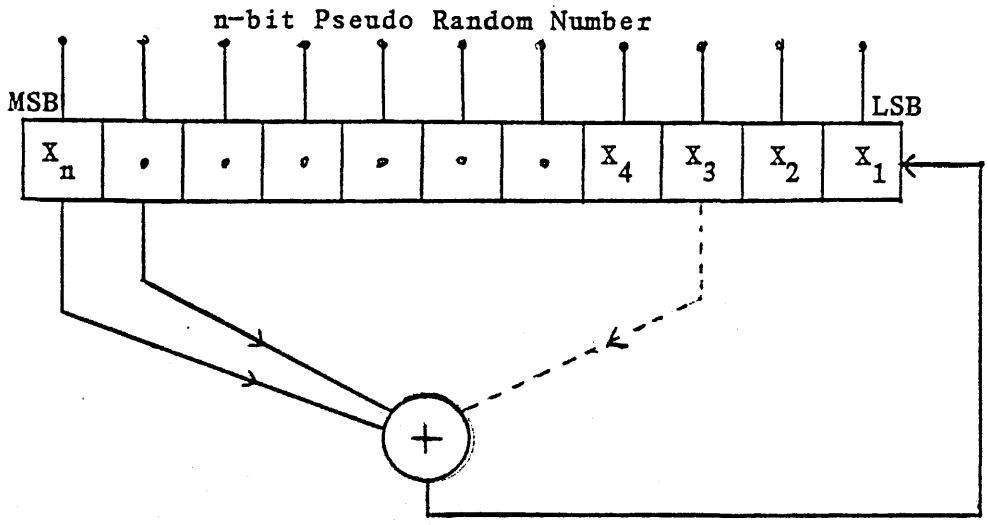


Fig.5.18. Arrangement for Generating a Pseudo-Random Sequence of n-bit Integers.

Shift Register Length(n)	Sequence Length	Tapping Points
2	3	X_1, X_2
3	7	X_2, X_3
4	15	X_4, X_3
5	31	X_5, X_3
6	63	X_6, X_5
7	127	X_7, X_6
8	255	X_8, X_6, X_5, X_4
9	511	X_9, X_5
10	1023	X_{10}, X_7
11	2047	X_{11}, X_9
12	4095	$X_{12}, X_{11}, X_{10}, X_2$
13	8191	$X_{13}, X_{12}, X_{11}, X_1$
14	16383	$X_{14}, X_{13}, X_{12}, X_2$
15	32767	X_{15}, X_7
16	65535	$X_{16}, X_{14}, X_{13}, X_{11}$

Fig.5.19. Tapping Points for Generation of Maximal Length Sequences.

Fig.5.20. Data A2 After Scrambling of Blocks.
Scrambling Segment Size = 4096 blocks.

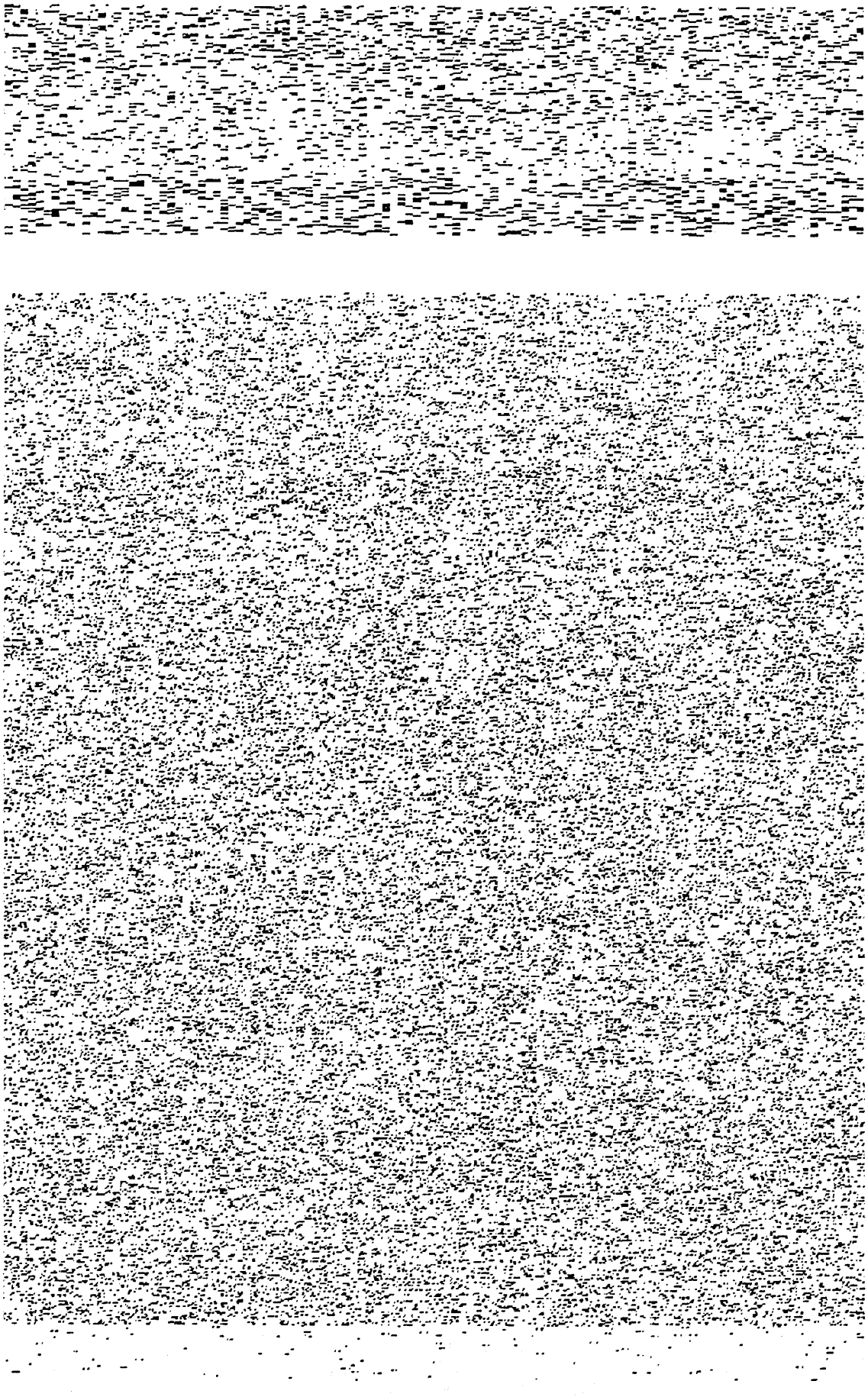


Fig.5.21. Data A1, SBIC with Scrambling of Blocks.
Field Size = 4 block-pairs, Scrambling Segment Size = 4096 blocks.

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Fig.5.22. Data A1, SBIC with Scrambling of Blocks.
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Fig.5.23. Data A2, SBIC with Scrambling of Blocks.
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Fig.5.24. Data A2, SBIC with Scrambling of Blocks.
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Fig.5.25. Data A2, SBIC with Scrambling of Blocks.
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Fig.5.26. Data A2, SBIC with Scrambling of Blocks.
Field Size = 32 block-pairs, Scrambling Segment Size = 4096 blocks.

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Fig.5.27. Data A4, SBIC with Scrambling of Blocks.
Field Size = 4 block-pairs, Scrambling Segment Size = 4096 blocks.

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC-tapes. Thus a set of "standard" digitised documents and drawings can be amassed for

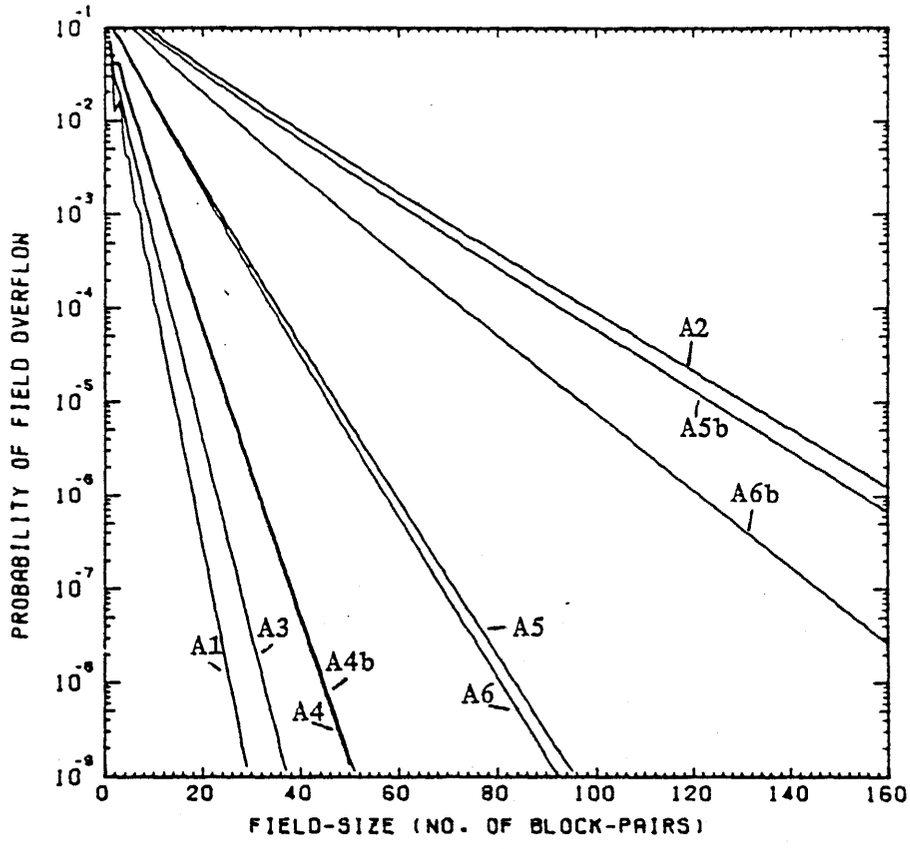


Fig.5.28. Probability of Field Overflow, P_F, against Field Size, F, for Test Images Assuming a Memoryless Block-Pair Source.

Fig.5.29. Data A2, Cascaded SBIC with 8/6 Coding. Scrambling of Blocks, Scrambling Segment Size = 4096 blocks. SBIC Field Size = 8 block-pairs.

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Fig.5.30. Data A2, Cascaded SBIC with 8/6 Coding. Scrambling of Blocks, Scrambling Segment Size = 4096 blocks. SBIC Field Size = 16 block-pairs.

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Fig.5.31. Data A2, Cascaded SBIC with 8/6 Coding. Scrambling of Blocks, Scrambling Segment Size = 4096 blocks. SBIC Field Size = 32 block-pairs.

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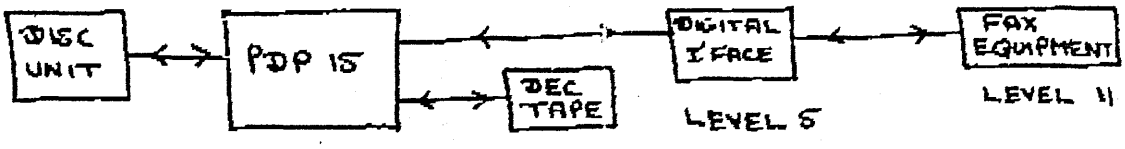
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Fig.5.32. Data A4, Cascaded SBIC with 8/6 Coding. Scrambling of Blocks, Scrambling Segment Size = 4096 blocks. SBIC Field Size = 4 block-pairs.

DATA TRANSFER



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be amassed for

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Fig.5.37. Data A2, SBIC with Scrambling of Blocks, Exposed to 1 in 32 Burst Transmission Errors. Field Size = 32 block-pairs.

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Fig.5.38. Data A2, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 1000 Random Transmission Errors. SBIC Field Size = 32 block-pairs. Scrambling of Blocks Performed.

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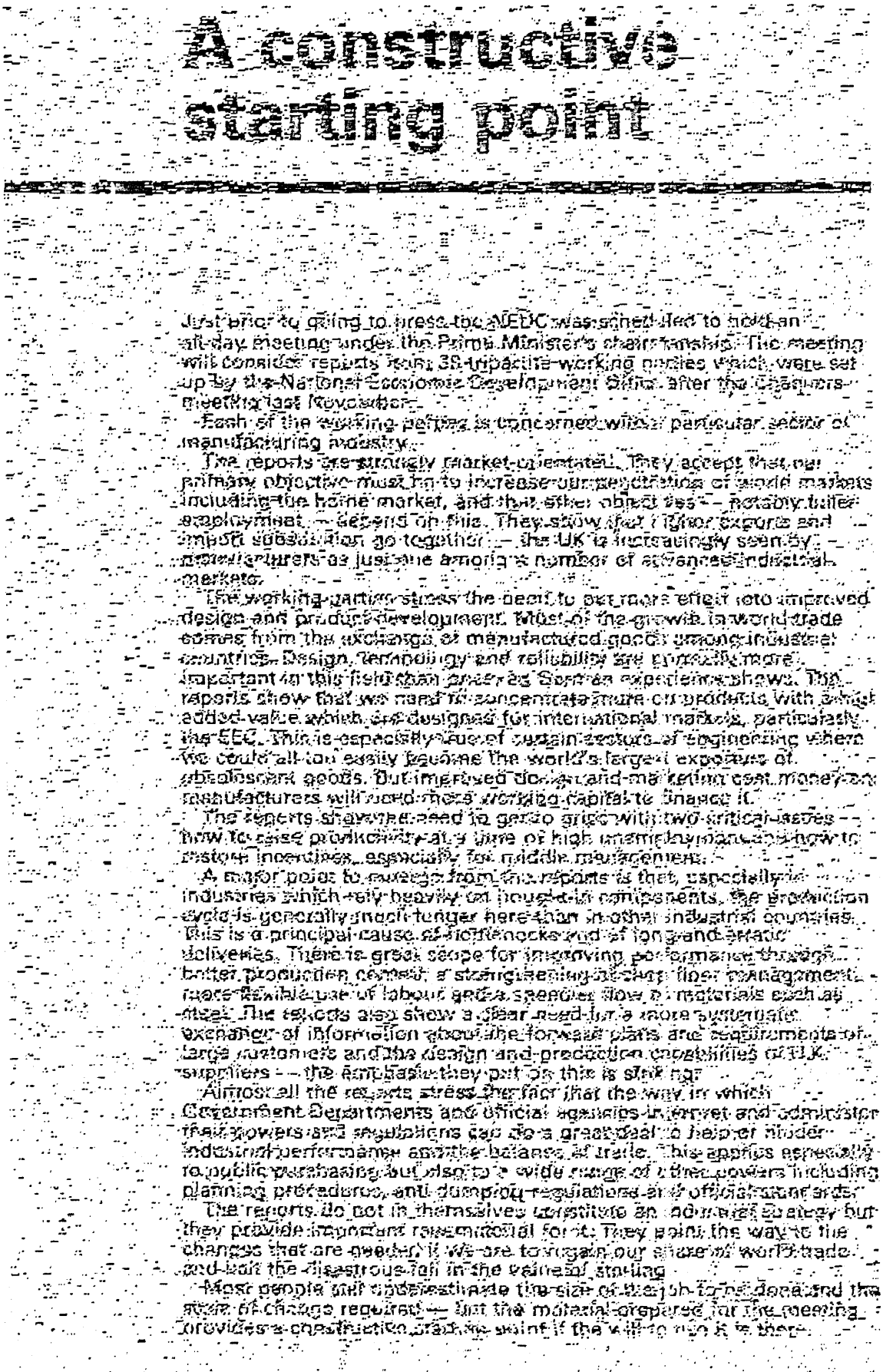
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Fig.5.41. Data A2, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 100 Random Transmission Errors. SBIC Field Size = 16 block-pairs. Scrambling of Blocks Performed.

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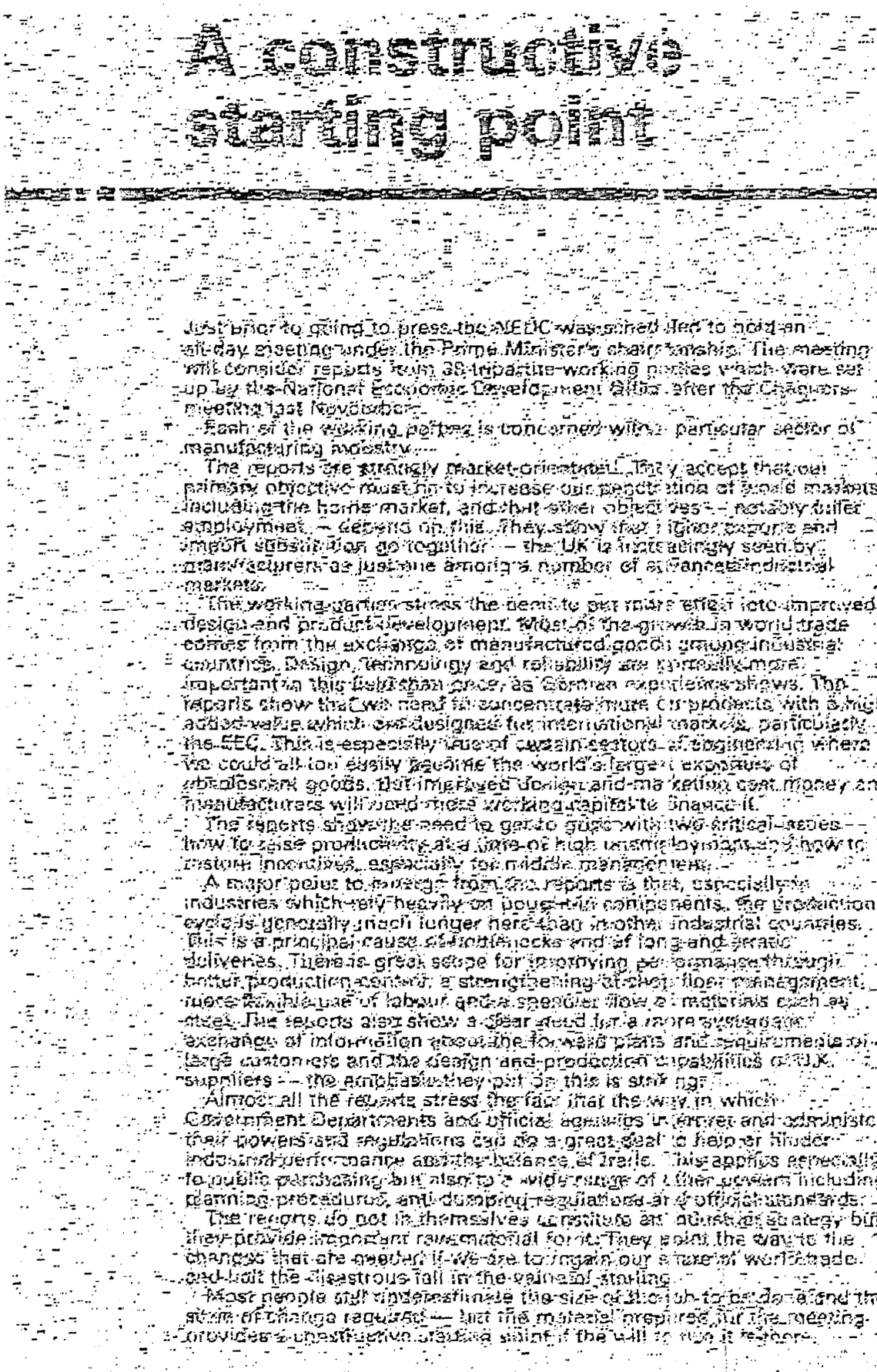
A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

Fig.5.42. Data A2, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 32 Random Transmission Errors. SBIC Field Size = 16 block-pairs. Scrambling of Blocks Performed.



A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives – notably fuller employment – depend on this. They show that higher exports and import substitution go together – the UK is frighteningly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the benefit per man effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are generally more important in this field than price, as German experience shows. The reports show the need to concentrate more on products with a high added-value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues – how to raise productivity at a time of high unemployment, and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials each step of the way. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of UK suppliers – the emphasis they put on this is striking.

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Fig.5.43. Data A2, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 100 Burst Transmission Errors. SBIC Field Size = 16 block-pairs. Scrambling of Blocks Performed.

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Fig.5.44. Data A2, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 32 Burst Transmission Errors. SBIC Field Size = 16 block-pairs. Scrambling of Blocks Performed.

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Fig.5.45. Data A1, Cascaded SBIC with 8/6 Coding, Exposed to 1 in 32 Burst Transmission Errors. SBIC Field Size = 4 block-pairs. Scrambling of Blocks Performed.

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Mr. X. Y. One
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Berks.
RG1 8LD.

23/9/76

Our ref. ABC/DEF/GO Your ref.

Dear Mr. One,

This letter has been written purely for the purpose of filling a part of the sheet of paper you see in front of you. I doubt very much whether you will be any wiser having read it, but I think you will agree that, from a distance, it looks like a very ordinary business letter. In fact, the sort of document which millions of people throughout the world receive every day. If I have succeeded in producing a "typical" letter, then I hope that the statistics I derive from it, and the processing which I perform on it, will also yield typical results for this class of document. In turn, such work may lead to a better understanding of the extent to which data compression techniques may be used. Please forgive me for wasting your time while you read this nonsense.

Yours sincerely,

D. W. FINDALL

P.S. If this letter did better your knowledge or understanding in any way, please let me know now.

CHAPTER 6

A DIGITISATION UNIT INCORPORATING THE SBIC COMPRESSION SYSTEM

6.1 Real-time Implementation of SBIC Compression System

In this chapter the development of a real-time system incorporating the SBIC technique for reduction of transmission time of the facsimile image is presented. This system has been constructed for use with Mufax analogue weather facsimile equipment and aims to achieve 10-minute transmission of a 22x18-inch weatherchart over the leased telephone circuit. In effect the analogue facsimile system is now replaced by a digital one in which redundancy in the digitised image is exploited to reduce the number of transmitted digits. Although the analogue equipment has facilities to enable 10-minute transmission by conventional analogue means, the performance has been found to be unsatisfactory over some leased circuits. This is largely due to the effects of restricted bandwidth and group delay distortion. Through digitisation an alternative transmission is possible. A straightforward digital approach will require the use of modems at each end of the line. This is an expensive solution and is circumvented by making the digitisation unit completely stand-alone ie. it incorporates its own digital transmission facilities. The low cost of the system has been made possible by putting to efficient use Z-80 microprocessors employed for compression and expansion, to realise a variety of transmission functions. This is possible because the relative simplicity of the compression and expansion operations allow for a large

amount of unused processing time to be made available. The software approach also results in a flexible transmission system.

In the following sections the design and implementation of the digitisation unit are described. Aspects of some transmission functions and requirements are briefly discussed where these are considered relevant. The software design is emphasised as this approach to implementation is relatively unconventional and is a key factor in achievement of low system cost.

6.2 System Considerations

Some features of the analogue Mufax weather facsimile equipment are first described. The Mufax K-150 Transmitter contains a scanner which consists of a cylindrical drum rotating at a constant speed and a traversing adjacent optical carriage on which is mounted the light source and sensor. The voltage output from this scanner is amplitude modulated onto a carrier and is transmitted to the receiver. In most transmissions the drum speed is set at 120RPM which allows the maximum size 22in.x18in. weatherchart to be transmitted in 20 minutes. A 240 RPM speed option is available which halves the transmission time but is only suitable on high quality leased circuits. The Mufax K-649 Receiver outputs the image on electrochemical paper which is marked by recording styli mounted on a helix and rotating at constant speed. It is started automatically and the recording speed and index of cooperation are also set by signals from the transmitter. Following reception of the start signal the receiver goes into a phasing stage lasting 30 seconds during which the transmitter sends start of line pulses (amplitude-modulated) and the receiver aligns its recording styli with these pulses. Following this, image transmission

proceeds and alignment of image becomes dependent on the stability of crystal-derived frequencies controlling the drive motors. Transmission is terminated when the stop signal consisting of a modulated tone is received from the transmitter.

The Mufax apparatus is at the present time used on the Meteorological Facsimile (MOLFAX) Network for the broadcast of weather information from the Meteorological Office in Bracknell to a large number of classified destinations (totalling more than a hundred) around Britain. Transmission occurs continuously throughout the day and night. On the Northern Loop of this leased network (which spans Northern England and Scotland) transmission is done at 120RPM speed setting because of poor line conditions. It is possible that a conversion to digital transmission may permit operation at 240 RPM over this ring circuit. In the design of the transmission system consideration is therefore given to the special frequency characteristics of this circuit. In particular the reduced bandwidth of this circuit is taken into account - the frequency space below 800 Hz is occupied by a telegraph channel. Apart from this little else was known of the circuit as access to it was not possible.

A straightforward digitisation of the system without compression will consist of digitising the output of the scanner, and feeding this to a modem. At the receiver the digital image signal is recovered from a second modem and fed to the recording amplifiers. Some arrangement for starting and phasing the receiver is also needed. The required transmission rate for this digital system is now determined for 240 RPM drum speed. Assuming that the CCITT recommended resolution of 200 pels/inch is desired the scan-line length of 18.7in. will contain a total of 3740 pels. At 240 RPM a line is scanned in 250ms. Hence the required rate of transmission is

3740 bits in 250ms or 14.96 Kbits/sec. More generally

Transmission Rate = Sampling Density X Drum Circumference X Drum Speed

(bits/sec) (pels/inch) (inches) (Hz)

A rate of 14.96 Kbits/sec clearly requires a highly sophisticated modem and exceedingly good circuits for successful transmission. If a compressor which features a CR of 2 is used at the transmitter the required rate is reduced to 7.5 Kbits/sec which is more within the capability of popular commercial modems. The nearest standard modem rate to this value is 7.2 Kbits/sec which corresponds to a resolution of 193 pels/inch. Subjective evaluation shows this sampling density produces excellent image quality. Further as the average height of characters in the weatherchart is slightly large at 2.5 mm a lower resolution of 128 pels/inch gives very tolerable image quality. At this resolution a cheaper 4800 bits per sec modem may be used.

Although it is totally feasible to convert to a digital system the cost of the modems is a prohibitive factor. Despite the general fall in prices, the cost of commercial modems which operate at the higher rates of 4800 and 7200 bps is still high. If the weather facsimile equipment is currently operating on a broadcast network a large capital outlay is demanded to install a modem at each of the numerous receiver sites. This is not to say that the use of modems will always be unattractive. For some circumstances gains in speed of transmission may be of overriding importance, or long-term economies may provide justification. Further, the modems may not neccessarily have to be dedicated to digital facsimile transmission alone.

In view of the high cost of the modem solution to digitisation it was decided that the digitisation unit should contain its own digital

transmission facilities capable of operating at the standard rates of 4800 bps and 7200 bps. It is clear that the inclusion of these facilities should not result in an expensive system. To this end the microprocessor at each end of the transmission line may possibly be utilised for the implementation of various transmission functions. However the limited capability of 8-bit microprocessors for signal processing operations is well-known and special software techniques will be required to enhance the speeds of computation.

In addition to low hardware cost the digitisation unit should require minimal interface to the existing facsimile apparatus. For a broadcast network this is especially important at the receiver end of the system. In view of this it was decided that the receiving unit should be completely detached from the Mufax recorder. A remodulator was incorporated into the unit which amplitude modulates the decoded image onto a local carrier before output to the recorder. A consequence of this strategy is an increased amount of circuitry for ancillary receiver functions like detection of control signals. The transmitter is allowed to make use of internal signals within the Mufax scanner thereby reducing hardware. Fig.6.1 shows the locations of the encoder and decoder sections which comprise the digitisation unit.

The main components of the digitisation unit are shown in Fig.6.2. At the transmitter the output signal of the constant-rate scanner is bi-level quantised and sampled. The resultant binary data is compressed and the output codewords are modulated on to a carrier for transmission over the telephone channel. At the receiver the codewords are recovered after the process of demodulation and detection and reconstitution of the image is carried out by the expandor. This is finally remodulated and fed to the

line signal input of the Mufax recorder.

The compression method employed is SBIC cascaded with fixed 8/6 block-to-block coding. The choice of 8 bits for the block size is most convenient as a low-cost 8-bit microprocessor may then be used efficiently to perform the coding and decoding. Further the performance for 8-bit blocks have been studied in the simulation on the computer. A fixed form of block-to-block coding is used instead of the adaptive universal coding because of its simplicity of implementation and also the images encountered in weather facsimile do not vary much in content. The homogeneous nature of images of the type in test images A5 and A6 also means that the scrambling of blocks pair to encoding is not essential. For high speed the block-to-block coding and decoding are performed using the ROM-lookup method. Entries for the ROM are similar to those used in the computer simulation.

As scrambling is not employed the field size F will need to be reasonably large in order that the probability of overflow is made sufficiently small. On the other hand it is desirable to keep the fields small in order to restrict the effects of transmission errors. It is also convenient to let a line contain an integer-number of fields with a small uncoded interval which is reserved for start of line information. The latter is desirable to prevent loss of field synchronisation in the course of transmission. At 128 pels/inch and 193 pels/inch a line consists of 300 and 450 blocks respectively. At the lower resolution the field needs to physically cover a larger section of image in order to increase the probability of all-white block pairs in the field. To this end a field covering half a line is used with the field size nominally set to 108 blocks. For the higher resolution a nominal field size of 54 block-pairs

is used which covers a quarter of a scan-line. These field sizes are made to be adjustable.

6.3 Choice of Modulation Method and Transmission Rates

The means of conveying the compressed image data to the receiver is now considered. For transmission over the bandpass telephone channel the binary stream may be recoded to obtain a power spectrum with very small low-frequency content or it may be modulated onto a carrier wave. The method of recoding is not usually used because the presence of a frequency offset in the received signal spectrum will result in incorrect detection. In the modulation method the amplitude, phase or frequency of a sinusoidal wave carrier may be varied in linear relation to the information signal. A comparison of the various merits for each type of modulation is given in [36]. For transmission rates above 2400bps the preferred modulation methods are vestigal-sideband amplitude modulation (AM-VSB) or quadrature amplitude modulation (QAM). For the digitisation unit a particular consideration is the truncated bandwidth of the Molfax Northern Loop - a reduced frequency range of 800-3000 Hz, and a bandwidth-efficient modulation method is therefore essential. The AM-VSB signal is essentially a signal-sideband signal whilst the QAM signal spectrum features both sidebands of the amplitude modulated spectrum but operates at a lower baud rate for the same rate of transmission. The QAM system also requires a two-channel equaliser at the receiver which is difficult to implement on a microprocessor. An incentive to the use of AM-VSB is that a VSB filter is already available in the scanner - which is used in the analogue transmission of the image. In view of the advantages it was therefore decided to use AM-VSB as the method of modulation for the compression system. The disadvantages of the method include greater sensitivity to

attenuation and group delay distortions and also variations in level of the signal.

The VSB filter inside the scanner is designed for a carrier frequency of 2400Hz which is a standard for VSB transmission over the telephone network. It is also convenient from the clock timing point of view to set the transmitted symbol rate at 2400 baud. The number of levels transmitted at this rate, is determined by the required resolution or sampling density of the image. For a compression ratio of 2, the use of eight and four levels, corresponding to transmission rates of 7200 and 4800 bits per second respectively, will result in sampling frequencies of 14.4 kHz and 9.6 kHz at the input to the compressor. As stated in the previous section this corresponds to horizontal resolutions of 128 pels/inch and 193 pels/inch respectively. The vertical resolution is fixed at 100 lines per inch and is determined by the pitch of the lead-screw which drives the traversing optical carriage at the scanner. In the author's view a sampling density of 125 pels/inch is acceptable. However the system is designed to allow a choice between the two densities with selection being determined by whether line conditions permit satisfactory transmission at the higher rate of 7200bps. In the absence of a return channel automatic fallback of transmission rate is not possible.

To facilitate recovery of symbol timing at the receiver a pilot tone is transmitted at a frequency of 800Hz which is just on the edge of the passband. Although the baud rate is the same as the carrier frequency the receiver is not able to use the extracted carrier because of the possible presence of offset in the received carrier frequency. Instead the difference in frequency between the pilot tone and carrier is obtained and multiplied up by 3/2 to get the desired frequency of 2400Hz.

6.4 Implementation of Encoder at Transmitter

6.4.1 System Functions

Fig.6.3 shows the functions which are performed in the encoder and the implementation is shown in Fig.6.4. Quantisation and sampling of the input from the scanner is easily accomplished using a comparator and D-type flip-flop. The clocked binary data is then formatted into 8 bits and read by the microprocessor. The processor compresses the image data and the output binary codewords are subsequently modulated on to a square-wave carrier at 2400Hz. Prior to this the modulating digital waveform is shaped by a filter. The processor outputs the modulated signal and pilot tone as 12-bit quantised samples at 9600Hz. The DAC output is then fed to the VSB filter inside the Mufax transmitter from which it subsequently outputs to line. The simplicity of the hardware here is made possible by using the processor employed for data compression to perform transmission functions. This is made possible by the relative simplicity of the SBIC compression method which makes available a large amount of surplus processing time. As a consequence apart from the DAC and increased memory requirements there is little in the way of extra circuitry. The integrated software approach has the additional advantage of being highly flexible - a feature which is very useful in the design of transmission equipment.

A more detailed diagram of the microprocessor circuitry is shown in Fig.6.5. The 6 MHz Z-80B CPU is employed and is supported by a 4Kx8-bit EPROM which contains the working program and 6 Kbytes of static RAM. To

minimise hardware, clock signals from the Mufax transmitter are used. This of course means that connections to internal components of the transmitter are required when installing the encoder but as the number of transmitters are small on a weathermap broadcast network this is not considered to be a major inconvenience. A number of control signals are also tapped from the transmitter circuits. These include the Start Transmitter which resets the microprocessor and initiates the sequence of events, the phasing pulses which provide the phasing information to the receiver for purposes of correct alignment of its recording stylus, and the Page Enable signal which is polled by the processor to ascertain the start and end of image transmission. A 2400Hz interrupt pulse train controls the input and output of data. For output a FIFO buffer is used so that the processor is free from timing problems when delivering output samples. The contents of the buffer are clocked out to the DAC at a constant rate of 9600Hz and the DAC output is returned to the transmitter's VSB filter from where it goes to line. The circuit diagram of the encoder is given in Appendix 3.

6.4.2 Input and Output Handling

The reading in of raw image data and writing out of signal samples to the FIFO buffer are initiated by pulses on the interrupt line which suspend the processor's main operations and force immediate response to I/O needs. As the pulses arrive at a constant rate of 2400Hz, for each interrupt four 12-bit samples are output to the FIFO buffer (which is clocked at 9600Hz) and the input flip-flop is scanned to determine if a new byte of image data is ready for input. Within the processor a dual buffer system stores the input and output data. Thus two buffers IA and IB hold alternately the input data for a coding field. When one is full a flag is set and the other is filled next. Similarly two buffers PBA and PBB hold the data for

output. For each data word taken out four samples are output to the DAC after filtering and AM modulation.The details of these operations are discussed later.The timing of events involved in the processing is shown in Fig.6.6.

6.4.3 The Compressor Program

The compression consists of two stages - SBIC compression of 16-bit block-pairs and 8/6 encoding of 8-bit block patterns. If a ROM method is used to implement the latter it becomes a relatively trivial procedure involving only a lookup operation. The flow diagram for the compression for a field of data is shown in Fig.6.6. The processor loops through this program throughout transmission and exits only when the end of transmission is detected on the Page Enable line. Throughout the compression program the processor is constantly interrupted for input-output operations. Thus the total time taken to advance through a compression cycle will be the sum of the total interrupt servicing time and the total execution time of the instructions in the program cycle. The latter depends of course on the image material, in particular the number of double-nonwhite block-pairs in the coding field. It is clear that for correct operation the compression cycle must be completed before the next input buffer is filled.

Referring to Fig.7.7, at the start of the compression cycle the processor polls the buffer ready flag. During this time the Page Enable line is also checked to determine if the transmission is ended. When the buffer flag is raised the processor identifies which of the buffers IA or IB has been filled and proceeds to copy the contents of the buffer into a temporary input store Z. There block-pair patterns are examined and the status of each is stored as a 3-bit word in buffer S1 (all-black patterns

are specially tagged). For double-nonwhite patterns the Hamming weights of the constituent blocks are obtained and the block with the smaller weight is stored in X1. The address location of this block is stored in X2. The Hamming weight is obtained by looking up a 256-byte table containing weight values of all possible patterns. Counts are kept of the number of double white and double nonwhite patterns in the field. When all block-pairs in the field have been examined the difference DIFF between the two counts is obtained. If the double-nonwhite count BBCNT exceeds the double-white count WCNT field overflow has occured and the selection of blocks for deletion is called for. This is done by recording the Hamming weights in X1 (and their address locations in X2) in descending order of magnitude. The sorting technique used here operates by successively finding the minimum values of a shrinking set. At each iteration the minimum value of the set of Hamming weights is found, this value is removed from the set and the next iteration does the same for the reduced set. In this way the address locations of the blocks to be deleted are found after DIFF iterations. Using the address indices now the approximate blocks in the input buffer Z are required to be blanked. However instead of clearing entries in Z their status words in S1 are altered. The nonwhite buffer for carrying is next formed in X1 by scanning the status words in S1 and copying the right blocks of double-nonwhite blocks from Z into X1. This has to be done after the deletion process to allow for block-pairs which have been subject to deletion. The encoding of the block-pairs then commences. For each block-pair the appropriate 2-bit header word and 8-bit data word are stored in separate buffers HA and OA respectively. For the all-white pattern an entry from the surplus buffer X1 is extracted if it is not empty and forms the data word for the block-pair.

At the end of the encoding process the codewords are packed into

two-bit or three-bit words, depending on rate of transmission, and stored in output buffers PBA or PBB. During this process the 8-bit data word is encoded with a 6-bit code derived from the 8/6 coding ROM table. In order to reduce the incidence of detected errors at the receiver the dibit or tribit words are Gray-coded. This is again performed through the use of coding tables.

On completion of these operations the processor returns to the start of the cycle where it waits for the next buffer to be filled. If the end of transmission is detected it exits from the cycle and configures the interrupt routine for output of the stop signal. The processor is finally halted after several seconds of this signal output.

6.4.4 Shaping the Transmitted Signal Spectrum

The output of the compressor consists of a train of pulses whose amplitudes belong to a set of 4 or 8 values for 4800 and 9600 bps transmission respectively. Direct modulation of this digital waveform on to a carrier, although convenient does not neccessarily provide for the best performance in terms of successful detection of the transmitted levels at the receiver. The shape of the modulating waveform has a significant effect on the amount of distortion which is seen at the detection instants at the receiver.According to Nyquist's vestigal symmetry theorem ISI is reduced (or eliminated at the zero crossing points) in baseband signalling if the transmission channel's magnitude response exhibits a symmetrical roll-off at its cut-off frequency and the phase response is zero or linear. Although for all such cases where these conditions are met the ISI component is zero at the zero crossing points of the impulse response the ISI increases rapidly if sampling jitter causes the detection instants to

stray from the zero crossing points - this ISI is worse for narrower roll-off regions. However wider roll-off regions imply a larger transmission bandwidth so a compromise of width of roll-off region is often required. A suitable roll-off characteristic is the raised cosine response which is superimposed on the ideal lowpass response of the channel cutting off at the Nyquist frequency of half the signalling rate. As seen from Fig.6.8 a wider roll-off incurs increased bandwidth but the amount of ringing and potential cause of ISI is reduced in the impulse response. The amount of roll-off can be represented by the percentage roll-off k where

$$k = \frac{\text{Half-Period of Raised Cosine}}{\text{Nyquist Frequency}} \times 100$$

Thus a 100% raised cosine spectrum corresponds to the fully cosinusoidal response which occupies twice the Nyquist bandwidth.

A typical telephone channel has a frequency response which is quite removed from the vestigial symmetry roll-off response described previously. The phase response is far from linear and instead of rolling off gently the attenuation response drops abruptly at the band edges. The presence of a lower cut-off frequency does not affect the validity of Nyquist's theorem for minimum ISI if symmetrical roll-offs occur on both edges of the frequency band (Fig.6.9). Obviously the transmitted signal spectrum in this case is that of an AM-modulated signal. Economical use of bandwidth is achieved by employing vestigial sideband modulation (VSB) in which a vestige or portion of one sideband (the upper in this case) is discarded. To avoid distortion after demodulation, which must be synchronous, a symmetrical cut-off about the carrier frequency is required.

As a result of the group delay and attenuation of the channel the received signal will contain intersymbol interference the extent of which

depends on the channel response. Whilst an equaliser can be used to reduce the ISI it is limited in performance by its finite length and cannot compensate fully for the severe attenuation at the band edges. It is therefore desirable to keep as much of the transmitted signal power to frequencies within the passband of the channel. For leased lines a relatively flat response exists between 400Hz and 3000Hz and a good aim is to locate the VSB spectrum including its symmetrical roll-offs within this band. On the Molfax network the 350-800Hz region is occupied by a telegraph channel so that the available bandwidth is 800-3000Hz. As the baud rate for transmission is 2400Hz a raised 25% cosine roll-off shaped about the Nyquist frequency of 1200Hz is a suitable design objective. As shown in Fig.6.10, after modulation the spectrum will exhibit the symmetrical roll-offs about 1200Hz and 2400Hz. The entire signal spectrum is now contained within the passband of the channel with little or no frequencies existing below 800Hz, the lower cut-off frequency of the Molfax circuit.

6.4.5 Implementation of 25% Raised Cosine Spectrum Filter

The means of implementing the pulse shaping filter which will give the desired symmetrical 25% roll-off about the Nyquist frequency is now considered. A further requirement of this filter is that the phase response should be linear. For this reason a digital transversal filter which exhibits symmetrical coefficients will be used. Such a filter always features a linear phase response and yields a finite pulse response described by the coefficient values. The filter equation is given by

$$Y_i = \sum_{j=0}^{N-1} C_i X_{i-j} \qquad 6.1$$

for an N-tap filter where the output Y_i at time iT is produced by the weighted sum of current and delayed samples X_{i-j} (see Fig.6.11). The filter design is one of determining the filter length N and the set of coefficients Cj. As the pulse response is defined by the values of the coefficients it is reasonable to set the coefficient values to the samples of the desired impulse response given in Fig.6.8(b). A total of 32 samples is taken with four samples per sampling interval of the response. This will require a clock frequency of 9600Hz for the 32-tap filter. This is considered to be adequate as the maximum analogue frequency at the output of the filter is now 4800Hz which is outside the channel bandwidth - any further increase in clock rate to accomodate more samples per signalling interval will be superfluous.

The transversal filter is normally implemented with the use of shift registers and summing operational amplifiers. As the input consists of only a few levels, the delay line of shift registers is not unduly complicated. However the use of analogue circuitry for weighting and summing makes the implementations sensitive to drift. This is avoided in a totally digital implementation in which digital computation is carried out on the input samples. The microprocessor is capable of performing arithmetic operations but most take a relatively long time to perform the many multiplications demanded in Eqn.6.1. Thus if the Z-80 microprocessor is to be used in performing the filtering and leave enough time for the compression and other functions, a high speed filtering algorithm will be required. One such algorithm is described in [37] and will be employed here. This avoids multiplications by the use of distributed arithmetic and precomputed coefficients. Details of the method are given in Appendix 1.

In the implementation the 32 taps are partitioned into 4 and lookup values are quantised to 16 bits. It is noted that the filter will output the desired sampled response when the input is a pulse whose width is the delay period. This means that the input will consist of a succession of such pulses arriving at the baud rate of 2400Hz. Thus for three-quarters of the time the input is zero. The distributed arithmetic delay line therefore only needs to be 8x3 bits long for an 8-level input. This delay line is readily accomodated in internal registers of the CPU thereby greatly enhancing speed of operations. It is also noted that the first of 4 sets of 8 coefficients is non-zero only for the middle coefficient which obviates the need for a lookup table. The total memory required for the lookup tables is reduced to $1\frac{1}{2}$ kilobytes. During each filter cycle four output samples are produced which are modulated on to a square-wave 2400Hz This simply involves negating the last two samples before output to the FIFO buffer.

6.4.6 Generation of Pilot Tone and Start/Stop Signals

To facilitate symbol timing recovery at the receiver a pilot tone of 800Hz is transmitted. This tone is best generated by the processor in order to preserve the correct phase relationship with the signal timing. A table of 16-bit sine-wave values is used, for this purpose a sine-wave value is looked up and added to the signal sample before each output to the FIFO buffer. The frequency of 800Hz is obtained by storing 12 samples of a period of sine wave and cyclically outputting these at 9600Hz. The amplitude of the tone is set at about an eighth of the maximum carrier amplitude.

The processor is also used to generate the start and stop signals

which indicate to the receiver the commencement and termination of a transmission. These take the form of modulated tones of 300Hz and 480Hz respectively. Although signals from the Mufax transmitter could have been used it was decided to generate these independently from the processor in order to maintain control of the transmitted line signal and its level. Within the interrupt service routine square-wave frequencies of 300Hz and 480Hz are readily generated by use of counters and presented to the input of the baseband filter.

6.5 Transmission of Synchronisation Information

Before transmission of the image commences the transmitter sends phasing pulses spaced at line intervals to the receiver. These will be used by the receiver to phase the recording element and also to set up the equaliser in the decoder. Following output of the start signal the processor sends an unmodulated maximum carrier level for a period of 2 seconds. The AGC amplifier in the decoder sets up the signal gain from this reference amplitude. The processor then reads the phase pulse line from the Mufax transmitter and presents this to the filter input for shaping and subsequent modulation. The pulses are of maximum amplitude and their widths are fixed at 20ms. The phasing period continues until the Page Enable line goes high indicating that the scanning of the image is commenced. The time period of the phasing stage is about 30 seconds during which 120 pulses are output at a frequency of 4Hz.

During transmission of the coded image start of line information is also dispatched at the start of each line as defined by the pulses on the Phasing Pulses line. This takes the form of a consecutive string of maximum positive levels at the input to the filter and terminated by a

second different level. To accomodate this the line of image does not contain exactly an integer number of fields but a little amount is left over to fit the start of line information in. During output of data a check is made of the number of fields and when the total in a line has been reached data input and output operations cease and the processor enters a sync mode in which it polls the Phase pulses line from the Mufax transmitter for the start of the next line. Until this is detected (see Fig.6.6) the processor feeds the filter with maximum positive levels. When the start of line is detected a special level is transmitted and input and output operations resume for a new field. At the receiver a number of consecutive maximum positive levels is the criterion for establishing end of line whereupon the receiver processor waits for the special level before it restarts its input and output operations.

Strictly speaking synchronisation during image transmission is not neccessary as long as framing information can be established at the start of the image transmission. However the system now becomes sensitive to any temporary loss of timing information however brief - once synchronisation is lost a catastrophic loss of image results. As the line of scan contains a small amount of dead time there is no actual sacrifice of image data in allocating a time slot for start of line synchronisation information. The output of maximum positive carrier level during this period also helps to sustain an in-phase carrier component in the line signal.

Fig.6.12 summarises the sequence of operations in the encoder. The timing of events is given in Fig.6.13.

6.6 Data-aided Carrier Sustenance

It is apparent that the type of modulation employed is a supressed-carrier system as no bias is added to the modulator input in order to produce an in-phase carrier component. The advantage of supressed carrier modulation is that all the transmitted power is in the information sidebands. Coupled with the use of VSB which removes most of the upper side-band an extremely efficient modulation system is thereby obtained. For a VSB system, however, a phase-coherent carrier is required for demodulation at the receiver and a direct extraction of the carrier is not possible. However by careful assignments of the codewords to transmitted levels a positive average value can be generated at the input to the modulator thereby ensuring a consistent in-phase carrier component. The first stage towards this aim is to convert the two's arithmetic representation of the quantised levels to a positive biased representation. For a 4-level system, a 2-bit wordlength will, in 2's complement arithmetic, represent the levels -2, -1, 0, 1 which has more negative than positive amplitudes. If an inversion is made at the input before filtering, the reverse is true. However, as filtering is performed using 2's complement arithmetic this will require a 4-bit input quantisation for an 8-level system. As the filter is implemented for a 3-bit input the equivalent effect is obtained by inverting the filter output instead.

On a typical weathermap there is a large amount of white background. For entire white or black fields the output codewords consists of repeating binary sequences (as shown in Fig.6.14). In view of the dominance of white blocks the codewords for general fields will exhibit frequent occurences of

the patterns 00 (header for double-white) and 000000 (6-bit codeword of all-white pattern). By assigning the dibit or tribit patterns which have the highest probabilities of occurence to positive values at the input to the filter, a strong positive average DC component can be generated. The code assignnations to transmitted levels is shown in Fig.6.15. The Gray code structure is preserved in these assignments. It should be noted that the the use of the natural binary code in 8/6 block-to-block encoding also yields a larger frequency of zeros as the more probable codewords are the smaller values of the binary word which contain few zeros.

6.7 Design and Implementation of Decoder

6.7.1 Decoding Considerations

Fig.6.16 shows the essential functions which are required to be performed at the receiver in order to recover the transmitted image. The principles of demodulation and detection are well-treated in many text books (eg.[38] and [36]) and are not discussed here. For an AM-VSB signal a synchronous demodulation is necessary for the retrieval of the baseband signal. This requires a phase-synchronous carrier which may be derived from the line signal. The recovered baseband is passed through an equaliser before detection of the transmitted levels. The timing in the detection process is also required to be phase-locked to the transmitter timing and is extricated from the output of the demodulator. The detected bit stream is decoded by the expander and the resultant image output is remodulated and fed to the recorder.

A more detailed block diagram of the decoder is shown in Fig.6.17.

The function of the AGC amplifier is to raise the input signal level fixed to a level fixed at the start of a transmission. It is thus activated only for a short duration following detection of the start tone. A correct level of the signal is of importance as an offset in gain here will produce a dc bias in the baseband signal which will lead to inaccurate equalisation. The carrier is extracted from the line signal by means of a bandpass filter and phase-locked loop. The output of the demodulator is digitised using an 8-bit analogue-to-digital converter and all further processing is performed by the microprocessor. The timing for this processing is derived using the extraction circuit consisting of the bandpass filter and phase-locked loop multiplier. This filters out the pilot tone and multiplies the frequency to the appropri ate values. The flip-flop output which is read by the microprocessor gives an indication of the period of transmission. The phasing signal to the recorder is provided by the output of the envelope detector which detects the phasing pulses at the input bandpass filter. These are delayed to compensate for delays in the decoding process and are subsequently remodulated.

For purposes of description the receiver is divided into a hardware section and a microprocessor section. The function of the hardware section is to recover the baseband signal and present it to the microprocessor for processing. In addition it provides the timing signals and carries out remodulation of the decoded image from the processor. The microprocessor section is a self-contained minimum microprocessor system containing the CPU, memory and interface circuitry.

6.7.2 Hardware Section of Decoder

Fig.6.18 shows the hardware section of the decoder. The activity of

selected signals is shown in Fig.6.19. The start and stop tone detectors each consist of a second-order high-Q bandpass filter implemented using the MF10 switched-capacitor filter IC, followed by a diode detector and comparator. When the start tone is detected the microprocessor is reset and the system enable flip-flop is set high. After a suitable delay the AGC amplifier is enabled. During this period the received signal consists of a continuous carrier at maximum amplitude. The smoothed rectified O/P of the voltage-controlled amplifier is compared with a preset voltage level and the amplifier gain is suitably adjusted using the 8-bit up-down counter and DAC until the correct level is obtained. During this time the time constant of the carrier phase-locked loop is reduced to a low value to allow fast lock-on to the carrier frequency. At the end of the AGC period the phase-locked loop reverts to its normal operating bandwidth. In this mode the time constant of the loop has been chosen to be large in order to reduce the effects of phase jitter of carrier at its input. The AGC stage is followed by the phasing period when the line signal consists of modulated pulses at the line frequency. In this period the phase of the carrier inverts during low levels of the phase pulses causing the phase-locked loop to fall out of lock. To prevent this a gated-type PLL is employed. The voltage at the input to VCO is held constant using a sample-and-hold amplifier during reversals of carrier phase. The gate timing is derived from the envelope of the output of the second-order active bandpass filter. The latter signal is also used to provide the phasing pulses to the Mufax recorder. The switch SW2 at the input to the AM modulator is controlled by the microprocessor. The modulation here is performed by the XR2206 IC which generates its own carrier frequency. The demodulation of the line signal is carried out by the analogue switch SW1 which is driven by the square wave carrier from the phase-locked loop. At

this point the pilot tone at 1600Hz is extracted by a high-Q second-order bandpass filter. The tone frequency is then multiplied up to obtain the baud rate of 2400Hz. The switched output is lowpass filtered to obtain the baseband signal. This filter also has to remove the pilot tone and a sharp cut-off is therefore demanded. A cascade of two MK5912 lowpass filters is used with the cut-off frequency being set at 1400Hz.

6.7.3 Microprocessor Circuitry

The microprocessor system forms the heart of the decoder and is responsible for a variety of signal processing functions. Fig.6.20 shows the block diagram of the microprocessor section. The 6MHz Z-80B CPU is supported by 4 kilobytes of EPROM which contain the working program, and 24 kilobytes of static RAM. Signal input to the processor is via the 8-bit ADC which requests an interrupt via the interrupt flip-flop at the end of each conversion. The digitisation rate is selected by the microprocessor and is either the baud rate of 2400Hz or 16 times this rate. The latter is used only during determination of the phase of the sampling clock. This phase is one of 16 possibilities as determined by the preset value of the divide-by-16 counter. The setting of the phase is performed by the microprocessor after receipt of the first phasing pulse. During this time the phase of the reference 2400Hz is recorded via the input port. The processed image output is loaded into the FIFO buffer which is subsequently clocked out and converted into serial format at a rate of 14.4KHz for 8-level transmission or 9600 Hz for 4-level transmission. The start and stop frequencies to the recorder are also generated by the micrprocessor and are output to the remodulator via the output port.

The microprocessor hardware is mounted on two circuit boards with one

being entirely a memory board consisting of a bank of 2Kx8 6116 RAMs. The remodulator IC is located on the same board as the CPU. The rest of the receiver circuitry occupies three boards in the prototype construction - the input stage which includes the AGC amplifier and tone detectors occupies one board, the synchronous demodulator and carrier extraction circuitry are located on the second, while the third contains the symbol timing extraction circuits. The circuit diagrams are given in Appendix 4. In the following sections the processing of the digitised baseband signal at the decoder is described. In particular the important task of equalising for the channel characteristics is discussed in some detail. Successful recovery of compressed data is possible only if the equaliser performs well. Also, for an amplitude-dependent signalling system, changes in signal level during data transmission will result in errors and some form of protection is required. This will be met by employing adaptive thresholding in the detection stage.

6.8 Automatic Equalisation of Channel

6.8.1 Choice of Equaliser

Equalisation of the channel at the receiver is essential for transmission of data at higher rates (above 1200bps) over the telephone network. The function of the equaliser is ideally to eliminate the intersymbol interference arising largely from the group delay of the telephone channel which was originally designed for voice transmission. As the latter is insensitive to phase distortion the phase characteristics of the channel were neglected. The quality of performance of the equaliser in the presence of noise influences the error rate at a given transmission

rate. The equaliser can be automatic ie. the equaliser coefficients are determined so as to match the channel's response at the start of transmission and then remain fixed in the course of transmission, or it can be adaptive in which case the coefficients are frequently updated throughout transmission in order to track the changes in channel response. For this digitisation system an automatic equaliser is used for the following reasons:

i) the variability of the coefficients in the adaptive equaliser implies the necessity for expensive hardware multipliers or very high speed processors whereas in the automatic equaliser multiplications can be performed using lookup tables by the microprocessor once the coefficients have been fixed.

ii) the channel characteristics of a leased line are not expected to alter drastically in the course of transmission. With most facsimile equipment images are transmitted a copy at a time with re-start of receiver between copies. This equaliser can then automatically be reset at the start of each transmission.

A number of equaliser configurations are available in the literature ([39-41]) but the most commonly used is the transversal filter (Fig.6.11). This equaliser has the advantage of being inherently stable and straightforward to implement as only repeated multiply-accumulate operations are involved. Although it is possible to equalise for the passband of the telephone channel it is more efficient in terms of equaliser length and complexity to perform the equalisation at baseband level.

In view of the critical importance of the equaliser in the nature of operations its design was given careful consideration. The following

sections describe the design and implementation of a highly flexible equaliser using the Z-80 microprocessor.

6.8.2 General Description of Equaliser

Fig.6.21(b) shows a typical received baseband pulse which has suffered group delay and attenuation distortion upon transmission through the channel. An ideal-type response is given in Fig.6.21(a). If the time origin is taken to coincide with the maximum pulse amplitude normalised to unity the sampled response I_i is given by

$I_i = A_i$ where $A_i = 1$ for $i=0$ and 0 for $i \neq 0$

and for the practical response of Fig.6.21(b) the sampled sequence X_i contains non-zero values for $i \neq 0$. The latter intersymbol interference (ISI) components will be superimposed on adjacent transmitted pulses leading to errors of detection.

With a suitable choice of coefficients the ideal transversal filter of infinite length and precision can eliminate the intersymbol interference. A practical transversal filter which is restricted to a finite length N and its coefficients are quantised, will leave some residual intersymbol interference. A mean square measure, E, of this distortion may be used as a criterion to determine the set of coefficient values for the equaliser - the N coefficient of the transversal filter are adjusted in order to minimise E. This mean square error is given by

$$E = \sum (Y_i - I_i)^2 \qquad 6.2$$

where I_i is the desired response and Y_i is the equalised response i.e.

$$Y_i = \sum_{j=0}^{N-1} C_j X_{i-j} \qquad 6.3$$

The minimisation of E is carried out by an iterative procedure in which the coefficients are adjusted to minimise the cross-correlation functions between the output and the delayed signal samples. For the jth coefficient the cross-correlation function is

$$R_j = \sum_i E_i X_{i-j} \qquad 6.4$$

In practice the summation needs to be performed for only a finite value as the output Y_i is zero beyond a range of i. In the fixed step-size algorithm for convergence of coefficients, each coefficient C_j is incremented or decremented by a fixed value depending on the sign of R_j (increment if negative) during each iteration. An iteration consists of shifting in the L samples of the input sequence, calculating the cross-correlation function for each tap and making the adjustments for the coefficients. For a given step size the number of iterations and hence the number of pulses which must be fed at the input until there is no more improvement in the equalised response, depends on the step size value, being larger for finer step size values. This is known as the convergence time. When the mean square error criterion is used to set up the equaliser, convergence is guaranteed if isolated test pulses are employed for the setting up.

It is apparent that the same pulse response may be used at the input for each iteration so that only one pulse response is needed. In practice

the presence of noise in the channel implies slightly different pulse responses at each iteration and it becomes necessary to equalise for a noisy channel. For reasonable signal to noise ratios (above 30db) convergence is unaffected and the coefficients settle at a set of values which display an amount of randomness.

6.9 Software Implementation of Equaliser

6.9.1 System Considerations

As with the raised cosine filter described earlier, transversal equalisers are usually implemented by dedicated hardware. Some of these employ analogue variable gain cells to implement the filter coefficients whilst using up-down counters and registers to effect changes in coefficient values. In the more sophisticated commercial modems it is common for all multiplications to be done by high speed digital hardware. An all-digital approach is clearly advantageous in that it avoids inaccuracies due to the effects of drift, analogue component tolerances,etc. If a processor is used for the implementation, a high degree of versatility is introduced which is not possible with a dedicated hardware system. The flexibility for alterations of equaliser parameters such as equaliser length and convergence algorithm, is immensely useful as the system can be modified to obtain the best performance in the experimental prototype.

As a microprocessor is already available at the receiver to perform expansion of the compressed data it is very desirable to use the same processor to implement the equaliser, thus avoiding much additional hardware. The problem is therefore, whether the 8-bit microprocessor can

achieve this objective. For the equalisation to be successful the processor must be able to carry out all the arithmetic operations required with sufficient accuracy to produce convergence and of course a satisfactory equalised response. This must be completed within the time available for setting up. Once the coefficients are preset the processor should be capable of real-time filtering with these coefficients and perform in parallel the expansion of received data. In addition, a number of other tasks, eg. adaptive thresholding and detection, are also required to be performed.

6.9.2 Choice of Parameter Values

The first consideration in the design of the equaliser is the number of taps N which defines the equaliser length. This is dependent on the amount of distortion introduced by the channel to be equalised and is therefore dependent on its amplitude and delay characteristics. If a Fourier series expansion of the frequency characteristic is made, the value of N may be set to Four times the highest Fourier series component [42]. However the detailed description of transmission characteristics is not known in general. A rough approach is to simply let the delay line entirely encompass the unsequalised impulse response ie. N>L where L is the number of samples describing the response. This is reasonable because the transversal filters operates to cancel out ISI by using pre-delayed and post-delayed weighted versions (echos) of the impulse response. The delay should therefore be of sufficient length to be able to cancel out the tail ends of the response.

Because L varies from one channel to another a fixed record of W samples is taken of the input response and presented to the equaliser for

equalisation. The response window size W must obviously be greater than the longest expected channel pulse response. A duration of 5ms is not uncommon for a 2400 baud pulse and a 10ms response may be taken as a reasonable maximum for a leased circuit. The latter gives a value of L of 24 samples so the window size W is set at 24. The equaliser length N is set nominally at 29 but may be increased up to 39.

Assuming N=29 the processor must be able to produce an output for this many taps inside the sampling interval of 417μs and have some time left to perform the various other functions. This gives an average processing time of 38μs per tap. Clearly it is out of the question to multiply coefficients and samples directly as suggested by Eqn.6.4. However, by storing the possible products of the known coefficient values each multiplication reduces to looking up the product using the delayed sample value as address to the table. High speed accumulation of these products and fast retrieval of samples from the the delay stack are of vital importance. A speed-optimised assembler language program for this purpose is described in Appendix 2. This makes use of a dual contiguous stack for delaying of samples and the stack pointer is used to retrieve the stored samples. With this program an average of 10μs is possible for a complete 16-bit product look-up and accumulation. For each coefficient a store of 512 bytes is required so that a total of 19 Kbytes are used to store the multiplication tables.

Using the lookup techniques the implementation of the equaliser after setting up of the coefficients becomes feasible. The setting up of the equaliser itself is now considered. The accuracy of the equaliser coefficients determines the amount of residual intersymbol interference after convergence. As previously described, real-time equalisation after

presetting of coefficients is achieved by looking up 16-bit products in the multiply operations. The input sample quantisation is set at 8 bits which gives a signal to quantisation noise ratio of about 48dB. This should be adequate as the expected line signal to noise ratio for a well-behaved line is about 40dB and thus the noise in the sampled signal will be dominantly line noise. As one input to the multiplier is 8 bits the other, which is the coefficient, is restricted to 8 bits for a 16-bit product. However in a signed multiplication of an a-bit number with a b-bit number the signed product requires only a+b-1 bits if either one of its two inputs never has its most negative value. Thus if the input sample X_i is constrained to the range of -127 to 127 (instead of its normal range of -128 to 127) the coefficient word length can be extended to 9 bits (two's complement representation).

With a K-bit coefficient wordlength the maximum signal-to-noise ratio at the input, if the residual distortion is treated as noise, is [42]

$$10\log_{10} \frac{2^{2k}}{N} \text{ dB}$$

For K=9, N=39 this gives a value of 38dB which should be quite tolerable as the contribution of line noise at the output of the equaliser is expected to be about 30dB.

The number of pulses needed to produce convergence depends on the initial unequalised distortion, the minimum coefficient step size and the noise at the input. First, however, the available setting-up time is considered. At the start of a weatherchart transmission the transmitter sends a succession of 'phasing pulses' which aligns the receiver's recording stylus so that the start of line is at the correct left end of the page. During transmission, synchronisation is maintained by use of

crystal-controlled frequencies to the drive motors. The receiver incidentally also uses the pulses to select the speed of recording for example 120 RPM or 240 RPM. The phasing period lasts for 30 seconds so that 120 pulses are transmitted at 250ms intervals (4Hz). It will be very convenient therefore to employ these available pulses to set up the equaliser thereby obviating any special time period for this purpose and keeping good compatibility with the normal output from the transmitting apparatus.

A setting up period of 30 seconds appears at first sight to be quite long but inspection of equations 6.1 and 6.4 show that a large number of multiplications are required. For each iteration 38 multiply-accumulations are needed to produce each filter output and for a 32-sample window, 69 filter outputs are required to be calculated. Further the calculation of a cross-correlation coefficient for each tap involves 16-bit by 8-bit multiplications and 24-bit accumulations. A total of 2662 8x8 bit multiplications and 2662 16x8 bit multiplications are needed to be performed. Assuming that one iteration must be completed before the next pulse arrives (this strategy is however not the one which is employed) a period of about 235ms (excluding pulse response duration) is available for an iteration. This places a limit of much less than 45μs as the average time per multiplication which is a severe constraint as multiplications can only be performed (for both inputs variable) by lengthy subroutines. However, a large number of the multiplications involve zero input values and by employing two tables of pointers the multiplications are reduced to only non-zero cases. Details of the method are given in a later section. With this technique a complete iteration cycle can be executed within the time between phasing pulses.

Methods of reducing the number of iterations for convergence are plentiful in the literature (examples in [40],[43]). The multiple-step or gearshift algorithm is particularly suitable for this microprocessor realisation on account of its simplicity and lack of calculations [40]. In this algorithm the coefficient is incremented or decremented by the same step size D for all coefficients with D stepping down to its least value (LSB of coefficient) as the number of iterations increases. A single-valued D will of course eventually produce convergence but only after a large number of iterations typically exceeding 150. A 3-valued D is chosen for the implemented system corresponding to coarse, medium and fine adjustment. The coarse step size is used in the first 8 iterations, the medium size is employed in the next 16 iterations and the remaining iterations make use of the fine step size.

6.9.3 Program for Implementation

The sequence of operations for the equaliser is shown in Fig.6.22. The first operation is to obtain the sampled step response of the baseband channel which is the response to a 20ms negative-going pulse transmitted during the phasing period. The response to the first transmitted pulse initially sampled at 16 times the normal sampling rate and stored in memory. The trigger to this operation is derived in a two-state process. In the first state a long string of consecutive high levels (greater than a mid-value positive threshold) is hunted for. This establishes the sampler to be in the correct state for the next stage which is the detection of a low level. When this has been detected the sampler is now assumed to be in the low-level region of the received step and it waits for the positive-going edge. After a fixed delay it starts to sample the

positive-going step response. For only the first step response the maximum value of the oversampled response is obtained and the phase of the subsequent clock is made to coincide with this largest value. This is done by outputting an adjustment to the preset value of a 4-bit presettable counter which divides down the 16-times clock rate to the normal sampling rate. The trigger signal is susceptible to noise and may produce time offsets in the captured step response. To ensure that all captured step responses are correctly aligned in time, the maximum value of the pulse response is found for each captured response and fixed at the sixth sample of the input sequence to the equaliser.

The next stage involves the capture of step responses using the same trigger strategy (Fig.6.23). For each step response the pulse response is obtained by taking the difference between adjacent samples of the step response.

The average of 64 pulse response is obtained at the end of the capture stage. The processor now proceeds to set up the coefficients of the equaliser. Apart from the main tap (fixed at 10th coefficient) which has been set to 127 the coefficients are initially zeroed. The location of the main tap has been determined by experimentation for the most satisfactory equalised response.

For each iteration the following operations are performed. The pulse response is passed through the delay line. At each pass the 16-bit filter output is compared with the desired response which is zero except for the main pulse whose height is set at the maximum positive value of 127x256. The 16-bit error is multiplied with each 8-bit value in the delay line and the 24-bit product is accumulated for each tap. For 35 taps and a 32-sample pulse response the length of the output sequence is 66 samples.

The time taken for a 16-bitx8-bit signed multiplication using a subroutine is 101μs. For 66 non-zero output samples the total multiplication time is 66x35x0.101 = 233ms. In addition a total of 35 9x8 bit multiplications are needed in producing a 16-bit filter output, consuming a total of 66x35x0.071 = 154ms. The overall total of 387ms for these multiplications in just one iteration of the setting-up procedure is quite excessive. A method of improving the speeds of the filter correlation process is now described. Fig.6.24 shows the states of the delay line in the matrix [M] for a 7-tap equaliser as a 4-sample pulse response is passed through it. It is seen that [M] is a sparse matrix in which more than half the elements are zero. This assumes that the pulse response is finite which is always true. Similarly the matrix [M'] in the calculation of the cross-correlation coefficients shown in Fig.6.25 is mainly sparse. Note that the error matrix [E] is the same as [Y] except for the value corresponding to the main signal at the equaliser output.

It is clear that the number of multiplications may be reduced to only the non-zero cases. This can be achieved by employing two index tables which identify the non-zero multiplicands in the calculation of the filter output Y_i or the cross-correlation coefficient R_i. The total multiplications is now given by NS each for the former and latter, where S is the length of the pulse response. This compares with N(N+S-1) multiplications in the original case. For N=35 and S=32 the total time taken for the non-zero multiplications is

1120x71μs + 1120x101μs = 193 ms

This total time is about half that for the straight multiplication method.

To perform the non-zero multiplications two tables ITAB and CTAB are used, each containing as many entries as there are output samples in an

iteration. The tables ITAB and CTAB contain respectively the indices of the filter coefficient and input sample for the first multiplication in the calculation of the filter output (Fig.6.26). As an example to produce the third output sample (indices are commenced from 1 and not 0) the first of three multiplications is between the third input sample and first coefficient. For succeeding multiplications the input sample index is decremented whilst the coefficient index is incremented. For each filter output only the cross-correlation coefficients for the non-zero delayed samples need to be updated. The index of the first cross-correlation coefficient is also given by ITAB and the number of updates is given by CTAB. The former will increment for succeeding updates operations.

Fig.6.27 shows the flow chart of the setting-up procedure. At the end of the cross-correlation calculations the filter coefficients are adjusted according to the signs of the corresponding cross-correlation coefficients. A step size of 8 is used in the first 8 iterations followed by 4 for the next 8 iterations and beyond that the step size is set to unity. The total number of iterations varies according to how gradually convergence is achieved and this depends on the nature of the unequalised response. It is nominally set at 70. For this number of iterations the total set-up time is found to be 13.3sec. This is within the 14sec available in the remainder of the phasing period (the first 16 seconds are used in the capture of the 64 step responses).

When all the iterations are completed the 16-bit lookup values are formed from the possible products of the 9-bit filter coefficients with the 8-bit signed input. For each coefficient a total of 512 bytes is required for a table. Thus a total of $17\frac{1}{2}$ Kbytes is needed for the 35 coefficients.

6.10 Adaptive Thresholding

After the multiply tables have been formed, the real-time filtering is performed, using the speed-optimised program described in Appendix 2. The filtering is carried out as an interrupt service routine with interrupt pulses corresponding to the sampling clock of 2400Hz. At the end of this service routine the processor returns to the main program where the operations of unpacking and expansion of data are performed. Within the interrupt service routine the equalised output is now subject to a detection process to ascertain the transmitted level. This is done simply by comparing the 8 most significant bits with threshold values and a binary search method is adopted for higher speed. Fig.6.28 shows the threshold levels for 8-level and 4-level transmission. Only the positive range of the output is employed because the equaliser has been trained for this range. In view of the cyclic nature of two's complement arithmetic an overflow will result in a negative number and the lower half of the negative range has thus been assigned to Band 7.

To reduce the effects of changes in line signal level in the course of a transmission an adaptive thresholding strategy is implemented. This is a decision-directed process in which the threshold levels are variable according to the average values of the equalised levels. A threshold value is taken to be the mid-point between the average values of its two adjacent equalised levels. The mechanism is illustrated in Fig.6.29. The output of the comparator gates the equalised output to the correct averaging circuit. After the running average is obtained the mid-level between this and the adjacent average output is calculated and the approximate threshold level

is updated. For each detected sample only one update of threshold level is activated, the choice of which depends on the detected value. The running average yields the average of 64 samples by a recursive relationship given by

$$A_i = A_{i-1} + \frac{x_i - x_{i-64}}{64} \qquad 6.5$$

where A_i is the current average and X_i is the sample in the delay stack.

6.11 Input-Output Handling and Start of Line Synchronisation

Following the detection of the equalised sample the data word is stored in one of the two buffers IA or IB. When one is full a buffer flag is set whilst the other is filled. By the time the second is filled the contents of the first should have been processed by the main program. At the end of a line ie. after a fixed number of buffers have been filled the hunt mode is invoked. In this mode the start of line codeword is searched for by correlating the detected words with the desired code pattern. When this is found the filling up of the input buffers IA or IB recommences (see Fig.6.30). This procedure avoids inefficient constant monitoring of the detected words for the start of line code sequence, with its consequent loss of valuable processing time.

The output of image data is also performed within the interrupt service routine. The expanded data is placed in 8-bit bytes in output buffers OA and OB by the main program alternating as with the input buffers. After the start of line code is detected the output buffer is emptied into a FIFO buffer upon succeeding interrupt pulses. When the

buffer is empty there is no further output for the next n number of interrupt pulses where n depends on the relationship between the input clock rate of 2400Hz and the output clock rate. This output clock unloads the 64x8-bit FIFO buffer and subsequently the unloaded data is converted to a serial stream and fed to the remodulator. This data may of course be alternatively fed directly to the writing amplifier of the recording unit if remodulation is not desired. The decoded serial data is clocked at the original sampling frequency of the image data. For the 8-level system this is 14.4KHz and the FIFO parallel-output clock is 1800Hz. Fig.6.31 shows the flow of data through the FIFO buffer. As the maximum separation between the output curve B and the input curve A never exceeds the FIFO buffer capacity there is no loss of data.

6.12 Expansion of Recovered Data

The expansion process is less complicated than the compression process at the transmitter. Two stages of decoding are involved - the reinstatement of white blocks, carried nonwhite blocks, all-black block-pairs and the decoding of the 8/6 coded data words. The latter is easily accomplished using a 64x8-bit ROM. In the reinstatement process the header bits are first separated from the bit stream and the 6-bit data words are stored in sequence in a temporary buffer. Just before storing, the two-bit header is inspected and if a 00 state is found the following carried block pattern is copied into a second store. When all the codewords in the field have been loaded into the stores, the image block-pairs are reconstructed from the header and data word. The 8/6 decoding process is carried out for the nonwhite blocks and the final

block-pair is stored in the output buffer. It is noted that the block synchronisation has been achieved with the detection of the start of line code.

The detailed implementation is illustrated by the flow chart of Fig.6.32. The expansion process is performed entirely by the main program which is interrupted at regular intervals (2400Hz) for filter and input-output operations. At the start of the cycle the input buffer ready flag is polled. During this loop the system enable flag is also checked to determine if the transmission has been terminated. If this occurs the processor proceeds to output the stop tone and eventually halts. When the input buffer flag goes high the filled buffer is identified and the unpacking of its contents commences. The objective here is to furnish the 8-bit codewords from the detected two-bit (for 4-level) or three-bit (for 8-level) words and also to decode the Gray-coded dibit or tribit patterns. The output is stored in buffer X1 and a secondary store X2 holds the carried nonwhite patterns. The reconstitution of the block-pairs of the field then commences. Each header is inspected and the appropriate reinstatements are made. For the double non-white block-pair the next byte is pulled out from the buffer X2 and inserted into the block-pair. The reconstituted block-pair is then stored in the output buffer OA or OB. The processor then re-starts the cycle and waits for the next input buffer to be filled.

The operations are however not interrupt-driven as in the transmitter but are carried out within the main program, using the CPU clock to provide the timing. This is because the interrupt pulses are derived from the line signal and may be unreliable at the very start and end of transmission.

6.13 Other Tasks Performed by the Decoding Microprocessor

In order to reduce hardware complexity and hence cost the microprocessor is used as much as possible to replace conventional circuitry. The start and stop signals to the Mufax recorder are synthesised by the processor. These take the form of square waves at frequencies of 1725Hz and 1950Hz respectively. The start signal from line is detected by the hardware tone detector whose output resets the microprocessor. The processor then sends a square wave to the remodulator to start up the Mufax recorder. The period is controlled by decrementing a counter. At the start of each field the the output of the hardware stop-tone detector is polled and if an active level is registered the processor terminates processing and issues a square-wave frequency to the remodulator.

It is useful to incorporate a test run option in the program in order to confirm the correct sequence of operations and assess the performance of the equaliser. For this purpose an 8-bit D-A converter has been included in the interface circuitry which allows various signals at various stages within the program to be displayed on the oscilloscope. This enables a useful check on the setting up of the equaliser, and by transmitting test data sequences the correct detection and adaptation to line signal gain variations may be visually confirmed. If desired it is also possible to include elaborate self-diagnostic tests for fault-finding applications.

6.14 Summary of Microprocessor Operations in Decoder

The overall sequence of operations executed by the microprocessor is as follows. Upon reset a download of the $3\frac{1}{2}$ Kbyte working program to memory from EPROM is initially performed. This avoids running of the program from slower EPROM and allows alteration of the working program as it is executed which is needed for speed efficiency. The first task performed by the microprocessor is the output of the start frequency to the remodulator lasting a period of 5 sec. Following this the processor switches the input to the modulator to receive the delayed phasing pulses from the envelope detector. It then sets the sampling clock at its oversampled frequency and waits to capture the first step response. The phase and frequency of the sampling clock are set and the capture of step responses commences. This is followed by the setting-up of the equaliser and eventual formation of the multiply tables for the real-time equalisation. The processor then switches the input to the modulator for modulation by the serial data from the FIFO output buffer and enables its interrupt for the filtering and input-output processes. In the meanwhile the recovered data stream is unpacked and expanded to obtain the image to be printed. At the end of the transmission a stop frequency is output to the modulator for a period of 5 sec. after which the processor is halted.

6.15 Cost of Digitisation Unit

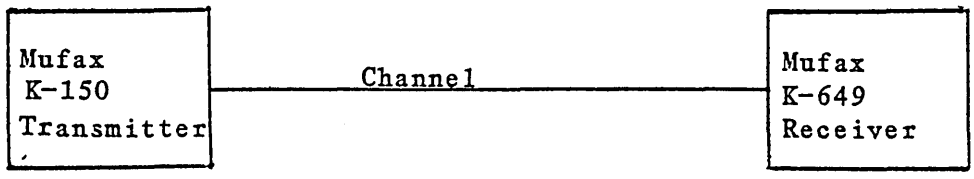
The total component cost of the encoder at the transmitting end was found to be about £50. A large cost contributor is the 12-bit DAC (£12)

and the static memory (£16). The cost of the latter is however falling rapidly. If digital transmission facilities had not been included the DAC would not have been needed. A memory of 4 Kbytes would have been adequate. The estimated cost then is £28. For the expansion unit the total component cost is about £100. A dominant cost item is the 20K static RAM (£60), which again is gradually becoming less expensive. Without the digital transmission facilities the estimated cost here is £30 As a comparison the price of a commercial modem at the present time is about £1500 for a 4800bps rate and £2000 for a 7200bps modem. A commercial version of the digitisation unit would cost approximately £500 which compares very favourably with the total cost of about £3000 for a commercial modem solution.

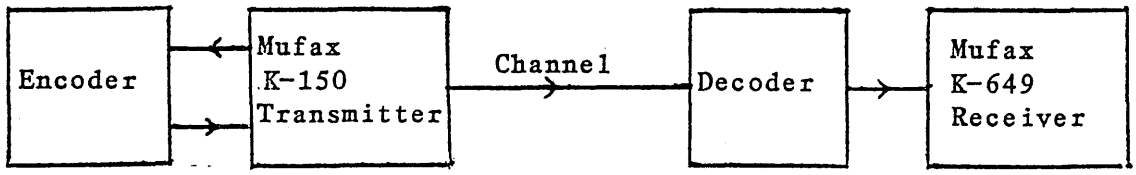
6.16 Conclusion

A low-cost SBIC compression system was developed which allowed a reduced rate of transmission of black-white facsimile images. Although the system was designed for use with weather facsimile equipment it is equally applicable to other analogue facsimile systems. The practical advantages of the SBIC technique were apparent in the development. The fixed-rate output of the compressor greatly simplifies input interfacing with constant-rate scanners and output interfacing for constant-rate transmission. The microprocessor implementation of the compression system has important advantages. Digital transmission functions may be performed by the same processors without incurring much additional complexity of hardware. This is possible only because the compression and expansion operations do not consume much processing time. The feasibility of using a commercial 8-bit microprocessor to implement a variety of vital

transmission functions was demonstrated. The result of this integrated software approach was a self-contained digital transmission system which was inexpensive and highly flexible.

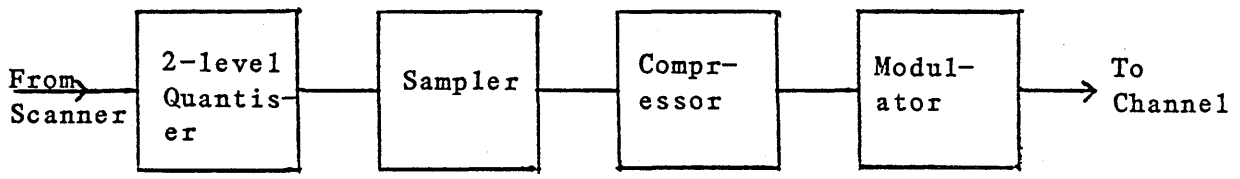


(a) Normal Analogue Transmission

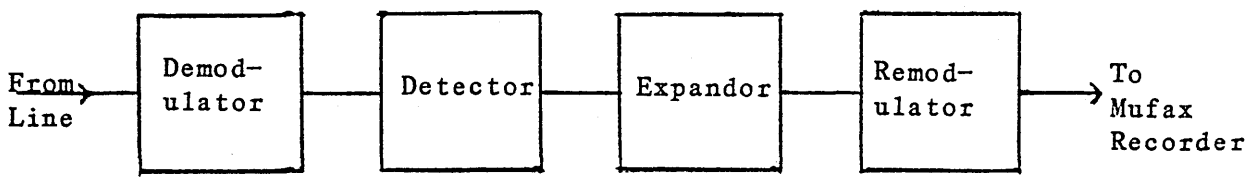


(b) Digital Transmission

Fig.6.1. Conversion to Digital Transmission of Analogue Facsimile Apparatus by Means of External Digitisation Unit.



(a) Encoder



(b) Decoder

Fig.6.2. System Components of Digitisation Unit.

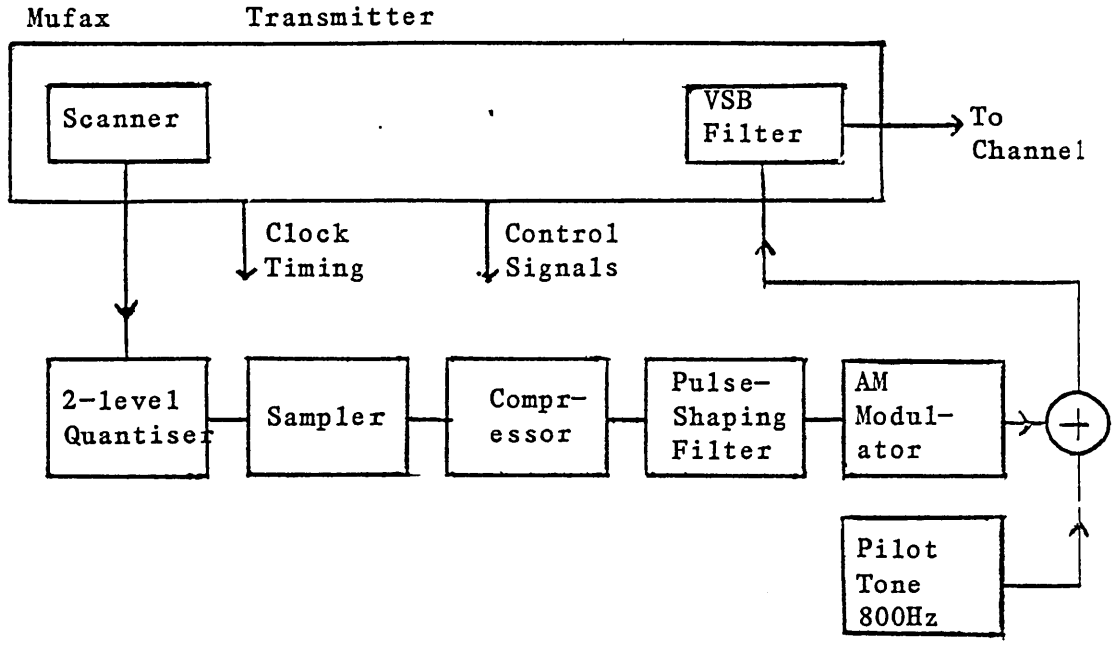


Fig.6.3. Block Diagram of Encoder

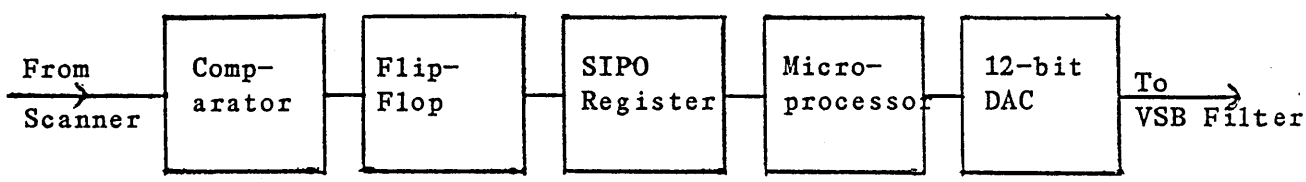


Fig.6.4. Hardware Organisation of Encoder

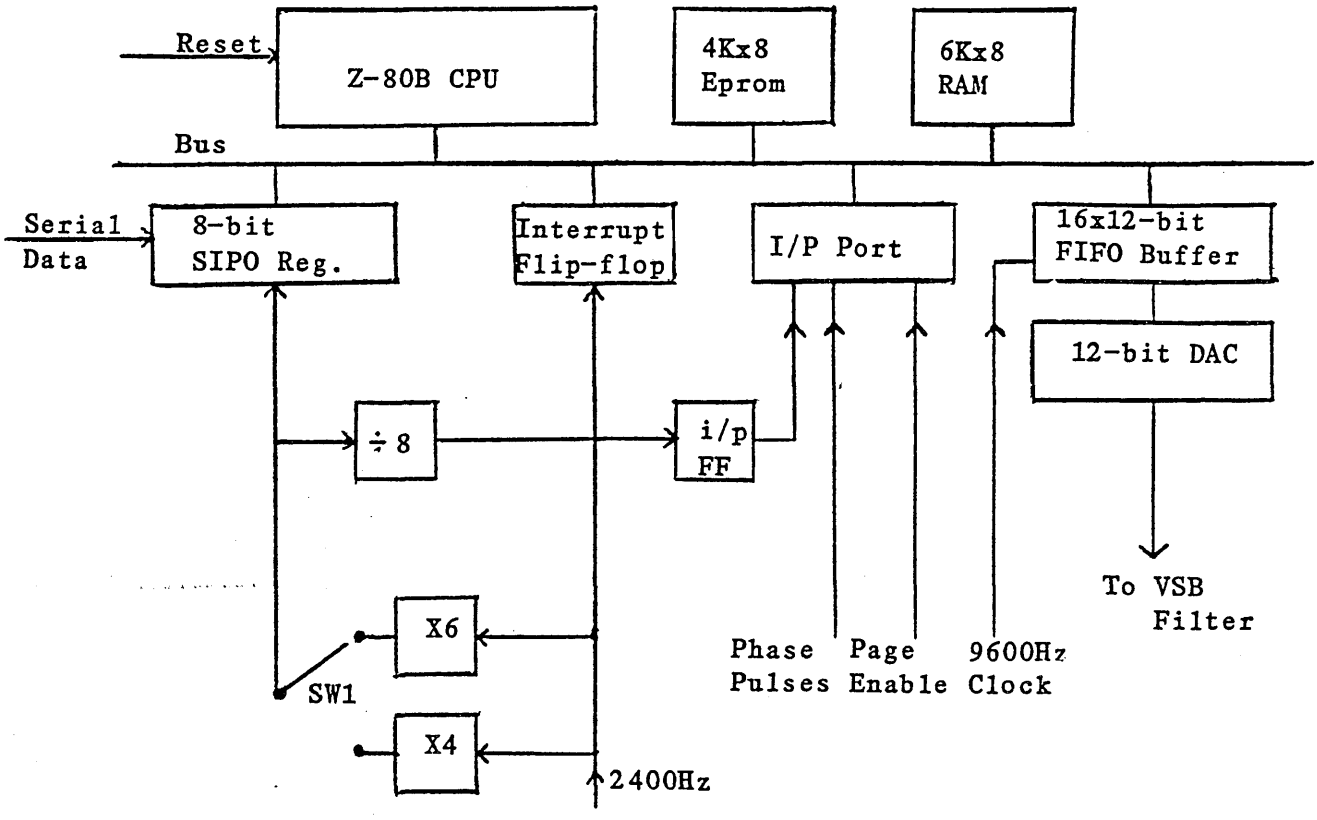


Fig.6.5. Microprocessor Hardware in Encoder

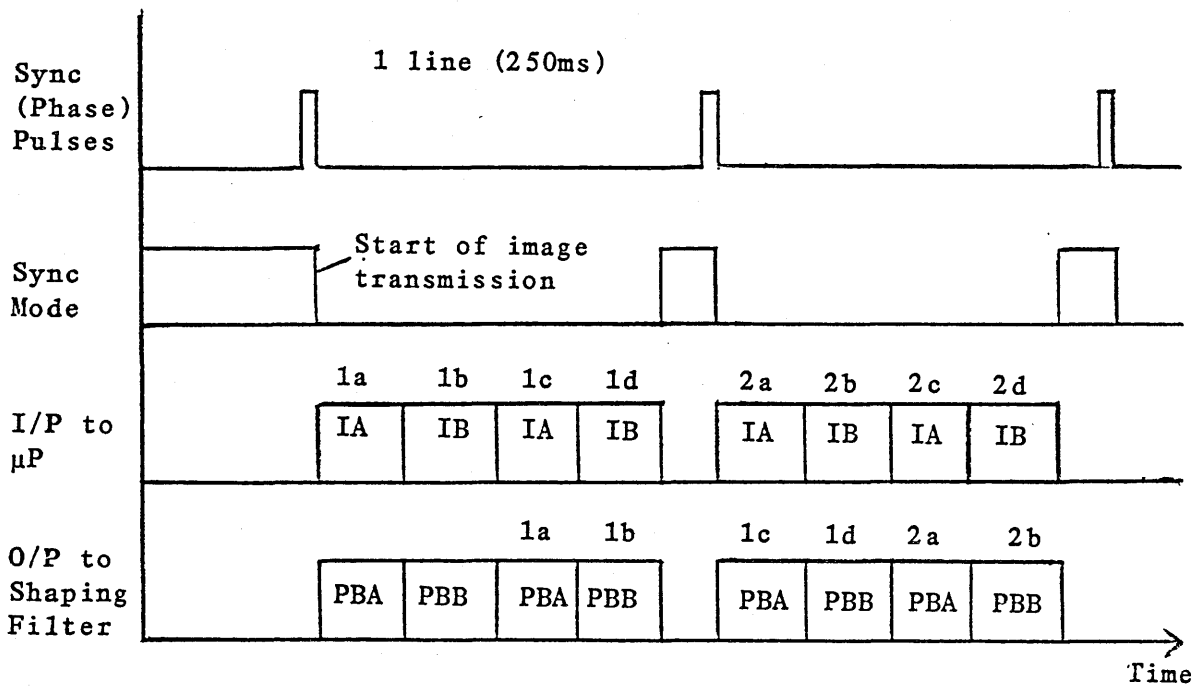


Fig.6.6. Buffer Handling at Encoder (4 fields per line).

Fig.6.7. Flow Diagram of Compressor Program.

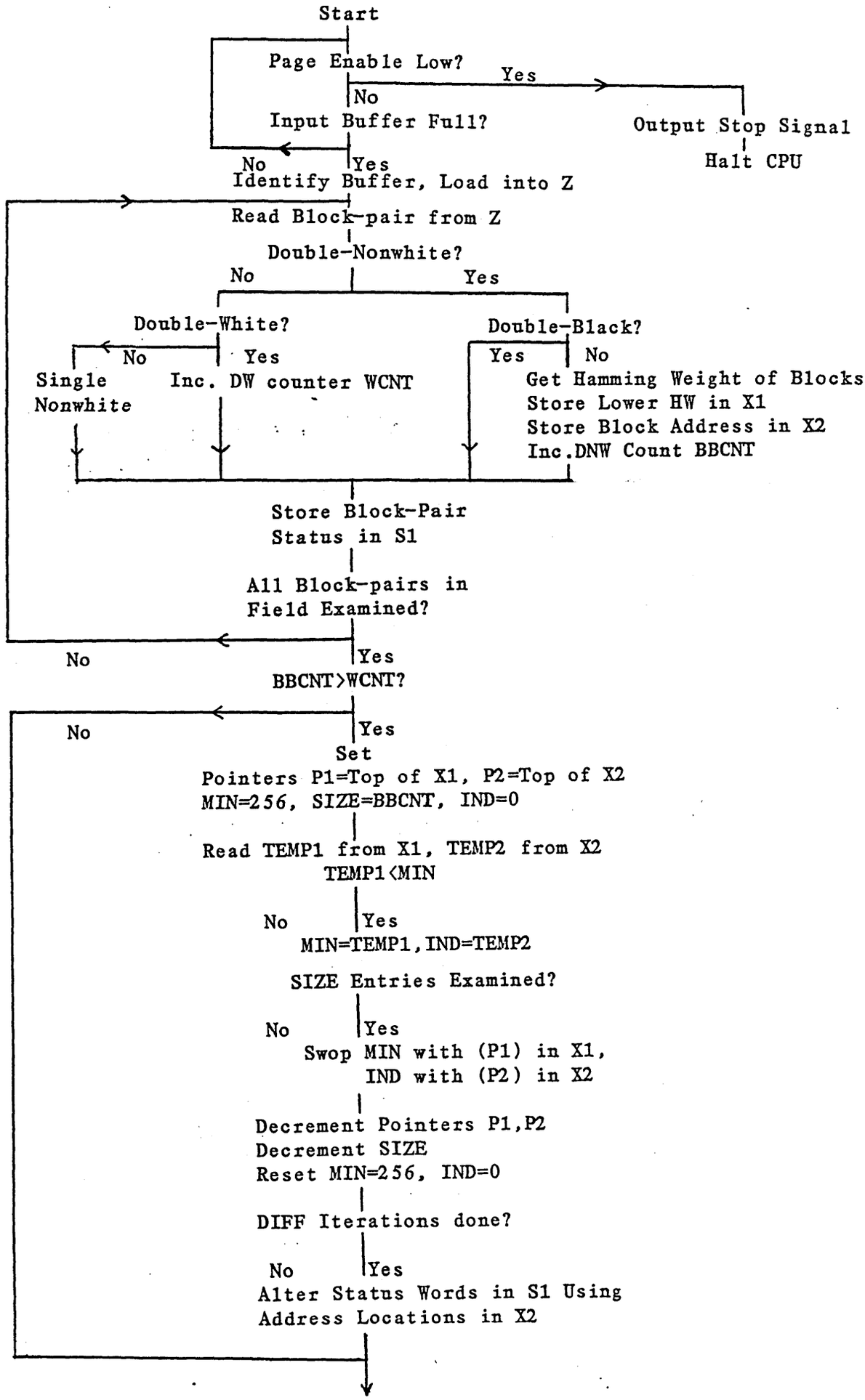
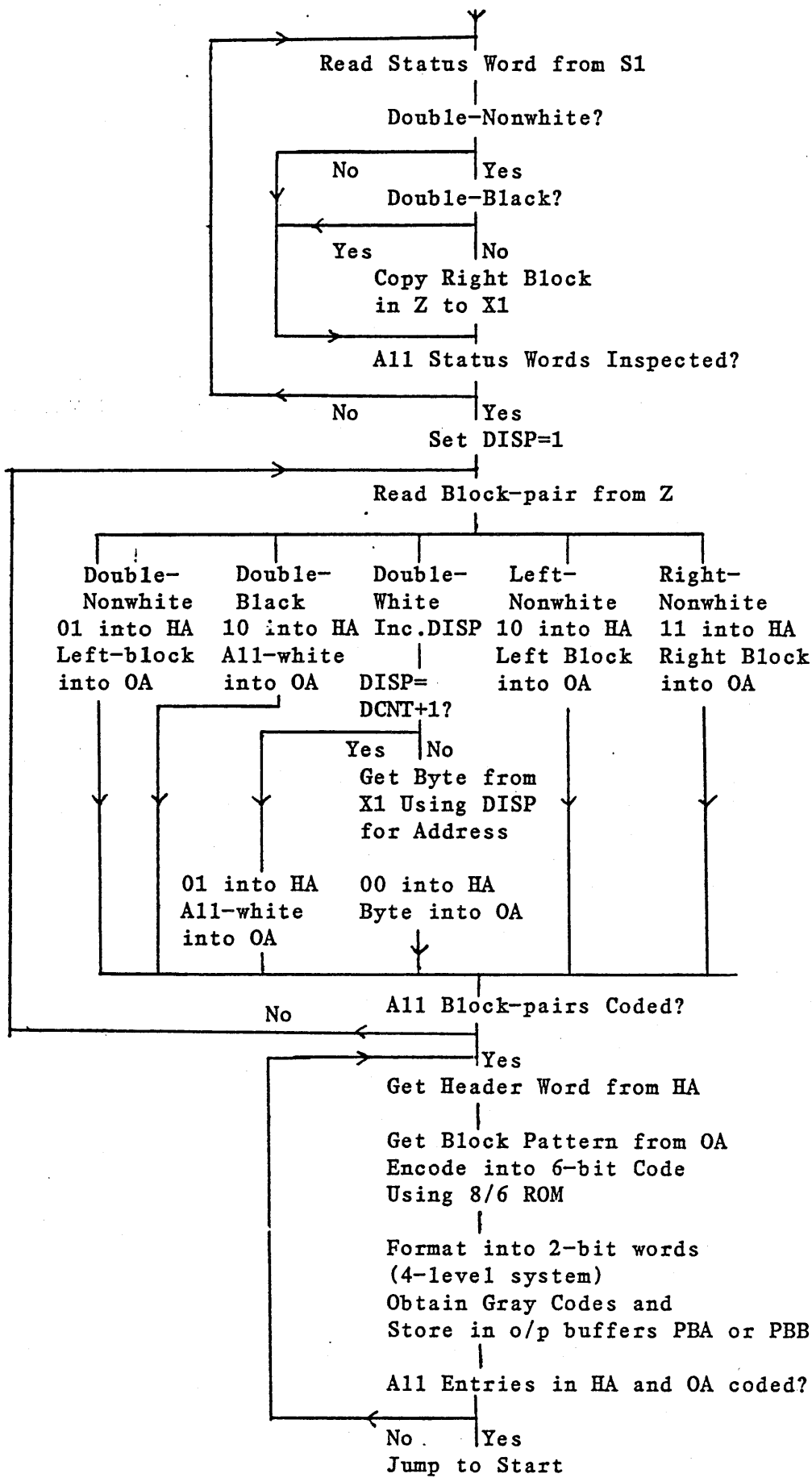
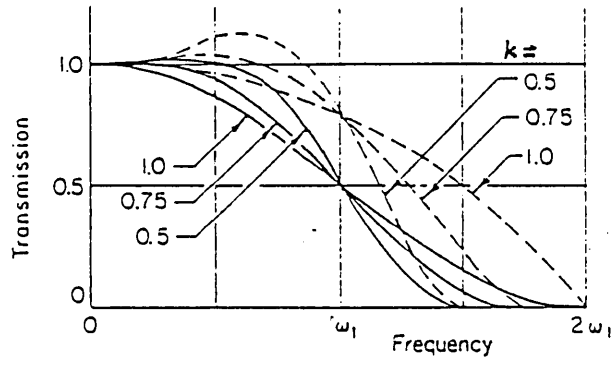
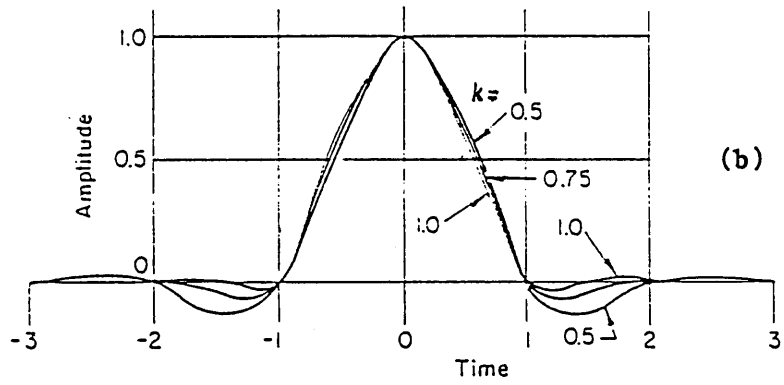


Fig.6.7. Flow Diagram of Compressor Program (Contd.)





(a) Amplitude Characteristic



(b) Impulse Response

Fig.6.8. Effects of Channel Characteristics on Impulse Response.

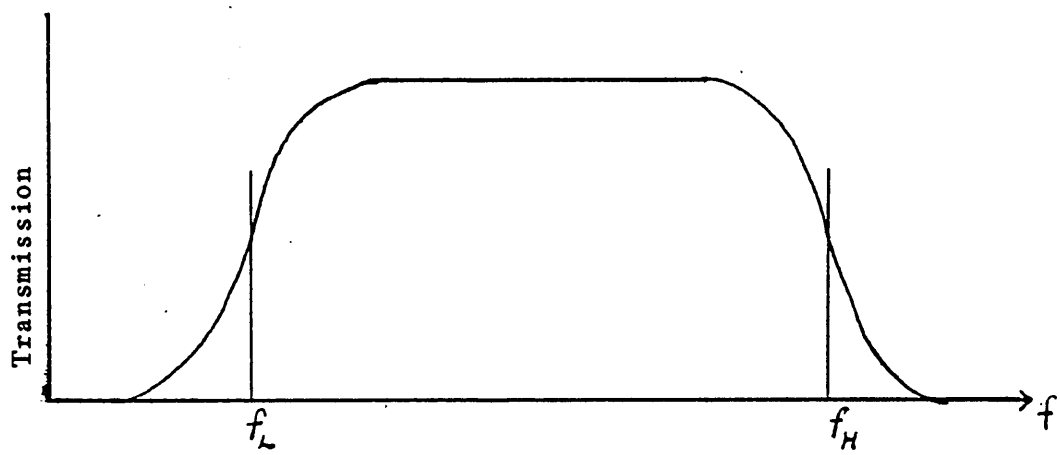


Fig.6.9. Bandpass Characteristic with Vestigial Symmetry.

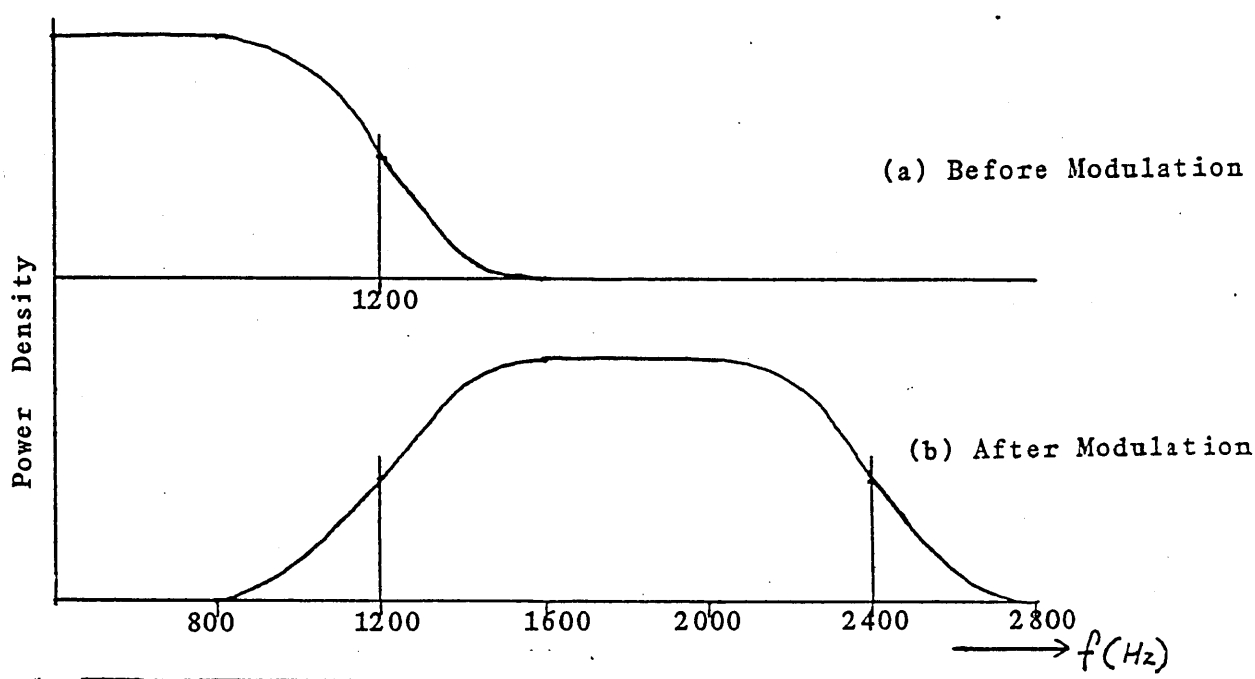


Fig.6.10. Design Objective of Transmitted Signal Spectrum.

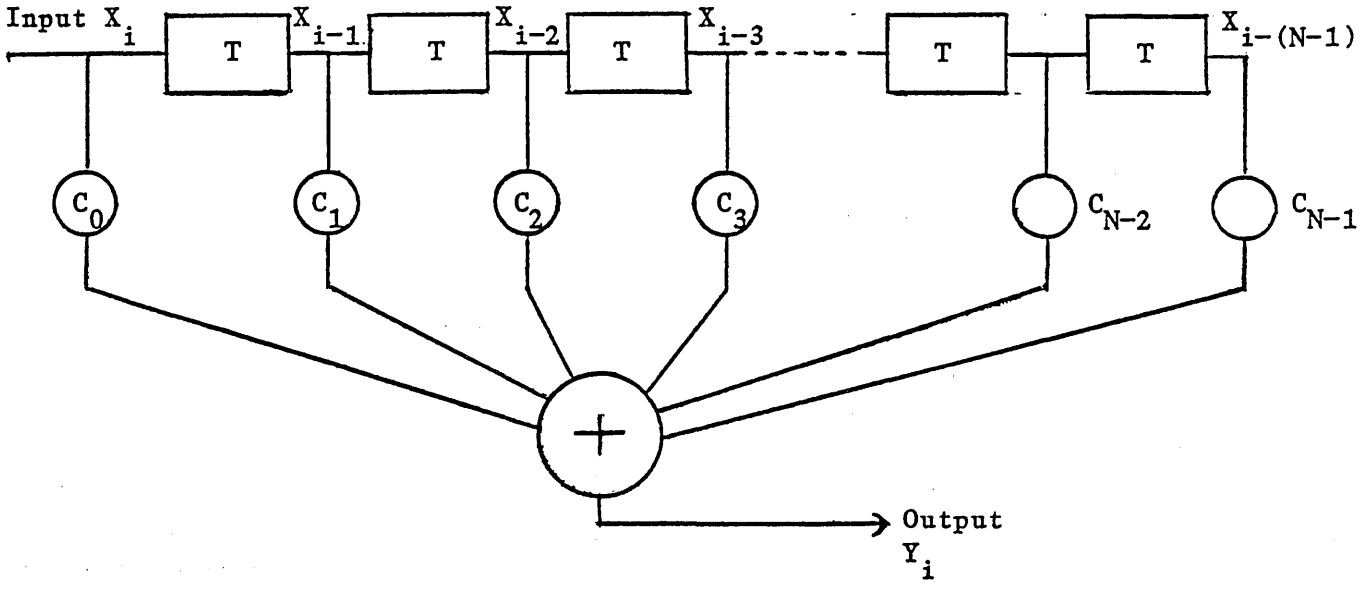


Fig.6.11. N-tap Transversal Filter.

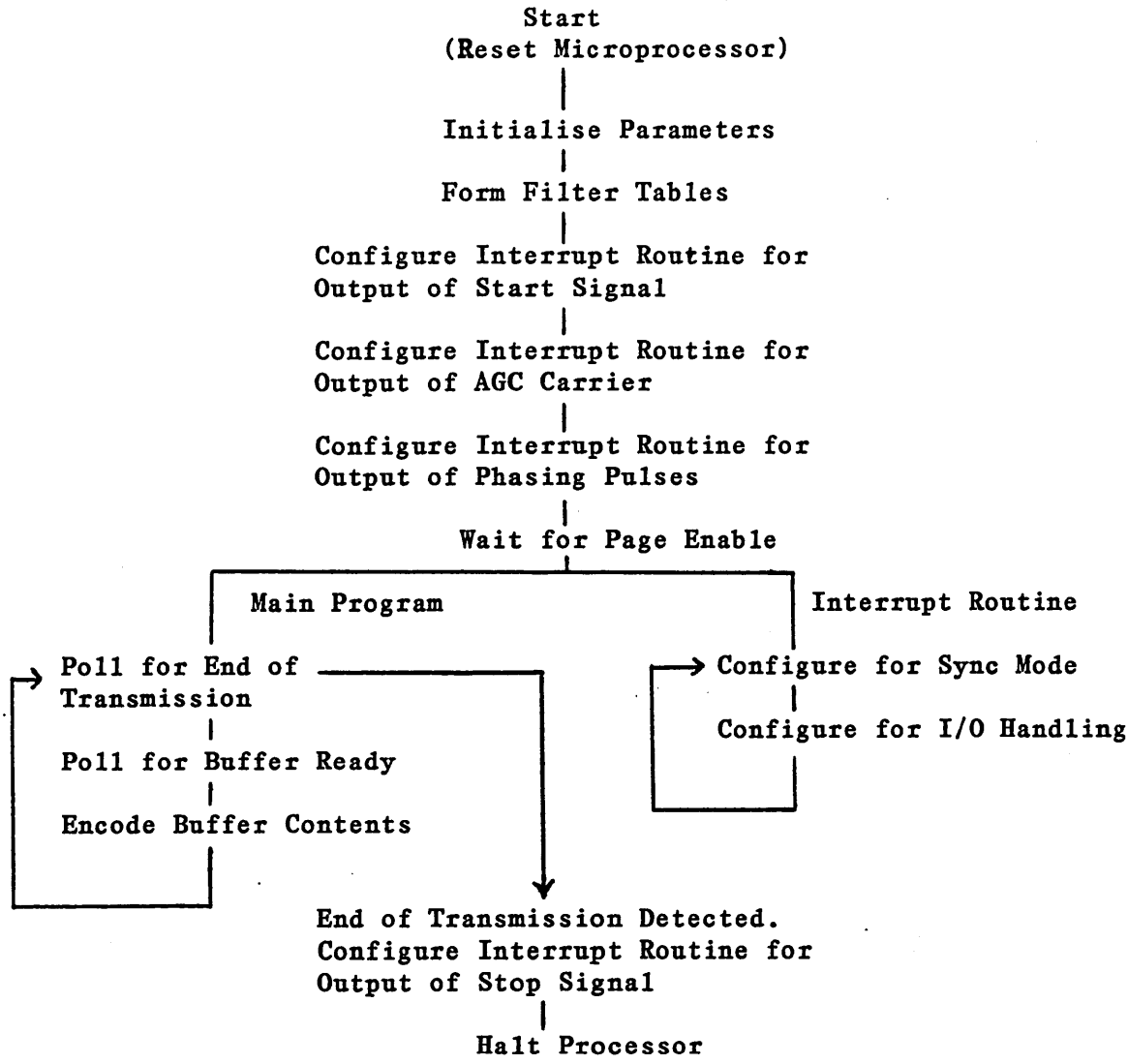


Fig.6.12. Sequence of Operations Performed by Microprocessor at Encoder.

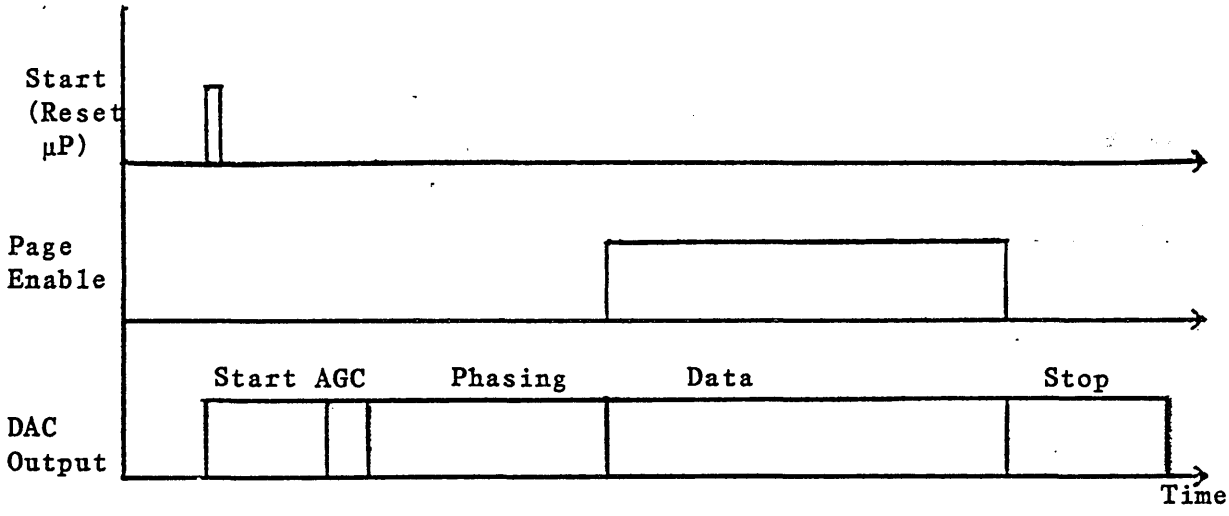


Fig.6.13. Sequence Timing at Encoder.

o/p Codeword Sequence for an All-Black Field:

10000000 10000000 10000000 10000000 10000000 10000000

Dibit Sequence:

10 00 00 00 10 00 00 00 10 00 00 00 10 00 00 00 10 00 00 00

Tribit Sequence:

100 000 001 000 000 010 000 000 100 000 001 000 000 010 000 000

o/p Codeword Sequence for an All-White Field:

01000000 01000000 01000000 01000000 01000000 01000000

Dibit Sequence:

01 00 00 00 01 00 00 00 01 00 00 00 01 00 00 00 01 00 00 00

Tribit Sequence:

010 000 000 100 000 001 000 000 010 000 000 100 000 001 000 000

Fig.6.14. Showing the Repetetive Nature of Dibit and Tribit Sequences When Field is All-Black or All-White.

4-level		8-level	
Gray Code	Transmitted Level	Gray Code	Transmitted Level
00	+2	000	+3
01	+1	001	+2
11	0	011	+1
10	-1	010	0
		110	-1
		111	-2
		101	-3
		100	+4

Fig.6.15. Codeword-to-Transmitted Level Assignations.

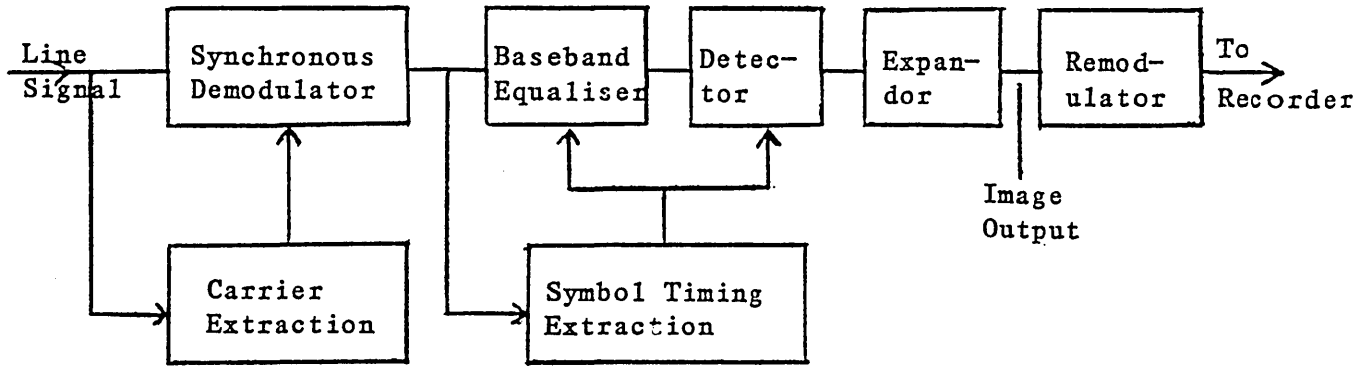


Fig.6.16. System Functions of Decoder.

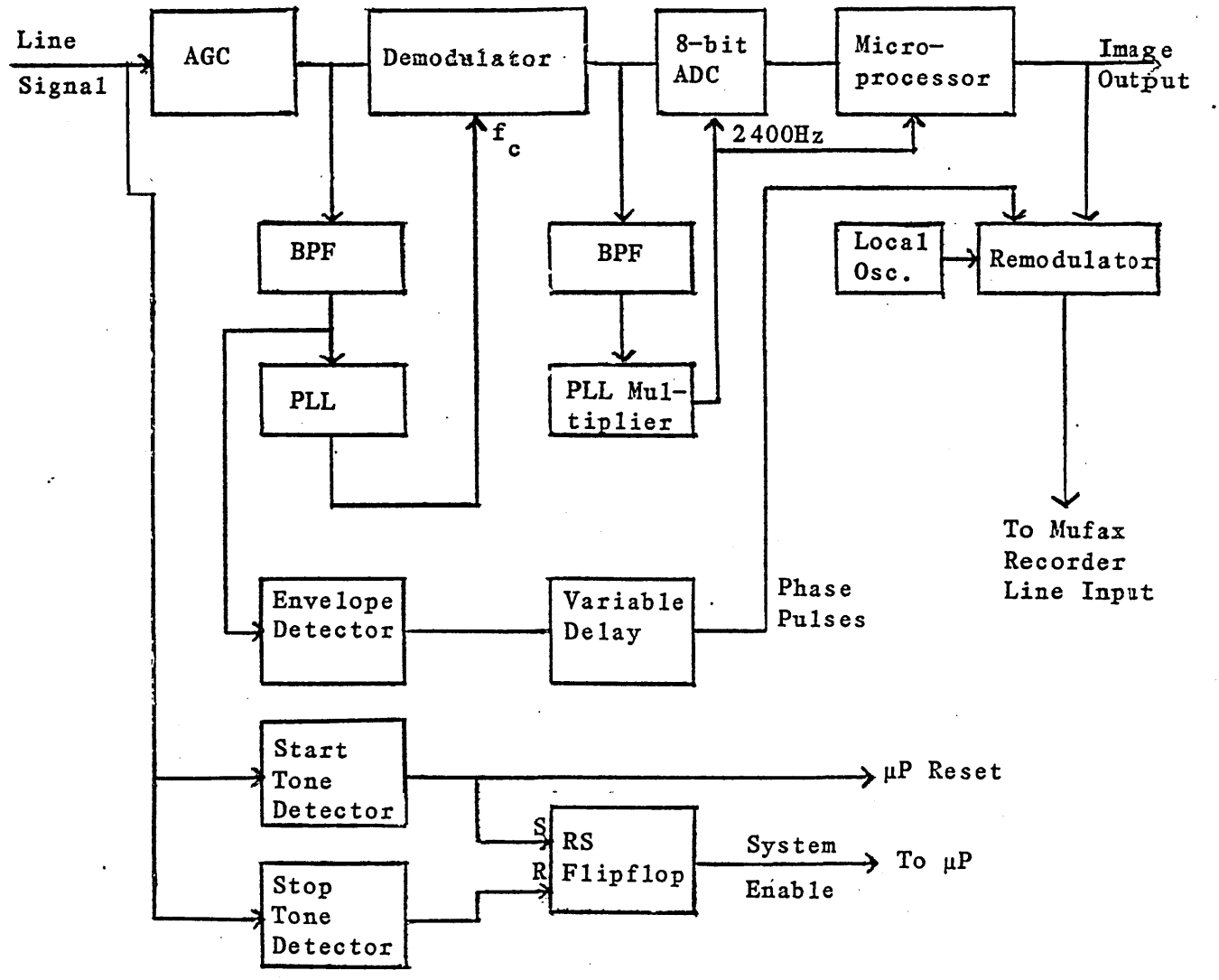


Fig.6.17. Block Diagram of Decoder.

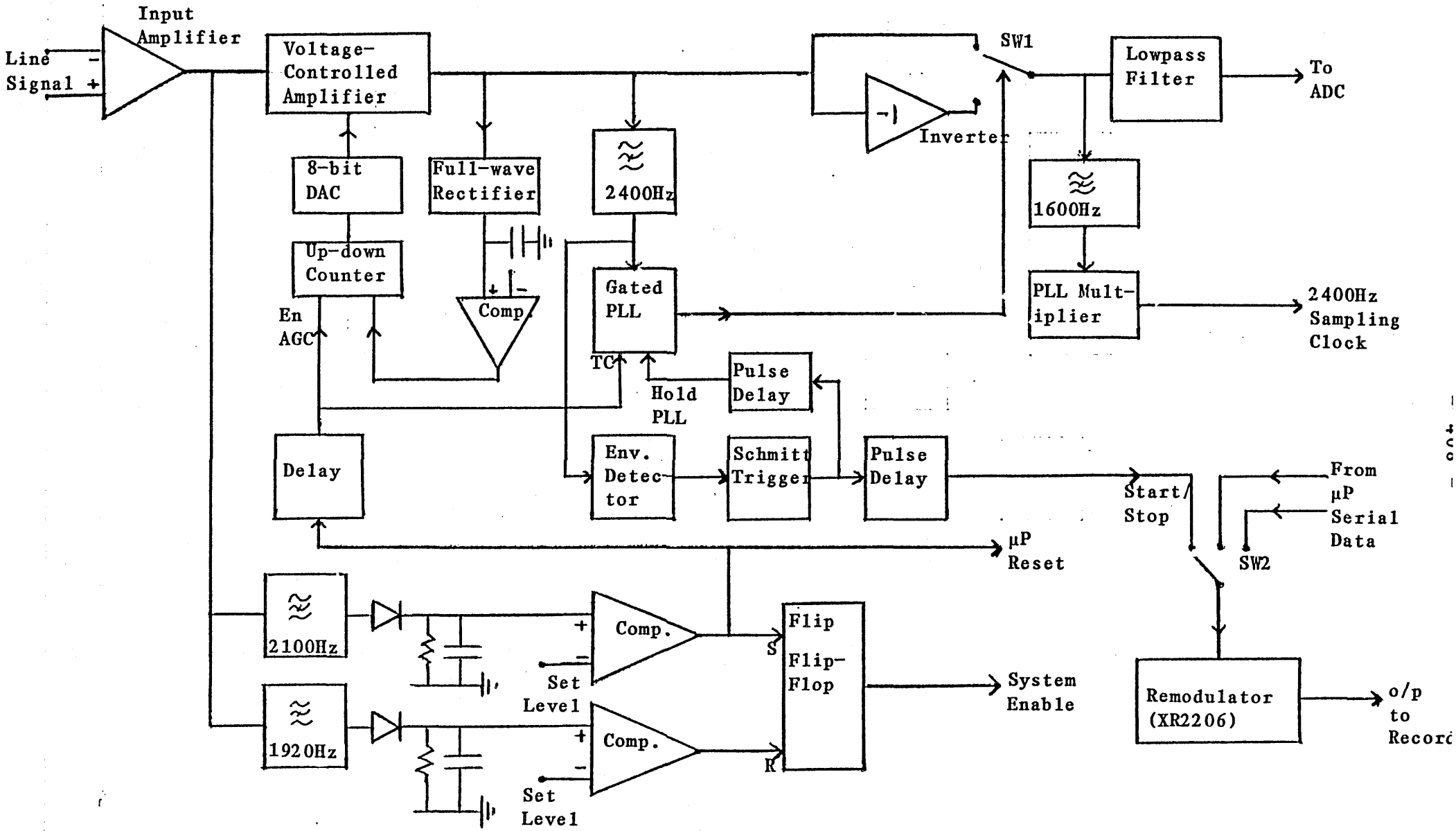


Fig.6.18. Hardware Section of Decoder.

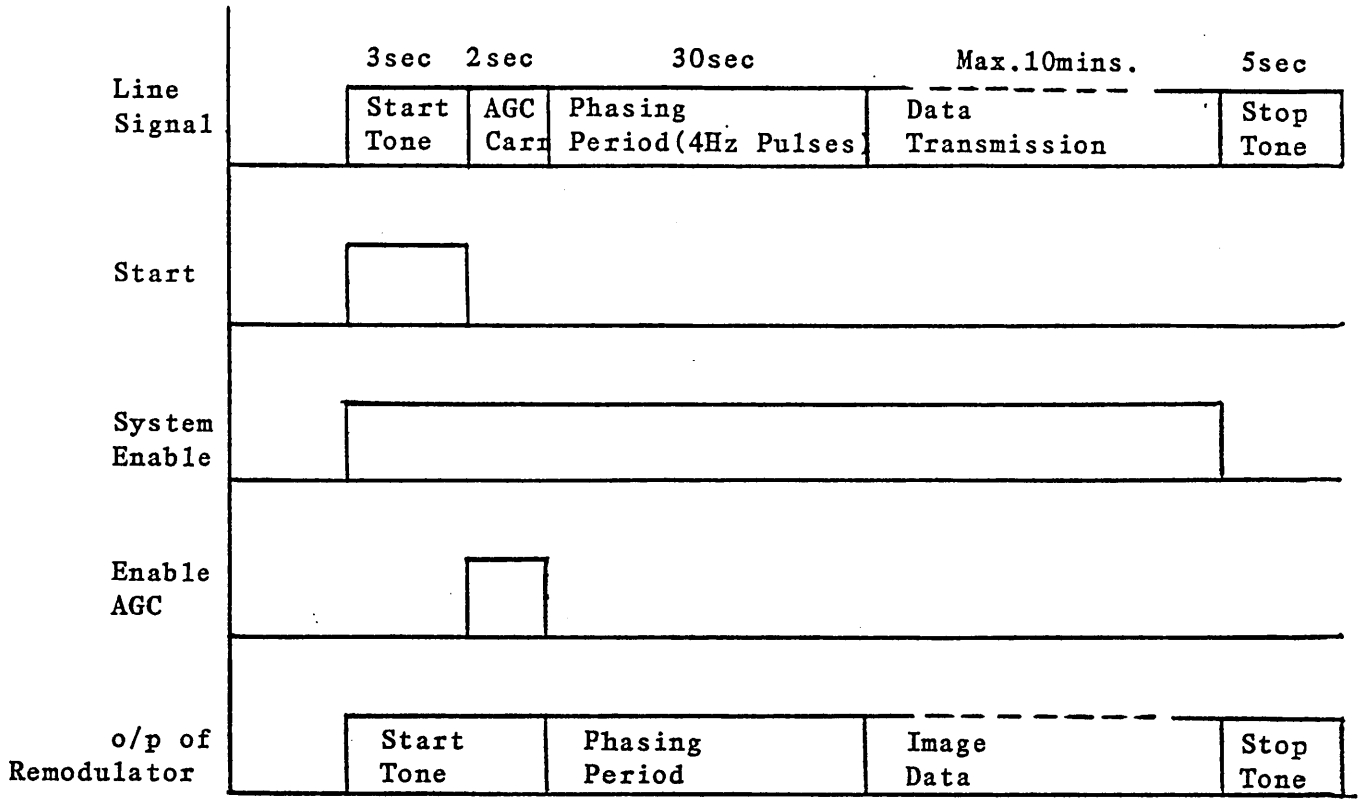


Fig.6.19. Activity of Signals at Decoder

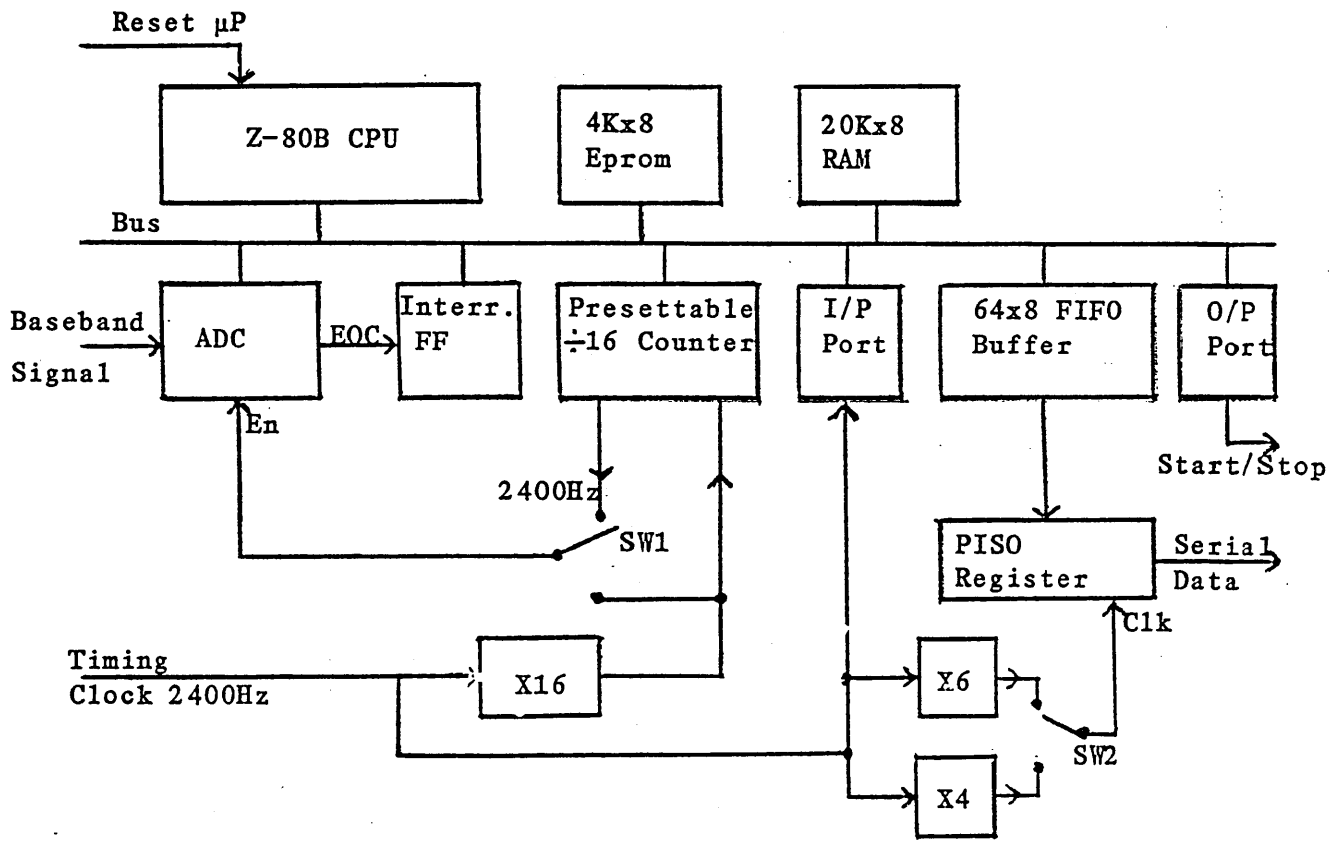
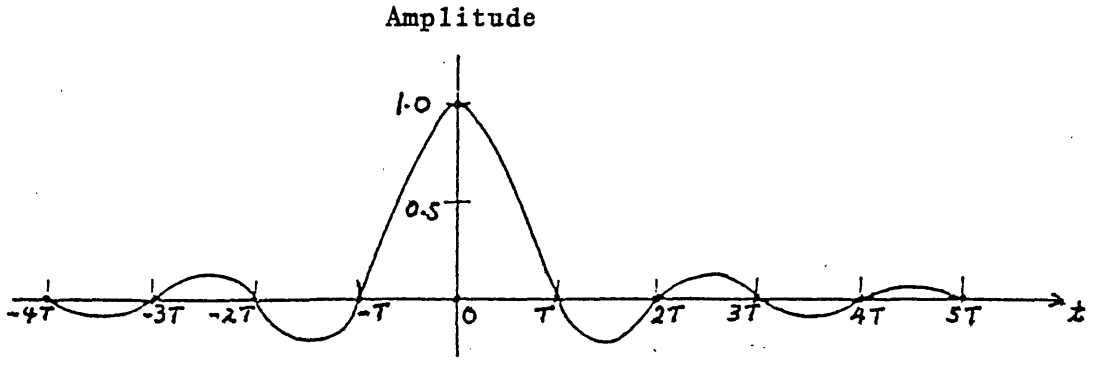
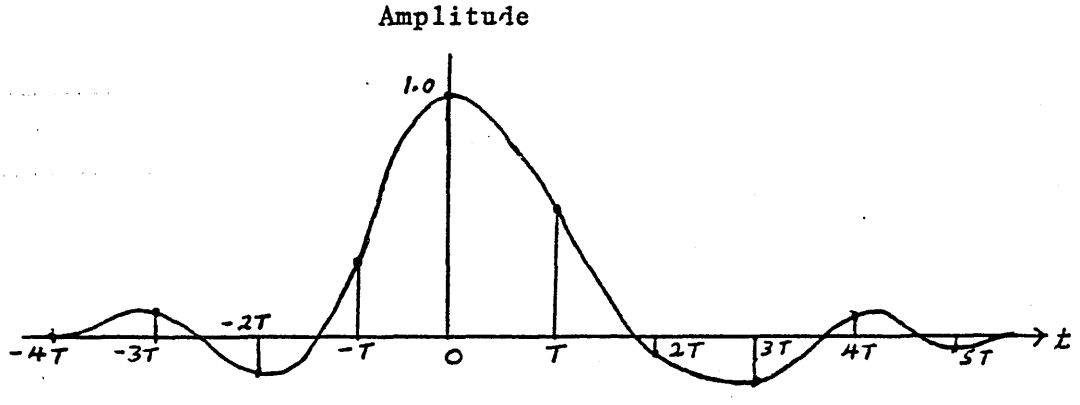


Fig.6.20. Microprocessor Section of Decoder.



(a) Ideal-type Response



(b) Practical Response

Fig.6.21. Examples of Received Baseband Pulse.

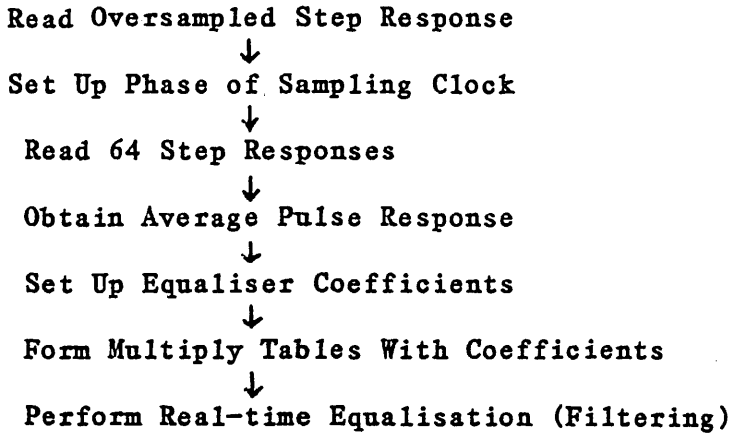


Fig.6.22. Sequence of Operations for Equalisation.

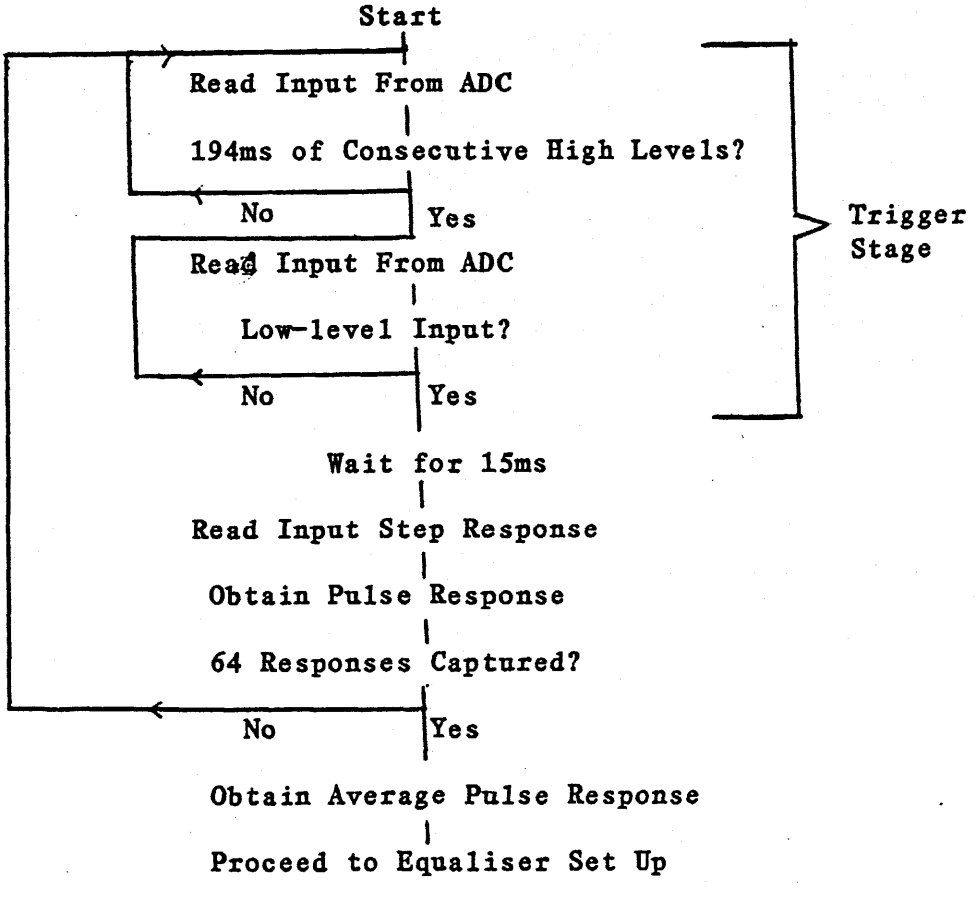


Fig.6.23. Flow Chart for Capture of Step Response

Output | Delay Line States | Coefficients

$$\begin{bmatrix} Y_0 \\ Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_5 \\ Y_6 \\ Y_7 \\ Y_8 \end{bmatrix} = \begin{bmatrix} X_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X_1 & X_0 & 0 & 0 & 0 & 0 & 0 \\ X_2 & X_1 & X_0 & 0 & 0 & 0 & 0 \\ 0 & X_2 & X_1 & X_0 & 0 & 0 & 0 \\ 0 & 0 & X_2 & X_1 & X_0 & 0 & 0 \\ 0 & 0 & 0 & X_2 & X_1 & X_0 & 0 \\ 0 & 0 & 0 & 0 & X_2 & X_1 & X_0 \\ 0 & 0 & 0 & 0 & 0 & X_2 & X_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & X_2 \end{bmatrix} \begin{bmatrix} C0 \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{bmatrix}$$

In general

$$\underset{(N+S-1)x1}{[\,Y\,]} = \underset{(N+S-1)xN}{[\,M\,]}\ \underset{Nx1}{[\,C\,]}$$

where:
N:no. of taps
S:length of finite pulse response

Fig.6.24. The Filtering Process for a Finite Input Sequence (N=7,S=3).

Cross-Correlation Coefficient | Error Sequence

$$\begin{bmatrix} R_0 \\ R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \end{bmatrix} = \begin{bmatrix} X_0 & X_1 & X_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X_0 & X_1 & X_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X_0 & X_1 & X_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X_0 & X_1 & X_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X_0 & X_1 & X_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X_0 & X_1 & X_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X_0 & X_1 & X_2 \end{bmatrix} \begin{bmatrix} E_0 \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \\ E_7 \\ E_8 \end{bmatrix}$$

In general

$$\underset{Nx1}{[\,R\,]} = \underset{Nx(N+S-1)}{[\,M'\,]}\ \underset{(N+S-1)x1}{[\,E\,]}$$

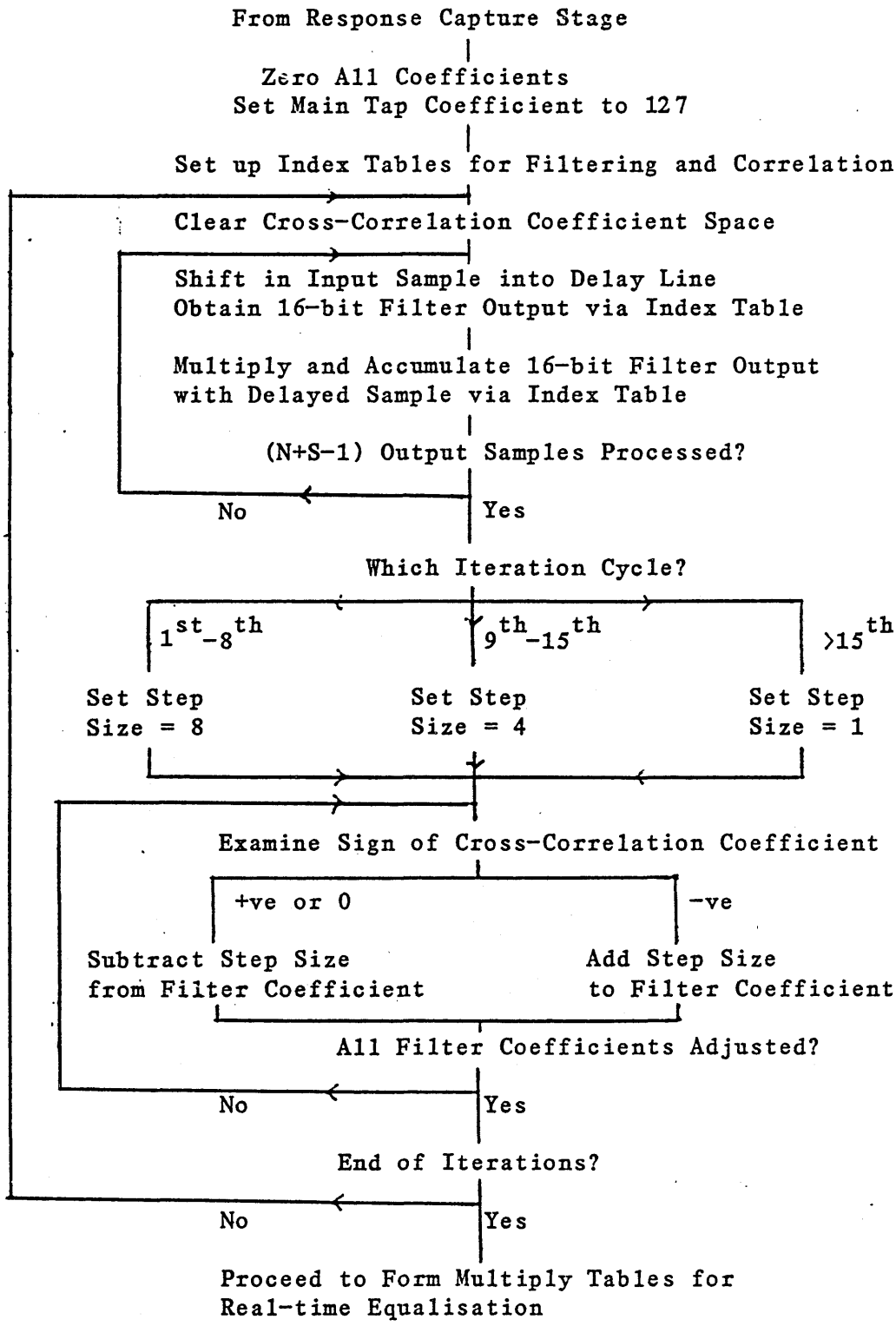
Fig.6.25. The Cross-Correlation Process for One Iteration Cycle in Equaliser Set-Up (N=7,S=3).

Entry No.	1	2	3	4	5	6	7	8	9
ITAB	1	1	1	2	3	4	5	6	7
CTAB	1	2	3	3	3	3	3	2	1

ITAB contains the starting filter coefficient number
CTAB contains the starting input sample number

Fig.6.26. Example of ITAB and CTAB Entries for a 7-tap Equaliser.

Fig.6.27. Flow Diagram for Setting Up of Equaliser.



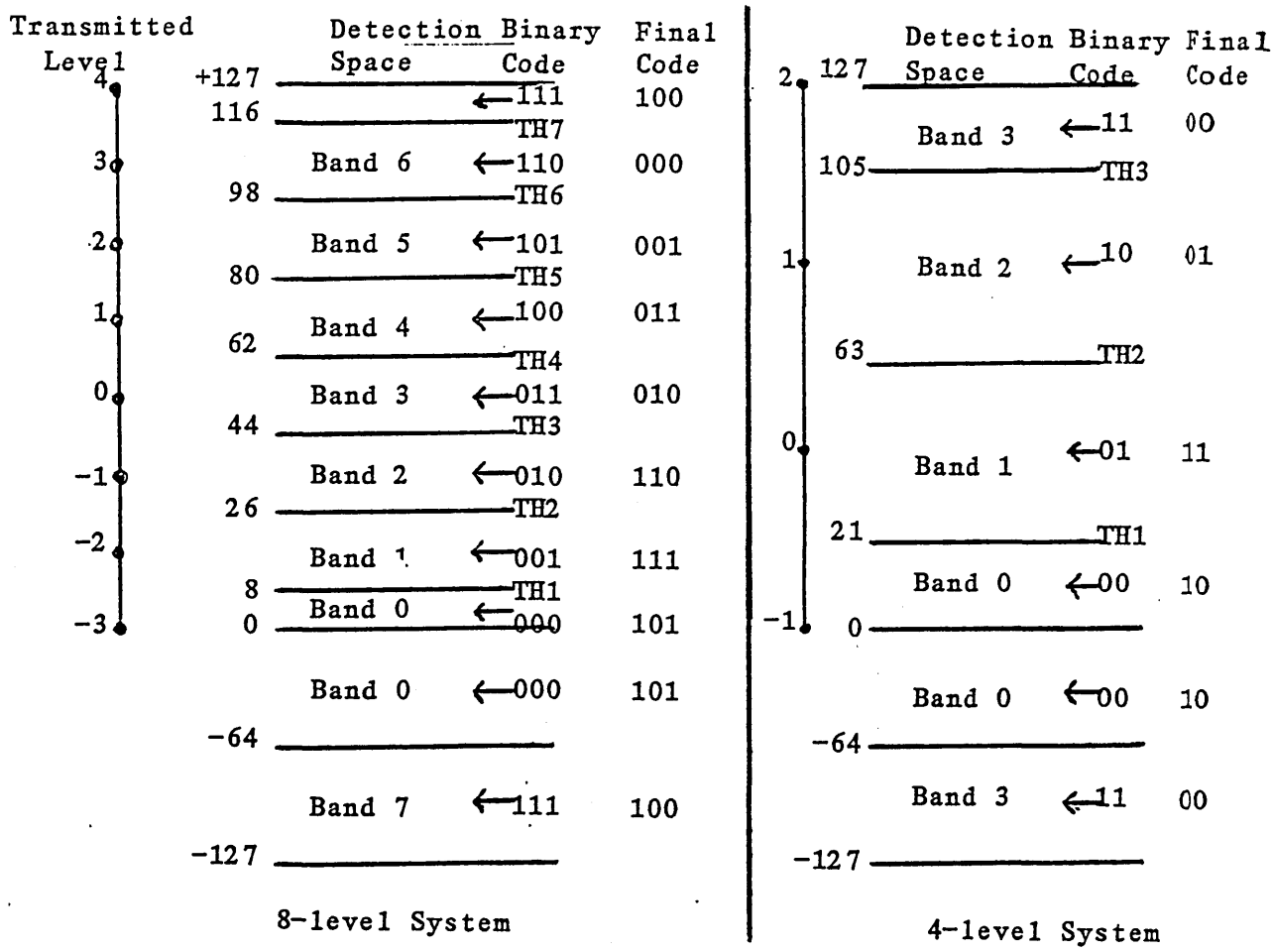


Fig.6.28. Threshold Levels for Detection.

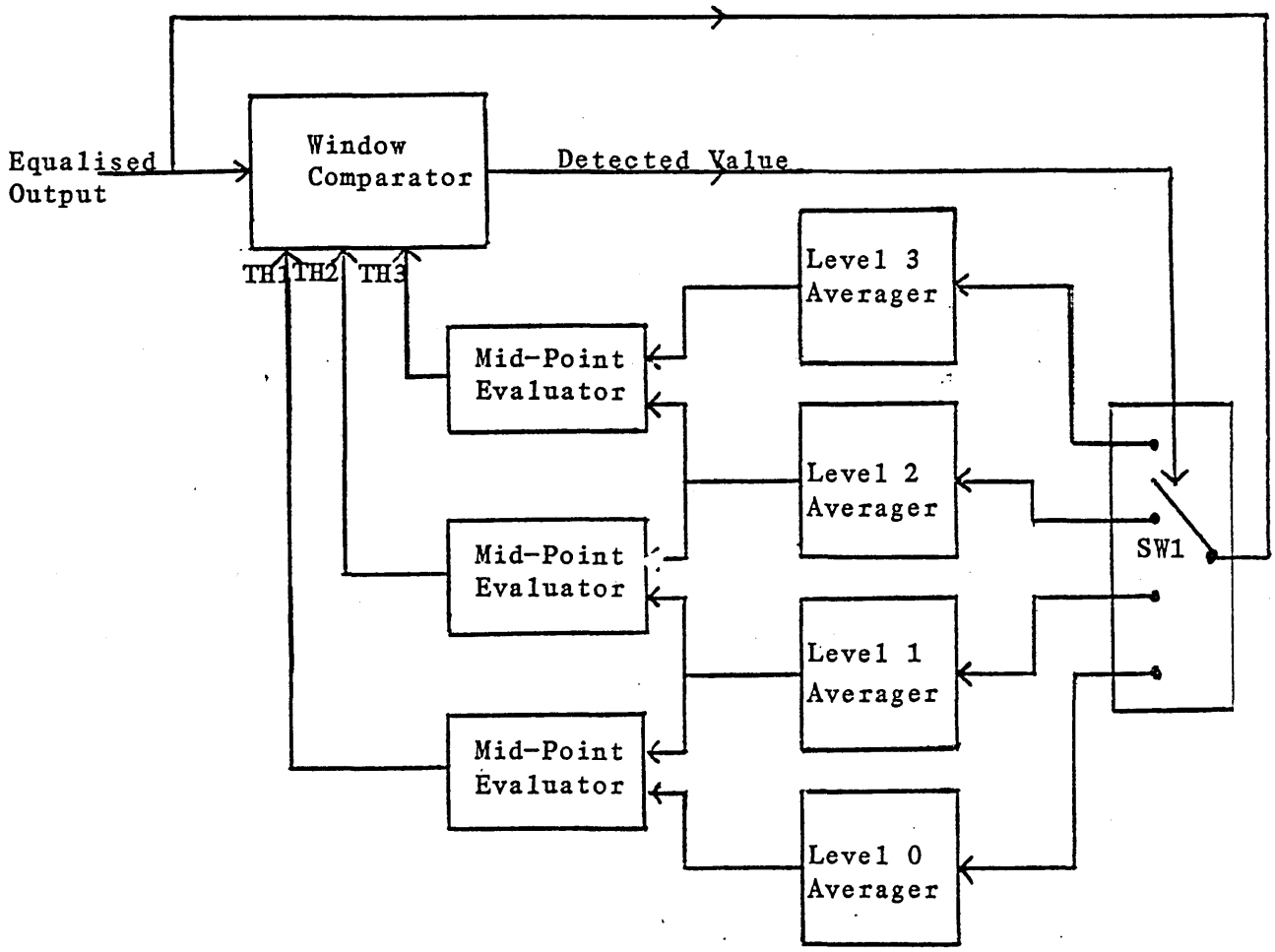


Fig.6.29. Adaptation of Threshold Levels for a 4-level System.

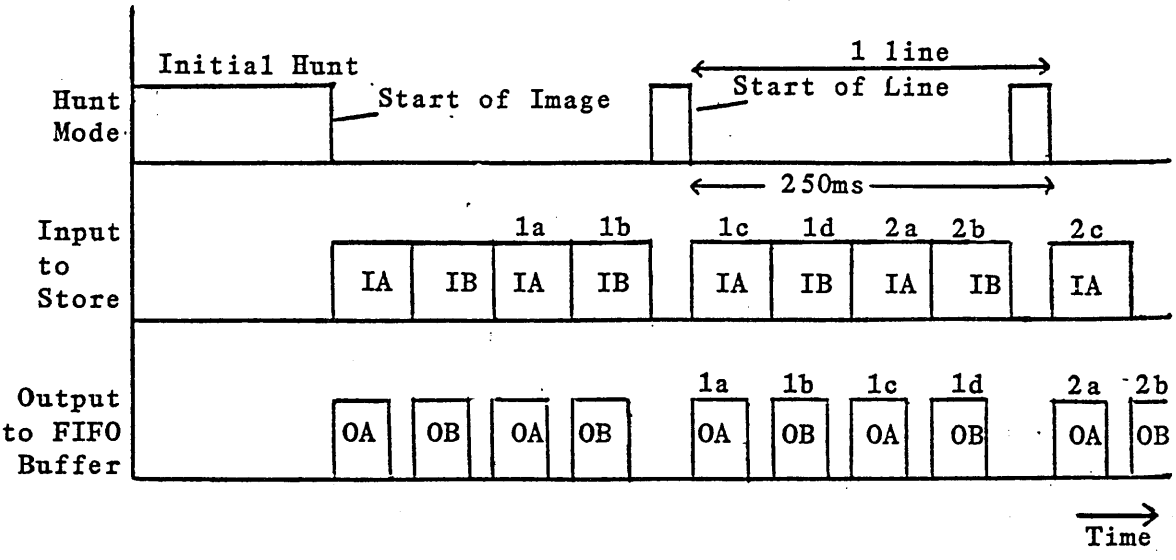


Fig.6.30. Input-Output Timing Sequence.

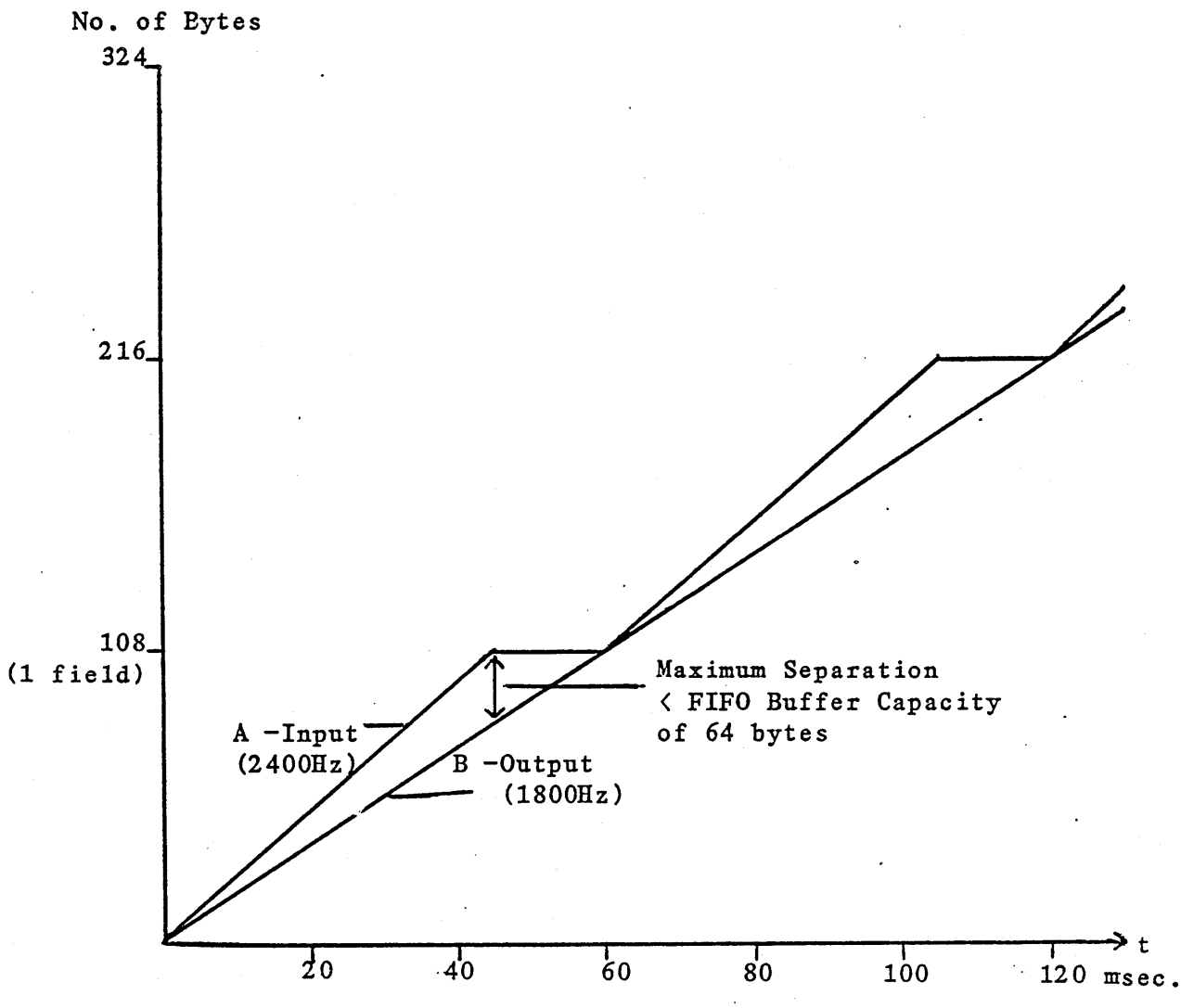
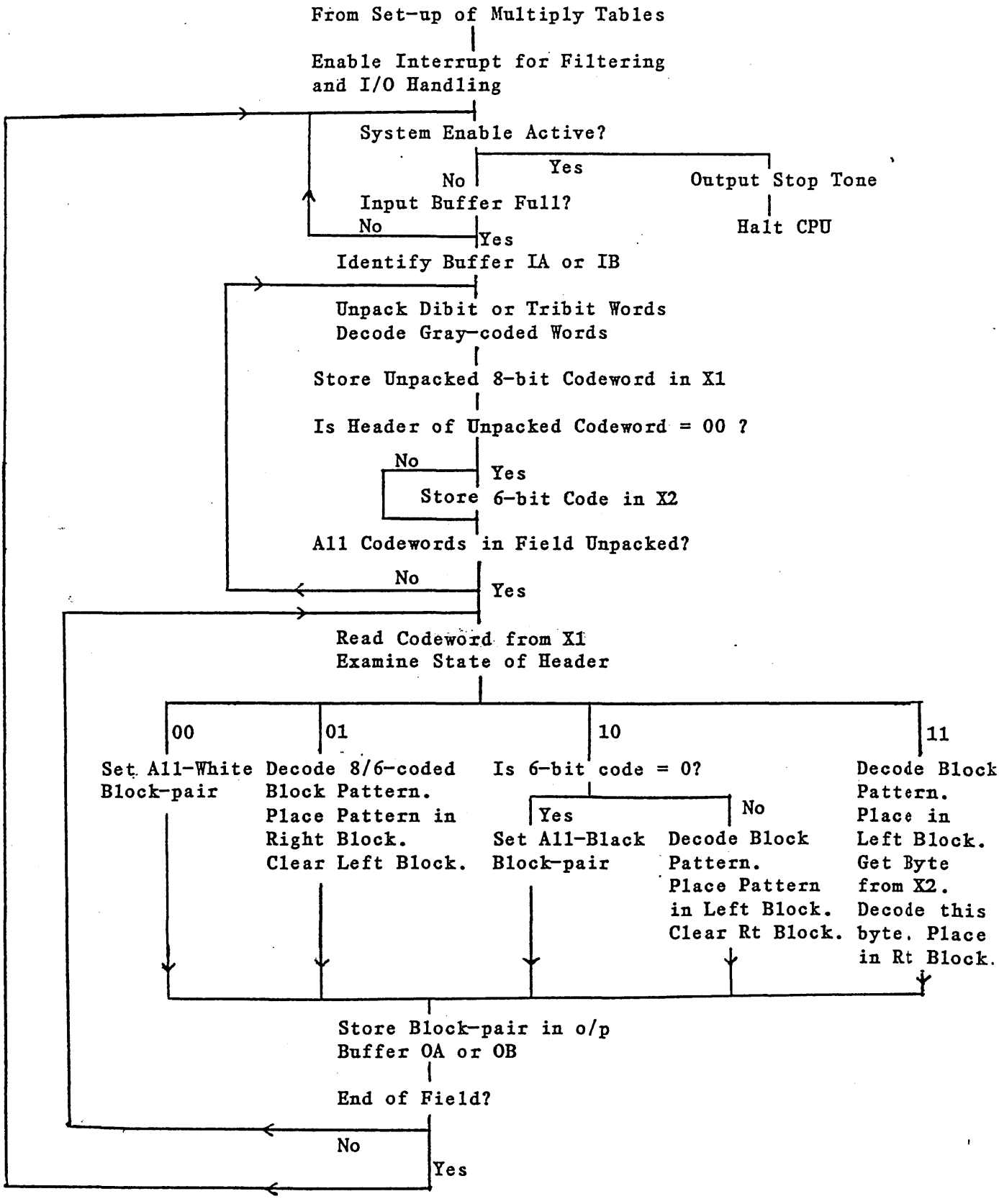


Fig.6.31. Data Flow for Output FIFO Buffer (8-level System).

Fig.6.32. Flow Diagram for Expandor Program.



CHAPTER 7

PERFORMANCE EVALUATION OF FACSIMILE DIGITISATION UNIT

7.1 Organisation of Chapter

The design and implementation of a digitisation unit which employed the SBIC method of compression was described in some detail in the previous chapter. In this chapter the performance of the finished prototype is discussed.

The performances of the working programs in simultaneously implementing compression and transmission functions are assessed. In particular the limits to real-time performance are ascertained for both encoder and decoder sections of the digitisation unit. The processing times for performing SBIC compression and expansion are analysed. By themselves the compressor and expandor sections of the programs (including input-output) are sufficient to realise a compression system given the means of transmitting the encoded bit stream. The characteristics of software-implemented filters are shown. These include the raised-cosine pulse-shaping filter at the transmitter and the equalising transversal filter at the receiver. In the latter case the equalised eye diagrams are obtained for 4-level and 8-level transmissions. The results of tests using bandpass filters to simulate the telephone channel are presented. The response of the adaptive detector to changes in line signal level is tested. Reconstructed images for 4800bps and 7200bps transmission over the

simulated line are given. Finally the results of trials carried out on the northern loop of the Molfax network are reported.

7.2 Performance of Encoder Program

The encoder implements a multitude of functions amongst which the compression of image data is a primary operation. In order to operate successfully the compressor program should execute sufficiently quickly so that the entire field is encoded and the codewords placed in its output buffer within the period of the field. If surplus time is available this may only then be used for performing other functions like input-output and filtering. The amount of surplus time dictates the number and variety of additional tasks that may be performed. In the following paragraphs the times of execution of the various tasks in the total working programs of the encoder and decoder sections of the digitisation unit are presented. The contributions of the individual tasks to the total processing cycle time may then be observed. The closeness of the actual processing time to maximum permissible levels is also recorded.

The working program at the encoder consists of two parts which are the main program and the interrupt service routine. The main program carries out the cascaded SBIC with 8/6 compression, on the contents of the input buffer which has been filled by the interrupt routine upon interrupt pulses from external hardware. The encoded field contents are stored as 2-bit or 3-bit words (depending on 4800bps or 7200bps transmission) in an output buffer and the main program's task is completed. It then returns to the start of the field-processing cycle where it polls the ready flag for the next input field. As described in the previous chapter alternating buffers are employed for input and output so that one is accessed by the interrupt

routine whilst the other is being processed by the main program. The binary codewords are translated to signalling levels in the interrupt routine through raised-cosine filtering and amplitude-modulation processes. The 12-bit output is then sent to the output FIFO buffer from where it is clocked out independently at 9600Hz to the DAC. To simplify interrupt processing a single interrupt routine has been used which is serviced at a constant rate of 2400Hz. Because output (to FIFO buffer) occurs at a faster rate than input (of 8-bit image bytes at 1200Hz or 1800Hz for 4800bps and 7200pbs systems respectively), the reading of the input byte is controlled by an external ready flag which is polled at the start of the service routine. For each interrupt cycle four output samples are placed in the FIFO buffer.

The compression of image data is commenced after several stages of operation following receipt of the start signal which resets the microprocessor. Initially the start tone is issued to line which is followed by output of maximum carrier level for AGC set-up at the receiver. This is followed by the transmission of phasing pulses for line synchronisation and equaliser-training at the receiver. The encoding of input data is activated following this stage upon receipt of the Page Enable signal. It is clear that the processing time for the encoding of image data is dependent on the distribution of block-pair states in the coding field. Obviously the encoding time will be greater when an overflow occurs in the field. As the shrinking set algorithm is used for sorting of blocks to be deleted the total encoding time becomes primarily dependent on the number of blocks which need to be deleted. The execution times for various preset field distributions are shown in Figs.7.1 and 7.2 for 4800bps and 7200bps systems respectively. These times are measured from the time difference between start and finish pulses as specially issued

from the running encoding program, and are not the results of calculations from clock cycle counts.

Referring to the figures, apart from the increase of execution time with increasing number of deletions in each field size the proportion of time taken up by compression over the field period time also increases with larger field sizes (see column for execution time expressed as percentage of field period time). This immediately suggests the use of smaller field sizes if a larger percentage of unused processing time is demanded but smaller fields unfortunately lead to higher probabilities of field overflow. For a fixed number of deleted blocks the encoding time varies depending on the actual distribution of the block-pair states. For example in Fig.7.2 two different field distributions resulted in deletion of 25% of blocks in the field but a higher encoding time was obtained when the number of double-nonwhite block-pairs was greater (75% of block-pairs in field). This may be attributable to the increased number of operations involved in processing each DNW block-pair compared to other states. Compared to SBIC operations the second stage of compression ie. 8/6 encoding of 8-bit patterns by looking up a table is inconsequential.

The penultimate columns in Figs.7.1 and 7.2 show the total times available for interrupt processing as each field is encoded. This time (difference between field period and encoding time) should not be exceeded if real-time operation is to be sustained. The average time available for each interrupt servicing is shown in the last column (the number of interrupts is fixed for each field size). The actual servicing time for each interrupt is not constant as the operations are not always exactly the same. For example input byte of image data may or may not be read depending on its ready flag and additional reinitialisation operations are

required when buffers are full, etc. From the displayed results it is clear that shorter interrupt service times are permitted when the number of deletions are small and the effect is worse for larger field sizes. The results for the 7200bps system are more critical in view of the higher throughput rate. From Fig.7.2 it is seen that very small interrupt servicing times are available for the worst case percentage deletion of 50%. At the largest field size of 432 blocks this condition results in an encoding time which exceeds the field period even in the absence of interrupts. Fortunately this field distribution is unlikely to be encountered in practice. For the 7200bps system the increased resolution and redundancy are likely to yield lower levels of block deletion than in the 4800bps system. A figure of 12.5% block deletion is a reasonable level as a design target. Using the distribution of 50% DNW, 25% RW and 25% DW responsible for this condition the compressor program was executed and real-time operation was found to be possible for the three field sizes. The total times taken to encode the field with interrupts were measured and are shown in Fig.7.3. In all cases the total encoding time falls short of the field period with the smallest margin being obtained for the largest field size of 432 blocks. The wider margins for the field sizes of 108 and 216 blocks prompted a further test using the distribution of 50% DNW, 50% RW in which 25% of blocks are deleted. Real-time operation was successfully achieved for these two field sizes but a failure was recorded in an attempt with the field size at 432 blocks.

A breakdown of the execution times for the various stages of the interrupt service routine is given in Fig.7.4. During image transmission the interrupt routine can operate in either 'data' or 'sync' modes. Each line of the image can be set to contain an integer number of fields (typically 1, 2 or 4). A short period of 5% of the scan-line is available

at the end of a each line during which no image data is read by the processor. This corresponds to the 'dead time' period characteristically present in fixed-rate scanners. During this period the interrupt service routine is in a sync mode and a constant level to the modulator is maintained. The interrupt routine recognises this period from an external pulse which it reads at the start of the routine. At the end of the pulse a special start of line code is transmitted and after initialisation of registers and pointers the interrupt routine switches to the data mode. In this mode bytes of image data are read and stored in the input buffer and formatted codewords are accessed from the output buffer. The digitally-encoded signal levels are filtered and modulated before being despatched to the DAC. A separate generation of a pilot tone is also performed which is added to the modulated signal output. From Fig.7.4 the measured time taken to perform the raised cosine filtering is 160μs. A further 54μs is consumed in synthesising the pilot tone. The total interrupt servicing time inclusive of input and output operations is 268μs which leaves a margin of 149μs which is exploited by the main program for its encoding operations.

7.3 Performance of the Decoder Program

As with the encoder program the working program at the receiver consists of a main program and a single multi-purpose interrupt service routine. During data transmission the main program decodes detected codewords stored in the input buffer filled by the detector section of the interrupt routine. The reinstated block-pairs are placed in an output buffer from where they are subsequently accessed in the interrupt routine for output to the external port. The expansion task of the main program is

completed when all block-pairs of the field have been reinstated and stored in the output buffer. The processor then polls the ready flag indicating the next buffer has been filled.

The operations involved in expansion are relatively straightforward, consisting mainly of re-forming block-pairs as dictated by the header states. The total decoding time for a field is therefore much shorter than the encoding time and there are no wide differences between times for various block-pair distributions in the field. Fig.7.5 shows measured typical decoding times from the set of three field sizes for the 7200bps system (performance for the 4800bps system is less critical and is not shown). The percentage of field period taken up by decoding is fairly constant at about 6%. This amount is in sharp contrast to that for encoding time which takes up 20% or more of the field period. The shorter decoding time is of vital importance as it enables a longer period for time-consuming equalising operations in the interrupt service routine. From the last column of Fig.7.5 the average time allowed for servicing an interrupt request is constant at 391μs for the three field sizes.

As with the encoder program the main program in the decoder unit is interrupted at the symbol baud rate of 2400Hz (417μs period). The single interrupt routine also takes up two modes - the hunt and data modes. For both modes the interrupt routine performs the processes of equalisation (transversal filtering), adaptive thresholding and detection. The hunt mode is invoked at the start of each line when the detected output binary sequence is monitored for the start-of-line code. This is carried out by correlating a delayed sequence of length 7 samples of the detected output with the code sequence. The correlation process is a relatively time-consuming process but extra time is available in the hunt mode because

of the absence of output operations (unloading output buffer contents to output port) during this period. When the start-of-line code is detected the interrupt routine initialises its registers and pointers and switches to the data mode. In this mode the detected binary word is saved in the input buffer and an output operation is performed. The output port is a FIFO buffer which is clocked out independently at the appropriate byte rate. This avoids the processor being unnecessarily held up by timing considerations for its output operations.

Fig.7.6 shows the approximate execution times of the various stages in the interrupt service routine. The equaliser length here is 29 taps. For the data mode the total interrupt cycle time of 364μs falls short of the 364μs average time found earlier to be the maximum permissible. The servicing time for the hunt mode exceeds this value but is less than the constant period between interrupts of 417μs. This is acceptable because during the hunt mode the main program will be likely to have finished its expansion operations and is simply polling for the next buffer to be ready. Further tests showed that the maximum equaliser length for which real-time operation is possible is 31 taps. If fixed thresholding is employed at the detector output instead of adaptive thresholding the maximum number of taps can be increased to 39. The execution time achieved for the highly-optimised program for the transversal filtering is 15.7μs for every two additional taps.

The performance of the working program has so far been described for 'steady-state' conditions when image data is being transmitted. The performance of the program in the setting up of the equaliser is of critical importance as it determines the feasibility of training the equaliser within the 30sec period available corresponding to the phasing

period. In this time about 120 baseband pulses at a rate of 4Hz (250ms intervals) are received from the transmitter. The equaliser set-up can proceed in one of two ways. Iterations can proceed on a pulse-by-pulse basis in which the step response is captured at the start of each iteration so that if 70 pulses are required to set up the equaliser the setting-up period consists of the duration of 70 received phasing pulses and the processor waits out the remaining pulses. For this to be successful the iteration cycle must execute in a time inside the 250ms between pulses. The alternative approach is to capture say 100 pulses obtain the average pulse reponse from these and use the average response to set up the equaliser. Then the total time to set up the equaliser must be less than the duration of the remaining 20 pulses. This approach has been adopted because it is more convenient to perform the setting up in a section of program separate from the actual capture of step response samples. The measured iteration cycle time for the maximum permissible equaliser length of 31 taps was 190ms. The number of samples in the pulse response window was 32. This suggests that the pulse-by-pulse approach to setting up is feasible. For the adopted approach a total of 13.3sec was consumed for the total setting-up of coefficients where 70 iterations were found to be adequate for this purpose using the 3-level step algorithm. The number of pulses contributing to the average pulse response was set at 64 so that setting up of the equaliser commenced 16sec after receiving the first training pulse. The time to set up the equaliser of 13.3sec is just inside the remaining available time of 14sec from the phasing period.

7.4 Transmission Characteristics

Within the encoder program the digital waveform at the output of the

compressor is conditioned to a form suitable for line transmission. The process involves tailoring the spectrum of the baseband waveform by means of a linear-phase transversal filter followed by amplitude modulation of a carrier wave of 2400Hz. Fig.7.7 shows the frequency spectrum of the output of the filter for a PRBS input. At a frequency of 800Hz the gain is 40dB down on the passband gain. The pilot tone of 800Hz is clearly visible over the signal spectrum and a dominant component of the carrier frequency is also present which should facilitate extraction of carrier at the receiver. This signal is further filtered by the VSB filter in the Mufax transmitter before output to line so that the upper sidebands are suppressed.

At the receiver coherent demodulation is carried out by employing a phase-locked loop to extract the carrier and mutliplying this carrier with the line signal. The resultant signal is passed through a lowpass filter which removes unwanted frequency terms so that the baseband signal is furnished. Fig.7.8 shows the amplitude response of the lowpass filter. This filter also removes out-of-band noise introduced during transmission. In Fig.7.8 two possible cut-off frequencies are displayed which are switchable by simply changing the clock frequency to the switched-capacitor filter. This option enables a switch to a wider baseband bandwidth if transmission over a more conventional telephone circuit is made.

The performance of the Z80-implemented equaliser is assessed with the use of three cascaded bandpass filters to simulate the transmission channel. Fig.7.9 shows the composite amplitude response of the filters. The received step response at the output of the demodulator is shown in Fig.7.10. This step response is sampled at 417μs intervals and the average of 64 digitised responses is used to set up the equaliser. At the output of the equaliser the initial unequalised pulse response is shown in

Fig.7.11. The same response after convergence of equaliser coefficients is shown in Fig.7.12. The difference between the two responses clearly demonstrates the practical effectiveness of the transversal equaliser trained using an MSE criterion, in reducing intersymbol interference. The equalised step response is shown in Fig.7.13. The ringing observed in the unequalised case of Fig.7.9 has been largely eliminated.

A digital 'eye diagram' may be obtained for the equaliser by displaying the sampled output of the equaliser on the oscilloscope with triggerring from the baud rate clock. The transmitted binary stream consists of a pseudo-binary sequence. Fig.7.14 shows the result for the 8-level system. The result without equalisation is shown in Fig.7.15. Here no eye opening is discernible which reflects the impossibility, without any form of equalisation, for successful data transmission at the rate of 7200bps. In Fig.7.14 the separations between signalling levels are visible which promise good recovery of transmitted data. For a 4-level system the equalised eye diagram shown in Fig.7.16 shows even better prospects for reliable data transmission. At this lower rate of 4800bps it is likely that an amount of noise may be tolerated without seriously affecting the data transmission.

7.5 Reconstructed Images at the Receiver

For the transmission rates of 4800bps and 7200bps the corresponding sampling densities for an 18.7-inch scan-line are 128 and 193 pels/inch respectively. The results of digitisation of a test chart at these densities are shown in Figs.7.17 and 7.18. These have been produced by directly feeding the digitised output of the scanner to the recording unit of the K-649 receiver. The test weatherchart is typical of the type of

images which are communicated by the facsimile equipment. From Fig.7.17 it is evident that the image quality for the lower sampling density is quite adequate. The results of applying 8/6 coding to these images is shown in Figs.7.19 and 7.20. Generally the degradation of image quality is not visible although some roughness of edges may be detected on close scrutiny in the lower-resolution case. The reconstructed images with the use of the constructed real-time compression system of SBIC cascaded with 8/6 block-to-block coding are shown in Figs.7.21 to 7.24. These have been obtained by running only the compression and expansion sections of the programs with a back-to-back connection of the compressor output and expandor input. Such a system will normally be used if a commercial modem was employed for data transmission. For the 4800bps system the results for three field sizes are shown which correspond to a quarter, a half and the whole of the active scan-line. The decoded image output in each case is remodulated before being fed to the line signal output of the K-649 receiver. Ideally this stage will have been avoided and the decoded data fed directly to the write amplifier of the recording unit to prevent deterioration of image quality.

Referring to the displayed reconstructed images the performance at 4800bps appears to be quite satisfactory. Little loss of black element content is registered for this test chart despite the absence of block scrambling. This may of course be attributed to the relatively scattered distribution of characters in the test image. Even if black pel loss occurs the intelligibility of content should not be severely affected. In meteorological facsimile true fidelity of reproduction is not so important as long as the correct interpretation of information is achieved.

The reconstructed images obtained when the in-built transmission

facilities are used for the communication of codewords to the receiver are shown in Figs.7.25 and 7.26. The field size in these images is set at a quarter of the active scan-line. The bandpass filters giving the response of Fig.7.9 were used to simulate the telephone channel. In each case the decoded image is remodulated and fed into the line signal input of the Mufax K-649 receiver. From the figures satisfactory quality of image is obtained at the lower rate of 4800bps whilst the higher rate yielded a distinctly finer quality of image.

7.6 Other Tests Performed on the Digitisation Unit

The effect of variation of line signal level was studied initially for the 4800bps system. At the decoder the incorporation of synchronisation sequences at the start of each line of image meant that field synchronisation is renewed at the beginning of every line and a brief loss of timing for example due to carrier fallout or loss of line signal, does not lead to a permanent loss of image. The detector at the output of the equaliser was designed to reduce the effects of signal level variation by adaptation of threshold levels. The performance of this detector is demonstrated in Fig.7.27. Here the line signal level was gradually decreased (manually) towards the bottom of the image as transmission progressed. No discernible deterioration of image occured in the top three-quarters of the image indicating that the detector had adapted well to the change of signal level. The limit of adaptation appears to be at the bottom end of the image where the measured level of signal was about half of that at the start of the image. A similar adaptation to signal level changes can be expected when the level increases rather than decreases over its nominal level but here a limiting factor is overflow of

the digitised sample as the input value exceeds the dynamic range of the 8-bit ADC. For the 7200bps system the tolerable range of level variation will be much smaller because when the overall level of the input to the detector reduces the decision bands for the 8 amplitude levels grow smaller leading to errors of detection. Tests carried out showed the line signal level could be reduced to seven-eights of its nominal value without adversely affecting the performance of the detector.

The effects of line noise were observed by injecting 20kHz bandlimited Gaussian white noise into the simulated channel. Fig.7.28 shows the reconstructed image for the 7200bps system when the received carrier-to-noise power ratio was 26dB (measured as a ratio of maximum carrier tone to noise in the absence of line signal). No sustained loss of image was observed and a high degree of intelligibility was maintained. For the 4-level system the wider eye openings should allow a higher tolerance to noise. The reconstructed image for a carrier-to-noise ratio of 17dB is shown in Fig.7.29. The effect of this level of noise is not too drastic although degradation of image was obviously incurred.

7.7 Results of Trials on the Molfax Network

Trial runs were carried out to investigate the feasibility of using the digitisation unit on the Molfax (Meteorological Facsimile) network. The leased circuit used in the tests starts out from the Meteorological Centre in Bracknell and traverses through northern Britain before returning to Bracknell. Over a hundred weather centres are serviced by the circuit with additional links to more remote sites tapped from these centres. Fig.7.30 shows the frequency response of this circuit. The amplitude response is reasonably good with less than 3dB gain variation in the

passband. However the group delay is very much outside British Telecomms specification (shaded region). For example, a group delay of about $6\frac{1}{2}$ms relative to minimum is observed at 600Hz which is considerably worse than may be found on switched circuits.

Fig.7.31 shows the step response of the channel recorded at the output of the demodulator. It is immediately apparent that the level of noise is extraordinarily high and even if perfect equalisation is achieved the level of noise will not permit discrimination of 8 levels at the receiver. Even with 4 levels transmission is unlikely to be satisfactory. The actual step response itself is buried in noise and a very large number of responses will be needed to average out the noise contributions. It is also unlikely that satisfactory setting up of the equaliser can be accomplished to equalise the severe channel response under such noisy conditions. In the tests the capture of the step response itself was difficult as the trigger instants varied excessively due to the noise, causing a variable phase shift of the capture window for each response.

It is difficult to see how the hostile conditions encountered on the Molfax network can be overcome to permit satisfactory data transmission at the rates of 4800bps and 7200bps, even with the most modern and sophisticated commercial modems available. The suppressed-carrier VSB modulation system employed is almost optimum in its efficiency in terms of concentrating transmitted signal power in the information-bearing sidebands and discarding a large proportion of the redundant upper sidebands. Improving the signal-to-noise margin by increasing the transmitted signal power is not possible over the telephone network where maximum permissible levels are strictly controlled.

7.8 Conclusion

The performance of the prototype system has demonstrated a lowcost solution to the digitisation of analogue facsimile systems. By integrating transmission functions with compression and expansion processes a compact system can be realised. The constructed system was designed for use with weatherchart transmission equipment and a transmission rate of 4800bps was found to be satisfactory with sampling at 128 pels/inch. The homogeneous nature of transmitted material avoids the need for initial pseudo-scrambling of blocks. The performance of the transversal equaliser implemented using an 8-bit commercial microprocessor was found to be very satisfactory. The method of detection employed worked well and made the signalling system insensitive to minor fluctuations in signal level especially in the 4-level case. The transmission system also stood up well to the presence of injected noise with good intelligibilty of reconstructed images being preserved for up to 19dB carrier-to-noise ratio in the 4-level system. Trials on the Molfax network were curtailed because of the excessive levels of noise present on the circuit.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	5.4	9.0	60	54.6	0.379
50%DNW,25%RW,25%DW	9	12.5	8.0	13.3	60	52.0	0.361
50%DNW,50%RW	18	25.0	11.8	19.7	60	48.2	0.335
100%DNW	36	50.0	19.0	31.7	60	41.0	0.285

(i) Field Size = 36 block-pairs = 72 blocks.
4 fields per line, 144 interrupts per field.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	10.7	8.9	120	109.3	0.379
50%DNW,25%RW,25%DW	18	12.5	18.5	15.4	120	101.5	0.352
50%DNW,50%RW	36	25.0	24.1	20.0	120	95.9	0.333
100%DNW	72	50.0	49.0	40.8	120	71.0	0.271

(ii) Field Size = 72 block-pairs = 144 blocks.
2 fields per line, 288 interrupts per field.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	21.3	8.9	240	218.7	0.380
50%DNW,25%RW,25%DW	36	12.5	47.6	19.8	240	192.4	0.334
50%DNW,50%RW	72	25.0	59.6	24.8	240	180.4	0.313
100%DNW	144	50.0	152.0	63.3	240	88.0	0.153

(iii) Field Size = 36 block-pairs = 288 blocks.
1 field per line, 576 interrupts per field.

Fig.7.1. Execution Times of Compressor Section of Encoder Program for 4800bps System.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	7.4	12.3	60	47.8	0.375
50%DNW,25%RW,25%DW	13	12.0	12.2	20.3	60	47.8	0.332
50%DNW,50%RW	27	25.0	16.8	28.0	60	43.2	0.3
75%DNW,25%RW	26	24.0	18.2	30.3	60	41.8	0.290
100%DNW	54	50.0	31.5	52.5	60	28.5	0.198

(i) Field Size = 54 block-pairs = 108 blocks.
4 fields per line, 144 interrupts per field.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	14.7	12.3	120	105.3	0.366
50%DNW,25%RW,25%DW	27	12.5	30.4	25.3	120	89.6	0.311
50%DNW,50%RW	54	25.0	38.7	32.3	120	81.3	0.282
75%DNW,25%RW	54	25.0	53.1	44.3	120	66.9	0.232
100%DNW	108	50.0	92.0	76.7	120	28.0	0.097

(ii) Field Size = 108 block-pairs = 216 blocks.
2 fields per line, 288 interrupts per field.

Distribution of Block-Pairs in Field	No. of Deletions (Blocks)	% Deletion	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
100%DW	0	0	34.7	14.5	240	205.3	0.356
50%DNW,25%RW,25%DW	54	12.5	84.7	35.3	240	155.3	0.270
50%DNW,50%RW	108	25.0	106.6	44.4	240	133.4	0.232
75%DNW,25%RW	108	25.0	170.2	70.9	240	69.8	0.121
100%DNW	216	50.0	310.5	129.4	240	-70.5	-

(iii) Field Size = 216 block-pairs = 432 blocks.
1 field per line, 576 interrupts per field.

Fig.7.2. Execution Times of Compressor Section of Encoder Program for 7200bps System.

Field Size (Blocks)	Encoding Time (ms)	Field Period (ms)	Margin (ms)
108	34	60	24
216	86	120	34
432	230	240	10

Field Distribution: 50% DNW, 25% RW, 25% DW.
Percentage Deletions = 12.5%

Fig.7.3. Field Encoding Times for 7200bps System.

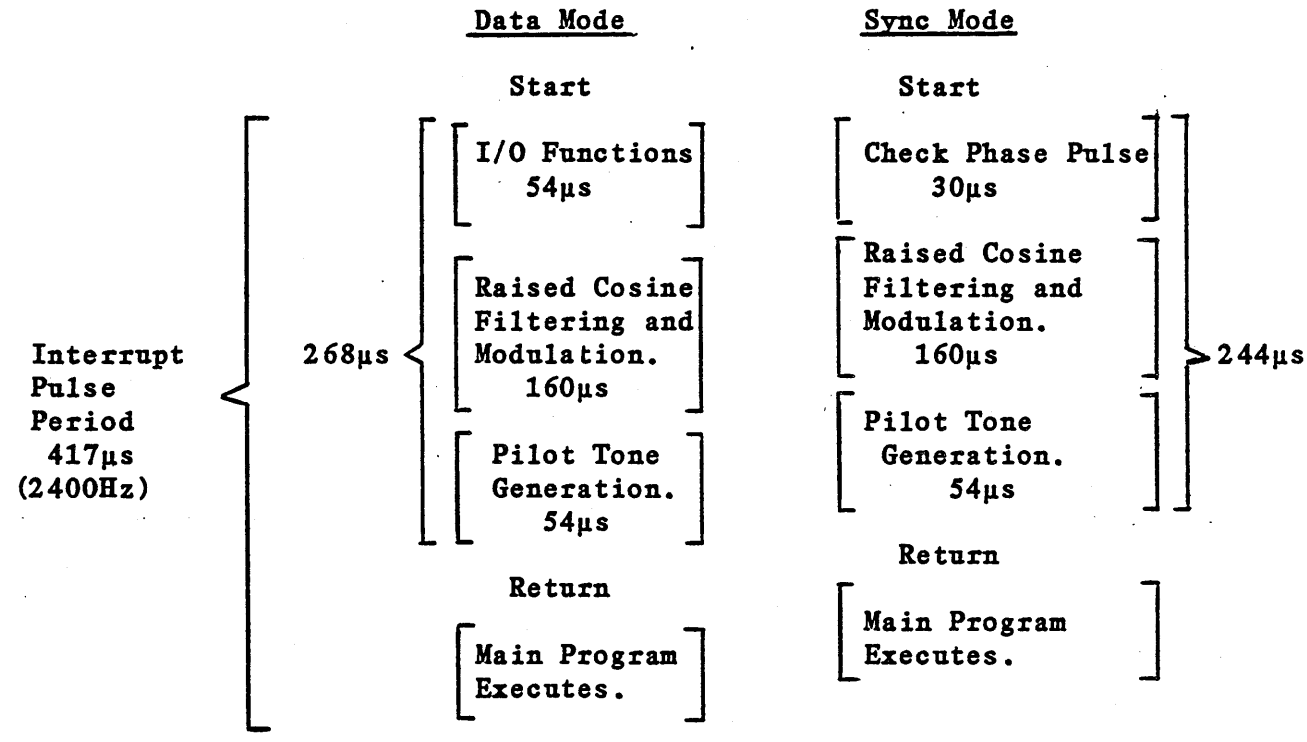


Fig.7.4. Showing Execution Times of Components of Interrupt Service Routine of Encoder Program.

Field Size (Blocks)	No. of Fields Per Line	No. of Interrupts Per Field	Execution Time (ms)	% of Field Period (ms)	Field Period (ms)	Max.Time for Total Interrupts (ms)	Av.Time Per Interrupt (ms)
108	4	144	3.75	6.25	60	56.3	0.391
216	2	288	7.4	6.17	120	112.6	0.391
432	1	576	14.5	6.04	240	225.5	0.391

Fig.7.5. Execution Times for Decoding of Field in 7200bps System.

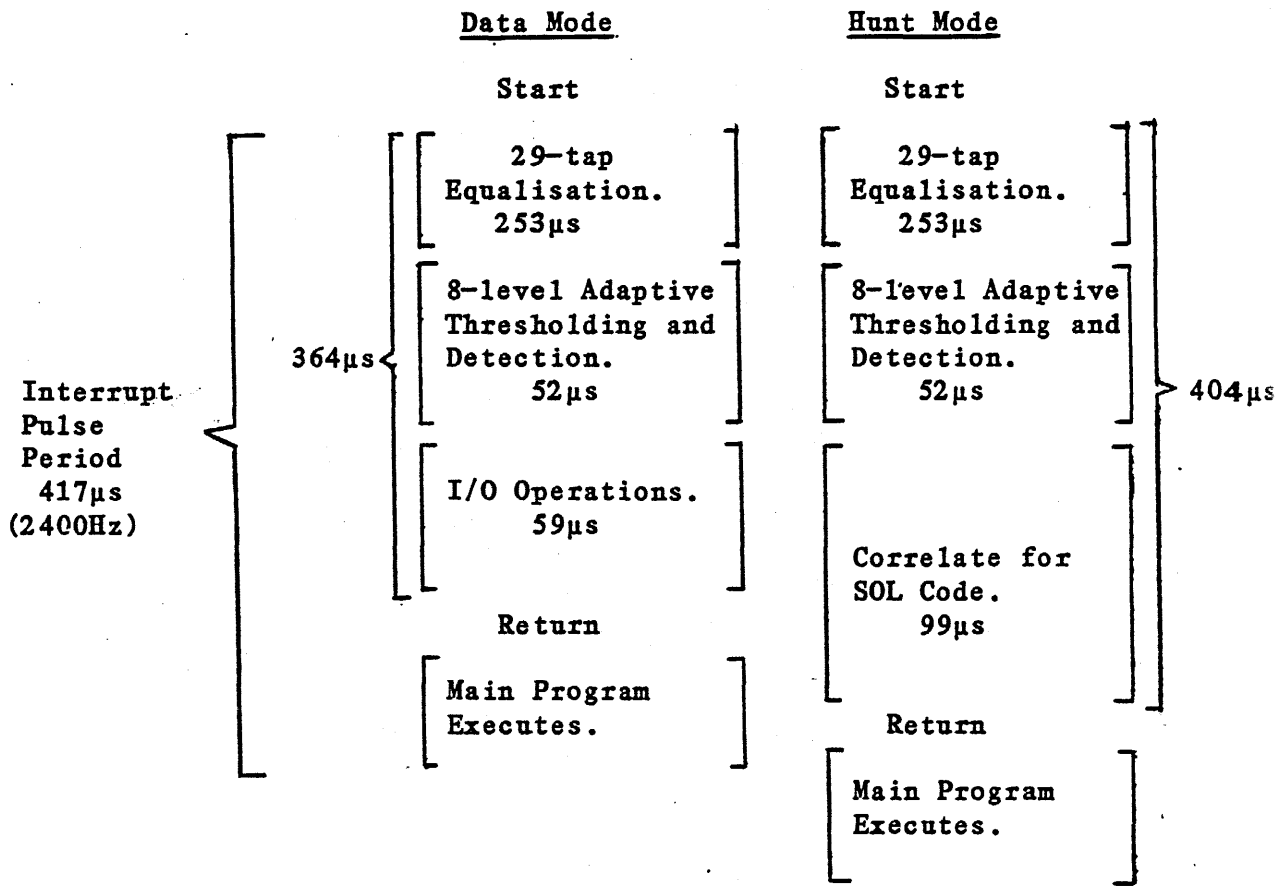


Fig.7.6. Showing Execution Times of Components of Interrupt Service Routine of Decoder Program.

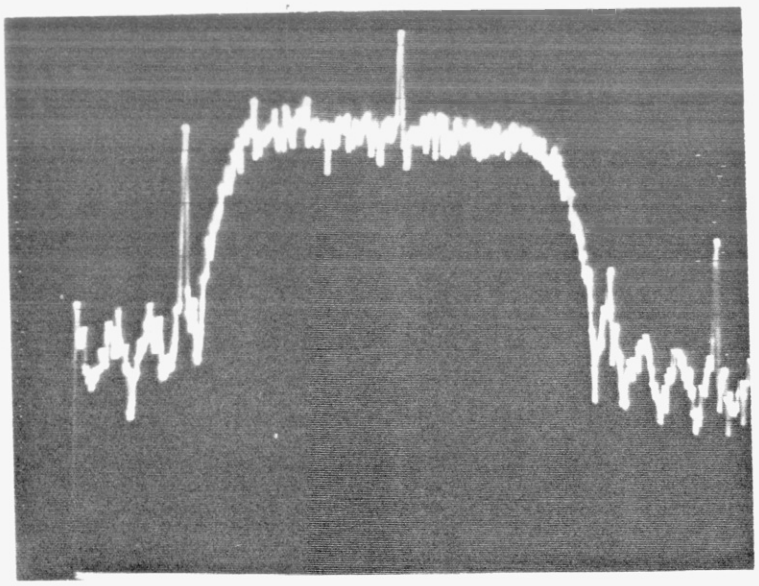


Fig.7.7. Spectrum of Output from Modulator (DAC Output) for PRBS Baseband Input.
Vertical Scale 10dB/div.
Horizontal Scale 500Hz/div.

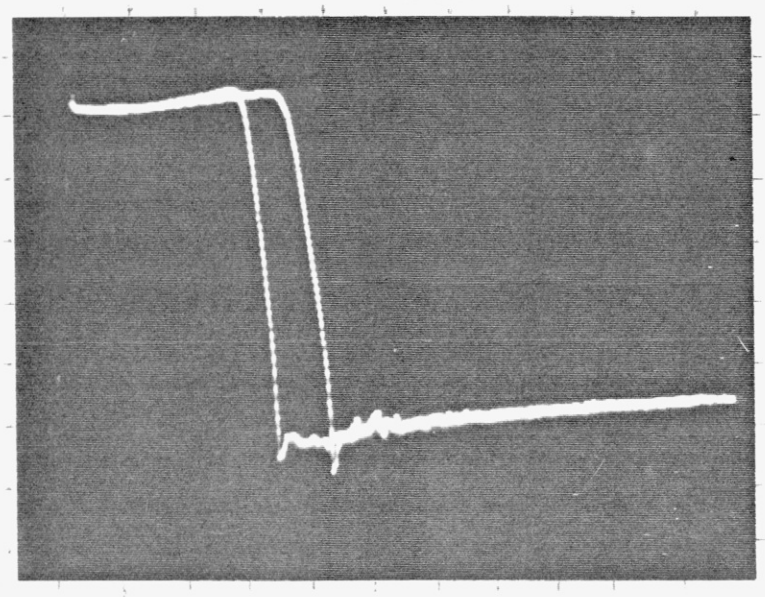


Fig.7.8. Amplitude Response of Demodulating Filter for 1200Hz and 1600Hz Cut-off Frequencies.
Vertical Scale 10dB/div.
Horizontal Scale 500Hz/div.

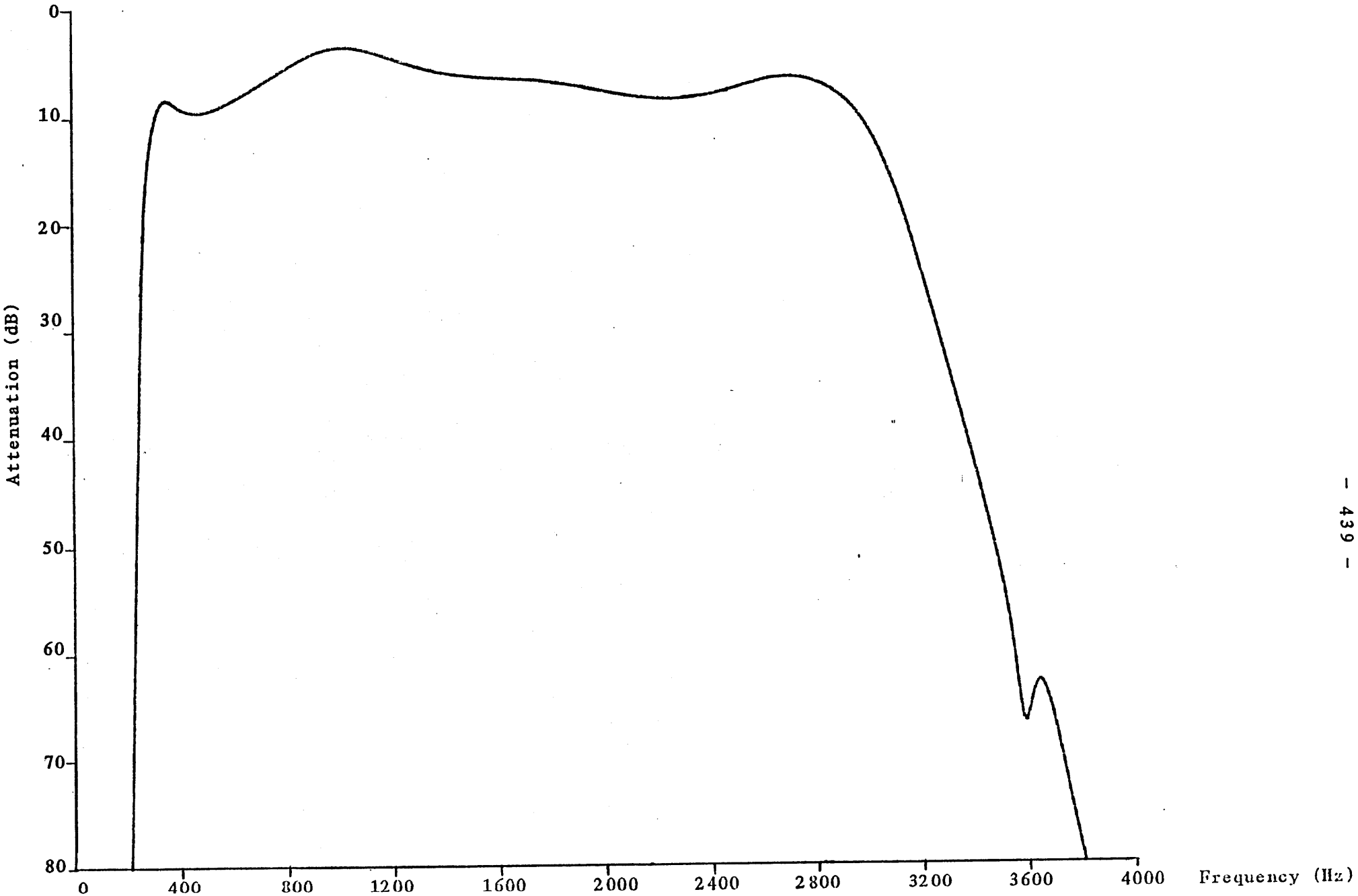


Fig.7.9. Amplitude Response of Simulated Telephone Channel.

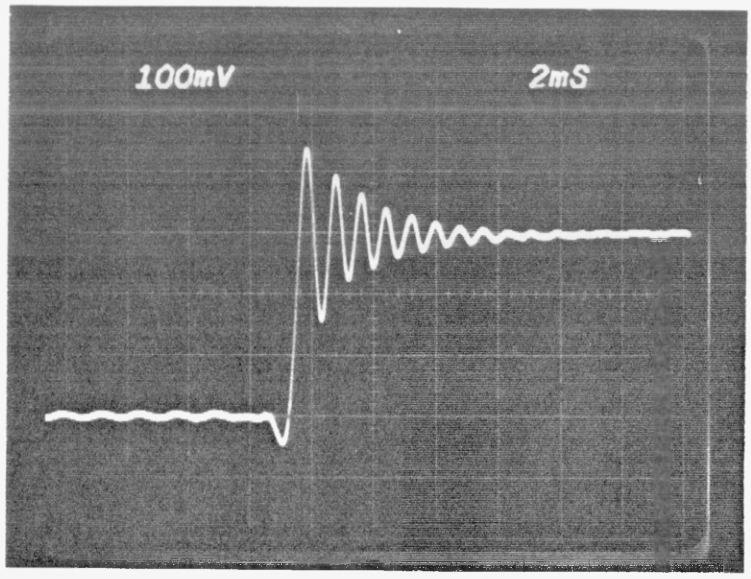


Fig.7.10. Step Response at Output of Demodulator for Simulated Telephone Channel.
Vertical Scale 100mV/div.
Horizontal Scale 2mS/div.

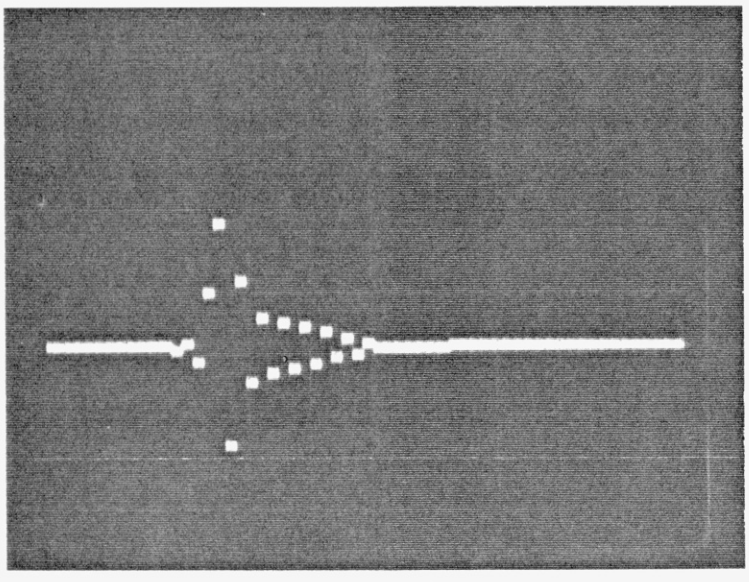


Fig.7.11. Average Pulse Response of Simulated Telephone Channel.
Sampling Interval = 417μs.

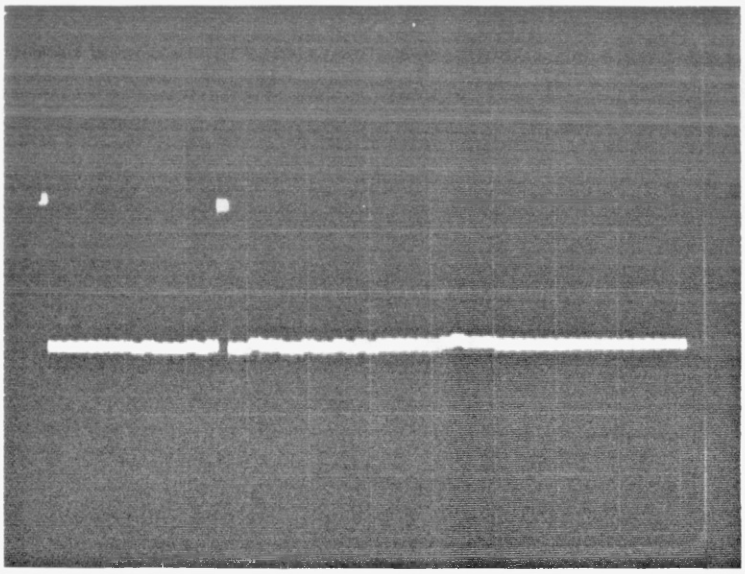


Fig.7.12. Equalised Pulse Response.

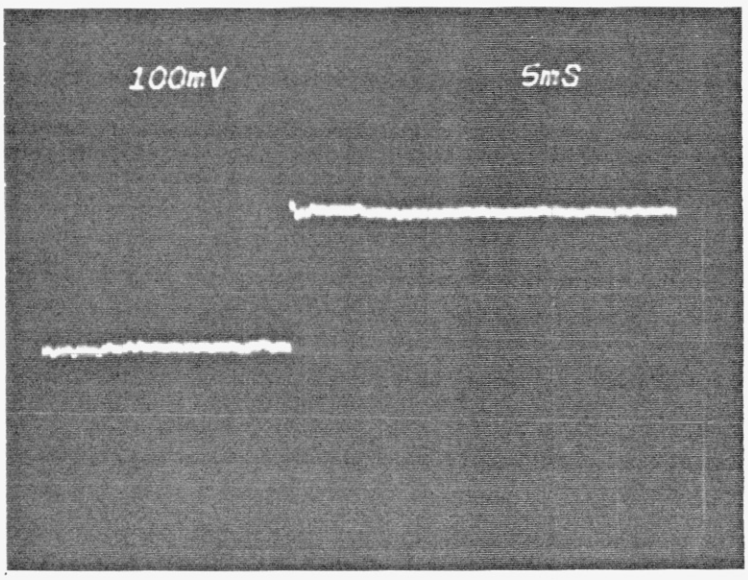


Fig.7.13. Equalised Step Response.

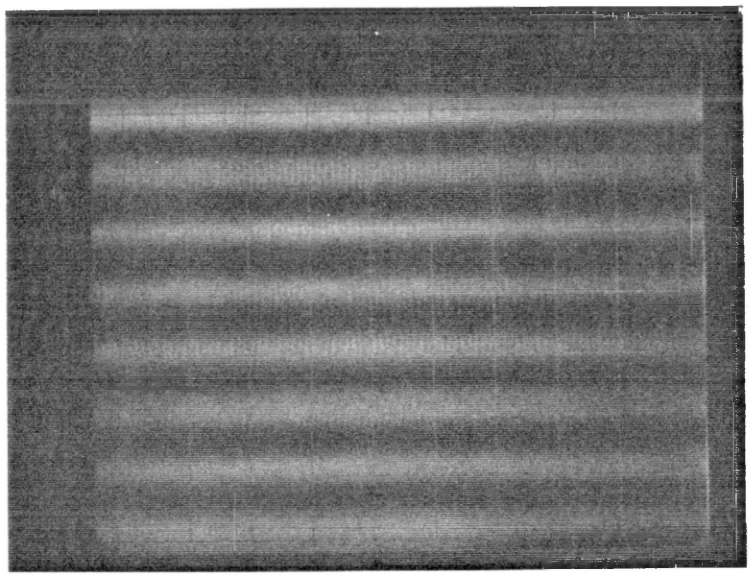


Fig.7.14. Digital Eye Diagram for 7200bps System (8-level).

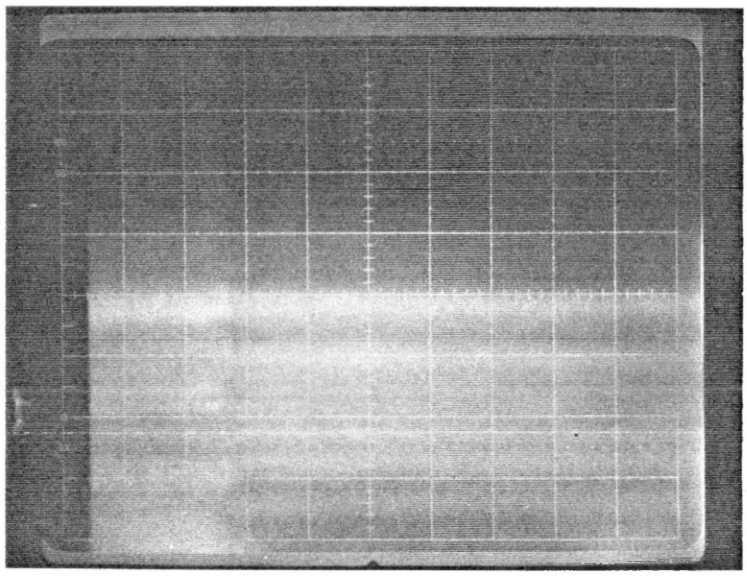


Fig.7.15. Unequalised Eye Diagram for 7200bps System (8-level).

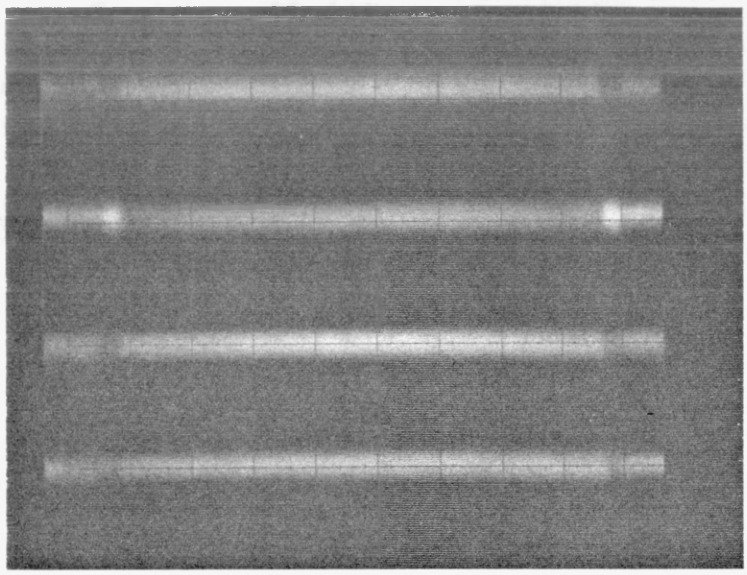


Fig.7.16. Digital Eye Diagram for 4800bps System (4-level).

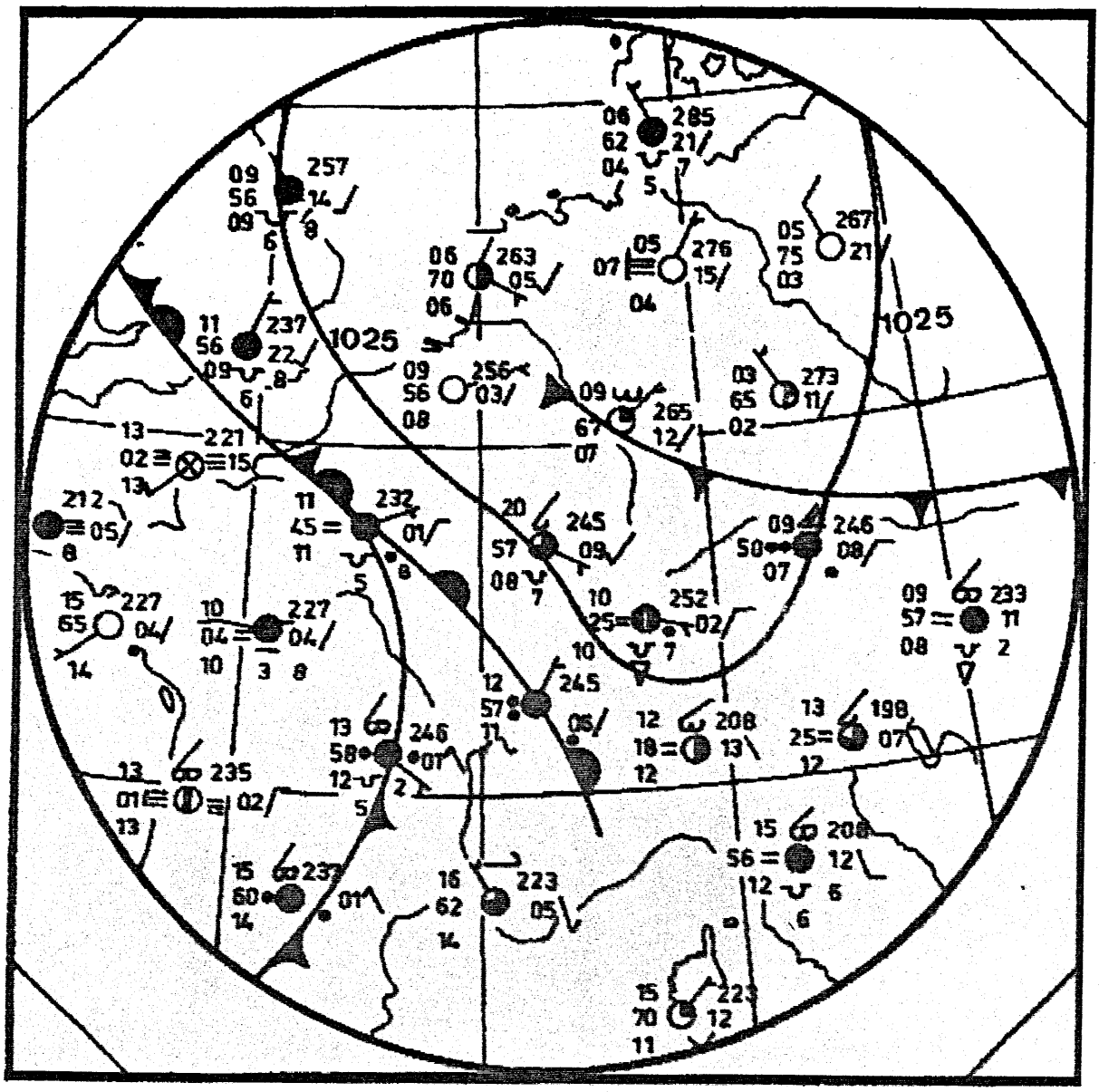


Fig.7.17. Test Chart Digitised at 128 pels/inch Resolution.

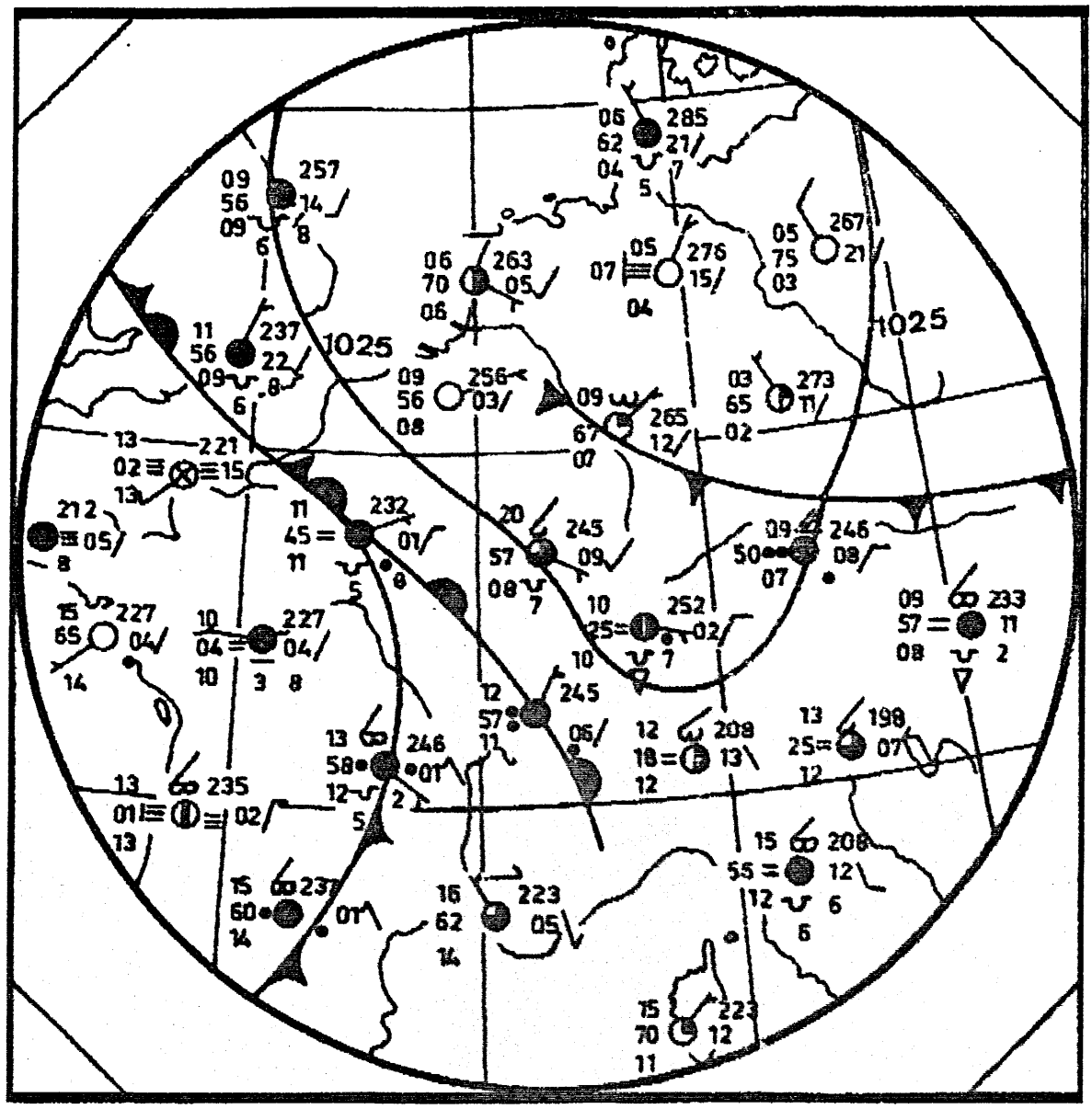


Fig.7.18. Test Chart Digitised at 193 pels/inch Resolution.

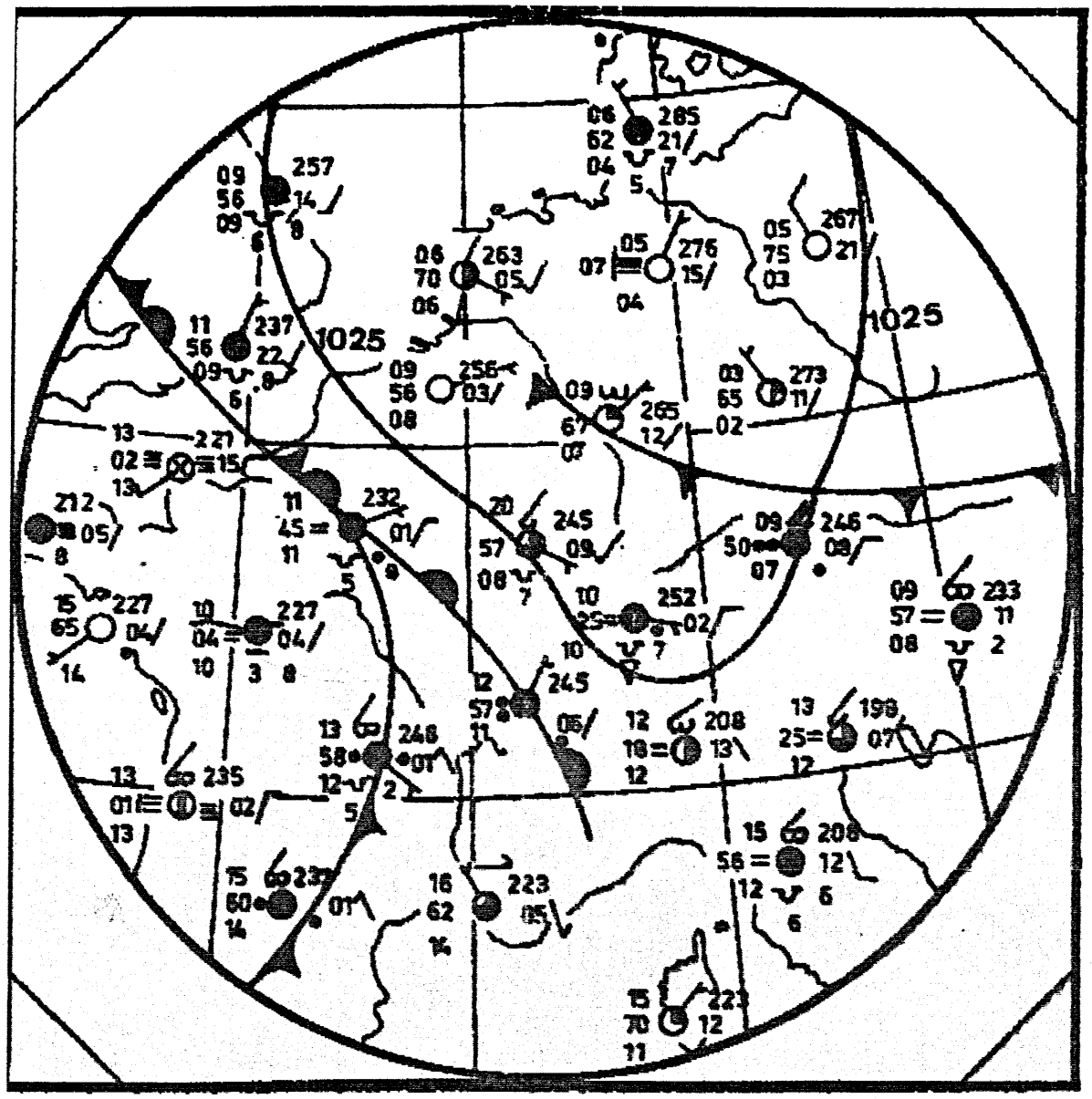


Fig.7.19. Test Chart Digitised at 128 pels/inch, 8/6 Compressed.

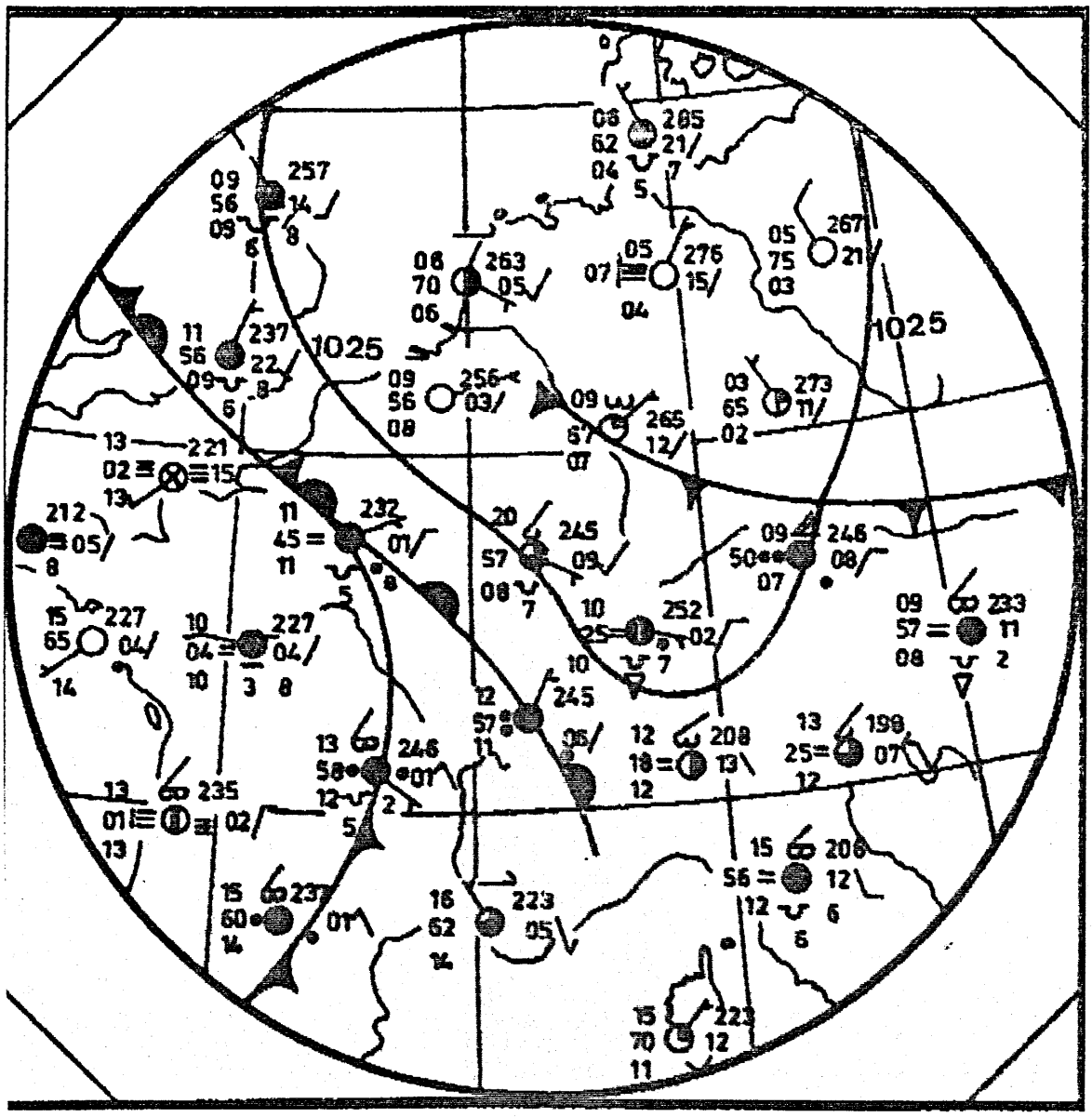


Fig.7.20. Test Chart Digitised at 193 pels/inch, 8/6 Compressed.

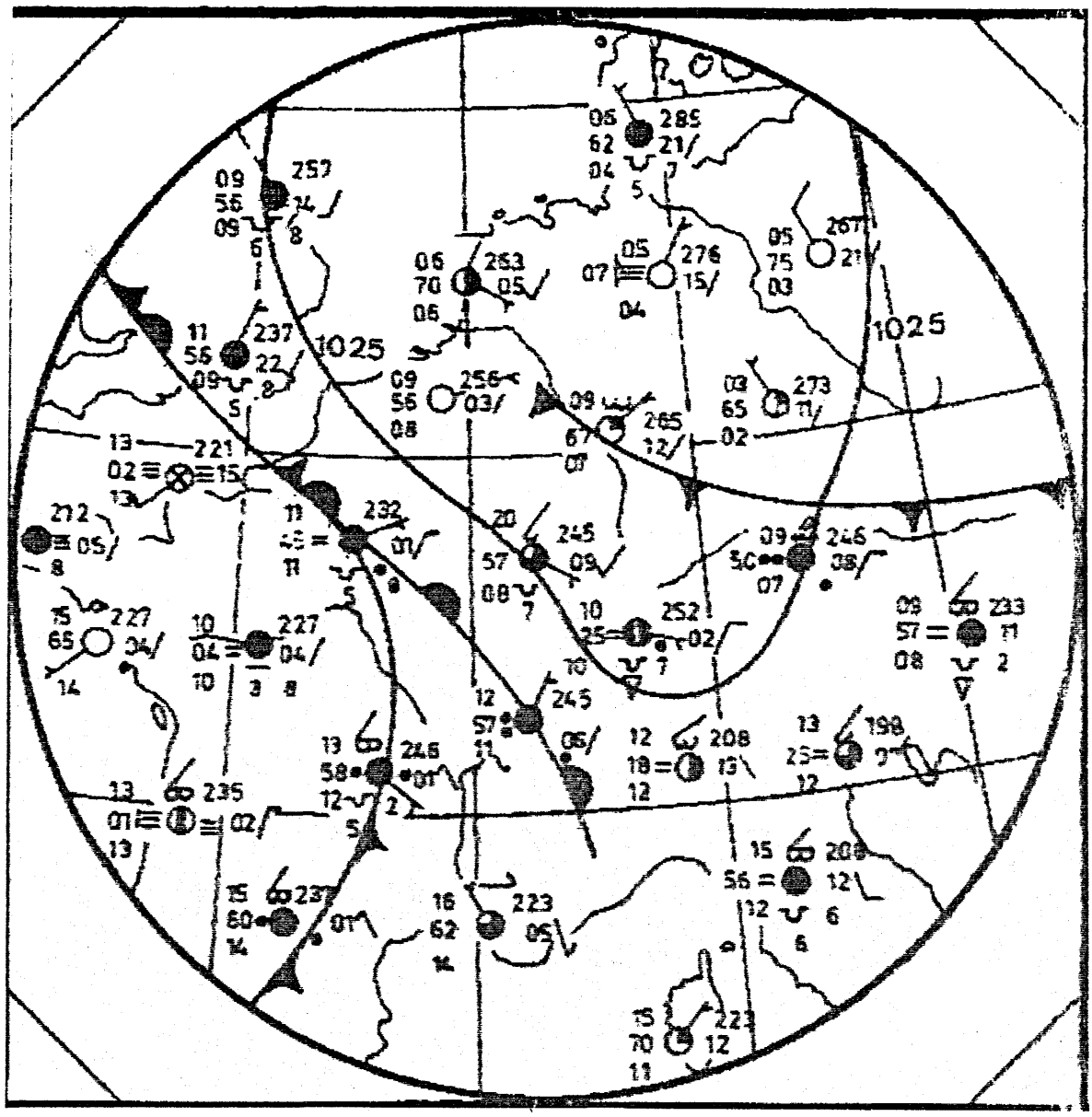


Fig.7.21. Reconstructed Image for 4800bps Back-to-Back Transmission.
Field Size = 36 block-pairs (1/4th scan-line).

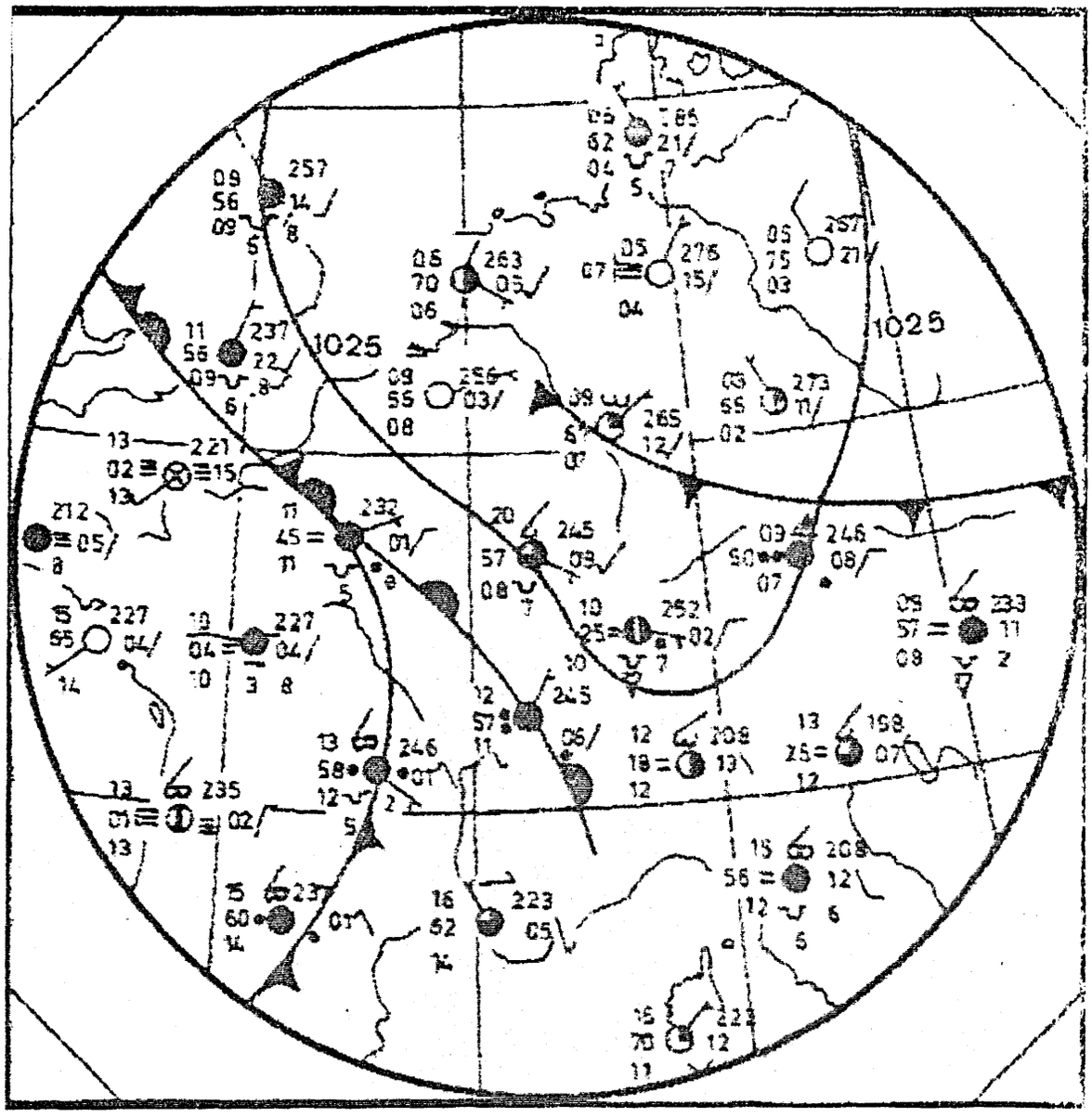


Fig.7.22. Reconstructed Image for 4800bps Back-to-Back Transmission. Field Size = 72 block-pairs ($\frac{1}{2}$ scan-line).

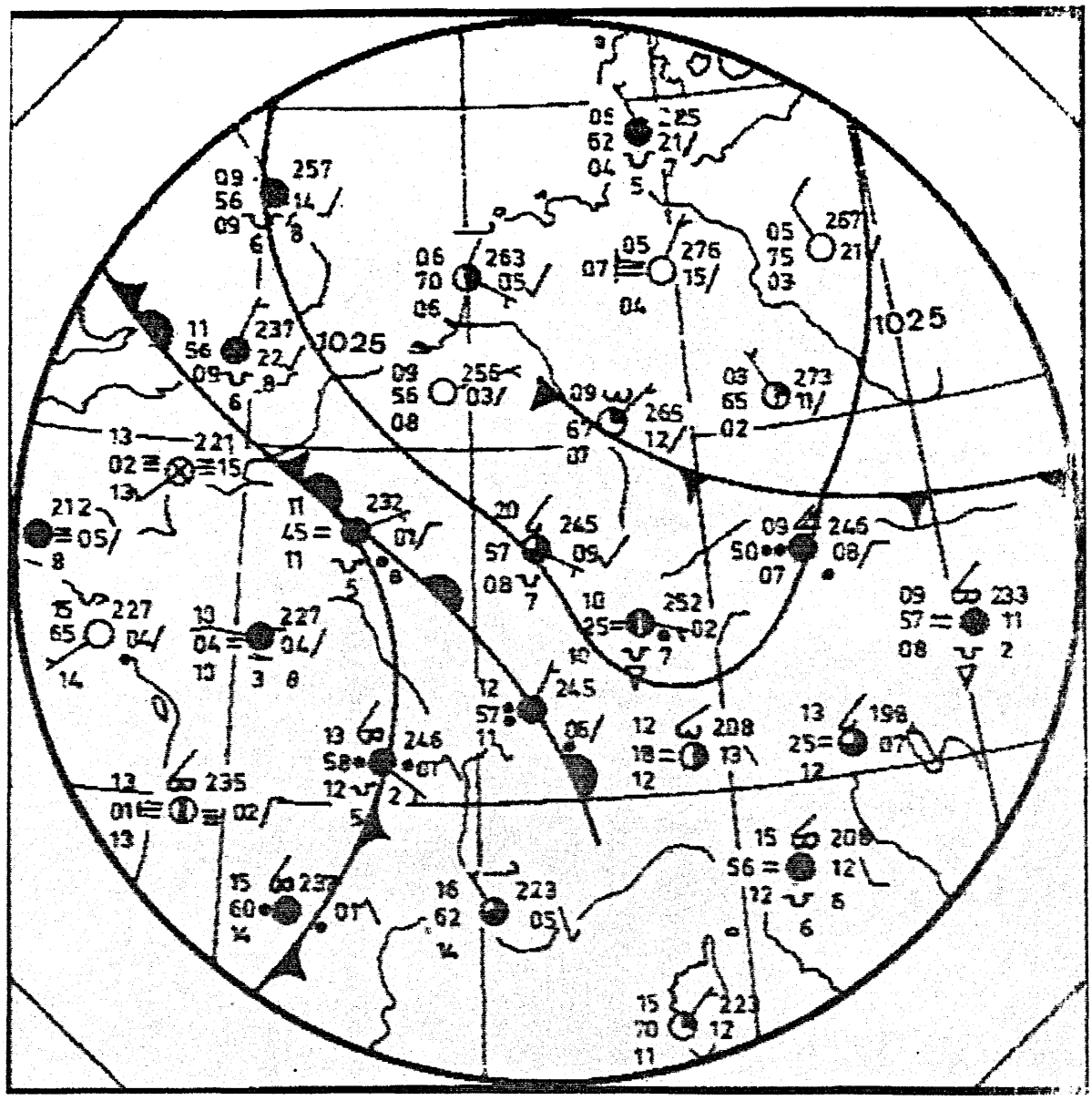


Fig.7.23. Reconstructed Image for 4800bps Back-to-Back Transmission.
Field Size = 144 block-pairs (1 scan line).

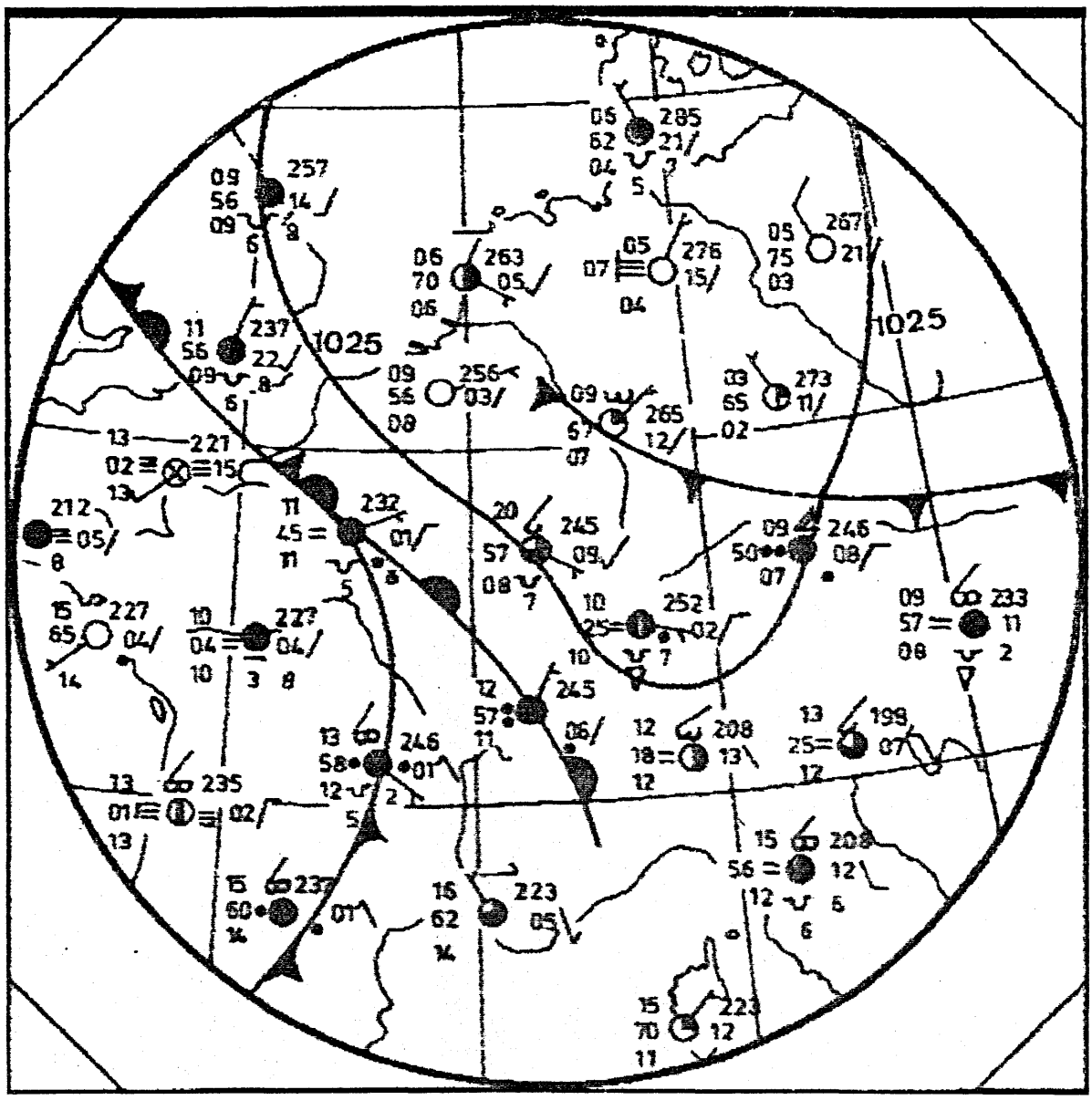


Fig.7.24. Reconstructed Image for 7200bps Back-to-Back Transmission.
Field Size = 54 block-pairs (1/4 th scan-line).

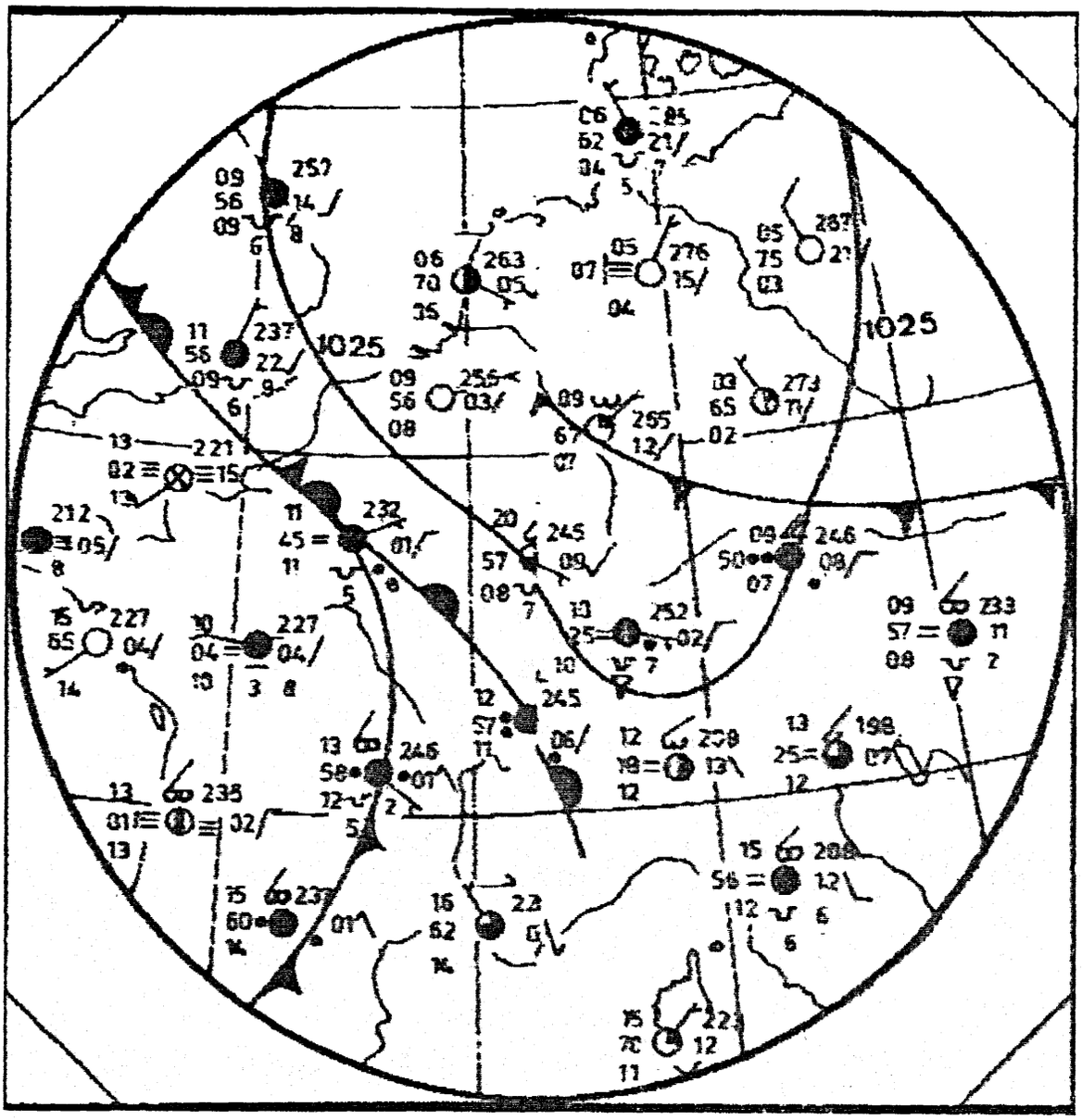


Fig.7.25. Reconstructed Image for 4800bsp (4-level) Transmission Over Simulated Telephone Channel.

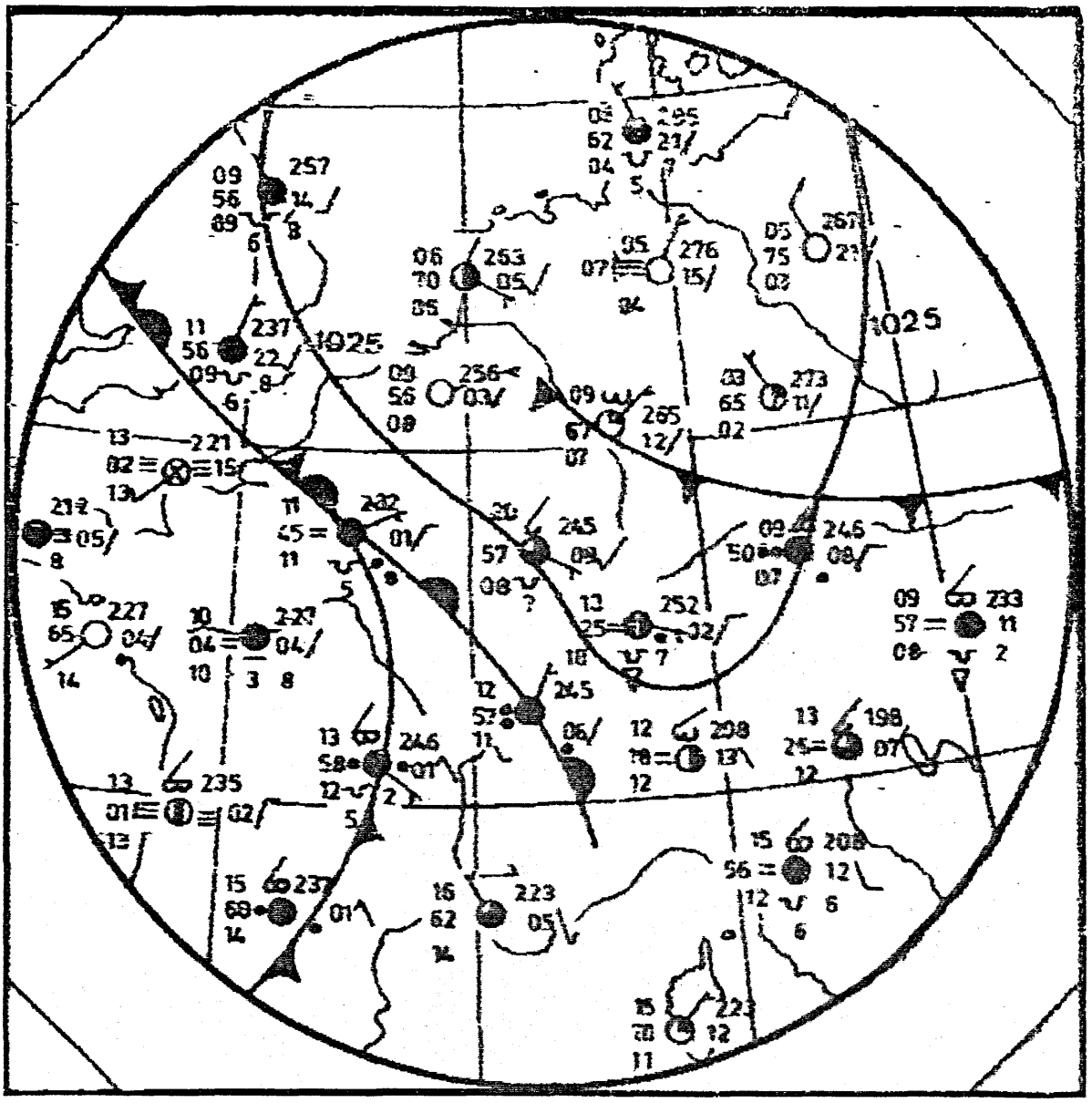


Fig.7.26. Reconstructed Image for 7200bps (8-level) Transmission Over Simulated Telephone Channel.

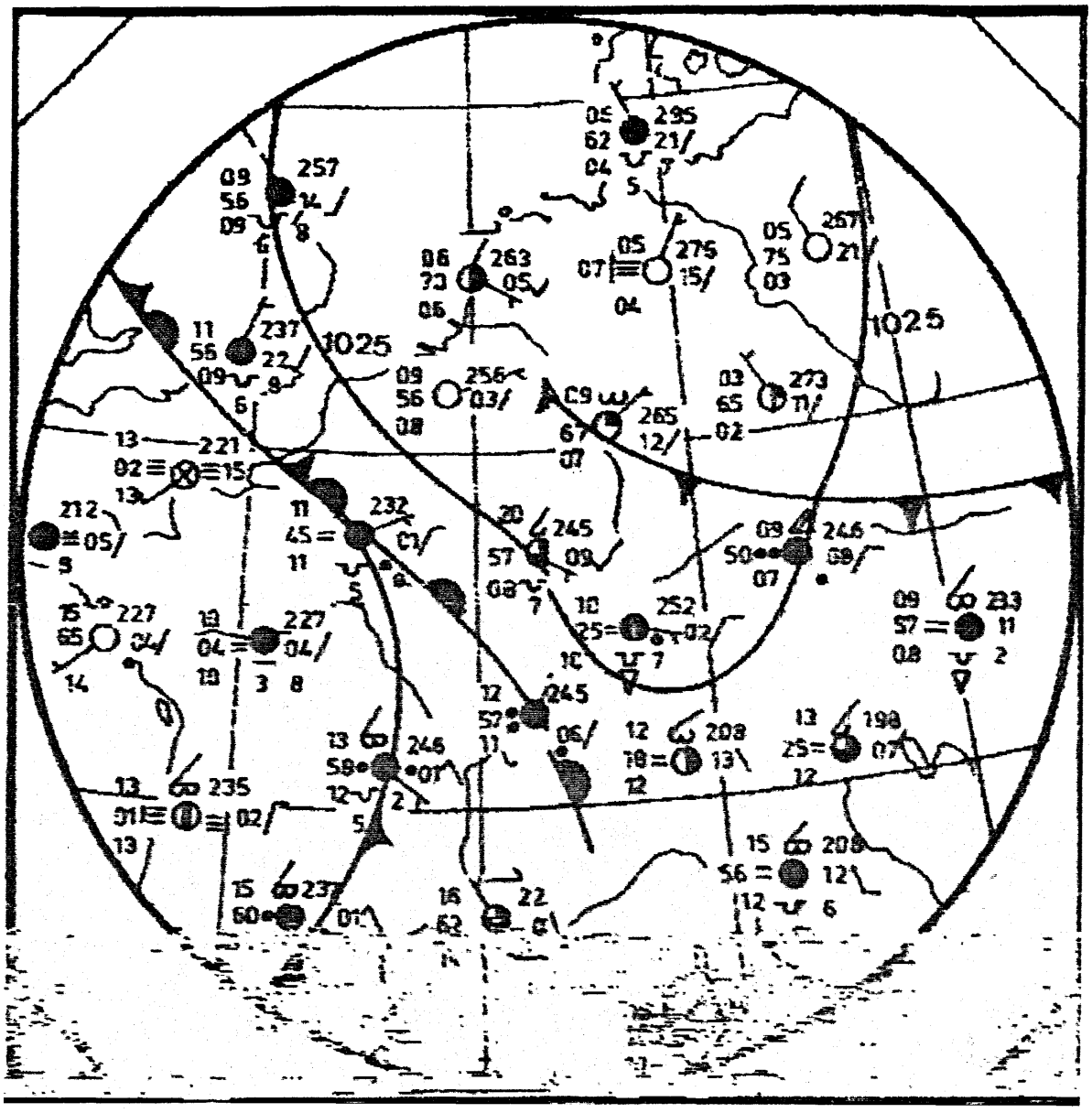


Fig.7.27. Showing the Effectiveness of Adaptive Thresholding for 4800 bps System (4-level).
Line Signal Level is Manually Reduced in the Course of Transmission.

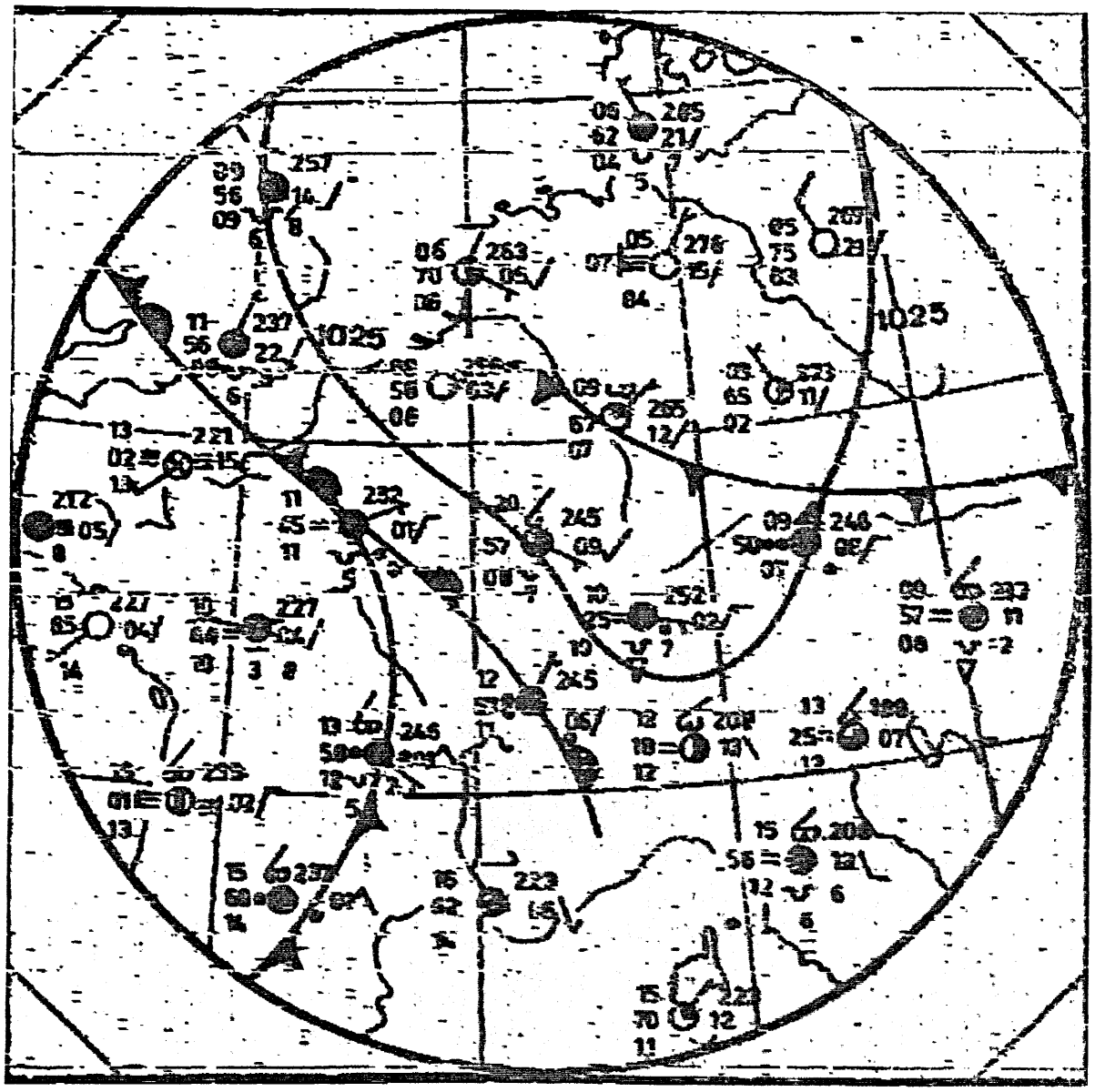


Fig.7.28. Reconstructed Image for 7200bps Transmission Over Simulated Channel With Added Noise. Carrier-to-Noise Ratio = 26dB.

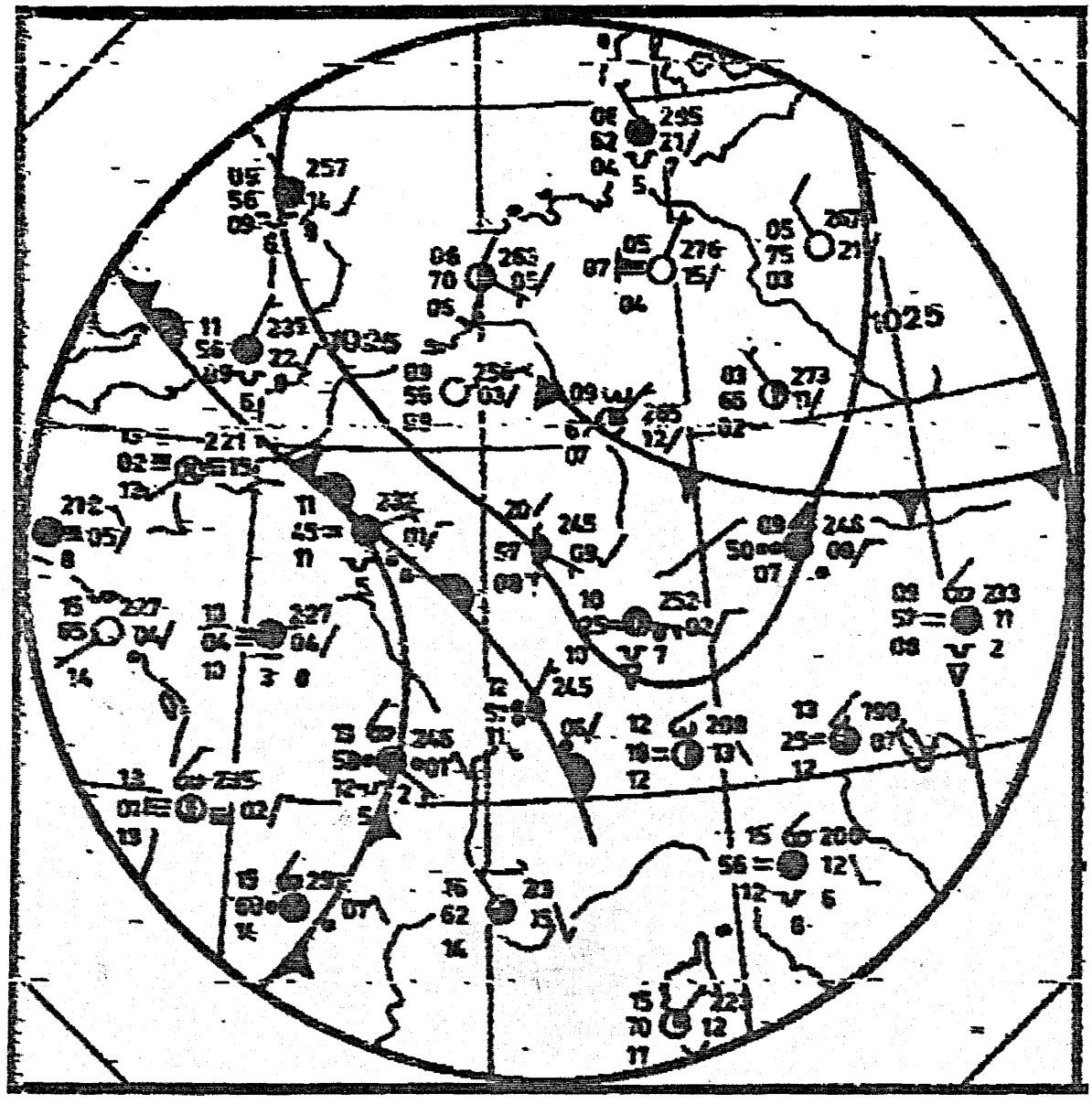
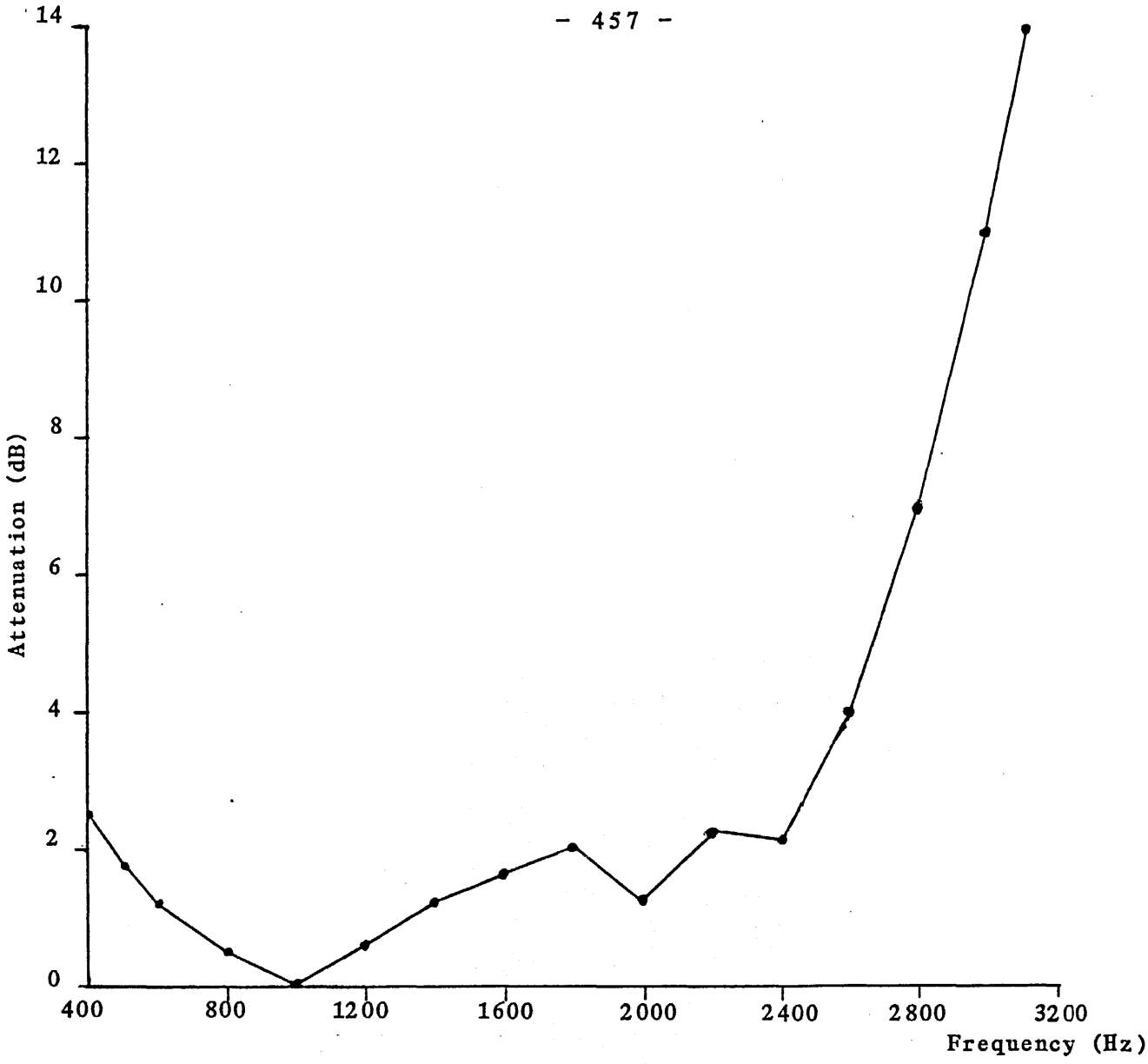


Fig.7.29. Reconstructed Image for 4800bps Transmission Over Simulated Channel With Added Noise. Carrier-to-Noise Ratio = 17dB.



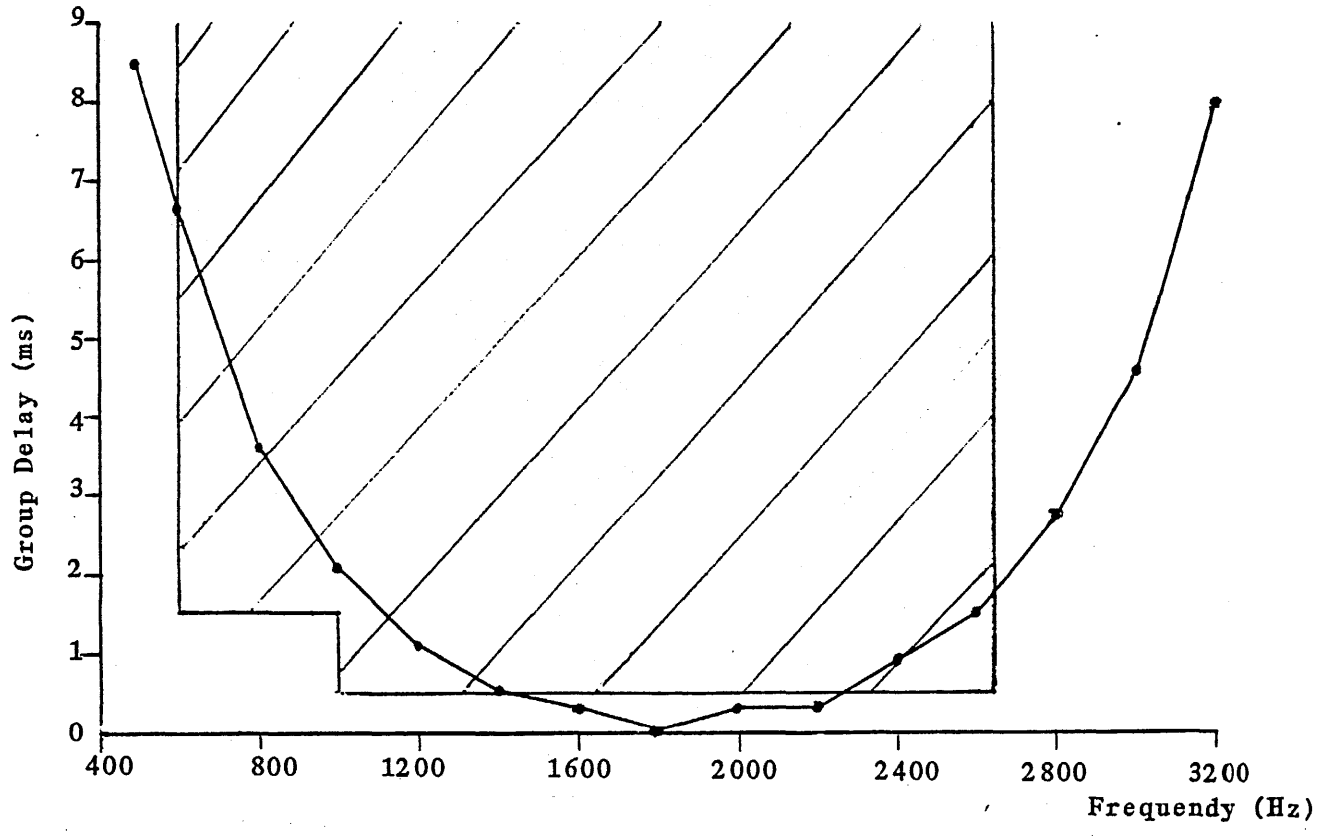


Fig.7.30. Frequency Response of Molfax Northern Loop Circuit.

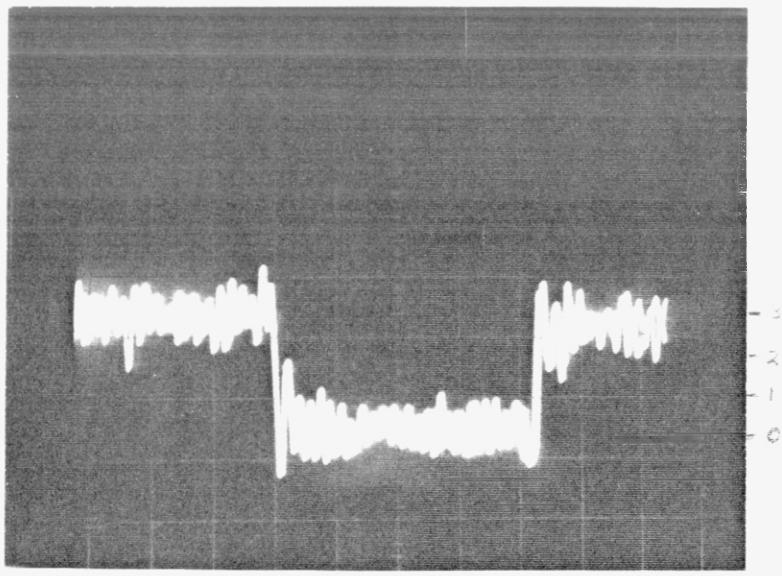


Fig.7.31. Step Response Recorded for the Molfax Northern Loop Circuit. Vertical Scale 1V/div, Horizontal Scale 5mS/div.

CHAPTER 8

CO-ORDINATE BLOCK INTERLEAVE CODING (CBIC)

8.1 Introduction to Co-ordinate Block Interleave Coding (CBIC)

In Chapter 5 a fixed rate compression method was proposed which basically interleaves nonwhite blocks of block-pairs into spaces of all-white block-pairs over a field of image blocks. The interleaving was performed on a sequential basis which makes it vulnerable to transmission errors. An alternative form of addressing the nonwhite blocks 'carried' in double-white spaces is through the use of coordinates. Each 'carried' nonwhite block has its coordinate information contained in its header and does not therefore depend on sequential order for its reinstatement. The result of a header corruption in the course of transmission does not affect other block-pairs giving rise to a very robust compression system. Such a system can be expected to be capable of withstanding average error rates of worse than 1 in 100 which will make it suitable for use over truly hostile transmission channels. In view of the use of coordinates in the coding process the method is called Coordinate Block Interleave Coding (CBIC).

The proposed encoding method for CBIC is illustrated in Fig.8.1. The input block-pair is delayed by D block-pairs with access available to all D block-pairs in the delay line. Coding is performed on the current block-pair at the input to the delay line. For each block-pair the output codeword consists of an R-bit header followed by an N-bit block pattern

where N is the block length. As in the SBIC method, five states are defined for the block-pair viz. Double-White(DW), Double-Black(DB), Left-White(LW), Right-White(RW) and Double-Nonwhite(DNW). The coding for LW and RW states is similar to that in SBIC but a code of R bits instead of 2 bits is output in the header followed by the appropriate N-bit nonwhite block pattern. When the block-pair features a DNW state the left-white block is transmitted preceded by the R-bit header code. In the event of a DW state the block-pairs in the delay line are scanned starting from the most delayed block-pair i.e. the right end of the delay line. The positions of the block-pair in the delay line are capable of being addressed by the R-bit header word. The scan is terminated when a DNW state is detected. The address coordinate of this DNW block-pair is conveyed in the header followed by the right block pattern of the DNW block-pair. The contents of the DNW block-pair are then blanked to prevent its being reselected in subsequent scans whilst still in the delay line. If no DNW state is found in the delay line the code for a LW (or RW, the choice is arbitrary) state is transmitted followed by an all-white N-bit pattern. If a DB state is registered for the current block-pair the transmitted codeword is the code for a RW (or LW) state followed by an all-white N-bit pattern. A coding example is illustrated in Fig.8.2.

It is clear that a DNW block-pair may be successfully transmitted only if a 'free' DW space is available whilst being held in the delay line. If this does not happen its left block is not transmitted leading to its deletion in the decoded image at the receiver. As with SBIC, the resultant loss of black elements is treated as an encoding distortion. The subjective effects will be similar to those already observed for the SBIC system. In the CBIC method the DNW block-pair inevitably loses its left nonwhite block if no DW block-pair occurs within the next D block-pairs.

Even if one is available the DNW block-pair must be the first DNW pair from the right end of the delay line in order for its left nonwhite block to be carried. Thus as each DNW block-pair enters the delay line it falls behind a queue of DNW block-pairs and if after D block-pairs no 'free' DW space is available, it drops out of the queue with its left block untransmitted.

The decoding procedure is quite straightforward. With reference to Fig.8.3 the input codeword is first separated into its header and block pattern components. Depending on the state of header code the block pattern is either inserted into the left or right position of the block-pair register which is initially cleared to all-zeros, or it is placed in the delay line as addressed by the header code, in the right side of the block-pair. When the codeword for the DB state is detected the block-pair register contents are simply set to 1. The output of the delay line is converted to serial form for feeding to the recording unit.

For an R-bit header the number of possible codes is 2^R. Two of these are needed to represent LW and RW states as described above. This leaves 2^R-2 possible address locations for the delay line of block-pairs i.e. $D = 2^R-2$. The compression ratio is given by

$$CR = \frac{2N}{R+N} \qquad 8.1$$

Unlike the sequential scheme the compression ratio here decreases with increasing length of the delay line. Therefore higher levels of compresssion are obtainable only with shorter delay lines which increases the incidence of block deletion. Table 8.1 shows the compression ratios obtainable with 8-pel blocks for various values of D. For a compression

ratio of 1.33 (corresponding to 25% reduction of transmission bit rate) a delay line of 14 block-pairs is featured with the header wordlength at 4 bits. This particular value of compression ratio is of interest as it is the maximum attainable from a fixed 8/6 mode of block-to-block compression.

In order to reduce the encoding distortion resulting from deletion of blocks a choice of right or left block of the double-nonwhite pair may be made depending on which has the lower Hamming weight. If the left block is selected for example the header is set for a right-nonwhite block-pair and the left block awaits being 'carried' in a subsequent double-white block-pair space. At the receiver the block-pair in the addressed location is examined to ascertain whether the carried block is to be reinstated as a left or right block. This deletion strategy will be adopted throughout the simulation of this compression system.

8.2 Results of Computer Simulation of CBIC

The CBIC method of compression was simulated for 8-bit blocks. In order to homogenise the block statistics a scrambling preprocessing operation was carried out before the encoding operation. The scrambling segment was set at 4096 blocks which was earlier found to be a good compromise between scrambling effectiveness and delay for the test images. The performance parameters employed for evaulation are P_B, the percentage of blocks which have been deleted, and P_L, the percentage of reconstruction errors (black pels lost). From Table 8.1 the compression ratios attainable with a block size of 8 pels are 1.14, 1.23, 1.33, 1.45 and 1.6 for values of the delay line length D at 62, 30, 14, 6 and 2 block-pairs respectively (R=6 to 2 bits respectively). The results of simulation are presented in Tables 8.2 and 8.3. It is seen that deletion-free operation

is obtained for all the test images at the value of D of 62 but the compression ratio here is too small to be significant. At D=30 corresponding to R=5 bits the level of black element loss is largely negligible (below 0.02%) for the 4 images which experienced deletion. Very small levels of black element loss (below 0.1%) are again observed at D=14 which results in a compression ratio of 1.33. These levels will be difficult to detect visually. Images A1, A4, and A4b were still encoded without error. At D=6 encoding distortion is incurred in all the images but in the majority of cases the levels are still less than 0.1%. When D is reduced to 2 which yields the maximum compression ratio of 1.6 possible with 8-bit blocks, the distortion reached visible levels. The largest amount was suffered by image A2 (0.86%). The reconstructed images for A2 are shown in Figs.8.4 to 8.6 for values of D=14, 6 and 2. At D=14 the reconstructed image is almost indistinguishable from its original. The quality of image for D=6 is probably acceptable although isolated breaks of characters may be spotted. The distortion for D=2 is clearly visible but no loss of intelligibility is suffered. Where the individual letter is unrecognisable the word can be made out from context. Further examples of images encoded with a delay line length of 2 block-pairs are given in Figs. 8.7 to 8.9. Despite the small length of delay the qualities of these images are very good and may be acceptable for the the benefits offered by the compression scheme. In general lower levels of distortion may be expected if the scrambling segment size is increased but at the expense of increased storage and time delay.

The effect of scrambling block-pairs rather than blocks of image was also investigated. Images A5 and A5b were used in the trials in which the scrambling segment size was set at 2048 block-pairs. The resultant values of P_B and P_L are compared with those for scrambling of blocks in Table 8.4.

The poorer performance in the case of scrambled block-pairs is clearly evident. For both images higher values of P_B and P_1 were always obtained for the set of values of D. For the image A5b error-free coding was no longer possible at the delay line length of 62 block-pairs.

8.3 Comparison of Performance with SBIC

Comparing the quantitative results of Tables 8.2 and 8.3 with those for SBIC in Tables 5.14 and 5.15 (for S=4096) a striking observation is the lower levels of distortion incurred by CBIC for similar lengths of delay. As an example the results for D=2 in CBIC and F=2 in SBIC show lower values of P_B in the former case for all the test images. The length of delay required for error-free coding is considerably less in the CBIC system. For example the worst-case image A5b was encoded without error at a value of D of 62 block-pairs but in SBIC a field size of 512 block-pairs was required. Unfortunately the compression ratio is dependent on delay length in the case of CBIC which resulted in a reduced compression ratio.

The operations involved in CBIC compression are generally simpler than its sequential counterpart. Considerations of compression ratio dictate that the delay length should be much smaller. For N=8, a maximum value of 14 block-pairs is suitable - longer lengths of delay will result in unattractively small amounts of compression. The deletion process is a great deal simpler as no sorting is required. A straight choice between the two constituent blocks of a block-pair with Hamming weight as criterion is readily achieved by logic circuitry. The scheme is thus highly suitable for a hardware implementation and is applicable to very high-speed facsimile systems.

The expected advantage of the CBIC scheme in respect of sensitivity to transmission errors has earlier been cited. Because each 'carried' nonwhite block contains its unique location address propagation of errors do not extend beyond a block-pair. The effects of transmission errors are examined in greater detail shortly.

8.4 Cascading with N/M Compression

The compression from the CBIC scheme can be increased by cascading with block-to-block coding at the expense of introducing additional distortion. The combined compression ratio is given by

$$CR = \frac{2N}{R + M} \qquad 8.2$$

Table 8.5 shows the compression ratios obtainable in an 8-bit system in which fixed modes of 8/6, 8/5 and 8/4 are combined with CBIC for various delay lengths. A combined ratio of 2.0 is achieved if the generally acceptable 8/6 mode of coding is cascaded with CBIC using a 2-bit header. Figs.8.10 and 8.11 show the results for images A2 and A4 for this arrangement. The differences between these and the uncombined CBIC results displayed earlier are difficult to detect visually. Improved quality of image is obtained when R is increased to 3 giving a compression ratio of 1.78. The resultant images for these are shown in Figs.8.12 and 8.13.

In principle the cascade of CBIC with N/M compression lowers the immunity to transmission errors because corruption of a single bit of the M-bit codeword results in the incorrect reinstatement of the whole block pattern. Nevertheless the system is still quite robust in its noise

performance and has the advantage of relative simplicity of implementation. It thus may have application in situations where a higher level of compression is required than can be provided by CBIC alone and a small loss in resistance to noise is acceptable. If very large levels of transmission errors are expected the cascade with N/M coding should be avoided.

8.5 Effects of Transmission Errors

The provision of co-ordinate information for carried nonwhite blocks ensures that no propagation of errors results outside two blocks of data from the corruption of an R-bit header word. Except for the all-black block-pair which is identified by a special (R+N)-bit word, the erroneous reception of a bit in the N-bit block pattern which is output for each pair of blocks of the image simply contributes to a single-pel error in the decoded image. Such errors are not seriously detrimental to the image especially if they do not occur in bursts. The corruption of a header word by a single or more corrupted bits in the R-bit header results in a false reinstatement of a block-pair. If the header denoted a carried block the resultant effect is an erroneous reinsertion of the block and the deprivation of the block from the correct block-pair location. Similarly if a right-white header is corrupted to give a DW state with a carried block the decoded block-pair will be all-white and a wrong insertion of the adjoined block pattern follows (two blocks in error). The probability of a header word being in error is equal to $1-(1-p)^R$ where p is the probability of a random error. The likelihood of header corruption therefore reduces as the word length decreases. In order to lessen the effects of transmission errors the size of the header word should be kept small so that a smaller proportion of the more sensitive header bits is present in

the transmitted data stream. The effect of reducing R is of course to increase the encoding distortion. Thus better noise performance is obtained at the expense of increased encoding distortion. The effect of the latter has been seen to be not too serious from an intelligiblity point of view and may be preferred to reconstruction errors due to transmission errors. The use of a shorter header also yields a higher value of compression ratio.

A simple means of detecting the presence of a corrupted header word is intrinsic in the reinstatement procedure for a carried block. The block-pair addressed by the header word must be either a left-white or right-white pair. If this is not the case an error has occurred which may be in the current header or a previous header which has earlier produced the incorrect state of the addressed pair. An inhibitive action may be taken in which no reinstatement of nonwhite block is made if the state of the addressed block-pair is not correct.

The effect of transmission errors was experimentally investigated by exposing via simulation the coded bit stream to both random and burst errors (from Gilbert-model source). Image A2 was used in the tests. The image blocks were scrambled in groups of 4096 blocks and a header word length of 2 bits was employed in the encoding. At the receiver a check of the block-pair state was carried out prior to reinstatement of a carried block and if an incorrect state was detected the reinstatement was aborted. Fig.8.14 shows the resultant reconstructed image after exposure to random transmission errors whose average rate of occurence is 1 in 32 bits. The degradation of the image is evident but the text is still readable at this high level of transmission errors. Much of the forms of characters are preserved to allow words and sentences to be made out from context. The

overall percentage reconstruction errors here is 4% which includes the black pel loss percentage of about 0.9% from the encoding process. The effect of burst errors at the same average rate may be seen in Fig.8.15. The image quality is slightly better here which may be attributed to the fewer number of header words which were corrupted because of error bursts coinciding with header words which would have been corrupted anyway by a single bit being in error. To discover the effects of even larger average rates of transmission errors the coded image was exposed to a 1 in 10 rate of burst errors and the result is shown in Fig.8.16. Only the heading is intelligible here, the text is not readable. This result suggests that an average error rate of 1 in 32 is closer to the limit for intelligiblity of decoded image under noisy conditions.

8.6 Hardware Considerations for Implementation

The instrumentation aspects of the CBIC scheme are now discussed. At the encoder, illustrated in Fig.8.17, blocks of the input serial data are taken for scrambling and stored in one of two SxN-bit stores, changing over after every S blocks. When the first store is full and the second commences to be filled the contents of the first are read in pairs into the two parallel-input registers R1 and R2. During this access the address to the store is provided by the data output of the ROM containing the set of S pseudo-random integers. This ROM is normally addressed by an incrementing counter but it may be alternatively addressed by the output of a subtractor which subtracts a displacement from the counter value (which points to the current block). The displacement gives the location of the nonwhite block to be interleaved in a double-white space. The use of the subtractor here avoids additional storage of the delay line of D block-pairs. The

displacement can be made directly equal to the address which is transmitted in the header word of the carried block. Thus the all-zero R-bit codeword may be used to designate a right-white block-pair, the next D binary values are used as addresses for a carried block and the last all-black codeword can represent the left-white block-pair. An all-black block-pair can be assigned the code of R black elements followed by an all-white block pattern. The white states of the blocks in the current block-pair held in R1 and R2 are readily detected using N-input NOR gates. The all-black state may be registered by a 2N-input NAND gate whilst a pair of nonwhite blocks is detected by NORing the outputs of the two white detectors. The selection of one of two nonwhite blocks for transmission in the case of a double-nonwhite block-pair is readily accomplished by use of a $2^N x \log_2 N$ bit ROM which outputs the Hamming weight directly for an N-bit input pattern. Using this ROM the Hamming weight of each block pattern is obtained and a comparison of the two values can be made by a digital comparator. The input of this comparator sets the corresponding bit of a 2-bit status register R6 (normally cleared) which identifies uniquely the block to be carried (this register contents are clocked into the delay register R7 at the end of each encoding operation). The block to be transmitted is then routed to the output block pattern register R3 via the switch S1 whilst the header register R4 is set to all ones or cleared depending on whether a right or left nonwhite block has been selected for transmission. When a left or right-white block is detected in R1 and R2 the switch S1 is set appropriately to output the nonwhite block whilst the header register is cleared or set to all-ones respectively. If an all-black pair is detected the header register is set to all-ones and the block register R3 is cleared. When a double-white pattern is registered at the input a nonwhite block is required if available. The address of this is generated by the

priority encoder which furnishes an R-bit address word for the most delayed DNW block-pair from the status bits of register R7. This address is then used to form a displacement from the present counter value to obtain the nonwhite block from store. The choice of left or right block is determined by the additional bit from the status register R7. To prevent re-usage of the nonwhite block the status bit has to be cleared which is accomplished by the R to 2^R-line decoder.(The delay shift register R7 consists of 20 individually clearable flip-flips). The R-bit address header from the priority encoder output header is also loaded into the header register for transmission. The switch S1 is of course set to accept the nonwhite block from store. Note that if no nonwhite block is available the priority encoder output is zero and the present all-white block pattern is read out from store, whilst the header for a right-white block-pair is transmitted. Much of the logic circuits are suitable for implementation by programmable logic array ICs (PLA's) which will reduce the component count considerably.

A scheme for the real-time implementation of the decoder is shown in Fig.8.18. The input serial coded bits are clocked into the block pattern and header registers R3 and R4 respectively. The header word is read by the logic unit which initiates action according to its state. If a left-white of right-white block-pair state is detected the block register contents are loaded into R1 and R2 whilst the other register is cleared. If an all-black block-pair state is found the two registers R1 and R2 are preset to the all-one state. If none of these states are detected a carried block may be assumed to be present. The registers R1 and R2 are cleared whilst the carried block is written into the delay line of 2D N-bit registers. The contents of R1 and R2 are serially clocked into this delay line at the end of each block-pair decoding operation. The correct register in the delay line into which the carried block is loaded, is

enabled by the address translator which effectively is a 2D-output decoder whose input word is formed from the header word which identifies the block-pair and an additional bit from the staus register which selects which block of the pair. The D-bit status register contents at any instant flag the unfilled blocks of block-pairs in the delay line, made up of presettable N-bit shift registers which are individually enabled from the address translator. The serial output of the delay line is reformatted into N-bit blocks by the serial-to-parallel converter and mapped back into their original positions using the set of S pseudo-random integers contained in ROM. Stores A and B (each of capacity SxN bits) alternately changeover so whilst descrambling proceeds in one, the contents of the other are being clocked out as the decoded data after a suitable parallel-to- serial conversion.

At the transmitter a delay of S blocks is incurred in the scrambling stage and a further delay of one block-pair is introduced in the encoding procedure. At the receiver a delay of 1 block-pair occurs whilst the codeword is clocked into the input registers R3 and R4 and subsequently a further delay of D block-pairs is incurred in the delay line. Finally the descrambling stage introduces a delay of S blocks (note the serial-to-parallel conversion also incurrs a delay of a block). Over the whole transmission the total delay experienced is about 2S blocks.

8.7 Conclusion

A highly-robust compression method was described in this chapter which is applicable in environments where the average rate of transmission errors is worse than 1 in 100. The fixed-rate method features initial pseudo-scrambling of image blocks which requires storage of a small section

of the image. A small amount of black element loss is introduced which has little effect on the intelligibility of the image. The results of computer simulation indicate that compression ratios of between 1.33 and 1.78 may be attained using 8-bit blocks with varying levels of distortion. For a delay length of 6 block-pairs (CR=1.45) reasonable-quality images were obtained. Visible levels of distortion were obtained for a delay length of 2 block-pairs (CR=1.6) but intelligiblity was largely preserved. Increased amounts of compression are possible if the method is cascaded with block-to-block coding but the immunity to transmission errors is reduced. The operations involved in the encoding and decoding processes are readily implementable using random logic circuitry which may be compactly realised nowadays by use of programmable logic arrays (PLA). The CBIC scheme thus offers an inexpensive and reliable means of compression which is also compatible with fixed-rate scanning systems.

Header Wordlength, R(bits)	Delay Length,D (Block-pairs)	Compression Ratio
6	62	1.14
5	30	1.23
4	14	1.33
3	6	1.60
2	2	1.78

Table 8.1. Compression Ratios for 8-bit CBIC.

Image \ D	2	6	14	30	62
A1	0.236	0.026	0.001	0.000	0.00
A2	2.665	0.854	0.128	0.002	0.00
A3	0.391	0.068	0.015	0.002	0.00
A4	0.363	0.017	0.000	0.000	0.00
A5	1.035	0.155	0.011	0.000	0.00
A6	1.149	0.197	0.010	0.000	0.00
A4b	0.528	0.050	0.000	0.000	0.00
A5b	2.972	1.069	0.327	0.059	0.00
A6b	2.189	0.646	0.138	0.019	0.00

Table 8.2. Percentage Deleted Blocks for 8-bit CBIC.

Image \ D	2	6	14	30	62
A1	0.069	0.007	0.000	0.000	0.00
A2	0.861	0.277	0.041	0.001	0.00
A3	0.101	0.016	0.004	0.001	0.00
A4	0.132	0.007	0.000	0.000	0.00
A5	0.307	0.047	0.004	0.000	0.00
A6	0.276	0.046	0.002	0.000	0.00
A4b	0.130	0.013	0.000	0.000	0.00
A5b	0.560	0.211	0.064	0.013	0.00
A6b	0.556	0.165	0.034	0.004	0.00

Table 8.3. Percentage Reconstruction Errors for 8-bit CBIC.

Image \ D		2	6	14	30	62
A5	1	1.413	0.204	0.018	0.000	0.000
	2	1.035	0.155	0.011	0.000	0.000
A5b	1	3.163	1.109	0.354	0.094	0.007
	2	2.972	1.069	0.327	0.059	0.000

(a) Percentage Deleted Blocks, P_B.

Image \ D		2	6	14	30	62
A5	1	0.402	0.059	0.005	0.000	0.000
	2	0.307	0.047	0.004	0.000	0.000
A5b	1	0.627	0.216	0.067	0.019	0.007
	2	0.560	0.211	0.064	0.013	0.000

(b) Percentage Reconstruction Errors, P_L.

1 - Values for Scrambled Block-Pairs (S = 2048 block-pairs)

2 - Values for Scrambled Blocks (S = 4096 blocks)

Table 8.4. Comparison of Performance between Scrambling of Block-Pairs and Scrambling of Blocks in CBIC.

R	N/M	Compression Ratio
6	8/6	1.33
5	8/6	1.45
4	8/6	1.60
3	8/6	1.78
2	8/6	2.00
6	8/5	1.45
5	8/5	1.60
4	8/5	1.78
3	8/5	2.00
2	8/5	2.29
6	8/4	1.60
5	8/4	1.78
4	8/4	2.00
3	8/4	2.29
2	8/4	2.67

Table 8.5. Combined Compression Ratios for 8-bit CBIC cascaded with 8/M Block-to-Block Compression.

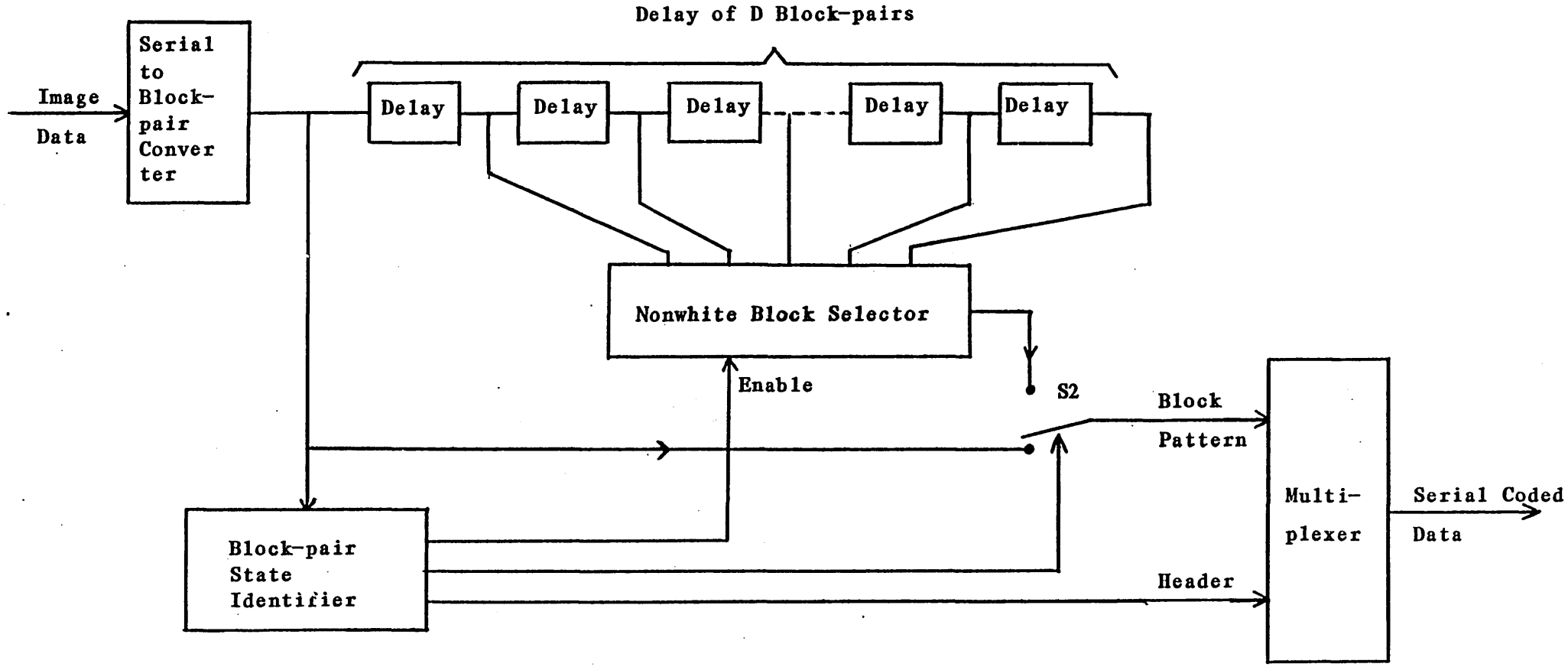


Fig.8.1. Encoding Scheme for Coordinate Block Interleave Coding.

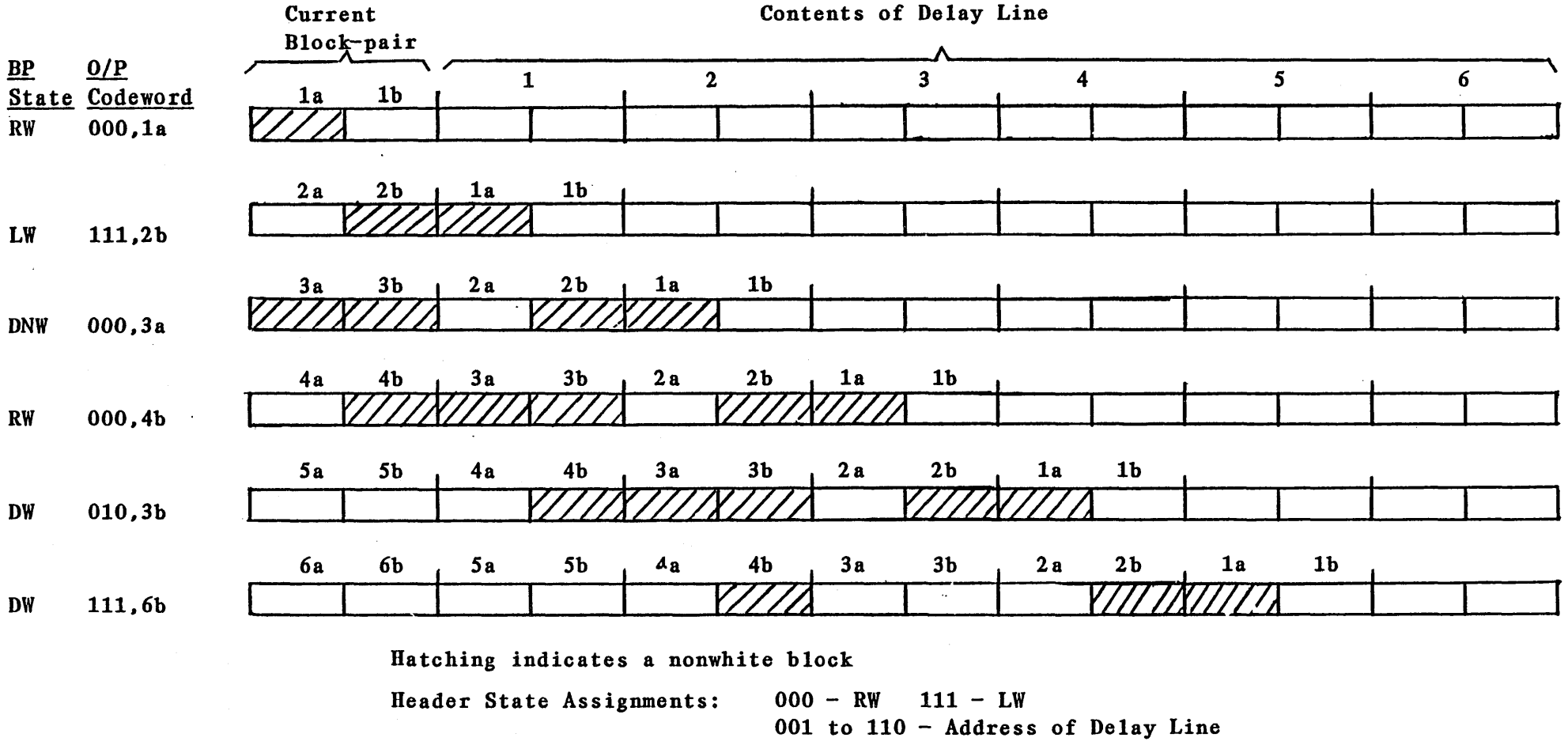


Fig.8.2. A Coding Example in CBIC (R=3).

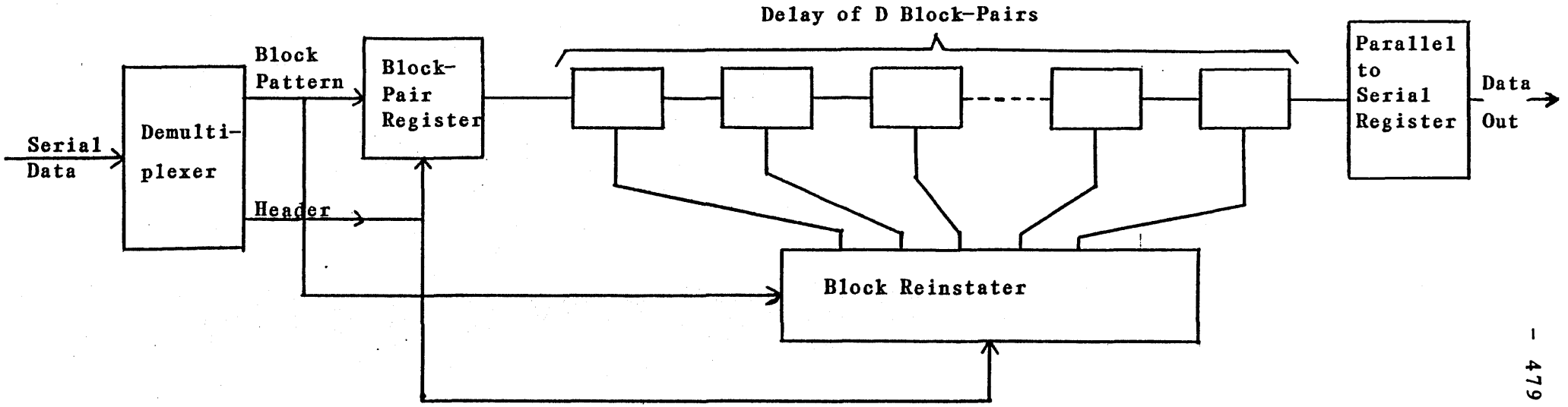


Fig.8.3. Decoding Scheme for Cordinate Block Interleave Coding.

Fig.8.4. Data A2, CBIC with D = 2 block-pairs, CR=1.6.

A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably fuller employment — depend on this. They show that higher exports and import substitution go together — the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

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Fig.8.5. Data A2, CBIC with D = 6 block-pairs, CR=1.45.

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Fig.8.6. Data A2, CBIC with D = 14 block-pairs, CR=1.33.

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Fig.8.7. Data A1, CBIC with D = 2 block-pairs, CR=1.6.

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Mr. N. E. One
1 Somewhere Rd.,
Newtown,
Berks,
RG1 8LD.

23/9/76

Our ref. ABC/DE/FG Your ref.

Dear Mr. One,

This letter has been written purely for the purpose of filling a part of the sheet of paper you see in front of you. I doubt very much whether you will be any wiser having read it, but I think you will agree that, from a distance, it looks like a very ordinary business letter, in fact, the sort of document which millions of people throughout the world receive every day. If I have succeeded in producing a "typical" letter, then I hope that the statistics I derive from it, and the processing which I perform on it, will also yield typical results for this class of document. In turn, such work may lead to a better understanding of the extent to which data compression techniques may be used. Please forgive me for wasting your time while you read this nonsense.

Yours sincerely,

D. W. TINDALL

P.S. If this letter did better your knowledge or understanding in any way, please let me know how.

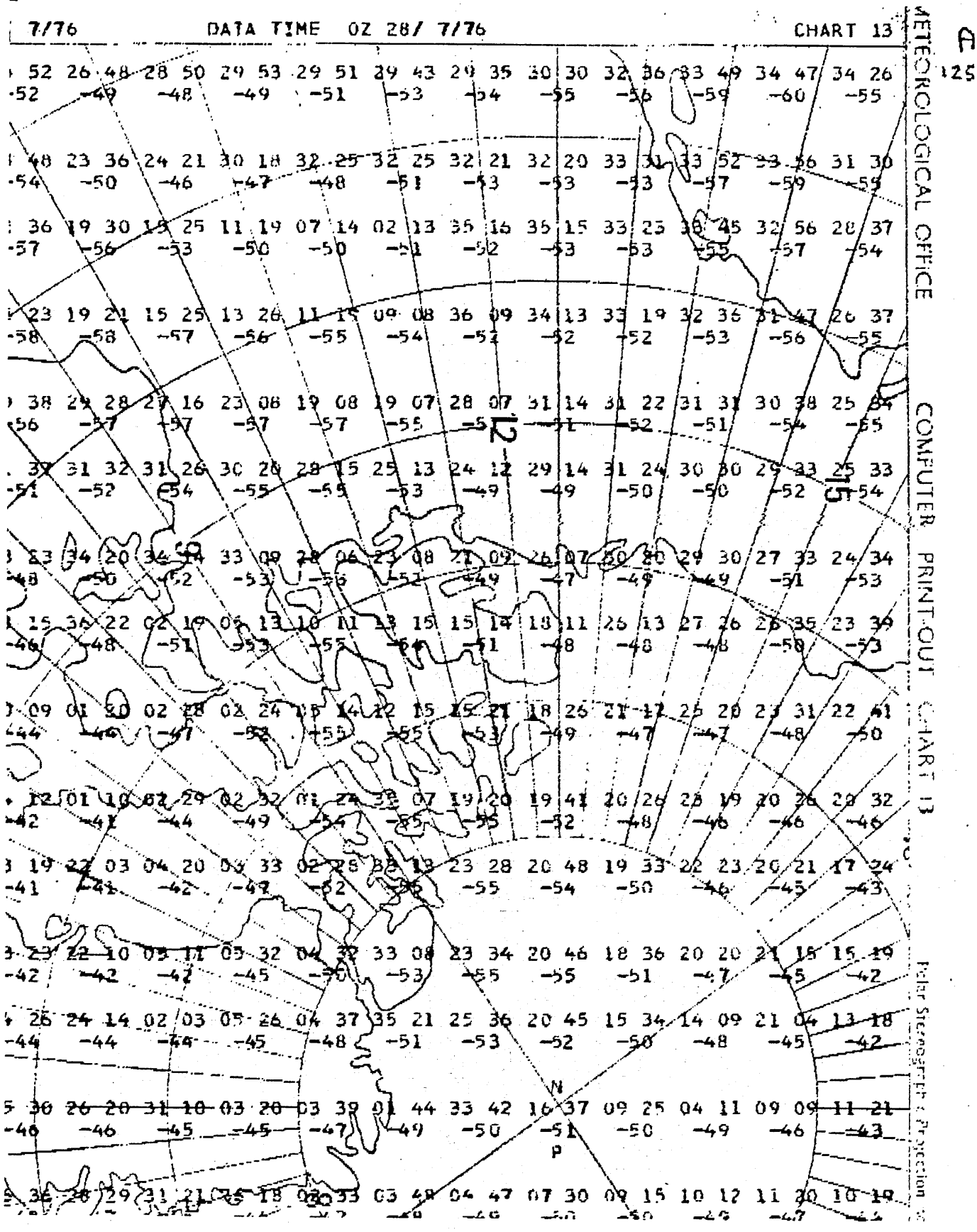
Fig.8.8. Data A4, CBIC with D = 2 block-pairs, CR=1.6.

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of standard digitised documents and drawings can be created for

Fig.8.9. Data A6, CBIC with D = 2 block-pairs, CR=1.6.



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Fig.8.11. Data A2, Cascaded CBIC with 8/6 Coding. D=6, CR=1.78.

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Fig.8.12. Data A4, Cascaded CBIC with 8/6 Coding. D=2, CR=2.0.

DATA TRANSFER.



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Fig.8.13. Data A4, Cascaded CBIC with 8/6 Coding. D=6, CR=2.0.

DATA TRANSFER.



Hardware at the facsimile transmitter will process the analog data, scanned from a document, in the following manner. The data is quantised to two levels and then sampled at a rate which is infinitely variable, giving a range of resolutions between 25 picture points/inch and 200 picture points/inch in the direction of scan. This two level serial data is split into 8 bit blocks which are transmitted as parallel data to the computer and accepted on receipt of an interrupt pulse. This interrupt pulse permits software handling of the data by using the automatic priority interrupt (API) system, featured on the PDP15 machine, in conjunction with the DOS operating system. The peripheral handler routine packs the 8 bit data to build 256 word buffers (two 8 bit blocks/18 bit computer word). When such a buffer is full, the data is written onto disc in consecutive disc blocks until all the data has been transferred. Both the digital interface and the disk use the API structure, but since the former is at a higher priority level, no data is lost during disk transfers. Two buffers are used so that one can be transferred to disk while the other is being filled with new data. Data cannot be stored permanently on disk so it is subsequently transferred, at a slower speed, onto DEC tapes. Thus a set of "standard" digitised documents and drawings can be created for

Fig.8.14. Data A2, Encoded by CBIC, Exposed to 1 in 32 Random Transmission Errors. D=2 block-pairs.

A constructive starting point

Just prior to going to press the NEDC was scheduled to hold an all-day meeting under the Prime Minister's chairmanship. The meeting will consider reports from 39 tripartite working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-orientated. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably fuller employment — depend on this. They show that higher exports and import substitution go together — the UK is increasingly seen by manufacturers as just one among a number of advanced industrial markets.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price, as German experience shows. The reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could all too easily become the world's largest exporters of obsolescent goods. But improved design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to public purchasing but also to a wide range of other powers including planning procedures, anti-dumping regulations and official standards.

The reports do not in themselves constitute an industrial strategy but they provide important raw material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people still underestimate the size of the job to be done and the scale of change required — but the material prepared for the meeting provides a constructive starting point if the will to use it is there.

Fig.8.15. Data A2, Encoded by CBIC, Exposed to 1 in 32 Burst Transmission Errors. D=2 block-pairs.

A constructive starting point

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The reports show the need to get to grips with two critical issues — how to raise productivity at a time of high unemployment and how to restore incentives, especially for middle management.

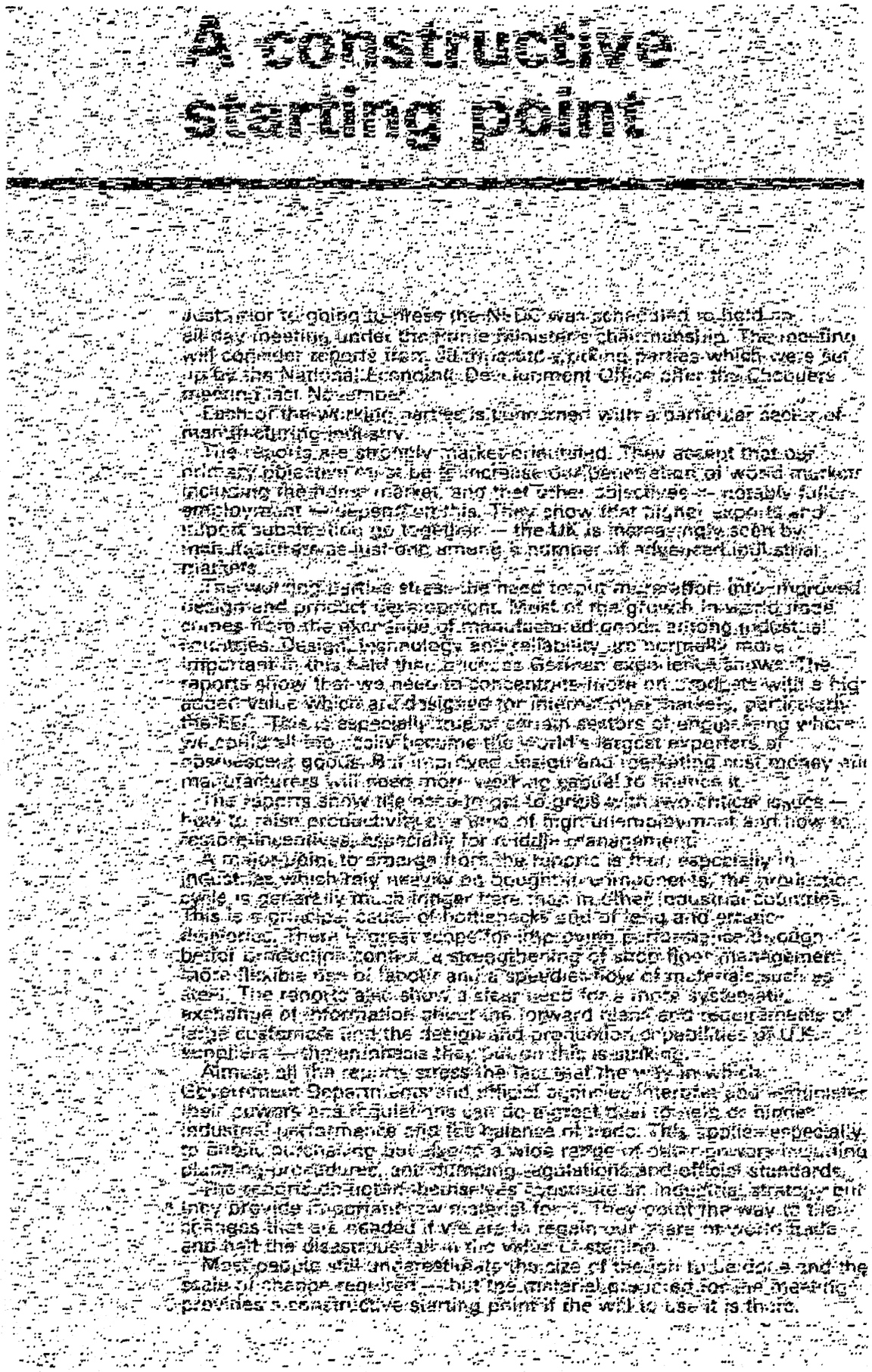
A major point to emerge from the reports is that, especially in industries which rely heavily on bought-in components, the production cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for improving performance through better production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of U.K. suppliers — the emphasis they put on this is striking.

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Fig.8.16. Data A2, Encoded by CBIC, Exposed to 1 in 10 Burst Transmission Errors. D=2 block-pairs.



A constructive starting point

just prior to going to press the NEDC was scheduled to hold an all day meeting, under the Prime Minister's chairmanship. The meeting will consider reports from 32 manufacturing working parties which were set up by the National Economic Development Office after the Chequers meeting last November.

Each of the working parties is concerned with a particular sector of manufacturing industry.

The reports are strongly market-oriented. They accept that our primary objective must be to increase our penetration of world markets including the home market, and that other objectives — notably full employment — depend on this. They show that higher exports and import substitution go together — the UK is messing up both, not just one, among a number of relevant industrial matters.

The working parties stress the need to put more effort into improved design and product development. Most of the growth in world trade comes from the exchange of manufactured goods among industrial countries. Design, technology and reliability are normally more important in this field than price. Germany exploits and owes the reports show that we need to concentrate more on products with a high added value which are designed for international markets, particularly the EEC. This is especially true of certain sectors of engineering where we could well become the world's largest exporters of non-electrical goods. But unless design and marketing cost money and manufacturers will need more working capital to finance it.

The reports show the need to get to grips with two critical issues — how to raise productivity, a task of management and how to restore incentives, especially for middle management.

A major point to emerge from the reports is that, especially in industries which rely heavily on sought-after engineers, the product cycle is generally much longer here than in other industrial countries. This is a principal cause of bottlenecks and of long and erratic deliveries. There is great scope for the more intensive use of design and production control, a strengthening of shop floor management, more flexible use of labour and a speedier flow of materials such as steel. The reports also show a clear need for a more systematic exchange of information about the forward plans and requirements of large customers and the design and production capabilities of UK suppliers — the enthusiasm they put on this is striking.

Almost all the reports stress the fact that the way in which Government Departments and official agencies interpret and administer their powers and regulations can do a great deal to help or hinder industrial performance and the balance of trade. This applies especially to energy policies but also to a wide range of other areas including planning procedures, and planning regulations and effluent standards.

The reports themselves constitute an industrial strategy but they provide important new material for it. They point the way to the changes that are needed if we are to regain our share of world trade and halt the disastrous fall in the value of sterling.

Most people will underestimate the size of the task to be done and the scale of change required — but the material produced for the meeting provides a constructive starting point if the will to use it is there.

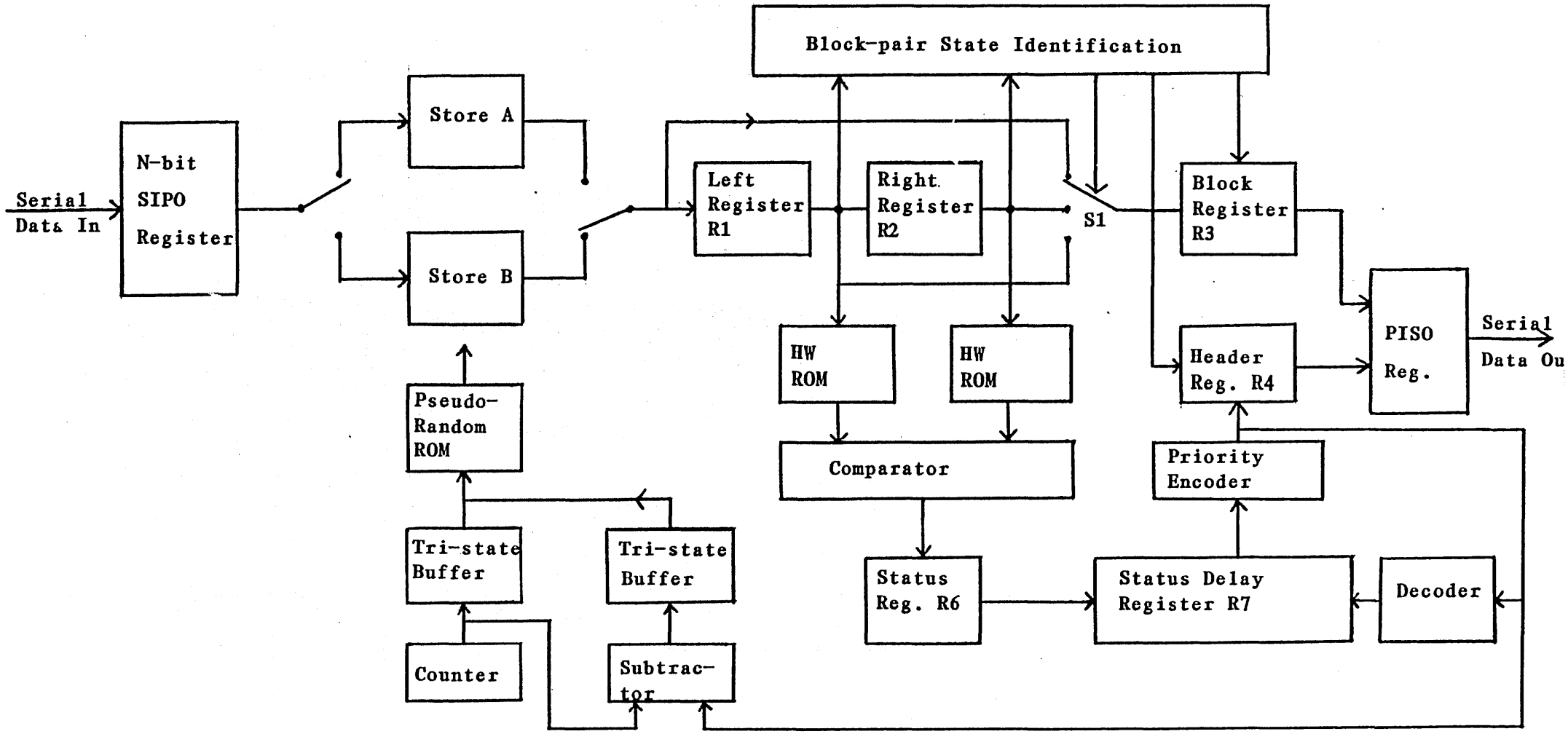


Fig.8.17. Implementation of CBIC Encoder.

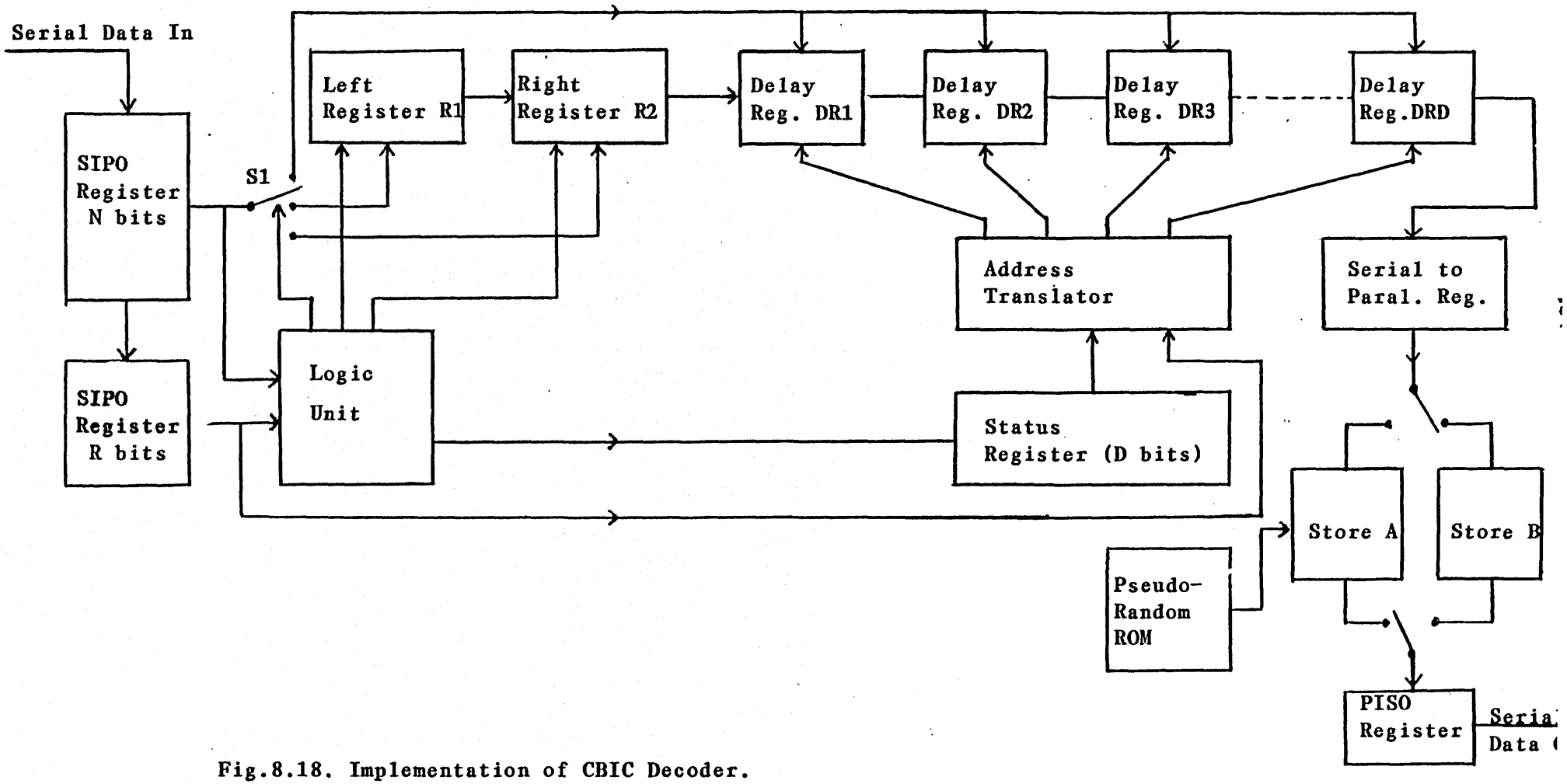


Fig.8.18. Implementation of CBIC Decoder.

CHAPTER 9

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

This research has concentrated on a study of low-cost methods of compression of bi-level facsimile images which feature a fixed-rate output and are able to withstand large levels of transmission errors. In the investigation into the universal block-to-block coding of black-white images a main observation has been that comparable or only slightly larger compression ratios are obtainable over a fixed block-to-block scheme which employs an a priori average codebook. The main advantage of the universal method is its immediate applicability to all images without the difficulty of acquiring image statistics. A price that has to be paid for this benefit is the increase in complexity of the coding procedure but with the availability of cheap microprocessors this cannot be regarded as a major disadvantage.

If levels of compression ratio are of prime consideration the partially-adaptive block-to-block coding scheme proposed in the study is able to offer increases in compression ratio over the fixed block-to-block schemes. For both fully and partially-adaptive schemes, higher values of compression ratio can be obtained by slotting transmitted codebooks or parts of codebooks in the line intervals which are usually present in constant-rate scanners.

The SBIC method of compression, which was introduced in this research,

was capable of error-free performance - an unusual feature of fixed-rate compression schemes. For the set of test images lossless coding was achieved by delaying an adequate number of scan-lines. The pseudo-scrambling of blocks prior to encoding allows a smaller coding field which results in better noise performance. If the field size is desired to be kept small the subjective effect of possible distortion due to field overflow can be improved by selecting the blocks to be deleted using a minimum distortion criterion. Compared with fixed N/M coding for the same block size, a gain of 20% in compression ratio was achieved by the SBIC method. For higher values of compression ratio the SBIC technique may be cascaded with block-to-block coding. A compression ratio of 2 was obtained in this way for the test images. The noise performance of this combined scheme remained high with satisfactory decoding possible at the average transmission error rate of 1 in 100.

The practicality of the SBIC system was demonstrated with the construction of a digitisation unit to serve existing analogue facsimile equipment. In this stand-alone unit special software implementations of transmission functions were developed to fulfill the objective of a low-cost system for transmission of digitised facsimile signals over the telephone channel. The most demanding of these has been the realisation of the channel equaliser which is vital for successful data transmission. By employing memory-intensive methods of processing a 31-tap automatic equaliser was successfully implemented which featured adaptive thresholding at its output. In realising these functions the microprocessors at the transmitter and receiver were those employed for compression and expansion of the facsimile data with consequent considerable reduction in complexity of hardware. The effective use of a commercial 8-bit microprocessor for real-time digital signal processing was also demonstrated in the

implementation.

An alternative form of interleaving blocks into the white background was proposed and investigated in Chapter 8. The use of coordinates for identifying positions of nonwhite blocks of double-nonwhite block-pairs in a delay line ensures the effects of transmission errors do not extend over a block-pair. A highly-resistant compression system is obtained which in the computer simulation gave good image quality at a compression ratio of 1.45. Visible but not unacceptable levels of black element loss were obtained at a ratio of 1.6. These compare with 1.33 obtainable by fixed block-to-block coding. The CBIC method is easily implementable in hardware.

Towards the end of this research further ideas have presented themselves which may be worthy of investigation. The cascade of SBIC with other fixed-rate methods is an interesting possibility. Stucki and Stern's sub-sampling methods may be cascaded with SBIC in order to yield compression ratios of 3.2 and 6.4 respectively. The results obtained with the lower-resolution image A5b in the simulation have showed that sufficient numbers of double-white block-pairs are present in the image despite the lower resolution, to give error-free coding. If this lossless coding were to be achieved in the SBIC stage of the system then the distortion will be due totally to the effects of sub-sampling. The levels of distortion due to sub-sampling and interpolation are generally higher than those obtained by block-to-block coding but these may be acceptable for the increased amount of compression.

The cascade of the sub-sampling method of Ismail and Clarke [35] with SBIC also holds interesting prospects. Like Stern's fixed-rate method of compression the compression ratio obtainable is 4 which when combined with

8-bit SBIC gives a combined compression ratio of 6.4. The pre-processing and post-processing operations described by these authors may also be employed to improve subjective quality. Again the decoded images for sub-sampled systems cannot be expected to be of acceptable commercial quality but the high compression ratio obtained here can make the degradation of image worthwhile. The fixed-rate nature of such combined compression systems can also be an important consideration.

In this research the simulation of SBIC was performed for 8-bit blocks. This choice of block size is probably the optimum choice for one-dimensional blocks in terms of compression yield and implementation complexity. The investigation into the use of two-dimensional coding blocks is a possible area for further research. Higher compression ratios can generally be expected for two main reasons. First the larger block size leads directly to a larger value of compression ratio. The incidence of double-white block-pairs does not fall off too rapidly as block-size increases so that overflow-free operation is still possible. The second reason is that larger blocks may be block-to-block encoded more efficiently than smaller blocks in terms of compression yield. For example Preuss [33] reported compression ratios of 2 and 3 using 5x5and 6x6 blocks respectively whereas the maximum compression ratio attainable with 8-pel blocks was only 1.33. If the former block sizes were adopted combined compression ratios of 3.6 and 5.1 will be obtained. However the use of larger blocks in block-to-block coding also rules out the straightforward ROM-lookup method of encoding. Other methods which can encode at higher speeds and require smaller storage capacities are required which can be a subject of investigation.

Another interesting avenue for further research is the extension of

the SBIC method where the basic coding unit is no longer a block-pair but a tri-block, quad-tuple block, etc. For example a tri-block consisting of 3 N-bit blocks is examined and a 3-bit header is used to convey the state information. Sequential interleaving can then proceed as in the original SBIC method but more nonwhite blocks will need to be carried which lead to higher probabilities of field overflow. The compression ratio here tends to 2.18 instead of 2.0 as the block size tends to infinity. For a quad-tuple block the maximum value of compression ratio is 2.67. Higher levels of compression ratio may be obtained by cascading with N/M coding.

In the study of the CBIC method of compression it was noted that a shorter delay line was needed compared to the field delay of SBIC for lossless coding. In the CBIC technique the compression ratio was dependent on the length of the delay line which resulted in relatively lower compression ratios if excessive distortion is to be avoided. A possible scheme which may achieve lossless coding with a smaller amount of delay is one which adopts the delay line configuration of CBIC but employ the header coding and sequential interleaving of nonwhite blocks featured in the SBIC method. Here the right nonwhite pattern of the most delayed DNW block-pair is selected for output when the current block-pair exhibits a DW state. A fixed wordlength of 2 bits is then adequate for the header which gives a compression ratio of 1.6 if 8-bit blocks were used. Such a system is equivalent to SBIC with overlapping fields. The effects of transmission errors is likely to be more serious than for the original SBIC method.

APPENDIX 1

DISTRIBUTED ARITHMETIC IMPLEMENTATION OF TRANSVERAL FILTER

An N-tap transversal filter is defined by

$$Y_i = \sum_{j=0}^{N-1} C_j X_{i-j} \tag{1}$$

where Y_i, X_i are the respective output and input values at time kT, T being the delay period, and C_j are the weighting coefficients.

Assuming the use of 2's complement arithmetic representation for the input samples, for a B-bit quantised input

$$Y_i = \sum_{j=0}^{N-1} C_j X_j \left[\sum_{r=1}^{B-1} x_{i-j,r} 2^{-r} - x_{i-j,0} \right] \tag{2}$$

where x=0 or 1 and $x_{i-j,0}$ is the sign bit. The input values are assumed to be normalised fractional numbers.

An interchange of summation order yields

$$Y_i = \sum_{r=1}^{B-1} C_j X_j \sum_{j=0}^{N-1} x_{i-j,r} 2^{-r} - \sum_{j=0}^{N-1} C_j x_{i-j,0} \tag{3}$$

If we define

$$P_{i,r} = \sum_{j=0}^{N-1} C_j x_{i-j,r} \quad \text{for } r=0,1....B-1 \tag{4}$$

we have

$$Y_i = \sum_{r=1}^{B-1} P_{i,r} 2^{-r} - P_{i,0} \qquad (5)$$

If $P_{i,r}$ were known the filtering reduces to an initial read operation of the first lookup value and to a series of (B-2) additions, (B-1) divide-by-two operations and a single subtraction. These steps are easily performed by a microprocessor. The values of $P_{i,r}$ may be obtained from a lookup table containing all possible values of $P_{i,r}$. The latter are simply all possible combinations of the sum of the M weighting coefficients. The addresses of the values $P_{i,r}$ needed in the processing of each sample can be derived from the bit outputs of the delay line (Fig.A1.1). A total of 2^N lookup values is required for an N-tap filter.

In an implementation therefore lookup tables are first formed from the set of weighting coefficients before processing commences on the input samples. The filter cycle itself consists of two stages. First the new input sample is shifted into the delay line, in a manner as shown in Fig.A2.1. Then for an input quantisations of bits, B lookup operations are performed using the delay registers as addresses. These are accumulated as given in Eqn.5. The process is simplified by noting that the equations can be expressed in the form

$$Y_i = (((\ \ldots\ldots(P_{i,B-1})2^{-1} + P_{i,B-2})2^{-1} + \ldots P_{i,1})2^{-1} - P_{i,0} \qquad (6)$$

ie. the filter output is obtained by successively dividing by two (a right-shift operation) and adding on the next lookup value. The final lookup value is subtracted from the accumulator contents.

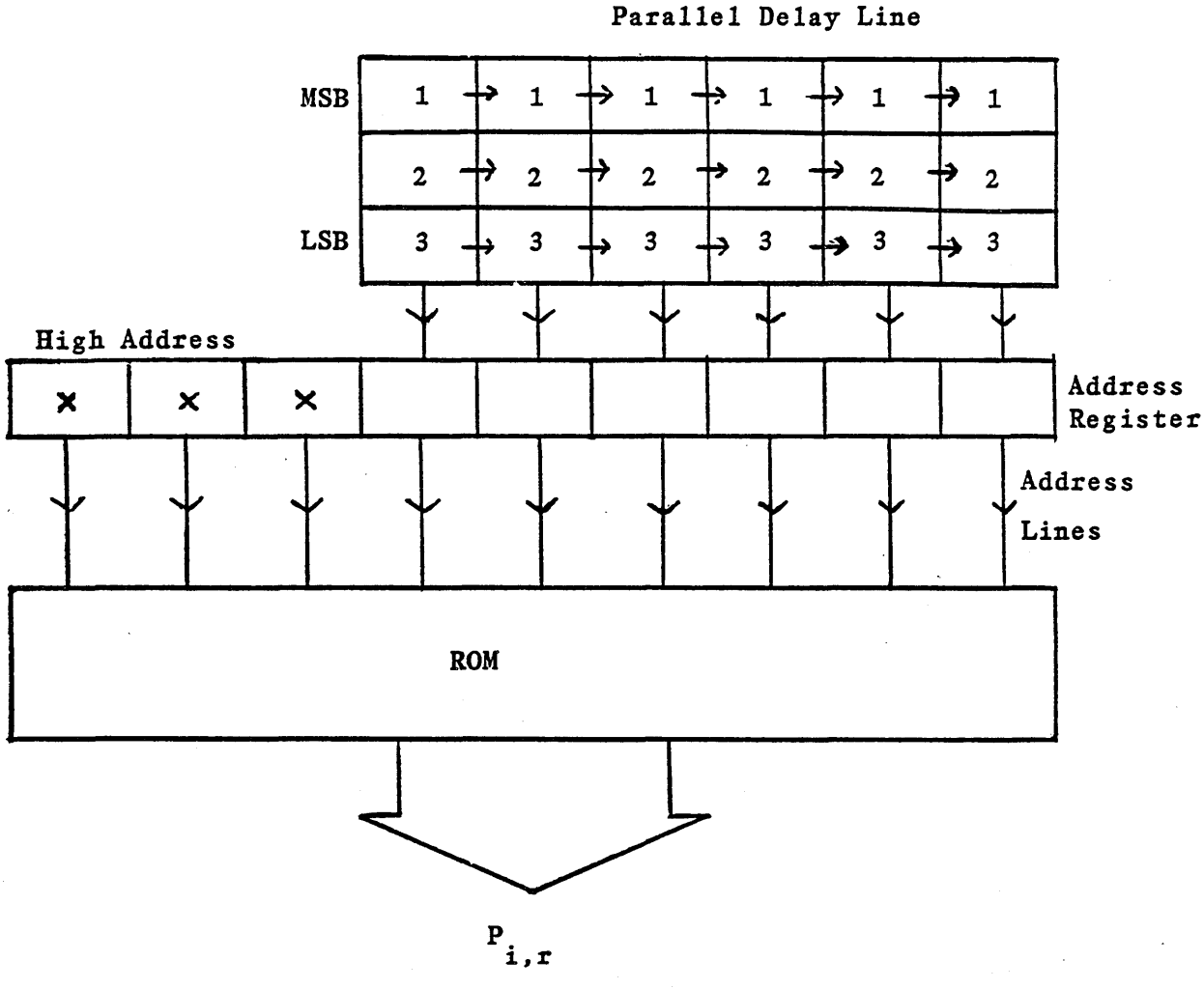


Fig.A1.1. Looking Up Precomputed Coefficient $P_{i,r}$ Using Delayed Samples (N=5,B=3).

APPENDIX 2

HIGH SPEED FILTERING PROGRAM USING MULTIPLY TABLES

For an N-tap FIR filter the filter equation is

$$Y_i = \sum_{j=0}^{N-1} C_j X_{i-j} \qquad (1)$$

For each input sample X_i the output Y_i is produced from multiplication of current and delayed input samples with a set of coefficients C_j (j=0 to N-1), and accumulation of the products. As the set of coefficients are fixed the multiply operations can be performed as a lookup operation where the input sample is used as an address to look up the product from a table containing all possible products. This product is then added to the accumulator and the process is repeated for the N filter coefficients.

The filter cycle therefore consists of accessing the input sample from the delay line, placing this in the address pointer, reading the product and adding it to the accumulator. The delay line has also to be updated with the current input sample which initially has to be read from the input source eg. ADC. A final output of the filter output sample is also required. The speed with which all of these can be done determines the filter cycle time, the reciprocal of which gives the maximum sampling rate of the filter. For higher throughput therefore the cycle time must be as small as possible.

The following paragraphs describe the implementation of a 7-tap filter

in which input sample and coefficient quantisation are both 8-bits and the accumulator is 16 bits. The 16-bit products are assumed to have been formed and stored in memory such that least significant bytes and most significant bytes of the products are held separately in adjacent memory blocks. Each 256-byte block will be tagged M_i^L for a low-byte store and M_i^H for a high-byte store. For the 7-tap filter the following tables have been formed:

Block Address(Decimal)	Table	For Filter Coefficient
100	M_0^L	C_0
101	M_0^H	
102	M_1^L	C_1
103	M_1^H	
104	M_2^L	C_2
105	M_2^H	
106	M_3^L	C_3
107	M_3^H	
108	M_4^L	C_4
109	M_4^H	
110	M_5^L	C_5
111	M_5^H	
112	M_6^L	C_6
113	M_6^H	

The tables must occupy contiguous blocks and the coefficients are sequentially ordered from C_0 to C_6.

The Z-80 processor is register-oriented in its architecture which implies that arithmetic and logical operations are most speedily executed when operands reside in the CPU registers. Unfortunately the Z-80 has only

6 internal 8-bit registers which means that most operands will be kept in memory. If high-speed filtering is to be possible the quick access of the operands situated in memory is of great importance.

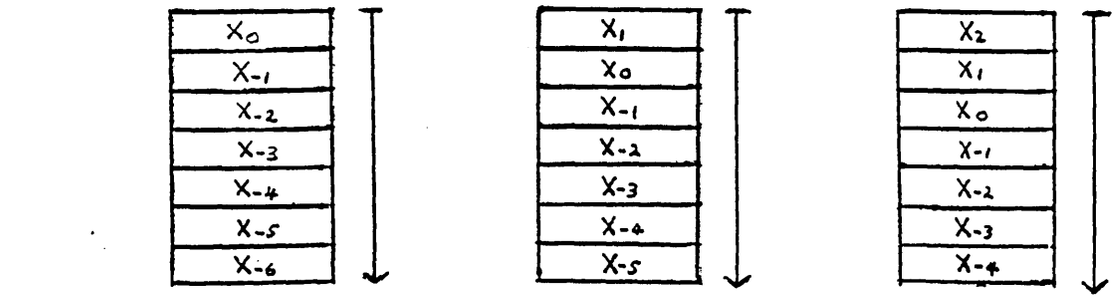
The delay operation in the filtering process is readily implemented using a memory stack. For each filter cycle the contents of the stack must be shifted down the stack in order to accomodate the latest input sample (Fig.A2.1a). The straightforward method of byte-by-byte transfer is clearly time-consuming and inefficient. An alternative technique is to employ a cyclic pointer which increments upon each update. When the pointer reaches the top of the stack it restarts at the bottom (Fig.A2.1b). Whilst the update procedure is much faster than in the case of block-transferring of stack contents, during subsequent access of the delayed samples in the filtering computations an additional checking operation is needed in order to determine if the pointer has reached the top of the stack. This slows down the filtering procedure to a large extent.

A high-speed compromise solution is to employ a dual stack (Fig.A2.1c). Two contiguous stacks S_A and S_B each of length 7 bytes hold the delayed samples. During an update the current sample is placed in S_A as in the previous method but here it is also copied into S_B, in a location 7 bytes from its position in S_A. In this way a contiguous delay line is assured so that during subsequent access in the filtering computations no check of the pointer is needed.

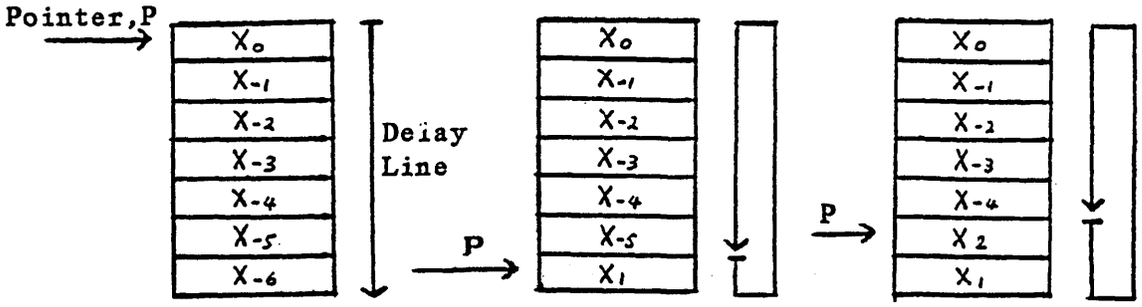
In the lookup-accumulate operations the contents of the delay line are used to address the lookup tables. A high speed method of accessing is to treat the delay line as the microprocessor stack and use the very efficient stack instruction POP to place the delayed sample in the CPU register. The

original stack pointer must of course be saved before these access operation which can be done at the start of each filter cycle. Consecutive POP instructions then automatically transfer the delay line contents, two bytes at a time, to the internal registers used for addressing. For the Z-80 the POP instruction executes in only 10 clock cycles which is very time-economical. At the end of the filter cycle the original system stack pointer is restored.

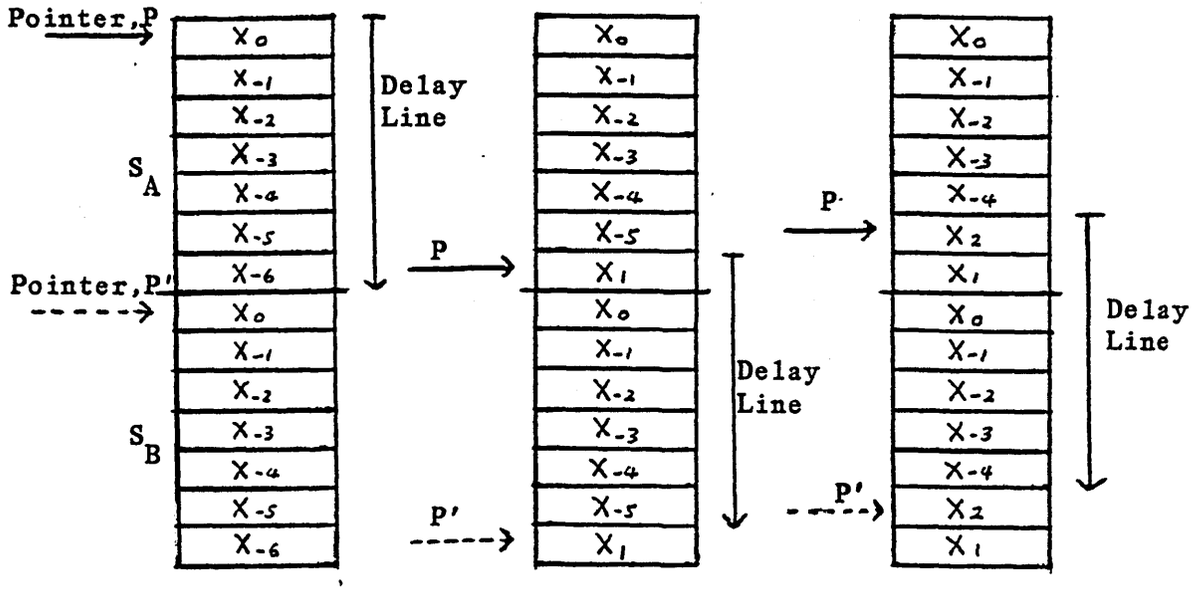
Once inside the CPU registers the delayed samples may directly address the lookup tables. For 16-bit lookup values the low byte is first added to the low-byte of the accumulator(16 bits), followed by addition-with-carry of the high byte of the lookup value to the high byte of the accumulator. The reason for storing high and low bytes of lookup tables in adjacent memory blocks (256 bytes per block) is now clear. To address the high-byte value the addressing register now only has to increment its high byte which is an economical operation. To further reduce the filtering cycle time decision repeating loops are avoided because of the time-consuming nature of decision instructions. Fig.A2.2 shows the source listing of a Z-80 assembler program for the implementation of an FIR filter whose length is programmable. Examples of filter cycle times are given in Fig.A2.3 where the Z-80B CPU (6MHz) is employed. It is seen that real-time filtering at 2.8kHz sampling rate is possible with a 50-tap filter which will allow a maximum input analogue frequency of 1.4 kHz. If faster microprocessors are used which also possess larger accumulators it should be possible to cover the entire telephony range of frequencies.



(a) Fixed Delay Line



(b) Cyclic Delay Line



(c) Dual Stack Delay Line

Fig.A2.1. Implementation of Delay Line.

```
17AD                ;
17AD                ;
17AD                ; EQUALISING FILTER
17AD                ;
17AD                ; STORE TEMP1 MUST HAVE SAME HI-ORDER (PAGE) ADDRESS
17AD                ; AS DELAY STACK DBUF WHICH MUST HAVE AN XX00H ADDRESS.
17AD  ED73321A   R4      SSPD   TEMP7 ; SAVE STACK POINTER
17B1  0842               IN     42H ; GET INPUT SAMPLE
17B3  47         R19     MOV    B,A ; PUT I/P SAMPLE IN B
17B4  218020     R20     LXI    H,TEMP1 ; SET HL TO TEMP1 ADDRESS
17B7  7E                 MOV    A,M ; GET CURRENT SAMPLE POINTER
17B8  3D                 DCR    A ; DECREMENT IT
17B9  CB77               BIT    6,A ; EXAMINE POINTER FOR OVERFLOW
17BB  CAC017             JZ     B2 ; GO TO B2 IF NO OVERFLOW
17BE                ; OVERFLOW - POINTER TAKES ON VALUE OFFH AFTER DECREMENT
17BE  3E1C               MVI    A,NT-1 ; SET POINTER TO PRIMARY BOTTOM
17C0  77         B2      MOV    M,A ; RETURN UPDATED POINTER
17C1  6F                 MOV    L,A ; PUT NEW POINTER IN L
17C2  70                 MOV    M,B ; SAVE I/P SAMPLE IN DELAY STACK
17C3  2C                 INR    L ; INC.POINTER
17C4  F9                 SPHL   ; SET STACK POINTER TO DELAY STACK ADDRESS
17C5  C61D               ADI    NT ; MOV POINTER INTO DUAL BUFFER (BELOW PRIMARY)
17C7  6F                 MOV    L,A ; PUT NEW POINTER IN L
17C8  70                 MOV    M,B ; SAVE SAMPLE IN DUAL BUFFER
17C9                ;
17C9                ;
17C9  68                 MOV    L,B
17CA  2622               MVI    H,TAB/256 ; SET HI-ORDER TABLE ADDRESS
17CC  4E                 MOV    C,M ; GET FIRST LOOKUP VALUE
17CD  24                 INR    H
17CE  46                 MOV    B,M
17CF                ;
17CF                     REPT   (NT-1)/2
17CF  D1                 POP    D ; GET NEXT TWO POINTERS
17D0  6B                 MOV    L,E ; PUT 1ST POINTER IN L
17D1  24                 INR    H ; ADVANCE TABLE ADDRESS
17D2  79                 MOV    A,C
17D3  86                 ADD    M
17D4  4F                 MOV    C,A
17D5  24                 INR    H ; ADVANCE TO HI-BYTE TABLE
17D6  78                 MOV    A,B
17D7  8E                 ADC    M
17D8  47                 MOV    B,A ; 16-BIT LOOKUP VALUE ADDED TO BC
17D9                ;
17D9  6A                 MOV    L,D ; PUT 2ND POINTER IN L
17DA  24                 INR    H ; ADVANCE TABLE ADDRESS
17DB  79                 MOV    A,C
17DC  86                 ADD    M
17DD  4F                 MOV    C,A
17DE  24                 INR    H
17DF  78                 MOV    A,B
17E0  8E                 ADC    M
17E1  47                 MOV    B,A ; 16-BIT LOOKUP VALUE ADDED
17E2                     REPND

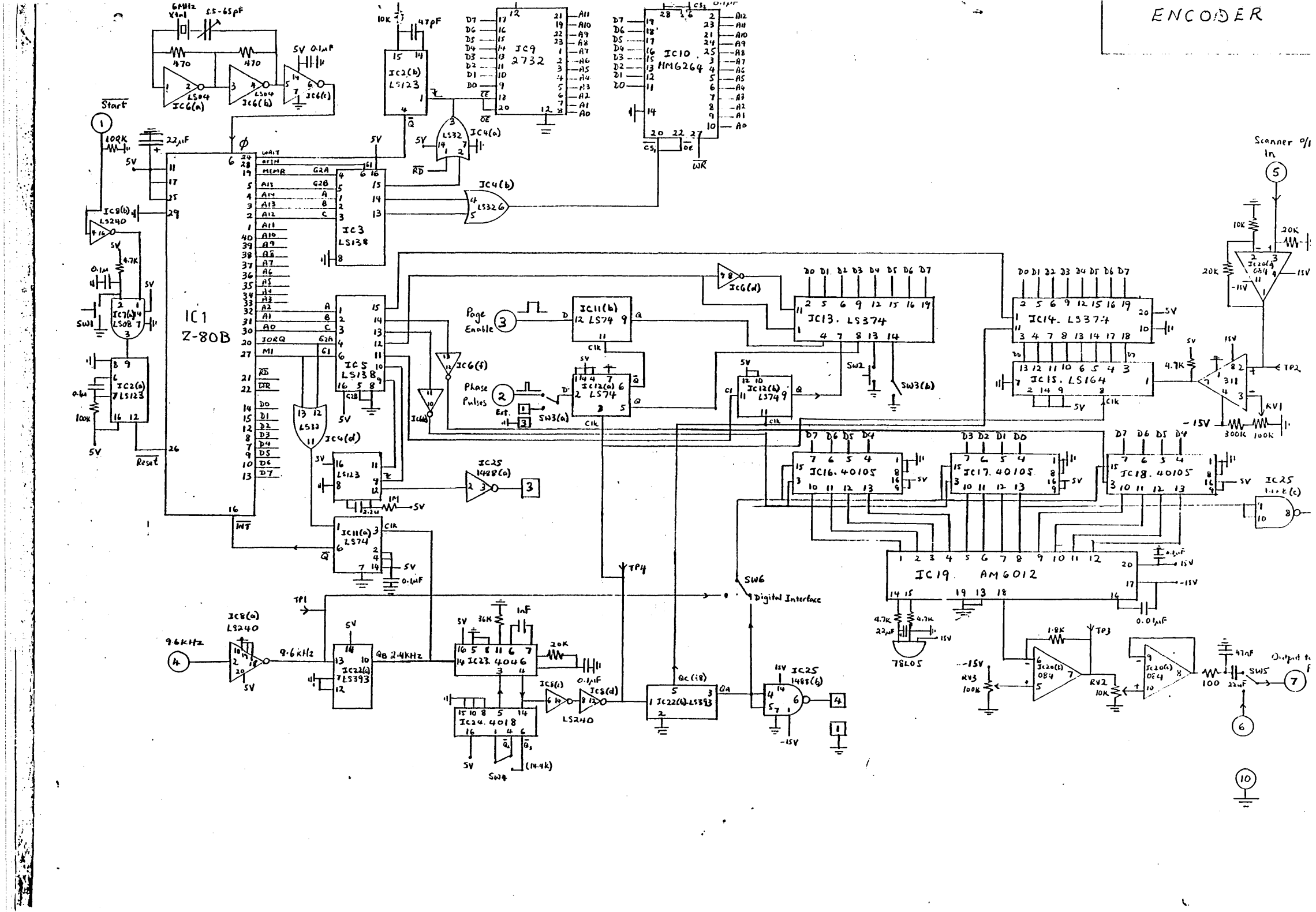
18D9                ;
18D9                ;
18D9  CB11               RL     C
18DB  17                 RAL    ; MULTIPLY RESULT BY 2
18DC  CB11               RL     C
18DE  CE0C               ACI    0 ; ROUND OFF RESULT
18E0  6F                 MOV    L,A ; PUT EQUALISED SAMPLE IN L
18E1                ;
18E1  ED7B321A   R21     LSPD   TEMP7 ;RESTORE STACK POINTER
18E5                ;
```

No.of Taps	Filter Cycle Time	Maximum Sampling Rate at Input
10	54µs	18.5kHz
20	122µs	8.20kHz
30	190µs	5.26kHz
40	268µs	3.72kHz
50	346µs	2.89kHz

Fig.A2.3. Cycle Times of Speed-Optimised FIR Filter Program (16-bit Accumulator).

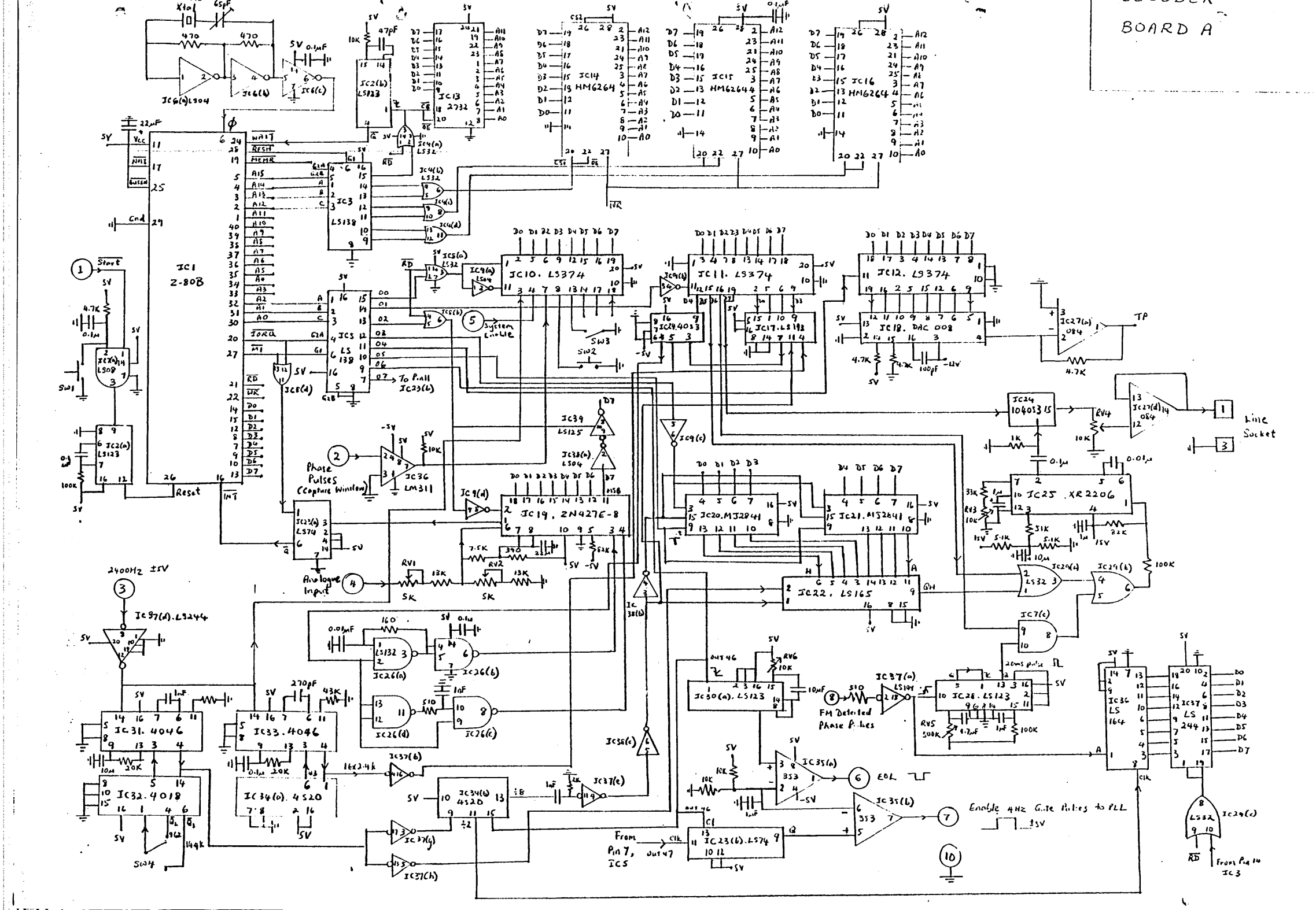
APPENDIX 3

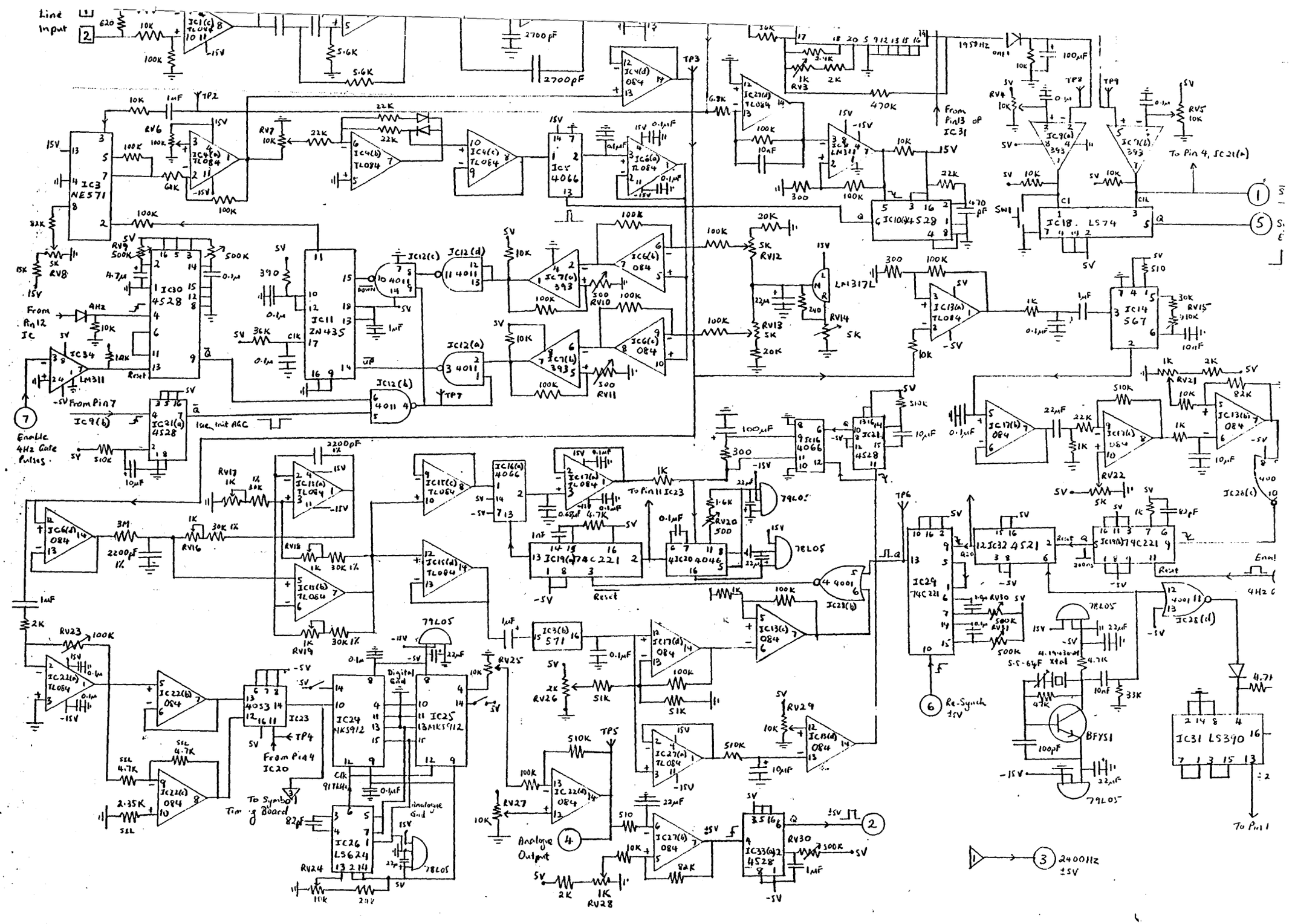
CIRCUIT DIAGRAM OF ENCODER


ENCODER
IC1 Z-80B
IC2 LS123
IC3 LS138
IC4 LS32 LS326
IC5 LS138
IC6 LS04
IC7 LS08 LS14
IC8 LS240
IC9 2732
IC10 HM6264
IC11 LS74
IC12 LS74
IC13 LS374
IC14 LS374
IC15 LS164
IC16 40105
IC17 40105
IC18 40105
IC19 AM6012
IC20 084
IC22 LS393
IC23 4046
IC24 4018
IC25 1488 1489
Start
Reset
Page Enable
Phase Pulses
Ext.
Digital Interface
Scanner o/p In
78L05
SW1
SW2
SW3
SW4
SW5
SW6
TP1
TP2
TP3
TP4
RV1
RV2
RV3
9.6kHz
2.4kHz
5V
-15V
15V

APPENDIX 4

CIRCUIT DIAGRAMS OF DECODER


BOARD A
IC1 Z-80B
Start
Reset
Phase Pulses (Capture Window)
Analogue Input
2400Hz ±5V
FM Detected Phase Pulses
EOL
Enable 4Hz Gate Pulses to PLL
Line Socket
TP
From Pin 7, IC5
From Pin 14 IC3
IC2(a) LS123
IC2(b) LS123
IC3 LS138
IC4(a) LS32
IC4(b) LS32
IC4(c)
IC4(d)
IC5(a) LS32
IC5(b) LS32
IC6(a) LS04
IC6(b)
IC6(c)
IC7(c)
IC8(d)
IC9(a) LS04
IC9(b)
IC9(c)
IC9(d)
IC10. LS374
IC11. LS374
IC12. LS374
IC13 2732
IC14 HM6264
IC15 HM6264
IC16 HM62644
IC17. LS193
IC18. DAC 008
IC19. 2N4274-8
IC20. MJ2841
IC21. MJ2841
IC22. LS165
IC23(a) LS74
IC23(b). LS74
IC24 4013
IC24.4013
IC25. XR2206
IC26(a) LS132
IC26(b)
IC26(c)
IC26(d)
IC26. LS123
IC27(a) 084
IC27(b) 084
IC27(c) 084
IC27(d) 084
IC30(a). LS123
IC31. 4046
IC32. 4018
IC33. 4046
IC34(a). 4520
IC34(b) 4520
IC35(a) 353
IC35(b) 353
IC36 LS 164
IC37 LS 244
IC37(a) LS194
IC37(b)
IC37(c)
IC37(d). LS244
IC37(e)
IC37(g)
IC37(h)
IC38(a) LS04
IC38(b)
IC39 LS125
IC36 LM311
SW1
SW2
SW3
SW4
5 System Enable
To Pin11 IC23(b)
Xtal
65pF
22µF
47pF
0.1µF
0.01µF
4.7K
10K
100K
1K
5K
7.5K
13K
16K
20K
33K
51K
62K
100pF
0.1µF
0.01µF
1µF
10µF
2.2µF
4.7µF
100µF
270pF
390
510
2K
10M
20M
43K
100K
149K
160
1nF
10nF
22nF
RV1
RV2
RV3
RV4
RV5
RV6
500K
+5V
-5V
-12V
Vcc
GND
WAIT
RESET
MEMR
IORQ
M1
RD
WR
INT
BUSRQ
NMI
HALT
Ø


Line Input
IC1(c) TL084
620
10K
100K
15V
5.6K
2700pF
IC4(d) 084
TP3
IC27(d) TL084
6.8K
36K
1K RV3
2K
470K
From Pin13 of IC31
1959Hz
100µF
10K
RV4 10K
RV5 10K
IC9(a) 393
IC9(b) 393
To Pin 4, IC21(a)
TP2
RV6 100K
IC4(a) TL084
IC4(b) TL084
IC4(c) TL084
IC5 4066
IC6(a) TL084
IC27(a) TL084
IC26(a) LM349
300
100K
10nF
IC10(b) 4528
470 pF
IC18. LS74
SW1
IC3 NE571
82K
15K RV8
5K
IC30 4528
500K
4.7µF
0.1µF
From Pin12 IC
4Hz
IC34
LM311
Reset
IC12(c)
IC12(d) 4011
IC12(b) 4011
IC12(a) 4011
IC7(a) 393
IC7(b) 393
IC6(b) 084
IC6(c) 084
IC11 ZN435
390
36K
CLK
300 RV10
300 RV11
20K
5K RV12
RV13 5K
20K
LM317L
240
22µF
RV14 5K
IC13(a) TL084
IC14 567
510
30K RV15
10K RV16
10µF
From Pin7 IC9(b)
IC21(a) 4528
Isec_Init AGC
Enable 4Hz Gate Pulses.
2200pF 1%
RV17 1K 30K
IC13(b) TL084
IC16(a) 4066
IC16(b) 4066
IC16(c) 4066
IC16(d) 4066
IC17(a) TL084
IC17(b) 084
IC17(c) 084
IC17(d) 084
IC32 4521
IC19(a) 74C221
IC19(b) 74C221
IC29 74C221
IC28(a)
IC28(b)
IC28(c)
IC28(d)
To Pin11 IC23
0.68µF
4.7K
0.1µF
1.6K RV20 500
RV18 1K 30K 1%
RV19 1K 30K 1%
3M
2200pF 1%
RV16
78L05
79L05
Reset
Re-Synch ±5V
RV21 1K 2K
RV22 5K
RV23 100K
IC22(a) TL084
IC22(b) 084
IC22(c) TL084
IC22(d) TL084
IC3(b) 571
IC23 4053
IC24 MK5912
IC25 MK5912
Digital Gnd
Analogue Gnd
RV25 10K
RV26 2K 51K
RV27 10K
RV28 2K 1K
RV29 10K
RV30 300K
RV31 500K
IC33(a) 4528
IC33(b) 4528
IC31 LS390
BFY51
4.7K
10nF
33K
100pF
5.5-64F Xtal
4.194304MHz
From Pin4 IC20
To Symbol Timing Board
82pF
IC26 LS624
91KHz
2.35K
SEL
TP4
TP5
TP6
TP7
TP8
TP9
Analogue Output
2400Hz ±5V
To Pin 1

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