

STUDIES OF STELLAR OSCILLATIONS USING A FABRY-PEROT SPECTROMETER.

by

Krzysztof Andrzej Roman Boleslaw

Pietraszewski.

BSc ARCS.

Astronomy Group,

Blackett Laboratory,

Imperial College of Science and Technology,

London.

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ABSTRACT.

I have designed and built a Fabry-Perot spectrometer in order to make measurements of radial velocity curves of Delta Scuti and other ultra short period variable stars with an accuracy of 100 ms^{-1} or better.

The spectrometer comprises a servo-stabilised Fabry-Perot etalon enclosed in a constant environment chamber. The control of the instrument and data handling is achieved with a microcomputer.

The design, construction and use of the spectrometer is described and a method of reducing the data is developed. The radial velocity curves of eight stars are presented, those of α Car, α Cir and 44Tau not having been previously observed.

The precision of measurement with the instrument has met the expected level and is about 30 ms^{-1} on bright stars.

Corrigenda

Page 55: The last sentence should read:

If a and b are about equal, as they should be, and the intensity change due to cloud, for example, is $a \rightarrow ka$ and $b \rightarrow kb$, then the ratio, R , becomes, $R = ka - kb / ka + kb = a - b / a + b$ (2.12), so, small transparency changes can be eliminated by rapidly chopping thus making any compensation channels unnecessary.

Section 2.5.8 should read:

2.5.8. Photomultiplier Dark Count.

For a dark count da the ratio, R , becomes;

$$R = [a + da - (b + da)] / [a + b + 2da] = a - b / a + b + 2da \quad (2.13)$$

The effect of dark count can easily be corrected for with a measurement of its value. Then the correction to the value of the ratio, R , is that da is equal to the dark count in equation 2.13.

Section 3.5.6 should read:

3.5.6. Noise in Data and Fourier Transforms.

If the data comprises N values of the ratio $x_n = a - b / a + b$ of mean value $\bar{x}$ and standard deviation σ from the mean then the error or the noise on the value of the mean is given by standard gaussian theory as;

$$\text{noise} = \frac{\sigma}{\sqrt{n}} \quad (3.20)$$

A FT of noise alone would show equal amplitudes at all frequencies. This is called white noise. However the distribution will itself be noisy and there will be a distribution of values about the mean.

If the mean value in the Fourier plane is $\bar{\alpha}$ then

$$\bar{\alpha} = \sigma / (\pi/2)$$

and the second moment about the mean will be, κ^2 ,

$$\kappa^2 = \sigma^2 / (4 - \pi/2).$$

This follows from the distribution of values in the Fourier plane which is a Bivariate Normal Distribution (Elsworth and James, 1981, Astron. Astrophys. 103, 131.). If the values x_n have a variance u^2 , then,

$$\sigma^2 = u^2 N / 2.$$

The mean value of the peaks in the Fourier plane gives a useful estimate of the noise in the FT and a marker against which significance can be assessed.

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CHAPTER 1

PROPERTIES OF DELTA SCUTI AND OTHER VARIABLE STARS
AND
METHODS OF DETERMINING THEIR RADIAL VELOCITIES.

1. Introduction.

This chapter describes the properties of Delta Scuti, Dwarf Cepheid and Ap type stars, and, summarises the various methods used to measure their radial velocities.

1.2. Delta Scuti Type Stars.

1.2.1. Properties.

Next to the White Dwarfs, Delta-Scuti type stars are the second most numerous group of variable stars. Delta Scuti type of variability is a common phenomenon and examples of Delta Scutis have been found in clusters such as the Hyades. The position of Delta Scuti stars is shown in the H-R diagram of figure 1.1.

Delta Scutis have spectral types A or F and are located from 2.5 magnitudes above the main sequence to below the standard Population 1 stars. Several stars in this group show low metallicities and high space velocities typical of Population 2 stars. Delta Scuti pulsation periods are usually less than the arbitrary limit of 0.3 days and have visible light amplitudes varying from a few millimagnitudes to 0.8 magnitudes, 0.2 magnitudes being typical.

Delta Scuti stars are usually called Dwarf Cepheids once their light amplitudes exceed 0.3 magnitudes. Such stars are also often called A1 Vellorum or RRs stars.

A survey of Delta Scuti type stars by Breger, Hutchins and Kuhl (1976) shows that the average ratio of velocity to light amplitudes is about $92 \text{ kms}^{-1} \text{ magnitude}^{-1}$. This ratio varies from star to star within a large range and so is not a very good characteristic of these stars. A quantity which is nearly constant for all variable stars is the ratio of

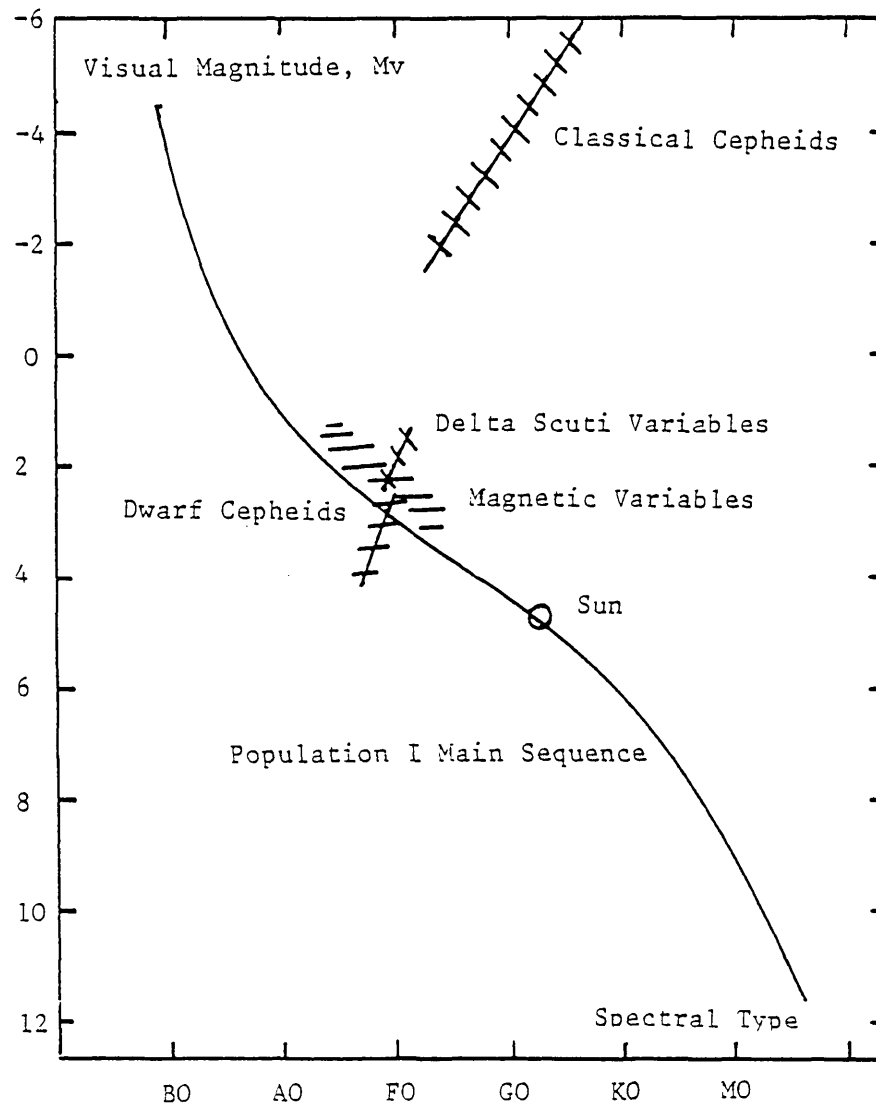


Figure 1.1 Position of Some Variables on the Hertzsprung-Russell Diagram.

surface expansion to luminosity amplitude which Breger, Hutchins and Kuhl (1976) find to be $0.11 \text{ magnitude}^{-1}$ on average.

They also find that the inverse radial velocity curve lags the light curve by 0.09 periods, and that the two curves are not always mirror images of each other.

1.2.2. Origins of Delta Scuti Pulsations and the One Zone Cepheid Model.

Delta Scuti stars, and Dwarf Cepheids, are the two groups of short period variables in the lower Hertzsprung Gap. This is located between the main sequence and the Cepheid instability strip. By virtue of their position in the H-R diagram, they can be considered to have similar properties to the Classical Cepheids. A simple model of Cepheids is the one zone model of Stellingwerf (1972).

The model consists of a rigid core surrounded by a single zone which is free to pulsate and has a constant composition. In order to simplify the equations and eliminate as many parameters as possible, Stellingwerf formulates the model with a period of oscillation equal to one cycle per second. This implies a shell of 10-15% of the stellar radius for the pulsation zone.

This pulsation zone size includes the He and the H ionisation zone of real Cepheids. Damping occurs deeper in the stellar interior and the one zone model does not allow direct calculations of this. All motions are assumed to be sinusoidal.

The results of the linear model predict that, as the effective temperature increases, the phase lag and maximum luminosity decrease. Also, that as the amplitude increases, i.e. radius variations increase, the maximum luminosity increases leaving the shape of the light curve unaltered. It also predicts that the pulsation constant Q increases with

increasing shell thickness and hence mass.

These predictions are consistent with observed properties of Cepheids.

The model also predicts that changes in the driving of the pulsations and the stars interior luminosity influences the maximum luminosity and the degree of assymetry in the light curves.

1.2.3. The Case of Delta Scuti Stars.

The model can be set up as for Cepheids but with the H and the He zones much thinner and more superficial. The H and the He II zones drive the oscillations with the He II zone dominating.

1.2.4. Main Sequence Delta Scuti Stars.

Delta Scutis situated on the main sequence have different properties to those in the instability strip. They have periods of about an hour with small light amplitudes of 0.02 magnitudes or less in the visible.

In his review, Breger (1979), states that the distribution of known Delta Scuti stars in the H-R diagram, main sequence and others, resembles the distribution of stars in general. He also gives a Period-Colour-Luminosity Relation for the visual magnitude M_v of Delta Scutis,

$$M_v = -3.052 \log P + 8.456 (b-y) - 3.121 \pm 0.31$$

(1.1)

Such PCLRs are constantly open for modification as the properties of newly discovered stars are taken into account. This relation is only empirical and is based on the observed properties of Delta Scutis.

1.2.5. Other Considerations.

The light and velocity curves of many Delta Scutis are variable in phase, shape and amplitude from cycle to cycle whereas others, such as Rho Puppis (discussed later) are entirely regular, or very nearly. This irregularity begs the question; Are these variables really periodic?

The irregularity may be real or apparent. If caused by two or more modes of oscillation of definite and constant period interacting together, then the periodicity is likely to be hidden to some extent.

Instabilities could be due to lengths of data which are too short or imperfect.

1.2.6. Properties of Dwarf Cepheids.

As mentioned above, these stars are often called A1 Vellorum or RRs stars, and are shown in the H-R diagram in figure 1.1. They are metal poor stars with short periods and large light amplitudes, in excess of 0.3 magnitudes. There is a lot of confusion about the evolutionary status of Dwarf Cepheids. They are believed to be post helium flash low mass stars. Their masses are generally thought to be about $0.5 M_{\odot}$ unlike the value of $1.7 M_{\odot}$ for Delta Scutis which are thought to be the Dwarf Cepheid evolutionary forerunner.

These views are changing, however, with more careful examination of data. The new properties of Dwarf Cepheids are almost identical to Delta Scuti except for the size of light amplitudes. Confusion had arisen due to the lack of suitable distance measurements. None of the Dwarf Cepheids have a significant trigonometric parallax except for SX Phe, which could, within the errors be placed in the $0.5 M_{\odot}$ or $1.7 M_{\odot}$ part of the H-R diagram. Dwarf Cepheid space velocities do not differ from the low amplitude Delta Scuti velocities except in a few cases which again are similar to the

general properties of the Delta Scuti type stars.

The question of separate classes for Delta Scutis and Dwarf Cepheids has yet to be settled. In general, both types of variables have similar properties, and as Breger (1979) states, the amplitudes of the oscillations are not suitable indicators of the star's evolutionary status. Eggen (1979) classes these two types of variables as ultra short period Cepheids and concludes that most of these stars are high mass little evolved stars which are blue stragglers.

1.2.7. Ap Stars.

Peculiar A stars have been known to be variable for a long time. The periods of variability have been attributed to large sunspots on the surface of rotating stars. The period of such variability is of the order of a few days and is the rotational period of the star.

Periods much shorter than these ranging from 6 to 60 minutes with small light amplitudes of 0.01 magnitudes have been observed, for example, 0.01 magnitude variation in HD24712 by Kurtz (1981) with period 6.15 minutes.

Percy (1975) detected amplitudes smaller than this in 21 Com. Two amplitudes ranging from 0.005 to 0.015 magnitudes with periods of 30 and 40 minutes. The ratio of these periods indicated that radial oscillations were present in 21 Com.

The short period Ap stars such as those reported by Kurtz (1978, 1981, 1983) imply higher order modes that are probably non-radial.

The amplitudes of these stars vary indicating beat phenomena.

1.3. The Need For High Accuracy Radial Velocity Measurements.

High accuracy measurements of stellar radial velocities have so far

been restricted to the sun or very bright stars. Radial velocities of stars with brightnesses of 3 to 10 magnitudes have been measured using some of the methods described in section 1.4 later. The methods have been lacking in precision with resulting errors not usually better than 0.5 to 1.0 kms^{-1} . There are some claims to standard errors of 0.1 kms^{-1} or better, but, as pointed out by Griffin and Griffin (1973), published evidence of them is scarce.

There is, therefore, clear evidence that there is a need for higher accuracy radial velocity measurements at the 100 ms^{-1} level.

1.3.1. Suitability of Short Period Variables for Radial Velocity Measurements.

In order to obtain a velocity curve in which all the possible periods appear, for a given length of data, Baglin et al (1973), suggest that integration times of not more than 10-20% of the pulsation period should be used. For most of the stars mentioned above the main pulsation period is of the order of an hour, making a suitable integration time of six minutes. Using the photon counting method described later, many data points can be collected in such a time enabling the search for much shorter periods.

Amplitudes of oscillation are 10 kms^{-1} or smaller, which with a line width of between 0.5 to 1.0 Å can be accommodated well in the steepest part of the side of an absorption line.

The spectral types A or F have sufficient spectral features for a suitable line to be chosen (see later). Continuous observations of these stars allow noise levels of less than 100 ms^{-1} on 5th. magnitude stars in an average five or six hour observing run on a moderately sized telescope, say 1.9 metres.

In general, Delta Scuti, Dwarf Cepheid and peculiar A type stars are well suited to interferometric observations of their radial velocities.

1.4. Introduction to measurements of Radial Velocity.

There now follows a brief review of methods used for determining radial velocities and some of the problems encountered.

1.4.1. Measurements of Radial Velocities.

The radial velocities of astronomical objects are usually measured by studying the effect of the Doppler shift produced by radial motion on features in the spectrum of the object. To find absolute radial velocities a comparison of the shifted spectrum with an unshifted or zero radial velocity spectrum must be made. The earliest such measurements were done by comparing, visually, stellar Balmer lines with those produced in a hydrogen discharge lamp at rest in the laboratory. Since these first attempts much more sophisticated methods have been developed.

1.4.2. Reference Spectra.

The first step forward was to record a stellar spectrum and a reference spectrum, such as an iron arc maintained near the spectrograph, on a photographic plate and to compare the two later using a microdensitometer. However, photographic plates have a poor quantum efficiency and this method, therefore, is not very efficient in its use of observing time.

1.4.3. Correlation Mask Spectrometers.

Griffin (1967) described a method of adapting a conventional spectrograph to use all the spectral elements of a stellar spectrum

simultaneously in order to determine the Doppler shift. The method involves using an appropriate mask in the focal plane of a spectrograph and collecting all the transmitted light on a single detector, a photomultiplier.

The mask may be an exposed spectrogram of the candidate star or a copy of it. A metal mask that will transmit no light in the parts representing continuum and most light in the parts representing absorption lines is often used. This is, then, simply a negative image of the spectrum, as one would expect.

Replacing this mask in the focal plane will stop a lot of the light from the star but in general some light will still pass. By moving the mask to align it with the new candidate spectrum will provide a minimum in the signal detected by the photomultiplier. The mask is then aligned and all the light from the continuum falls on the opaque areas of the mask and the absorption lines where little light is present will fall on the transparent areas.

By measuring the shift of the mask needed to bring it into alignment with the spectrum of a star of known radial velocity, the radial velocity of the candidate can be found. A high quality measurement using the standard technique, without the mask, would only have to be done once for the standard comparison star.

The advantages of this method are that the whole spectrum used is made to fall on one detector and the same resolution may be used for all stars, the dimmer ones having a lower signal to noise ratio but drastically reduced integration times compared to the standard method. A further advantage is that the continuum does not contribute noise to the result.

The difficulties are that a mask is quite difficult to produce very

accurately as photographic emulsions change by shrinking or stretching during development and the spectrographs are large and sensitive to temperature changes bringing on mechanical instabilities.

A further problem is that only limited amounts of spectrum may be used since the reciprocal dispersion is not proportional to wavelength whereas Doppler shift is, which would cause a mismatch between mask and spectrum.

There may also be a mismatch between the mask and the stellar spectrum due to differing features but this would still show a minimum for the "best" match.

Such arrangements are used routinely for radial velocity measurements and have accuracies of about $1\text{--}2 \text{ kms}^{-1}$.

An instrument called Coravel (Baranne et al 1979) is a Griffin mask radial velocity spectrophotometer which produces results with an average precision of 0.5 kms^{-1} on stars down to 14th. magnitude. This instrument has been made as simple to use as possible and needs no adjustments to the structure by the observer. This has allowed the designers to make a more delicate and precise instrument. It incorporates an echelle grating with its advantages of high dispersion, great spectral range and efficiency.

1.4.4. Correlation Spectrophotometry without a Physical Mask.

In a conventional mask spectrophotometer all the light passing through the mask is made to fall on the single detector thus destroying the information carried about the shape of the spectrum. However this information may be recovered by using a multi-element detector and mask constructed digitally in the memory of a computer. By replacing the photographic plate in a standard spectrograph by a multi-element digital detector, the part of the spectrum used can be recorded digitally. After

each short integration time the digital mask can be used to weight each element according to its position and produce a value for the amount of light that would pass through a mask. The digital mask can be scanned across the spectrum to find the best match and hence the radial velocity. If each frame is recorded then many of these frames can be used to find the average profiles of lines in the spectrum. Such a mask has the advantage that it can be very quickly swapped for another by recalling it from another part of the computers memory, it is also insensitive to temperature changes and only depends upon the original from which it was constructed. Any expansion or contraction in the detector has the same effect as a physical mask changing its dimensions but modern multi-element detectors such as CCDs are usually cooled by a liquid gas and are dimensionally very stable. This method therefore combines the large amount of information obtained using photographic plates and the advantages of observing a large part of the spectrum at one time.

1.4.5. Improvement of the Standard Spectrum.

Griffin and Griffin (1973) suggested the use of telluric absorption lines as standards instead of an iron arc spectrum produced near the spectograph. This would make the optical path the same for star and standard, the standard being more similar to the spectrum in as much as they would both be absorption lines. The two spectra would be recorded simultaneously. The shortcomings of the Telluric lines are that they do not appear throughout the spectrum, there would be a reduction in the number of measurable lines due to the blending of some of the lines from both spectra and exposure times may be greatly different. Such a standard would limit the objects to non-variable stars of a certain brightness. The method would also show up Doppler shifts due to bulk motions of the

atmosphere.

Other standards include absorptions produced in a HF absorption cell as described by Campbell and Walker (1979), through which starlight is passed before entering a spectograph, attaining precisions of about 15 ms^{-1} .

Both these methods have the advantage of telluric lines, the same optical path, etc., but would be unaffected by atmospheric and similar changes.

Serkowski (1972) describes a technique which uses a polarization grating spectrometer and a multi-element detector to measure radial velocities with 1 kms^{-1} precision.

1.4.6. Radial Velocities without Gratings.

With all the problems associated with mask spectrometers other systems have been devised. Some of these are described as follows.

1.4.7. Brookes' and Isaak's Resonant Scattering Method.

Isaak (1961) described a method whereby light from the source, selected by a narrow interference filter, is scattered resonantly from a vapour of sodium in a magnetic field. The sodium absorption line is split by the magnetic field so that the anomalous Zeeman components are separated by the width of the incoming line. The input light is first made circularly polarised and is then scattered and finally a small fraction of it is detected by a cooled photomultiplier. Depending upon the Doppler shift different amounts of light will be scattered in each polarisation enabling the shift to be measured. The sodium vapour cell is extremely stable allowing noise levels of $\sim 1 \text{ ms}^{-1}$ to be achieved on the Sun. The use of resonant scattering limits observations to very bright objects with velocities less than $\pm 6 \text{ kms}^{-1}$ since the absorption cell line cannot be tuned

in wavelength by more than a linewidth.

1.4.8. Michelson Interferometer.

This method by Forrest (1982) comprises a solid, field widened, Michelson Interferometer, shown in figure 1.2, which uses both input and output beams. Both beams are used for signal and reference light. This is done by using a different frequency for both. The reference source is used to servo the path difference at a pre-chosen value. If at such a path difference the intensity (of the signal) in both beams is the same then changes in radial velocity will change the ratio of the intensities in the two beams while the sum of their intensities remains unchanged. By rapidly chopping between beams and between photon counting channels, errors due to seeing and guiding are eliminated as well as removing the effects of any mismatch in the two electronics and optics halves of the instrument. This method is limited to stars which have line widths suited to the path difference of the solid Michelson block being used. Different blocks can be used for different widths of lines. The method regularly produces noise levels of a few ms^{-1} to a few tens of ms^{-1} .

1.4.9. Fabry-Perot Interferometer.

This method is the subject of the rest of this work. Essentially the passband of servo controlled Fabry-Perot etalon is chopped between the points of inflection of a stellar absorption line under computer control. The Fabry-Perot is held in a stable environment to minimise or eliminate drifts. By monitoring the ratio of intensities at the two selected chop positions the radial velocity can be determined.

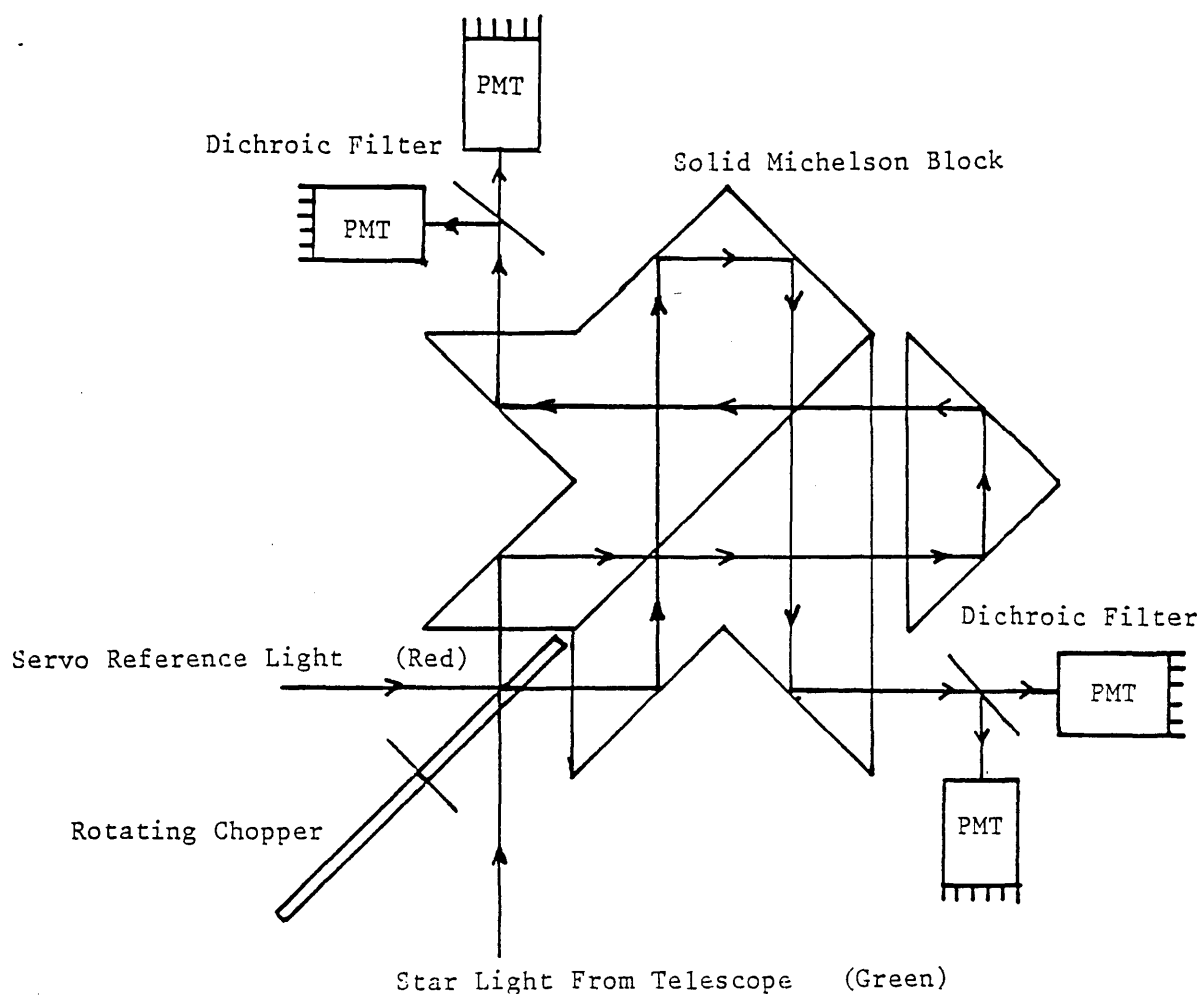


Figure 1.2 Solid, Field Widened Michelson Interferometer

CHAPTER 2

THE INTERFEROMETER.

2.1. Preliminary Requirements.

A target precision for a new instrument to measure radial velocities must first be set. With the lack of accurate radial velocity measurements a realistic and achievable target precision is 100 ms^{-1} . Whether this can be achieved depends upon many factors. These include line shapes in stars, resolution required to match the lines and noise in any of the control electronics, among others.

2.2. The Interferometer.

2.2.1. Choice of Interferometer.

The Fabry-Perot Interferometer was chosen over a conventional grating or Griffin mask type grating or Michelson interferometer because of its simplicity and the availability of a highly developed servo and FP etalon system developed within the Imperial College Astronomy Group, described by Hicks, Reay and Scaddan (1973) and marketed by Queensgate Instruments, under the name CS100. Also, a more important reason for using such an interferometer is its large throughput, allowing large apertures to be used.

2.2.2. Spectral Resolution.

Having decided on a Fabry-Perot interferometer, the choice of spectral resolution must be considered. The final choice must be an optimum for finding the required information; the radial velocity. A low resolution would result in a wide instrumental profile which would afford a high signal to noise ratio but low sensitivity to radial velocity, whereas a very high resolution would give a narrow instrumental profile

and a poor signal to noise ratio, but would be more sensitive to radial velocities if the same time of observation is considered for both cases. There would be a limit after which increasing the resolution would not increase the sensitivity to radial velocity but would allow the line profile to be mapped out in finer detail. However, since only radial velocities are required, the highest resolutions are not necessary. An estimate of the required resolution can be obtained by considering the chosen line width as the resolution element then,

$$\frac{\lambda}{\delta\lambda} = \frac{6000}{1.0} \quad (2.1)$$

this then gives a resolution of approximately 6,000 with a line width of 1Å at 6000Å. Such a line width is typical for Delta Scuti variables.

2.2.3. Choice of Spectral Line.

An absorption line suitable for radial velocities measurements must have a number of essential properties. These are that it must be as deep and symmetric as possible and well away from other spectral features. The depth and symmetry of the line determine its sensitivity to Doppler shifts and the linearity with which these shifts can be measured. A line well isolated from other lines will be free from blending which would lead to spurious velocities due to the different slopes on either side of the line which would not be different with a single or clean line. The line must also be in the visible range of the spectrum where optical coatings and detector technology are at their finest. This would avoid the need for costly balloon flights and cryogenics needed in other wavebands and would allow well proven technology to be used.

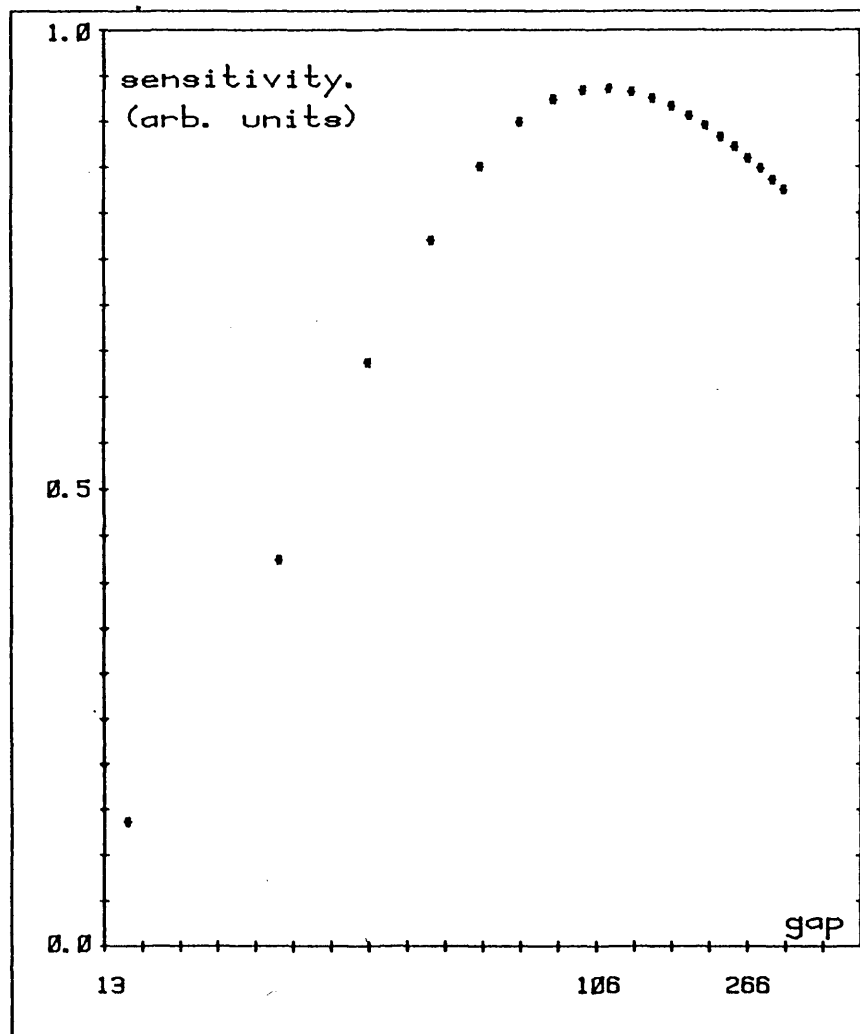
By consulting the Photometric Atlas of Stellar Spectra, Hiltner and Williams (1946), the line which suits the above requirements and appears in the spectra of most A and F type stars, was chosen to be the FeI 5317.4 Å line.

In Delta Scuti type stars this line has a full width at half maximum from about 0.7 to 1.3 Å and depths from about 80%. Its shape is gaussian or very nearly so.

2.2.4. Determination of Spectral Resolution.

Having chosen the stellar absorption line, and estimated the resolution to work at, the final choice of gap for the etalon must be considered in greater detail. In order to find the optimum gap and hence resolution for the given line shape, a computer simulation was done. By convolving the instrumental profile for different gaps with the standard line profile and calculating the sensitivity of the combination and the signal to noise ratio it would produce, the ideal gap was calculated. The final choice of gap also required consideration of the servo electronics noise. Measurements by the developers of the servo electronics (Q.I., 1981) showed that the electronic noise produced a plate movement of $\lambda/10^4$. The result of the computer simulations are shown in figure 2.1 with the electronic noise, and the programme used is reproduced in Appendix 2.1.

The final choice of gap was 100 microns.



2.2.5. Range of Likely Radial Velocities.

The velocities that might be encountered range in amplitude from a few hundreds of ms^{-1} to about ten or fifteen kms^{-1} . Such velocities represent shifts in the mean position of the spectral line of between 0.8% to 15% of the line width, assuming a 1 Å wide line, i.e. 60 kms^{-1} . Monitoring the light intensity on the linear portion of the absorption line yields a linear measure of the line's position and hence the radial velocity. Small velocities producing small intensity changes are linear. What is the largest radial velocity that will produce a linear change in intensity? The answer to this question can be found by examining the simulated line profile, a simple gaussian, of figure 2.2. The side of the line is linear to $\pm 15\%$ of the full width at half maximum (FWHM). The best point to choose to monitor the line position is the point of inflection which falls half way along the linear region just below the FWHM point. At this point there is an equal linear distance above and below, allowing an equal swing in velocity about the mean velocity. The width of the line at the point of inflection is roughly 90% of the FWHM. As a line becomes narrower, its profile resembles the Lorentzian profile more. This profile is much sharper and has greater linearity, but for Delta Scuti stars a gaussian is a good approximation to the line shape.

The chosen line can cope with the range of velocities likely to be encountered, i.e. $\pm 12 \text{ kms}^{-1}$

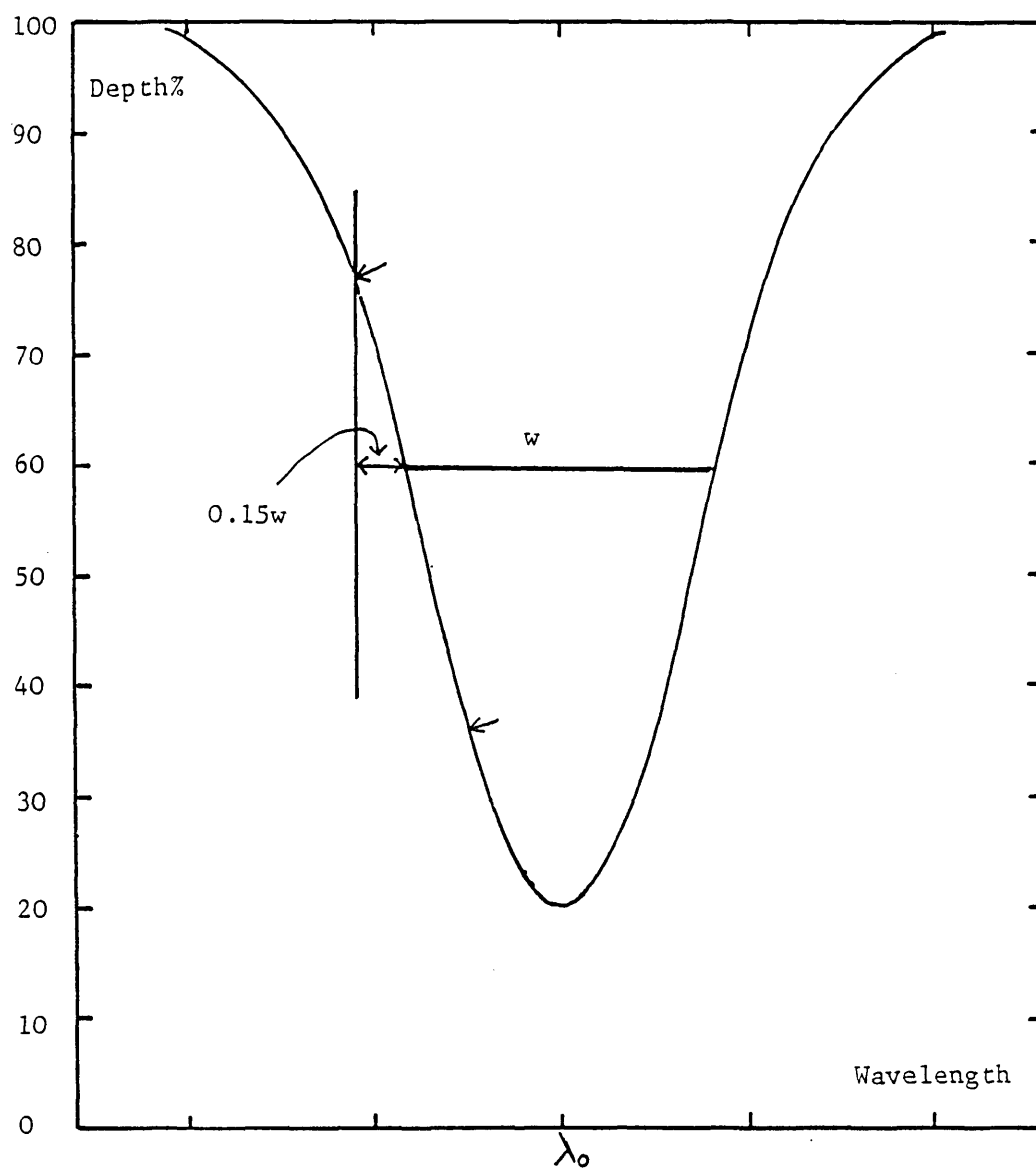


Figure 2.2 Simulated Gaussian Line Profile Showing Linear Region

2.3. The Theory of the Fabry-Perot Interferometer.

The detailed theory of Fabry-Perot interferometers is not set out here. Only the results which were needed in the design and use of the instrument are presented. More detailed treatments may be found in the Optics literature, for example, Born and Wolf (1975).

The instrumental function for a FP etalon is an Airy function of the general form;

$$\tau = \frac{T^2}{(1-R)^2 \left[1 + \left\{ \frac{2NR \sin\left(\frac{2\pi n t \cos\theta}{\lambda}\right)}{\pi} \right\}^2 \right]} \quad (2.2)$$

Where τ is the transmission, R and T are the reflected and transmitted intensity coefficients, n is the refractive index of the medium between the plates, t is the gap between the plates and θ is the angle of the incident light. Nr is the reflective finesse and is defined by the equation

$$Nr = \frac{\pi\sqrt{R}}{1-R} \quad (2.3)$$

This function produces a "comb" of transmission maxima when

$$\sin\left(\frac{2\pi n t \cos\theta}{\lambda}\right) = 0$$

or

$$2\pi n t \cos\theta = m\lambda \quad (2.4).$$

where m is the order of interference. The transmission maxima and the spacing between them, the inter-order spacing or the spectral free range, $\Delta\lambda$, is defined by the equation;

$$\begin{aligned}\Delta\lambda &= \frac{\lambda^2}{2nt\cos\theta} \\ &= \frac{\lambda}{m}\end{aligned}\tag{2.5}$$

The effective finesse, N_e , is defined as the ratio of inter-order spacing to the FWHM of one of the transmission maxima by;

$$N_e = \frac{\Delta\lambda}{\delta\lambda}\tag{2.6}$$

$\delta\lambda = \text{FWHM}$

or,

$$N_e = \frac{\lambda}{m\delta\lambda}\tag{2.7}$$

The effective finesse is therefore an indicator of the quality of the transmission function. The higher the finesse, the narrower the profile.

The effective finesse is that finesse which an experimenter most readily measures and it embodies all the mechanisms which go to degrade the performance of the etalon. The quality of the plate coatings, the smoothness of the plates and the range of angles of the light passing through the etalon contribute to a limiting value of the finesse.

The defect finesse, N_d , caused by irregularities of the plate surfaces, such as roughness is governed by the quality of the polishing of

the surface. For plates polished to $\lambda/200$, $N_d = 100$.

This value of the defect finesse can be further degraded by plate bowing or stresses producing slight surface bumps.

The finesse defined by the reflectivity of the coatings, N_r , can be quite accurately controlled when the coatings are deposited and knowing the reflectivity, it can be calculated from equation (2.3).

A reflectivity of 97% gives a reflectivity finesse of about 100.

The light passing through the FP will not generally be quite parallel and will be spread over some small range of angles due to a physical stop in the optical arrangement. A range of angles in the incident light will broaden the maxima, thus reducing the overall finesse. The finesse, N_a , due to a range of angles, is given by

$$\begin{aligned} N_a &= \frac{2\pi}{m\Omega} \\ &= \frac{2}{m\Delta\theta^2}, \end{aligned} \tag{2.8}$$

where Ω is the solid angle of the cone of rays corresponding to a range of angles, $\Delta\theta$, passing through the FP. Since the resolution, R_a ,

$$R_a = N_a.m,$$

we have;

$$\Delta\theta^2 = \frac{2}{R_a} \tag{2.9}$$

R_a is the resolution of a perfect FP. This is an approximate relation known as the Jacquinot criterion and it defines the optimum luminosity and resolving power product. The effect of this constraint is to only include rays from the central spot of the ring pattern.

The effective finesse cannot exceed the lowest of the aperture, reflectivity or defect finesses and if these can be considered gaussian then it is the r.m.s. value of the three.

Having constrained the usable range of angles for a given resolution of FP, then, if its area is A , its throughput, T , can be defined such that;

$$T = A\Omega_{FP} \quad (2.10)$$

Ω_{FP} is the solid angle passing through the FP. The throughput is a conserved quantity. When a FP is used at a telescope, the throughput must be maintained so that;

$$A\Omega_{FP} = AT\Omega_T \quad (2.11)$$

where AT is the telescope area and Ω_T is the solid angle projected on the sky.

2.4. The Design of the Interferometer.

In order that the interferometer performs with the required precision, certain considerations must be taken into account. These are set out below.

2.4.1. General Description of Interferometer.

It was proposed to feed light from the Cassegrain focus of a telescope to the interferometer by means of a fibre optic light guide. The optical system, including the etalon, was to be as simple as possible with as few elements as possible. The whole interferometer was to be enclosed in a controlled environment to improve stability and remove temperature, pressure and humidity effects. The usual way of minimising these has been to temperature control the etalon and to flush it with a dry gas to maintain a constant humidity. These methods have drawbacks. Temperature control is usually difficult due to the effect of the dry gas (which may not always be as dry as it should be), passing through the etalon (see also section 2.4.7). Pressure has always been neglected. A further constraint on the instrument was that it should be cheap to build and simple to operate.

2.4.2. The F.P. Etalon.

A Queensgate Instruments ET28 etalon was chosen. It has a 28mm. clear aperture and is the smallest available etalon for use with the servo control electronics, CS100. The gap for the etalon was chosen earlier to be 100 μm , which gives a nominal resolution of 10,000 in the visible.

2.4.3. Use of Fibre Optics.

Fibre optics have several very useful properties. They allow an instrument to be placed away from the hostile environment in a dome and be free from stresses which are encountered on a Cassegrain mounted system. Also, they scramble all the image information by multiple reflections and only preserve angles of incident rays. This allows for a constant and evenly illuminated input aperture, removing all spurious radial velocities due to the image wandering about the "slit" by one or two seconds of arc caused by seeing etc.

The most efficient fibre types are the silica core with silica cladding step index fibres which are well suited to astronomical use. In order to maximise the fibre's transmission, light must be inputted and collected at relatively low f /numbers. From a typical curve for such fibres, figure 2.3, it can be seen that the majority of light entering at $f/4$ emerges at $f/2$. Such an arrangement would allow most of the light exiting the fibre to be collected. Transmission of these fibres in the visible is also fairly good at about 70%.

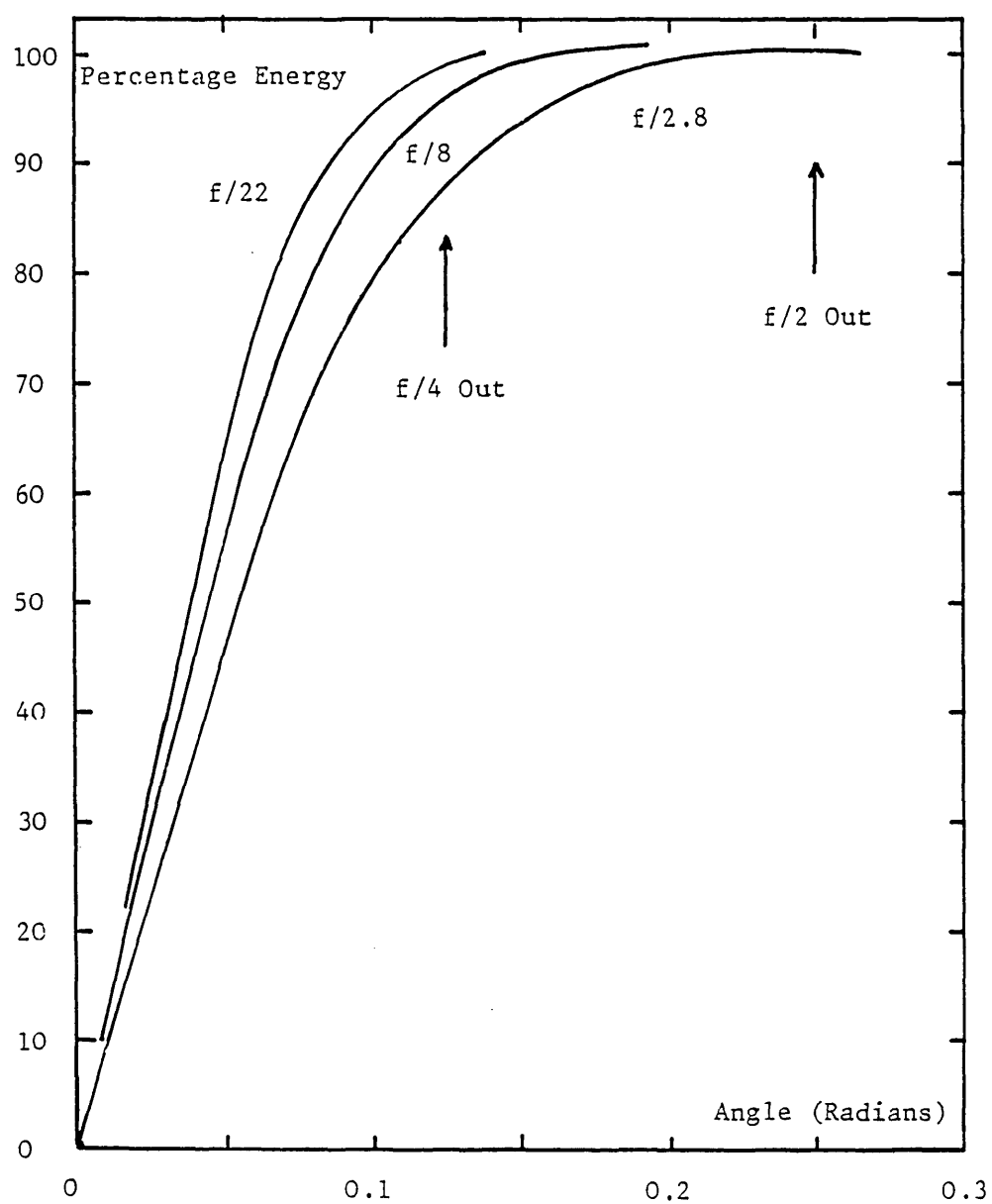


Figure 2.3 Distribution of Light with Angle Emerging From a Fibre Optic Cable For Different Input Angles.

2.4.4. Choice of Fibre Optic and Collimating Lens.

The fibre chosen was a QSF 400/600 ASW fibre of about 20m. length. It has a core diameter of 400 μm . The etalon defines the beam diameter to about 25mm. and the fibre dictates an $f/2$ collecting lens. This suggests a lens of focal length of 50mm. The best available lenses which fit this specification are photographic camera standard lenses. They are relatively cheap and of excellent quality. However, can such a fibre and lens combination be used without degrading the resolution of the etalon? The Jacquinot criterion (2.9) limits the range of allowed angles for a given resolution. The chosen resolution suggests a range of angles no greater than $\sqrt{2} \cdot 10^{-2}$ radians. The fibre core (input aperture) subtends an angle of 8 milliradians. Such a combination is suitably close to the most efficient case.

By converting a telescope beam to $f/4$ using a focal reducer lens, the fibre can be fed light at the required input angle and at this angle it presents an aperture of 14 seconds of arc, which makes guiding very easy with images up to about 3 or 4 seconds of arc from a 1.5m telescope.

2.4.5. Other Orders of the F.P.

In order to prevent confusion from other F.P. orders, a narrow band interference filter was used to isolate the line. With an effective finesse of 30 and a FWHM of 0.5 $\text{\AA}$, the inter-order distance is approximately 15 $\text{\AA}$. Also, a flat top to the filter profile is desirable. A three cavity interference filter with a band width of 10 $\text{\AA}$, of centre wavelength similar to the line of interest but slightly to the red, would be a suitable choice.

Such a filter was placed in the collimated beam of the system in a

mount which allowed the filter to be tilted thus allowing for any shifts of the line position due to recessional velocity. Placing the filter before the etalon in the collimated beam removes unwanted light before it reaches the etalon. The necessary baffling was provided by a bellows between the filter and collimating lens. A backlash free transducer (LVDT differential transformer) was used to measure the angle of tilt of the filter.

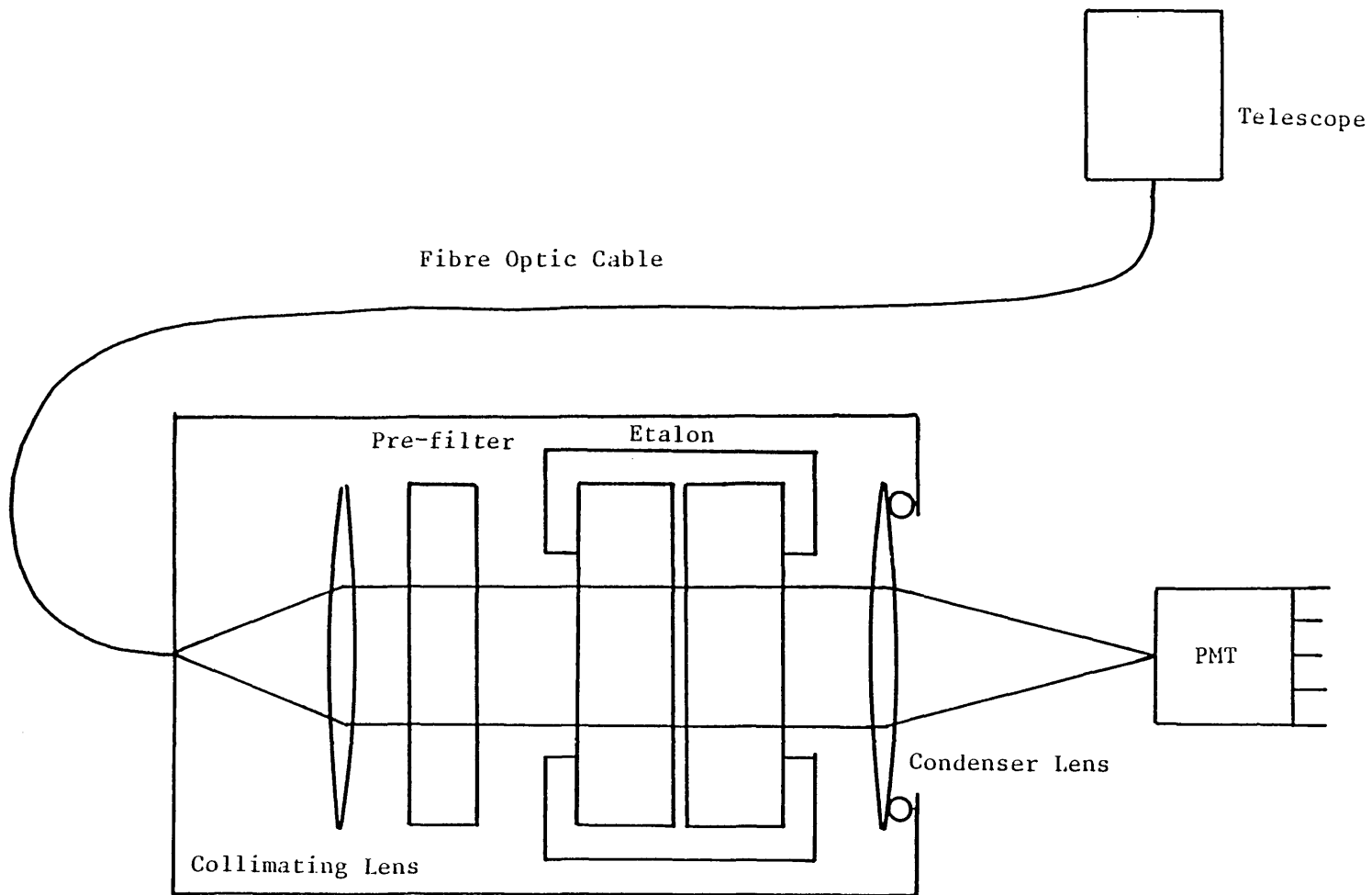
2.4.6. Output Optics and Detector.

A RCA 31403A/02 type photomultiplier operating at -70°C was used. These photomultipliers have high quantum efficiency, about 20%, and very low dark counts of only a few per second. Light passing through the etalon was focused onto the photocathode using a simple lens which had been anti-reflection coated to improve its transmission. The optical system is shown schematically in figure 2.4.

2.4.7. Environmental Effects.

Changes in pressure, temperature and humidity introduce drifts and noise to the signal and may give rise to spurious periodicities in the velocity curves of stars. The most vulnerable parts of the instrument are, of course, the etalon and the filter. The filter is usually immune to the pressure and humidity changes, but suffers drifts to the of about 0.2 Å per degree rise in temperature. The etalon, having an air spaced gap, is immune to none of these. Pressure and temperature drifts both change the refractive index of the air in the gap, and humidity changes cause changes in the optical coatings on the plates by absorption of water.

Figure 2.4 Schematic Of Optical Layout



The change in refractive index n , dn , due to a change in pressure of dp mbar is,

$$dn = 3.10^{-7}.dp,$$

and

$$\frac{dn}{n} = \frac{d\lambda}{\lambda}$$

therefore,

$$d\lambda = \lambda dn,$$

since n is almost 1 for air,

$$d\lambda = 3.10^{-7}\lambda dp$$

This implies a velocity drift of v , such that

$$V = 3.10^{-7}cdp$$

c is the speed of light, so that,

$$v = 90 \text{ ms}^{-1} \text{ per mbar.}$$

Similarly, for changes in temperature

$$dn = \frac{(n-1)dT}{273}$$

or,

$$d\lambda = 1.1.10^{-6}\lambda dT$$

or,

$$v = 1.1 \cdot 10^{-6} \text{cdT}$$

so, for a change of 1 °C at 0°C a velocity drift of $v = 330 \text{ ms}^{-1}$ would result. The magnitudes of these drifts are enough to lose the required accuracy for small changes in temperature and typical changes in pressure, as, for example, when a weather front is passing.

The etalon would also suffer plate deformation if subjected to fairly rapid changes in temperature, i.e. bowing, which would further reduce accuracy. This effect is difficult to monitor without breaking up the etalon and observing the effects on the plates directly.

2.4.8. Eliminating Environmental Effects.

Sealing the whole optical system in a pressure tight, temperature controlled chamber has a more beneficial effect on stability than just removing environmental effects. As the number of air molecules within the chamber will be constant, so will the refractive index, according to the following relation,

$$\frac{n-1}{\rho} = \text{constant},$$

(Longhurst p. 453, 1967)

This removes the necessity for accurate temperature control, since the density is constrained, by the sealed chamber, to be constant. However, temperature control to $\pm 0.5^\circ\text{C}$ is still necessary to prevent thermal gradients distorting the figure of the plates.

An amount of dessicant is also kept in the pressure sealed chamber to attract as much water vapour as possible away from the etalon coatings.

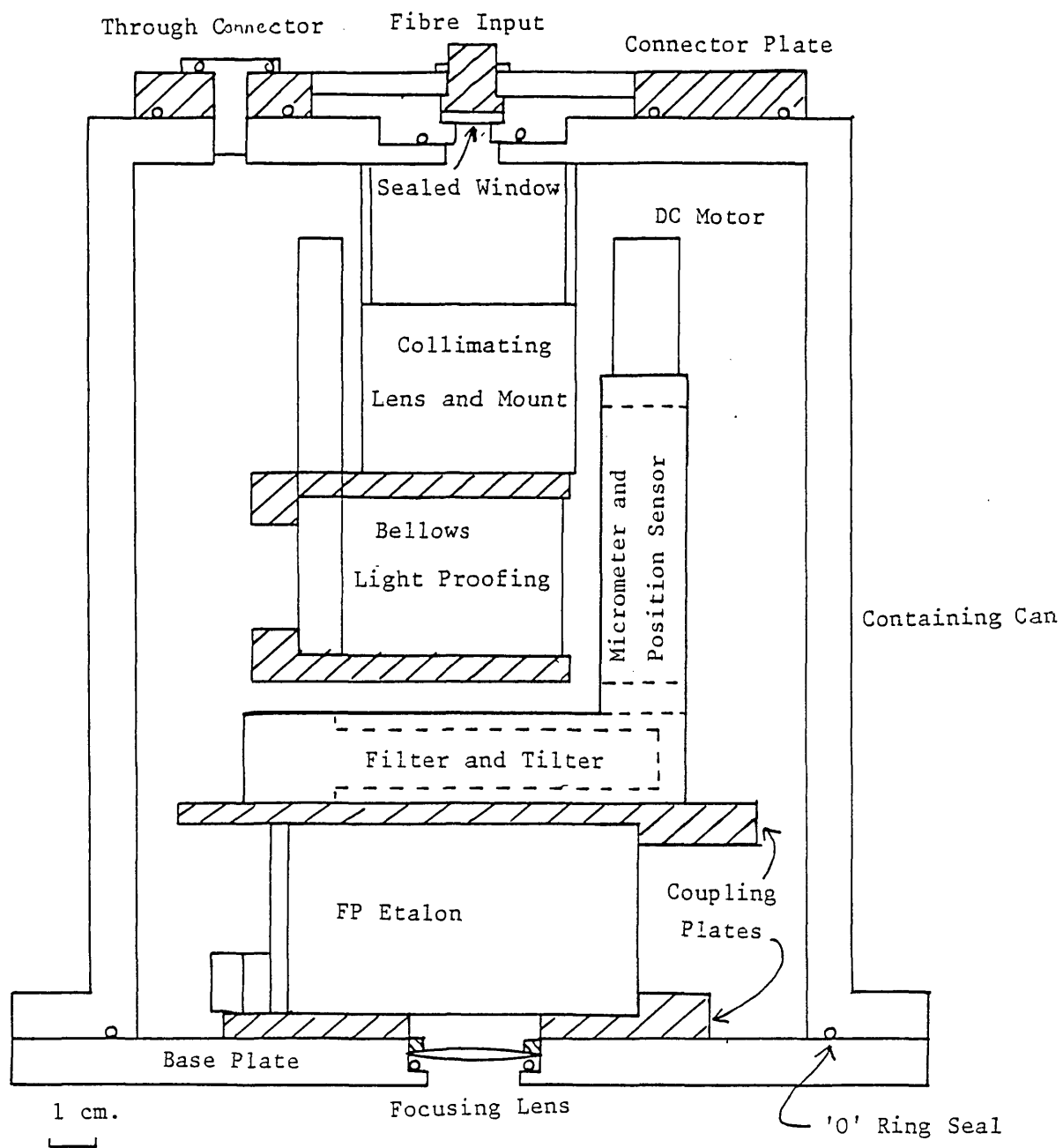


Figure 2.5 Complete Optical and Mechanical Arrangement

By far the most dramatic effect is produced by the fibre light feed which removes the whole instrument from the harsh conditions in the dome to a mild laboratory or warm room nearby. Such a room can be maintained at a reasonably constant temperature and minimise the temperature effect on the servo system electronics.

The complete optical layout is shown in figure 2.5.

2.4.9. Pulse Counting.

This task is done by a purpose built board of electronics, the MLV100TB by LeCroy, which is used primarily to test the MLV100 integrated circuits. Photoelectron pulses from the photomultiplier are seen by the MLV100 chip and a pulse of constant height and duration is produced. This pulse is then made suitable for TTL circuitry and this can be counted by a scaler interfaced to the microcomputer.

2.4.10. Control of the Instrument.

An AIM65 microcomputer is used to control the CS100 servo electronics and hence the etalon, to count pulses and to partially reduce incoming data, send it to the storage medium (digital cassettes) and to display it on a chart recorder and VDU. The Basic programme is shown in appendix 2.1. Figure 2.6 shows the flowchart of the breakdown of tasks involved in the control of the instrument (to be discussed fully later). Figure 2.7 shows a block diagram of the interconnections between the individual "modules" of the instrument.

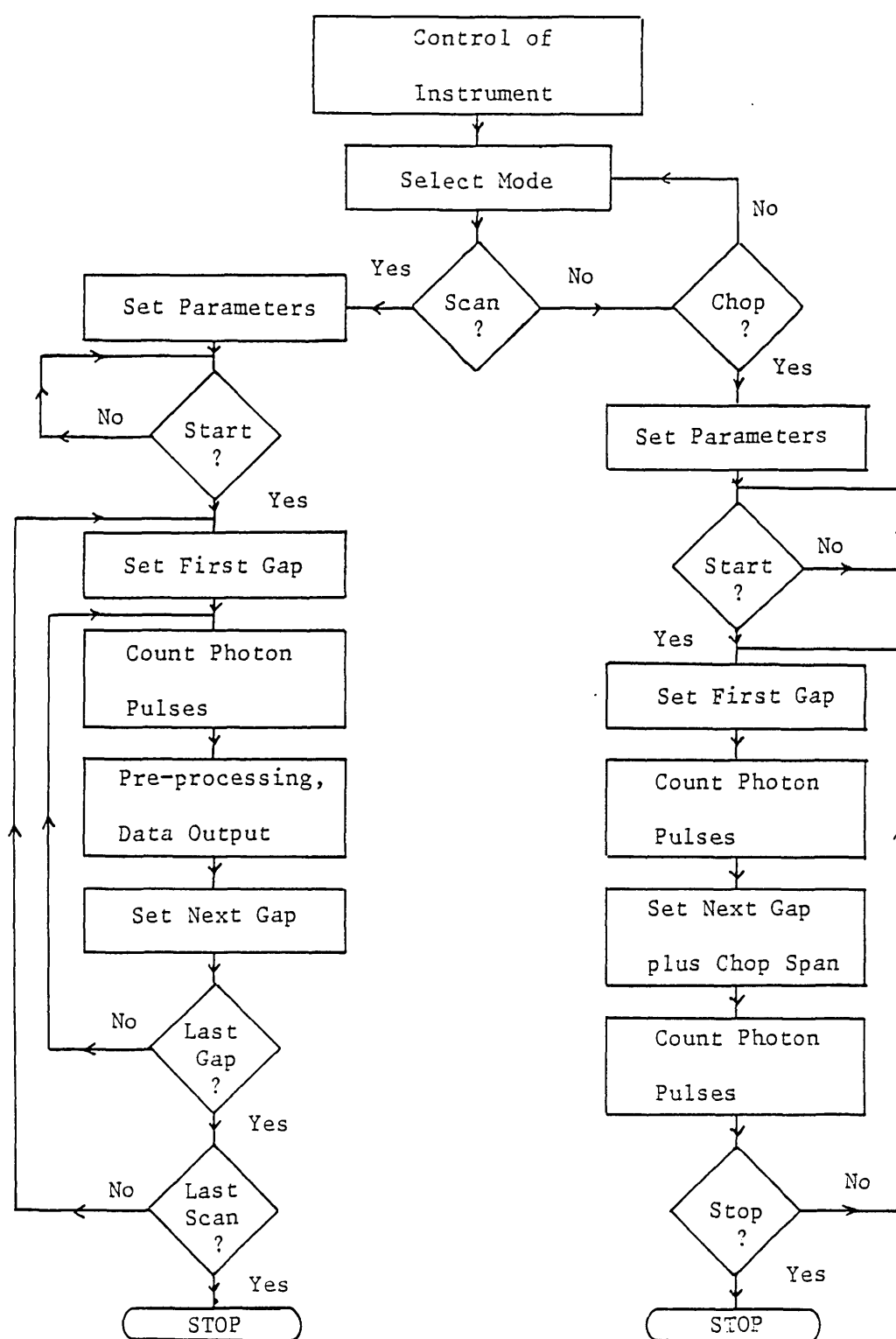
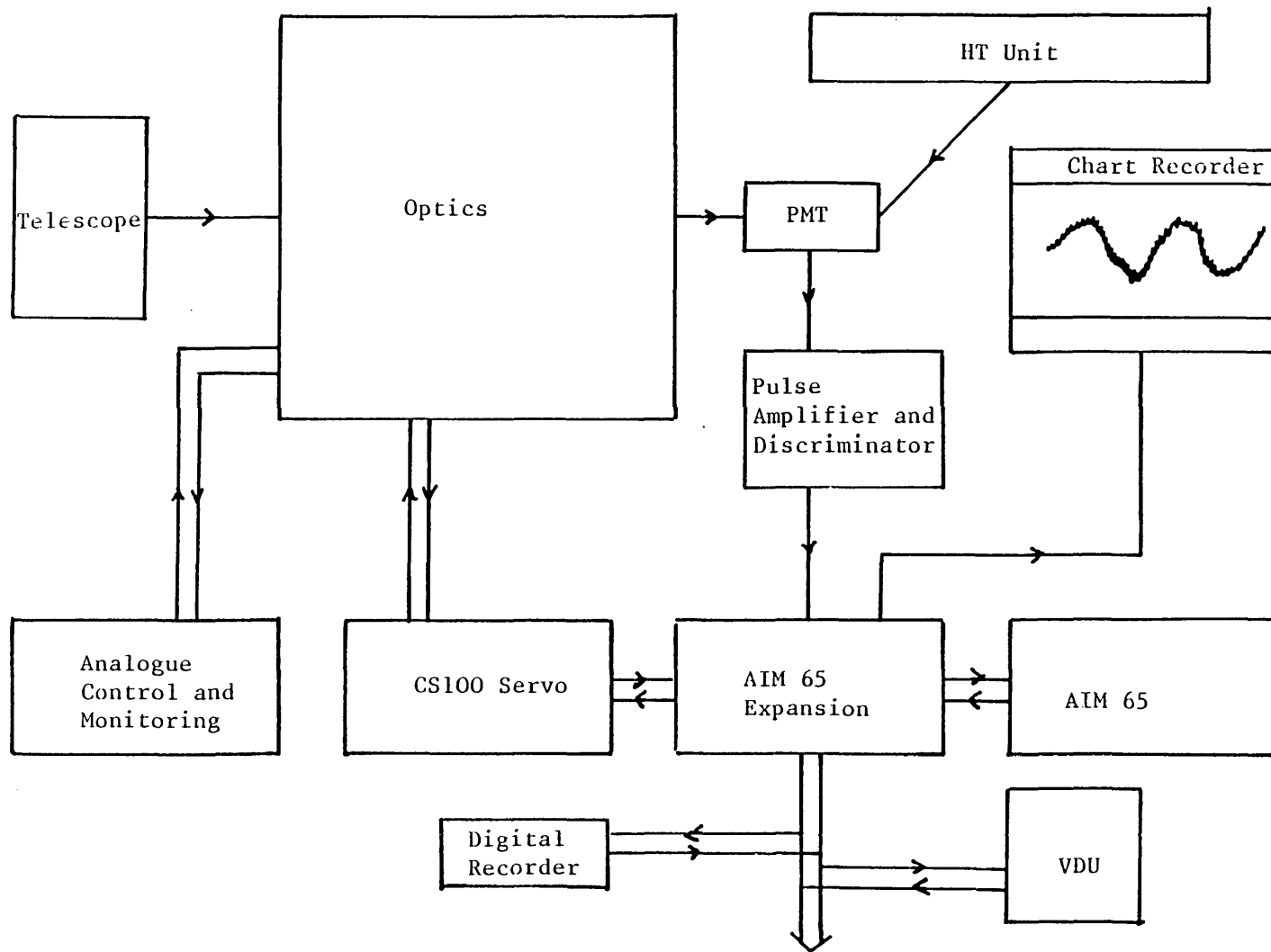


Figure 2.6. Task diagram of the control of the instrument.

Figure 2.7 Block Diagram Of The Instrument.



2.5. Use of the Instrument.

2.5.1. Modes of Operation.

A Fabry-Perot interferometer can either be made to scan or to chop. Scanning involves changing the wavelength of transmitted light in a series of steps to map out a short region of the spectrum being observed. Chopping involves changing the passband of the interferometer regularly between two points in the spectrum to monitor the ratio of intensities at those points.

2.5.2. Scanning.

By examining equation 2.4, i.e.

$$2nt\cos\theta = m\lambda,$$

scanning can be achieved by changing the refractive index of the medium in the gap, changing the gap itself, or by changing the angle of the light passing through the interferometer. Since the FP in the instrument being described here is on axis, with a constant angle of 0 degrees of the light passing through it, a constant temperature and pressure, the gap must be varied differently. The servo control system allows digital offsets, representing the gap, to be used. These are generated by the microprocessor and translated to plate movements by the servo system. Using the capacitance micrometry system this can be done extremely accurately and reliably.

2.5.3. Chopping.

This mode requires the FP passband to be switched rapidly between two different wavelengths on a line profile in the spectrum of a star. Changes in the line position would, if the chop points are chosen to be at the points of inflection, produce changes in the ratio of the intensities at the two points. Any method of chopping involving changing the pressure or temperature is likely to be slow and mechanical tilting would be positionally not accurate enough. The capacitance method is both fast and accurate. The positional accuracy is far better than the limits set by 100 ms^{-1} and etalon plates take a few tens of milliseconds to settle. Above all, it is extremely simple to use.

2.5.4. Operating Procedure (Experimental Method).

After the equipment has been assembled, a bright source such as a laser line, is used to check the condition of the etalon. The finesse and parallelism, previously set by eye or in pre-observing laboratory tests, are recorded by scanning the FP through the laser emission line. This can be done for two adjacent orders. The resulting profiles can then be used to calculate the finesse by using equation (2.6) and the experimentally determined FWHM and inter-order spacing. The parallelism is judged by the symmetry of the profile and if any asymmetry is present the servo must be adjusted. There are certain difficulties associated with this method. The primary one is that the laser line, usually red, is well away from the filter passband and the peak of the etalon coatings. This either necessitates the removal of the filter or using a greatly reduced flux which can be "forced" through the effectively opaque wings of the filter. Removal of the filter would disturb the system by changing the composition

of the air in the chamber and by introducing temperature gradients. This solution is not acceptable. The small amount of "forced" light must be used and has proven satisfactory. A further difficulty may be encountered by the difference of coating characteristics at the laser wavelength and the wavelength of interest.

2.5.5. Observations of Stellar Lines.

Before radial velocity observations can be made the exact position of the stellar line must be found. This is easily done by rapidly scanning the FP through the filter passband many times. The technique involves stepping the FP across the 10 Å passband with steps of 0.5 Å. This gives 21 points per scan. Rapidly repeating this, with typical dwells of 0.2 seconds per point, increases the integration time to attain the required accuracy while minimising the effects of changes in transparency of the atmosphere. It is, in fact, possible to observe line profiles through very bad weather conditions with increased integration times and no noticeable deterioration of line profiles.

If the stellar line is present, it will show as a dip of approximately two points in width, i.e. $\sim 1\text{\AA}$, and should fall easily within the filter passband. A recessional velocity exceeding 500 kms^{-1} would shift the line well out of the filter passband, but such high velocities do not occur for the objects of interest, described in Chapter 1.

A slight adjustment of the filter tilt may be needed to centre the line in the filter passband. A scan of the line with much greater detail can then be done in order to find the best "chop points".

2.5.6. Chopping and Calibration.

The two points of inflection on the line give the most sensitive positions to changes in radial velocity, by virtue of having the steepest slopes. The width of the line and hence the chop span are found by inspecting the line profile. A first choice for the inflection points can be made and tested by chopping between those points. The "best" position is one where the two intensities are equal. A second choice can then be made and tested. This procedure may be repeated until the two intensities are deemed as equal as possible. Such a procedure takes very little time and provides a calibration of the sensitivity of the FP and absorption line combination to radial velocities, since a change in the servo position of the etalon defines very accurately a change in transmitted wavelength and hence velocity. Thus the rate of change of the ratio of the intensities near the points of inflection can be found. Once the best position has been found, no more changes need to be made and the star may be observed for as long as needed.

2.5.7. The Benefits of Rapid Chopping.

This technique removes the effect of small fluctuations in transparency that would otherwise either ruin the data or introduce periodicities into it. The usual method of doing this is a compensation channel, be it a second detector measuring intensities only or another "standard" star. The changes produced when a thin band of high cloud passes through the telescope-star line of sight would be, in general, a reduction in flux if not total obscuration of the star. These fluctuations in transparency would show a periodicity indicative of the structure in the cloud, i.e. sharp boundaries etc. By chopping rapidly, at 5 Hz or

faster, many cycles can be completed in the relatively slow time of the transparency changes. By taking the ratio of the intensities, a and b , at the points of inflection these slow changes can be effectively eliminated. If a and b are about equal, as they should be, and the intensity change due to cloud, for example, is da then the ratio, R ,

becomes;

$$\begin{aligned} R &= \frac{a+da-(b+da)}{a+b+2da} \\ &= \frac{a-b}{a+b+2da} \end{aligned} \quad (2.12)$$

and if $a+b \gg 2da$,

$$R = \frac{a-b}{a+b}$$

so, small transparency changes can be eliminated by rapidly chopping thus making any compensation channels unnecessary.

2.5.8. Photomultiplier Dark Count.

The effect of dark count can easily be corrected for with a measurement of its value. Then the correction to the value of the ratio, R , is that da is equal to the dark count in equation 2.12. When bright stars are being observed the effect of dark count with the RCA31403A type detector is negligible. It can become a serious problem if the star is dim and the integration time is long and the signal is not really different to the dark count. Figure 2.8 shows the percentage error when dark count is not considered.

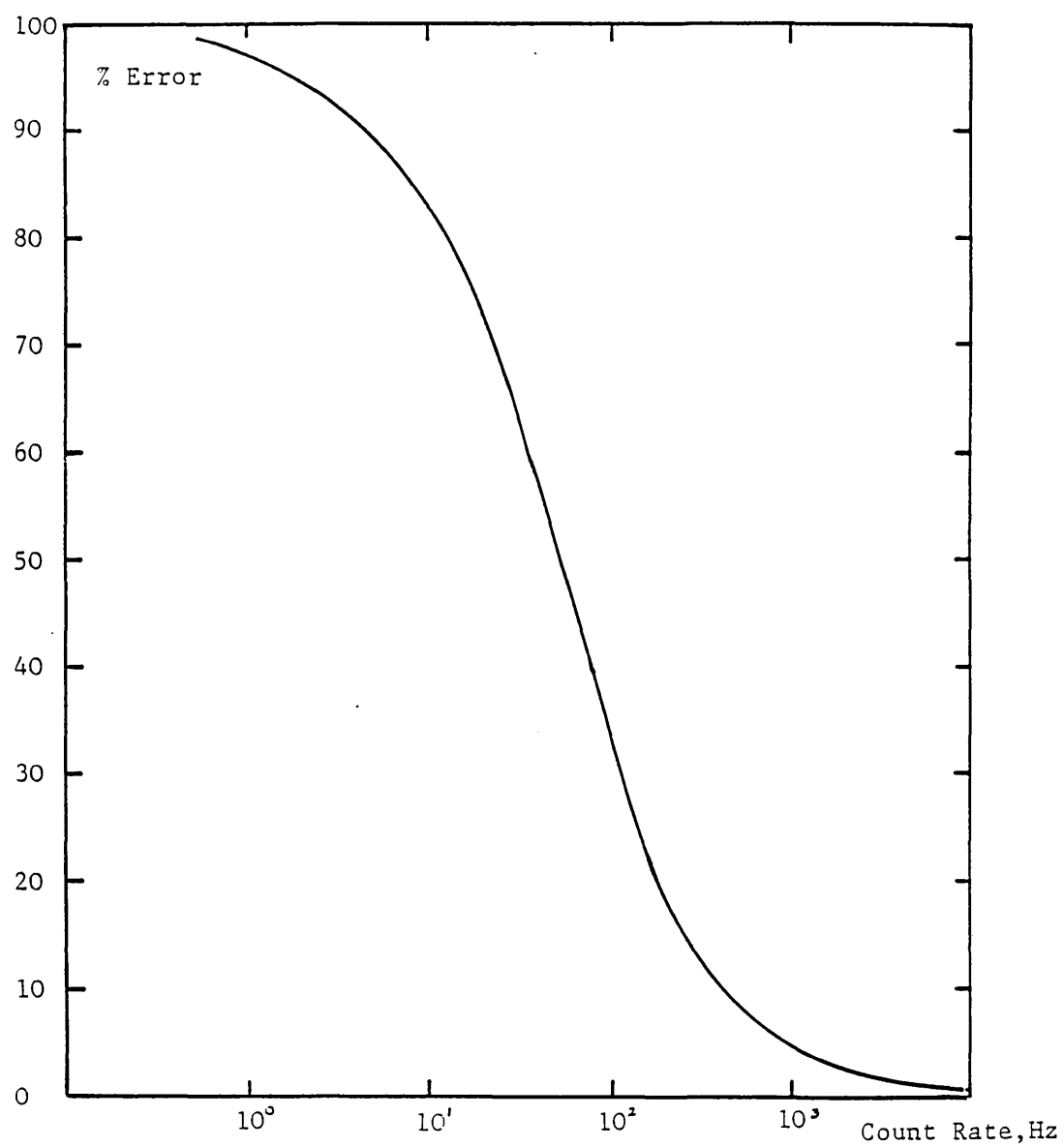


Figure 2.8 Percentage Error Incurred When Neglecting
Dark Count At Various Count Rates.
(Dark, $2da=50$)

2.5.9. Integration Times.

The question that now arises is, for how long must a star be observed before a certain accuracy is attained? If the number of photons collected each second by the detector is x and the line has a hypothetical triangular profile and 50% depth with a width of $0.7 \text{ \AA}$ then a shift of 100 ms^{-1} would be equivalent to $1/400$ th. of the linewidth since the line is 40 kms^{-1} wide. Chopping at the FWHM points implies $a = b = 0.75x$. Now 100 ms^{-1} change would change the signal by

$$\frac{x}{400}$$

i.e.

$$\delta A = 0.0025x$$

The signal, when chopping is

$$2\delta A = 0.005x,$$

and the fractional change in signal;

$$\frac{2\delta A}{x} = 0.005.$$

The signal to noise ratio;

$$\begin{aligned}\frac{S}{N} &= \frac{\sqrt{x} \cdot 2\delta A}{x} \\ &= \frac{2\delta A}{\sqrt{x}}\end{aligned}$$

Now in a time, t , n photons will be collected;

$$n = xt,$$

so that,

$$\frac{s}{N} = \sqrt{n} \cdot k$$

where k is the dimension-less quantity

$$k = \frac{\Delta N}{N} = \frac{2\delta A}{x}$$

then,

$$\frac{S}{N} \propto \sqrt{t}.$$

So, increasing the length of observation only increases the signal to noise ratio as the square root of the time. For a positive '3 σ ' detection,

$$\frac{S}{N} = 3.$$

Figure 2.9(a) shows this relation for various magnitudes of stars being observed on a 2m telescope. Figure 2.9(b) shows the hypothetical line profile.

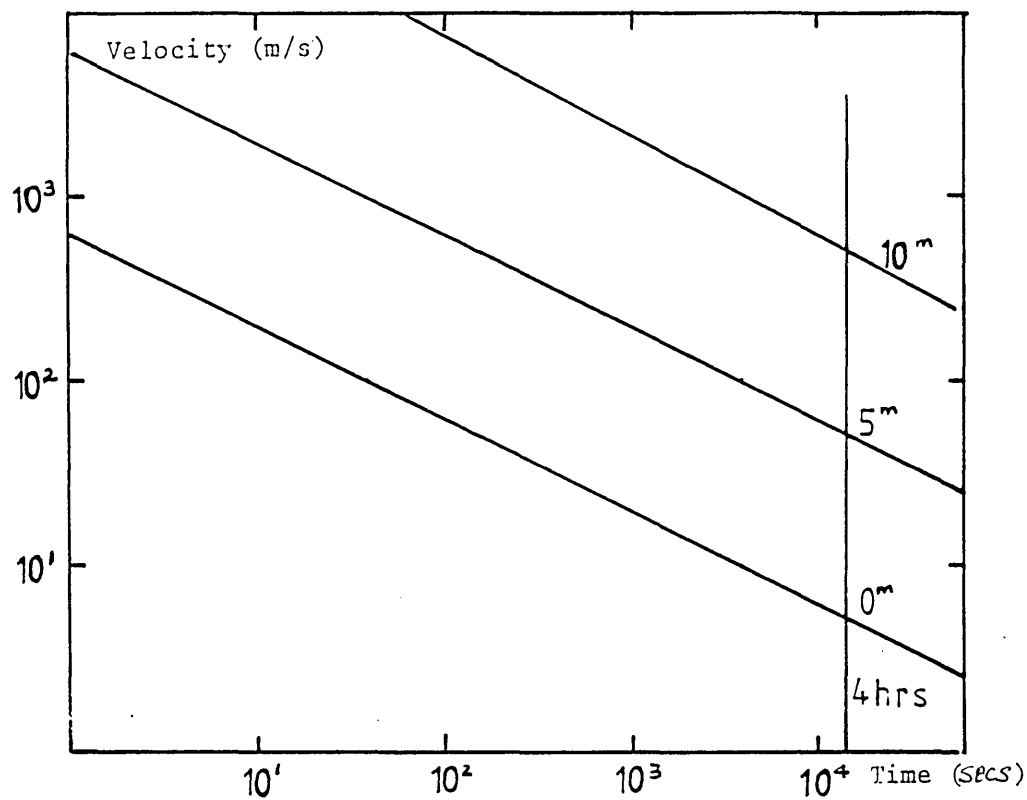


Figure 2.9a Observing Time Required For Various Accuracies.

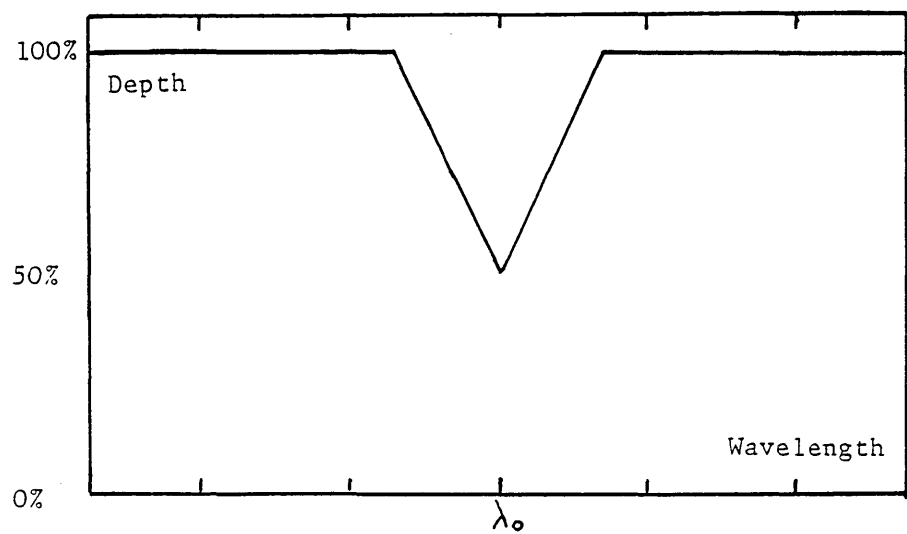


Figure 2.9b Line Profile Used For Above Simulation

2.6. Performance.

Tests to determine the stability of the instrument were conducted both at Imperial College in London and at Izaña in Tenerife. The form of the tests was the same in both cases. A standard emission line from a lamp or a laser was used. The FP was then set to chop on the line continuously for periods up to about 50 hours. The procedure was the same as described above in section 2.5.5. Only one difference from observing stellar lines must be noted. That is, the cooled RCA C31034 photomultipliers were not used but replaced with a side entry EMI tube that can be left unattended for many hours (unlike the RCA tube which will be irreparably damaged if allowed to warm up while counting even a moderately high count rate). The data so collected was binned into lots of 500 second integration times. Any detail lost with such low time resolution are not relevant to the long term stability of the instrument.

The laboratory space in Imperial College provides a less stable environment for the instrument than the Coudé room at Izaña. This is due to the high electrical and thermal activity produced by lifts and other heavy equipment.

The stability tests were, therefore, conducted during the weekend when the building is virtually empty. Figure 2.10(a) and (b) show the signal and its Fourier Transform of a run using a cadmium lamp. The noise on each point in the signal was approximately 343 ms^{-1} giving an overall noise of 16.6 ms^{-1} for the whole data. The main features in the FT are low frequency drifts due to temperature drifts over the weekend. The temperature has some effect on the CS100 electronics and on the light source and over a weekend period the temperature drifts slowly downwards. The long term drifts with periods of about one day (2nd. point in the

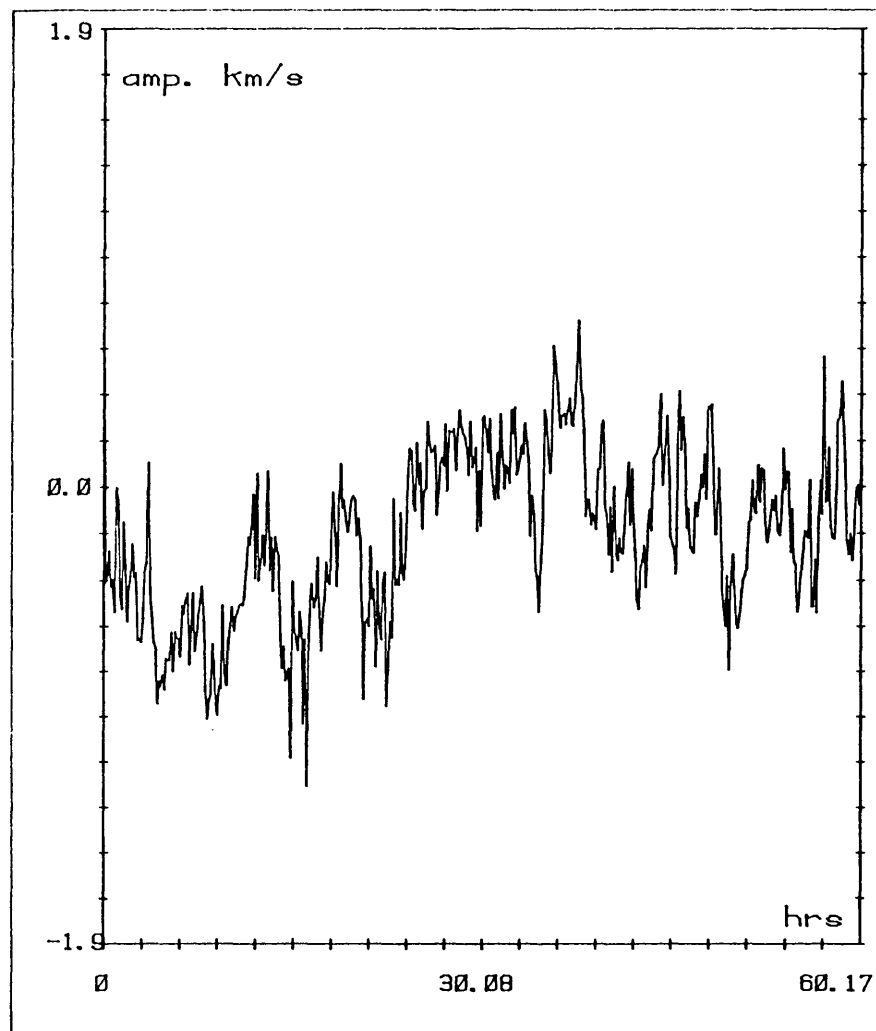


Figure 2.10(a).
Stability run on Cd red line.
Weekend 5.8.83 to 8.8.83.

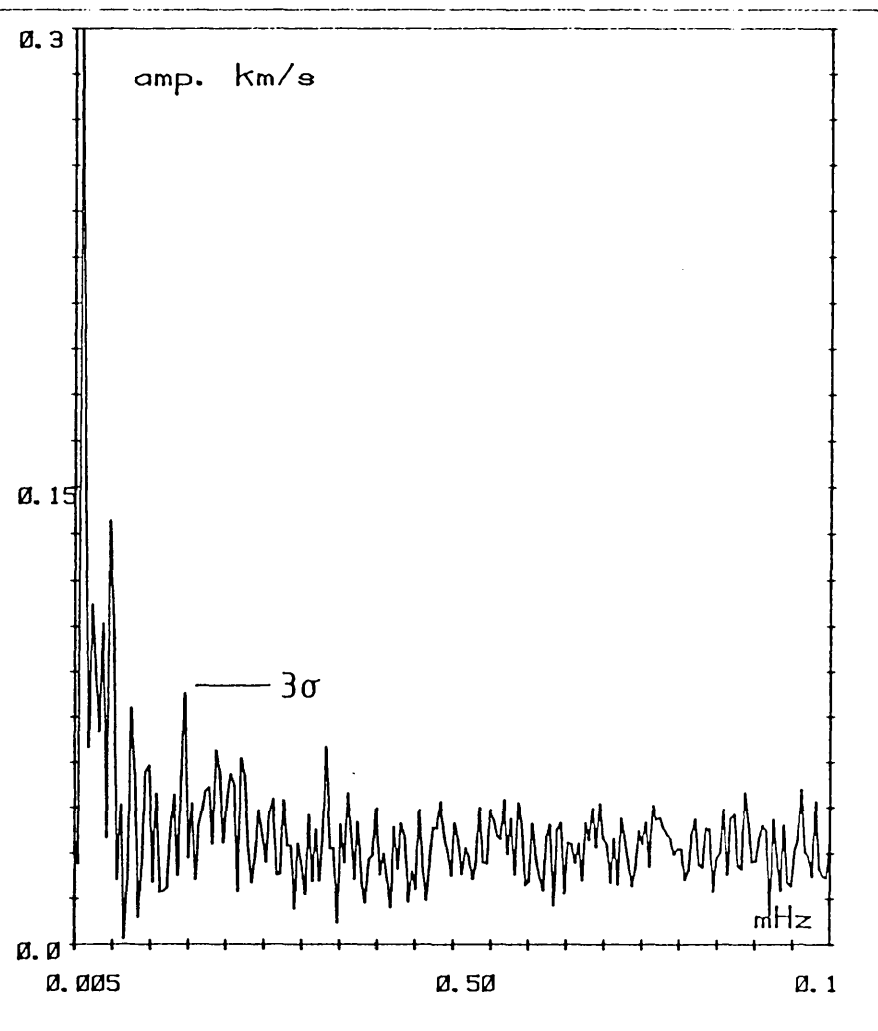


Figure 2.10(b).
Fourier Transform of data opposite.

transform) are most probably due to slight fluctuations in the mains voltage.

Figure 2.11(a) and (b) show the stability run on a laser line done at Izaña, Tenerife. The instrument was set up and powered from a stabilised mains supply and left unattended for the duration of the run. During the run, there was a steady linear drop in temperature which correlated well with the 196 ms^{-1} signal giving a change of better than $\lambda \cdot 10^{-6}$ per $^{\circ}\text{C}$. This has been corrected for in figure 2.11(a) by simply removing the slope. The FT shows no features other than a residual drift of low frequency at the 100 ms^{-1} level. The overall noise on the data is less than 15 ms^{-1} .

2.7. Sources of Error - A Summary.

The major sources of drifts and errors due to weather type conditions can be eliminated. Temperature, pressure and humidity of the material in the gap is constant, and this eliminates pre-filter drifts as well as gap drifts. The temperature of the servo electronics can be kept constant to within 1°C (an observer guiding in the same room as the instrument provides enough heat to make up the heat losses of the room) and is recorded and can subsequently be corrected for if it cannot be kept constant in severe conditions. Errors due to dark count are easily eliminated and sky background, etc., is negligible in the tiny $0.5\text{\AA}$ bandwidth of the FP. Apart from shot noise, calibration errors may be the most significant errors present. If, for example, the stellar line profile varies during the time it takes to do several calibrations or to take several line profiles, an error will result and only an estimate of the sensitivity will be available.

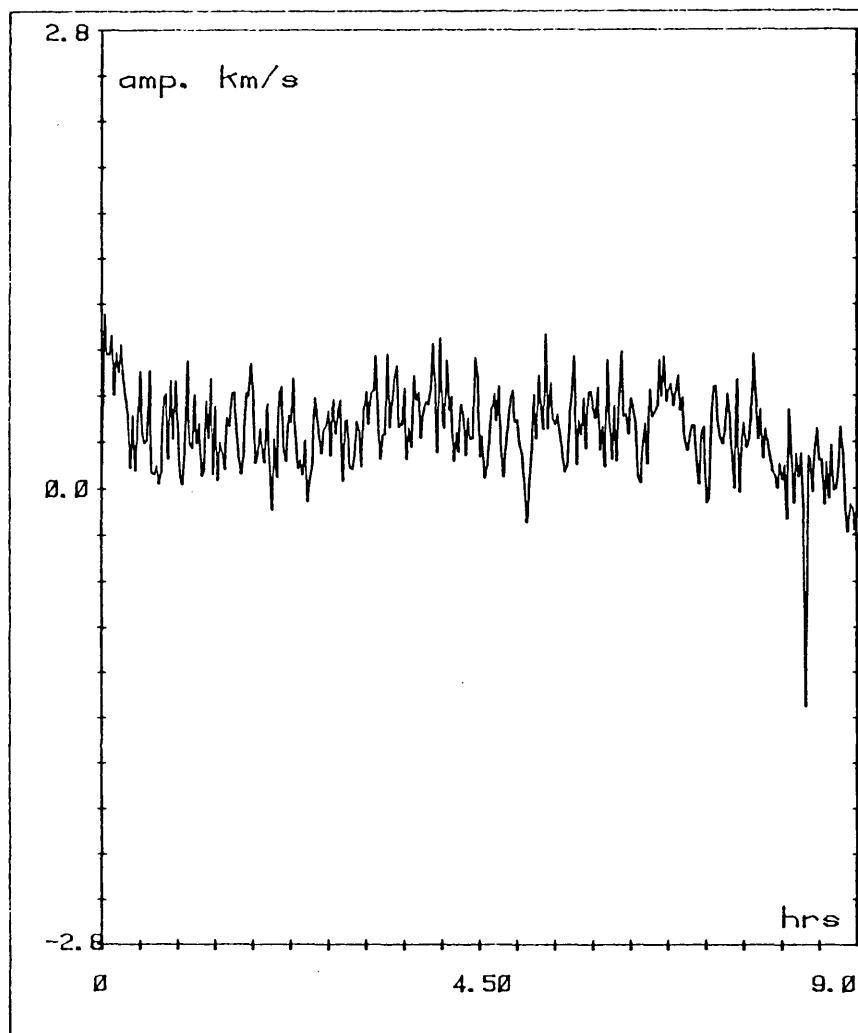


Figure 2.11(a).
Stability run on red laser line.
Tenerife 12.10.83.

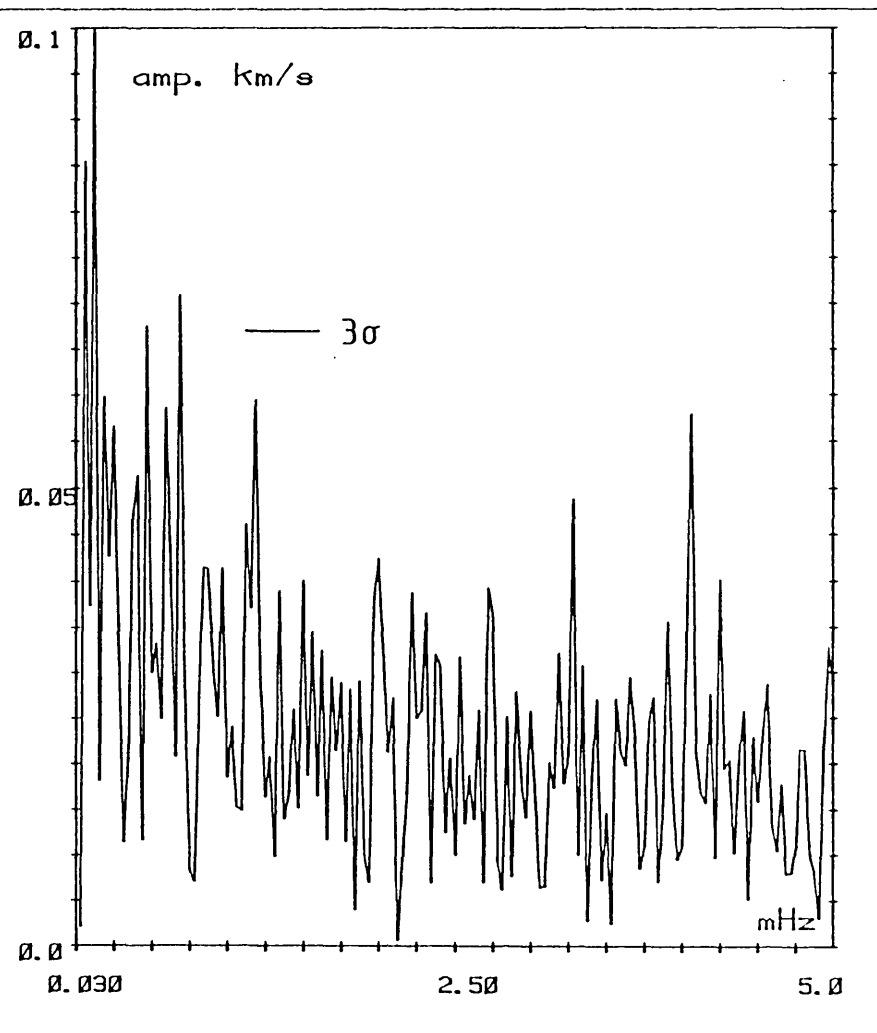


Figure 2.11(b).
Fourier Transform of data opposite.

2.8. Summary of Observing Trips.

The instrument described above has been used on the 1.9m. telescope at S.A.A.O. in February 1983 and on the 1.5m. I.R.F.C. at the Observatorio del Teide, Tenerife in May 1983 and again in October 1983.

A development version of the instrument, discussed in appendix 2.1, was used also in Tenerife in July 1982 and December 1982.

CHAPTER 3

DATA REDUCTION.

3.1 Introduction.

This chapter attempts to describe the general form of the data and methods used to extract information from it.

3.2 The Data.

The information contained in the data acquired with the instrument described in the previous chapter is essentially the line profiles and velocity curves of a star, the results of scanning and chopping (sections 2.5.2 and 2.5.3). The format of the data obtained during a scan is shown in figure 3.1. The header contains the following information;

- (i) tape identification (if a fresh tape is used);
- (ii) a brief description of the object;
- (iii) the scan number;
- (iv) the beginning servo position, end servo position, number of rapid scans;
- (v) the value of memory location \$1A02, defining the integration time;
- (vi) the date;
- (vii) the filter tilt.

The information recorded in the header is then used to initiate the scan. These values are entered manually and the scan started. The value of the integration time is not entered in this manner but must be entered using a more lengthy procedure designed to avoid altering it accidentally.

After completion of the scan, two columns of numbers are recorded. The first is the photon count and the second is the servo position at which the count was taken. The numbers in the second column are the decimal equivalents of the negative binary logic assignments of the servo positions, and so do not match the straightforward decimals found in the

TAPE 2DCT83B SCAN OF LINE IN
BETA AQUILLA 17/10.83
SCAN 1 BETA AQUILA 0,40,100
TILT -3.00V

13611	4095
12804	4093
12773	4091
12703	4089
12450	4087
12216	4085
11573	4083
11168	4081
10770	4079
10563	4077
10465	4075
10825	4073
11160	4071
11698	4069
12521	4067
12775	4065
12997	4063
12927	4061
13252	4059
13377	4057
13253	4055

[illegible]

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Figure 3.1. The format of the data obtained during a scan.

header. These are simply related such that:

4095-decimal assignment = decimal equivalent of binary assignment.

However, to avoid making this calculation repeatedly, the output to the printer on the computer has the decimal assignments.

A simple representation of the line is given by a bar chart which follows the numerical data.

Figure 3.2. shows the format of the recorded data during a chop run to find the velocity curve. The header for a chop run contains the following information;

- (i) a brief description of the object and occasional comments;
- (ii) the servo position;
- (iii) the linewidth, LW, (chop span);
- (iv) the number of rapid chops per datum, T;
- (v) the exact time at which the run is started.

Five columns of numbers are then recorded, the first two being the intensities in photon counts, at the FWHM points of the line. The servo position, chop span and the scan increment (redundant in chops), are then recorded.

For both scans and chops there are 32 characters per line, enabling convenient recording of blocks of 256 characters on digital cassettes.

```
CHOP1 BETA AQUILA SERVO TO 12,  
LW=14,T=50 START TIME 20:13:30  
12673 11285 4107 14 2  
6257 5547 4107 14 2  
6343 5856 4107 14 2  
6452 5692 4107 14 2  
6604 5936 4107 14 2  
6633 5880 4107 14 2  
6784 5899 4107 14 2  
6627 5946 4107 14 2  
6553 5861 4107 14 2  
6731 6072 4107 14 2  
6625 6150 4107 14 2  
6683 6029 4107 14 2  
6477 5917 4107 14 2  
6792 6278 4107 14 2
```

Figure 3.2. The format of the data obtained during a chop run.

3.3 Preliminary Reduction of Data.

3.3.1 On-line Processing of Data.

A limited amount of processing is done on line. A simple Basic routine calculates the heights of the bars in the bar chart display of the line profile. This routine simply subtracts the minimum value in the data from every data point and normalises each point to the maximum value. Finally it scales these numbers to a maximum of 30 characters (asterisks) and two control characters (CR,LF) in order to fill each line with 32 characters only. The Basic programme is shown in appendix 3.1.

In the case of chop data, a machine code subroutine calculates $a-b/a+b$ and sends the result to the digital to analogue (DAC) converter. The voltage so produced is displayed on a chart recorder for immediate examination. A typical example of this is shown in figure 3.3 where an oscillation is quite identifiable.

3.3.2 The Ratio $a-b/a+b$.

If the counts, a and b , are limited in accuracy by photon shot noise then the standard deviation from the mean value of a or b will be σ_a or σ_b , according to Poisson statistics.

Then,

$$\sigma_a = \sqrt{a}$$

and

$$\sigma_b = \sqrt{b}$$

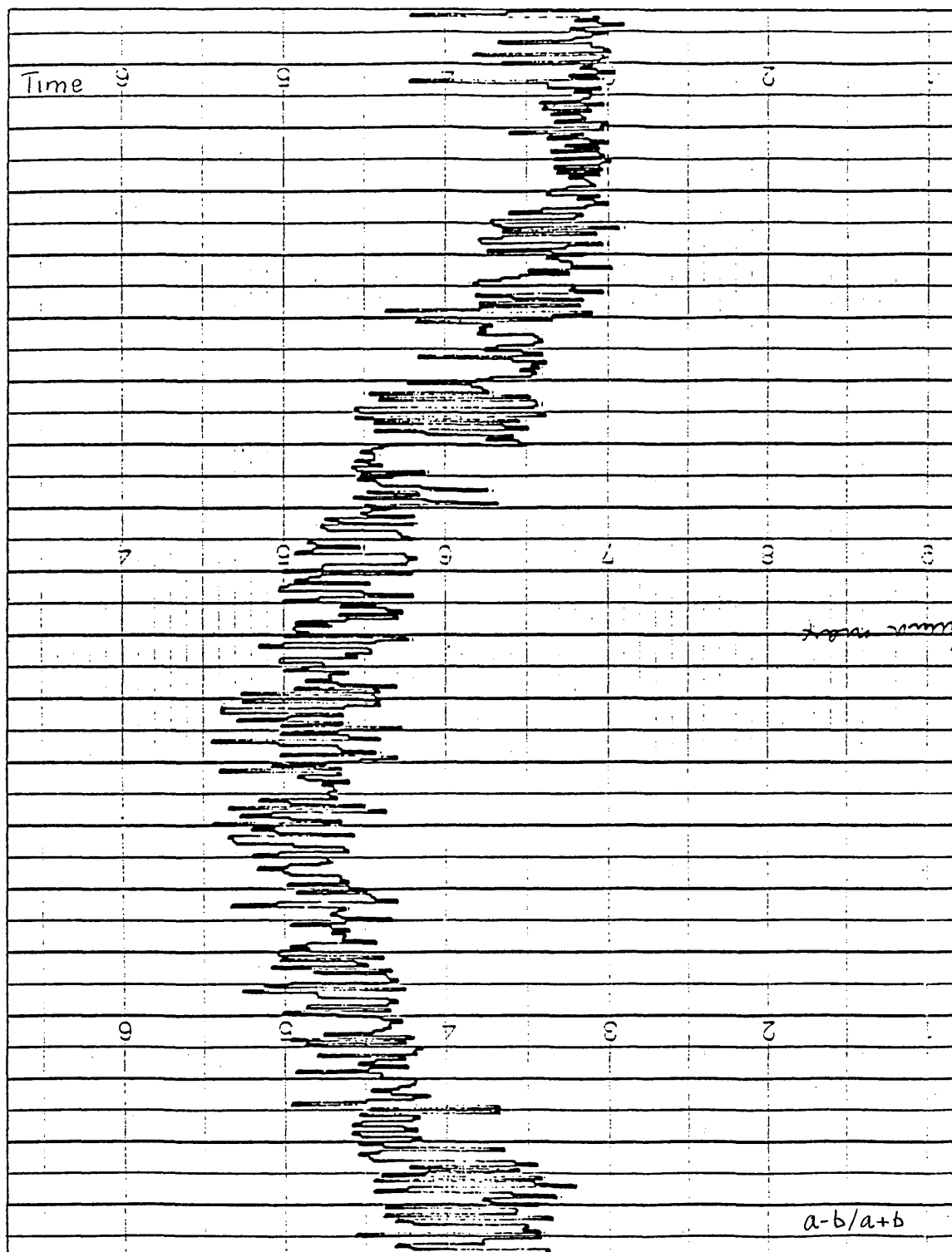


Figure 3.3. Example of DAC output to the chart recorder during observations (oscillation of 44 Tau).

and if $u = b/a$, the ratio r is;

$$r = \frac{a - b}{a + b} = \frac{1 - u}{1 + u}.$$

From standard statistics theory, the uncertainty in r , σ_r , and the uncertainty in u , σ_u , are related as follows;

$$\sigma_r = \sigma_u \cdot \frac{dr}{du}$$

and

$$\frac{dr}{du} = \frac{2}{(1+u)^2}$$

Also;

$$\frac{\sigma_u}{u}^2 = \frac{\sigma_a}{a}^2 + \frac{\sigma_b}{b}^2$$

Now if $a \approx b$, then $u \approx 1$,

then;

$$\sigma_u^2 = \frac{\sqrt{2}}{\sqrt{n}}$$

And if $a \approx b \approx n$.

So that finally;

$$\sigma_r = \frac{1}{\sqrt{2n}} \quad (3.1)$$

Thus an error inversely proportional to the square root of twice the count a or b is introduced to the ratio r . This error is carried through to all subsequent reduction processes.

3.4 Further Processing of Data.

The data recorded at an observatory on digital magnetic data cassettes can easily be transferred into a 'hard disc' file in the Astronomy Group's PDP-11/23 mini computer via the RS232 interface on both cassette recorder and computer. The data can then be backed up on magnetic tape, which in turn may be used to transfer the data to a more powerful machine. This however was not necessary since the PDP-11 was able to cope with all that was asked of it.

The language used was standard Fortran 66.

3.4.1 Sensitivity to Radial Velocity.

This is calculated by two separate methods. The calibration chops used to find the best positions as described in section 2.5.6 can be used to find signal levels at a few different points near the best position. Once these have been calculated, the slope of the line near FWHM can be calculated. Knowledge of the velocity equivalent of a change of 1 step in servo position then allows the sensitivity to be calculated.

The line profile obtained by scanning can also be used. By plotting the signal, $a-b/a+b$, that would be obtained (at all the points across the line) with the chop span used to record the velocity curve data, a curve similar to figure 3.4(b) would result. Figure 3.4(b) is the differentiated form of the line shown in figure 3.4(a).

The slope of the straight line part of the curve is the rate of change of signal per servo step near the best position, i.e. near the FWHM position. The sensitivity can then be calculated from this value of the slope.

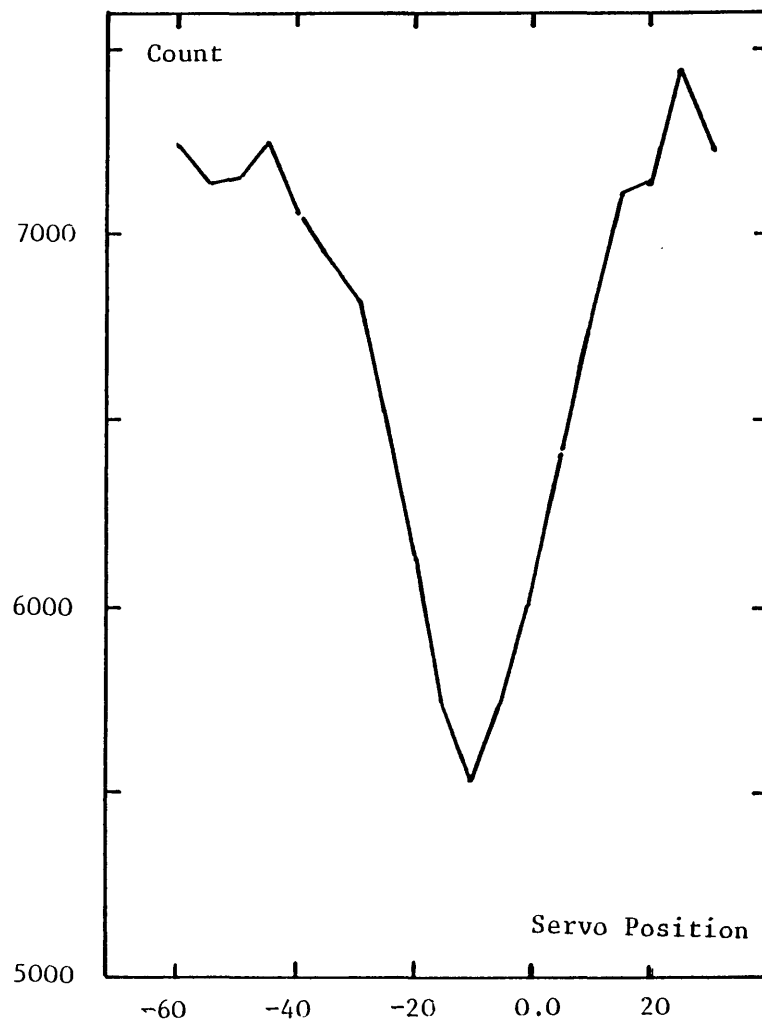


Figure 3.4a Line Profile in Del Del.

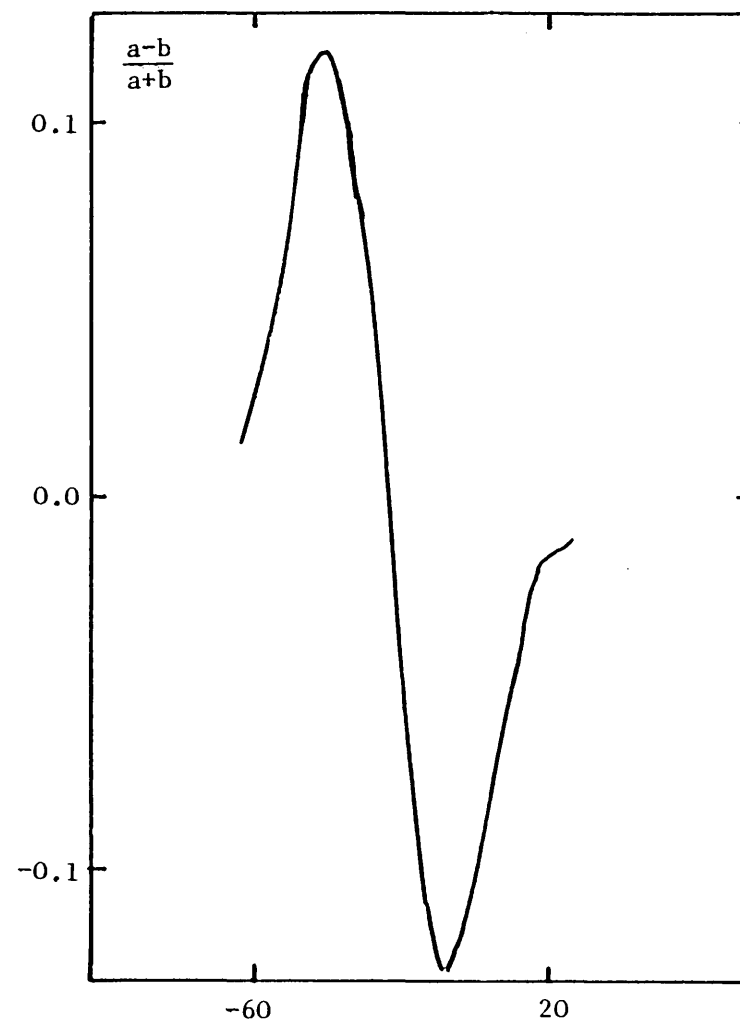


Figure 3.4b Differentiated Form of Line Opposite.

3.4.2 The Radial Velocity Curve - Calculation of $a-b/a+b$.

The ratio $R = a-b/a+b$ can be simply calculated using the programme shown in appendix 3.2. The 'standard' procedure is usually to strip all unwanted numbers from the data file including the header and the final three columns (see figure 3.2) and calling the programme. The values of $a-b/a+b$ are corrected for dark count and stored in another file ready for plotting and for further reduction.

3.5 Analysing the Radial Velocity Curve.

3.5.1 Introduction.

The method of Fourier Transforms is used to find the amplitude and frequency of any periodicities that might be present in the data but not always obvious to the eye when examining the velocity curve. There now follows a summary of the theory of Fourier Transforms.

3.5.2 The Method of the Fourier Transform.

To perform a Fourier Transformation on discrete digital data, the discrete Fourier Transform must be used. The discrete FT has the form;

$$G(i\omega) = \sum_{n=0}^{n=N-1} x_n \cdot e^{(-i\omega_n T)} \quad (3.2)$$

The $G(i\omega)$ are the complex amplitudes of the components of frequency ω_n , x_n are the data, n takes its values from the range 0 to $N-1$ and N is the total number of data points taken.

If each datum takes a time T_s to collect then the total number of

data points and the bandwidth, T , are related such that;

$$T = NT_s \quad (3.3)$$

From Equation (3.2) it can be seen that the FT is a periodic function with period;

$$\frac{2\pi}{Ts}$$

where T_s is in seconds.

This ranges from

$$\pm \frac{\pi}{Ts}$$

Periodicities in the data which vary faster than this will not be detected, neither will periodicities larger than the length of data be detected.

The frequency interval between the complex amplitudes, $G(i\omega)$, is such that;

$$\begin{aligned} \Delta\omega &= \frac{2\pi}{NT_s} \\ &= \frac{2\pi}{T} \end{aligned} \quad (3.4)$$

The maximum frequency, called the Nyquist frequency, ω_N , will occur for some complex amplitude, and

$$\omega_N = k_{\max} \Delta\omega \quad (3.5)$$

For any, kth, amplitude the frequency, ω_k , will be such that

$$\omega_k = k \cdot \frac{2\pi}{NTs} \quad (3.6)$$

so that Equation (3.5) becomes;

$$\omega_N = k_{\max} \cdot \frac{2\pi}{NTs} \quad (3.7)$$

However, the maximum frequency, ω_N , is π/Ts ,

This implies that;

$$k_{\max} = \frac{N}{2} \quad (3.8)$$

The range of values taken up by k , the amplitudes of the various frequencies, is from 0 to $N/2$, whilst the data points, x_n , are such that n varies from 0 to $N-1$.

This implies that the FT will yield $(N/2)+1$ amplitude estimates from N data samples of the function being measured. In this case the function is the velocity curve.

If there is a peak in the FT at a frequency ω_k , then the period, τ_k , is:

$$\begin{aligned} \frac{1}{\tau_k} &= \frac{\omega_k}{2\pi} \\ &= \frac{k}{NTs} \end{aligned}$$

or,

$$\tau_k = \frac{T}{k} \quad (3.9)$$

$G(i\omega)$ is a density function representing the complex amplitude per unit bandwidth:

$$G(i\omega) = A\omega T$$

$A\omega$ is the complex amplitude so that;

$$G(i\omega) = A\omega T = \sum_{n=0}^{n=N-1} x_n (\cos \omega_n Ts - i \sin \omega_n Ts) \quad (3.10)$$

or,

$$A\omega T = \sum x_n \cos(\omega_n Ts) - i \sum x_n \sin(\omega_n Ts) \quad (3.11)$$

The amplitude of $A\omega$, $|A\omega|$, is then;

$$\begin{aligned} |A\omega|^2 T^2 &= (\sum x_n \cos \omega_n Ts)^2 + (\sum x_n \sin \omega_n Ts)^2 \\ &= a_n^2 + b_n^2 \end{aligned} \quad (3.12)$$

and the phase, ϕ_ω , of the periodicity is;

$$\tan(\phi_\omega) = \frac{\sum x_n \sin \omega_n Ts}{\sum x_n \cos \omega_n Ts} \quad (3.13)$$

The above forms the basis of the Fourier Transform Method. It yields estimates of the periods, amplitudes and phases of periodicities in a set of samples, x_n , of some function.

3.5.3 Fourier Series.

If $f(t)$ is a function represented by a Fourier series such that;

$$f(t) = A_0 + \sum_m A_m e^{(i\omega_m T)} \quad (3.14)$$

then the A_m are the complex amplitudes of the harmonics present in the function, $f(t)$, and have the usual form;

$$A_m = a_m \pm i.b_m \quad (3.15)$$

Most functions can be represented as a series in this way and if sine/cosine waves of the amplitudes, periods and phase dictated by the series were added, the function $f(t)$ could be exactly reconstructed if enough such components were included.

Representing the data in this way, however, does not make significant periodicities obvious as does the Fourier Transform. However, there is a strong relationship between the two methods.

From Parseval's Theorem the mean square power of a frequency estimate is P_m such that;

$$P_m = \frac{1}{2} \cdot C_m^2 \quad (3.16)$$

where;

$$C_m^2 = a_m^2 + b_m^2$$

Now for the n th. frequency estimate, from (3.10),

$$G_n = A_n T_s \quad (3.17)$$

and

$$|G_n| = |A_n|Ts$$

A_n is the complex amplitude of an harmonic estimate and has a bandwidth of the sampling time, T_s , so the amplitude of an estimate in that particular bandwidth, A_n^1 , is,

$$A_n^1 = A_n Ts$$

So from (3.15) and (3.16)

$$|A_m| = \frac{1}{2} |C_m| = \frac{1}{2} G_m$$

then the amplitude, A_k^1 ,

$$A_n^1 = 2G_n \frac{T_s}{T}$$

or,

$$A_n = \frac{2G_n}{N} \quad (3.18)$$

This relation, (3.18), is used to find the amplitude of a peak in the FT.

The programme used is shown in appendix 3.3.

A test of the FT programme is to see whether it will separate a manufactured signal comprising two sine waves of different amplitude. Figure 3.5 shows two such sine waves superposed and their FT. The signal waves are defined as;

$$y = \sin\theta + 4.\sin(10.\theta)$$

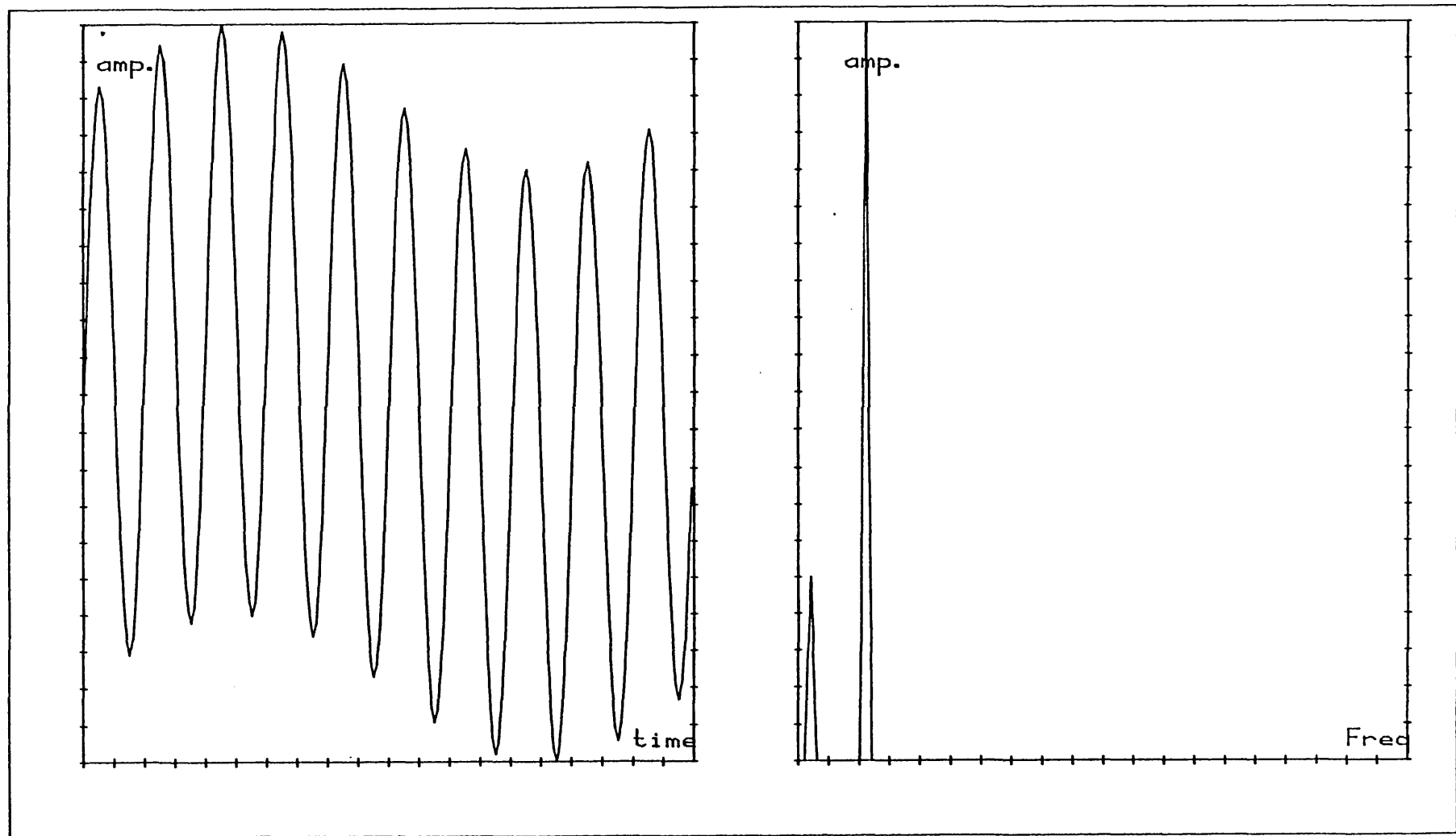


Figure 3.5(a).
Superposition of two sine waves.

Figure 3.5(b).
Fourier Transform of sine waves opposite.

The transform shows two peaks in the correct ratio of heights and at the correct frequencies.

3.5.4 Aliasing in Fourier Transforms.

The function representing the FT is periodic with period $2\pi/T_s$ and contains frequencies up to a maximum value which is the Nyquist Frequency. It was stated above that frequencies greater than this will not be seen in the FT. This is so since by sampling the light curve, *g, of a star* with a sampling time that corresponds to the Nyquist frequency all higher frequencies are excluded. The integration time averages them and they do not appear. However, if the data is examined in a different manner such that the Nyquist frequency is lower than the maximum frequency in the data, the FT will detect this frequency but its value will not be clear. It will show as an alias and if the distribution is continuous, the frequencies that are greater than the Nyquist frequency will distort part or most of the form of the distribution. This effect is demonstrated in figure 3.6(a) and (b). Figure 3.6(a) is the transform of an attempt to reconstruct a square wave by the addition of sine waves of the correct amplitudes and periods, i.e.;

$$f(x) = \sum_n \frac{1}{n} \sin nx$$

where n are all odd integers.

The fundamental and six harmonics were combined. (This constitutes a further test of the FT routine). 100 data points were used at arbitrary intervals, say unity, and these defined the maximum frequency as 50 cycles in the whole data. Figure 3.6(b) shows the same attempt at reconstruction of a square wave as figure 3.6(a) but with the 53rd. harmonic

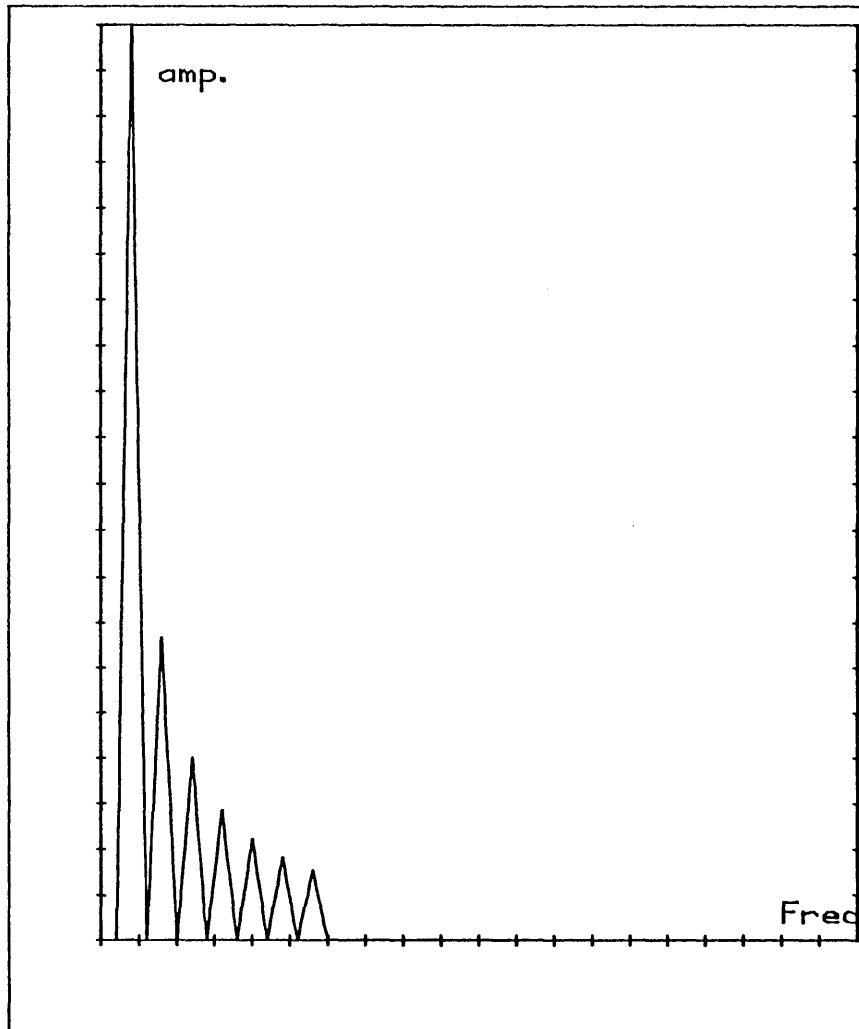


Figure 3.6(a).
Fourier Transform of a simulated
square wave without aliasing.

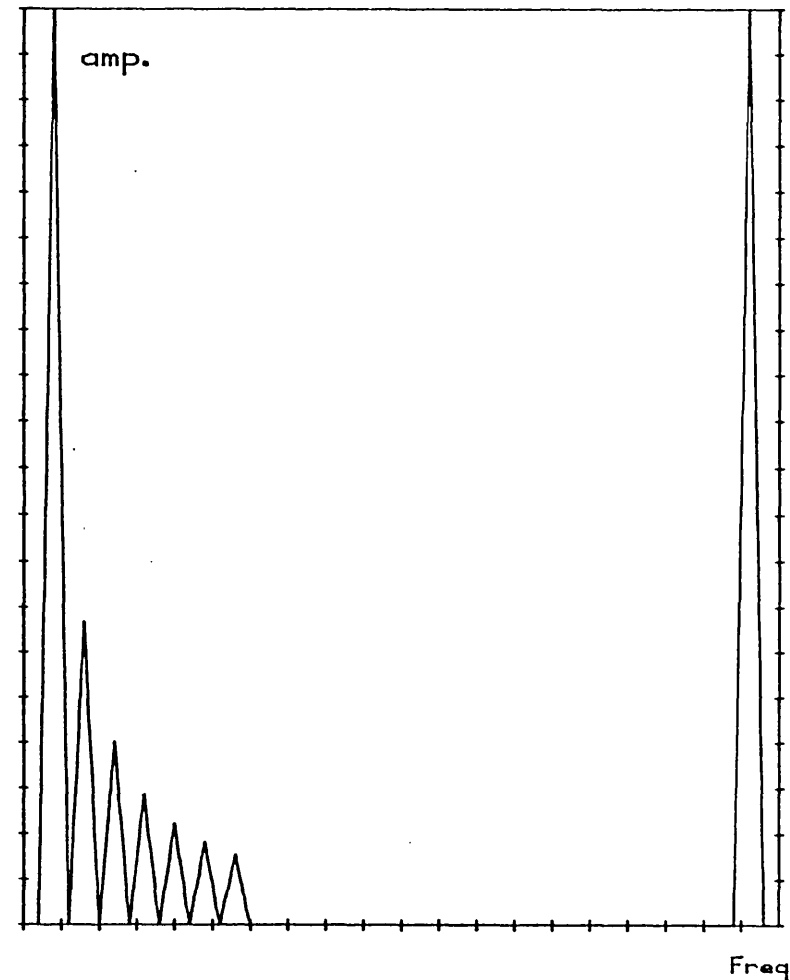


Figure 3.6(b).
Fourier Transform of a simulated square
wave with aliasing at the high frequency.

included (with incorrect amplitude for the square wave). The 53rd. harmonic is aliased and appears as the absent 47th. harmonic.

3.5.5 Fast Fourier Transforms.

The equation (3.2) can be re-written as;

$$G_k = \sum_{n=0}^{n=N-1} x_n e^{(-i2\pi kn/N)} \quad (3.19)$$

This, then, is a numerical summation in which no function occur. The products kn can be calculated only once. This is the Fast Fourier Transform or FFT. It is much faster than an ordinary FT but is limited in the number of data points it can handle, i.e., only certain multiples of numbers can be used. Its main use is for on-line transformation which require speed and do not need to be of exactly the final number of data points taken but can be shortened to the nearest convenient multiple. It is also used whenever speed is essential.

3.5.6 Noise in Data and Fourier Transforms.

If the data comprises N values of the ratio, $x_n = a-b/a+b$, of mean value $\bar{x}$, and standard deviation, σ , from the mean, then the error or noise on the value of the mean is given by standard gaussian error theory as;

$$\text{noise} = \frac{\sigma}{\sqrt{N}} \quad (3.20)$$

A FT of noise alone should show equal amplitudes at all frequencies. This is called white noise. However, the amplitude's distribution will itself be noisy. There will be a distribution of amplitudes about the mean

value and the standard deviation of this distribution is equal to the mean. This holds true for transforms with signals as well as noise. If there are N data points where mean amplitude in the Fourier plane is $\bar{\alpha}$ then;

$$\frac{2 \cdot \bar{\alpha}^2}{N} \approx \frac{\sigma}{\sqrt{N}} \quad (3.21)$$

This is an approximate relation between the noise in the whole data and the mean amplitude of frequencies in the Fourier plane and the two quantities are usually within a factor of 2. The mean value of the peaks in the Fourier plane gives a useful estimate of the noise in the Fourier plane and a marker against which significance can be assessed.

3.5.7 Calibration of Noise in Fourier Transforms.

The noise can be estimated as outlined above in section 3.5.6. This gives the approximate relation of (3.21).

By adding sine waves of known amplitude, phase and period to data, the significance of any peaks that are present can be tested, if some doubt still remains. The amplitude of the noise in the data is easily calculated and by adding a sine wave of, say, three times the amplitude of the noise to the data and performing a FT, a peak at the chosen frequency should appear. This will then determine which peaks already present are significant and calibrate the FT in terms of " σ ".

3.5.8 Removing Slopes from the Data.

If there has been a linear drift imposed upon the data, this can be removed easily by using a least squares method to find the slope and intercept of the straight line that best fits the data and then removing

it. This will also enable the drift to be calibrated in terms of a rate of change in signal. The main advantage of this is in estimating the deviation from the mean in the data which gives a value of the noise. This is, clearly, different or over-estimated if there is a slope present.

A further advantage of removing the slope is that it would show as a very significant peak near the zero frequency end and would dominate the transform making other peaks difficult to recognise. The programme used to remove slopes is shown in appendix 3.4.

3.5.9 Removal of the DC Term in Fourier Transforms.

The series representing a function, equation (3.14), has a frequency independent term A_0 . This is the first term in the Fourier Transform and occurs at zero frequency. It is simply the mean value or constant level of the function or data. By subtracting this value from all the points in the data and leaving them distributed about zero will reduce the first point in the transform to a value very close to zero. This is a useful procedure making the Fourier Transform easier to interpret, since if the first point were very large it would dwarf any other peaks that may be significant.

3.5.10 Interpretation of Fourier Transforms.

Removal of slopes and D.C. terms makes the remaining peaks easier to identify as significant or not. The usual criterion for this is that a peak should be at least three times the noise, '3 σ '. This makes the estimation of noise very important. A further aid to making the noise more identifiable is to smooth the resultant Fourier Transform to, most usually, a 1mHz bandwidth. This usually reduces the level of the estimate of the noise and makes peaks that may be significant more pronounced and, perhaps, easier to identify. This does not remove the 3 σ criterion.

3.5.11 Smoothing Data.

In cases where the signal is obviously many times the level of the noise and is easily seen without a Fourier Transform some smoothing can be done in order to make the determination of periods and amplitudes simpler. By smoothing the radial velocity curve the apparent level of the noise is reduced and the main features are enhanced, all 'jagged' noise features are 'smoothed out'. One method of smoothing the data is to replace each datum by an average of itself and several subsequent points. This averaging process preserves the number of data points but produces spurious results for the last several points in the data where no more data is available. This running average is simple to implement and produces a more presentable velocity curve. The programme used to perform this smoothing is shown in appendix 3.5.

Another method used to reduce the apparent level of the noise is to calculate mean values of data in larger time intervals than the integration time. This does not lose any frequency information of lower frequency than that of the new integration time but averages out information present in the higher frequencies. It also reduces the number of data points to be treated in the reduction.

Any high frequency information lost in these methods of smoothing is likely to be only noise as oscillations with such high frequencies will have such small amplitudes as to be well below the noise level of the instrument.

3.5.12 The Effect Of Earth's Rotation.

The rotation of the Earth has an effect on the measured velocity curve. The sun and the stars are fixed objects relative to the

astronomical observer on the Earth who is rotating, along with his instruments, once a day about the Earth's axis. This circular motion is imposed upon the velocity curve and may be corrected for. Standard computer algorithms exist that calculate the correction required for any star observed at any latitude. These are, however, extremely long and could not be used on-line without a large computer. Estimates of the effect can be made very easily. If the star under observation happens to be at the meridian at midnight then its velocity relative to the observer will be zero but the rate of change of velocity will be maximum. This can be seen in figure 3.7(a). The maximum value of this velocity is 440 ms^{-1} at the equator. The instantaneous velocity at any other latitude will be v , such that;

$$v = \frac{10.\pi \cos \gamma}{72} \text{ km}^{-1}$$

from figure 3.7(b), where γ is the latitude. And, since the motion is circular, then;

$$v(t) = \frac{10.\pi \cos \gamma}{72} \sin(\omega t + \phi) \text{ kms}^{-1} \quad (3.22)$$

where $\omega \sim 7.3 \cdot 10^{-5} \text{ radians second}^{-1}$. The phase, ϕ , is the phase of the star at midnight, i.e. if the star is on the meridian at midnight then $\phi = 0$. The magnitude of the earth's velocity may not always be significant, but it is important to realise that it may contribute to the results of a Fourier Transform.

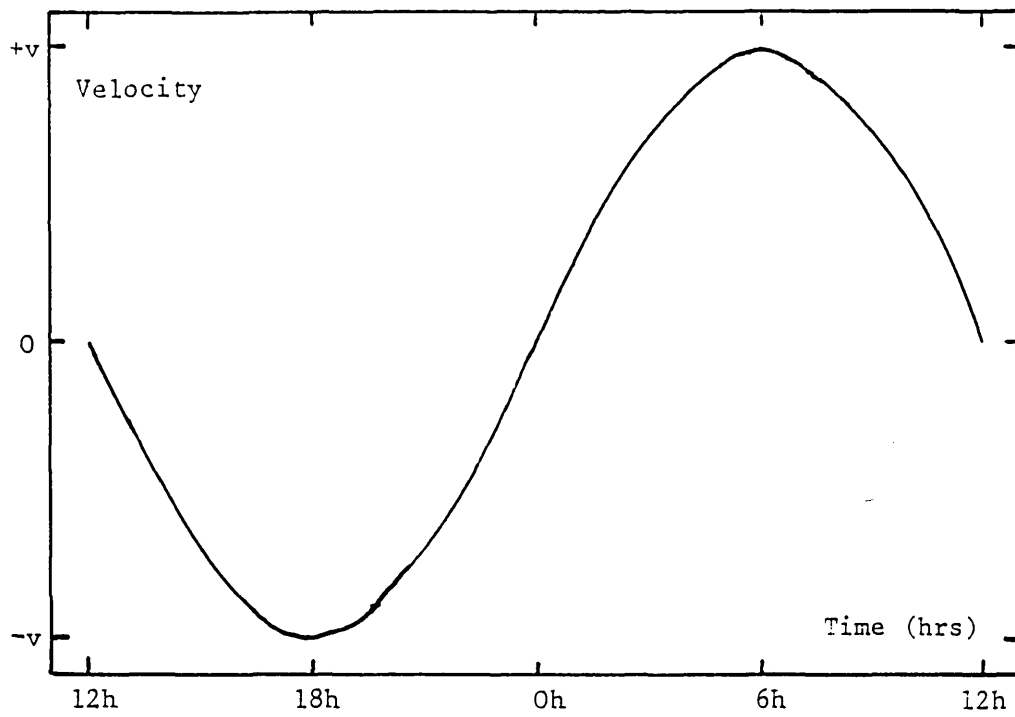


Figure 3.7a Earth's Rotational Velocity.

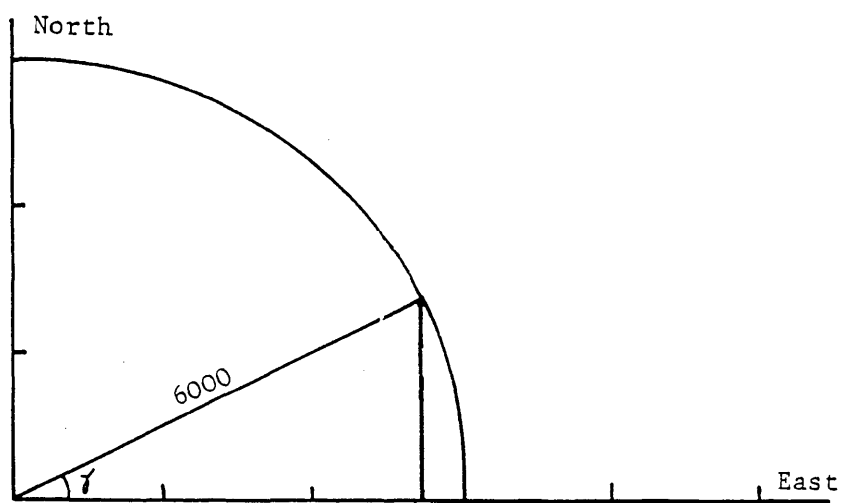


Figure 3.7b Component of Earth's Rotational Velocity at Latitude γ

3.6 Other Techniques.

3.6.1 Strings of Separated Data.

There may exist strings of data separated by lengths of time when no observations were made, either due to bad weather, or daylight hours etc. If precise timings for the beginnings and ends of these strings are known an attempt at analysing them 'coherently' can be made. Firstly, the data must be spaced by exact numbers of manufactured data, the mean value, usually zero, that would have filled that time had observations been possible. Once this has been done a string of data results which is nominally continuous. A Fourier Transform can then be taken. A limit on the number of data points in such a string is the available memory of a computer. Data points taken at 10 second intervals with separations of days between strings can very rapidly, if not immediately, exhaust the available memory of most computers. There are over 8000 10 second integrations possible in 24 hours. Precautions must be taken to ensure that the data are exactly spaced in time with the 'missing' data or spurious periods may result. There will be amplitudes in Fourier Transforms due to the separations in the data and these are likely to produce many harmonics of the square wave type. The interpretation of such results would be very difficult indeed, especially if the data is multi-periodic. Another method of analysing such data is the string-length method described by Dworetzky (1983), although it is probably more suited to single observations than strings of data.

3.6.2 More Sophisticated Reduction.

Mention is made here of the maximum entropy method only for completeness. This method attempts to calculate a 'true signal' from

limited and imperfect data using constraints derived from an examination of the data. The most probable solution obtained within the constraints is the one obtained by the maximum entropy method.

3.7. Summary Of Data Reduction Used.

The method of reducing data is usually quite obvious and is suggested by the character of the data. One of two paths is usually followed depending upon whether an obvious radial velocity variation is present or not.

3.7.1 Reducing Apparently Featureless Data.

For data with no apparent signal it is assumed that, if the signal exist, it will be buried in the noise. In order to extract a radial velocity variation from the noise the method of Fourier Transforms (section 3.5.2) must be used. The general procedure is as follows:

- (i) Calculation of the ratio $a-b/a+b$ (section 3.4.2) i.e. the radial velocity curve.
- (ii) If a linear drift is apparent, such as is due to the Earth's rotation or to temperature drifts etc. (section 2.4.7), this may be corrected for (section 3.5.9).
- (iii) A Fourier Transform is then taken and examined for significant features (section 3.5.10).

This is the simplest reduction method, although step (ii) is not essential. It is a useful indicator of the magnitude of any drifts etc.

Further reduction such as smoothing the data or the Fourier Transform may be considered necessary, but need not always be used.

3.7.2 Reducing Data With An Obvious Radial Velocity Variation.

When an obvious velocity variation is present, and visible by eye, once the radial velocity curve has been plotted, then the prime objective is not to discover it as in section 3.7.1 but to find its period and amplitude accurately. The general procedure is as follows:

- (i) Calculation of the ratio $a-b/a+b$.
- (ii) Removal of linear drifts.
- (iii) The mean level of the data must be set to zero.
- (iv) The maxima and minima and the zero crossings of the data are found.
- (v) A value of the period and the amplitude (in the parameters of the data, i.e. the amplitude in the ratio space r and the period in multiples of the integration time) is found.
- (vi) Crude pre-whitening i.e. removal of the main feature may be tried.
- (vii) If the variation is sinusoidal a straight line with no slope will be left and a Fourier Transform may be taken.
- (viii) If the variation is not sinusoidal or of a single period then step (vi) will be very difficult without sophisticated curve fitting etc. and so the method of section 3.7.1 to find the amplitude and periods must be followed.

CHAPTER 4

ASTRONOMICAL OBSERVATIONS.

4.1. Introduction.

Several of the stars observed using the Fabry-Perot have been observed previously by other workers. Therefore, in this chapter, for each of the stars observed, a brief history of past observations is presented where such observations exist. These histories are only meant as a comparison and may not necessarily be complete. The data will then be presented and discussed and finally compared with the previous observations.

4.2. Canopus - α Carinae. HR 2326

This was the first star observed using the instrument described in Chapter 2. It was observed during a run on the 1.9m telescope of the S.A.A.O. in Sutherland in February 1983. The brightness of this star allowed a good calibration of the instrument's precision to be obtained and allowed focusing and alignment to be done quickly. There have not been any previous radial velocity measurements on this star to determine a radial velocity curve. Neither have there been any photometric measurements done due to its brightness of $M_v = -0.9$. Its spectral type is FOII.

4.2.1. The Radial Velocity Curve of Canopus.

The radial velocity curve of Canopus is shown in Fig. 4.1(a). The duration of the data was 14304 seconds and 4200 points were collected at a rate of one point in 3.406 seconds. Figure 4.1(a) shows the data combining 10 such points giving a separation of 34.06 seconds between points with a total of 420 points.

There are no obvious periodicities visible within the radial velocity curve. Any features have the characteristics of random noise. Scatter about the mean level can be estimated as approximately 0.005 in the ratio R . The change in ratio R , ΔR , for a change in radial velocity of 1 kms^{-1} corresponds to;

$$\Delta R = 9.87 \cdot 10^{-3} \text{ per kms}^{-1}.$$

This implies that the scatter is approximately 500 ms^{-1} per point. A more accurate value can be found from the results of the Fourier Transform

programme of Appendix 3.3. This programme calculates the variance of the data, var. The standard deviation of any point in the data, σ_1 , from the mean (reduced to zero in the programme) is then,

$$\sigma_1 = \text{var} \quad (4.1)$$

Also the noise can be estimated for the whole data, i.e. σ from:

$$\sigma = \frac{\sigma_1}{\sqrt{n}} \quad (4.2).$$

For the data of figure 4.1(a) $\sigma = 32.5 \text{ ms}^{-1}$.

4.2.2. The Velocity Spectrum of Canopus.

The Fourier Transform shown in figure 4.1(b) is the velocity spectrum of the data in figure 4.1(a) and spans the frequency range 0.07 to 14.7 mHz. The maximum amplitude is 226 ms^{-1} and the mean level, $\bar{\alpha}$, is 61 ms^{-1} . Any significant peaks must be 3σ above the mean level (see section 3.5.6 and Equation (3.21)). From Equation 3.21 the noise in the Fourier domain will be approximately,

$$\frac{2.2 \cdot \bar{\alpha}^2}{N},$$

where $N = 420$, the number of data points. This value is about 16 ms^{-1} .

In Figure 4.1(b) there are no significant peaks, only some low frequency drift peaks and two spikes greater than 3σ which seem too narrow to be significant. Smoothing the FT with a 10 point running average i.e. 0.7 mHz bandwidth, shown in Figure 4.2(a) produces no significant peaks about the mean level. A Fourier Transform was taken of only the intensity,

B, in order to check for correlations between intensity and radial velocity. Figure 4.2(b) shows the FT of the intensity. The frequency range is 0.07 to 14.7 mHz and the maximum count is 20,000 photons. There are several features which are significant. These are the low frequency drifts in intensity present throughout the observing run and are clustered near the 0.07 mHz end). There is also a group of peaks near 11 mHz which corresponds to a period of about 90 seconds. This could be due to guiding errors (done by hand) or due to some component of the telescope drive rotating once every 90 seconds and producing a shift in image and hence intensity. Comparing the frequencies present in the radial velocity and intensity transforms shows no correlation between peaks.

4.2.3. Canopus - Conclusions.

During the 4 hour run on Canopus a noise level of about 30 ms^{-1} was attained. No radial velocity variation was found above the 100 ms^{-1} level.

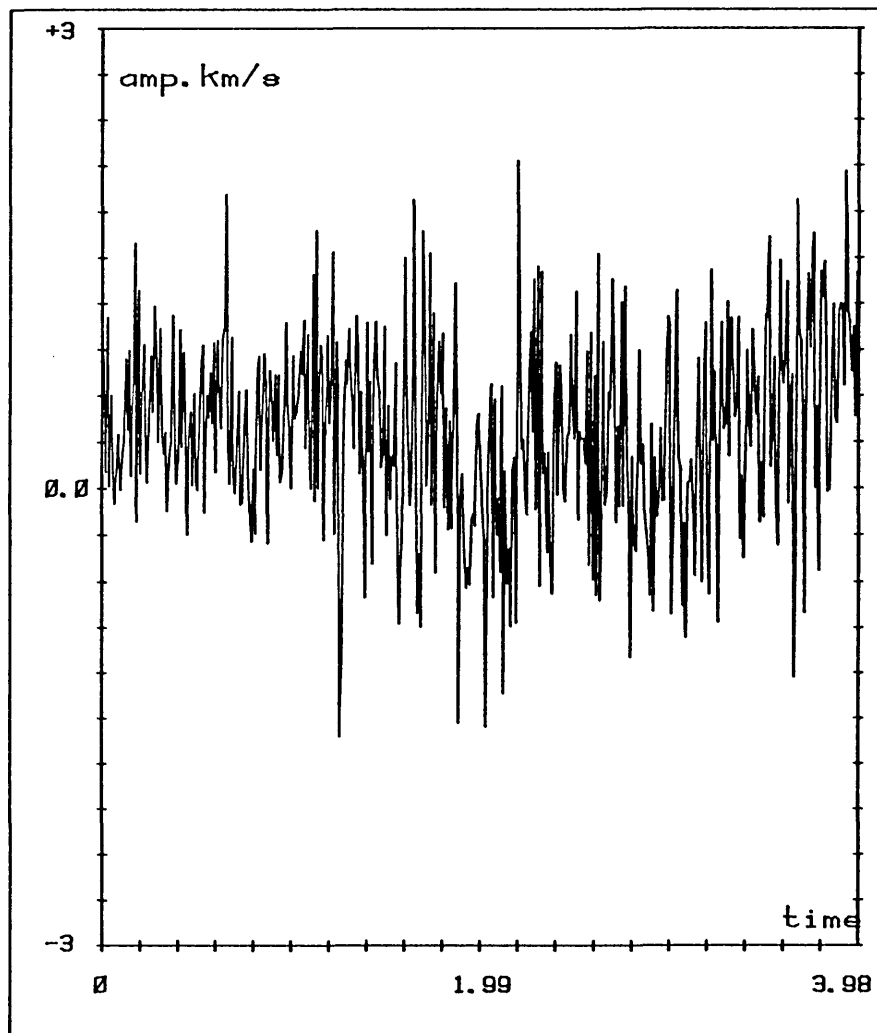


Figure 4.1(a).
Radial velocity curve of Canopus.
Data of 24.2.83 starting 21:01:00.

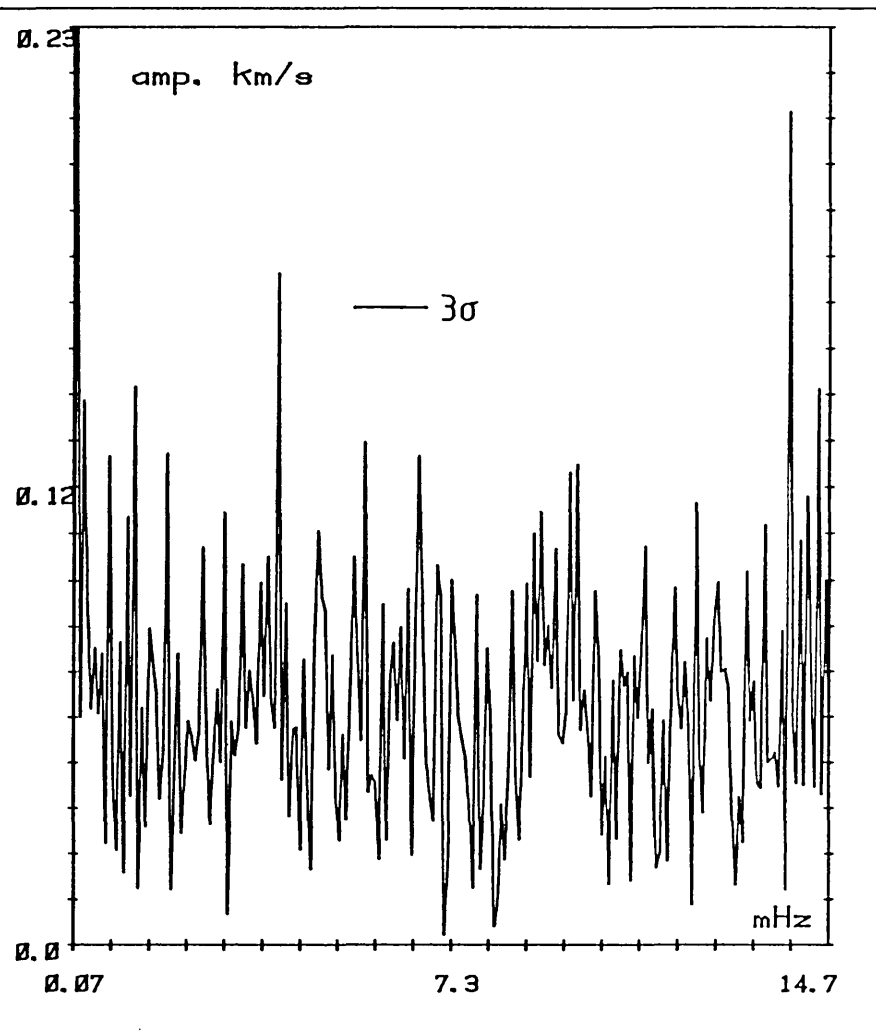


Figure 4.1(b).
Fourier Transform of data opposite.

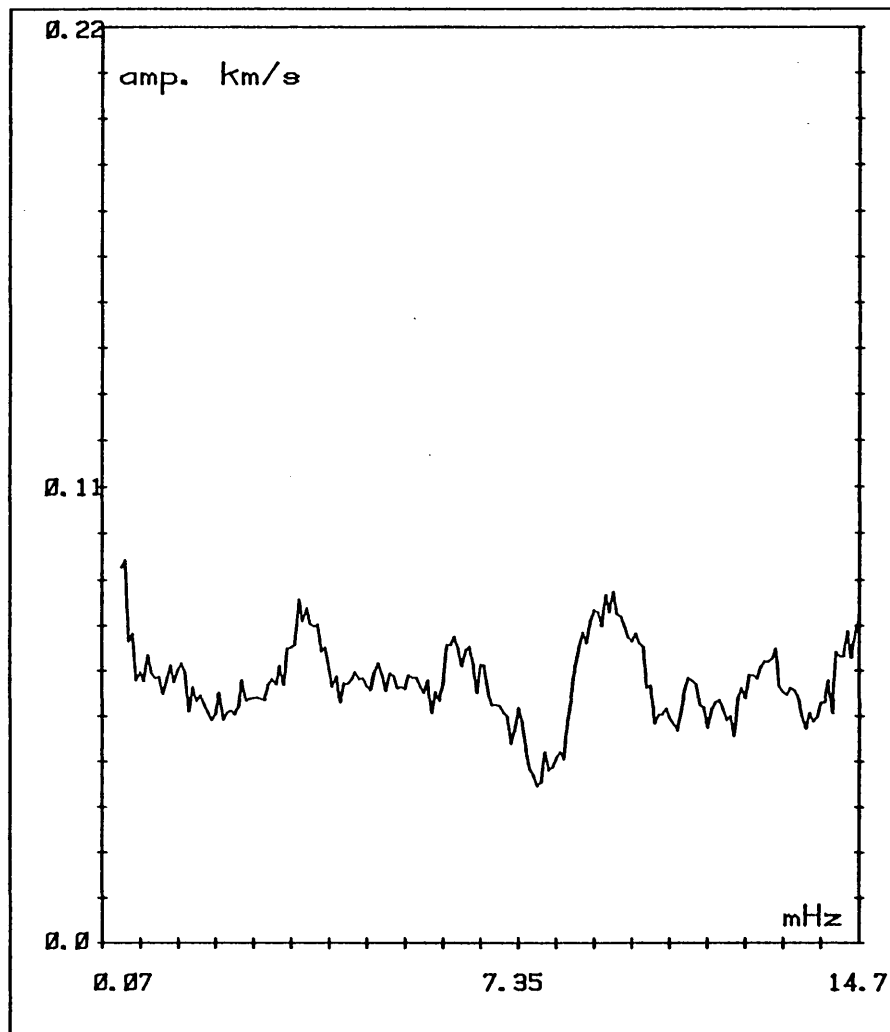


Figure 4.2 (a).
Fourier Transform of figure 4.1(b) smoothed
with a 0.7 mHz bandwidth running mean.

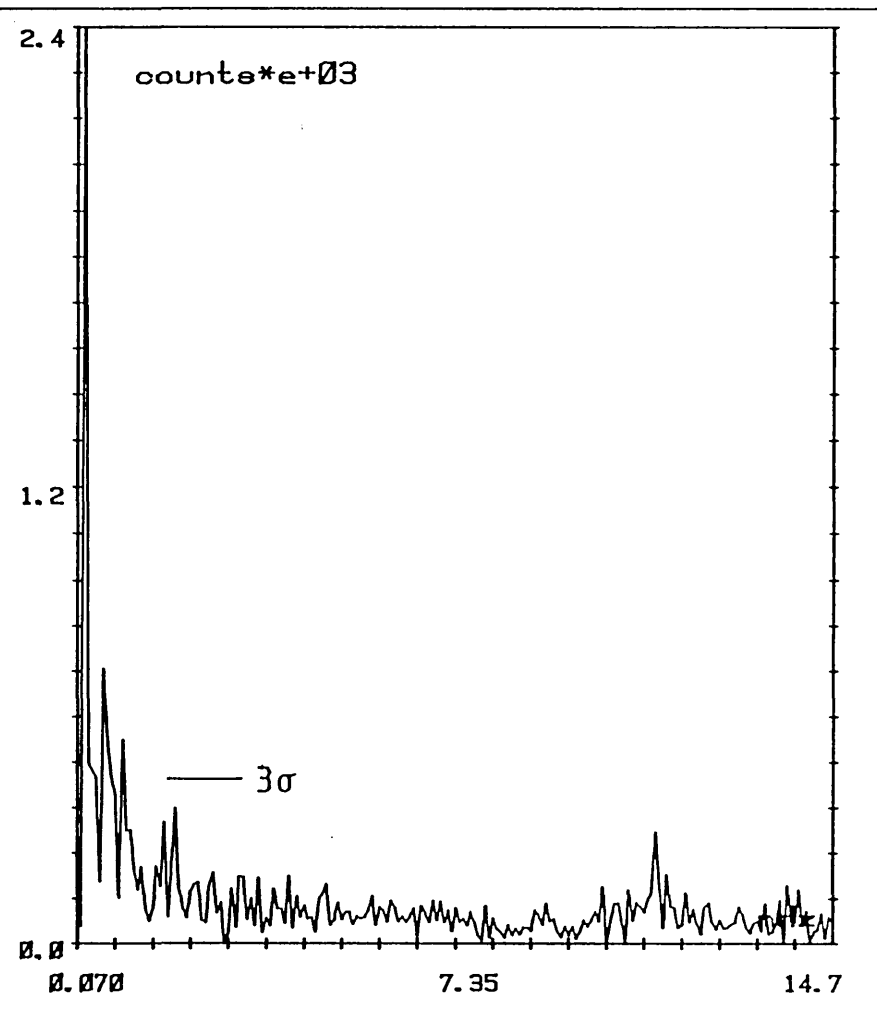


Figure 4.2 (b).
Fourier Transform of the intensity of the
data on Canopus of 24.2.83 starting 21:01:00

4.3. α Circini HR 5463

This star was observed during the run on the 1.9m telescope at S.A.A.O. in Sutherland in February 1983 in order to measure its radial velocity curve for the first time and to search for the 6.8 minute period seen in the light curve, section 4.3.1 below.

The magnitude of α Cir is $M_v = 3.19$ and its spectral type is FOp. The star was observed on three nights, only one of which is of good quality, the other runs being ruined by bad weather conditions.

4.3.1. Previous Observations of α Cir.

The photometric variability of α Cir was discovered by Kurtz and Cropper (1981). They detected a period of 6.8 minutes in its light curve and classified it as a rapidly oscillating Ap star. There have been no observations of the radial velocity curve of α Cir.

4.3.2. The Radial Velocity Curve of α Cir.

The radial velocity curve of α Cir is shown in Figure 4.3(a). The data comprises 316 points taken at the rate of 1 point in 31.56 seconds. The total duration of the data is 9973 seconds, 2.77 hours. The sensitivity of the system when observing the line in α Cir is such that the change in ratio $\Delta R = 4.962 \cdot 10^{-3}$ per kms^{-1} . Figure 4.3(a) shows no large radial velocity variation. The main feature is the increase in noise resulting in a wider trace towards the end of the run when the star was rapidly obscured by cloud. Using Equation (4.2) $\sigma = 180 \text{ ms}^{-1}$ for the data in Figure 4.3(a).

4.3.3. The Velocity Spectrum of α Cir.

Figure 4.3(b) shows the velocity spectrum of α Cir, spanning the

frequency range 0.1 to 15.8 mHz. The maximum amplitude is 320 ms^{-1} . As can be seen from Figure 4.3(b) there are no significant features in the velocity spectrum. The maximum velocity peak occurs at the 25th. point in the transform which corresponds to a frequency of 2.51 mHz (from Equation 3.9) or a period of 399 seconds or 6.65 minutes.

4.3.4. α Cir - Conclusions.

The data collected in the 2.77 hours of observing of α Cir only hints at an oscillation with a 6.65 minute period. It is not possible to confirm that the radial velocity of the star varies with a similar period as the light curve. A continuous run of approximately 8 hours would improve the signal to noise ratio sufficiently to show whether the 25th. point in the transform is significant or not.

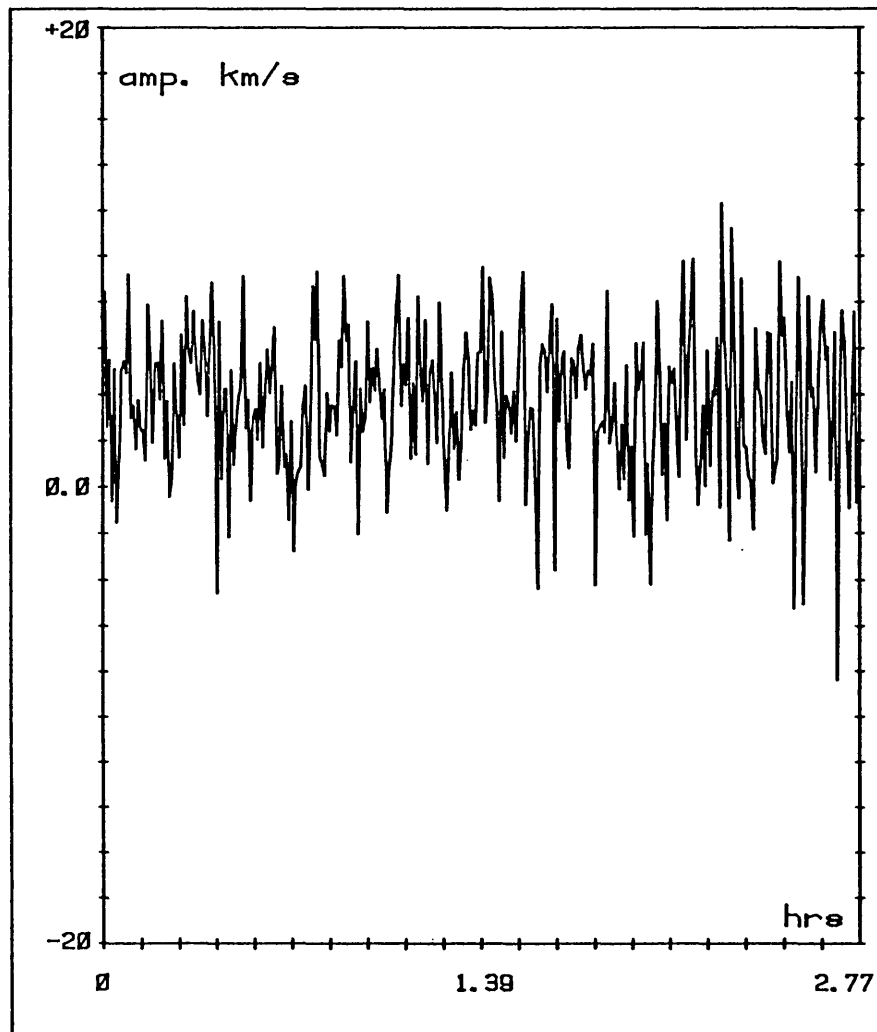


Figure 4.3(a).
Radial velocity curve of Alpha Cir.
Data of 24.2.83 starting 02:03:00.

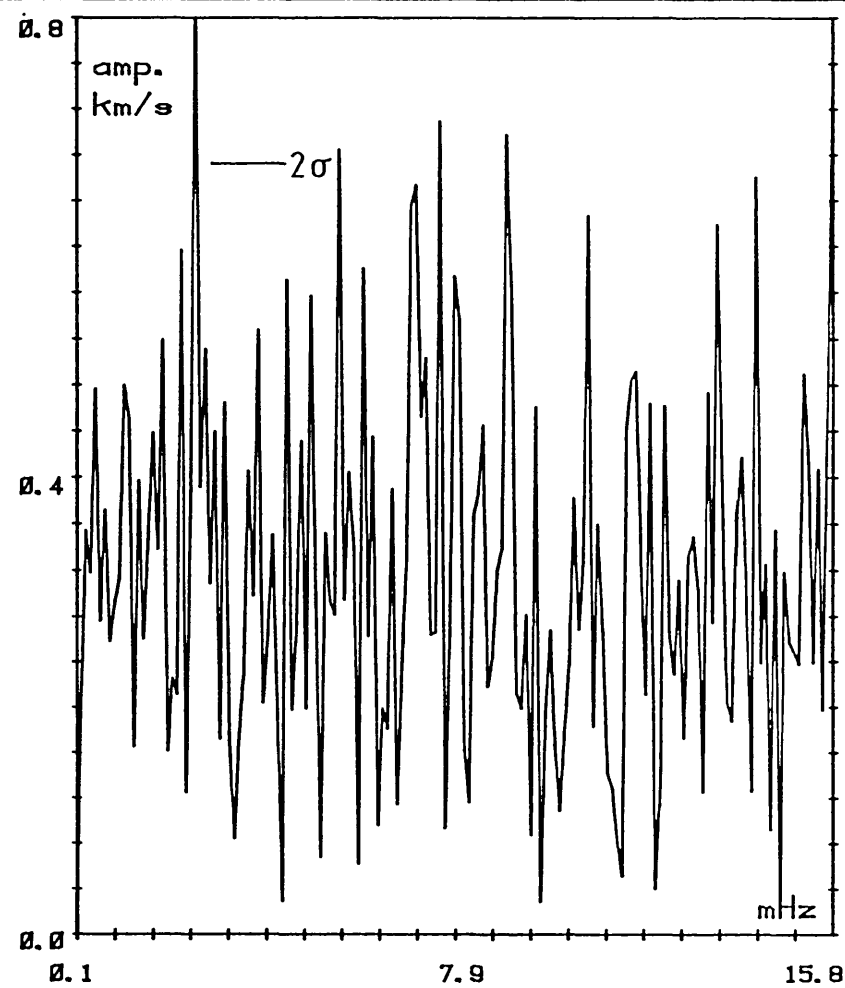


Figure 4.3(b).
Fourier Transform of data opposite.

4.4. ρ Puppis HR 3185.

This star was observed on three separate nights for up to 4.2 hours with the 1.9m telescope at S.A.A.O. in Sutherland in February 1983. The length of observation in each case was limited by the end of good weather conditions. The star was observed primarily as a test of the instrument i.e. to demonstrate the ability to measure radial velocity variations.

ρ Pup has a visual magnitude $M_v = 2.81$ and a spectral type F5IIp.

4.4.1. Previous Observations of ρ Puppis.

The fact that ρ Pup has a variable radial velocity was first reported by Reese (1903). More recent observations of the radial velocity were conducted by Struve et al (1956), after Eggen (1956a) had announced the photometric variability of the star. Figure 4.4 shows the light and radial velocity curves obtained by Eggen and Struve et al. Both of these curves were combined from observations made on five separate nights. Danziger and Kuhl (1966) and Bessell (1967) also observed ρ Pup and obtained simultaneous radial velocity and light curves. However, these last two groups of workers could not agree on the pulsation mode, or the effective gravity of the star. Most recently Balona and Stobie (1983) have observed this star, obtaining simultaneous radial velocity and light curves, the radial velocity was measured with an accuracy of 1 to 2 kms^{-1} , with velocity drifts less than 5 kms^{-1} over the night. ρ Pup is a Delta-Scuti type star with a single period of 3.38 hours and radial velocity amplitude of about 10 kms^{-1} .

4.4.2. The Radial Velocity Curves of ρ Pup.

The three nights' observations are shown in Figures 4.5(a), 4.6(a) and (b). The data comprises 430, 205, and 430 points respectively with 1 point corresponding to an integration time of 31.56 seconds. Each curve is plotted on the same time scale, 0 to 3.77 hours. The sensitivity to changes in ratio is:

$$\Delta R = 0.0102 \text{ per } \text{kms}^{-1}.$$

The curves of Figure 4.6 are of poor quality, being cut short or degraded by bad weather. Figure 4.5(a) shows just over a full cycle of the periodicity. The amplitude is 8.99 kms^{-1} and the period is 3.39 hours. The noise level for this data is 176 ms^{-1} .

4.4.3. The Velocity Spectrum of ρ Pup.

The velocity spectrum of ρ Pup is shown in Figure 4.5(b), spanning the frequency range 0.074 to 15.8 mHz. The mean amplitude is at a velocity of 162 ms^{-1} . This value is larger than it would otherwise be if the oscillation were absent. The Fourier Transform is dominated by the peak at the period defined by $k = 1$ and $k = 2$ i.e. 3.77 and 1.88 hours, which includes the period of the oscillation, 3.39 hours. The oscillation is so large that Fourier analysis is only useful for finding other periods, which are, in fact, absent.

4.4.4. ρ Pup - Conclusions.

An oscillation of period 3.39 hours and amplitude 8.99 kms^{-1} has been found. There no other periods present with amplitudes $\geq 200 \text{ ms}^{-1}$. These values agree well with previously published values (section 4.4.1.). The data is too short to search for periodicities longer than 3.39 hours.

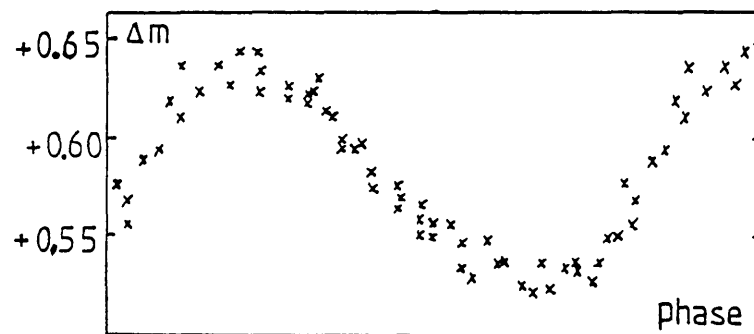
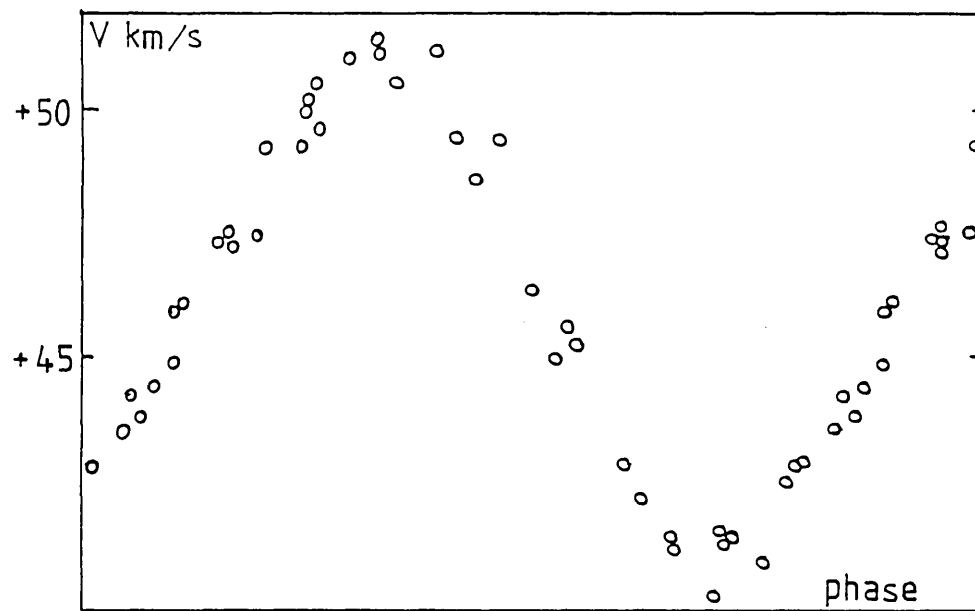


Figure 4.4. The radial velocity curve (top) of ρ Pup (Struve et al., 1956) and the light curve (Eggen, 1956).

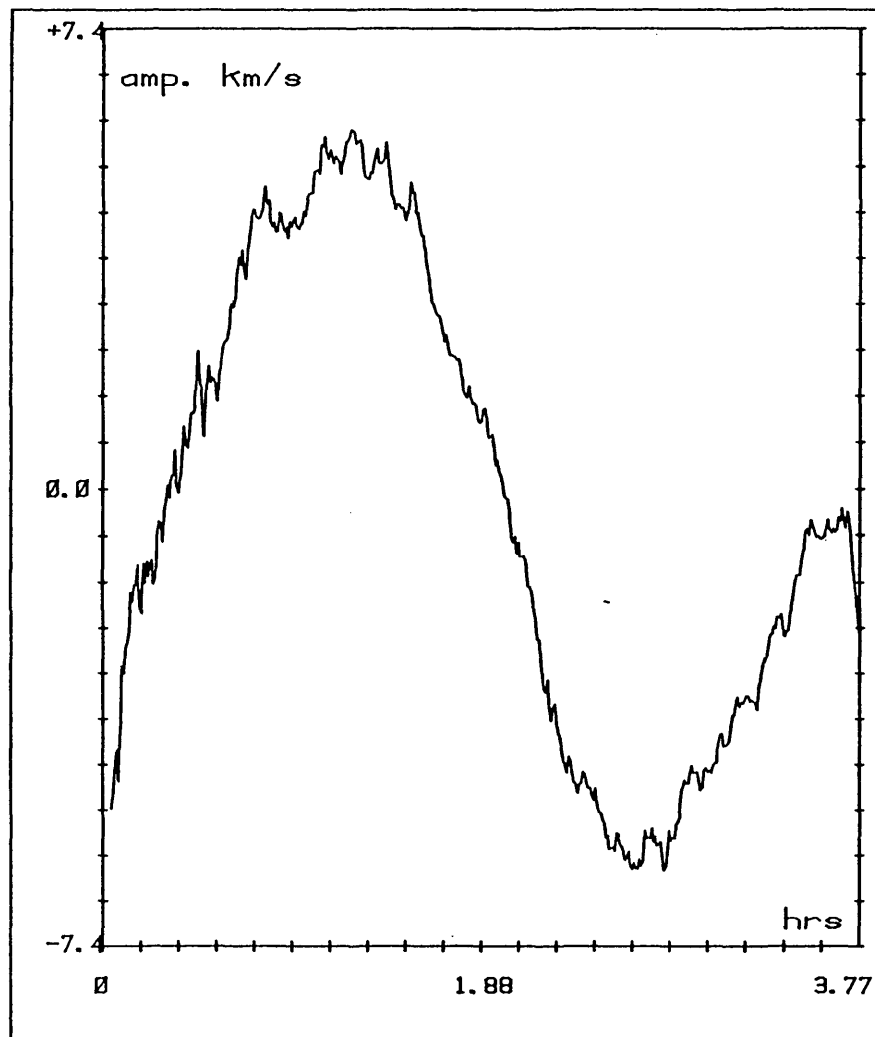


Figure 4.5(a).
Radial velocity curve of Rho Pup.
Data of 25.2.83 starting 20:27:00.

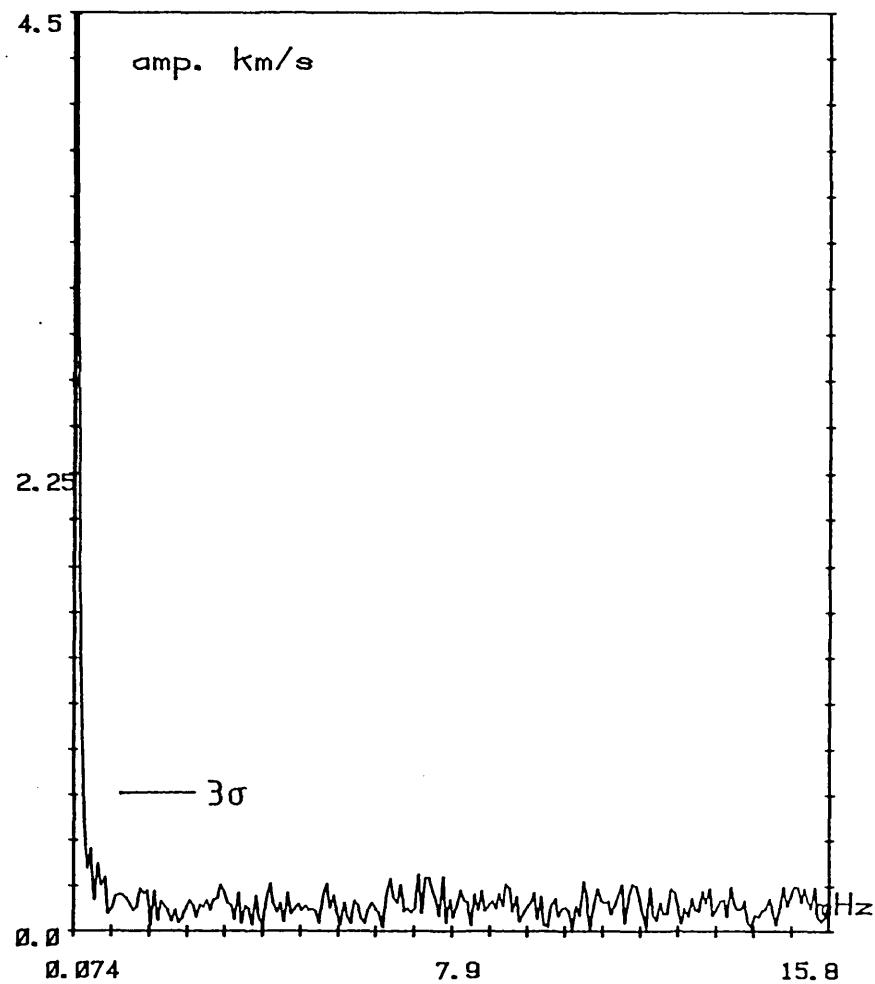


Figure 4.5(b).
Fourier Transform of data opposite.

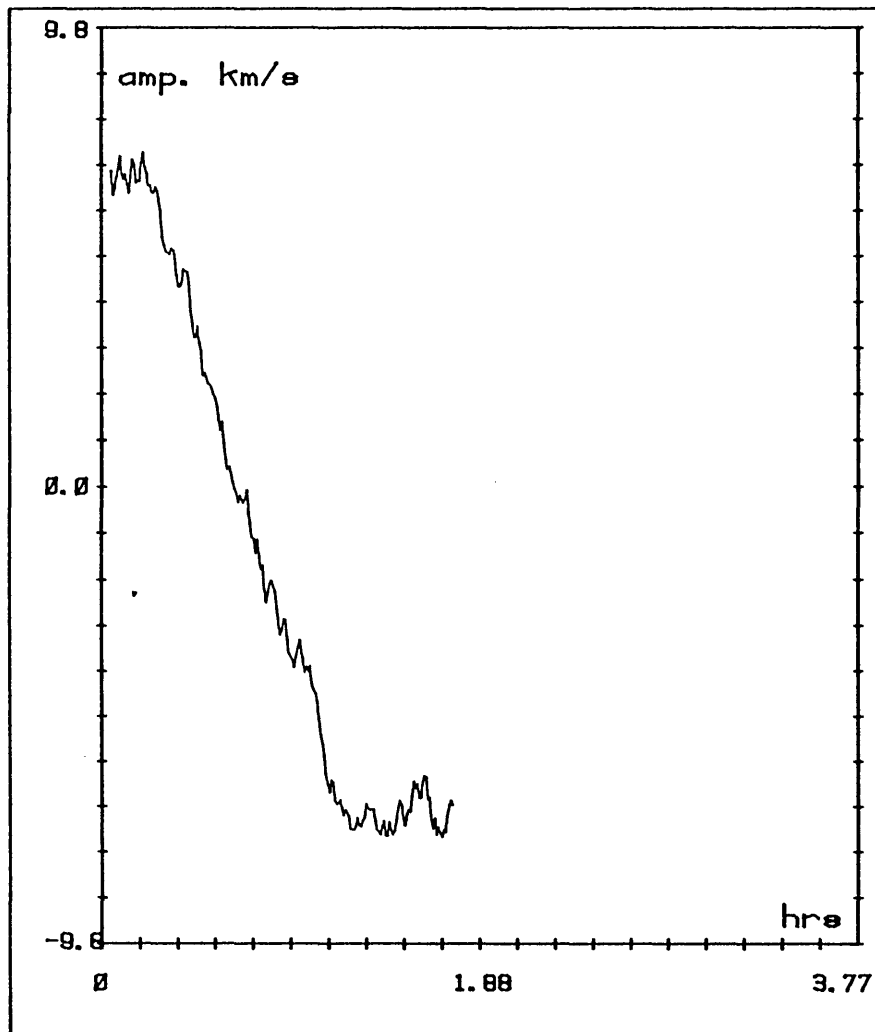


Figure 4.6(a).
Radial velocity curve of Rho Pup.
Data of 27.2.83 starting 21:01:00.

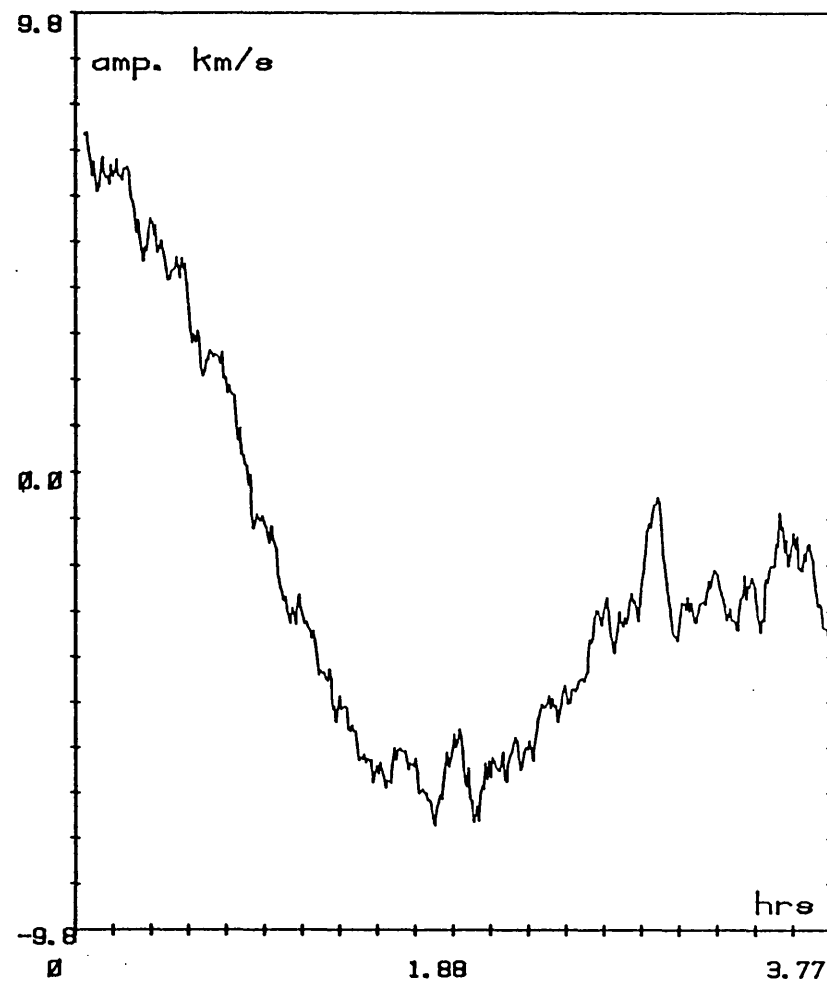


Figure 4.6(b).
Radial velocity curve of Rho Pup.
Data of 28.2.83 starting 20:31:00.

4.5. 44 Tauri HR 1287.

44 Tau was observed during a run on the 1.5m I.R.F.C. at the Observatorio del Teide in Tenerife in October 1983. It is the faintest star so far observed with the instrument described in Chapter 2, having a visual magnitude $M_v = 5.41$ and spectral type F2 IV-V. 44 Tau was observed in order to obtain, for the first time, an accurate radial velocity curve for this star and to determine the performance of the instrument on fainter stars.

44 Tau is a Delta - Scuti type star.

4.5.1. Previous Observations of 44 Tau.

Since Danziger and Dickens (1967) discovered its variability, observations of 44 Tau have been mainly photometric. Danziger and Dickens (1967) observed it spectroscopically only to determine the width of its lines. Further photometry was done by Desikachary (1973), Percy (1973), Percy and McAlary (1974) and it was established that it pulsated with two periods, i.e. 3.48 and 2.51 hours and that these may be non-radial modes. Observations by Morguleff et al (1976a) (which comprised simultaneous photometric and spectroscopic observations), however, revealed that no periodicities are present in the pulsation of the star. Wizinowich and Percy (1979) have established that the periodicities are most certainly due to radial oscillations with the above mentioned periods.

4.5.2. The Radial Velocity Curve of 44 Tau.

44 Tau was observed for 5.22 hours during which 930 data points were collected at a rate of one every 20.19 seconds. The radial velocity curve is shown in Figure 4.7(a). The data was first smoothed using a running

average of 10 points (Appendix 3.5) and then plotted. The sensitivity to changes in ratio $\Delta R = 8.98 \cdot 10^{-3}$ per kms^{-1} . Figure 4.7(a) shows what appears to be a sinusoidal variation in radial velocity with period of 2.88 hours and amplitude 13.8 kms^{-1} . The amplitude diminishes towards the end of the run and the semi-periods decrease steadily. Figure 4.8(a) shows an attempt at pre-whitening the data, i.e. removing a component of the oscillation from the data once it has been identified and analysing the remaining data again. The period of the sine wave removed from the data was 2.86 hours, the period dictated by the semi-period of the mid portion of Figure 4.7(a). Removing this component does not leave a straight line suggesting that more than one frequency is present, although the central region seems reasonably flat. The noise level as calculated from the statistical variance of the data is 166 ms^{-1} . This is an overestimate due to the presence of the sine waves in the data. There are regular variations, near the maxima and minima of the velocity curve, which are simply smoothed noise and do not appear in the Fourier Transforms as peaks. The noise level here is 30 ms^{-1} , a more representative value.

4.5.3. The Velocity Spectrum of 44 Tau.

Figure 4.7(b) shows the Fourier Transform of the data. It is dominated by the peak at $k = 2$, 2 cycles in the sample, corresponding to a period of 2.6 hours (the mean period of the data) and a semi-amplitude of 6.5 kms^{-1} . There are no other significant features. Figure 4.8(b) shows the transform of the pre-whitened data. There is a peak at $k = 1$ and a broader peak centred at $k = 3$, periods of 5.22 and 1.74 hours, amplitudes of about 1.0 and 0.6 kms^{-1} . There are no other significant features.

4.5.4. 44 Tau - Conclusions.

A large and variable radial velocity variation has been found in the run on 44 Tau. The mean period agrees quite well with previously published values of one of the periods (section 4.5.1). The length of data is too short to find and separate the two periods present. The variable nature of the velocity curve suggests that one or more other periods are present. Trying to pre-whiten the data only improves the estimate of the shot noise present but manufactures periodicities, which are quite obviously not present (although the mean of these artifacts is identical to the longer period, 3.48 hours).

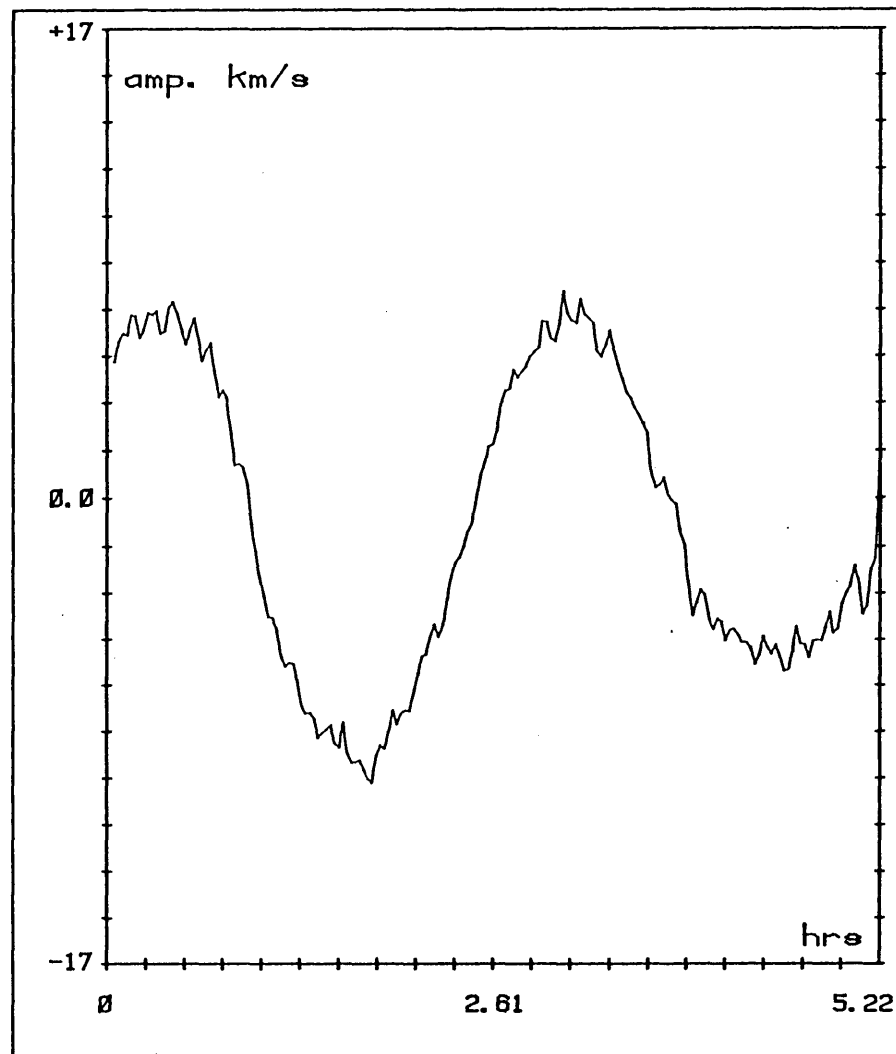


Figure 4.7(a).
Radial velocity curve of 44 Tau.
Data of 13.10.83 starting 01:16:10.

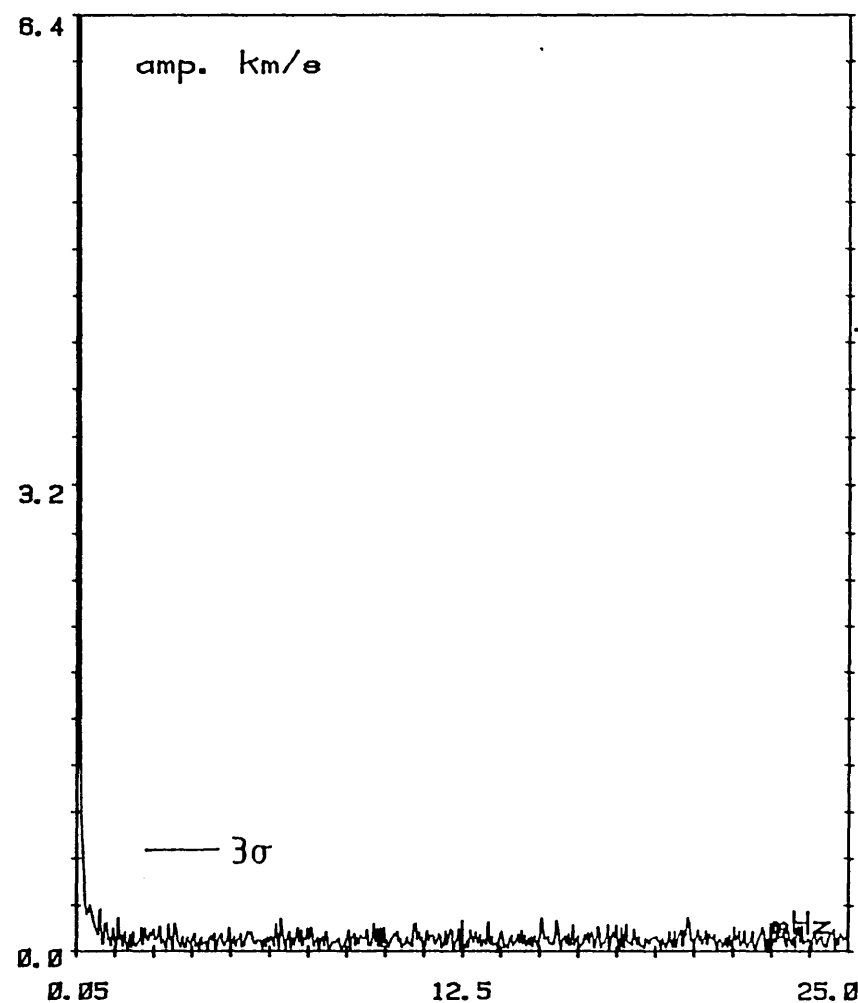


Figure 4.7(b).
Fourier Transform of data opposite.

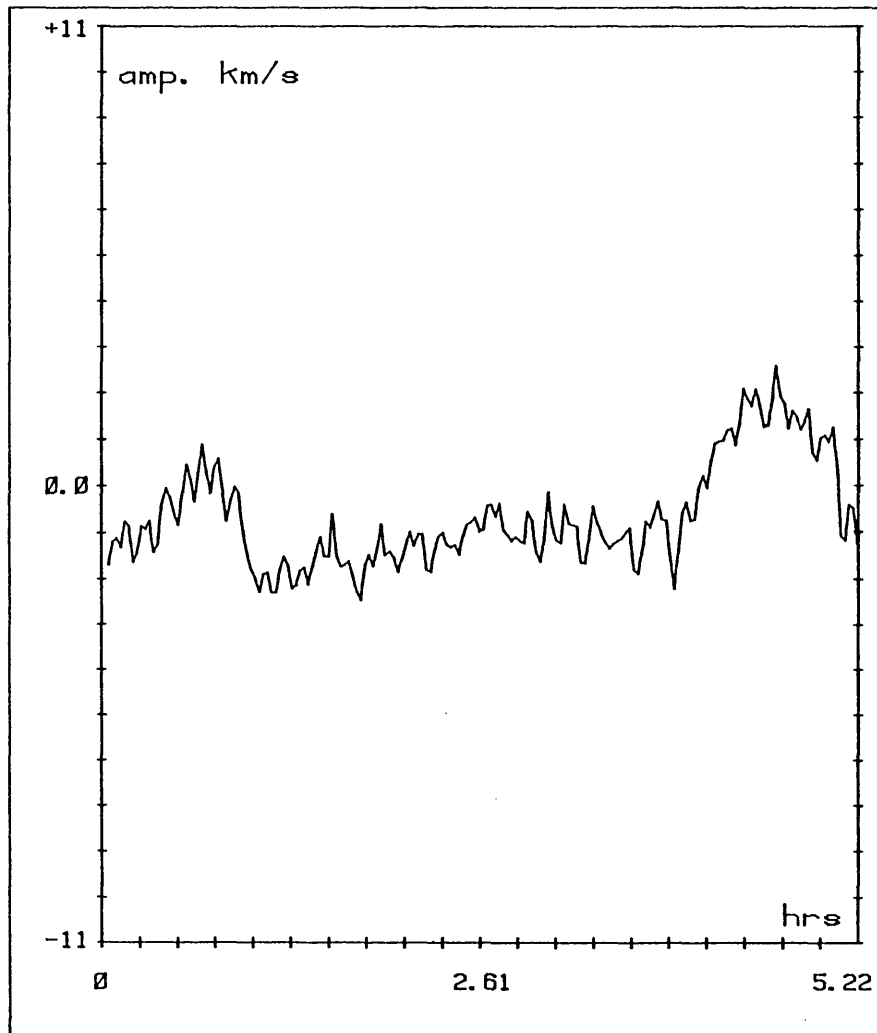


Figure 4.8(a).
As for figure 4.7(a).
Main sine wave removed (see text).

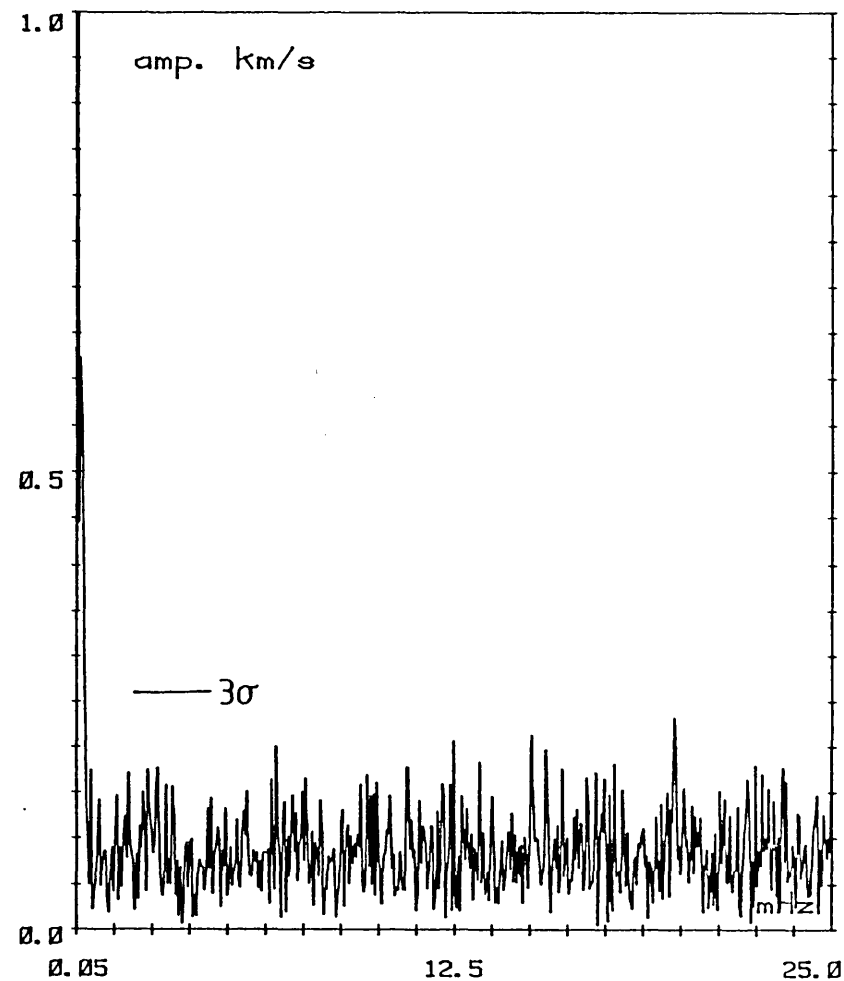


Figure 4.8(b).
Fourier Transform of data opposite.

4.6. 14 Aurigae HR 1706.

14 Aur was observed during the run on the 1.5m I.R.F.C. at the Observatorio del Teide in Tenerife in October 1983 for a period of 4.27 hours in order to obtain an accurate radial velocity curve. Its magnitude is $M_v = 5.06$ and its spectral type is A9V. It is a member of a close spectroscopic binary with a period of 3.79 days.

4.6.1. Previous Observations of 14 Aur.

The variability of 14 Aur was discovered by Danziger and Dickens (1967). Chevalier et al (1968), Hudson et al (1971) and Morguleff et al (1976b) observed the star both photometrically and spectroscopically and concluded that the oscillation, of period 2.1 hours, had a variable amplitude. Fitch and Wiśniewski (1979) analysed 158 hours of photometry and concluded that the variable amplitude was due to three modes of similar period beating together.

4.6.2. The Radial Velocity Curve of 14 Aur.

14 Aur was observed for 4.27 hours and a total of 761 data points were collected. The radial velocity curve is shown in figure 4.9(a) where two cycles of the oscillation, the period being 2.093 hours and amplitude about 2.9 kms^{-1} , can be seen. There is a slope present in the data, which corresponds to a change of about 6 to 8 kms^{-1} over the whole length of the data, which is much greater than the velocity of rotation of the Earth (section 3.5.12) and any instrumental drifts (section 2.6). The noise level is 107 ms^{-1} , probably an over estimate due to the presence of a slope and the radial velocity variation.

4.6.3. The Radial Velocity Spectrum Of 14 Aur.

Figure 4.9(b) shows the Fourier Transform of the data. The maximum peak is at $k = 1$, i.e. a period of 4.27 hours due to the slope in the data. A second peak at $k = 2$, period 2.155 hours represents the two cycles seen in the data. The semi-amplitude, from the transform, of this component is 0.42 kms^{-1} . There is a further significant peak at $k = 4$ of period 1.068 hours, half the actual period of the data. This peak has a semi-amplitude of 0.24 kms^{-1} .

4.6.4. 14 Aur - Conclusions.

The data collected on 14 Aur shows a sinusoidal-like oscillation with a superimposed slope. This is consistent with previously published data. The length of data is too short to show the binary nature of this star and its companion and the amplitude of each cycle is not sufficiently different to determine whether there are any further periods present.

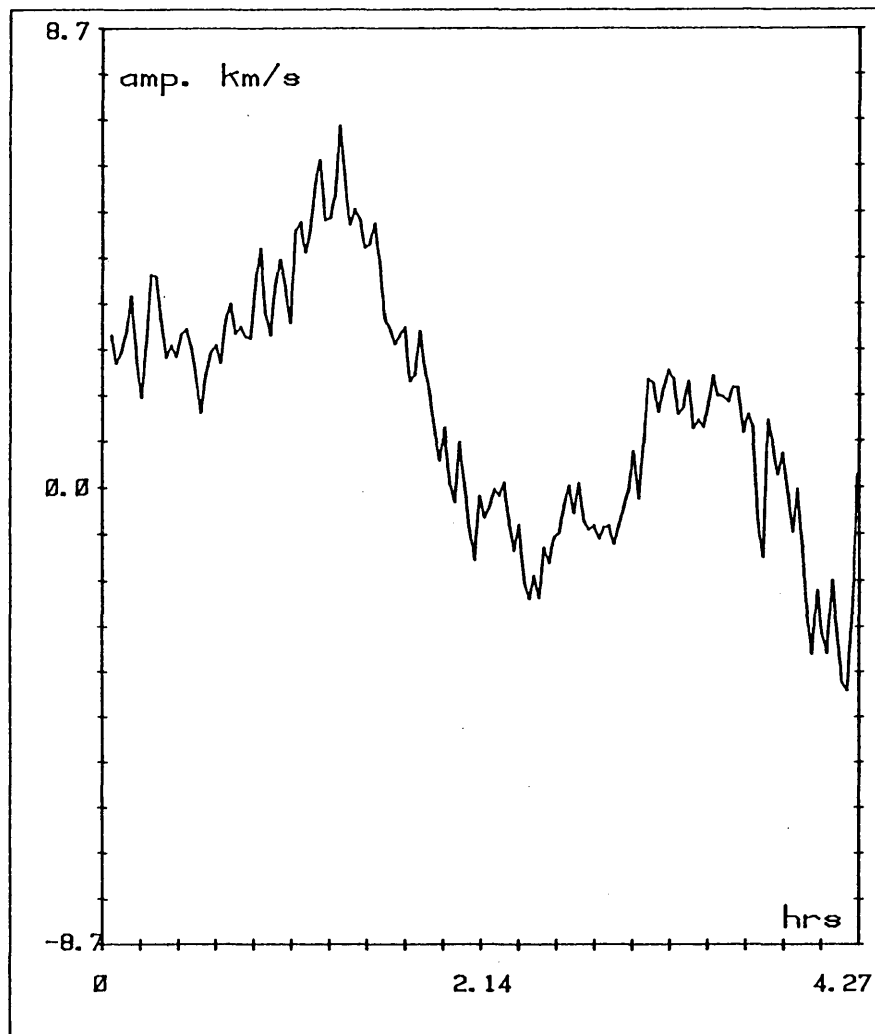


Figure 4.9(a).
Radial velocity curve of 14 Aur.
Data of 16.10.83 starting 02:04:50.

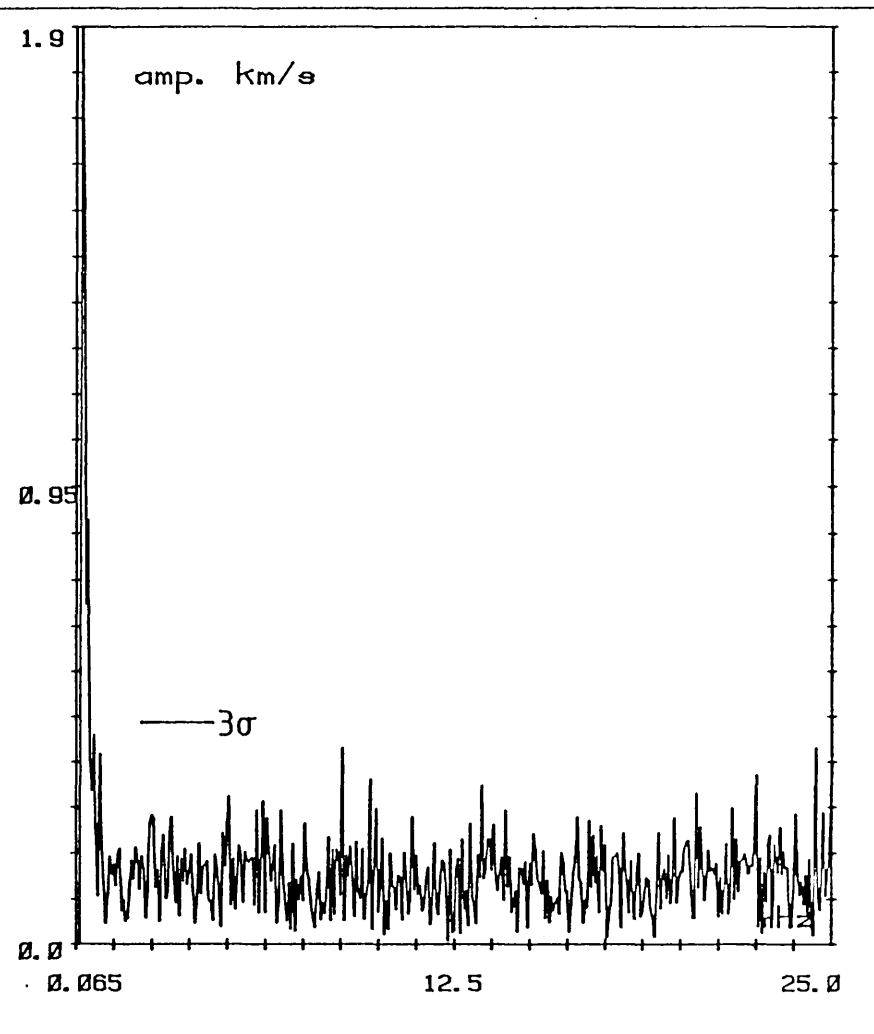


Figure 4.9(b).
Fourier Transform of data opposite.

4.7. δ Delphini HR 7928.

This star was observed for 3.51 hours during the run in October 1983 on the 1.5m I.R.F.C. at the Observatorio del Teide in Tenerife in order to obtain an accurate radial velocity curve. The spectral type of δ Del is F0IVp and its visible magnitude is 4.43.

4.7.1. Previous Observations of δ Del.

Eggen (1956) reported the photometric variability of this star, with period 3.24 hours, and concluded that it belongs to the Delta Scuti type variables. Wehlau and Leung (1964) observed δ Del photometrically on 25 separate nights and derived an expression for the light curve in terms of 6 frequencies. Kuhl and Danziger (1967) conducted simultaneous spectroscopic and photometric observations of δ Del and found a velocity amplitude of 5.5 kms^{-1} . Van Genderen (1973) confirmed an average period of 3.24 hours. The most interesting results are those of Duncan and Preston (1979), namely that δ Del is a member of a binary system in which both components pulsate. They have identified the periods of both stars with previously observed periods mentioned above. The orbital period of the system is 40.58 days.

4.7.2. The Radial Velocity Curve Of δ Del.

The 626 points collected are shown in figure 4.10(a). The variation in radial velocity is obvious, with amplitude 4.9 kms^{-1} and period 3.24 hours. There is an indication that the amplitude may be variable, i.e. multiperiodicities may be present, in that the upward going part of the curve does not reach the same level as the maximum of the previous cycle. The data is too short to tell if there is an overall variation due to the

orbital period of the binary system. The noise level of the data is 96 ms^{-1} .

4.7.3. The Velocity Spectrum of δDel .

The Fourier transform is shown in figure 4.10(b). The oscillation present in the data is shown as the maximum amplitude peak at $k = 1$ with semi-amplitude 2.3 kms^{-1} and period 3.52 hours, from equation (3.9), and includes the period 3.24 hours. There are no other significant features in the transform.

4.7.4. δDel - Conclusions.

The data collected in October 1983 shows an oscillation of period 3.24 hours and amplitude 4.9 kms^{-1} . These values agree well with previously published data (section 4.7.1). There is some evidence of a variable amplitude and hence multiperiodicity in the data.

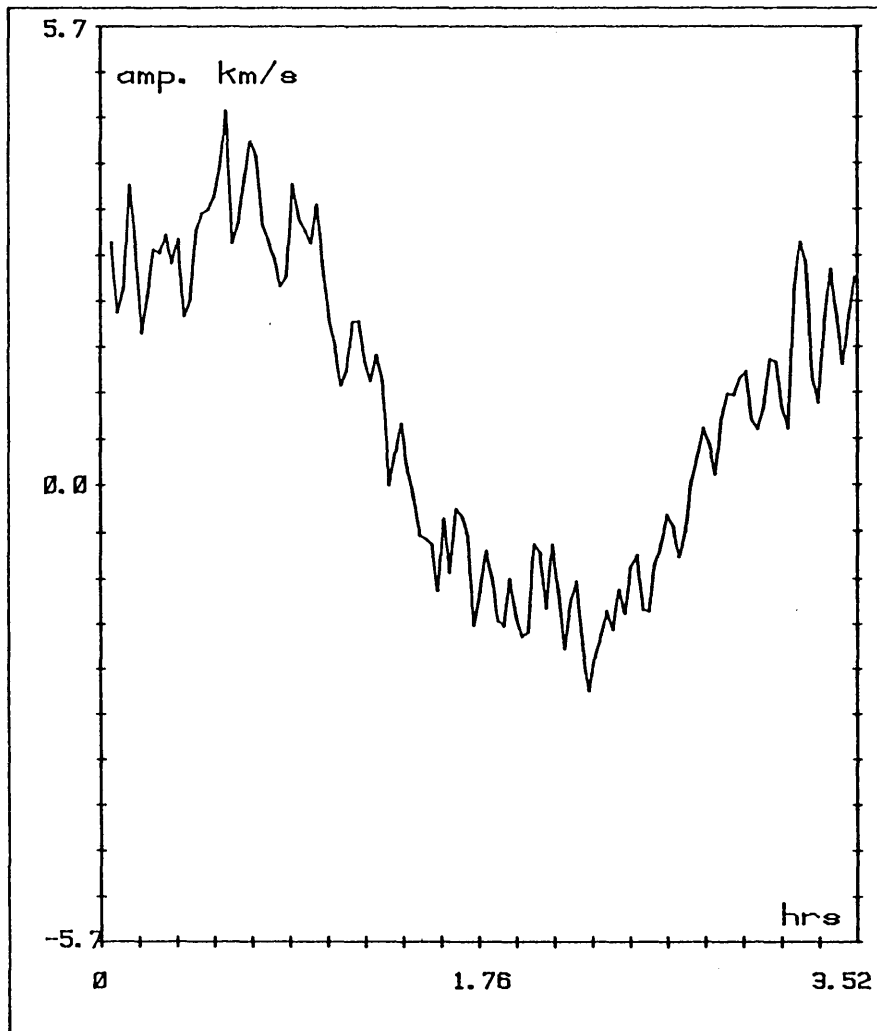


Figure 4.10(a).
Radial velocity curve of Delta Del.
Data of 18.10.83 starting 20:03:45.

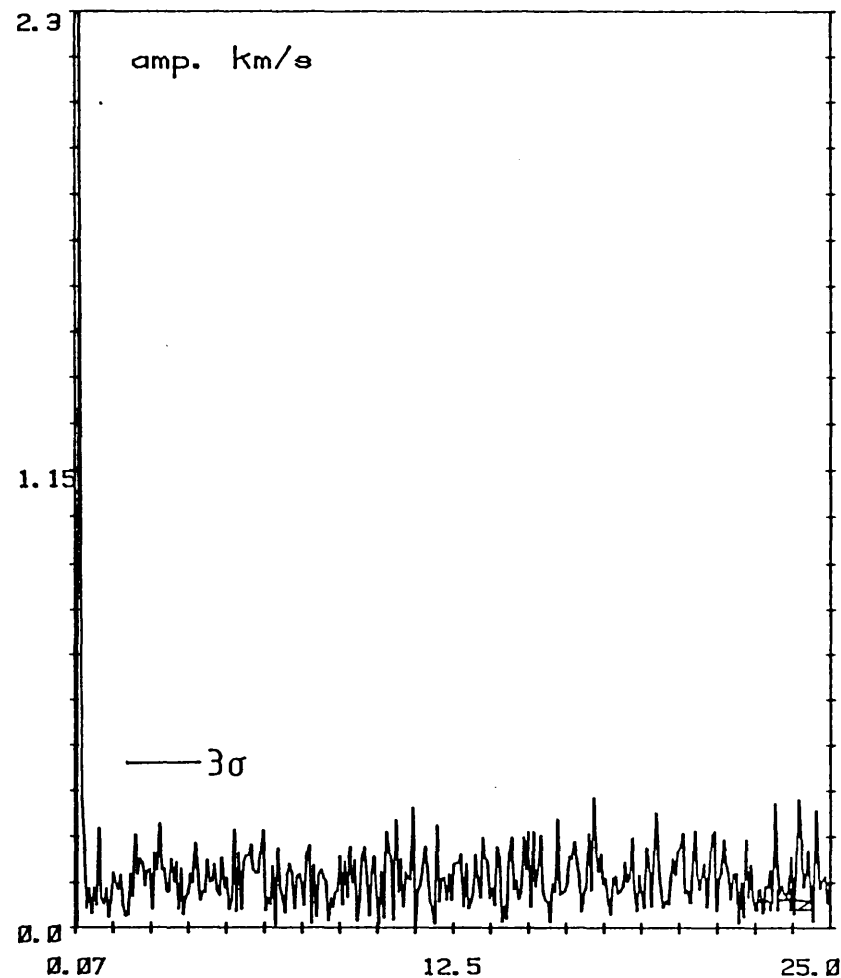


Figure 4.10(b).
Fourier Transform of data opposite.

4.8. β Cassiopeiae HR 21.

β Cas was observed for 4.99 hours during the run on the 1.5m I.R.F.C. at the Observatorio del Teide in Tenerife in October 1983 as a direct comparison of the technique used by Yang et al (1982), described in section 4.8.1 below. Also since its rotational velocity is high i.e. $v \sin i = 70 \text{ kms}^{-1}$ (Millis, 1966) and a broad line can be expected β Cas was observed to gauge the performance of the instrument with a broad-lined star.

β Cas has a visual magnitude of 2.27 and a spectral type F2III-IV.

4.8.1. Previous Observations Of β Cas.

Mellor (1917) suggested that β Cas was variable with a velocity amplitude of 2 kms^{-1} and a period of 27 days, typical of a binary star. However Abt (1965) found it to be a typical F2IV star and concluded that there was no evidence of binary motion. Millis (1966) observed β Cas photometrically and found variability in the light curve, typical of Delta Scuti type stars, with a period of 2.503 hours. Recent measurements of the radial velocity by Yang et al (1982) using the HF absorption cell (discussed for Na vapour in section 1.4.6) following 2 cycles of the oscillation show a period of 2.5 hours and an amplitude dependant upon the observed line or lines. Yang et al claim a precision of 0.2 kms^{-1} .

4.8.2. The Radial Velocity Curve Of β Cas.

The radial velocity curve of β Cas is shown in figure 4.11(a). This shows the 4450 points (collected at the rate of 4.043 seconds per point) binned into groups of points with integration times of 40.4 seconds and shows two complete cycles of the oscillation. The period is 2.5 hours and the amplitude 7.08 kms^{-1} . The noise level in the data is 150 ms^{-1} . This

value of the noise is calculated for the whole data and is an overestimate. A sample of a few points sets the noise level at about 60 ms^{-1} when the oscillation does not dominate the calculation. An interesting feature of the velocity curve is its resemblance to a "sawtooth" waveform. This implies that harmonics should be present of some integral multiple of the basic period. Smoothing the data with a 50 point running average ($q = 50$ in appendix 3.5) produces a more sinusoidal appearance as can be seen in figure 4.12(a). Smoothing will produce such effects and destroy information of higher frequencies and must therefore be used carefully. The noise level on the smoothed data is 118 ms^{-1} (less than the unsmoothed value).

4.8.3. The Velocity Spectrum Of βCas .

Figure 4.11(b) shows the Fourier Transform of the data with a peak at $k = 2$ i.e. 2.50 hours and semi-amplitude 3.9 kms^{-1} . There are no other significant peaks thus ruling out any harmonics with amplitudes greater than the noise. The sawtooth waveform can be simulated by the series;

$$f(x) = \sum_n \frac{1}{n^2} \sin nx$$

where n are odd integers. The first harmonic ($n = 3$) should be at 50 minutes, 0.33 mHz, $k = 6$, with an amplitude of about 430 ms^{-1} , just below the 3σ level. There is no peak approaching this amplitude at this point ($k = 6$).

The Fourier Transform of the smoothed data shows much less detail and only one significant peak at $k = 2$.

4.8.4. β Cas - Conclusions.

The data collected on β Cas show an oscillation of period 2.5 hours and amplitude 7.09 kms^{-1} . There is no evidence of any other periodicities present in the Fourier Transform of the data. The period of the oscillation agrees excellently with previous values (section 4.8.1). However, the amplitude is a factor of about 3 too large. This is due to the difficulty of calibrating the system with the line in β Cas, which is broad and produces a steep sided and shallow instrumental profile.

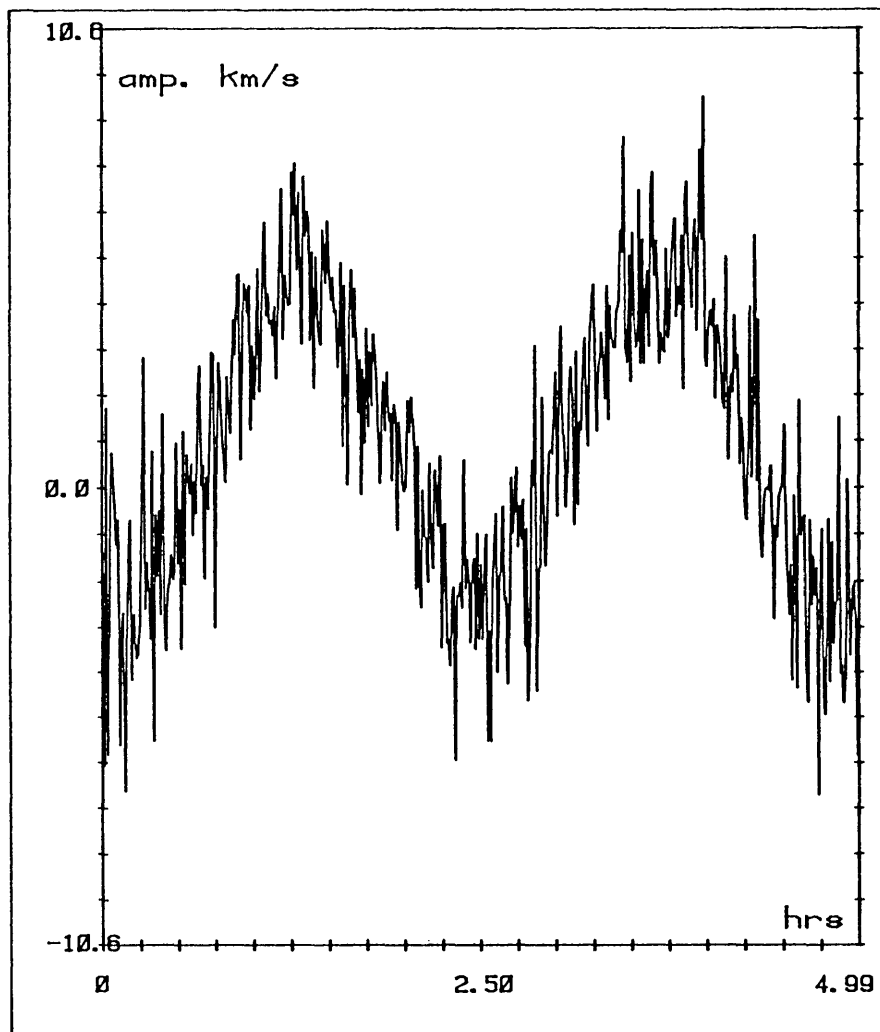


Figure 4.11(a).
Radial velocity curve of Beta Cas.
Data of 18.10.83 starting 00:06:30.

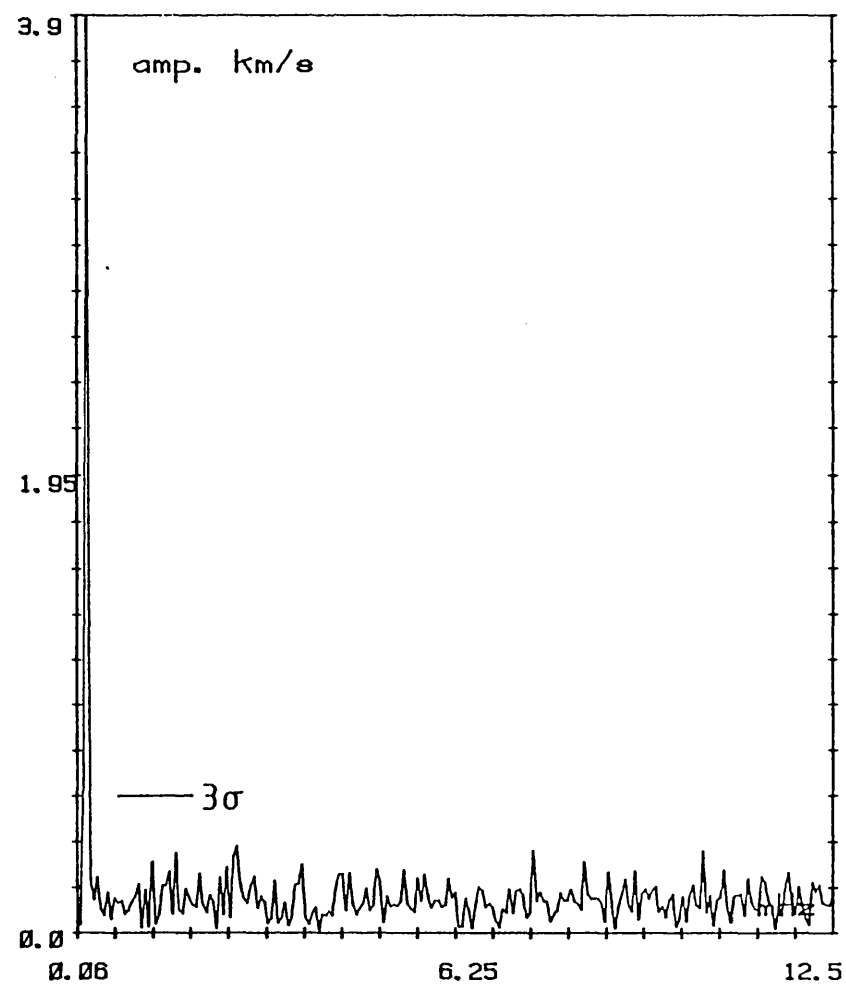


Figure 4.11(b).
Fourier Transform of data opposite.

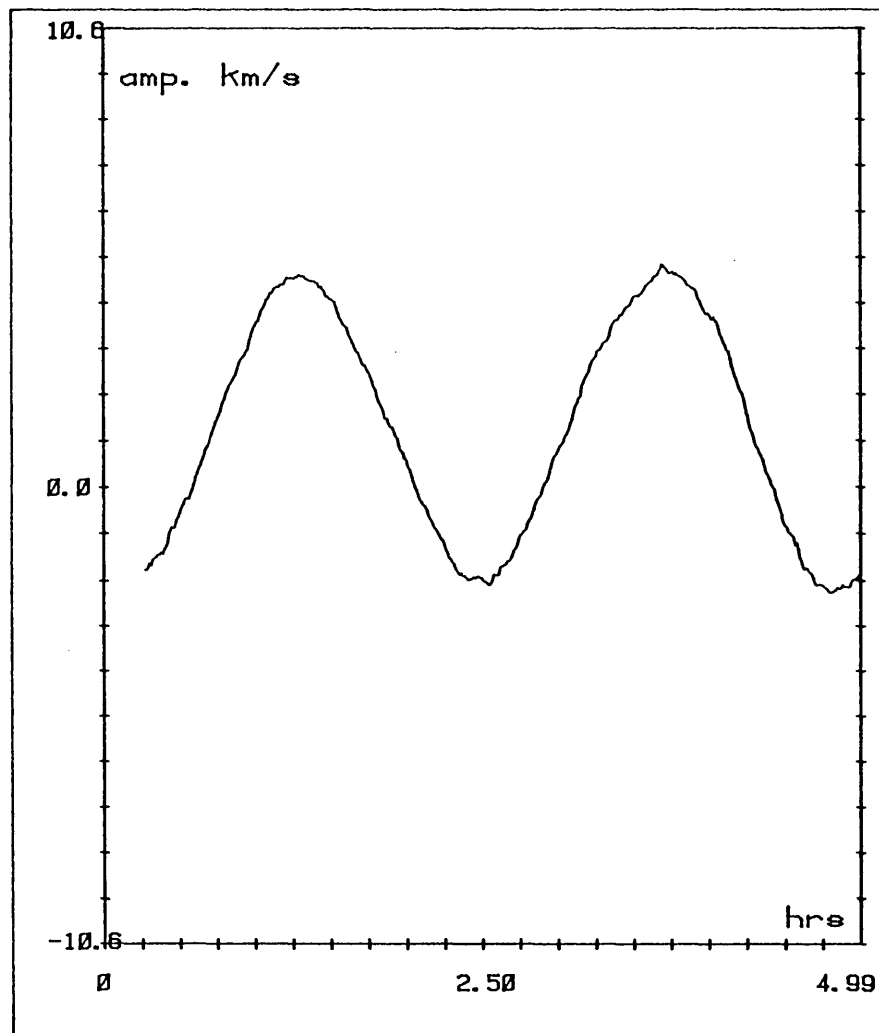


Figure 4.12(a).
Same as for figure 4.11(a).
Smoothed with a 50 point running mean.

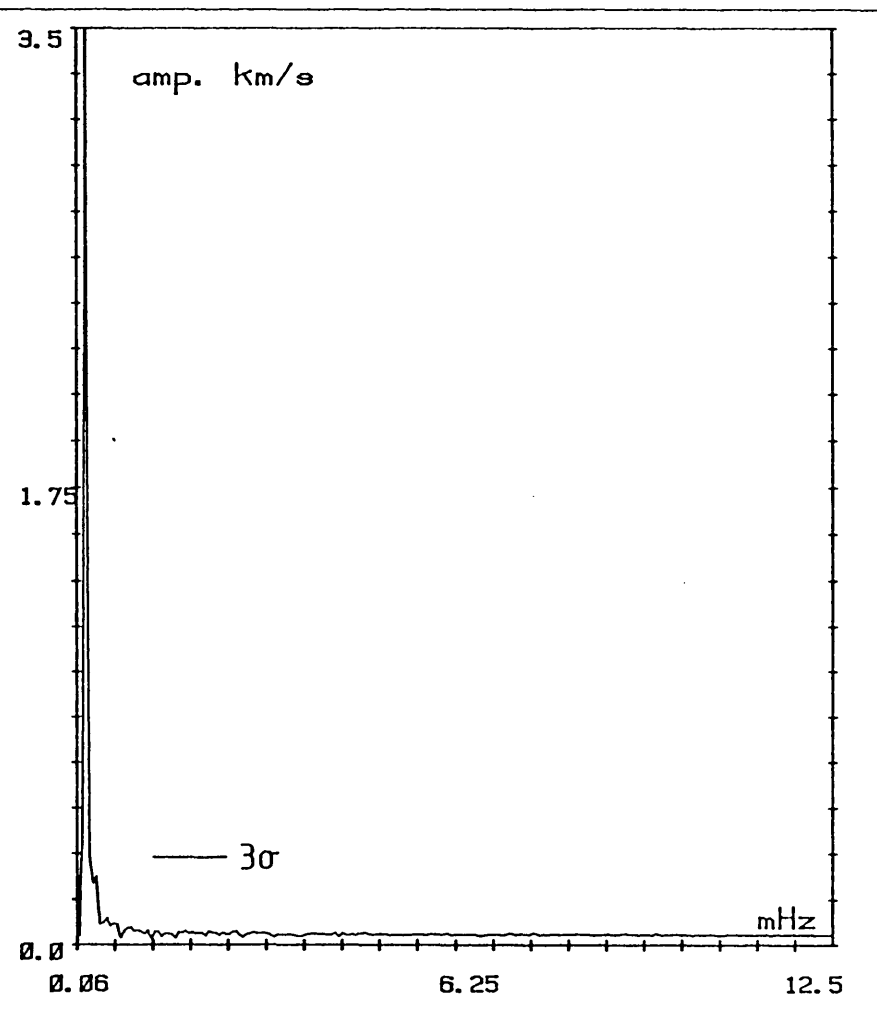


Figure 4.12(b).
Fourier Transform of data opposite.

4.9 β Aquilae HR 7602

β Aql was observed for up to 3.28 hours on 4 separate nights during the run on the 1.5m I.R.F.C. at Observatorio del Teide in Tenerife in October, 1983 for the purpose of following up the observations done a few months earlier by Forrest (1983) (described in section 4.9.1 below).

β Aqu has a visual magnitude and spectral type of 3.71 and G81V respectively.

4.9.1 Previous Observations of β Aql.

β Aql has only been observed once before, by Forrest (1983), in order to determine its radial velocity curve. Various rapid variations of the order of 200 ms^{-1} and periods of tens of minutes were found using the Michelson Interferometer, discussed in section 1.4.8, on U.K.I.R.T. with observations lasting up to ~8 hours.

4.9.2 The Radial Velocity Curves of β Aql.

The radial velocity curves of β Aql are shown in figures 4.13(a), 4.14(a), 4.15(a) and 4.16(a). The observed line in β Aql is deep and narrow and allows a good sensitivity to changes in radial velocity and hence lower noise levels than most of the other stars observed. The largest value of the noise for any of the observations is 52 ms^{-1} for the observations on the 16th. October 1983. Examining each of the velocity curves reveals no large radial velocity changes as for β Cas (section 4.8), for example, the only variations are linear slopes due to drifts (section 2.6) or the Earth's rotational velocity.

4.9.3 The Velocity Spectra of β Aql.

The velocity spectra are shown in figures 4.13(b), 4.14(b), 4.15(b) and 4.16(b). The Fourier Transforms show peak semi-amplitudes from about 0.2 to 0.8 kms^{-1} . Figure 4.16(b) shows an apparently lower noise level due to the large drift present in the data. No significant features can be seen in any of the β Aql Fourier Transforms.

4.9.4 β Aql - Conclusions.

There are no significant features present in the data acquired on β Aql. The noise levels attained range from -35 to -50 ms^{-1} . The periodicities found by Forrest (1983) cannot be confirmed from these data. Further observations at a larger telescope for longer periods of time are needed to improve the quality of the data and attempt to identify any periodicities.

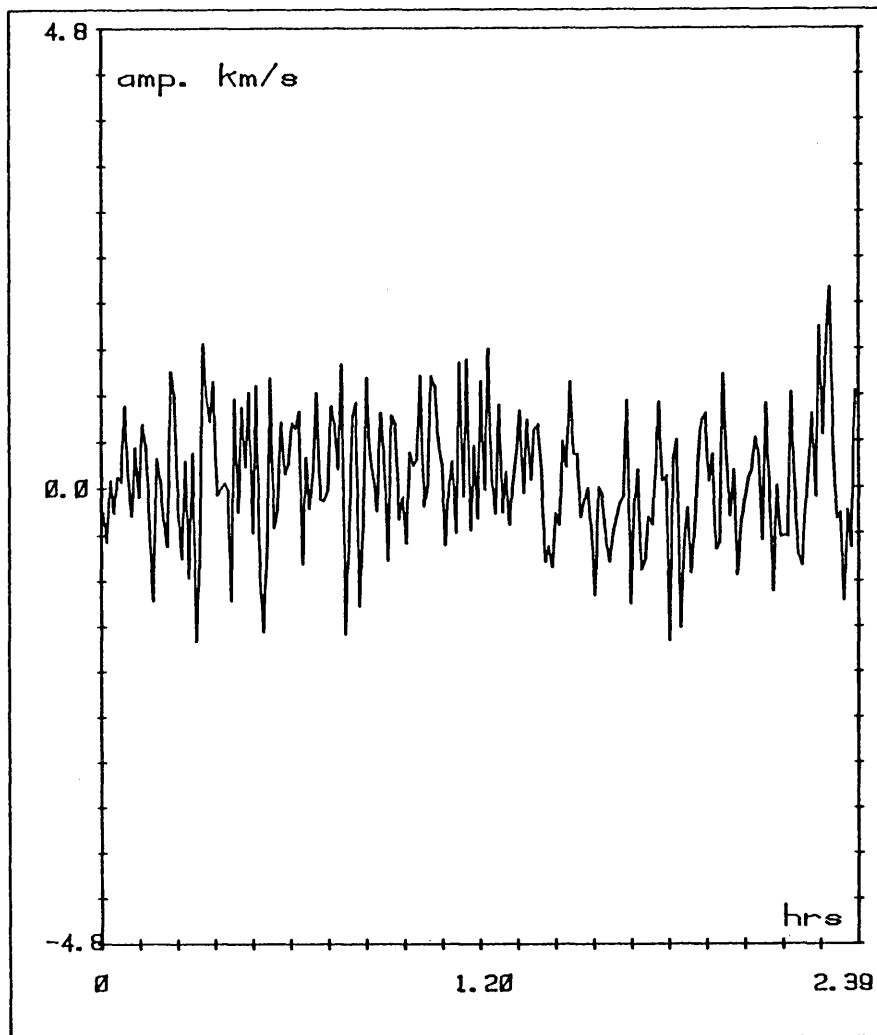


Figure 4.13(a).
Radial velocity curve of Beta Aqu.
Data of 11.10.83 starting 21:07:30.

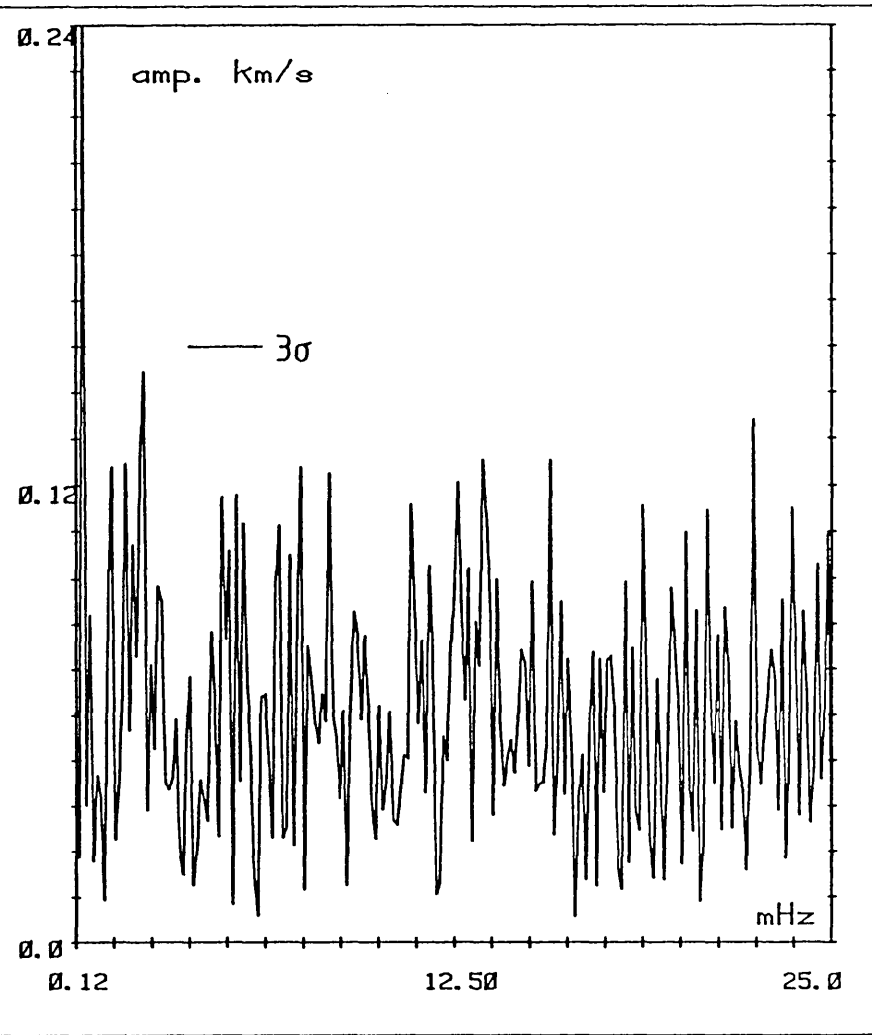


Figure 4.13(b).
Fourier Transform of data opposite.

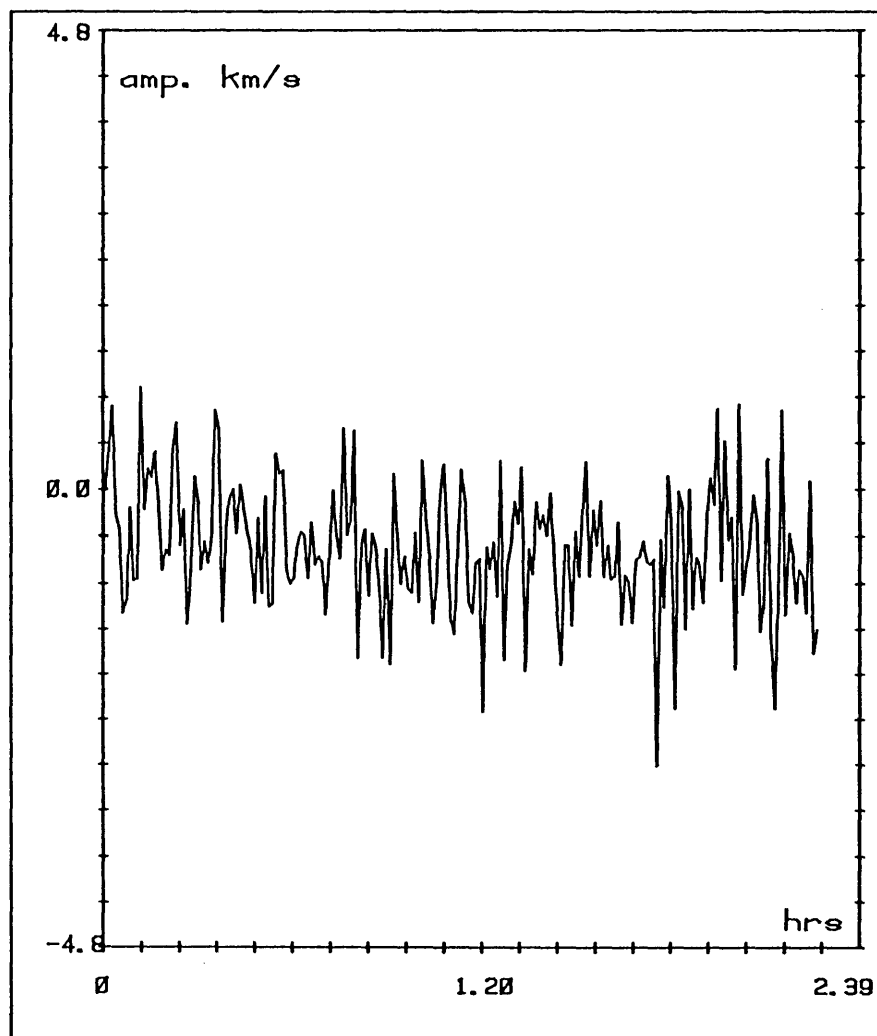


Figure 4.14(a).
Radial velocity curve of Beta Aqu.
Data of 13.10.83 starting 21:40:30.

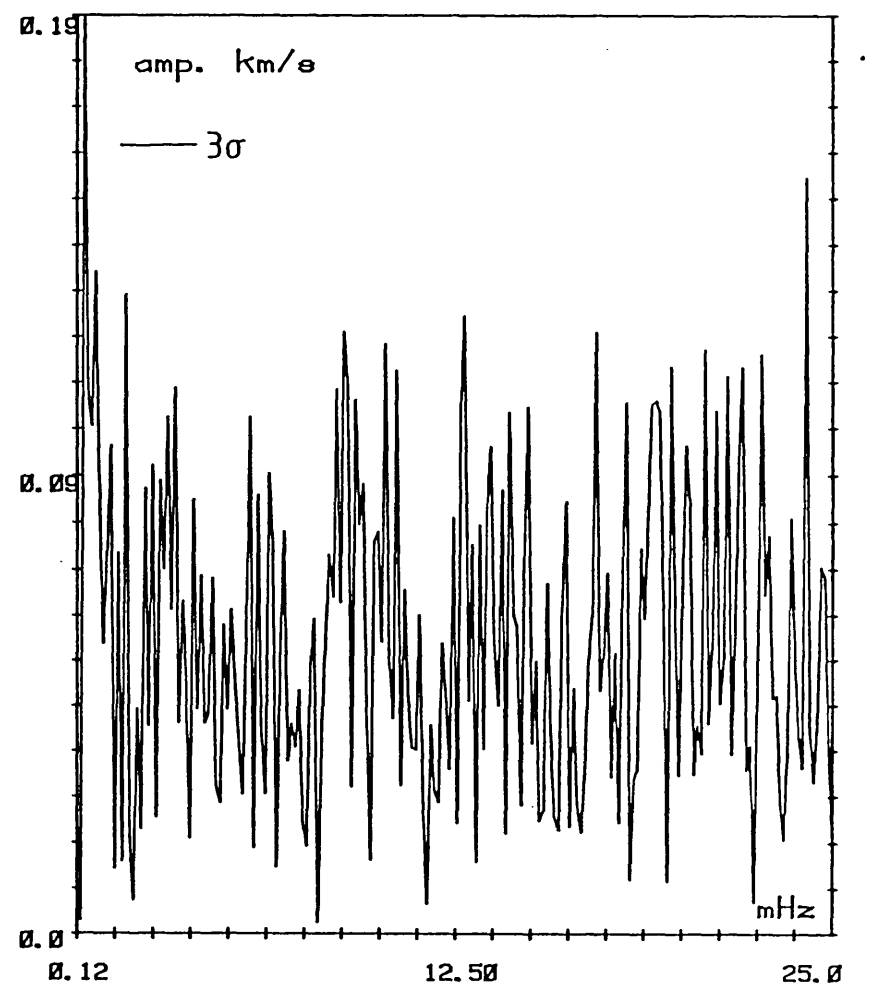


Figure 4.14(b).
Fourier Transform of data opposite.

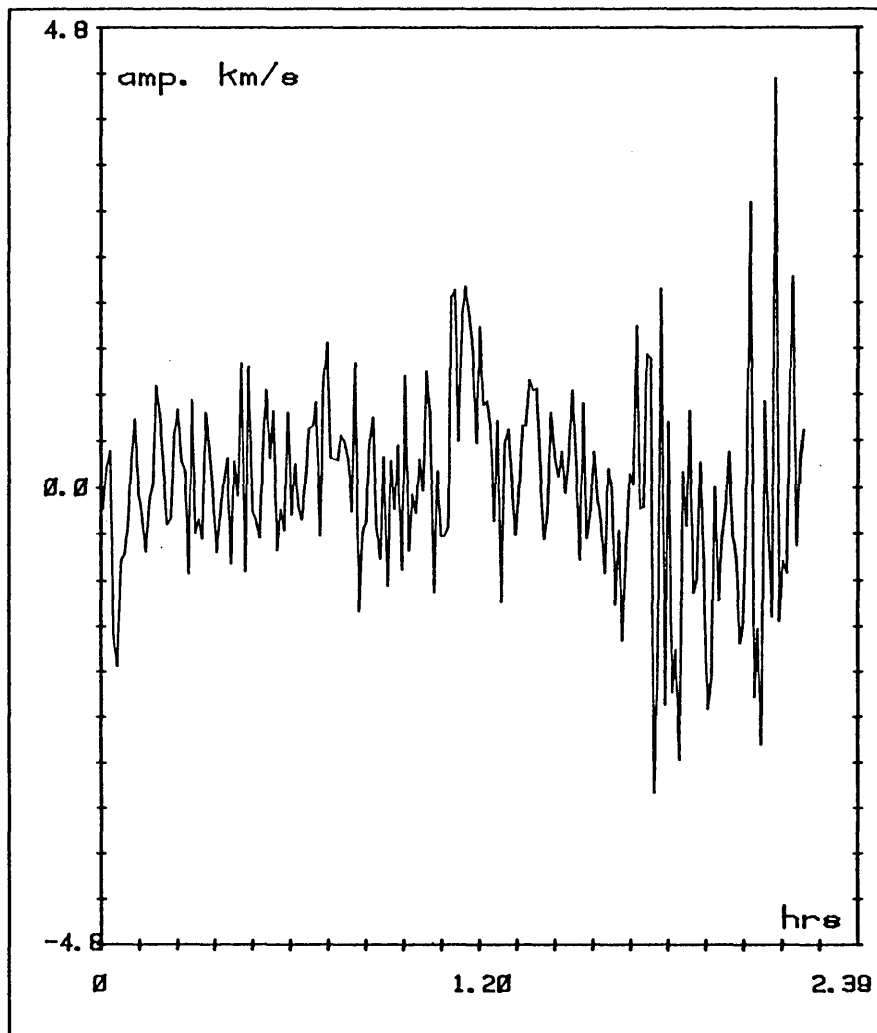


Figure 4.15(a).
Radial velocity curve of Beta Aqu.
Data of 16.10.83 starting 20:32:00.

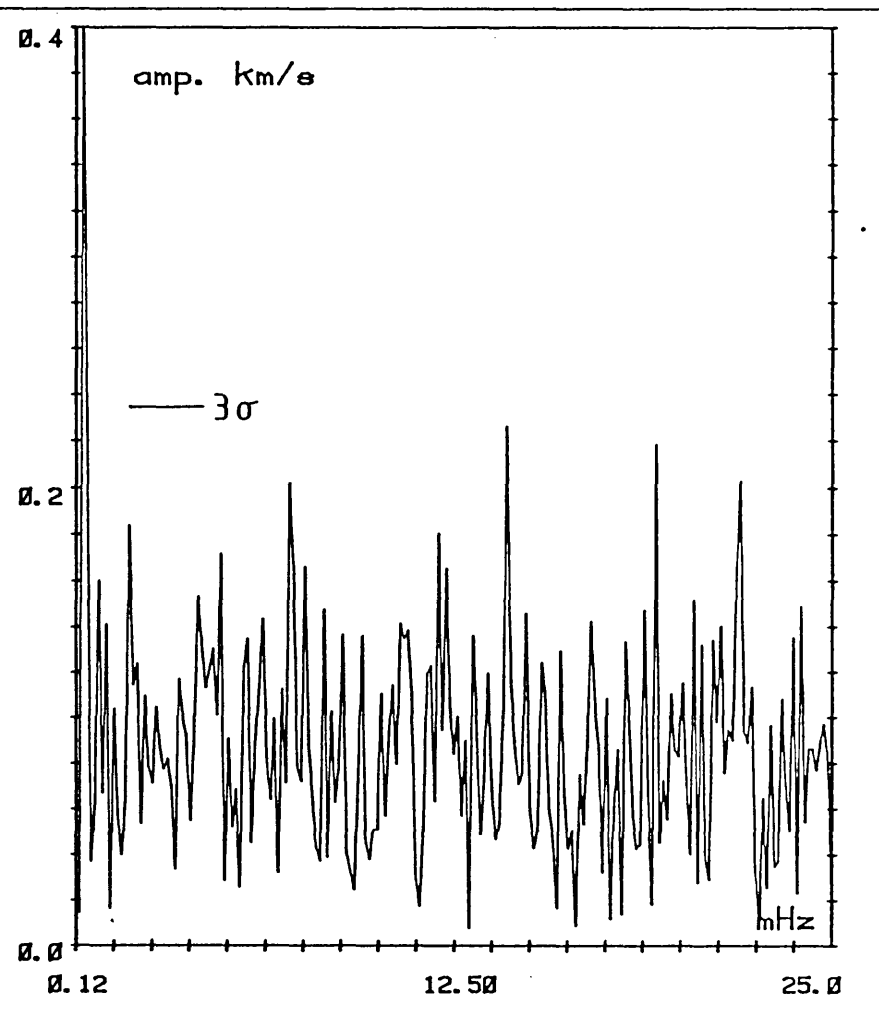


Figure 4.15(b).
Fourier Transform of data opposite.

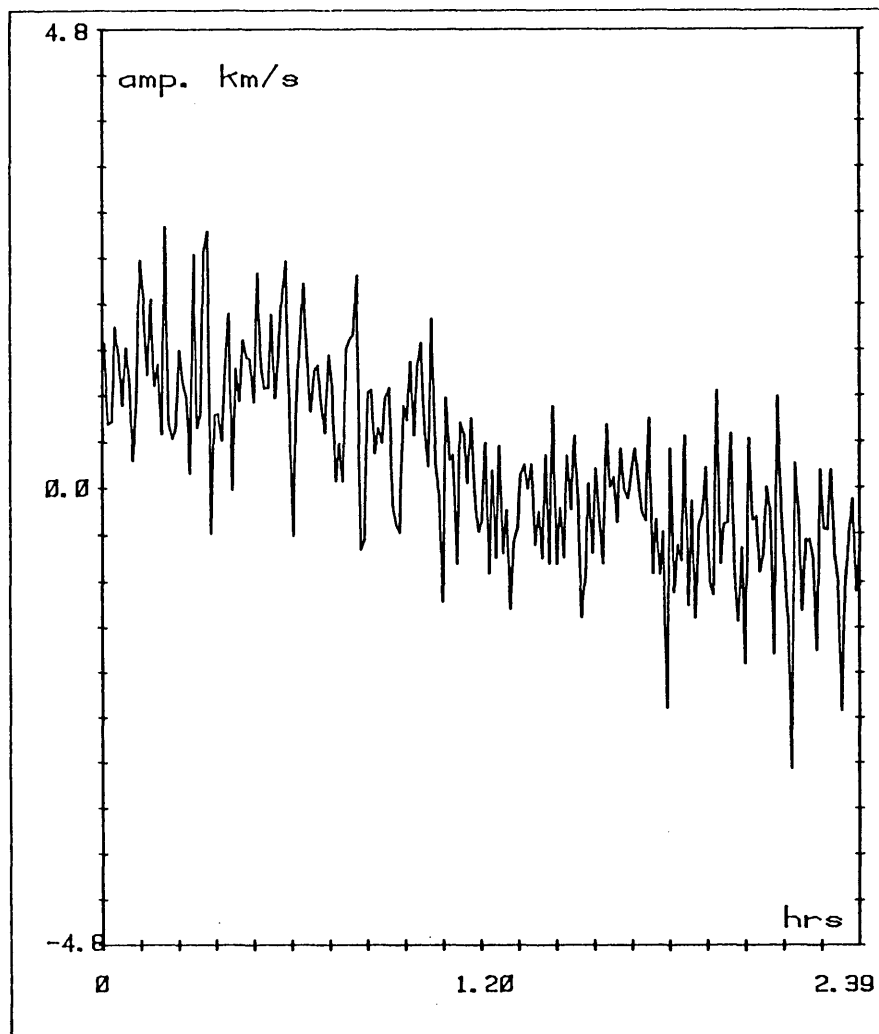


Figure 4.16(a).
Radial velocity curve of Beta Aqu.
Data of 17.10.83 starting 20:21:30.

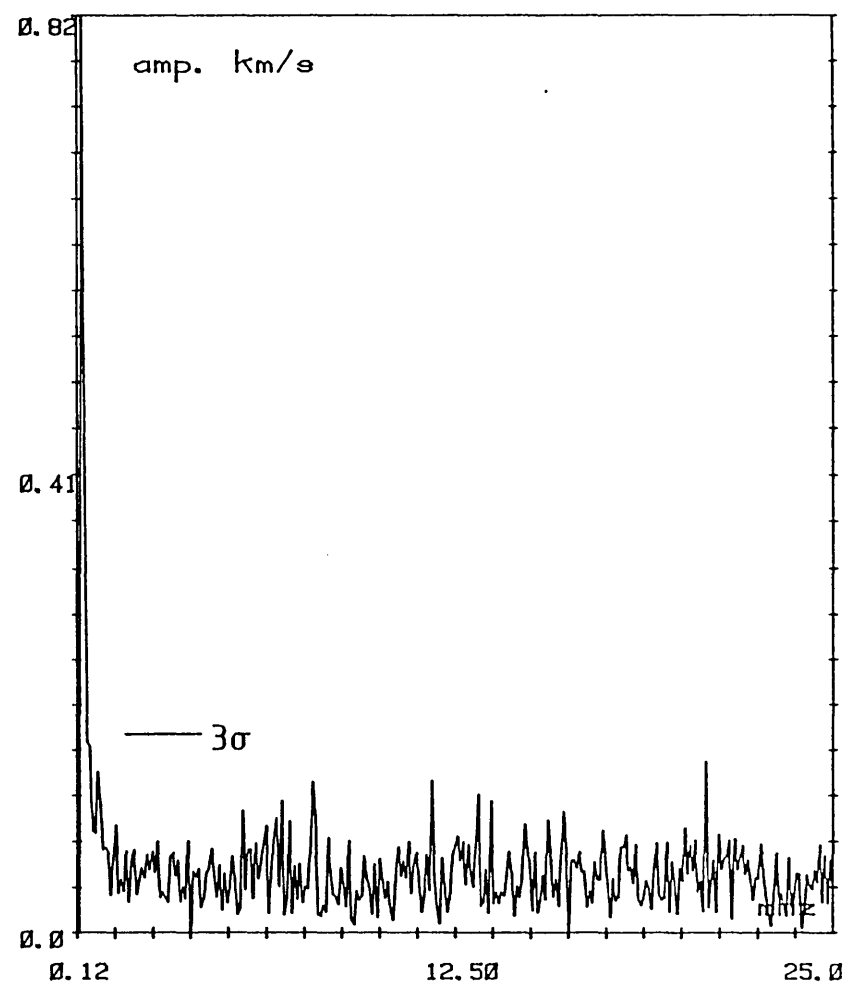


Figure 4.16(b).
Fourier Transform of data opposite.

4.10. Summary of The Astronomical Data.

In all eight stars have been observed using the Fabry-Perot spectrometer described in chapter 2. Table 4.1 below summarizes the results obtained for these stars and lists some of their properties.

<u>Star.</u>	<u>Mv.</u>	<u>Sp. Type.</u>	<u>Known Periods.</u> <u>Amp. kms⁻¹</u>	<u>Periods Found.</u> <u>Amp. kms⁻¹</u>	<u>noise ms⁻¹</u>
α Car	-0.9	F0II	none	none	30
α Cir	3.19	F0p	6.8 min (P)	6.8 min ? 1.6?	180
ρ Pup	2.81	F5IIp	3.38hrs ~10	3.39hrs 8.99	176
44Tau	5.41	F2IV-V	3.48hrs(P) 2.51hrs(P)	2.88hrs 13	176
14Aur	5.06	A9V	2.1hrs	2.093, 1.068hrs 2.9, 0.48	107
δ Del	4.43	F0IVp	3.24 5.5	3.244 4.9	96
β Cas	2.27	F2II-IV	2.5 2	2.5 7.08	150
β Aql	3.71	G8IV	10's mins ~0.2	none	>50

(P)-photometric periods only.

Table 4.1. A Summary of the Stars Observed.

CHAPTER 5

FUTURE DEVELOPMENTS.

5.1. Introduction.

There are many possible ways in which the instrument described in Chapter 2 can be used and improved in the future. Some of the possibilities are open for immediate exploitation such as simultaneous radial velocity and photometry whereas others require long term planning and significant alterations to the mechanical structure of the instrument. This chapter aims to discuss these possibilities in two parts, those immediately possible and those that are possible at a later stage.

5.2. The Immediate Future.

5.2.1. Simultaneous Spectroscopic and Photometric Observations.

The variable stars described in Chapter 1 are all likely to have variable light and radial velocity curves although the variability may be more easily detected photometrically for very low amplitude oscillations. The relationship between light and velocity curves is usually given in terms of a relative phase, i.e. the phase between maxima of light and radial velocity curves. By observing the same star with two different, but nearby telescopes (or even the same telescope), the velocity and light curves can be recorded simultaneously. As two separate instruments and data acquisition systems need to be used, accurate timings of the beginning and the end of the runs in both cases are needed. This enables the relative phase to be calculated most precisely. A purpose built instrument using the same light paths, etc. on a telescope would be the ideal situation but as yet there is no such instrument.

More important, however, than the relative phase of the light and velocity curve is the ability to deduce the mean stellar radius from them using a Wesselink type method. This method is described below.

5.2.2. The Wesselink Method for Determining Stellar Radii.

The Wesselink method requires both radial velocity and light curves to be measured simultaneously. The underlying assumption of the method is that the colour index, B-V, of the star is a unique monotonic function of its effective temperature and that the bolometric correction,

$$m_v - m_{bol} ,$$

is a unique monotonic function of the colour index.

This implies that, at different phases, when the star has the same colour index, it will have the same effective temperature, T_e .

In general, however, the apparent magnitude of the star at such phases will be different. This difference gives the ratio of luminosities, and consequently, radii at the two phases, i.e.,

$$\begin{aligned} \Delta m_v &= m_{1v} - m_{2v} \\ &= m_{1bol} - m_{2bol} \end{aligned}$$

since

$$m_v = BC + m_{bol}$$

where BC is the bolometric correction and m_{bol} is the bolometric magnitude.

The ratio of luminosities is;

$$2.5 \log \frac{L_1}{L_2} = m_{2\text{bol}} - m_{1\text{bol}}$$

$$= \Delta m_V$$

Also,

$$\log \frac{L_1}{L_2} = 2 \log \frac{R_1}{R_2}$$

assuming

$$L = \sigma T_e^4 4\pi R^2$$

and,

$$\sigma_1 = \sigma_2$$

σ = Stefan's constant

and,

$$T_{e1} = T_{e2}$$

Therefore;

$$\Delta m_V = 5 \log \frac{R_1}{R_2}$$

Integration of the radial velocity curve between the two phases gives the difference in radii, ΔR . Thus knowing that

$$\Delta R = R_2 - R_1$$

and the ratio of the radii, q ,;

$$q = \frac{R_2}{R_1}$$

R_2 and R_1 can be found.

Also, the mean radius can be found from the displacement curve.

Among the objections raised to the Wesselink method, as pointed out by Evans (1976), was that radial velocities are determined by the motions of the region where FeI lines are formed and may not represent the motions of the surface of the star. Also, the colour index may not be a unique function of temperature, being affected by electron pressure, turbulence and effective gravity. Wesselink (1946) also considered this problem in the case of δ Cephei, but dismissed it on the evidence of Brück and Green (1941), who studied spectrographic plates of sufficient resolution to show single lines and not blends, but found no evidence to show variable velocity through the star's interior.

Fernie and Hube (1967) suggested that without simultaneous spectroscopic and photometric observations problems in phase matching data (by different workers) with errors of 0.05 periods and separated by many cycles would introduce intolerable errors into the determination of radii. Variable stars with apparently variable periods would suffer such errors if simultaneous observations do not exist.

A period-radius relation can be built up for a class of variable stars such as the one by Evans (1976). The above applies to radially pulsating stars. For the application to non-radially oscillating stars see Balona and Stobie (1979).

5.2.3. Line Profile Variations.

The technique of rapidly scanning a stellar line (Section 2.5.5), enables the line profile to be determined in a small fraction of the star's period. For example, 1.4% photometric accuracy can be attained in about 400 seconds on the 5th. magnitude star 44 Tau, on a 1.5m telescope, which allows a maximum of about 20 profiles to be collected in one period, i.e. 0.12 days. The radial velocity curve could be reconstructed from the changes in the centre of gravity of the line profiles. By changing the pre-filter and etalon combinations, broader or narrow lined stars could be investigated in this way.

Yang et al (1982) have reported profile variations during the cycle of the CaII line in the Delta Scuti star β Cas (see also section 4.8), these variations being well correlated with maxima and minima of the radial velocity.

It would therefore be interesting and profitable to investigate this phenomenon in other Delta-Scuti type stars with the rapid scanning technique.

5.2.4. Cluster Dynamics.

An interesting and, perhaps, ambitious problem would be to measure radial velocities of individual stars in globular clusters to provide dynamical data for theorists developing models of such objects. Assuming each of the stars in any globular cluster have the required line, then by observing the stars, relative radial velocities may be mapped. For an absolute calibration a nearby standard radial velocity star must also be

periodically observed. If a sufficiently large telescope were used, the brightest stars in the globular cluster could be observed to an accuracy of about 1kms^{-1} in 10-15 minutes. Such stars would inevitably be dim, 9th. or 10th. magnitude.

Such velocity measurements are just possible if a large telescope and a fairly bright cluster could be found.

Gunn and Griffin (1979) have observed the globular cluster in M3. Data such as the distance, mass distribution and mass spectrum as well as velocity data need to be collected for a model of the system. Such a project is non-trivial and would require a large amount of observing time although it seems within the bounds of the instrument described in Chapter 2 to make these velocity measurements.

At present, measuring individual stars only is possible and would take an enormous amount of telescope time. All, or a large number of the stars in a cluster could, however, be observed with an imaging FP and multipoint detector made as stable as the instrument described in Chapter 2. This would speed up the work and make the observations of many stars simultaneous and not prone to noise such as bad patches of weather between observations.

5.2.5. Binary Stars.

A more pedestrian goal would be the study of binary stars. More accurate velocity measurements could easily be made for short period close binaries. Much work has been done on binary stars including Abt (1965) and Proust et al (1981) who have compiled a catalogue of visual binary stars which have other variability also.

5.2.6. Instrumental Improvements.

A simple to implement improvement to the instrument would be the use of a single board computer (SBC) to control all the routine functions of the instrument such as photon counting, dumping data to digital cassette and chart recorder, etc. This type of improvement represents a trend in the Imperial College Astronomy Group that would enable the user of an instrument to have more completely reduced data at the end of the night than is usual.

This is possible since, while the SBC carries on its routine functions, a second, more powerful, computer can be used to reduce the incoming data independently of the instrument and of 'on-site' computer facilities, if any. Such an improvement can be made in a very short time.

5.3. Medium Term.

5.3.1. Standard Wavelength Source.

A very stable source of some convenient wavelength would allow periodic calibration of the instrument. Such a source would have to be constant with respect to the instrument over long periods of time. Two possibilities for choice of wavelength exist. The simplest choice would be to make the standard line similar to the stellar line. This would be done using a solid Fabry-Perot etalon of the correct thickness. For the present instrument an 'emission' line every $3\text{\AA}$ would give two or three peaks within the filter profile. One of these could be chosen as the standard and periodically a reference chop would be made on this line. The correction obtained from the reference chop could be used as the error signal for the CS100 servo or just recorded for later treatment of the data. In order to use the correction as an error signal the CS100 would

require modification to increase its resolution when changing the gap.

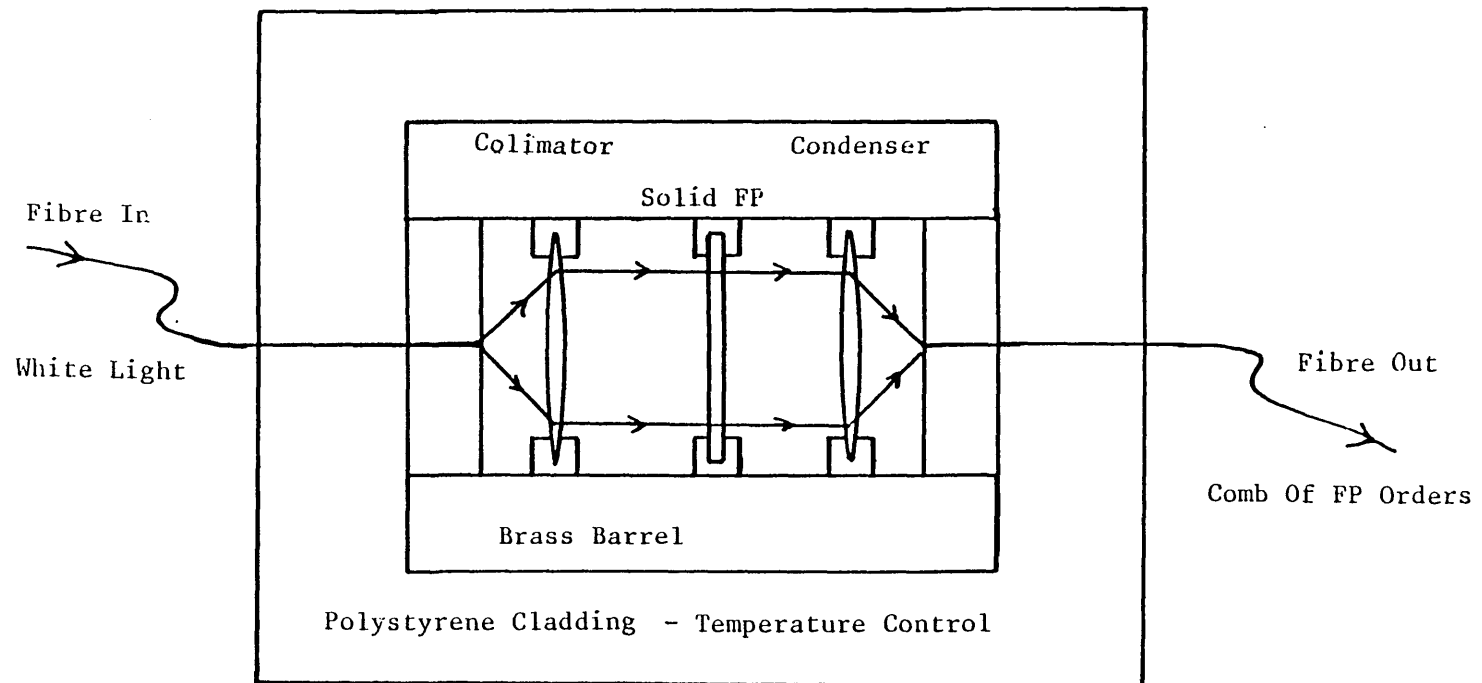
A method of switching in the standard source and excluding the stellar line would have to be used (a system of electronic shutters would be suitable). A further requirement is that the light from either source should travel the same path to the detector. This can be achieved in two ways, namely, the standard source can be placed at the telescope and focused onto the fibre or that a special fibre be constructed with the usual single core surrounded by many fibres of smaller diameter forming a bundle at the standard source. The advantage of the second method is that the source can be situated in a mild environment. The fibre would have to be so constructed that the outer fibres of the bundle would still conform with the Jacquinet Criterion (equation 2.9). Such a standard is available and has been tested (Bell 1983a) and is shown schematically in figure 5.1. A more elaborate system would have the standard wavelength different to the stellar wavelength passing through the system continuously. A dichroic beam splitter just before the detector would then separate the standard wavelength and reflect it to a second detector. A similar system is used by Forrest (1982). A second detector would require the instrument to be rebuilt and the computer software to be expanded.

5.3.2. Use of Many Stellar Lines.

By introducing more stellar lines to the instrument an improvement in efficiency would result. For n lines the improvement would be $\sqrt{n}$.

The filter which isolates the single stellar line would be replaced by a spectrograph. The extra lines would be fed to the instrument along individual fibre optics leading from a specific hole in a mask in the focal plane of the spectrograph. Each of the lines would naturally be at a different wavelength and if passed to the instrument would show as

Figure 5.1 Standard Wavelength Reference Source.



different lines. This would form a very confusing picture from one order to the next. By putting each fibre at a slightly different angle to the axis the lines can be made to superimpose. This can be seen from equation 2.4,

$$2nt\cos\theta = m\lambda$$

The positioning of these fibres must be very accurate and the stability of the spectrograph must be good.

Work is being done on such a spectrograph system (Bell 1983b).

5.3.3. Detection of Extra Solar Planets.

A long term project requiring much work and preparation is the detection of extra solar planets. An instrument which is very stable indeed i.e. has a standard reference and has a multiplex advantage would be used to observe a programme of many candidate stars and many standard stars every 2 or so months for a period of 10-20 years. The stability of an instrument would have to be so good as to allow a velocity of about 12ms^{-1} over 10 years, as for Jupiter orbiting Earth, to be detected in one or more stars. Over such a long period the question of detector deterioration and the ageing of electrical components and optical coatings becomes very important. An instrument would have to remain in an effectively unchanged condition over a very long period. Much interest has been shown by Campbell and Walker (1979), Griffin and Griffin (1973), Serkowski (1976) and NASA Workshop (1980) in the detection of extra solar planets.

APPENDICES

```

      program conv2
c program to convolve the two functions defined by
c the subroutines fabry and star.
c the program takes two convolution integrals and
c finds their numerical difference as a measure of
c slope (sensitivity to radial velocity) and also
c finds their mean value as a measure of area(flux)
c
      common conv(500),sl(500),fp(1000)
      real*8 sum1,sum2,diff
c
c define wavelength step
c
      dl=0.033e-10
c
c input width of stellar line
c
      type *, 'width in Angstroms'
      accept *,angstm
      halfw=angstm*1e-10
c
c input the depth of the stellar line
c
      type *, 'depth as a percentage'
      accept *,adepth
      deeth=adepth/100
      type *, 'halfw,deeth'
      write(7,*)halfw,deeth
c
c call the star array into existence
c
      call star(halfw,deeth)
      type *, 'write to file'
      type *,
c
c open file for data
c
      call assign(3,'itemp.ksp',-1,'new')
      l=20
      do 20 i=1,20
      m=50*i
c
      sum1=00
      sum2=00
      call fabry(m,halfw,s,sep)
c
c convolve sl and fp at the two places
c

```

Appendix 2.1. Programme used in the determination of spectral resolution of the interferometer.

```

      do 30 k=1,500
c
c use fp(k+250) because fp array is
c 2times larger than sl array
c
      conv(k)=sl(k)*fp(k+242+1+1)
      sum1=sum1+conv(k)
30    continue
c
      do 40 k=1,500
      conv(k)=sl(k)*fp(k+242+1)
      sum2=sum2+conv(k)
c
40    continue
      diff=sum2-sum1
      slope=diff/y
      smean=(sum1+sum2)/2
      signal=slope*sart(smean)
      axis=sax/y
c
c write data to file
c
      write(3,*) alog10(axis),-1*signal
20    continue
      call close(3)
      stop
      end
      subroutine star(halfw,depth)
c
c subroutine to simulate a gaussian line profile of
c width halfw, position centre, and depth depth
c
      common conv(500),sl(500),fp(1000),ratio(2)
      real*8 centre,halfw,start,d1
c
c define the parameters
c
      centre=5319e-10
c
c define d1 as one step in CS100 servo positions
c for a 100 micron gap etalon as 0.033 A/point
c
      d1=0.033e-10
      start=centre-250*d1
c
c iterating 500 times to generate
c the gaussian profile
c

```

Appendix 2.1. Cont.

```

do 10 i=1,500
  t=start-centre+dl*float(i-1)
  a=t/halfw
  e=-4*0.69315*a*a
  sl(i)=1-depth*exp(e)
10  continue
  return
end
subroutine febre(m,halfw,w,sap)
c
c subroutine that generates the airy function for
c different values of the order m.
c
      common conv(500),sl(500),fp(1000),ratio(2)
      real*8 wave,lamba
      integer w
c
c define the parameters
c
      fines=30
      pi=3.141593
      dl=0.033e-10
c
c calculate the start wavelength, wave,
c to be 500*dl to the left of the line
c calculate the sap
c
      swave=5319e-10
      wave=swave-500*dl
      sap=swave*m/2
c
      v=(5319e-10**2)/(2*sap*fines*dl)
c
c set fp array to zero for the case when only
c one order is required the range must be
c selected in the next stage
c
      do 10 i=1,1000
        fp(i)=00
10    continue
c calculate distance between orders and define
c limits of iteration as +/-half inter order
c distance to exclude next orders
      v=(swave**2)/(4*dl*sap)
c
c truncate v

```

Appendix 2.1. Cont.

```

      w=int(v)
      if(w.le.499) goto 3
      w=499
c
c iterate to produce the airy function
c
3      do 20 l=500-w,500+w
         lambda=wave+d1*float(l)
         pex=2*pi*gap/lambda
         a=sin(pex)
         b=(2*k*fines/pi)**2
         f(l)=1/(1+b)
20     continue
      return
      end

```

Appendix 2.2. Development Instrument.

As a design study the following instrument was assembled. It was of a cheap and cheerful construction. The housing of the instrument comprised a large aluminium box previously used for an imaging Fabry-Perot system (Atherton 1978 Ph.D. thesis). Within this frame a Fabry-Perot interferometer, a filter wheel and input/output optics were mounted. The input optics were not optimum for light collection but satisfied the Jacquinot Criterion (equation 2.12). The Fabry-Perot etalon had a nominal gap of $400\text{ }\mu\text{m}$ i.e. a nominal resolution of 50,000, suited well to observing stellar lines of $0.1\text{ }\text{\AA}$ FWHM. Such lines are to be found in the sun. Light was fed to the instrument via an optic fibre and a RCA 31403A/02 type photomultiplier was used as the detector. The FP was enclosed in a cast iron pressure chamber which did not quite seal properly. A tin foil exit aperture was needed to remove extra images of the input caused by small angle reflections in the instrument. The whole instrument was enclosed in a large and clumsy polystyrene jacket in an attempt to minimise the effect of temperature changes. The main source of instability was the filter wheel. An inherited device that both tilted the filter and, if necessary, changed it to another. The repeatability of the position of any filter in the wheel was, at best, very poor.

This instrument was used with a little success to observe the solar $5317\text{ }\text{\AA}$ line and the 5 min. oscillations of the sun shown in figure A2.1. The lines present in Delta-Scuti type stars were too broad to be identifiable and could not be detected.

A few modifications were then made to the instrument, namely changing the etalon gap to $100\text{ }\mu\text{m}$ and changing the filter accordingly to be $10\text{ }\text{\AA}$ FWHM multi-cavity filter.

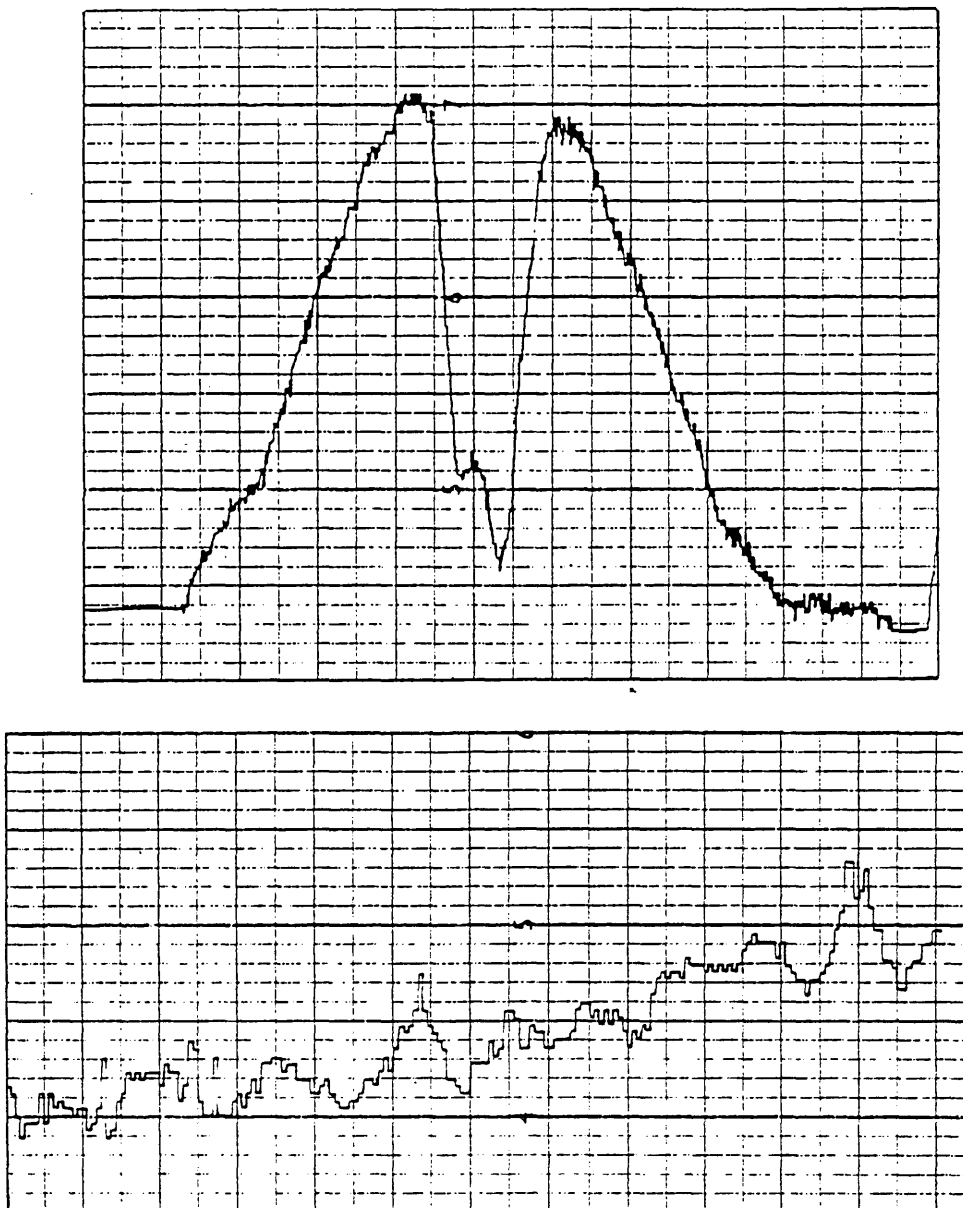


Figure A2.1. The 5317 Å line (top) in the Sun as seen with the 400 μm etalon and (bottom) a short run showing the 5 minute oscillation.

Other minor adjustments were also made.

Changing the gap to 100 μm enabled lines in Delta-Scuti stars to be observed with maximum efficiency (see chapter 2). However this made observations of solar lines very difficult. The solar line was previously used to check the filter alignment. After many difficulties the line at 5317 Å in 14 Aur and ρ Pup were observed but runs on these stars proved impossible due to a chance catastrophic failure of the servo system. The instrument was used in London to determine the effects of pressure and temperature on it. Control of the instrument was achieved using an AIM 65 microcomputer. The control programme was written wholly in Basic and this in itself introduced a large inefficiency of a factor of two due to the slowness of the Basic Interpreter used to convert the commands into machine code. Data was logged onto digital cassettes.

This instrument allowed the rapid scanning and chopping technique to be perfected and the necessary facts about stability to be learnt. The instrument of chapter 2 was then designed and built.

```

LIST
10 POKE 41988,16
20 POKE 41989,16
30 POKE 04,128
40 POKE 05,26
50 X=USR(N)
60 POKE 04,160
70 X=USR(N)
80 INPUT" 1=SCAN/0=
CHOP";Z
90 IF Z=1 THEN 2000
100 IF Z=0 THEN 100
0
110 GOTO 80
200 N=-N
210 NH=INT(N/256)
220 NL=N-256*NH
230 NH=15-NH
240 NL=255-NL
250 RETURN
300 POKE 7941,00
310 INPUT" 1 TO RES
ET";C
320 IF C=1 THEN 340
330 GOTO 530
340 INPUT" 1=CHANGE
SERVO";D
350 IF D=1 THEN 370
360 GOTO 400
370 INPUT" SERVO PO
SITION";GAP
380 N=GAP:GOSUB 200
390 POKE 7942,NL:PO
KE 7943,NH
395 POKE 7942,NL:PO
KE 7943,NH
400 INPUT" 1=CHANGE
LINEWIDTH";E
410 IF E=1 THEN 430
420 GOTO 460
430 INPUT" LINEWIDT
H";L

```

```
440 IF L>255 THEN 4
30
450 POKE 7936,L
460 INPUT" 1=CHANGE
TIME";F
470 IF F=1 THEN 490
480 GOTO 530
490 INPUT" TIME";CY
C
500 CYC=2*CYC
510 IF CYC>255 THEN
490
520 POKE 6912,CYC
530 RETURN
600 POKE 04,128
610 POKE 05,28
620 PRINT" START HE
ADER NOW"
630 X=USR(N)
640 RETURN
700 INPUT" START";S
TART
710 INPUT" END";LAS
T
720 INPUT" SCANS";C
OUNT
730 DA=(LAST-START)
/20
740 N=START+DA:GOSU
B 200
750 POKE 5713,NH:PO
KE 7942,NL
760 POKE 5713,NH:PO
KE 7943,NH
780 N=LAST:GOSUB 20
0
785 POKE 7946,NL:PO
KE 7947,NH
800 POKE 7937,DA
820 RETURN
830 DIM S(21)
835 A=00:B=5623
840 FOR I=1 TO 21
```

```

845 C=A+B
850 LB=PEEK(C):HB=PEEK(C+1)
855 AD=(START-DA)+I*DA
860 POKE 6480,LB:POKE 6481,HB
865 POKE 6482,00
870 HIGH=INT(AD/256)
875 LOW=AD-256*HIGH
880 POKE 6483,255-L
885 POKE 6484,15-HIGH
890 POKE 04,96:POKE 05,25
895 X=USR(N)
900 S(I)=LB+256*HB
902 PRINT!S(I);AD
905 A=A+2
910 NEXT I
915 SMAX=S(1):MINS=S(1)
920 FOR I=2 TO 21
925 IF S(I)>MINS THEN
EN 935
930 MINS=S(I)
935 IF S(I)<SMAX THEN
EN 945
940 SMAX=S(I)
945 NEXT I
950 POKE 04,16:POKE 05,25
955 FOR I=1 TO 21
960 ASTRSK=INT((30*(S(I)-MINS))/SMAX)
965 POKE 6401,ASTRSK
970 X=USR(N)
975 NEXT I
980 RETURN
1000 GOSUB 600
1010 GOSUB 300

```

```
1020 POKE 04,16
1030 POKE 05,27
1035 PRINT" CHOPPIN
G"
1040 X=USR(N)
1050 GOTO 1040
2000 POKE 7941,01
2010 GOSUB 600
2020 GOSUB 700
2030 POKE 04,192
2040 POKE 05,22
2050 X=USR(N)
2060 POKE 04,96
2070 INPUT" ENTER 1
TO GO";BO
2080 X=USR(N)
2082 COUNT=COUNT-1
2084 IF COUNT>00 TH
EN 2080
2090 GOSUB 830
2100 RUN
```

```

      program eratio
c
c program to calculate  $a-b/a+b+2d$  from a set
c of a,b and produce an index for plotting on
c the xs plotter
c
      dimension a(48),b(48),c(48),d(48)
      integer d
      n=48
c
c input dark count
c
      type *, 'input dark count'
      type *,
      accept *, dark
c
c read in arrays a and b
c
      type *, 'read from file'
      type *,
      call assign(3, '1temp.kap', -1, 'read only')
      do 10 i=1,n
c
c n is the number of elements in the array of data in
c file 1TEMP.KAP
c
      read(3,*) a(i),b(i)
      d(i)=float(i)
      aminus=a(i)-b(i)
      aplus=a(i)+b(i)+2*dark
      c(i)=(aminus/aplus)
10    continue
      call close(3)
c
c having calculated the difference over the sum and
c generated an index for the plotting routine write
c a and d into a new file ready to be plotted
c
      type *, 'write to file'
      type *,
      call assign(3, '2temp.kap', -1, 'new')
      do 20 i=1,n
      write(3,*) i,c(i)
20    continue
      call close(3)

```

Appendix 3.2. Programme used to calculate the ratio $a-b/a+b+2d$.

```
c
c find max and min of c(i)
c
      Cmax=c(1)
      Cmin=c(1)
      do 30 i=1,n
      if(c(i).lt.Cmin) Cmin=c(i)
      if(c(i).gt.Cmax) Cmax=c(i)
30    continue
c
c print Cmax and Cmin to VDU
c
      write(7,300) Cmax,Cmin
300    format(3x,5hCmax=,g15.4,3x,5hCmin=,g15.4)
c
c data is now ready to be plotted
c
3000   return
      end
```

```

      program ft
c
c define number of data points
c
      n=25
c
c dimension accordingly
c
      dimension ratio(25),d(25),G(25)
      integer d
c
c read in arrays a and b from file itemp.kap
c
      type *, 'read from file'
      type*,
      call assign(3,'itemp.kap',-1,'read only')
      sum=0.0
      do 10 i=1,n
      read(3,*) 1,ratio(i)
      sum=sum+ratio(i)
10    continue
      call close(3)
c
c calculate the dc level
c
      dclevl=sum/n
c
c calculate the variance
c
      avar=0.0
      do 25 i=1,n
      diff=(ratio(i)-dclevl)**2
      avar=avar+diff
25    continue
      var=avar/n
      write(7,222) var,dclevl,n
      write(6,222) var,dclevl,n
222    format(3x,4hvar=,s15.8,3x,8hdclevel=,s15.4,3x,2hn=,i5)
c
c define Tdw as 2pi/n
c dw is the frequency interval
c t is the sampling period(not specified for routine)
c
      Tdw=2*3.141592654/n
c
c calculate the n/2 spectral estimates by
c summing the sine and cosine series for each
c value of ratio
c

```

Appendix 3.3. Fourier Transform Programme.

```

      Gsum=0.0
      do 30 k=0,n/2
c
c   This gives n/2+1 estimates.
c
c   zero temporary values of the sums
c
      sc=0
      ss=0
      do 40 i=1,n+1
c
c   define argument
c
      xn=ratio(i)-dclevl

      theta=Tdw*k*(i-1)
c
c   calculate the difference squared
c
      diff=(ratio(i)-dclevl)**2
      sc=sc+xn*cos(theta)
      ss=ss+xn*sin(theta)
40    continue
c
c
c   calculate power of estimate
c   produce an index for plotting
c
      G(k)=sqrt(sc**2+ss**2)
      Gsum=Gsum+G(k)
      d(k)=k
30    continue
      sumdev=0.0
      do 37 i=0,n/2
      amean=2*Gsum/n
      dev=(G(k)-amean)**2
      sumdev=sumdev+dev
37    continue
      varnc=sumdev*2/n
c
c   find maximum value of G(k)
c

```

Appendix 3.3. Cont.

```

      Gmax=G(0)
      do 55 k=1,n/2
      if(G(k).lt.Gmax) goto 55
      Gmax=G(k)
      Kmax=k
55      continue
      write(7,333) Gmax,Kmax
      write(6,333) Gmax,Kmax
333      format(3x,5hGmax=,a15.8,3x,5hKmax=,i6)
      write(7,4000) Gsum
      write(6,4000) Gsum
4000      format(3x,5hGsum=,3x,a15.8)
      write(7,3500) amean
      write(6,3500) amean
      write(7,3550) varnc
      write(6,3550) varnc
3500      format(3x,17hmean of ft peaks=,a15.8)
3550      format(3x,21hvariance of ft peaks=,a15.8)
      type *, 'write G(k) to file'
      type *,

c
c calculate the normalised G(k)
c
      call assign(3,'2temp,kap',-1,'new')
      do 501 k=0,n/2
      G(k)=G(k)/Gmax
c
c write d(k),G(k) into file
c
      write(3,*) d(k),G(k)
501      continue
      call close(3)
c
c FT of a,b in file 1temp,kap should now be in
c file 2temp,kap ready for plotting
c
      stop
      end

```

```

      program remslp
c
c this program calculates the coefficients a,b in a least
c squares fit to  $y=ex+b$  assuming all the standard deviations
c are equal
c  $a=(sumx2*sumy-sumx*sumxy)/delta$ 
c  $b=(sumxy*sum-sumx*sumy)/delta$ 
c  $delta=sum*sumx2-sumx*sumy$ 
c sumy2 is calculated for the variance
c
c the program then removes the slope of the data
c by adding -acoef*ratio(i) to the data
c this leaves the intercept unaffected
c
      dimension ratio(316),c(316),d(316)
      integer d
      n=316
c
c read in array ratio
c
      type *, 'read from file'
      type *,
      call assign(3,'1temp.kaf',-1,'read only')
      do 10 i=1,n
c
c n is the number of elements in the array of data in
c file 1TEMP.KAF
c
      read(3,*) 1,ratio(i)
10      continue
      call close(3)
c
c find the various values as needed from above
c first of all zero the temporary stores
c
      sum=0.0
      sumx=0.0
      sumx2=0.0
      sumxy=0.0
      sumy2=0.0
c
c iterate to find these sums
c
      do 20 i=1:n
      x=float(i)
      sum=sum+1
      sumx=sumx+x
      sumy=sumy+ratio(i)
      sumx2=sumx2+x*x
      sumxy=sumxy+x*ratio(i)
      sumy2=sumy2+ratio(i)**2
20      continue
Appendix 3.4. Programme to remove slopes from data using a least squares
fit.

```

```

c
c now calculate the coefficients
c
      delta=sum*sumx2-sumx**2
      bcoef=(sumx2*sumy-sumx*sumxy)/delta
      acoef=(sumxy*sum-sumx*sumy)/delta
c
c write acoef,bcoef to VDU
c
      write(7,222) acoef,bcoef
222      format(3x,2ha=,s15.4,3x,2hb=,s15.4)

      type *,
c
c now remove the slope from the data and write it to
c file 2temp.kaz ready to be plotted
c
      type *, 'write to file'
      type *,
      call assign(3,'2temp.kaz',-1,'new')
      do 30 i=1,n
      c(i)=ratio(i)-acoef*float(i)
c
c write to file 2temp.kaz
c
      write(3,*) i,c(i)
30      continue
      call close(3)
      stop
      end

```

```

      program smooth
      dimension ratio(975),a(975)
      integer n,a
      n=975
      a=100
c
c read in array a and b
c
      type *, 'read from file'
      type *,
      call assign(3, '1temp.kap', -1, 'read only')
      do 10 i=1,n
c
c n is the number of elements in the array of data in
c file
c
      read(3,*) 1,ratio(i)
10    continue
      call close(3)
c
c having read in the file smooth it with a running mean
c and write this into a file ready for plotting
c
      type *, 'write to file'
      type *,
      call assign(3, '2temp.kap', -1, 'new')
      do 20 k=1,n+1
c
c zero the array element a(k)
c
      a(k)=0.0
      do 30 j=1,a+1
      a(k)=a(k)+ratio(k+j-1)
30    continue
c
c find the average of the a points
c
      a(k)=a(k)/a
      write(3,*) k+a/2,a(k)
20    continue
      call close(3)
      stop
      end

```

Appendix 3.5. Programme used to smooth data with a running mean of q points.

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