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Martian Aeronomy with Mutual Radio Occultation

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Abstract

This thesis employs mutual radio occultation (RO) to investigate the dynamics of the Martian ionosphere and upper atmosphere. This method, which is sometimes referred to as crosslink RO or inter-satellite RO, involves transmitting a radio signal between a transmitter and receiver. As the radio waves propagate, their trajectories are slightly bent due to refractivity gradients in the planetary atmosphere. These refractivity changes are linked to temperature and pressure in the neutral atmosphere, and electron density in the ionosphere.

In 2019, work commenced to enable mutual RO operations between ESA's Mars Express (MEX) and ExoMars Trace Gas Orbiter (TGO). This configuration eliminates previous geometric limitations, enabling observations across the entire Martian day. This is the first instance of such an approach being routinely applied to a planet other than Earth. This thesis presents 71 RO profiles obtained using this method, including 34 from previously inaccessible midday regions.

The novel dataset enables new investigations into Martian aeronomy, particularly the diurnal variation of ionospheric layer altitudes and electron densities. The inclusion of midday profiles revealed that electron density in these regions varies far less than previously assumed. This analysis also provides conclusive evidence that the lower M1 ionospheric layer persists during midday and reveals a counterintuitive trend where thermospheric neutral temperatures increase with angle from the sun. Finally, mutual RO is used to examine the Martian ionospheric response to solar weather events. A fortuitous measurement taken just 10 minutes after the impact of a major X_3 -class solar flare captured the largest M1 layer on record, with a 278% enhancement. This corresponded to a threefold increase in local X-ray irradiance. Contrary to prior assumptions that electron density scales with the square of solar intensity, this result suggests a more linear relationship between flare intensity and ionospheric response.

Declaration

I declare that, except where explicitly stated otherwise and referenced, the work presented in this thesis is my own.

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—Jacob Parrott, London, June 2025

At the time of thesis submission, the work presented in this thesis lead to the following peer-reviewed publication:

Parrott, J., Svedhem, H., Witasse, O., Wilson, C., Müller-Wodarg, I., Cardesín-Moinelo, A., et al. (2024a). First results of Mars express—ExoMars trace gas orbiter mutual radio occultation. *Radio Science*, 59, e2023RS007873. <https://doi.org/10.1029/2023RS007873> (Cover issue)

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Whilst this thesis has my name on the front cover, it resulted from the efforts of several people.

Those who find this thesis either online or physically might read the abstract and look through the figures. Nonetheless, there are at least three people who will have to read this tomb through in its entirety. I thank the reviewers Professor Andrew Coates and Dr Adam Masters for their time and comments.

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Lastly, thanks goes to my Mia. A thesis typically doesn't have a word limit, but if I were to try and express how much your support, humour and love means to me, then I would somehow find the ceiling.

‘Given the existence as uttered forth in the public works of Puncher and Wattmann of a personal God
 quaquaquaqu with white beard quaquaquaqu outside time without extension who from the heights of divine
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 skull the skull in Connemara in spite of the tennis the skull alas the stones Cunard tennis... the stones... so
 calm... Cunard... unfinished...’

Lucky’s Speech upon being commanded to ‘think!’

*from Samuel Beckett’s **Waiting for Godot***

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Nomenclature

Abbreviations, Acronyms & Initialisms

AGC Automatic Gain Control

CME Coronal Mass Ejections

DeepONet Deep Operator Neural Net

DSN Deep Space Network

ECMWF European Centre for Medium-Range Weather Forecasting

EDDS ESA Ground Operations System Data Dissemination System

EOLPT Electra Open Loop Processing Tool

ESA European Space Agency

EUV Extreme Ultra Violet Radiation ($\lambda = 10\text{-}121\text{ nm}$)

FFT Fast Fourier Transform

FISM2 Flare Irradiance Spectral Model-Version 2

FPGA Field Programmable Gate Array

GPU Graphical Processing Unit

I&Q Inphase and Quadrature Encoded Data

IMF Interplanetary Magnetic Field

IR Infrared Radiation

JPL Jet Propulsion Laboratory

MCD Mars Climate Database

MHD Magnetohydrodynamic

MIRI Mars Initial Reference Ionosphere Model

MTGCM Mars Thermosphere General Circulation Model

RFI Radio Frequency Interference

RO Radio Occultation

Rx Receiving Antenna

SC Spacecraft

SEP Solar Energetic Particles

SNR Signal-to-Noise Ratio

SPICE Spacecraft, Planet, Instrument, C-matrix, Events - Ephemeride Framework

SZA Solar Zenith Angle (Angle from Sub-Solar Point)

TCXO Temperature Compensated Crystal Oscillator (TCXO)

TEC Total Electron Content

Tx Transmitting Antenna

UHF Ultra High Frequency. 0.3-3 GHz

USO Ultra Stable Oscillators

Mission & Instrument Names

CHAMP CHAllenging Minisatellite Payload (Radio Occultation Mission)

COSMIC Constellation Observing System for Meteorology Ionosphere and Climate Mission
(also called FORMOSAT)

EDM Schiaparelli Entry, Descent and Landing Demonstrator Module

EXIS Extreme Ultraviolet and X-ray Irradiance Sensor

GEOS-15 Geostationary Operational Environmental Satellite 15

GNSS Global Navigation Satellite System

InSIGHT Interior exploration using Seismic Investigations, Geodesy, and Heat Transport

LPW Langmuir Probe and Waves instrument

MARSIS Mars Advanced Radar for Subsurface and Ionosphere Sounding Instrument

MARSIS AIS MARSIS in Active Ionospheric Sounding Mode

MAVEN Mars Atmosphere and Volatile Evolution

MELACOM Mars Express LAnder COMmunication

MEX Mars Express (sometimes written as MEx)

MGS Mars Global Surveyor

MRO Mars Reconnaissance Orbiter

MRS MEX Radio Science Instrument (Sometimes denoted MaRS)
 NGIMS Neutral Gas and Ion Mass Spectrometer
 ODY Mars Odyssey Mission
 RISE Rotation and Interior Structure Experiment
 ROSE Radio Occultation Science Experiment
 SPICAM UV and IR Atmospheric Spectrometer
 STATIC Suprathermal and Thermal Ion Composition Instrument
 TGO Trace Gas Orbiter

Physical Constants

ξ_0 Permittivity of Free Space. $8.854 \times 10^{-12} \text{ m}^{-3} \text{ kg}^{-1} \text{ s}^4 \text{ A}^2$
 e Elementary Charge. $1.602 \times 10^{-19} \text{ C}$
 e Euler's Number. 2.718
 G Gravitational Constant. $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
 g Acceleration due to Martian Gravity. 3.75 m s^{-2}
 h Plank Constant. $6.626 \times 10^{-34} \text{ J s}$
 k Boltzmann Constant. $1.38 \times 10^{-23} \text{ J K}^{-1}$
 M Mass of Mars $6.39 \times 10^{23} \text{ kg}$
 m_e Electron Mass. $9.109 \times 10^{-31} \text{ kg}$
 r_{exo} Nominal Altitude of Martian Exobase. 200 km
 AU Astronomical Units. $1.495 \times 10^8 \text{ km}$

Symbols

β Refractive Radius. km
 χ Solar Zenith Angle. $^\circ$
 λ Jean Limit. m s^{-1}
 ρ Density. kg m^{-3}
 σ Particle Cross-section. m^2
 ε Bending Angle. $^\circ$
 ζ Collision Parameter. Dimensionless
 a Impact Parameter. km

E_k	Kinetic Energy of Particle. eV
f	Frequency. Hz
$F_{10.7}$	Irradiance at the 10.7 cm Radio Band. Solar Flux Units
F_{mEUV}	Irradiance in the EUV Band. mW m^{-2}
f_p	Plasma Frequency. Hz
f_t	Transmit Frequency. Hz
H	Scale Height. km
H_e	Electron Density Scale Height
hf	Photon Energy. J
m	Mass of Gaseous Specie. kg
n	Particle Density. kg m^{-3}
n	Refractivity. Dimensionless
N_e	Electron Density. cm^{-3}
T_e	Electron Temperature. K
U	Molecular Velocity. m s^{-1}
V_{esc}	Escape Velocity. kg m^{-3}
z	Altitude above the Martian Spheroid. km

Chapter 1

The Martian Ionosphere

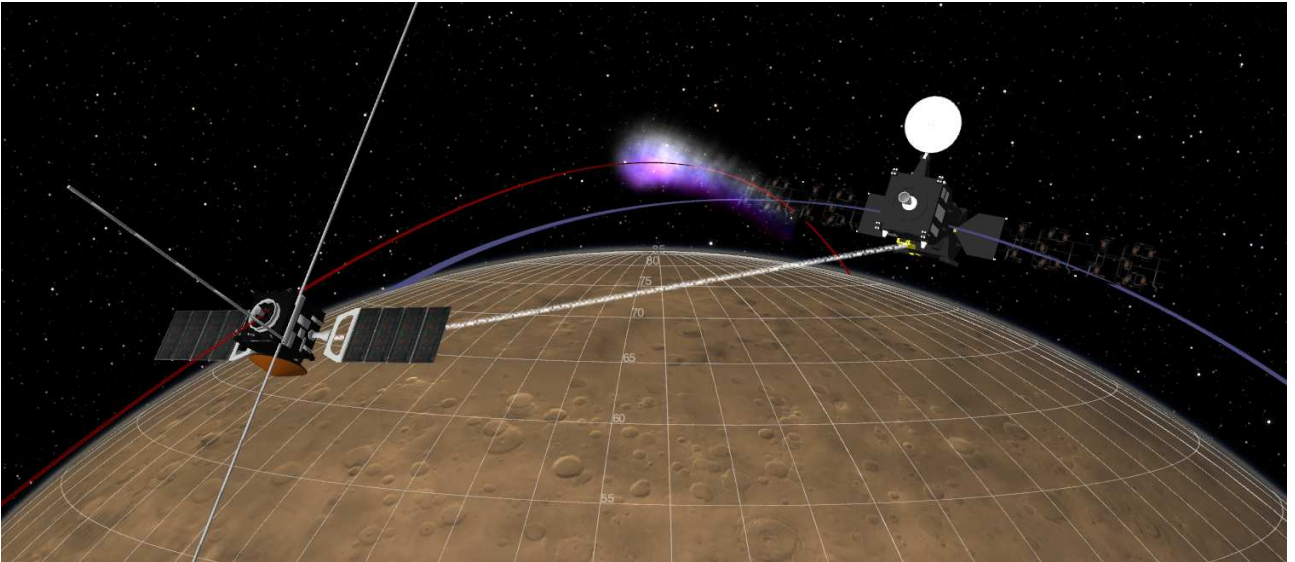


Figure 1.1: Simulation of a mutual radio occultation measurement over the Martian north pole. The purple filament descending to the Martian surface represents the volume of ionosphere that is being probed during the observation. There is a 100X scale for the Mars Express (left) and Trace Gas Orbiter (right) models. The white line between the spacecraft represent the 437.1 MHz radio link and the red and blue trajectories are the spacecraft orbits. This has been produced with a modified version of the open-source Cosmographia software.

Similar to the gaseous envelopes found throughout the solar system, the Martian atmosphere exhibits a radial structure. It begins with the highest neutral density at the planet's surface and gradually diminishes to nearly zero as it approaches the interplanetary medium.

However, the principal focus of this PhD has been using mutual radio occultation to measure the ionosphere. This is a separate vertical regime that is used to explain the distribution of ionised particles. It co-exists at roughly the same altitude as the mesosphere, thermosphere

and exosphere. It exists due to chemical processes and ionisation mechanisms, primarily driven by solar extreme ultraviolet radiation (EUV) and x-ray ionization, as well as impact ionisation caused by photoelectrons and their secondaries (Rishbeth & Mendillo, 2004). During nighttime, when these ionisation sources wane, the ions in this region gradually recombine to form neutral molecules, where the dissociative recombination process operates on a timescale of around 10 minutes (Peverall et al., 2001).

1.0.1 Ionospheric Structure

The Martian ionosphere can be broken into two layers. The highest electron density can be found in the M2 layer located at approximately 120–150 km in altitude, and the secondary M1 layer, found at around 90–110 km. These layers are often likened to the Earth’s F_1 and E layers due to their similar atmospheric pressures of 4×10^{-6} mb and 5×10^{-5} mb, respectively (Rishbeth & Mendillo, 2004). The M2 layer is produced via photoionisation with EUV photons ($\lambda=10\text{-}100$ nm), and the lower M1 is caused by higher energy soft X-ray ($\lambda=1\text{-}10$ nm) photons and their secondaries.

The ionosphere consists of plasma, which is technically an ionised gas. Because of this ionisation, particles not only interact via pair collisions (like a normal gas) but also via electromagnetic fields. There are three criteria that must be fulfilled for a gas to be considered this other state of matter. Firstly, it should be quasi-neutral, meaning there should be no net charges across the medium. Then, a plasma should exhibit collective behaviour so that it moves in bulk according to external electromagnetic perturbations. Finally, the size of the plasma medium must be much larger than a Debye length (λ_D). This parameter is the distance to which a charge can exert an appreciable force. Say we place a point charge in the middle of a large plasma system. This charge would draw opposite-charged particles towards it, and like-charges away. This leads to a ‘sheath’ forming around the point charge where the ions have been attracted in or repelled away. The thickness of this sheath is called the Debye length. This is an important plasma criterion because the medium would no longer be quasi-neutral if the entire system was dominated by a single point charge and its electric

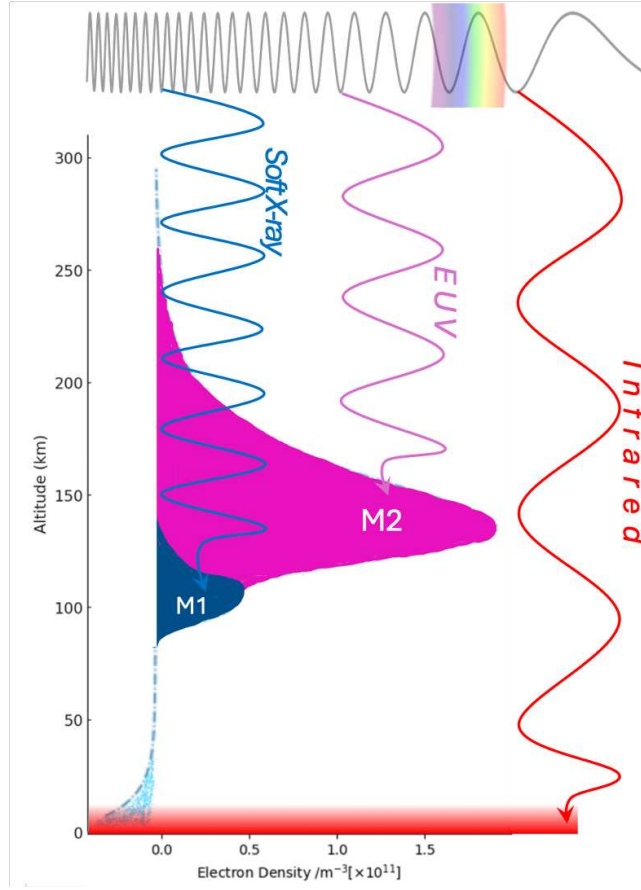


Figure 1.2: A cartoon showing a spectrum of electromagnetic radiation, with the soft X-ray and EUV bands producing the M1 and M2 layers, respectively. Also shown is the infrared radiation, which can penetrate the atmosphere and warm-up the surface. The visible light band has been indicated as a rainbow on the spectrum to show that infrared light is the other side of the visible spectrum to our photoionising bands. A shaded blue area below 50 km is the neutral atmosphere, which is often seen as a negative electron density.

sheath. λ_D depends on the electron density and temperature and can be described with the following equation:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}} \quad (1.1)$$

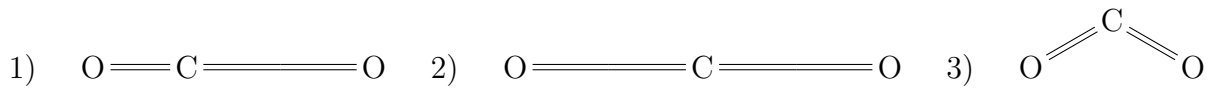
Where ε_0 is the permittivity of free space, K_B is the Boltzmann constant, T_e is electron temperature, n_e is electron density and e is the elementary charge.

Figure 1.2 has been produced to highlight this notion that two separate frequency bands in the electromagnetic spectrum produce two distinct layers in the Martian ionosphere via photoionisation. But other frequency bands are also important, shown as the infrared in the figure, which can penetrate the atmosphere and warm-up the ground, driving winds.

The higher M2 layer is counter-intuitively produced by the lower energy EUV photons

because CO_2 is extremely efficient at absorbing this wavelength of radiation. The 12-100 eV photons can ionise the electrons in the outer valence orbitals of CO_2 . This is the outer-most orbital and therefore the molecule has a large absorption cross-section for EUV. This can therefore occur at lower CO_2 densities at higher altitudes. On the other hand, soft x-ray photons, typically with energies of 100-1000 eV, will ionise electrons in the inner s-shells of oxygen or carbon. These are the inner-most shells, that means soft X-ray has a smaller absorption cross-section for CO_2 , so the neutral density of CO_2 must get far greater, at lower altitudes, for significant ionisations to occur. As soft X-ray is so energetic, the ionisation products (photoelectrons or Auger electrons) are often superthermal and cause secondary ionisations as tertiary collisions take place.

CO_2 is such a good absorber because it can be photoionised by a broader frequency range of EUV radiation due to its molecular structure. CO_2 is a linear triatomic molecule which can experience several different vibrational modes. Shown below is 1) asymmetric stretching; 2) symmetric stretching; and 3) rotational bending. These vibrational modes are achieved by varying photon energies to get different 'vibrionic transitions'. The required energies for these are low, typically in the energy range of infra-red (IR) radiation. But, this allows for a broader range of possible photon energies to ionise CO_2 because a portion of their energy transfer can go into a range of other vibrionic transitions.



In Figure 1.3, we observe two distinct peaks in electron density: the upper M2 layer and the lower M1 layer. However, previous studies have pointed out that this specific morphology is only expected during periods of high solar activity, as the M1 layer is absent during times of reduced X-ray emissions. The Martian ionosphere is also comparatively sparse when compared to the Earth with values of 2×10^5 and $2 \times 10^6 \text{ cm}^{-3}$ respectively (C. Ho et al., 2002).

The structure of the Martian ionosphere is primarily governed by photochemical processes as photochemical timescales are smaller than transport timescales (Fox et al., 2017).

Consequently, the ionospheric layers generally conform to an α -Chapman profile, illustrated in Figure 1.3. This profile arises from the interaction between the exponential increase in neutral

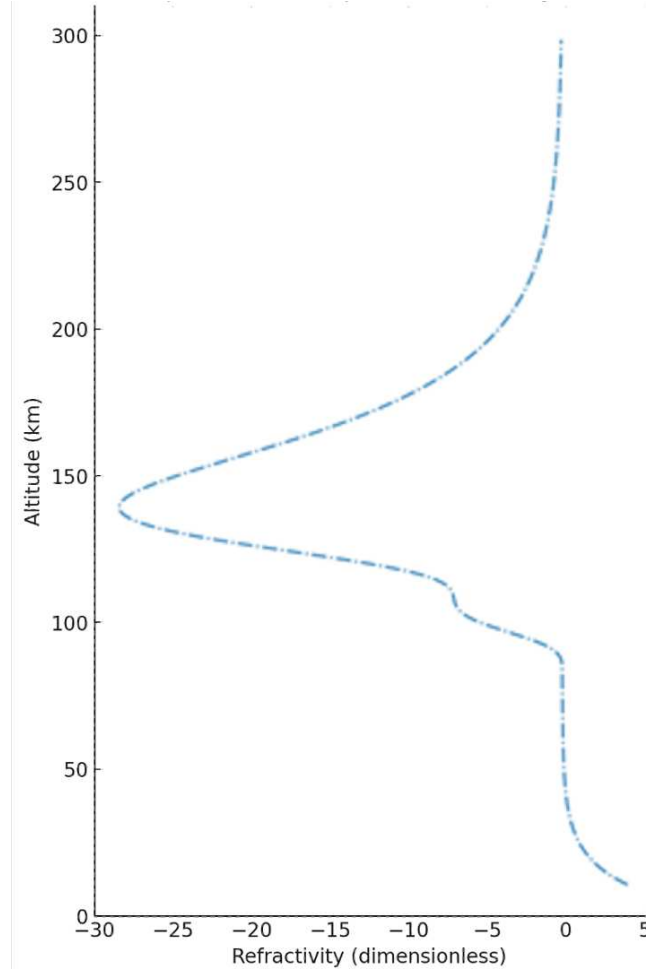


Figure 1.3: Simulated subsolar Martian refractivity profile up to 300 km altitude. Showing two ionospheric layers that are typical α -Chapman layers. The M2 layer is at 140 km and the M1 is at 100 km. A faint exponential decay can be seen below 30 km, this is the effect of the lower neutral atmosphere.

density with decreasing altitude and the optical depth of radiation at specific wavelengths. In other words, the topside of the Chapman profile reflects the e -folding nature of neutral atmospheres, while the bottom side is shaped by reduced radiation penetration at lower altitudes. This is described in this equation for the two superimposed ionospheric layers:

$$N_e(z, \chi) = \sum_{l=M2}^{M1} \exp \left\{ \left[\frac{1}{2} \left(1 - \frac{z - z_l}{H_l} - \exp \left(-\frac{z - z_l}{H_l} \right) \sec SZA \right) \right] \right\} \quad (1.2)$$

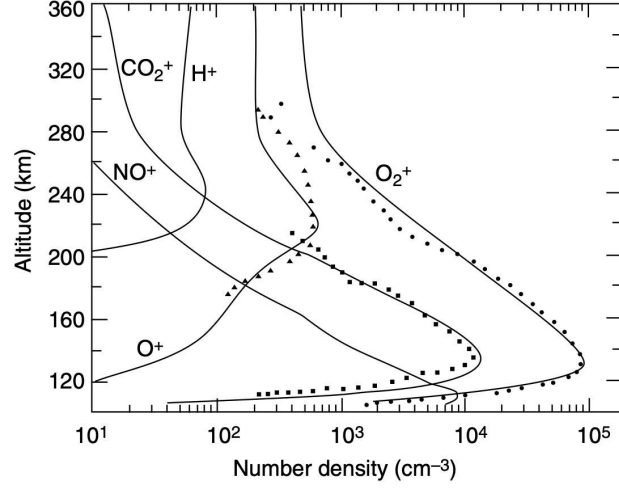


Figure 1.4: Averaged Ion composition by altitude based of the measurements by the Viking landers' mass spectrometers (Chen et al., 1978). The dots are the real measurements and the solid lines are the fits. This shows that the dominant ion around the M1 and M2 ionospheric peak is O_2^+

1.0.2 Ionospheric Chemistry

The average vertical distribution of ions can be seen in the Viking lander mass spectrometer readings in Figure 1.4; showing that the most dominant form of ion in the ionosphere is O_2^+ , followed by CO_2^+ . More recent measurements can be found from the Mars Atmosphere and Volatile Evolution mission (MAVEN) deep-dip campaign with the Neutral Gas and Ion Mass Spectrometer (NGIMS) (Mahaffy et al., 2015). However, this lacks the data for the M1 and M2 altitudes. To begin to understand these two main ions, we should start by covering their photochemical equilibrium equations. At photochemical equilibrium, the production rates equal their loss rates, i.e:

$$P(O_2^+) = k_1 n(CO_2^+) n(O) + k_3 n(O^+) n(CO_2) \quad (1.3)$$

$$P(CO_2^+) = k_1 n(CO_2^+) n(O) + k_2 n(CO_2^+) n(O) + \alpha_1 n(e) n(CO_2^+) \quad (1.4)$$

where $k_1 = 1.64 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$, $k_3 = 1 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$, $k_2 = 0.96 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$. α_1 in

Equation 1.4 is a complex non-linear value related to thermal electron temperature. It can be

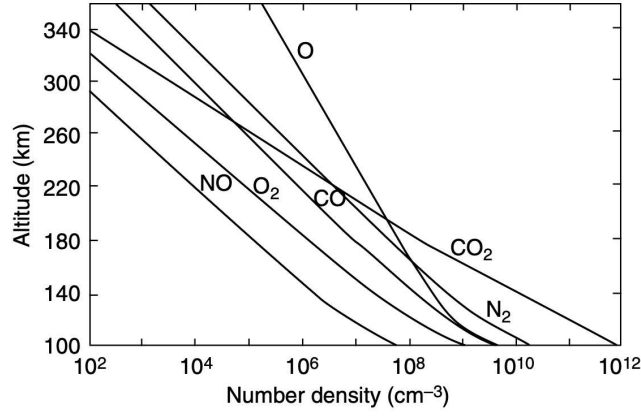


Figure 1.5: Averaged Ion composition by altitude based of the remeasurements by the Viking landers’ mass spectrometers (Chen et al., 1978), showing that CO_2 is the dominant specie up to 220 km, then lighter atomic oxygen becomes dominant.

Molecule	Composition
CO_2	95.1%
N_2	2.7%
Ar	1.9%
O_2	0.16%
O_3	0.03%
H_2O	$\sim 0.03\%$
NO	70-1100 ppm
CH_4	0.05 - 60 ppb
SO_2	~ 0.2 ppb

Table 1.1: Atmospheric composition by volume across all altitudes, adapted from Haider, 2023

modelled as $1.95 \times 10^{-7} (T_e/300)^{-0.7} \text{ cm}^3 \text{ s}^{-1}$ for temperatures less than 1200 K and $7.39 \times 10^{-8} (T_e/1200)^{-0.56}$ if above (Fox et al., 2021). Evidently, CO_2 is a key constituent for the synthesis of both the two major ions, so why is it so abundant on Mars? The present day Martian atmosphere evolved into the low-pressure dry and cold envelope of mostly CO_2 that we see today.

A key driver for the presence of the Martian ionosphere is the atmospheric chemistry. As can be seen in Figure 1.5, CO_2 makes up the majority of the atmosphere, namely up to around 220 km. Above this altitude, atomic oxygen becomes dominant due to its lighter mass and because it’s produced by the photoionisation equation below (Equation 1.6). The vertically and globally averaged neutral compositions are found in Table 1.1. The dominance of CO_2 is explained by the following: Just like Earth, the Martian atmosphere is e-folding, meaning that for a given scale height (H), the atmosphere will become less dense by a factor of e . This

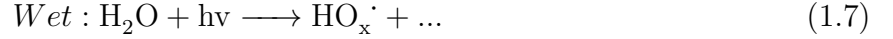
happens because we assume that the martian atmosphere is at hydrostatic equilibrium, meaning that the system is gravity dominated and pressure is due to the weight of the gas. This leads to the total weight of the gases above a certain altitude reducing exponentially as altitude (z) rises, ie. $\rho(z) = \rho_0 e^{-z/H}$. The scale height for lower atmosphere is 11 km, so 63.2% of the total mass of Mars' atmosphere can be found under 11 km. Taking this calculation further, the percentage mass under 220 km can be found via $1 - \exp(-\frac{220}{11})$, leading to only $2.1 \times 10^{-7}\%$ of Mars' atmosphere being found above this height. Given that CO₂ is dominant for the lower altitudes, the total averaged neutral composition for the entire atmosphere is dominated by CO₂ also.

The key reactions for the creation and destruction of CO₂ are:



Where hf is an incident photon (h being the plank constant of 6.626×10^{-34} Js and f being the frequency of the incident photon). Equation 1.5 is a far slower reaction when compared with the latter Equation 1.6. In the absence of any stabilising mechanism, the majority of the Martian atmosphere would convert to CO and O₂ within 4000 years (atomic oxygen is rarely found naturally in the lower atmosphere so this readily converts to O₂(Mendillo et al., 2002)). The recombination of CO and O to produce CO₂ is considered a slow reaction as the reaction is 'spin-forbidden'. This means that the reactants and product in the chemical equation posses different quantum spin states. Clearly this is not the case as CO₂ has remained as the dominant species in the Martian atmosphere due to its reactions is sped up by the use of a catalyst; evident by the m , or chaperone, in the first formula. The catalyst in this case is likely hydroxyl radicals (HO_x·). These radicals come in a variety of forms: OH·, HO₂·, H₂O₂·. Chaparones can also come in the form of nitrogen compounds such as NO₂· and NO₃·. These come about via two means: 1) the photolysis of water or 2) the reaction of gases with oxygen radicals (called the 'dry phase') (Mendillo et al., 2002). An example of these two reactions are

shown below:



The concentrations of CO_2 vary latitudinally with season as it condenses and sublimates from the Martian poles. Again, because CO_2 makes up the vast majority of the lower atmosphere, this has huge implications for the entire system. The total mass of the regional atmosphere can vary by 30% between seasons, and the surface pressure varies between 900 and 750 Pa (James et al., 1992). Mars has a greater axial tilt than Earth with a value of 25° . This obliquity combined with its oblateness¹ leads to long continuous winter nights at the poles. Here, the CO_2 condenses out of the atmosphere and is sequestered into the crust, only to be released again as it sublimates during the spring and summer.

As stated, H_2O is an important catalyst for the production of CO_2 , which in turn, is critical for the formation of the ionosphere. Given this, it's important to note that concentrations of water are periodic throughout the Martian year. During the winter period, the atmospheric water content drops by a factor of two as it is frozen into the poles. However, due to H_2O 's lower volatility, it freezes first, with CO_2 then covering the polar caps. Water can only sublime once the CO_2 has left,. This leads to H_2O concentrations following the CO_2 trend, but lagging by a few months. The cycle also means that CO_2 and H_2O concentrations begin to increase at the high latitudes before the vapours move equatorward.

Coming back to k_1 , k_2 , and k_3 from Equation 1.3 - 1.4, these are the reaction rates for the combination of photoionised CO_2^+ or O^+ and neutral atomic oxygen (which Figure 1.5 shows as being abundant at altitudes above 220 km). Specifically, k_1 , k_2 , and k_3 are the reaction rates for the following respective equations:

¹oblateness is the degree to which a planet's shape deviates from being a perfect sphere, resulting in a slightly flattened shape at the poles and a bulging at the equator.



As transport is minimal during the day and the main source of ionisation is the sun, the abundance of CO_2^+ maps closely to neutral CO_2 concentrations, which in-turn closely follows the thermal structure of Mars' atmosphere up to the homopause (defined in the following section). Due to this temperature dependants, an in-depth description for the physics of the thermal structure shall now be explained.

1.1 Atmospheric Thermal Structure

The vertical morphology of an atmosphere is often discussed in terms of its temperature structure. On Earth, this structure is traditionally divided into distinct regions: the Troposphere, Mesosphere, Thermosphere, and Exosphere. Figure 1.6 illustrates that Mars shares some of these region names due to similar temperature variations with altitude. In this context, we use density as a proxy for temperature and pressure because they are intricately related as follows:

$$\rho(z) = \rho(0) \exp\left(-\int_0^z dr/H(z)\right) \quad (1.12)$$

where the scale height $H(z)$ is:

$$H(z) = \frac{kT(z)}{gm} \quad (1.13)$$

where $T(z)$ is the temperature for that height, g is the acceleration due to Martian gravity 3.75 m s^{-2} and m is the species mass. However, it's important to note that pressure behaves

as a continuous inverse-exponential function, so density is primarily influenced by variations in temperature. As previously stated, the pressure gradient within an atmosphere is characterized by a scale height, which represents the altitude at which density decreases by a factor of e (e-folding), assuming the atmosphere is in hydrostatic equilibrium.

Figure 1.6 shows the structure of the Martian neutral atmosphere, which is characterised by distinct regimes of temperature and density gradients. The following walks through these regions, from the Martian surface up to the interplanetary medium.

Troposphere (0-40 km): The lowest region of the Martian atmosphere is the troposphere, which exhibits a negative temperature and density gradient. This gradient is a result of the surface serving as the primary heat source for the region. The Martian crust has the ability to absorb a wide spectrum of solar radiation, unlike the surrounding air molecules. This region extends from the surface to approximately 40 km in altitude. The term 'Tropo' is derived from the Greek word for 'rotating' or 'turbulence,' which is fitting as convection plays the dominant role in energy transport within this region. The troposphere maintains a relatively warmer temperature compared to higher regions due to substantial amounts of dust particles that absorb more solar energy. This acts as a greenhouse effect as the dust particles absorb the solar radiation and then re-emit the long-wave IR radiation equally upwards and downwards, in effect, trapping heat below. Additionally, there is a more traditional greenhouse effect caused by CO_2 , which impedes the escape of infrared radiation into space (Gonzalez-Galindo et al., 2008).

Mars lacks a region known as the stratosphere. On Earth this is a dry region where the temperature climbs with altitudes. This does not exist on Mars because it lacks the amount of Ozone to produce sufficient local heating. This occurs due to the lack of O_2 on Mars needed to produce sufficient quantities of Ozone (O_3)

Mesosphere (40-110 km): Above the tropopause lies the mesosphere, encompassing altitudes ranging from approximately 40 km up to 110 km. Within this region, there is a consistent trend of decreasing temperatures with increasing altitude. This phenomenon can be attributed to the radiative cooling effect of carbon dioxide. CO_2 molecules undergo a process

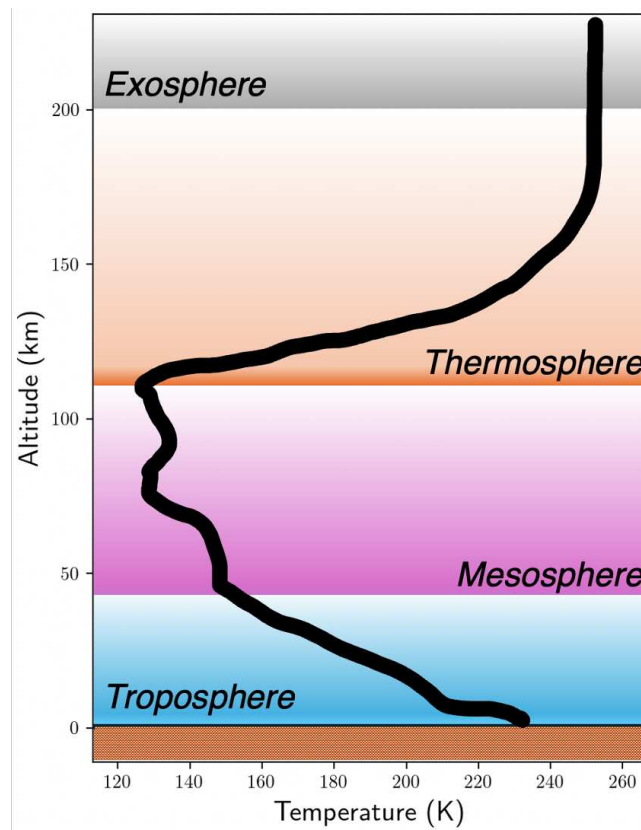


Figure 1.6: The typical vertical temperature profile of Mars with four regions labelled; approximating the tropopause to 40 km, the mesopause to 110 km and the exobase at 200 km. The purpose of this sketch is to show the general trends of the temperature in the four regions.

where they convert local enthalpy (total heat content) into IR radiation, with a portion of this radiation travelling upward toward space. In other words, only about half of the emitted radiation escapes the planet because the emission from a parcel of CO₂ is isotropic, meaning roughly 50% of it propagates upward, providing a net cooling effect. An in-depth investigation for why heat transfer properties of CO₂ depend on altitude can be found in Appendix A.

Thermosphere (110~200 km): Above the mesopause lies the thermosphere, typically spanning altitudes from 110 km to 200 km (Mendillo et al., 2002). It's important to note that this upper boundary is a subject of debate within the aeronomic community, with some sources occasionally suggesting altitudes as high as 250 km (González-Galindo et al., 2015). This region is characterized by a distinctive temperature profile, exhibiting an asymptotic increase in temperature from approximately -140°C to -20°C (133 K-253 K). Beyond an altitude of around 200 km, the thermosphere becomes nearly isothermal.

The temperatures in the thermosphere are profoundly influenced by the intensity of EUV flux, which is closely tied to both the solar longitude and the solar cycle. This dependency on solar longitude is particularly relevant to Mars due to its relatively large eccentricity of 0.0934, resulting in varying equatorial midday solar flux levels ranging from 1.35×10^{-4} to $1.9 \times 10^{-4} \text{ W m}^{-2}$ at perihelion and aphelion, respectively (Sánchez-Cano et al., 2018).

González-Galindo et al., 2015 calculated that the thermospheric density at 140 km can vary 3×10^{-10} to $10 \times 10^{-10} \text{ kg m}^{-3}$. Their research also demonstrated that peak thermospheric temperatures experience an increase of approximately 90 K from solar minimum to maximum.

Moreover, Figure 1.6 reveals a steep thermal gradient at the thermobase, indicating the substantial amount of downward molecular conduction (Mendillo et al., 2002). This downward conduction process ceases at the mesopause, primarily due to the presence of CO₂. The mesopause represents the highest altitude at which CO₂ can accumulate in significant concentrations. Beyond this point, CO₂ molecules undergo photolysis, splitting into CO and O (emphasised in Figure 1.5), subsequently losing their ability to emit IR radiation. As discussed in Appendix A, without a mechanism for the thermosphere to effectively radiate its accumulated heat, thermal energy is transported downward through molecular collisions.

Exosphere ($>\sim 200$ km): As we ascend in altitude, the atmosphere progressively thins out. When we reach the outermost layer of the Martian atmosphere, known as the exosphere, it becomes so tenuous that collisions between particles are negligible. The exosphere's lower boundary is referred to as the exobase, and everything below it adheres to a Maxwellian distribution. In simple terms, this means that the kinetic energy of particles within this region conforms to a normal distribution centred around an average value of $E_k = \sqrt{2kT(z)/m}$. This follows logically as the collisionality will share E_k amongst neighbouring particles.

Figures 1.4 and 1.6 show the CO_2^+ densities only map to the thermal structure up to around 120 km. This is because a separate vertical regime takes into effect; specifically the mixing ratios. The separation between the homosphere and heterosphere exists around 120-125 km on Mars (Fox et al., 1996). The separation of these two layers is called the homopause and it denotes the altitude to which the individual gaseous species need to be considered separately. In the homosphere, the difference mixing ratios of all types of particles are kept relatively constant due to turbulence. Above this, however, each species has its own scale height, and transport is dominated by diffusion instead of wind and wave dynamics. The heterosphere is known as a gravitational diffusive equilibrium because gravitational force is equal to the partial pressure of each species. The CO_2^+ trend is therefore only sustained to the homopause because the lighter atomic oxygen becomes the more abundant tracer, altering the values for k_1 , k_2 , and k_3 .

1.2 Further Ionospheric Dynamics

The Martian ionosphere's characteristics are contingent upon the SZA. The terminator is a highly dynamic region of the ionosphere. As solar flux wanes around 90° SZA, the existence of the ionosphere is dominated by transport and sustained for around 80 minutes at the equator (Cui et al., 2015). In the deep night, its persistence is primarily sustained by electron precipitation from the solar wind (Yao et al., 2019), organised by the intrinsic crustal magnetic fields and their interactions with the interplanetary magnetic field (Adams et al.,

2018). The electrons in the solar wind ultimately make their way to the nightside of Mars by spiralling along the magnetic field lines connecting the 'draped' magnetic field and the crustal fields rooted on the surface. This phenomenon was recently quantified by Withers et al., 2022, who utilized the Radio Occultation Science Experiment (ROSE) on MAVEN to measure the night side ionosphere. This revealed a peak electron density ranging from 2×10^{10} to $4 \times 10^{10} \text{ m}^{-3}$ at altitudes of 60 to 90 km, localized around the open intrinsic magnetic fields.

An occasional third layer may be noticed around 75 km. It is theorised that this is due to metallic deposition by meteoric flux. This layer was first mentioned in Pätzold et al., 2005, where they noted that in 10 out of 120 radio occultations showed faint non-Chapman layer occurring between 65 to 110 km. This layer was observed to be geographically localised and sporadic. They also noted that these layers could occur at all latitudes, but seemed to be restricted to only the daytime. It is speculated that the main constituents for this layer are Mg^+ & Fe^+ . These have been deduced via comparison with the Earth's ionosphere (where an additional in-situ measurements can be taken), where a similar sporadic ionospheric layer can be seen. However a recent paper by Peter et al., 2023 states that a considerable proportion of the identified meteoric layers could be attributed to the ionisation of $<2 \text{ nm}$ X-ray radiation.

The morphology of the ionospheric profile seen in Figure 1.3 can change as a result of global dust storms (typically occurring annually at the perihelion point of the Martian year). This is not because of a triboelectric effect (static from friction) within the dust storms, nor because of a charge exchange between the ions in the regolith (similar to the reasoning behind the Mg^+ layer). The net opacity of the dust reduces the surface albedo and increases the broadband absorption of solar flux. This radiative forcing causes a thermal tide which raises the altitude of the mesosphere-thermosphere-exosphere and its embedded ionosphere. This phenomena has been measured by the Suprathermal and Thermal Ion Composition (STATIC) (McFadden et al., 2015) instrument onboard MAVEN during the December 2020 global dust storms. Interestingly, this was also picked up by the Mariner 9 spacecraft dust storm observation in 1972, but was only noticed when Withers et al., 2015 reanalysed the radio link between the spacecraft and ground station and noticed slight frequency shift at higher than expected altitudes due to the elevated ionosphere.

This symmetric radial expansion of the ionosphere can also be achieved by a relatively simple mechanism. Perihelion noon delivers 32% more insolation (solar flux) than aphelion noon ($(\frac{1.38AU}{1.67AU})^2 = 0.826^2 = 0.682$). There is similar radiative forcing to dust storms where the atmosphere expands adiabatically into space and its constituent ions are raised to higher altitudes.

1.3 History of Probing the Ionosphere

In total there have been 49 missions to Mars, of which less than half have completed their nominal mission. Table 1.2 lists some of these key events relevant to the ionosphere:

Year	Event
1964	Mariner 4 noted a single ionospheric layer at 135 km via radio occultation (Fjeldbo & Eshleman, 1968) and a lack of a magnetic field.
1971	Mariner 9, Mars 2 and Mars 3 discover the planet-wide dust storms. These are now known to increase the altitude of the ionospheric layers (Kliore et al., 1970).
1976	Viking 1 spotted a smaller M1 ionospheric layer at 110 km with its retarding potential analyser (Hanson et al., 1977).
1998	Mars Global Surveyor detects the crustal magnetic fields. These are known to modulate the ionospheric distribution (Acuña et al., 1999).
2007	Mars Odyssey (ODY) and Mars Reconnaissance Orbiter are used in a cross-link radio occultation demonstration to probe the ionosphere (Ao et al., 2015).
2015	MAVEN captures the first in situ measurement of the electron density with its Langmuir Probe and Waves instrument (LPW) (Ergun et al., 2021).
2020	MEX and TGO begin their mutual radio occultation campaign to investigate the ionosphere (Parrott et al., 2024).

Table 1.2: Pertinent previous missions to Mars which included measurements related to the ionosphere.

Today, we have many ways to measure ionospheres. These can be in the form of in-situ measurements or remote sensing. The following Table 1.3 shall cover the most common forms that have been taken to Mars:

Instrument	Description
Radio Occultation (RO)	RO has been used on Mars for seven successful missions (Mariner 4,6,7,9, MEX, MGS and MAVEN) and is considered the key technique as a result of its simple, cost-effective ability to probe the whole vertical profile of the Martian limb. While RO can be cheaply implemented with standard communication equipment, bespoke RO instruments have three improvements: an USO, dual frequency duplex link capability, and a steerable high-gain antenna.
Mass Spectrometer	NGIMS onboard MAVEN (Withers et al., 2015), uses an in-situ instrument to detects the density and type of ions in the ionosphere by passing them through a magnetic field such that they fan out into a spectrum according to their masses. Given the same velocity, a lighter C^+ ion will curve more due to its smaller kinetic inertia when compared to a heavier CO_2^+ ion. Its position on a sensor will therefore infer the specie of ion, with the intensity giving density.
Langmuir Probe	Also known as an electrostatic probe, this in situ tool will find the saturation current in a plasma (and therefore it's electron density) by gradually increasing the potential difference between two nodes separated by the testing medium. As voltage increases, so does current, up to a point where the current is saturated (Mott-Smith & Langmuir, 1926). Greater detail on its operation can be found in Section 4.3.1.
Ionosonde	This measures electron densities on a single side of an ionospheric peak, such as the M2, by transmitting a chirp-signal that successively increases in frequency. The signal will be reflected back when the frequency matches the plasma frequency, therefore giving electron densities at different heights (plasma frequency is later described in Equation 2.11). As frequencies will only increase, a decrease in density with altitude would be impossible to measure. Given this, only a single side of a peak can be measured, therefore omitting the lower M1 layer.
Solar Wind Analyser	Like that found on MAVEN, this in situ instrument characterises the density, temperature and velocity of passing ions (Halekas et al., 2015).
Solar UV Spectrograph	Part of the energy imparted in the EUV and X-rays is re-emitted as UV. This emission can be studied by spectrograph (Bertaux et al., 2006).

Table 1.3: Direct and indirect ionospheric probing techniques

1.4 Summary

The Martian atmosphere, like those of other planetary bodies, is a complex and layered system, diminishing in density from the planet's surface to the interplanetary medium. Its upper layers, encompassing the mesosphere, thermosphere, and exosphere, are of particular interest due to the interaction between solar radiation and atmospheric particles. The ionosphere, a vertical region characterised by ionised particles, coexists at these altitudes and forms as a result of chemical processes and ionisation mechanisms driven primarily by EUV and soft X-rays radiation.

Mars' ionosphere exhibits temporal and spatial variability influenced by solar activity, seasonal cycles, and the planet's lack of a global magnetic field. Beyond the ionosphere, the

Martian atmosphere as a whole represents an intricate system influenced by planetary rotation, surface topography, and the interplay of thermal and photochemical processes. The seasonal cycles of CO₂, water ice sublimation and condensation shape the global atmospheric circulation, redistributing energy and particles.

There is a long history of measuring the ionosphere of Mars, dating back to the 1964 Mariner 4 mission. Today, we have a large range of remote sensing and in-situ techniques for measuring it; ranging from mass spectrometers, Langmuir probes and radio occultation.

1.5 Motivation

Understanding the driving forces of the Martian ionosphere is critical for future habitation as it greatly effects communication uplink capacity and the amount of radiation protection. The largest factor for the electron density and altitude of the ionospheric layers is the position of the sun, or SZA. However, we currently have a poor understanding of how this ionospheric structure varies throughout the entire Martian day. Scientists must extrapolate data from near the terminator to infer what the ionosphere is like in midday, leading to most models over-predicting electron densities for SZA values lower than 60° . Also the ionospheric densities at the terminator are far more variable than during the midday. This introduces problems when trying to parse all the possible other ionospheric forcing such as heliocentric distance, irradiance, dust loading and magnetic topology. This variability in this high-SZA region near the terminator is due to the density-by-SZA gradient being much steeper here, significant day-night plasma transport and a key requirement for the processing being violated in this region (assumption of spherical symmetry, more on this in Appendix C). As the key parameter for the ionosphere is SZA, one needs to normalise this to separate contributions of the other sources of forcing. This would be done effectively by using measurements from the more stable midday regions. For example, the ionosphere is so stable during the midday that when the SZA is 45° , the peak electron density is about 85% of the subsolar value. Due to this, having whole profiles from the midday regions will allow for easier separation of all forcing. We currently lack this; for example, the lowest SZA measurement recorded by MAVEN's ROSE RO instrument is 45° and this is exceedingly rare with 0.1% of measurements being below 70° . This is similar for MEX MaRS, but it's minimum is 50° . Furthermore, there is contention in the ionospheric communities for how the layer altitudes should change throughout the Martian day. For instance, we still don't know whether the M1 ionospheric layer should be visible during the midday (Mayyasi & Mendillo, 2015). Idealised Chapman theory states that the peak electron density should reduce with SZA with a factor that is equal to the neutral scale height. Nonetheless, midday electron density measurements currently predict a density that it is half what is expected. As the PI for the MAVEN ROSE

instrument said in Withers et al., 2024: ‘*this shows our troubling lack of understanding of the fundamentals of the thermosphere–ionosphere system*’.

The most common whole day ionospheric measurements come from sounding instruments. However, if we opt to use these instead, we will lack any information about the lower ionosphere and lower neutral atmosphere; both of which are driven by separate dynamics, with this will limiting our understanding of atmospheric-ionospheric coupling. Adding to this, these instruments introduce a significant altitude uncertainty (eg. $\pm 7\text{km}$ for MARSIS (Withers et al., 2024)), leading to models producing subsolar peak density altitudes ranging from 120-130 km. As this difference is a whole neutral scale height, the pressure varies by a factor 2.7 between these heights. This has significant implications for our modelling of reactions and collision rates in ion-neutral interactions, as well as for our understanding of ion-drag which affects winds and atmospheric escape rates. Furthermore, the lower M1 ionospheric layer is unmeasurable with sounders, so a range of ionospheric dynamics are not being explored. This is of paramount importance as this region has been known to cause radar and communication blackouts (Sánchez-Cano et al., 2019).

Finally, we do not have long-term synoptic measurements from the same instrument, which would otherwise be important for analysing the effect of the longer-timescale solar cycle trends. Instead, currently we piece together whole profile RO measurements from MGS at solar maximum, MAVEN ROSE at solar minimum and MEX’s MaRS in between to complete the solar cycle. Each instrument will inherently come with its own biases. Whole solar cycle studies exist but do not report on findings below the main ionospheric peak. It is important that we have measurements that are synoptic and evenly spaced across all coordinates and SZA, and with a high enough cadence so that short timescale effects can be monitored.

1.6 Goals

Now that the motivation of this thesis has been layout out, we can identity the goals. This thesis is to explore the Martian upper atmosphere and ionosphere via the use of mutual radio

occultation (shown in Figure 1.1). This first chapter has set the groundwork for key scientific questions raised in this thesis; describing the environment and chemical processes leading to the typical ionospheric structures we see today. Chapter 2 describes the new measurement technique forming the core of this thesis, namely mutual radio occultation. It shall begin with the fundamentals of what conventional radio occultation is, followed by how performing radio occultations *mutually* between two spacecraft is beneficial, after which is a description of the specific spacecraft hardware. Chapter 3 discusses the entire processing chain, from the receiving of raw spacecraft binaries to the derivation of physical parameters, such as vertical electron density profiles. Due to the absence of an Ultra-stable Oscillator on the spacecraft, this processing required development of techniques to compensate for random signal drifts, resulting in 18 months of development. As such, this chapter also includes some of the pertinent dead-ends that led to improvements. Chapter 4 compares our observations with data from other instruments and numerical models in order to validate our observations and reduction technique. Chapter 5 explores how the ionosphere's structure varies throughout the entire Martian day. Alongside this, a method for obtaining the thermospheric temperature is described and these results are then used to elucidate a strange phenomenon that thermospheric temperatures increase as we measure higher solar zenith angles. Chapter 6 dives into solar weather phenomena such as coronal mass ejections and solar flares, as well as how they interact with the Martian ionosphere. This chapter surrounds a single serendipitous measurement that occurred just a few minutes after a solar flare hit Mars. This thesis finishes in Chapter 7, concluding this body of work with a conclusions and suggestions for further research.

1.7 Hypotheses

A previously mentioned, mutual radio occultation allows us to get full electron density profiles from the midday regions of the martian ionosphere. Before starting this research, however, it would be good to layout what my hypotheses for the dynamics of the ionosphere are, such that I can address them later. Chapters 5 and 6 provide novel scientific content, so

you can find how these hypotheses are addressed at the end of those chapters. I will come back to these also in the conclusions.

1. Ionospheric Density Increases as $\text{SZA} \rightarrow 90^\circ$

Prior to analysing the data, a purely geometric argument suggested that the electron density of the dayside ionosphere should be greatest directly beneath the sub-solar point ($\text{SZA} = 0^\circ$). Specifically, I would assume a production rate $P \propto \cos \text{SZA}^{0.5}$ and a Chapman peak height that varies as $z_m \propto \sqrt{\sec \text{SZA}}$.

2. Absence of an M1 layer During the Midday

Martian ionospheric chemistry places the M2 peak near 130 km, with the M1 peak expected 20 to 25 km lower. However, this M1 layer should not exist during the midday as the altitude for EUV to reach peak opacity changes differently to soft X-ray. During the midday, the larger M2 layer is peak is so low that it dwarfs the smaller M1 layer (Mayyasi & Mendillo, 2015).

3. Altitude Variation Driven by Slant-Path Illumination

For a Chapman atmosphere the peak height z_m satisfies

$$N(z_m) \sec \text{SZA} \simeq \sigma^{-1},$$

where N is the vertical column density and σ the photo-absorption cross-section.

Because $\sec \chi$ increases with zenith angle, the altitude that meets this criterion must rise, giving the classical result

$$z_m(\chi) = z_m(0) + H \ln(\sec \text{SZA}),$$

with H the local neutral scale height. Thus, the peak should migrate upward as SZA increases.

4. Post-Noon Neutral Temperature Maximum

Thermal inertia in the tenuous thermosphere delays the temperature maximum relative to the energy input. Although EUV heating peaks at 12:00 LT, models and MAVEN/NGIMS observations show maximum neutral temperatures near 13:00–14:00 LT at ~ 150 km, consistent with a 1–2h lag.

5. Scale-Height Reduction with Increasing SZA

The neutral scale height is $H = kT/mg$. Where m is the molecular mass of CO_2 at 7.308×10^{-26} kg, k is the Boltzmann constant, and gravity g is dependent on altitude. As SZA increases away from noon, EUV heating weakens, the neutral temperature T falls, and H reduces in proportion.

6. Negligible Crustal-Field Influence at Local Noon

Crustal fields modulate plasma transport, but at local noon the photo-ionisation rate dominates. Consequently, crustal control should only be evident on the nightside.

7. Chapman-Theory Response to Solar Storms

Classical Chapman scaling gives the peak electron density as such, $\frac{F_f}{F_0} = \left(\frac{N_f}{N_0}\right)^2$, where F_f is the flux during the flare and F_0 is the nominal flux.

Chapter 2

Mutual Radio Occultation

The discussion about the benefits of doing radio occultation mutually and the introduction to the spacecraft have been published in: *Parrott, J., Svedhem, H., Witasse, O., Wilson, C., Müller-Wodarg, I., Cardesín-Moinelo, A., Schmitz, P., Godfrey, J., Reboud, O., Geiger, B., Sanchez-Cano, B., Nava, B., Migoya-Orue, Y. (2024a). First results of Mars express—ExoMars trace gas orbiter mutual radio occultation. Radio Science, 59, e2023RS007873. <https://doi.org/10.1029/2023RS007873> (Cover issue)*

2.1 Radio Occultation

A radio occultation (RO) observation occurs when a radio transmitter and receiver are obscured from each other by a planetary atmosphere. Just before the signal is lost, the line of sight between the two antennas grazes the planet's limb, progressively penetrating deeper into the atmosphere until reaching a medium of sufficient opacity; be that a planetary surface for rocky planets, or a dense atmosphere on the gas giants. During this process, the signal traverses different atmospheric layers, each possessing varying refractive properties, resulting in a slight frequency shift called the residuum ($f(t)$), as shown in Figure 2.1. After accounting for the Doppler shift caused by the relative motion of the two spacecraft, this frequency shift

can be analysed to determine the refractive properties of the atmosphere. These properties can then be used to estimate the neutral atmosphere's density and the electron density of the ionosphere (Fjeldbo et al., 1971, Kliore et al., 2004, Withers et al., 2020). Traditionally, RO observations for planets other than Earth involve a spacecraft orbiting the planet and a ground-station on Earth, where they usually utilise the spacecraft's deep space communication equipment, typically at X-band and/or S-band (8-12 GHz and 2-4 GHz, respectively) (Withers et al., 2020 Pätzold et al., 2004a).

A RO measurement can be of two schemes. It is known as an ingress occultation if the transmitter and the receiver begin the measurement when they have a clear line of sight. As the measurement continues and time passes, the vector between the two will continue to drop in altitude until the vector is blocked by the planetary surface and the two antennas are occluded from each other. This can also happen in the opposite direction, where the scheme is referred to as egress. Here, the measurement begins when the two antennas cannot see each other as they are under the horizon and they come into view as the observation continues. Generally, ingress occultation is preferred as the receiver can have an accurate measurement of the frequency before the vector starts to enter refractive mediums such as the atmosphere and ionosphere, thus making the calculation of the residuum easier.

The refractive properties of Martian atmosphere are a product of the pressure and temperature in the neutral atmosphere and the electron density of the ionosphere. More precisely, if we define refractivity as $\mu = (n - 1) \times 10^6$, where n is the more commonly used 'refractive index', then we can state:

$$\mu_n = C_0 \frac{P}{T} \quad (2.1)$$

where

$$P = N_n k T \quad (2.2)$$

so

$$\mu_n = C_0 k N_n \quad (2.3)$$

where P is pressure, T is temperature, k is the Boltzmann constant of $1.38 \times 10^{-23} \text{ J K}^{-1}$, N_n is the neutral number density m^{-3} and C_0 is a constant $1.3 \times 10^{-6} \text{ K m s}^2 \text{ kg}^{-1}$ for the martian atmosphere which is assuming the standard homosphere atmosphere of 95.3% CO_2 , 2.7% N_2 and 1.6% Ar (Tellmann et al., 2013). The neutral refractivity value has the opposite sign to the ionosphere's refractivity, since they have opposite effects in the direction of the radiowave's bending. The ionosphere's refractivity is calculated with:

$$\mu_e = -C_1 \frac{N_e}{f^2} \quad (2.4)$$

where C_1^1 is $-40.26 \text{ m}^3 \text{ s}^{-2}$, N_e is the electron number density and f is the transmit frequency that are used for the RO. In total, this leads to the integrated refractivity being:

$$\mu = C_0 k N_n - C_1 \frac{N_e}{f^2} \quad (2.5)$$

If we can obtain refractivity by height ($\mu(z)$), then we can infer the values for $N_n(z)$ and $N_e(z)$. The method for which $\mu(z)$ is acquired from $f(t)$, which is the small frequency shift produced from the refraction and involves the transformation called Abelian Inversion. However, this requires the frequency by height ($f(z)$) instead of frequency by time parameter ($f(t)$). To obtain this, one must use accurate time and location information (ephemerides) to calculate the geometry of the ray between the satellite and the ground-station.

2.1.1 The Abel Transform

RO is used prolifically on the Earth as it is a cost-effective keystone measurement. This means that RO data is used to calibrate other atmospheric measurements as it is so ubiquitous and resistant to cloud opacity. Thousands of residuums are therefore collected every day and inverted to refractivity profiles in the same way. This inversion is specifically called inverse-Abel Transform. This method is fast, but comes with its drawbacks and

¹ C_1 is found through $\frac{e^2}{8\pi^2\epsilon_0 m_e}$, which approximated to -40.2592. ϵ_0 is the permittivity of free space and m_e is electron mass.

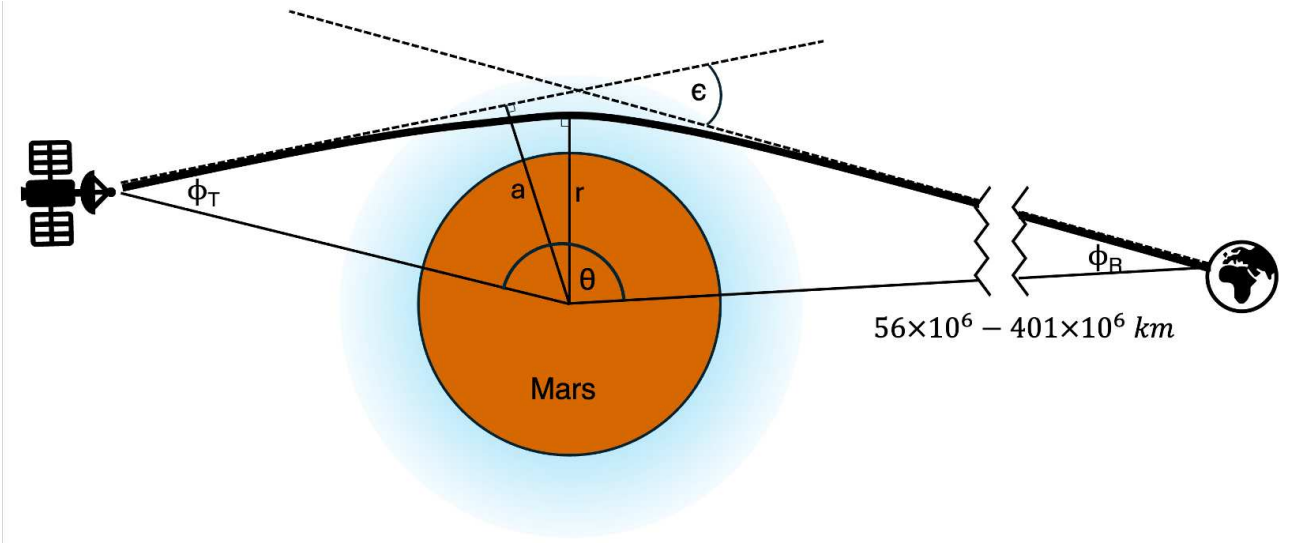


Figure 2.1: A diagram of Martian conventional RO with the geometric labels $a, \epsilon, \theta, \phi_T, \phi_R$ required to conduct conventional model inversion. Depending on solar longitudes of Earth and Mars, the distance back to the ground-station on Earth can vary from 56×10^6 - 401×10^6 km. The blue haze around Mars represents the Martian limb, which the radio link is refracting through. An important note from this diagram is that the impact parameter is a and not r .

requires integration with multiple quasi-collocated measurements to acquire reliable results (Palmer et al., 2000). Now I shall introduce and discuss the Abel transform, shown in Equation 2.10; thereby demonstrating how $f(z)$ is transformed into $\mu(z)$.

The first step in the model inversion is to map out the geometric parameters. Shown in Figure 2.1, the key parameters are the bending angle and the impact-parameter, ϵ and a respectively. The impact-parameter is defined as the distance from the point where the bending begins and the center of curvature such that

$$r_R \sin \phi_R = r_T \sin \phi_T = a \quad (2.6)$$

and ϵ is acquired via Bouguers rule² (page 123 of book (Born et al., 1999)),

$$\epsilon = \phi_R + \phi_T + \theta - \pi \quad (2.7)$$

With ϵ and a now defined, the Abel transform can be taken from first principles. Equation

²This rule is based of the conservation of angular momentum for a particle in a gravity field, the similarities can be seen as the ray is curved towards the center for refractivity

2.8 is the forward Abel Transform in its simplest form, describing a ray going through a homogeneous spherically symmetric medium:

$$A \{f(r)\} = 2 \int_y^\infty \frac{f(r)r}{\sqrt{r^2 - y^2}} dr \quad (2.8)$$

In the literature, this formula is often cited, but not explained. I shall further elaborate here. Notice that this equation uses r and y from Figure 2.2, where they describe the same direction but with different dimensionalities. The integrand is being evaluated from height y to ∞ because the ray drops to the minimum height of y and then propagates *again* through the medium above this height. This entry and exit notion is the reason for the multiplication of 2. If the denominator was not present, this equation would provide Total Electron Content (TEC), so to get N_e , we must divide by length. Again evident on Figure 2.2, a now-imaginary x axis could be used to calculate the radius of the 3D shape via a simple Pythagorean calculation $r = \sqrt{x^2 + y^2}$. This value of x is the distance that the ray would travel through the homogeneous medium.

To adapt this equation to work with heterogeneous stratified mediums, Fjeldbo and Eshleman, 1968 formulated this adaption:

$$\varepsilon(a) = -2a \int_a^\infty \left(\frac{\partial \ln \mu(\beta)}{\partial \beta} \right) \left(\frac{1}{\sqrt{\beta^2 - a^2}} \right) d\beta \quad (2.9)$$

The left hand side is now $\varepsilon(a)$, which is the bending angle as a function of the impact parameter. This is the proxy for the 3D electron density and can be derived from a phase shift at the receiver. β is the refractive radius, which is slightly different to r as it is slightly corrected for by refractivity, which only slightly varies from unity (ergo, $\beta = z\mu$). With $f(z)$ from Equation 2.8 being the equivalent of $\mu(\beta)$, the natural logarithm term might seem unusual, but real-valued result of the integration through a circle on a complex plane increases with $\ln(z)$ (Section 11.4-Cauchy's integral (Bak & Newman, 1997)). The numerator in Equation 2.8 has become a partial differential because the refractivity gradient

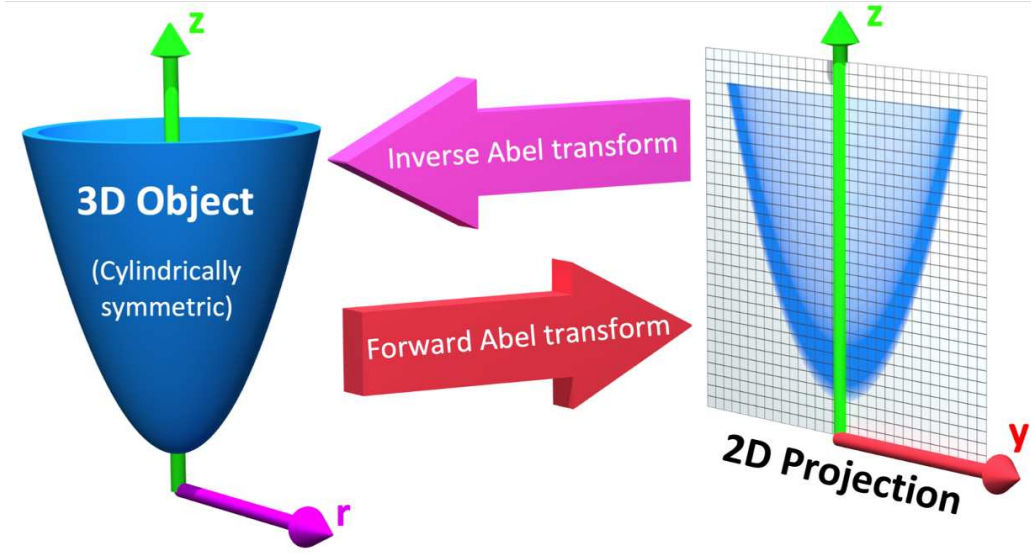


Figure 2.2: Cartoon of the Abel Transform, mapping symmetric 3D densities to pixel intensities on a 2D plane (Hickstein et al., 2019). This figure also emphasises that the Abel Transform can go in both directions.

with height is required. To reiterate, refraction only occurs when there is a refractivity gradient. The a can be seen on the outside of the integrand because Equation 2.8 had $f(r)r$ and with linearity rules, r can be brought to the outside. Finally, the minus is there because the bending angle has negative correlation to height. In other words, the impact parameter shrinks as the angle increases.

So far, only the forward transform has been described. By reversing Equation 2.9 and setting $\mu(\beta)$ as the subject, vertical refractivity profiles from bending angles (which come from the residuums) are acquired via the inverse Abel Transform:

$$\ln \mu(\beta) = \frac{1}{\pi} \int_{\beta}^{\infty} \frac{\varepsilon(a)}{\sqrt{a^2 - \beta^2}} da \quad (2.10)$$

2.2 *Mutual* Radio Occultation

There are several techniques for measuring the martian ionosphere (see Table 1.3). However, the topic of this thesis involves an improvement to the well-established RO method described above. A remarkable improvement to conventional RO is to put both the transmitter and receiver in orbit around the same planet. This comes with several significant benefits:

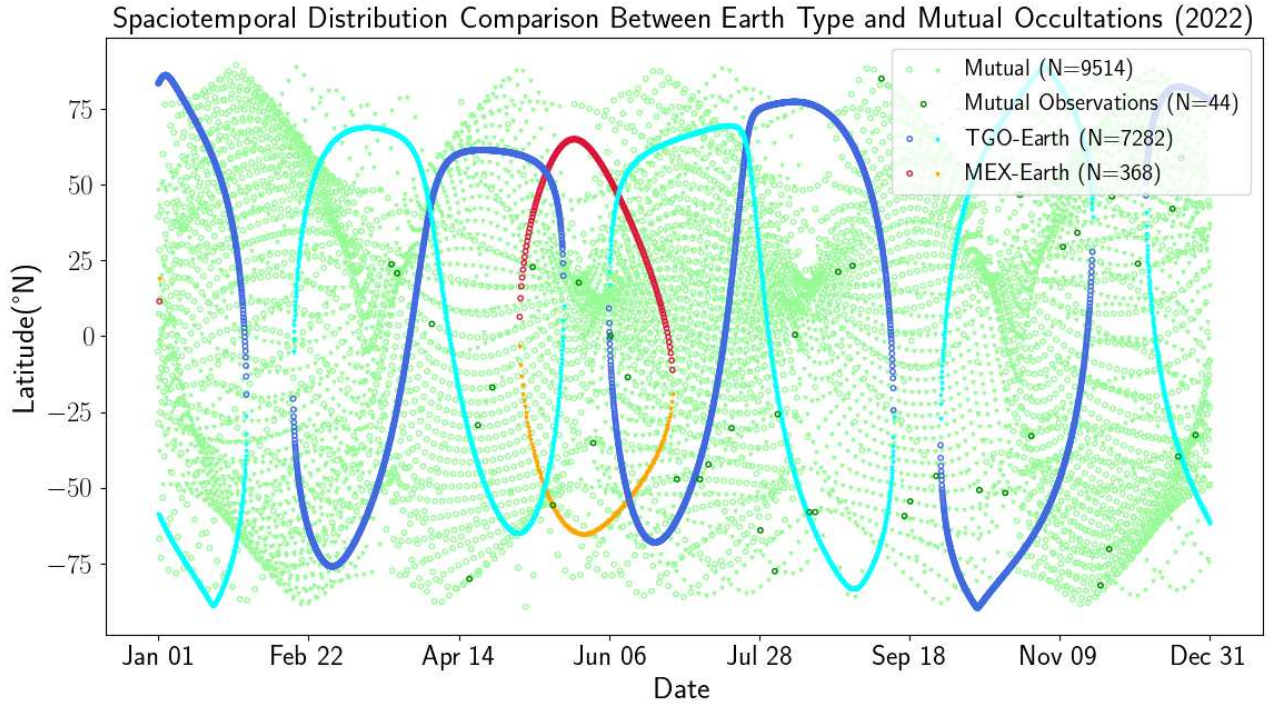


Figure 2.3: Spatiotemporal distribution of all potential RO opportunities for the year 2022. Shown are TGO-Earth (blue) and MEX-Earth (red) RO having a periodicity throughout the year and limited coverage. Ingress are indicated by darker colours and Egress occultations have a lighter hue. Mutual RO opportunities (green) are shown to have a considerably denser spaced distribution in latitudes. Actual Mutual RO observations that have been conducted in our experiment are indicated in dark green.

1. The latitudes of conventional RO measurements are similar between successive orbits. Over a matter of weeks, conventional RO events vary in Martian latitude by less than 10° . This means that in a particular Martian season, only a limited range of latitudes can be measured (e.g. only polar or only equatorial regions). This is due to the heliocentric layout of Mars and Earth being similar from day-to-day and the fact that the nodal procession of the spacecrafts' orbit is slow. The Mars-Earth horizon therefore occurs in a similar position with each successive orbits. Figure 2.3 highlights this, by showing that TGO-Earth and MEX-Earth conventional occultations are restricted to very specific latitudes on a short timescale, whereas the orbits of MEX and TGO (shown in Table 2.1) produce a far broader latitudinal coverage for mutual RO. Also, spacecraft-to-Earth occultations can only occur in specific seasons along the Martian year, whereas mutual RO can occur in any season. This is evident in Figure 2.3, where the red MEX points are constricted to just 1.5 months of 2022.
2. Similarly, due to the relative positions of Mars, Earth and the Sun, the

Radial Histogram for Solar Zenith Angle of Different Occultation Types (01/05/22 - 01/08/22)

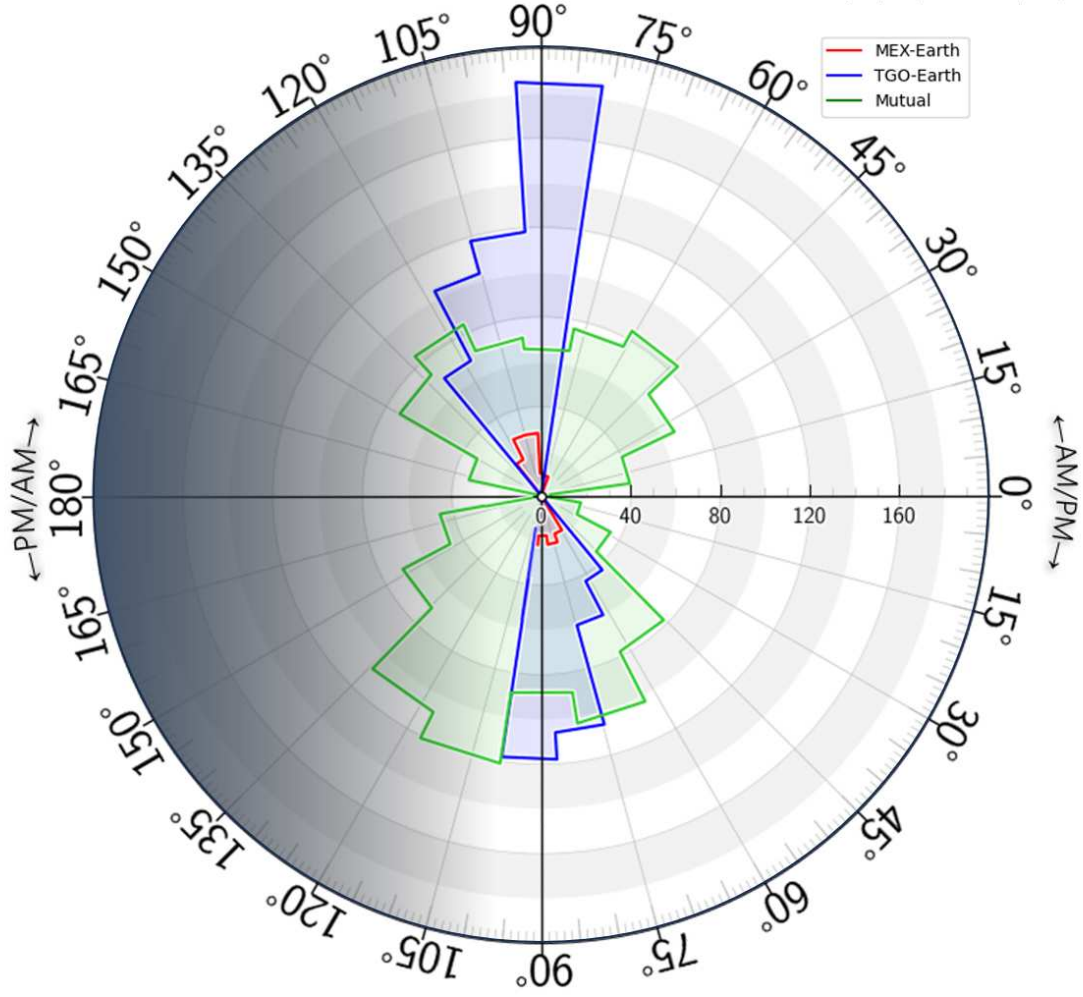


Figure 2.4: Radial histograms to indicate the SZA distribution of all spacecraft-to-Earth and spacecraft-to-spacecraft (Mutual) (green) RO opportunities during a three month period in 2022. SZA is indicated around the circumference and the population is shown on the x-axis within the plot. This plot shows that TGO-Earth (blue) and MEX-Earth (red) RO cluster in a specific SZA dawn/dusk range during this period, whereas the mutual occultations cover most SZA values.

spacecraft-to-Earth RO is also constrained to similar values of local time and SZA in any given season. A rough guide for the possible range of SZA for occultations with Earth has been provided by Tamburo et al., 2023, with $90 \pm 180 \times 1AU/\pi a$, where a is the semi-major axis of the orbit of the occulted planet, in astronomical units. This simple formula loosely applies to Mars occultations as it does not account for the relatively larger eccentricity of the Martian orbit. For example, in a three month period, TGO-Earth RO only covers SZA of 81° - 130° (ingress) and 50° - 100° (egress), while mutual occultations offer a much more even distribution of SZA, as shown in Figure 2.4.

This expanded coverage is crucial for understanding atmospheric conditions across different regions of Mars. For instance, the primary factor influencing Martian ionospheric densities is the SZA, with ROSE on MAVEN achieving their lowest SZA measurement at 45° (Withers et al., 2024). Such angles are exceedingly rare, with simulations indicating that only 0.1% occur below 70° , resulting in a lack of critical data for midday Martian conditions. While lower SZA RO measurements can be found in the Mariner 9 and Viking 1 archives, these only extend down to 47° and 53° , respectively (Vogt et al., 2016). This is further emphasised by Figure 2.5, which shows the local time and latitude distribution for the mutual RO measurements between 02/04/21 and 17/06/24.

3. Having the receiver and transmitter (Rx and Tx, respectively) on the same planet means that interplanetary plasma does not have to be accounted for. For conventional occultation, the resultant frequency shift can be dominated by heliophysical parameters instead of the target ionosphere or atmosphere. Additionally, not having the Rx inside the atmosphere of the Earth greatly simplifies the processing of the data, since meteorological datasets do not have to be integrated into the processing.
4. With signal strength reducing with distance squared, the Mars-Earth distance of 0.54 - 4.01×10^8 km is more than 25,000 times further than the 15,000 km maximum distance of the mutual RO tests. It should be noted that much lower amplification equipment is used for mutual RO than Earth occultation. However, the noise is far

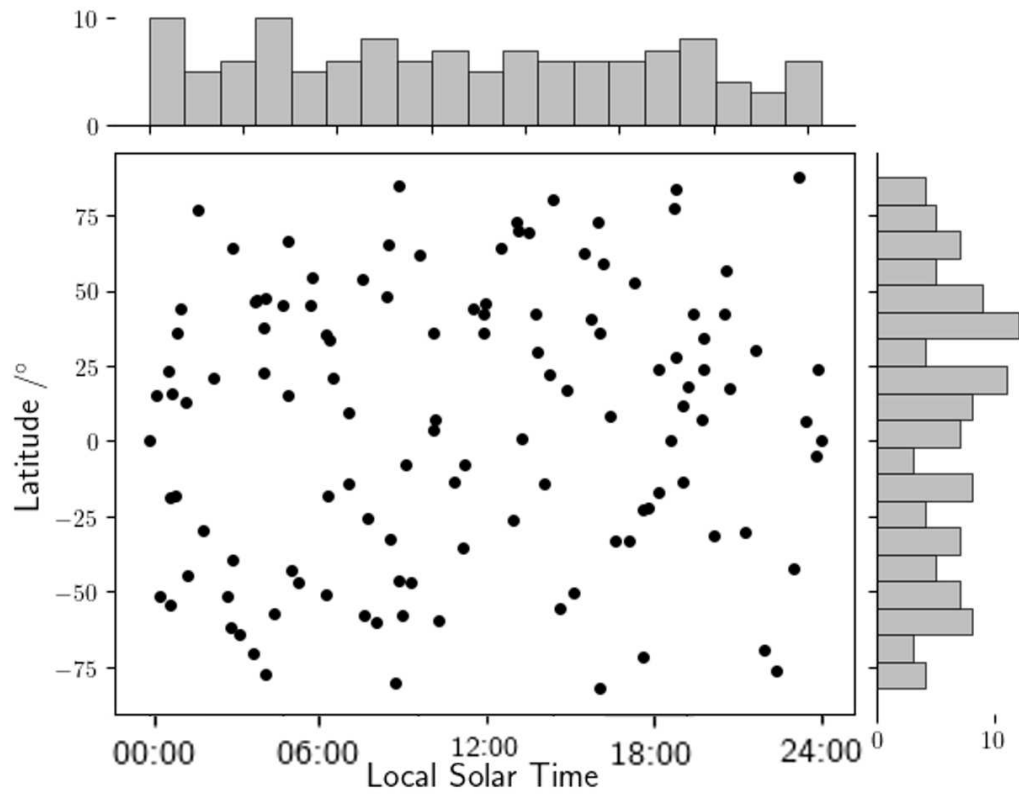


Figure 2.5: Distribution of 124 mutual radio occultations with latitude on the y-axis and local solar time on the x-axis. This shows that mutual RO provides an even synoptic coverage, this is highlighted by the histograms placed on the axis to show the even spread.

lower at these smaller distances; leading to a favourable signal-to-noise ratio (SNR).

5. Under-used equipment can be retroactively repurposed to carry out mutual RO. In this ESA example, both Tx and Rx are lander communicators. This is an important feature because this equipment was repurposed with very little extra financial investment. The costly parts of the campaign have already been completed, i.e. the hardware has been developed and inserted into Martian orbit. In short, mutual RO allows one to maximise scientific returns from a minimal financial investment.
6. Although this has not been done for the measurements described in this thesis, mutual RO has the potential to ‘eavesdrop’ on other passing radio communications. Despite Global Navigation Satellite System (GNSS) satellites not transmitting signals that are specifically designed to be used by RO satellites, COSMIC (S. Ho et al., 2020) and CHAMP RO satellites use them regardless. For example, there is the potential to use Mars Relay System communication links to probe the Martian atmosphere, provided that the carrier frequency is obtainable. If telemetry can successfully be filtered out of the side-bands then minutia in the carrier frequency can be ascertained. Practically this transpires as MEX and TGO not needing dedicated time in their schedules, increasing the number of opportunities available to conduct mutual RO. This technical improvement needs development and will be discussed as further work in Section 7.2.1.

2.3 MEX - TGO Mutual Radio Occultation Operations

Now that the general theory of mutual RO has been introduced, the specific hardware and coordination can now be described. This experiment is summarised in Figure 2.6, showing the two satellites being used are the European Space Agency’s (ESA) Mars Express (MEX) and ExoMars Trace Gas Orbiter (TGO). MEX has an elliptical orbit and TGO’s is circular, which is further elaborated in Table 2.1. This figure also shows moment when the longitude of the ascending node (Ω) of MEX and TGO are separated by around 90° . This is not permanent as the differing inclination of the two orbiters varies this Ω value and produces very different

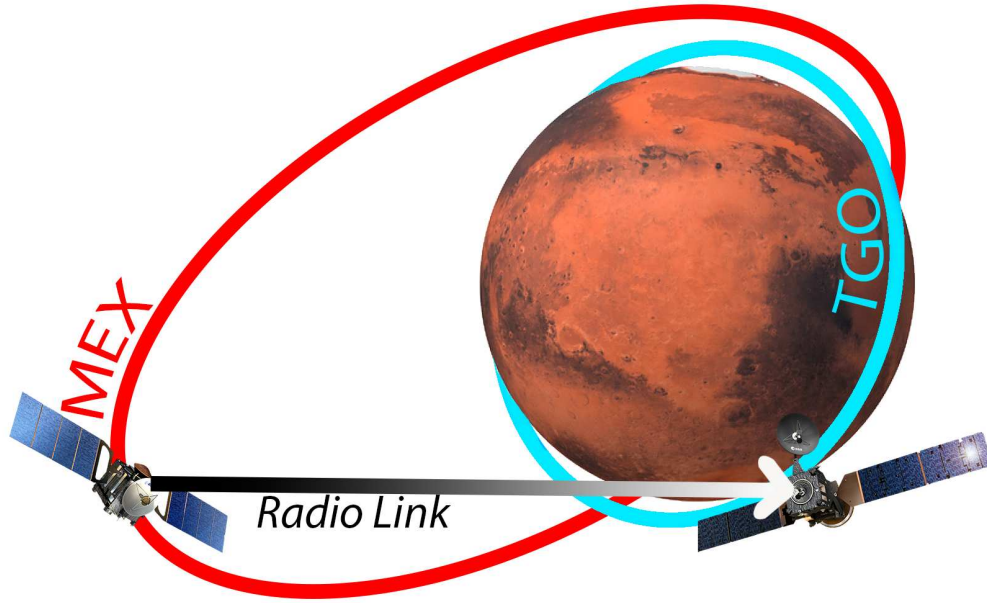


Figure 2.6: Orbital configuration of MEX (red) and TGO (blue) during a typical mutual RO observation, with a black/white arrow indicating the direction of the radio link between the two spacecraft

occultation geometries, sometimes leading to measurements that are unusable (more on this in Section 3.3)

Orbit parameters	Transmitter (MEX)	Receiver (TGO)
Pericentre altitude (km)	350	380
Apocentre altitude (km)	10500	430
Eccentricity (<i>dimensionless</i>)	0.57	0.007
Inclination (°)	87	76
Period (hours)	7.5	2

Table 2.1: Approximate orbit characteristics of the transmitting and receiving satellites. See (Cardesín-Moinelo et al., 2021) and ESA SPICE kernels for detailed orbital parameters

2.3.1 Trace Gas Orbiter Rx - Electra

TGO is shown in Figure 2.7 and is the orbital element of the ExoMars mission which was first proposed in November 2001 as part of ESA’s Aurora Programme. The original goal of ExoMars was to establish if life had ever existed on Mars, then later an additional goal was appended to ‘demonstrate new technologies paving the way for a future Mars sample return mission in the 2020s’. Over time, the missions solidified into three segments on-board two separate launches. The Trace Gas Orbiter and the Schiaparelli Entry, Descent and Landing

Demonstrator Module (EDM) were launched together on the 14th of March 2016. The payload arrived at Mars seven months later on the 19th of October, where the EDM separated and attempted to land on the surface, whereas TGO entered a long aero braking orbit where it entered its final orbit and began its science mission on the 24th of April 2018. The third segment of the ExoMars mission consists of the Rosalind Franklin Rover (internally at ESA named M2020), which has been delayed due to the breakdown of cooperation with Roscosmos following Russia's invasion of Ukraine.

So far the TGO mission has been considered a resounding success with many scientific achievements. TGO helped to map out potential landing sites for the subsequent ESA rover and NASA's next rover with its stereoscopic camera CaSSiS (Thomas et al., 2017). Finally, the neutron detector FREND (Mitrofanov et al., 2018) revealed surface water deposits, some even near the equator (which is crucial for potential human habitation).

A concomitant role of TGO is being a member of the Mars Relay System. This is a network to share the data traffic from the landers across multiple ESA and NASA orbiters, thus increasing downlink throughput to Earth. For this reason, the equipment ESA opted to use to link with its Schiaparelli EDM was a NASA designed radio called Electra. The Electra radio was designed by NASA Jet Propulsion Laboratory (JPL) and has flight heritage from Curiosity, MRO and MAVEN. Its similarity with other missions' radios allows for easier relaying between rovers and orbiters, including the Schiaparelli Entry, Descent and Landing Demonstrator Module (EDM) (Ball et al., 2022) (frequency offset of EDM-TGO link during its descent is later shown in Figure 3.2). However, the EDM's landing was famously not successful due to unforeseen spinning leading to the altitude sensor being off-nadir, therefore measuring a larger distance than the true altitude, resulting in it detaching from its parachute too late and impacting the surface violently. This left the Electra radio on-board the TGO underutilised for years, save for its regular comm-link with the Mars Relay System where 50% of NASA's landers traffic passes through. The Mars Relay System is a shared network involving most NASA and ESA assets at Mars. It allows for higher a data-rate to Earth, even when the uploading antenna does not have line-of-sight to a ground-station.

Electra is a modern highly flexible Ultra High Frequency (UHF) communications system (Edwards & Charles, 2023) and is presently flying on several NASA missions. It was provided by NASA to ESA as a part of the ExoMars collaboration. It can operate at 16 different transmit frequencies and 16 receive frequencies in any combination in the 390-450 MHz band (Taylor et al., 2006). For these MEX-TGO RO measurements, the receiving frequency was set to the nominal MEX transmission frequency of 437.1 MHz. The recording is done in Open Loop Recording mode, i.e., there is no attempt to lock on the incoming signal and the recorder is running 'in the blind' at a sampling frequency up to 128 kHz. Both In-phase and Quadrature signals are sampled simultaneously. This sample frequency is more than sufficient to account for the worst case expected frequency shift, to ensure that the signal always is within the bandwidth of the system. At a later stage it was decided to lower the sampling rate to 32 kHz to reduce the generated data volume, as I showed there were no adverse effects in doing so.

On MRO, Electra is driven by an Ultra Stable Oscillator (USO) providing excellent short and long term frequency stability to the transceivers. Unfortunately, this is not the case for Electra on TGO, where a Temperature Compensated Crystal Oscillator (TCXO) is used instead. It is adequate for the purpose of communication with the assets on the Martian surface, but is marginal when used for radio science measurements. At present, however, it has not been possible to quantify in detail how the performance of the RO is affected by the TCXO and its ageing.

2.3.2 Mars Express Tx - MELACOM

ESA's first mission to the red planet was Mars Express (MEX), shown in Figure 2.8. Namely 'Express' due to a novel approach taken by ESA to emphasise commonality between similar missions, leverage industry and collaboration with the scientific community, hence reducing cost and expediting development time. It also had the fastest transfer there ever was/has been since to a unique orbital alignment that will not repeat for another 60,000 years. MEX shares many instruments with Venus Express and Rosetta, such as their space platforms

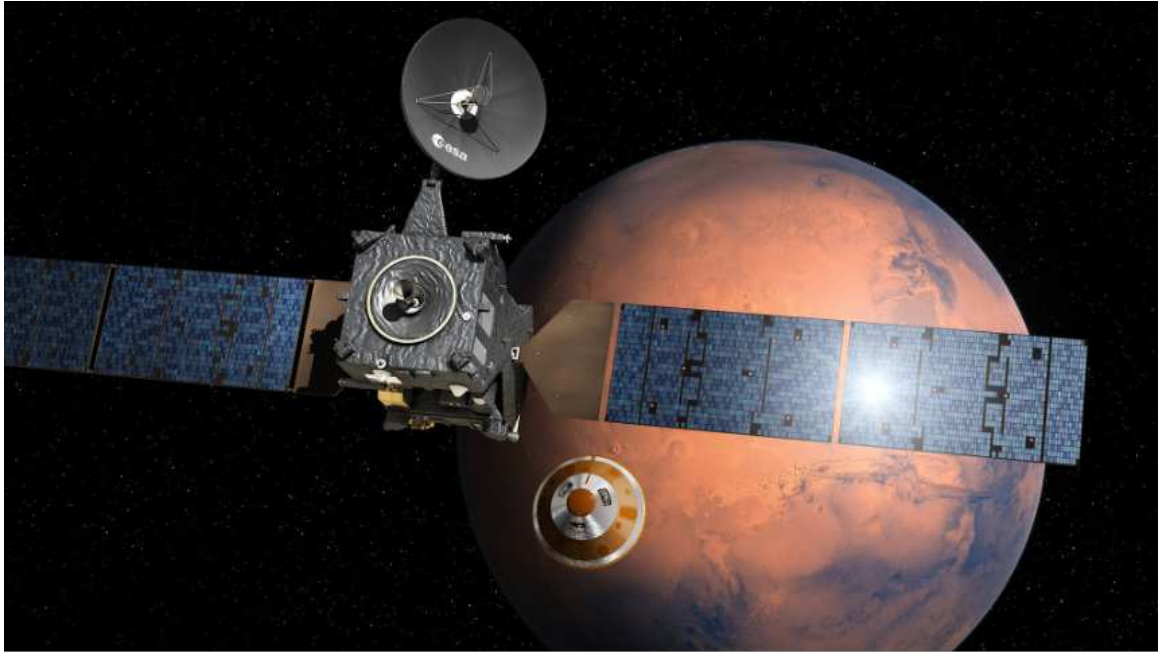


Figure 2.7: Artist impression of the receiving satellite called Trace Gas Orbiter. Also shown is its lander segment named the Schiaparelli (Credit: ESA)

(Fregat) and ground segments; enabling MEX to be developed in a record time of five years.

MEX was launched on the 2nd of June 2003 and arrived on the 20th of December of the same year. Its roster of achievements are also impressive: The OMEGA instrument (Bibring et al., 2004) made the first detection of hydrated minerals, which indicated Mars had a less arid past. The ASPERA-3 payload (Barabash et al., 2006) elucidated how the atmosphere might have become so thin due to the constant stripping by solar winds. Much progress was made by the High Resolution Stereo Camera (HRSC) (Jaumann et al., 2007), which revealed evidence of recent volcanism, glacial terrains, and provided a high-resolution map of Phobos and Deimos. Also the Planetary Fourier Spectrometer (PFS) revealed the spatial variability of methane with seasons and how there could be large deposits of methane at the polar caps (Geminale et al., 2011).

Similar to TGO, MEX was also carrying a lander. Named the Beagle-2 (Wright et al., 2003), it was declared lost on the 6th of February 2004 after failing to make a sequence of uplinks upon reaching the surface. No consensus has been reached as to the cause. Initially, the main hypothesis was that mid-altitude dust caused the air to be warmer and less dense, ergo reducing the efficacy of the parachutes. This led to Beagle-2 crashing onto the surface.

However this theory was updated in 2015 when the HiRISE camera on NASA’s MRO spacecraft found the dormant Beagle-2 lander on the surface. It was noted that only 2 of its 4 solar panels had deployed correctly. Crucially, one of the not deployed solar panels was blocking the UHF antenna, rendering it isolated on the surface (Bridges et al., 2017). The MELACOM transponder on board MEX, which was designed to communicate with the lander, never received any transmissions. At the time of writing this thesis, MELACOM has been in space for almost 22 years, but its oven-controlled oscillator makes it a perfect candidate to transmit a signal for an mutual RO.

MELACOM (Mars Express LAnder COMmunication) was chosen to be the transmission source as its Open Loop recording capability is much less than that of TGO’s Electra unit and wouldn’t be able to record a signal with sufficient precision and sampling rate for radio science observations (*James Godfrey, 2020, pers comm*). However, MELACOM’s oven stabilised oscillator means that it could potentially provide a stable carrier signal. The oscillator’s Allan variance, which is a metric for the stability of an oscillator, is stated to be better than 5×10^{-12} (C-MAC, 2000). This is considered to be very good, even if it is not as good as an USO.

In preparation for the ExoMars arrival at Mars, a performance characterisation of the MELACOM system, including the oscillator accuracy, was done from the Arecibo radio telescope, Puerto Rico in November 2013. It was determined that the frequency only differed from the nominal frequency by 52 Hz (Gurvits, 2014). This is well in line with the expected ageing since the launch.

2.3.3 The MEX-TGO Radio Link

The receiving frequency of one of the two spacecraft had to be changed to match the transmit frequency of the other since the Orbiter-to-Lander UHF communication radios are used here for a direct link between the two orbiters, meaning one spacecraft must either transmit at a receiving frequency or receive at a transmit frequency. Fortunately, the TGO Electra radio can accomplish this, whereas the MEX MELACOM radio lacks this versatility. TGO was



Figure 2.8: Artist impression of the transmitting satellite named Mars Express (Credit: ESA).

therefore configured to receive at 437.1 MHz, the transmit frequency of the MEX MELACOM relay radio.

RO at UHF frequencies are especially effective for measuring ionospheres, as opposed to the neutral atmosphere. This is due to the specific plasma frequency (f_p) of the ionosphere (measured in Hz), which occurs when electron and ion momentum acts as a restoring force against an electric field between an electron and an ion. This frequency increases with electron density such that,

$$f_p = \frac{1}{2\pi} \sqrt{\frac{N_e e^2}{m_e \xi_0}} \quad (2.11)$$

where N_e is the electron density in m^{-3} , e is the elementary charge 1.602×10^{-19} C, m_e is the electron mass 9.109×10^{-31} kg and ξ_0 is the permittivity of free space $8.854 \times 10^{-12} m^{-3} kg^{-1} s^4 A^2$. For frequencies below the plasma frequency, an incident wave will be fully reflected. For frequencies much higher than the plasma frequency, an incident wave will propagate with only little effect through the medium. However, for frequencies only slightly above the plasma frequency, an incident wave will propagate through the medium but will be refracted and will experience a phase shift. With $n^2 = 1 - \frac{\omega_p^2}{\omega^2}$, where $\omega_p = 2\pi f_p$, ω is the transmit radio frequency and n is the refractive index (Born et al., 1999), it can be seen

that the lower the frequency is, the higher the effect will be on the propagation, as long as the frequency is above the plasma frequency. Therefore, at UHF the effect is much stronger than it is at S- or X-band.

2.3.4 Link Budget

Apart from the frequency selection, the specifics of the radio link should be discussed. The maximum distance between the two spacecraft during a RO can be up to approximately 15,000 km. In order to avoid interfering with scientific observations by any of the other investigations on MEX or TGO, dedicated pointing is not used for the mutual RO sessions. Both SC are usually pointing with their UHF antennas to near Nadir. Therefore, the off-bore-sight angles towards each other are typically below 75° . Maximum distance and maximum off bore-sight pointing on both SC never occur simultaneously because MEX's MELACOM antenna is always near nadir at apoapsis, therefore pointing towards the lower altitude TGO. Given this, a compensation of +6 dB has been applied to this worst case scenario. The minimum expected received power at Electra should be close to -140.6 dBm at these view angles and ranges, as shown by Table 2.2. At the UHF frequency (f_t) of 437.1 MHz and an estimated noise temperature of 500 K, combined with the carrier loop SNR (SNR_{CL}) of 30 dB, this results in a voltage SNR of 44.8 ($SNR_V = \sqrt{2 \times SNR_{CL}}$). This leads to a carrier phase error of just 22.3 mrad (SNR_v^{-1}), causing a relative pathlength measurement error of 2.4 mm ($SNR_v^{-1}/f_t 2\pi$). Alternatively this is 3.6 mHz error in frequency. ($(f_t 2\pi - SNR_v^{-1})/2\pi$) We anticipate that the contribution of thermal noise will be insignificant in comparison with systematic errors, for example, oscillator drift (more on this drift in Section 3.3).

2.3.5 Planning

Mutual RO uses orbiter communications equipment which is transmitting the same frequency as used for Orbiter to Lander Forward Link operations. Considering that there are currently

Parameters	Values
Tx	
RF Power	37 dBm (5W)
Antenna Gain	-7 dBi
Circuit Loss	-1 dB
Transmitted Power	29 dBm
Medium	
Space Loss	-168.1 dB
Boresight Compensation	6 dB
Rx	
Antenna Gain	-7.1 dBi
Circuit Loss	-0.4 dB
Error Propagation	
Total Received Power	-140.6 dBm
Noise Spectral Density	-171.6 dBmHz ⁻¹
Rx Power / Noise (1 second)	31 dBHz
Carrier Loop Bandwidth	1 Hz
Radio Loss	-1 dB
Carrier Loop SNR	30 dB
Voltage SNR (1 second)	44.8
Phase Error	22.3 mrad
Pathlength Error	2.4 mm
Frequency Error	3.6 mHz

Table 2.2: The worst case link budget and physical error propagation for a MEX-TGO Mutual RO observation with the maximum distance and off-boresight angles.

five Mars orbiters (TGO, MEX, MRO, ODY, and MAVEN) which are communicating in this frequency band with Mars surface assets, extreme care needs to be taken to avoid radio frequency interference (RFI) with other orbiter to lander relay communications when planning the UHF radio science measurements.

The planning of mutual observations is performed by the Science Operations Centres (SOC) of both MEX and TGO missions (Cardesín-Moinelo et al., 2021). This planning process starts with an opportunity analysis of the geometric conditions, identifying the time periods where the line of sight between MEX and TGO intersects the limb of Mars, for when the tangent point altitude is between 0 and 400 km. Additionally, the orientation of both orbiters must be such that the UHF antennas are in view to each other, i.e., both antenna boresight angles are below 75° and the distance between the SCs must be less than 15,000 km to ensure a favourable SNR. These calculations were completed with SPICE, and where part of a deliverable to ESA which can be found on GitHub (Parrott, 2022). These visibility windows are then considered potential candidates for RO measurements.

The scheduling process needs to take into account the operational constraints, not only from both spacecraft, but also from any other possible lander relay communications occurring at Mars. Relay operations are considered critical, therefore any orbiter to lander view period is considered as a “no-go zone” for RO observations. These view periods are provided by ESA’s spacecraft operations center (ESOC) to the science operations centers (ESAC), typically 12 weeks prior to the Medium-Term Planning Period which covers 4 weeks of operation. Exclusion periods of special operations by TGO and MEX are also avoided, such as orbit control manoeuvres, SC maintenance periods and MEX communication passes.

Finally, the science planners take all the visibility and feasibility opportunities into account to select the optimal RO observations, either ingress or egress occultations with the best geometrical conditions (lowest distance, best visibility angles, largest altitude range) as well as maximizing the desired seasonal coverage with respect to latitude, longitude and local time.

Once the mutual RO slots are selected and the full science plan is confirmed for both missions, the science planners at ESAC generate the pointing timeline and the commanding

parameters for all MEX and TGO payloads, including the relay antennas. About 8 weeks prior to execution the timelines are passed on to the mission planners at ESOC for verification. At this stage the orbiter attitude and spacecraft resource profile (for power consumption and data generation) gets “fixed” and Mission Planners at ESOC provide the selected mutual RO slots to the JPL Mars Relay Operations System (MaROS) as information to the Lander community. This helps to identify potential RFI conflicts in case a relay overflight opportunity comes up at a later stage (e.g. due to updated orbit predictions). In case any RFI conflicts between MEX-TGO Radio Science and NASA relay operations are detected prior to the Short-Term Planning process, when spacecraft commanding is generated, mutual RO observations might have to be withdrawn because relay operations take priority over UHF mutual RO.

Typically, one mutual RO observation was selected every week, covering the limb from the surface up to 400 km, with a default duration of 10 minutes, in which MEX transmits the UHF carrier to TGO, recording in open loop and generating a data volume of about 307 MB. This data is later downlinked to Earth with the same priority as the rest of TGO’s science data and without affecting the relay data traffic. As of November 2024, this cadence has been increased to two per week due to my efforts in minimising the operational requirements by reducing the sampling rate from 128 kHz to 32 kHz. The results of this planning can be found in the planning table, which in a later chapter in Table 4.1.

2.4 Summary

RO is a technique for studying planetary atmospheres and ionospheres. It occurs when a radio signal and is transmitted between two spacecraft is obscured by a planetary limb. As the radio vector grazes the planet’s limb, it progressively penetrates deeper atmospheric layers before being blocked entirely. After accounting for Doppler effects due to the relative motion of the spacecraft, the resultant frequency shifts can be analysed to determine refractivity. This information allows the inference of the neutral atmospheric density and ionospheric

electron density.

Traditional radio occultation setups involve a spacecraft in orbit around the target planet and ground stations on Earth, utilising standard deep-space communication frequencies like X-band and S-band. However, the technique described in this thesis utilises pre-existing lander communication equipment at a frequency of 437.1 MHz. This innovation allows more flexible observation geometries and enhanced coverage.

The hardware being deployed in this measuring technique has been introduced, including some general introductions to the MEX and TGO spacecraft. Specifics were also provided about the radio link between the MELACOM transmitter and the Electra receiver.

Chapter 3

Processing Chain

The final processing chain presented in this chapter has been published in: *Parrott, J., Svedhem, H., Witasse, O., Wilson, C., Müller-Wodarg, I., Cardesín-Moinelo, A., Schmitz, P., Godfrey, J., Reboud, O., Geiger, B., Sanchez-Cano, B., Nava, B., Migoya-Orue, Y.. (2024a). First results of Mars express—ExoMars trace gas orbiter mutual radio occultation. Radio Science, 59, e2023RS007873. <https://doi.org/10.1029/2023RS007873> (Cover issue)*

3.1 Introduction

The following section describes how the final electron density profiles are obtained from the raw binary bitstreams being downlinked from TGO. I have been responsible for the entire processing chain as this task was initially given to me during my previous employment. At the start of my PhD, I had got as far as seeing a Net Doppler (containing the frequency shift due to the atmosphere *and* the Doppler due the relative motion of the two spacecraft). The work in this PhD has involved simulating the Doppler shift, dealing with the lack of the unstable oscillator, ameliorating various other hardware issues and deriving the final electron density vertical profiles.

This chapter begins with an overview of the general stages in the data reduction process, highlighting the specific challenges encountered due to the hardware’s original design not

accommodating radio occultation (RO). Following this, I detail the precise processes I employ to generate accurate vertical profiles.

3.2 Data Reduction

The steps outlined below provide a very general framework. For specific details and any spacecraft-specific considerations, please refer to the subsequent sections of this chapter.

1. The spacecraft performs the RO measurement using its repurposed lander-comm Low Gain Antenna, and the downconverted open-loop recording is stored locally on the spacecraft.
2. When there is line-of-sight to Earth and high priority data have been sent, the spacecraft will use its High Gain Antenna to downlink to Earth's Deep Space Network (DSN).
3. The raw binary bitstream is received via ESA and NASA's ground station and is stored in a system called 'ESA Ground Operations System Data Dissemination System' (EDDS).
4. The raw data is downloaded and stored locally.
5. This data is 'encapsulated', meaning the important information is dispersed throughout the bit stream around various other data types such as timing and voltage data. 'Decapsulation' is required to find the In-phase and Quadrature (I&Q) representation of the waveform.
6. A fast Fourier transform (FFT) is applied to the I&Q data, converting the waveform from the time domain to the frequency domain, thus revealing the carrier frequency. This process utilizes a sliding FFT, allowing for a series of frequency measurements that illustrate how the carrier frequency varies during the measurement.
7. Isolate the carrier tone from the rest of the open-loop recording, this produces the Net Doppler.

8. Throughout the measurement, frequency variations arise due to both atmospheric refraction along the ray-path and Doppler shifts caused by the relative motion of the spacecraft. The next step involves simulating the spacecraft's motion and the resulting Doppler Shift.
9. The calculated Doppler shift is subtracted from the Net Doppler, yielding the residuum (defined later in Section 3.2.1). This residual discrepancy is the minor frequency shift induced by the refraction of radio signals through the atmospheric and ionospheric media.
10. An inverse Abel transform is applied to this residuum, converting the frequency time-series into a vertical refractivity profile, as elaborated in Section 2.1.1.
11. Use Equation 2.1 and 2.4 to find neutral atmosphere and ionospheric parameters.
12. Store I&Q, Orbit Geometries, Net Doppler, Residuum, Refractivity Profiles and Electron Density Profile datasets in the ESA Guest Storage Facility for public use by the wider scientific community.

3.2.1 The Residuum and the Vertical Profile

Throughout the rest of this thesis, the *residuum* and *vertical refractivity profile* shall be discussed extensively, so we shall now describe in detail what these are, and how they relate to each other. In the processing chain, the residuum is acquired prior to the vertical profile. Ideally, this residuum represents the frequency shift caused by the ionosphere and atmosphere. However, it often includes frequency shifts from other sources, such as oscillator drift. While previous studies often refer to this as the "residual Doppler," it is technically not a Doppler shift as it is not caused by the relative motion between the two spacecraft. The term was introduced by Pätzold et al., 2016 to enhance verbal accuracy.

Figure 3.1 presents a simulated profile consisting of two ionospheric layers and a lower neutral atmosphere, while the right column illustrates the corresponding residuum. These results

were derived using my ray-tracing method, which is described in Appendix C. A dashed red line is visible on the residuum graphs, indicating the altitude of the tangent point and corresponding to the right axis. The tangent point is defined as the 3D location on the vector between the two spacecraft that is closest to the planet's surface. As previously described, the tangent point during an RO observation can either be increasing or decreasing in altitude throughout the measurement depending on whether the RO is an ingress or an egress type. In the example depicted in this figure, the observation represents an ingress occultation, as the ionospheric and atmospheric effects appear at the end of the observation. In the remainder of this thesis, the segment of the residuum during atmospheric influence is referred to as the "limb portion," and the segment when the tangent point is in the vacuum of space (with no refractive effects) is referred to as the "vacuum portion."

Panel C and D in Figure 3.1 provide a closer view of the limb portion. The following description will walk through the annotated steps as if we are following the tangent point descending as time progresses during this ingress RO observation, explaining how features in the residuum are formed. The key point is that the residuum essentially acts as the derivative of the profile, albeit with slight corrections for spherical symmetry.

1. As the tangent point descends into the limb portion, where electron density is increasing, the received carrier frequency also begins to increase.
2. At this stage, the electron density is rising at its *fastest rate*, so the residuum indicates the largest frequency shift.
3. The tangent point reaches the M2 altitude, where electron density is at its peak. At this maximum, the change in density is $0 \text{ m}^{-3}\text{s}^{-1}$, causing the residuum to fall to 0 Hz.
4. The smaller M1 ionospheric layer introduces a small inflection in the profile. In this simulation, it appears as a minor shoulder on the M2 layer, so the rate of change in density never quite reaches zero; it only approximates it. Consequently, the residuum illustrates a second smaller ionospheric feature at around -60 seconds.

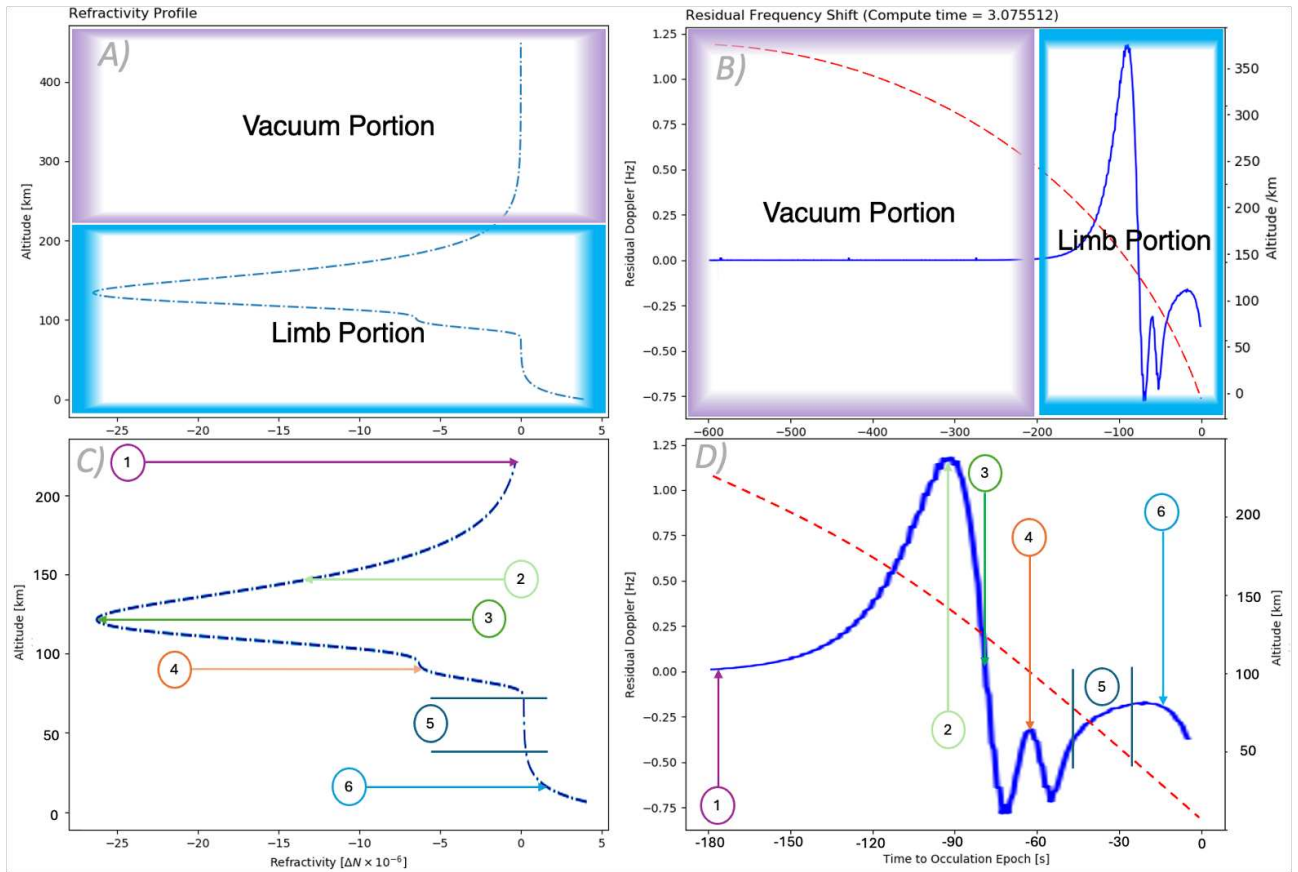


Figure 3.1: An annotated guide to the relationship between vertical refractivity profiles and residuum, using a simulated Martian limb. Panel A is a simulated electron density and panel B is the resultant residuum. Panel C and D are cropped versions of the panels above to highlight the different stages of the limb portion.

5. A relatively flat segment typically occurs in the limb portion where the ionosphere has mostly dissipated, and the neutral atmosphere is insufficiently dense to affect refractivity. This creates a profile remaining around 0 m^{-3} for approximately 20 km. This part is probably the most counterintuitive aspect of the profile-residuum conversion. Despite a flat profile segment, the residuum does not drop to 0 Hz due to the correction for spherical symmetry. Although the profile might not show refraction in this segment, the ray between the two spacecraft still traverses higher spherically symmetrical layers. This effect becomes more pronounced as the tangent point descends further into the limb.
6. As the neutral density begins to increase, it exhibits refractive properties opposite to those of the ionosphere. Consequently, the residuum bends in the opposite direction to what was observed at point 1 in this figure.

3.3 Pertinent Processing Chain Development

In developing this processing chain, numerous challenges emerged due to the limitations of the spacecraft hardware. It's important to clarify that these are not technically 'faults,' as the hardware was not originally designed for such measurements. A prominent issue was the absence of an Ultra Stable Oscillator (USO), which posed a significant challenge because we needed to extract a residuum with an amplitude of approximately ± 1 Hz. While this lack of stability was not problematic for its primary function as a transceiver for telemetry (since a heterodyne receiver could isolate the carrier tone and demodulate the telemetry from the waveform) it was inadequate for our purposes. Consequently, a solution to this issue was necessary. Other critical challenges included the orbital configurations, which were not ideal for mutual RO, and the fact that Electra did not record the exact start time. These issues are elaborated upon in the following section.

The upcoming section details the relevant events during the development of the processing chain. This task was the most substantial undertaking in my PhD, and it involved numerous efforts that did not yield fruitful results. This chronologically ordered account is derived from the 238 pages of notes taken between November 3, 2021, and January 27, 2023.

Rewriting Decapsulation Software The Electra hardware on TGO was constructed using JPL technology, although the construction and software development were contracted to the British aerospace company BAe. Initially, the software functioned nominally for reading Electra-specific formatted data, or 'encapsulated' data. However, since the orbit insertion in 2018, while the Electra firmware had undergone updates, the software for reading it had not been updated accordingly. The original software was designed to read the I&Q waveform¹, the signal level, and the encoded time. The waveform included both modulated data, such as housekeeping data or rover commands, and the crucial

¹Let's define this term. In-phase is a wave that has not had any phase shift and Quadrature is 90° out of phase, like a sine and cosine functions. With the identity $a\cos(x) + b\sin(x) = A\cos(x + \phi)$, we can alter the phase and amplitude of the resultant sinusoid by changing just the amplitude of the in-phase and quadrature component. So the I&Q dataset is just a sequence of two amplitudes at the cadence of the sampling frequency (at first this was 128 kHz). Continuing this identity, the resultant magnitude of the received waveform is $\sqrt{a^2 + b^2}$ and the phase is $\arctan(\frac{b}{a})$.

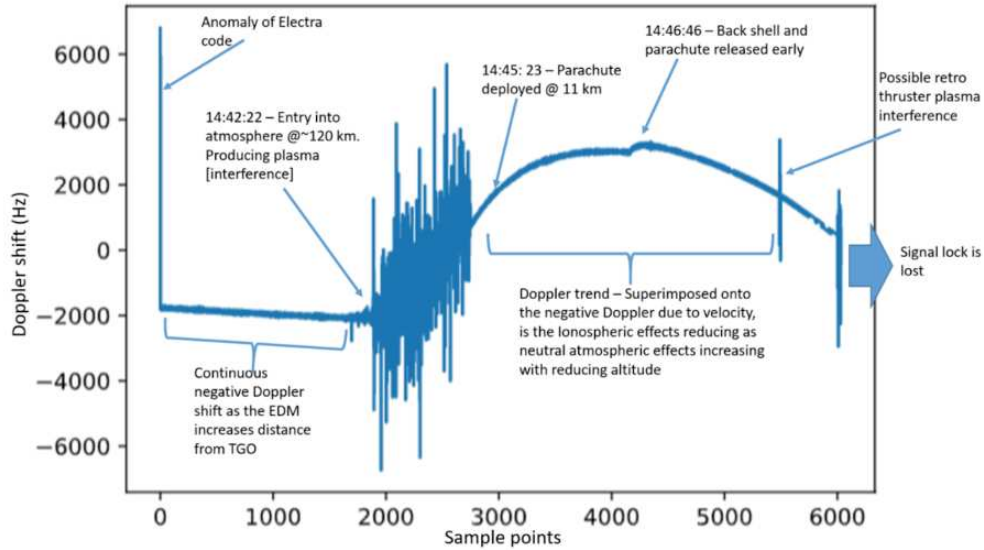


Figure 3.2: Annotated Net Doppler of the TGO Electra- Schiaparelli link during the descent of the Schiaparelli EDM. This data was collected from TGO Electra and was processed as a way to test the replacement for the BAe spacecraft data decapsulation software.

carrier tone. As a consequence, the 'Electra Open-Loop Processing Tool' had to be entirely reworked to extract these essential I&Q data from the raw Electra bitstream. Thankfully, I had access to the original BAe C-source code, which was designed for a specific Linux distribution called 'Red Hat' (legacy version). This presented one of the first challenges, prompting me to begin addressing this task even before receiving the first mutual RO dataset. Fortunately, we had access to the Electra-Schiaparelli radio link dataset during the ill-fated descent and landing. Figure 3.2 was created to validate the tool's functionality, confirming its accuracy as the frequency readings aligned with the documented timeline of the Schiaparelli EDM descent. This dataset was selected for validation as it had a well established timeline. This timeline included Doppler shifts due to the relative motion of the lander away from TGO, ionospheric effects and interference from the high concentrations of the plasma produced by the retro-thrusters.

MEX MELACOM Firmware Upgrade For the first eight mutual RO trail tests,

MELACOM was incapable of transmitting a simple carrier wave. Instead, it transmitted its HAIL sequence. This sequence involved regular deliberate silent periods which made it impossible to find a consistent carrier tone. In addition to the silent periods, there were also idle and HAIL periods that would disturb the carrier

measurements further. The sequence rendered around 60% of the signal useless, as supported by the sequence found in Table 3.1.

In typical data relays to a lander or rover, the MELACOM radio initiates communication by transmitting a HAIL signal to the designated surface asset. Upon receiving the HAIL, the lander responds, and after a handshake, the radio link between the two spacecraft is established, allowing for bidirectional data transfer between the antennas. The HAIL sequence consists of short periods of unmodulated carrier transmission, followed by a modulated signal and a subsequent transmission drop, repeating every 22 seconds as detailed in Table 3.1. This pattern is not conducive to radio science experiments and its effects can be seen in Figure 3.3.

To rectify this, the task of upgrading the firmware was contracted to Qinetiq UK. As required by ESA regulations, the updated firmware needed to be tested on an Avionics Test Bench (ATB) on Earth before it could be uploaded to the flight hardware. This requirement introduced delays, particularly as the COVID pandemic limited physical access to the ATB in Toulouse, France. Consequently, the first eight measurements suffered corruption due to the HAIL sequence. Once successfully tested on the ATB, the firmware update was uplinked and tested in-flight in March 2021, and it has been utilized for all subsequent observations.

The result of this firmware amendment can be found in Figure 3.3, which shows a net Doppler being corrupted at regular intervals in the left panel. The large vertical lines are when no carrier tone was detected and the noise at the end, after 8000 samples, is when the radio link between MEX and TGO was occluded by the Martian surface. On the other hand, this figure also shows a clean net Doppler in the right panel that was recorded after the firmware upgrade to remove the HAIL sequence. This measurement was from an egress occultation so the link is interrupted by occlusion at the beginning of the measurement and the large noise at the endpoint of the test is because MELACOM switches off before Electra stops recording. It is evident in this figure that the removal of the HAIL sequence greatly increases the proportion of the signal that is usable for radio science purposes.

time (s)	5	variable	10	2.048	2
Mode	Only Carrier	HAIL Data	Only Carrier	Idle	OFF

Table 3.1: Default HAIL sequence transmission from MEX MELACOM antenna, showing only 15 seconds of pure carrier tone, making residuum extraction difficult.

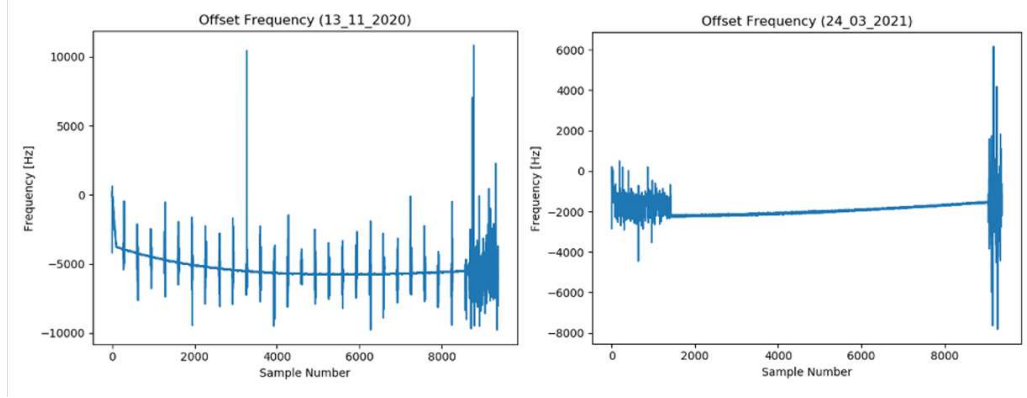


Figure 3.3: A comparison between the original HAIL sequence in the left panel and the updated simple carrier tone in the right panel. Showing the removal of the regular silent periods where no carrier tone could be ascertained (shown as the large spectral peaks in the first panel).

Variable time-offset from Electra Accumulating Clock Error

To extract the residuum from the net Doppler measurement, accurately simulating the position of the two spacecraft is crucial, making precise timing essential. This was the first instance where Electra required precise timing commands. Initial results indicated that there was a variable delay in Electra’s command timing. ESA’s investigations revealed that this issue stemmed from time being recorded as a floating-point number, resulting in an accumulation of errors as small decimal values compounded over time. To address this, the Electra local clock was reset prior to each mutual RO measurement, thereby mitigating the timing discrepancies.

Short Timescale Noise Reduction

After successfully isolating the carrier tone using a sliding FFT on the I&Q data, an unusual type of noise, as illustrated in the blue line in Figure 3.4, was observed. Initially this noise was attributed to the unstable oscillator, leading to concerns that it would affect all future readings. To address this issue, various signal processing techniques were employed. While one might initially consider using a simple averaging filter, Figure 3.4 reveals periodic compressions and rarefactions in the noise, which render a straightforward moving average filter ineffective.

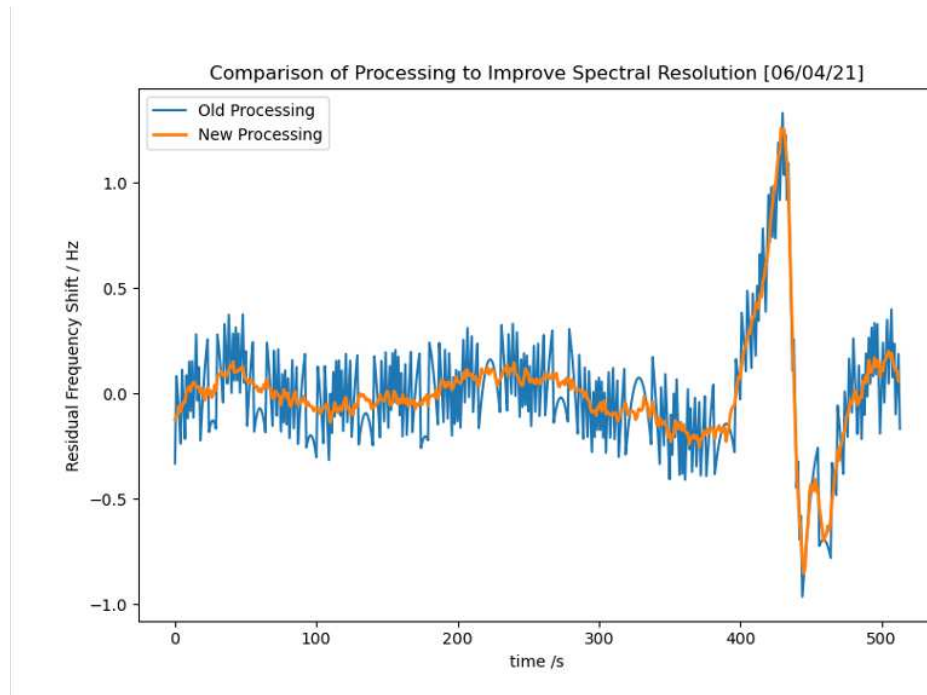


Figure 3.4: A comparisons between residuums from before (blue) and after (orange) signal processing techniques. The blue residuum shows clear 'staircasing' effects which was due to the low spectral resolution.

Kalman Filter As a means to remove the high frequency noise, a Kalman filter was experimented with. This is a recursive algorithm that runs through the time series in steps n and uses the few previous values to predict $n + 1$. In effect, this removes the small timescale noise as the previous values at $n, n - 1, n - 2 \dots$ all inform together what the next value should be. This type of filter is prevalent across engineering as a way of removing random noise. For example, an accelerometer component will constantly emit thermal noise, so are often connected to a Kalman filter such that just the larger amplitude, longer timescale signals are read. This was not helpful however because if we extended the Kalman filter further back to improve the prediction, then it would introduce a larger time delay.

Wavelet Analysis To overcome the lack of spectral resolution, an alternative to the FFT was trailed. Unlike the Fourier transform, this does not represent a waveform as a series of cosine and sine functions. Instead, it breaks the waveform down into small time-localised wavelets. This allow for simultaneous frequency and time domain analysis. This tool can be used to denoise the signal by simply ignoring the too small or big wavelet components and reconstructing the waveform with only

the wavelets that are around 1 second long. This method was ultimately dropped as it produced a lower frequency resolution than the methods described later.

Savitzky-Golay Filter If a trend is not periodic but also doesn't fit on a straight line, then the trend could be second order. Sometimes referred to as the polynomial least-squares smoothing filter, it behaves much like a moving average filter but has additional properties like adjusting for the delay and transient effects found at the beginning and end of the signal. The Savitzky-Golay filter, instead of calculating an average, will produce a moving polynomial fit for a frame of data points. This can be used to produce a complex waveform constructed of many smaller curves; or given a very large frame size, can produce one polynomial fit. I did not continue with this method as the order required throughout the residuum would change significantly throughout a measurement (eg first-order for the vacuum portion and high-order for the limb portion), which this method could not cope well with.

Short Term Neural Net This method involved providing a large sample of the noise to a neural network, enabling it to 'learn' the characteristics of the noise. Such a network can identify complex temporal variations in the noise, including the compressions and rarefactions observed in Figure 3.4. I attempted this method using the Long Short-Term Memory (LSTM) package in the sklearn Python library. However, it became apparent that the approximately 400 data points in the vacuum portion, is an insufficient amount of data to train the neural network effectively.

Custom Denoiser 'Enveloping' Given the shortcomings of previous attempts to filter out short-timescale noise, I devised my own solution, which I termed 'enveloping.' This method involves bounding the noise between two limits by identifying sign-changes in the derivative of the residuum to pinpoint the peaks and troughs. The midpoint between these boundaries is then taken and interpolated to form a new residuum. This process is recursive until the limb portion remains unchanged.

I subsequently discovered that this method resembles a component of the

Hilbert-Huang transform, as described by Huang and Wu, 2008, particularly in a sub-process known as Empirical Mode Decomposition. In this approach, a waveform is iteratively enveloped between its local maxima and minima, and the middle line between the upper and lower boundaries is determined. This middle line is referred to as the 'intrinsic mode function' (IMF). The enveloping process can be recursively executed until the IMF is reduced to a simple monotonic trend.

Lack of Spectral Resolution After numerous unsuccessful attempts to eliminate the short-timescale noise, I started to artificially recreate the same type of noise. I discovered that plotting a polynomial and then rounding down its values creates an appearance of noise similar to a staircase pattern. By performing a polynomial detrend on this staircase pattern to flatten it, the resulting noise matched what I had observed. This realisation indicated that the issue was insufficient spectral resolution, with the carrier frequency values effectively being rounded down within the spectrogram.

When designing the window size for the sliding FFT, one must balance two conflicting outcomes. A larger window size enhances spectral density; however, fewer windows fit within the input time series, resulting in reduced time resolution. Conversely, using a smaller window improves time resolution but at the cost of spectral resolution. With a 10-second window, a 0.1 Hz spectral resolution can be achieved. Given that our residuums are all sub-Hz, this 0.1 Hz was established as the minimum resolution. However, a 10-second FFT window is impractical, as it would obscure short-time scale features, such as the effects of the small M1 ionospheric layer. Overlapping windows can increase time resolution; for instance, a 10-second window with a 90% overlap provides a time resolution of 1 second. Nevertheless, the resulting spectrogram would still exhibit temporal smearing and miss small structures in the vertical electron profiles.

It was a relief to ascertain that the noise was not due to hardware issues but rather my processing's lack of spectral resolution. Consequently, several methods were implemented to address and resolve this issue.

Butterworth Filter To isolate the carrier frequency and create a narrow bandpass, a

Butterworth filter was applied. This choice was made because the Butterworth filter offers an optimal gradual roll-off towards the stopbands, minimizing any sharp discontinuities in frequency (something highly undesirable in a filter). Nonetheless, a significant drawback of this approach is its lack of adaptability over the time series. As a result, the kHz-level Doppler shift can cause the carrier frequency to drift into the stopbands, compromising the filter's effectiveness.

Square Windowing and Sinc Fitting At first, the sliding FFT windows were convoluted with a Hanning function to reduced sharp discontinuities when the time series is 'cut up' into window lengths. However, this might have been the wrong idea, as removing part of the waveform with windowing reduces the precision of the FFT. Using a square window (boxcar window) would produce sharp discontinuities, but the frequency response is predictable. A square window produces a sinc function (sometimes called a Mexican hat) in the frequency domain. The central value of this sinc function can be fit to the spectral peak in the periodograms using a minimisation process. This idea was carried over to a simpler version discussed later called 'Spectral Peak Gaussian Fitting'.

Phase Lock Loop A digital phase-locked loop (DPLL) seemed particularly promising, as it had been effectively utilized in tracking a signal from MEX MELACOM using the Arecibo telescope (Gurvits, 2014). A DPLL has the capability to precisely track the carrier tone and adapt to its Doppler shifts. The accuracy of this tracking can be iteratively refined through multiple passes of the DPLL. Ultimately, I stopped this approach as I found it challenging to tune the DPLL to be both narrowband enough to achieve sub-Hz frequency resolution and wideband enough to accommodate the kHz range of Doppler shifts. As I write this thesis, I believe I might have benefited from persevering with this method, as it appears well-suited to address this noise issue. Nevertheless, I have managed to achieve comparable results through an alternative approach that is later described.

Spectral Peak Skew Fitting As there was not enough fidelity in the spectrum, a custom spectrum centroid finding algorithm was developed by Håkan Svedhem of

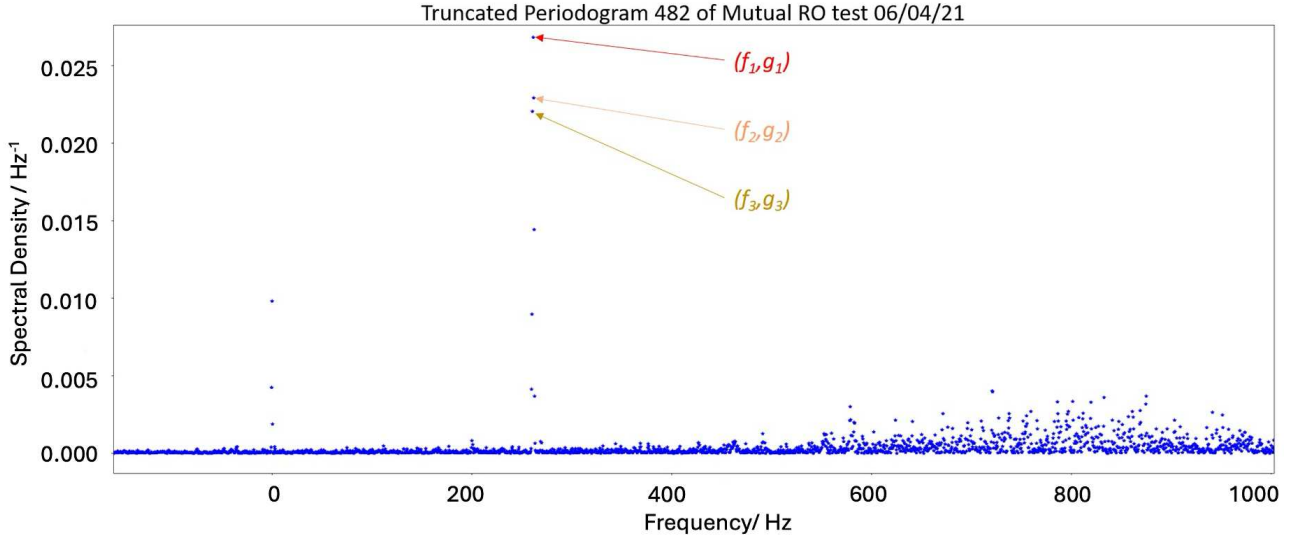


Figure 3.5: A periodogram displayed as a scatter graph to highlight the individual points that make up a single spectral peak. The top three spectral densities are labelled according to equation 3.1

TU Delft, The Netherlands. To find the true peak frequency one must combine the frequency positions and spectral densities of the two neighbouring points. Such that,

$$f_{true} = \frac{(1 - skew)f_1^2 + skew f_3^2 - f_2^2}{2(f_1 - f_2) - 2 skew(f_1 - f_3)} \quad (3.1)$$

where,

$$skew = \frac{\ln \frac{g_1}{g_2}}{\ln \frac{g_1}{g_3}} \quad (3.2)$$

and f and g correspond to the coordinates of the points in the periodogram, as shown as (f_1, g_1) , (f_2, g_2) , (f_3, g_3) in Figure 3.5.

Spectral Peak Gaussian Fitting Figure 3.5 displays a spectral peak along with its adjacent datapoints within a periodogram. Upon examining this peak more closely, the peaks typically appears Gaussian and comprises around seven points. This observation was utilised by applying a Gaussian fit to each periodogram to determine the true peak frequency. This approach is analogous to the sinc function fitting mentioned earlier. The center of the sinc function closely resembles a Gaussian shape, so effectively, this method employs a simpler fitting shape to

achieve the same result. This method proved highly effective, as illustrated in Figure 3.4, and was subsequently integrated into the final processing chain.

Inaccurate Electra Time Up until this point in the processing chain development, I had been using the commanding time provided by ESOC as the UTC for the beginning of my simulations. The commanding time is the UTC for when the uploaded instructions onboard TGO tell the Electra antenna to power on and start recording. This is not the UTC for when ESA transmits the commands up to TGO via the DSN, as there is always a 4-9 minute light travel time delay (depending on relative solar longitudes). However, questions were raised about the accuracy of this ESOC commanding time. Fortunately, Electra recorded the onboard time at regular intervals *throughout* the 10 minute measurement. This recorded time also offered a chance to characterise the local oscillator drift, as I would be able to tell that the oscillator is at a lower frequency than normal if the spacecraft time was later than the actual UTC. As a reminder, this timing is important as the Doppler shift will be in the kHz range at our UHF band. But the residuum due to the change in refractivity will be less than 1 Hz, so we need to be ultra-precise with our start time otherwise we could get a >10 Hz drift, completely dwarfing our signal. Two methods were employed to find the real start time.

Electra Firmware Investigation Initialisation This project involved the expertise of the Electra engineers within JPL as we needed to know exactly how Electra 'knows' the time. However, there was a large delay in receiving their input. While the project began at this point in the development timeline, it was only addressed after the my first paper was published, as such will be discussed at the end of this section.

SPICE Simulation Interpolation In absence of the expertise from JPL, I endeavoured to find a solution myself. If we assume that the real start time of each measurement is somewhere near the UTC commanding time, then the simulated Doppler shift should be very close to the Net Doppler recorded at Electra. There exists an exact start time where the Net Doppler minus the simulated Doppler

looks completely flat (hovering around 0 Hz), especially for the vacuum portion. I developed a solution where I would produce 40 Doppler simulations for each measurement, for ± 20 seconds around the commanding UTC. This seemingly large range was chosen as there was one measurement which deviated by +18 seconds. This solution was almost perfect, as it could adapt to any timing inaccuracy. However, it could not account for sub-second variation as SPICE only operated in intervals of whole seconds. Interpolation was required and this was done by producing a 600 by 40 array and carrying out a 100X bivariate spline. The array was 600 cells tall because the Doppler simulations were 600 seconds long (10 minute), and the width of 40 was because there are 40 separate Doppler simulations (± 20 seconds). The 100X bivariate spline in effect produced 4000 different Doppler simulations, with a timing precision of 10 ms that I could then compare against the Net Doppler. The best Doppler simulation was chosen by performing a least-mean-square (LMS) fit to the vacuum portion of the residuum, when the tangent point is above 220 km.

Small Residuum Amplitude due to Orbit Geometry - Once the timing issue was solved, I noticed that measurements from similar locations would produce very different residuums. As shown in Figure 3.6, the mutual RO measurements on 10/03/23 and 08/05/23 are taken from similar SZA, positions in the solar cycle and latitudes. But the M2 ionospheric feature (see Section 3.2.1) in the resultant residuums differ by a factor of three. The noise floor for each mutual RO measurement is relatively consistent so a reduction in ionospheric feature size is effectively a reduction in SNR. The cause for this is orbit geometry. MEX and TGO have an elliptical and circular orbit, respectively. They also have different nodal-precessions so they oscillated between being antiparallel and coplanar. As discussed in Section 3.2.1, the tangent point is the position in 3D space between the MEX and TGO. This point can descend/ascend steeply during the RO observation, or it can change in altitude slowly and produce a profile that is dragged over the martian surface, similar to what is seen in Figure 1.1. The frequency shift in the residuum is proportional to the change in refractivity *per second*. Given this, if the

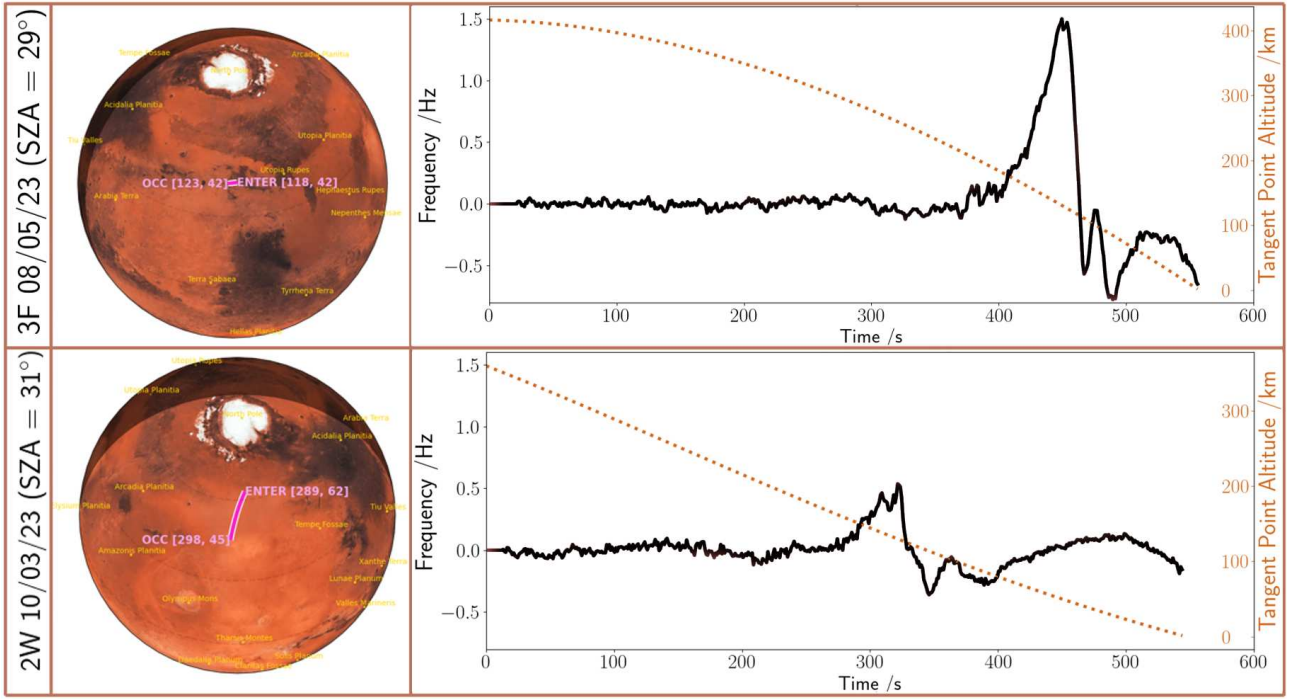


Figure 3.6: Two residuums to highlight the different features created by the M1 and M2 ionospheric layers, taken from Mutual RO with similar SZA but different grazing angles (the angle between the surface tangent at the point of occultation and the highest altitude tangent point) . This shows that the amplitude of the features in the residuum are smaller if the tangent point descends slower, worsening the SNR. This slower descent can be seen by the red dotted line that maps to the right hand side y-axis. On the left is a map of the ground trace (pink line) of the RO, showing the tangent point for the mutual ROs from 08/05/23 and 10/03/23 travelled an arc distance of 219 km and 1051 km, respectively. When future RO opportunities are selected, smaller ground traces are preferred.

rate of the change in refractivity reduces, then the ionospheric feature will reduce in amplitude. The rate of tangent point ascent/descent is fastest when the two spacecraft orbits are antiparallel. In other words, if we view the orbits along the axis of rotation, it would appear that one spacecraft is orbiting clockwise, and the other is anti-clockwise. The top panel in Figure 3.6 shows a large ionospheric feature with a tangent point that descends very quickly; this can be seen by the small pink ground trace. Comparing this to the bottom panel, the ground trace has been stretched over the martian surface, inferring that the tangent point is descending very slowly. This leads to the small ionospheric feature and low SNR.

This discovery meant that the 'grazing angle' is now accounted in the RO selection (see Section 2.3.5). In addition, this knowledge was fed into the orbit selection for the upcoming mission proposal 'M-MATISSE'. This is a two spacecraft mission to Mars with bespoke mutual RO equipment on board and should be confirmed by 2027.

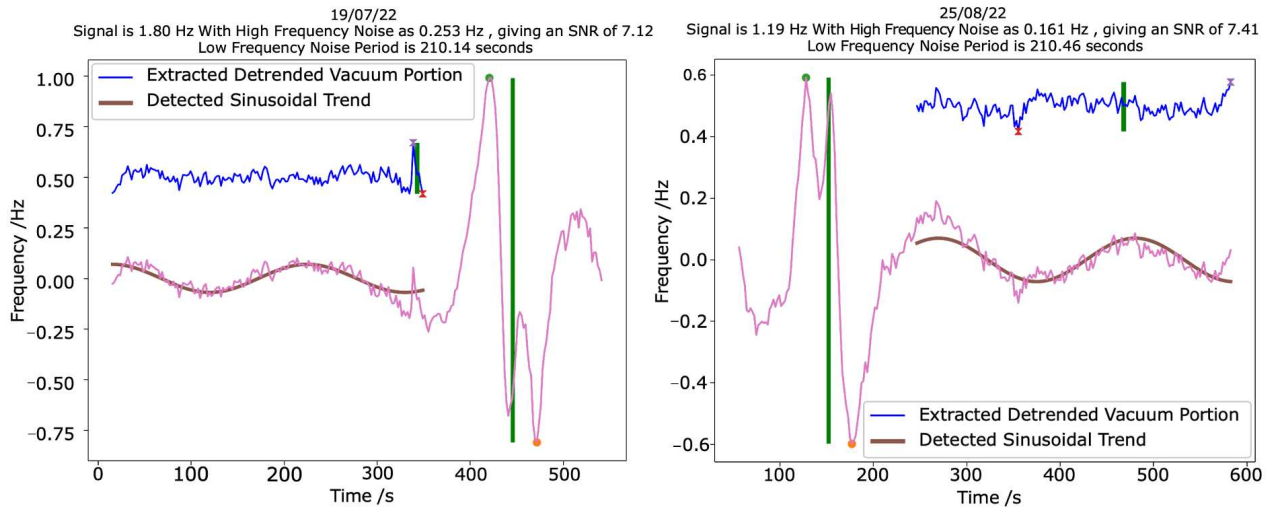


Figure 3.7: A comparison between the long and short timescale SNR for two residuums. The left panel is from an ingress RO and the right is for an egress RO. This figure shows the longer timescale oscillator drift as sinusoid (brown) and the detrended vacuum portion of the residuum is superimposed in blue. Vertical green lines on both the residuum and detrended vacuum portion are to help calculation of SNR.

Oscillator Drift The most significant challenge encountered during the development of this processing chain was the unconstrained oscillator drift, as neither transceiver was designed for precise frequency acquisition. This drift was a result of both satellites lacking Ultra Stable Oscillators (USOs), each with varying degrees of stability. MEX MELACOM was considered the more stable of the two antennas, as it was equipped with an Oven-Controlled Oscillator, whereas Electra featured a Temperature-Corrected Oscillator, which demonstrated an Allan variance 100 times larger.

Figure 3.7 illustrates ingress and egress residuums with the oscillator drift superimposed in brown. Both measurements exhibit a large sinusoidal oscillation of differing frequencies. The blue line at the top of the plots represents the detrended residuum, which is the original residuum minus the brown sinusoid, highlighting the short-timescale noise. This figure demonstrates how the combination of both unstable oscillators resulted in an unpredictable drift that could influence the final electron density profiles. Addressing this drift required careful consideration of several factors, explored in the following sections.

Temperature Investigation Temperature plays a critical role in the performance of oscillators, as the stiffness of the piezoelectric quartz affects the frequency at which

it resonates, given a constant input voltage. The temperature of the local oscillator can be influenced by factors such as current passing through the device (ohmic heating $\propto I^2 R$), temperatures of nearby components, and environmental factors like direct irradiance as the spacecraft's attitude changes. I conducted an investigation into these three aspects.

Firstly, I observed a correlation between increased oscillator drift and the amount of time since the Electra antenna was last activated. While the Electra antenna was routinely used as part of the Mars relay, occasional usage after several idle hours correlated with significant oscillator drift. It was deduced that during these periods, the oscillator cooled to ambient temperature and was in the process of reheating throughout the measurement. To address this, the commanding protocol was updated so that the Electra and MELACOM antennas are now turned on 10 minutes before any measurements are taken.

The second investigation focused on the impact of nearby components. This aspect of my research was limited, as I lacked the required security clearance to access the Electra circuit diagram, which was 'ITAR-protected' and classified under United States military technology. We eventually relied on our JPL colleagues for this information, though it was obtained much later.

The third investigation examined whether drift increased as the Electra antenna was exposed to sunlight. Situated on the exterior of the TGO, Electra could move in and out of direct sunlight as the spacecraft rolled to keep some instruments nadir-pointing. Using SPICE, I analysed moments when there was a direct vector between the sun and the Electra side of TGO. However, this analysis showed no correlation between oscillator drift and attitude. The study was ultimately incomplete, as I didn't account for the shadows cast by the solar panels (an element not factored in by SPICE). Addressing this omission would require a different approach and with limited time, my focus shifted away from Electra to exploring whether temperature variations across the transmitter at MEX could be contributing to the problem.

Figure 3.8 illustrates the temperature across the MELACOM transmitter on MEX over a ± 10 -hour period surrounding a mutual RO transmission. There are five temperature sensors distributed across the device. The purple and red lines represent the exposed antenna portions; these sections show variances due to their distance from the internal heaters, making their temperature chiefly influenced by attitude and solar irradiance direction. In contrast, the orange, blue, and green lines denote the internal components of the MELACOM transmitter. Despite MELACOM's oven-controlled nature, where temperatures generally remain within a 3°C range during the 20-hour measurement, there is a noticeable exception at 10:42:33, coinciding with a mutual RO observation. Here, we observe a clear 10-minute warm-up period followed by a 7°C spike during transmission, which then diminishes exponentially over the subsequent hour.

Despite the oven-controlled mechanism this notable temperature spike leads to a slight deviation in the Tx carrier tone from the nominal 437.1 MHz. This concern was escalated to ESA engineers, who determined that the observed drift was significantly greater than what the existing temperature fluctuations would suggest. Unfortunately, we could not determine a definitive expected drift amount to allow for its removal during processing. It became evident that pursuing a spacecraft engineering solution to the oscillator drift issue was not feasible. Instead, it necessitated developing a signal processing solution capable of accommodating the variable error present in each measurement.

Adaptable Polynomial Fit - With temperature investigations proving unfruitful, I attempted to remove the oscillator drift based on how it drifted during the vacuum portion of the signal. This portion is when there should be a negligible effect from the martian ionosphere and atmosphere, so any apparent deviation should be due to the oscillator drift. Multiple fitting methods were trialled, including the fitting of a catenary curve. I ultimately decided on fitting an adaptable polynomial fit, which was adaptable as artifacting could occur if the order is too high. The order of the fit was iteratively increased until the LMS value across the vacuum portion

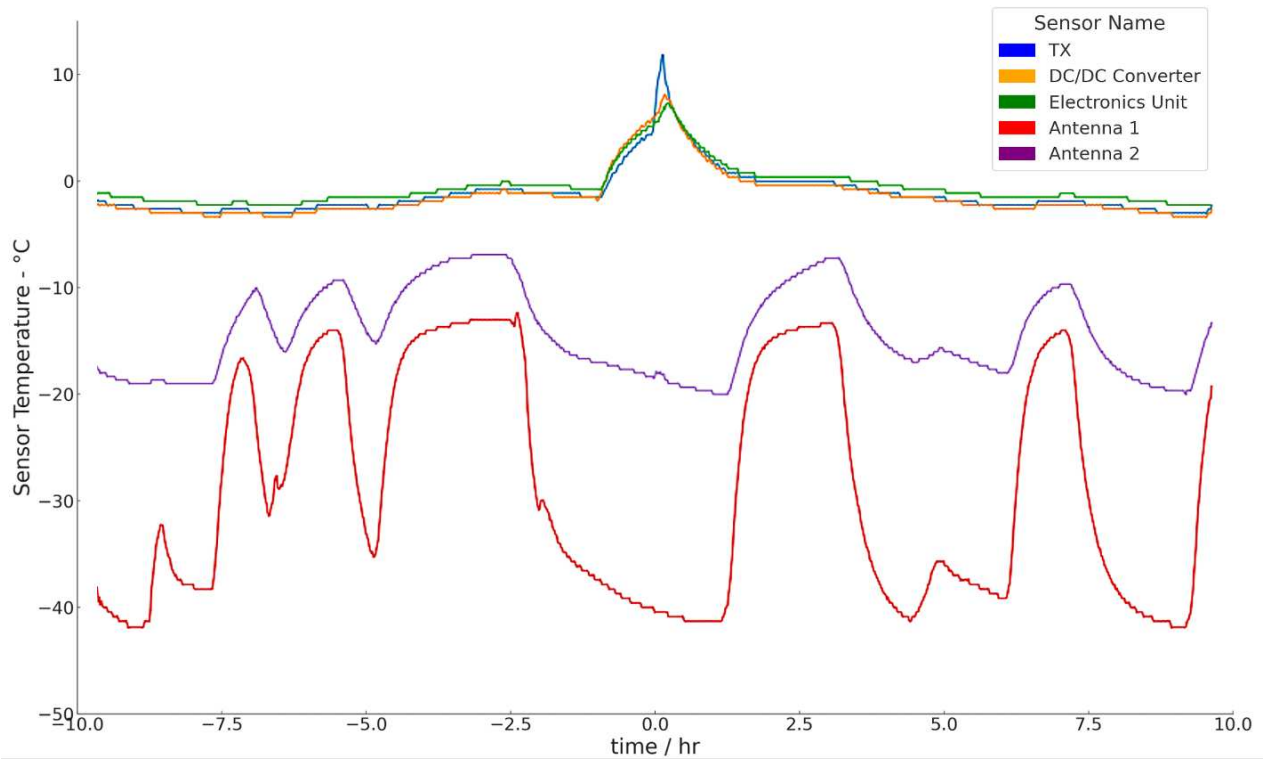


Figure 3.8: Evidence of an investigation into the temperature of MELACOM, as this was expected to be the cause of the variable frequency offset. On show are five temperature readings from sensors placed across MELACOM. The purple and red are from sensors placed on the outside, where their fluctuations are mostly due to solar irradiance with a changing attitude. The spikes for the orange, green and blue internal sensors in the centre of the graph are due to ohmic heating when MELACOM is transmitting to TGO.

was sufficiently small. Typically this resulted in an order-4 polynomial.

I then realised that some of this oscillator drift might be produced during the earlier Doppler subtraction stage, so I also replaced that with the same polynomial fit. This was an order-6 polynomial as this would be the highest polynomial that could form from the relative velocities of two spacecraft moving around in 3D space. This was the method used for the majority of the PhD, until the realisation that the oscillator drift during the vacuum portion of the residuum bears no correlation to the drift during the limb portion. Subtracting a drift based from the vacuum portion, adds an error into the important ionospheric portions, therefore invalidating all my results.

Use of a Mid-Limb Anchor Point - I needed to find something that would help inform what the drift would be throughout the *entire* residuum, not just the vacuum portion. Fortunately Ao et al., 2015 implemented a method that uses an anchor point within the limb portion of the residuum. As shown in segment 5 of Figure 3.1, there is a 50-60 km segment of the typical vertical profile that tends to 0 m^{-3} . We could use the point in the residuum that corresponds to this point in the profile as an anchor point. This way we know the oscillator drift for the vacuum portion by fitting to it, and now we know it up to the anchor point, therefore allowing for reliable measurements of the M1 and M2 layers between these points. However, as discussed in Section 3.2.1, this 0 m^{-3} density anchor point is not as easy as finding the correct time in the residuum and bringing it to 0 Hz. We need to use a forward Abel-transform (see Section 2.1.1) to find where the residuum should be to make the profile 0 m^{-3} at 50-60 km. This required an iterative approach where a linear bias was applied to the residuum and a forward abel-transform was employed to get the profile closer and closer to 0 at 50-60 km. This was part of a minimisation algorithm which typically involved around 50 iterations, each with their own Abel-transform.

Until this point, I had been using an Abel-transform written by a team in the Abdus Salam Centre for Theoretical Physics, Trieste. This team had been

contracted to perform some simulation work for the MEX-TGO mutual RO campaign. The software had been written in MATLAB, which made the integration with my python processing chain difficult. It is possible to call a MATLAB package from python, but this has significant computation overheads, and each call to the package takes around 20 seconds. These issues were resolved by converting their MATLAB scripts into a python programme, allowing for an Abel transform to be carried out in less than a 1 seconds. In total, this anchor point technique took around 40 seconds of processing on a midrange AMD Ryzen 5600X processor. This was also the method used for the results in Parrott et al., 2024, and it only had one small correction made to it for the following articles (see Section 3.4.1).

JPL Collaborations With the processing chain mostly complete and the first paper on MEX-TGO mutual RO published, collaboration with JPL began in September 2024 to find some engineering solutions to the timing and frequency offsets.

Electra Timing Investigation Electra would record the wrong time as it encapsulated the I&Q waveform. With the aid of SPICE simulations, it would appear that Electra would sometimes be as wrong as +18 seconds. At first, it was pointed out that I needed to use a coefficient when converting the binary time stamps into time. I was also told that this value for time is with respect to the main time keeping functions on board TGO. The coefficient was sealed behind ITAR- protected documents and I had never been sent the timing datasets for the TGO spacecraft. Once both these were included in my time calculations, we found that the Electra recorded time was ± 0.2 seconds from the commanding time.

Variable Net Doppler Frequency Offset Again, with the aid of SPICE simulations, I could see that the Net Doppler would have a large frequency offset; this is different to the oscillator drift discussed above as this offset is large and constant throughout the measurement. It could be anywhere from 650-670 Hz. We know that this was a hardware ageing problem as we performed a few RO observations using a redundant antenna called Electra-2, which saw a slightly smaller offset of

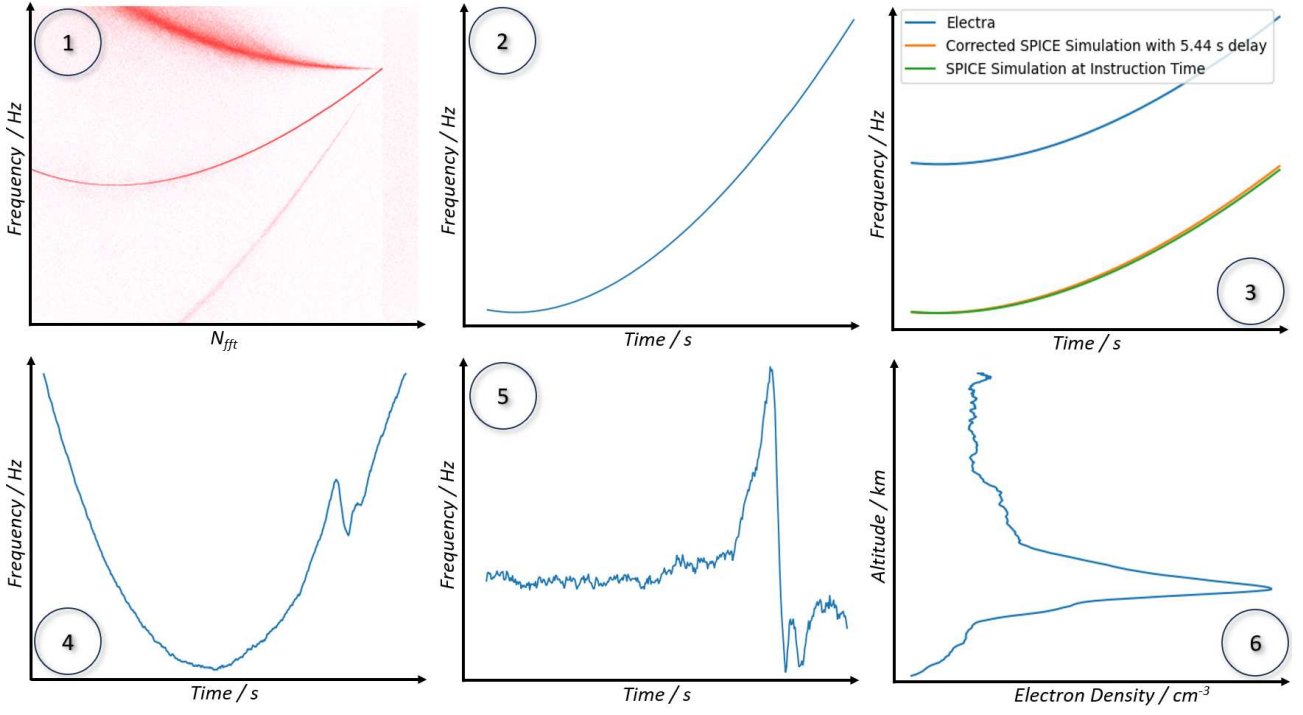


Figure 3.9: A graphical representation of the outputs to the steps in Section 3.4. The mechanics of each of these steps are described at length in this section. 1: Spectrogram acquired from performing an FFT on the I&Q data, 2: The carrier in (1) is isolated via selecting the peak spectral densities, then the signal is truncated and has its frequency resolution interpolated, 3: A SPICE Doppler simulation is used to predict what the frequency shift should be if there was just a vacuum between the two spacecraft, 4: The corrected SPICE Doppler signal from (3) is subtracted from the signal (2). Note that the scale is significantly increased in this panel, 5: A low order polynomial fit is removed from (4) and the 70-80 km zero refractivity assumption is leveraged in an Abel-Inversion minimisation. Note that the scale is further increased in this panel, 6: Abel-Inversion and conversion to electron density.

600-620 Hz. We knew that oscillators are adjusted throughout the spacecraft lifetime to account for ageing by changing an internal multiplier on the onboard FPGA. This multiplier is used when converting oscillator ticks into a sampling frequency. If the oscillator slows down, then the multiplier is slightly incremented. Ultimately the multiplier was corrected to account for the local oscillator (prior to frequency multiplication) being 63 Hz off.

3.4 Final Processing Chain

The following is the final processing chain, and will be enumerated with its corresponding outputs found in Figure 3.9.

1. The primary objective for this processing stage is to extract the peak carrier frequency from the MEX transmission. Firstly, a spectrogram is extracted from the I&Q data by means of a FFT with a 2^{18} point Hanning window, corresponding to 2 s, and an overlap of 50%. With a 10-minute observation and a sampling frequency of 128 kHz, this produces around 585 periodograms. This window size was chosen as a compromise between frequency and time resolution. The goal was to increase the frequency resolution as much as possible by increasing the window size, to a limit, as a larger window might render the small timescale M1 ionosphere feature indistinguishable. The M1 layer is the fainter secondary ionospheric layer found below the M2 layer. Figure 3.6 shows two examples of the residual frequency shifts caused by the ionosphere and atmosphere, called the residuum. From the observation on 08/05/23, 450 s marks the M2 features and the smaller bump at 480 s represents the contribution by the M1 ionospheric layer. This is the layer that can be missed if the window size is set too large (say, around 4 seconds long). For a RO observation with a steep grazing angle, the tangent point is typically within the M1 ionospheric layer for around 10 seconds, with the current window size, this allows for only nine data points to describe the M1 morphology. Attempting to increase the spectral resolution any more by increasing the FFT window size will worsen this.

2. Depending on the orbital configuration, the data must then be truncated to exclude times when MEX's tone is not detected. For ingress occultations, this occurs at the end of the observation as the spacecraft-to-spacecraft vector is intercepted by the Martian surface, and for egress measurements, this occurs at the beginning and can be delayed for 10-60 seconds as the MEX-TGO vector is intercepted by the Martian surface. To increase the frequency resolution further, a Gaussian curve was fitted to the highest spectral density in each periodogram. These spectral peaks are shown in the two periodograms of Figure 3.10. The curve fitting was done on the peak density and its six surrounding points. The mean value in this Gaussian (the peak) is taken as the true received carrier frequency. The lack of resolution would lead to spectral artefacts in the residuum and ultimately, this reduced the magnitude of these artefacts by 4.8 times.

Spectrogram of Electra Dataset (06/04/21) with Periodograms for $N_{FFT} = 240, 440$

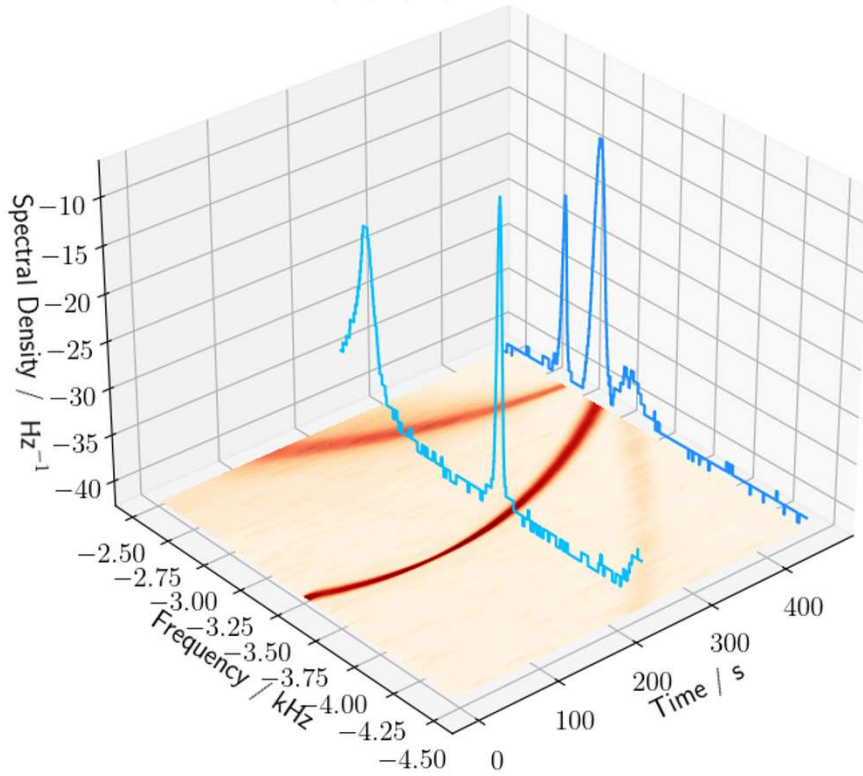


Figure 3.10: A spectrogram for an ingress Mutual RO with two periodograms superimposed on the z-axis. The periodograms correspond to the 240th and 440th Fast Fourier Transform (FFT) windows. The darker colours in the spectrogram directly correspond with the larger spectral density seen in the periodograms. As well as showing evidence of multipath scattering, this figure shows the individual peaks in the periodograms that are used for fitting a Gaussian curve to, as a means to increase the spectral resolution.

3. The total frequency shift measured by the receiver is dominated by the Doppler shift caused by the relative velocities of the two spacecraft, hereafter called geometric Doppler. This must be removed from the signal as it can be three orders of magnitude larger than the frequency shift imparted onto the signal due to the ionosphere and atmosphere. The geometric Doppler is simulated using SPICE (C. Acton et al., 2018), an ephemeride framework developed by JPL’s Navigation and Ancillary Information Facility (Acton & Charles, 1996). The operational positional kernels for MEX and TGO are updated regularly by the ESA SPICE Service, so each simulation uses accurate post-processed spacecraft ephemerides.

Initially, the correct geometric Doppler could not be found as the exact start time for the observation was not known. As previously mentioned, the timestamps in the bitstream did not reach the required precision. The start point for the simulation was therefore based on TGO commanding time, which can vary by ± 18 seconds. This was overcome by simulating ± 20 geometric Doppler shifts with starting intervals of 1 second and constructing a 40 by 600-sized matrix, to which a 2D rectangular bivariate spline was applied. This operation interpolated the 40 simulations at 10 ms intervals, in effect producing 4000 Doppler shift simulations to compare against. The geometric Doppler with the smallest difference from frequency recorded at Electra is then chosen.

As discussed in previous Section 3.3, there is a variable frequency offset and frequency drift for many reasons. This offset can simply be subtracted by taking the minimum absolute geometric Doppler value for the SPICE simulation and subtracting this from the same point in the real Electra recorded Net Doppler. The variable frequency drift, however, is far more challenging to overcome. The following processing steps consist of two fitting functions. The first is a form of polynomial fit and the second is a linear bias that ensures that 50-60 km has an N_e profile close to 0 m^{-3} (The reasoning for this assumption is described further on).

4. The frequency drift must be adjusted in order to account for the absence of an USO. An example of this drift can be seen in panel 4 of Figure 3.9. In order to do this, the tangent point is planned well above the ionosphere for most of the observation duration,

so most of the residuum should be at 0 Hz for the majority of the elapsed time. All non-zero values during this vacuum portion of the residuum are known to be artefacts which are most likely due to this frequency drift. This can be removed by fitting a polynomial to the vacuum portion and an additional point in the residuum which corresponds to the time the gradient in the residuum is 0 Hz s^{-1} (and the tangent point height is about 40 km). This addition, for when the tangent point is within the limb, is required as simply extrapolating the polynomial throughout the entire measurement will seldom produce an accurate residuum. This is because the frequency drift during the vacuum portion does not inform what the drift during the limb portion will be as the drift is random and not predictable from the previous portion of the signal. The polynomial fit is not designed to pass through this point exactly. There is an arbitrary frequency offset applied such that the atmospheric portion of the residuum does not cross the 0 Hz axis. This can be seen in Figure 3.6, where dataset 08/05/23 does not cross the 0 Hz axis at the end of the measurement, whereas dataset 10/03/23 does, only 08/05/23 will produce valid N_e profiles in this case. This value of 0.2 Hz offset is not critical. A further investigation shows a parametric test which demonstrates that the following processing step compensates for any assumption made here. Figure 3.11 goes into more detail of describing this frequency offset resilience. There is one final aspect to this fitting; the polynomial order can vary between 3 and 4 to minimise the error introduced to the regions that are not being fitted over. The introduced error will be larger the further away from the fitted regions, and this error grows if an even higher order polynomial is used. The order of the polynomial is therefore kept as low as possible by iterating this fitting process with increasing order until improvements to the χ^2 value over vacuum portion is negligible. Sometimes a 4th-order polynomial is required, but the next measurement will only require a 3rd-order. This order value must be kept dynamic as the frequency drift is inconsistent.

Although the vertical offset used during the first fitting in the processing is selected arbitrarily, the final results are very resilient to any error that may be introduced with this assumption, as seen in Figure 3.11. This vertical offset marks the distance from the

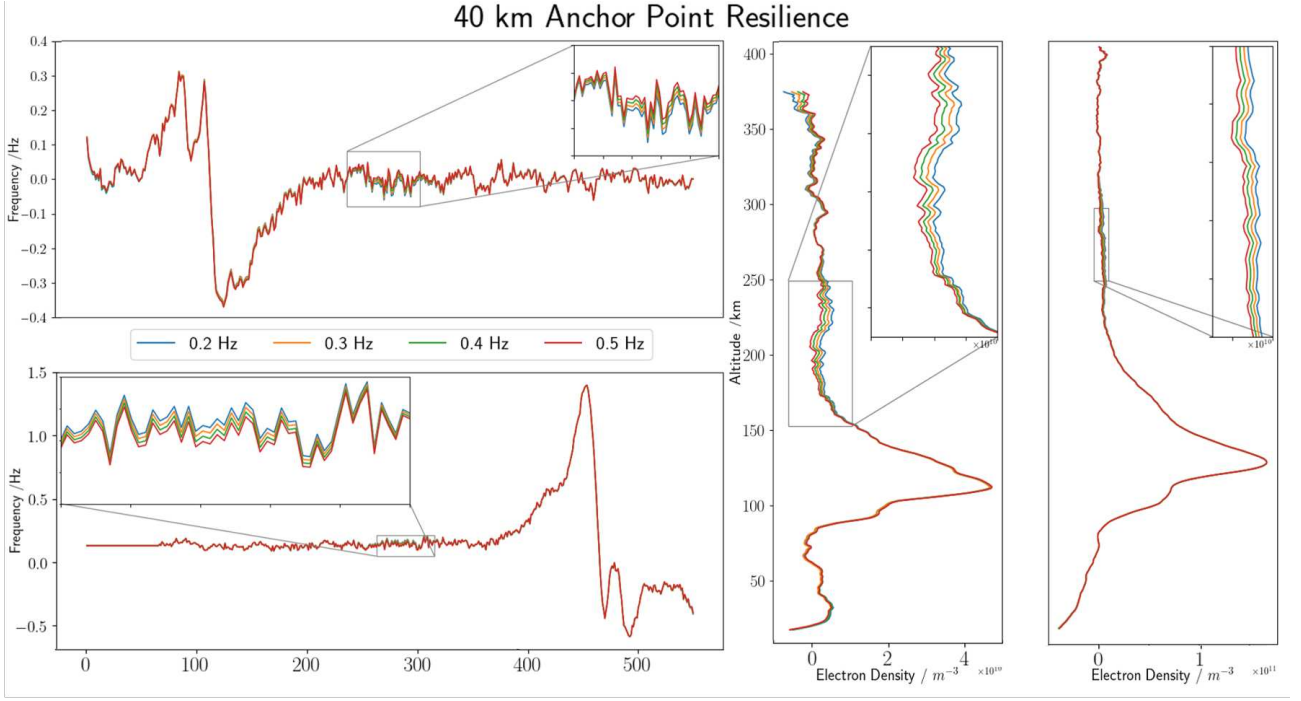


Figure 3.11: Two examples of a residuum and profile that show how the arbitrary frequency offset on the 40 km point has a near-negligible effect. The top residuum corresponds to the left profile and is an egress mutual radio occultation and the 40 km anchor point would be at around 30 seconds, whereas on the ingress dataset on the bottom has an anchor point at 550 seconds. Four different amounts of frequency offset are shown, starting from 0.2 Hz and finishing with 0.5 Hz

0 Hz axis that the polynomial fit must pass through to ensure that the residuum does not cross the 0 Hz axis. For the results shown in this article, a 40 km point vertical offset was set to 0.2 Hz, but this value matters little, as the second fitting corrects for this. If the first fitting results in a residuum with a non-physical form, it is accounted for later in the processing chain since the second fitting brings the 50-60 km region in the N_e profiles close to 0 m^{-3} . Figure 3.11 supports this, by showing the variation in residuum and resultant N_e profiles vary very little, even when a vertical offset of 0.5 Hz is applied to the 40 km point. Also, this variation is only seen around 300 s on each residuum because this is the middle of measurement. Step four of this processing chain does not have any effect on the high altitude portion of the residuum, and step five then corrects for any changes that have occurred at the low altitude portions. Thus, leaving just the middle of the residuum to display any signs of artifacting.

5. One final amendment is required to ensure an accurate residuum. A linear frequency bias is applied to the residuum to guarantee a refractivity close to zero at 50-60 km

altitude, whilst not affecting the higher portion of the profile when the tangent point is in the vacuum of space. Typically, for Martian radio occultations, this portion of the profile is always near zero, irrespective of solar activity, SZA variation, and the presence of dust storms (Fox & Yeager, 2006). This is similar to the method carried out by Ao et al., 2015 in their ODY – MRO crosslink occultation demonstration. The subtle difference between the 40 km point and 50-60 km should be reiterated here. The 40 km point is where the gradient in the residuum is 0 Hz s^{-1} . We use this point to act like an anchor in stage 4 to ensure that the residuum does not pass the 0 Hz x-axis, which would render this stage 5 impossible. The 50-60 km region is the part of the vertical N_e profile where the density is close to zero. This is an iterative process wrapped around an Abel-inversion (Fjeldbo & Eshleman, 1968); produced by the International Centre for Theoretical Physics, Trieste, under contract for ESA (Nava et al., 2020). Such that this minimisation algorithm could run as fast as possible, the Abel-inversion MATLAB codebase was converted to python, so that it could be integrated with the existing processing stack. The resultant bias applied is minimal, never rising more than 0.1 mHz s^{-1} .

6. The final residuum from (5) is converted into bending angles and this is then processed through an Abel-inversion to produce a refractivity profile. From this an N_e profile is derived by using Equation 3.3 (Ando et al., 2012)

$$N_e = \frac{nf_t^2}{\alpha} \quad (3.3)$$

where

$$\alpha = \frac{e^2}{8\pi^2\epsilon_0 m_e} = -40.2592 \text{ m}^3 \text{s}^{-2} \quad (3.4)$$

where n is refractivity (dimensionless) and f_t is the transmit frequency of $4.371 \times 10^8 \text{ Hz}$.

3.4.1 Processing Chain Amendment

The previous list showed the processing method in Parrott et al., 2024, with this being improved by myself at a later date. A significant enhancement has been introduced to improve the reliability of the final vertical N_e profiles. Specifically, steps 4 and 5 in the previous section outlined two procedures designed to account for variable frequency drift caused by the unstable oscillator. The initial step involves fitting a polynomial of variable order to the 'vacuum portion' of the residuum, ensuring it closely approximates the data and intersects at the point where the ionosphere and neutral atmosphere counteract; thereby producing a gradient of 0 Hz s^{-1} . The subsequent step entails iteratively applying an increasing linear frequency bias during the inverse Abel transform until the N_e in the 70-80 km region of the resultant vertical profile is minimized to near zero.

However, this linear bias introduced errors as its magnitude increased over time, leading to significant discrepancies toward the end of the measurement. These errors often manifested as artificially high electron densities in the lower neutral atmosphere, sometimes exceeding the M2 peak density.

To address this issue, the two steps have been consolidated into a single process, thereby eliminating the need for the linear bias stage. The polynomial detrend's effectiveness is now validated by minimizing the N_e in the 50-60 km region after the Abel inversion. The revised approach involves adjusting the polynomial detrend to account for the oscillator drift in the vacuum portion of the residuum, while allowing for a small offset from the 0 Hz s^{-1} point up to $\pm 0.5 \text{ Hz}$. This offset is determined through an optimization algorithm that iteratively adjusts the value until the same physically realistic low N_e is achieved in the 50-60 km region.

3.5 Summary

The chapter on the processing chain provides a comprehensive description of the steps undertaken to derive electron density profiles from raw binary data. The chapter outlines the

development and challenges of converting raw data into usable scientific information and describing the development process.

Initially, the raw data from TGO requires decapsulation to isolate useful components like the I&Q representation essential for determining carrier frequencies. A FFT is applied to convert the waveform from time to frequency domain, revealing a carrier tone. These frequency involves both atmospheric refraction and Doppler shift due to relative spacecraft motion. A simulated Doppler shift, reflecting the spacecraft's movement, is calculated using SPICE ephemerides and subtracted to yield a residuum; indicative of contributions to refractivity by the atmosphere and ionosphere.

A significant concern in the data processing is the removal of short-timescale noise inherent from the spacecraft's instruments. Several methods, from Kalman filters to custom-designed approaches like 'enveloping' have explored to manage this noise and artifacting.

The complexity of accurately simulating geometric Doppler shifts, given an uncertain start time for measurements, resulted in leveraging multiple simulation runs interpolated with 2D bivariate splines for precision. Additionally, the analysis of residuum amplitude variations associated with orbit geometry configurations highlighted further adjustments necessary for accurate data interpretation.

Another challenge addressed is oscillator drift due to the lack of an USO on either spacecraft. This drift introduces variable frequency errors into the measurements. After investigating external temperature influences, and considering alternative drift sources, polynomial and anchor point techniques were adopted to control the oscillator drift impact.

Chapter 4

Results

The results presented in this chapter have been published in:

Parrott, J., Svedhem, H., Witasse, O., Wilson, C., Müller-Wodarg, I., Cardesín-Moinelo, A., Schmitz, P., Godfrey, J., Reboud, O., Geiger, B., Sanchez-Cano, B., Nava, B., & Migoya-Orue, Y. (2024a). *First results of Mars express—ExoMars trace gas orbiter mutual radio occultation*. *Radio Science*, 59, e2023RS007873. <https://doi.org/10.1029/2023RS007873> (Cover issue)

and ,

Parrott, J., Svedhem, H., Sánchez-Cano, B., Witasse, O., Wilson, C., & Müller-Wodarg, I. (2025). *Ionospheric analysis with Martian mutual radio occultation*. *Journal of Geophysical Research: Planets*, 130, e2024JE008854. <https://doi.org/10.1029/2024JE008854>

4.1 Introduction

Having outlined the general structure of the Martian ionosphere and introduced the mutual RO technique alongside a comprehensive description of the processing chain, the subsequent section will present the profiles obtained using this innovative methodology. This chapter will showcase all the profiles acquired thus far, followed by a validation of four specific profiles.

The various validation sources will also be discussed, encompassing three models and four instruments. Notably, the MaRS conventional radio occultation instrument was specifically commanded as a result of this PhD, to provide validation against the mutual RO datasets.

4.2 Measurements

The primary objective of showing the forthcoming profiles is to investigate the photochemical region of the ionosphere, beneath 200 km. The electron densities in the diffusion region, located higher up, are deemed too unreliable given the current noise floor of our RO measurements. These specifications are outlined in Table 4.1, with the corresponding profiles illustrated in Figures 4.1 and 4.2. Organized chronologically, the profiles depict the Martian ionosphere and lower neutral atmosphere under a range of conditions. The timing and geometric values have been produced locally, using my code which is shared publicly at (Parrott, 2022). The only external data source is the Lyman- α values, which are from the LASP Interactive Solar Irradiance Datacenter (Kretzschmar et al., 2018).

Date	UTC Start	UTC of Occ	SZA (°)	Lat (°N)	Lon (°E)	Local Time	Max Alt (km)	Scheme	Solar Dist (AU)	$F_{10.7}$	Ly-a ($mW m^{-2}$)
02/04/21	15:09:00	15:18:16	14	13	144	11:04	399	ingress	1.62	71	1.44
06/04/21	03:30:00	03:38:49	34	43	352	11:01	415	ingress	1.62	71	1.45
14/04/21	23:32:00	23:33:09	82	43	61	05:55	394	egress	1.63	75	1.47
18/05/21	07:07:00	07:08:32	63	80	346	11:18	368	egress	1.65	79	1.49
25/05/21	00:08:00	00:09:05	36	54	153	11:07	321	egress	1.65	79	1.45
22/07/21	00:06:00	00:07:20	32	-8	6	12:18	374	egress	1.67	91	1.49
06/04/22	02:14:21	02:23:47	62	4	224	07:55	387	ingress	1.42	117	1.72
27/04/22	13:52:20	13:52:55	50	-17	13	15:28	326	egress	1.42	117	1.66
18/05/22	05:00:27	05:09:23	39	-56	276	10:52	343	ingress	1.42	117	1.64
27/05/22	13:21:22	13:22:00	41	18	246	10:59	407	egress	1.39	121	1.79
01/06/22	11:01:00	11:09:50	69	-35	263	06:46	347	ingress	1.39	121	1.74
13/06/22	03:18:23	03:28:08	73	-14	288	17:07	350	ingress	1.39	121	1.73
30/06/22	14:06:29	14:15:16	39	-47	261	14:41	379	ingress	1.38	99	1.75
08/07/22	10:46:11	10:55:28	32	-47	17	13:57	379	ingress	1.38	135	1.75
19/07/22	19:49:30	19:58:45	5	-30	322	11:56	380	ingress	1.39	146	1.82
25/08/22	09:02:31	09:03:14	59	21	164	14:37	397	egress	1.41	118	1.67
30/08/22	14:49:09	14:49:57	51	23	112	13:30	391	egress	1.41	120	1.72
17/09/22	04:50:41	04:51:41	59	-59	346	07:44	371	egress	1.43	137	1.72
19/09/22	06:00:57	06:01:21	58	-54	350	07:49	379	egress	1.43	136	1.69
28/09/22	14:05:55	14:06:52	66	-46	307	07:03	373	egress	1.44	136	1.71
13/10/22	15:14:55	15:14:54	70	-51	227	17:08	334	egress	1.44	136	1.69
22/10/22	01:41:59	01:42:40	69	-52	149	16:57	378	egress	1.47	103	1.67
27/10/22	20:43:17	20:52:23	68	47	240	14:28	425	ingress	1.48	126	1.76
31/10/22	09:34:47	09:35:14	21	-33	46	11:58	367	egress	1.49	129	1.79
11/11/22	04:36:05	04:36:43	67	29	168	08:11	399	egress	1.50	135	1.73
24/11/22	07:47:32	07:56:41	75	-82	289	11:12	379	ingress	1.52	104	1.85
07/12/22	14:38:51	14:39:33	80	24	45	17:09	403	egress	1.53	142	1.81
14/12/22	06:03:10	06:04:38	77	65	209	15:17	409	egress	1.54	157	1.74
19/12/22	19:33:50	19:34:17	53	42	45	14:15	418	egress	1.55	152	1.73
21/12/22	22:19:24	22:28:18	41	-40	4	13:05	380	ingress	1.55	136	1.75
22/12/22	16:28:43	16:29:09	60	59	97	12:49	377	egress	1.55	131	1.78
27/12/22	04:07:52	04:16:36	33	-33	312	12:07	380	ingress	1.56	152	1.86
04/01/23	08:44:08	08:53:03	27	-8	294	10:18	353	ingress	1.57	150	1.85
09/01/23	05:10:05	05:18:19	80	48	138	17:14	369	ingress	1.57	182	1.75
27/01/23	01:14:13	01:23:28	74	12	214	07:02	384	ingress	1.59	140	1.79
01/02/23	03:27:34	03:37:18	81	83	227	06:52	397	ingress	1.60	131	1.86
09/02/23	00:07:25	00:16:29	76	77	5	07:42	407	ingress	1.61	203	1.87
15/02/23	17:21:54	17:31:12	63	73	231	11:44	391	ingress	1.61	171	1.81
23/02/23	14:03:27	14:12:27	54	64	339	10:40	368	ingress	1.62	147	1.87
26/02/23	18:39:46	18:48:46	59	62	275	08:58	365	ingress	1.62	156	1.87

Date	UTC Start	UTC of Occ	SZA (°)	Lat (°N)	Lon (°E)	Local Time	Max Alt (km)	Scheme	Solar Dist (AU)	$F_{10.7}$	Ly-a ($mW m^{-2}$)
10/03/23	03:53:34	04:02:40	32	45	299	12:31	359	ingress	1.63	170	2.01
20/03/23	15:17:13	15:26:23	54	69	212	11:26	434	ingress	1.64	157	1.96
17/04/23	14:21:09	14:22:09	77	-58	151	12:33	381	egress	1.66	175	1.88
01/05/23	20:57:44	21:06:43	26	28	206	13:50	410	ingress	1.66	156	2.05
08/05/23	06:20:01	06:29:18	29	42	123	13:37	416	ingress	1.66	164	1.94
15/05/23	05:34:23	05:43:25	53	62	230	15:32	429	ingress	1.66	139	1.86
27/06/23	23:05:49	23:05:49	13	36	326	11:23	389	egress	1.66	158	198
20/07/23	15:21:38	15:21:32	48	57	259	08:39	404	egress	1.65	188	1.90
24/07/23	23:20:47	23:20:41	63	88	246	12:59	328	egress	1.65	188	1.92
19/08/23	20:15:50	20:16:14	83	54	278	19:29	433	egress	1.63	156	2.03
24/08/23	05:52:15	05:52:51	37	-13	64	12:01	325	egress	1.63	156	1.86
28/08/23	08:38:51	08:48:02	47	70	45	11:04	345	ingress	1.63	156	1.97
12/09/23	10:09:36	10:10:26	51	73	193	12:38	431	egress	1.61	157	2.01
19/09/23	03:03:29	03:03:46	46	30	304	08:39	404	egress	1.61	162	1.96
27/09/23	13:32:12	13:32:44	63	44	206	07:11	414	egress	1.60	156	1.99
10/10/23	08:46:55	08:56:12	60	38	176	16:23	388	ingress	1.58	160	2.04
16/10/23	12:08:14	12:18:07	31	36	146	13:51	417	ingress	1.58	145	1.96
24/10/23	20:49:55	20:50:36	44	-26	83	12:51	351	egress	1.58	145	1.93
29/10/23	12:52:15	12:52:39	49	-33	244	12:37	316	egress	1.58	145	1.92
07/12/23	07:17:15	07:18:04	73	24	45	17:01	385	egress	1.51	129	1.98
11/12/23	09:36:40	09:37:20	64	36	38	16:14	401	egress	1.51	120	1.94
20/12/23	09:42:17	09:42:34	39	22	96	14:24	399	egress	1.50	189	1.88
26/03/24	09:19:01	09:28:16	79	17	207	07:08	397	ingress	1.39	150	1.89
31/03/24	00:17:09	00:17:02	66	-5	168	16:23	376	egress	1.39	132	1.95
10/04/24	03:42:05	03:41:57	26	-45	157	12:28	305	egress	1.39	132	2.03
19/04/24	19:44:20	19:45:00	8	-18	11	12:30	377	egress	1.38	220	1.88
26/04/24	15:08:14	15:08:42	56	34	145	12:25	393	egress	1.38	169	1.87
08/05/24	03:54:39	03:55:34	36	-22	21	09:24	381	egress	1.38	208	1.88
15/05/24	08:37:11	08:37:56	54	-70	10	08:39	313	egress	1.38	216	1.96
31/05/24	17:01:35	17:10:44	57	9	139	15:05	327	ingress	1.39	184	1.83
17/06/24	19:41:19	19:42:16	35	8	212	11:21	362	egress	1.39	180	2.17

Table 4.1: Specification table for all mutual radio occultation measurements between TGO and MEX between 02/04/21 and 17/06/24.

At the time of writing, the MEX-TGO mutual RO campaign is still ongoing, with a cadence of roughly two per week. So far, we have conducted 124 occultations across the full range of latitudes and local times, as illustrated in Figure 2.5. Of these, 71 successfully yielded day-side vertical electron density profiles. The measurements span SZA values from as low as 5.2° close to the sub-solar point to 171° near the anti-solar point. Notably, 35 of these observations were conducted below the minimum SZA of 46.8° typically achievable by the ROSE MAVEN experiment, highlighting our ability to comprehensively study for the first time the near-noon dayside ionosphere. Additionally, 18 readings were obtained from the nightside; however, only the day-side vertical profiles and their corresponding specifications are presented in this article. Numerous other mutual RO measurements have been discarded due to reasons listed next in Section 4.2.1.

With these figures, we are immediately able to determine the behaviour of the M2 peak density and altitude with changing SZA and find a clear correlation with increasing SZA, which agrees well with previous work (Němec et al., 2011, Fox and Weber, 2012, Sánchez-Cano et al., 2013, Mendillo et al., 2013, Fallows et al., 2015 & Segale et al., 2024). For instance, Panel G of Figure 4.2 demonstrates the M2 peak altitude rising and its density decreasing as the SZA increases. A more detailed analysis of these profiles will be provided in Chapter 5.

4.2.1 71 Profiles Selected from 124 RO Measurements

At the time of writing, 124 mutual ROs have taken place between MEX and TGO. From these, 71 vertical electron density profiles have been extracted. A summary of these profiles can be found in Table 4.1. There are a multitude of reasons for why this number is smaller than the total number of occultations. The primary reason is that 19 tests occurred with SZA angles greater than 100 degrees (beyond the terminator/on the night side), with no photoionization at night and only some localised ionisation from solar wind electron precipitation (Adams et al., 2018), and minimal plasma transport. The ionospheric electron densities are below $1 \times 10^{10} \text{ m}^{-3}$ and their effects too weak to currently be extracted from the residuum signal. Therefore, our current processing method is not suitable on the nightside as

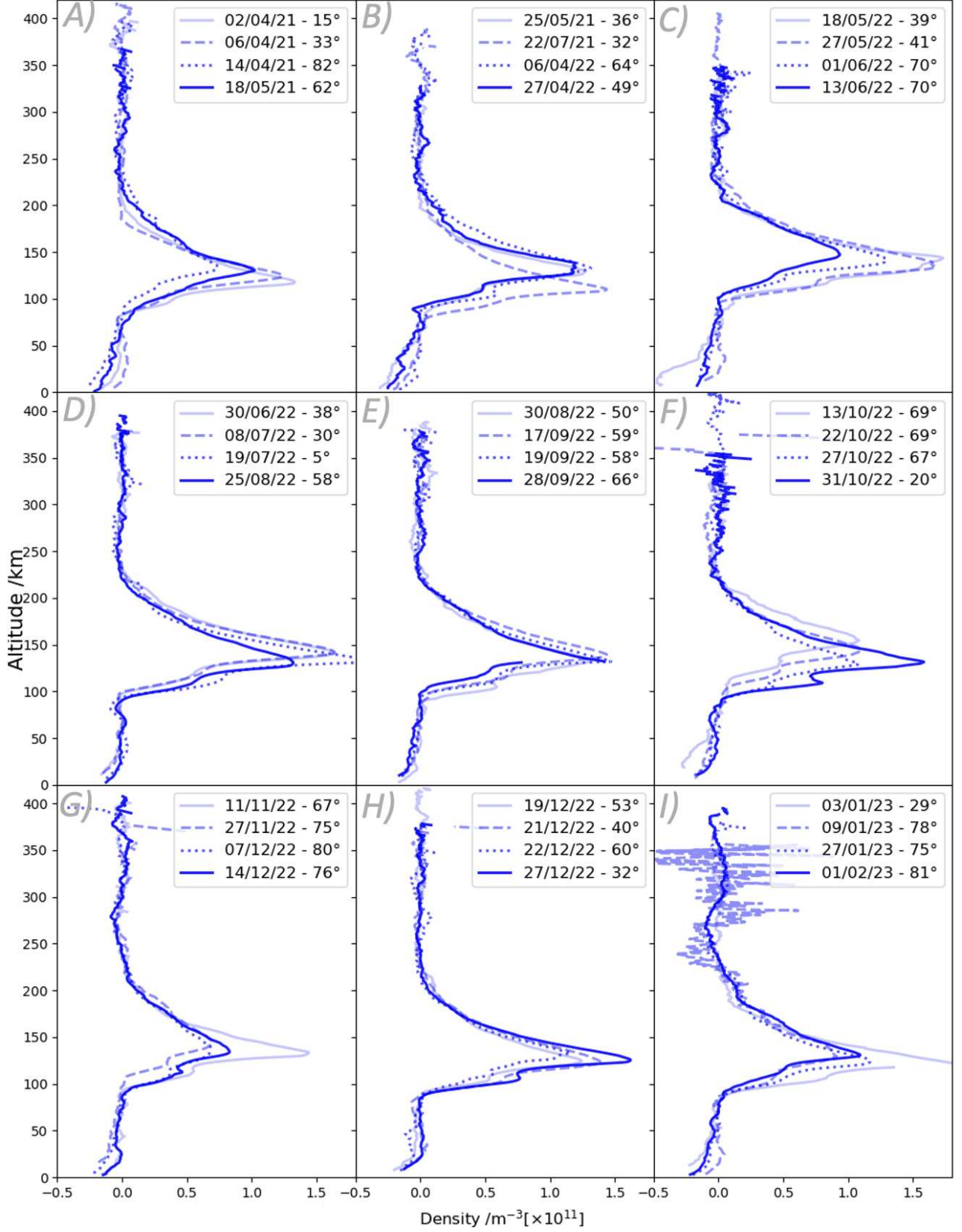


Figure 4.1: All the vertical electron density profiles that have been acquired via mutual radio occultation between Mars Express and Trace Gas Orbiter until 17/06/24. As well as the Solar Zenith Angle, the legend for each plot informs when the measurement took place such that it can be checked in Table 4.1.

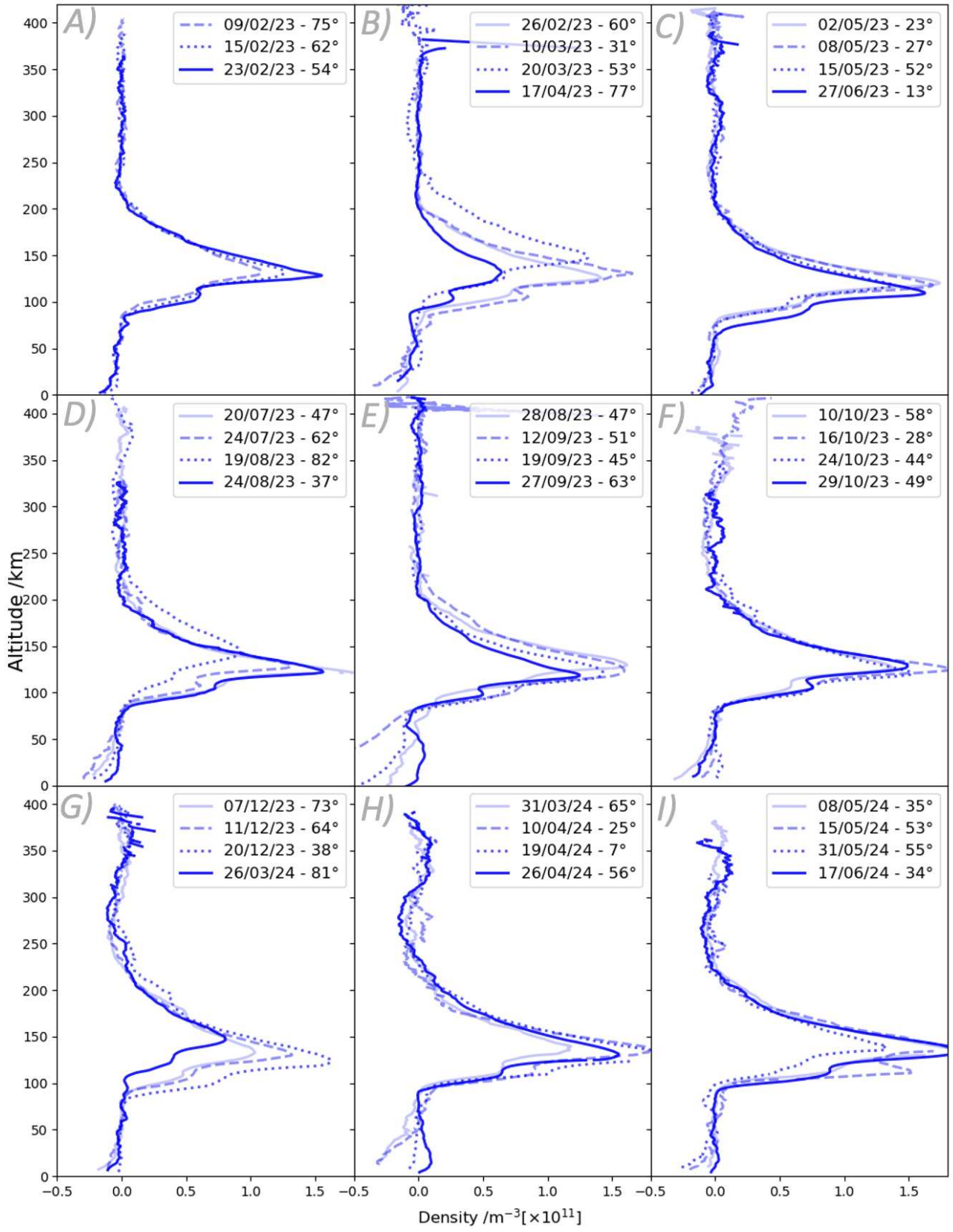


Figure 4.2: All the vertical electron density profiles (cont).

there are no key residuum features to reference.

The second reason is due to a scheduling error. As previously discussed in Section 3.3, a 10-minute warm-up period for Electra began prior to each mutual RO observation to ensure the oscillator's temperature remained stable during the test. Unfortunately, this warm-up was not included in the spacecraft commanding for 12 measurements. This number was larger than expected because this issue went unnoticed in the data for some time as I had not received the data due to a bottleneck in downlinks caused by the solar conjunction.

The third category of occultations that could not be analysed are those where MEX was transmitting its HAIL sequence for the first eight tests; this looping 22 s signal was modulated and had regular silence periods (further discussed in 3.3). However, 75% of these measurements are still usable so these eight datasets still have potential value for proving 'eavesdropping' capability, as is discussed further in Section 7.2.1.

For six of the occultations, the orbits of MEX and TGO were such that the tangent point descended very slowly. The amplitude of the ionospheric features in the residuum is proportional to the derivative of electron density with respect to time. If the tangent point descends too slowly then the residuum features can be minimised to a point below the noise floor of $1 \times 10^{10} \text{ m}^{-3}$.

Five occultations were unsuccessful due to MEX not transmitting at the correct time early on in the campaign when joint MEX/TGO scheduling was not automated. The occurrence of the scheduling errors led to MEX RO transmissions becoming more automated to reduce the probability of future errors.

Finally, two observations were conducted when the Martian limb was not between the two spacecraft. This was done to test the oscillators' stability in the absence of an atmosphere or ionosphere.

4.3 Validation

To validate the profiles, two have been presented in Figure 4.3. This figure illustrates the electron densities obtained on 07/12/22 and 27/06/23, corresponding to panels A and B, respectively. The profile in panel A was selected for its high SZA of 80° , allowing for a direct comparison with conventional RO data. Also shown is a profile from a MAVEN ROSE measurement taken under similar conditions, specifically on 07/11/22 at 18:11:18 UT, with a latitude of 44° and a SZA of 80° . Additionally, panel A features a comparison with in-situ electron density measurements from MAVEN's Langmuir Probe and Waves instrument (LPW) (Andersson et al., 2015), specifically those obtained during Deep-Dip campaign 4 on 08/09/15. Unfortunately, such a comparison is not possible for the profile in panel B, as MAVEN has not conducted a deep-dip to the required sub-150 km altitude with a sufficiently low SZA, as described further in Section 4.3.1.

A second set of profiles can be found in Figure 4.4, from 14/12/22 (egress with SZA value of 77°) and from 27/12/22 (ingress with a SZA close to noon with 33°). 0 km on the y-axis indicates the average Mars radius of 3389.1 km, not the ground. There is a vertical uncertainty of 6 km for both profiles. Also included are comparisons with NeMars (Sánchez-Cano et al., 2013) and Mars Initial Reference Ionosphere Model (MIRI) (Mendillo et al., 2013) semi-empirical models. The model inputs for 27/12/22 are SZA 32° , coordinates [312,-32], $F_{10.7}$ 151.7, Mars Solar Distance 1.558 AU. The inputs for 14/12/22 are SZA 76° , coordinates [209,65], $F_{10.7}$ 157.4, Mars Solar Distance 1.541 AU. Data from MARSIS-AIS is also superimposed, effort was made to find measurements with similar SZA. The specific MARSIS dataset for 14/12/22 is Orbit Number: 10424, Ionosonde Number: 225 and the for 27/12/22 ; Orbit Number: 10675, Ionosonde Number: 93.

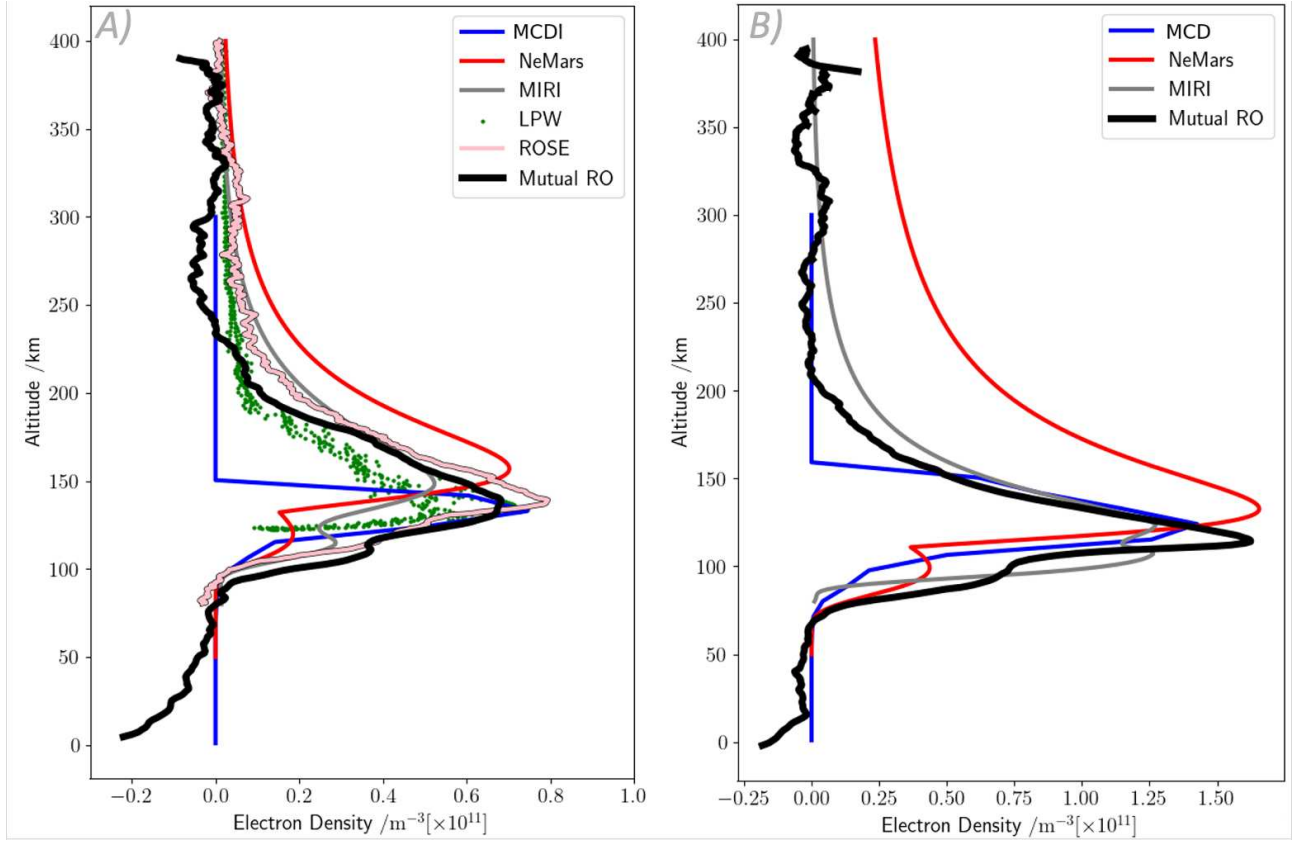


Figure 4.3: Vertical electron density acquired via mutual RO (black) for the dates of 07/12/22 (panel A) and 27/06/23 (panel B). Both profiles are compared with three models: Mars Climate Database (MCD)(blue), NeMars (red) and MIRI (grey). The inputs for all the models are given in Table 4.1 . Panel B has a measurement from a low solar zenith angle of 13° and panel A is from a higher angle of 80°, which is more comparable to conventional RO. As such, it has been compared with a MAVEN ROSE measurement. Panel A also includes in-situ measurements from MAVEN's LPW.

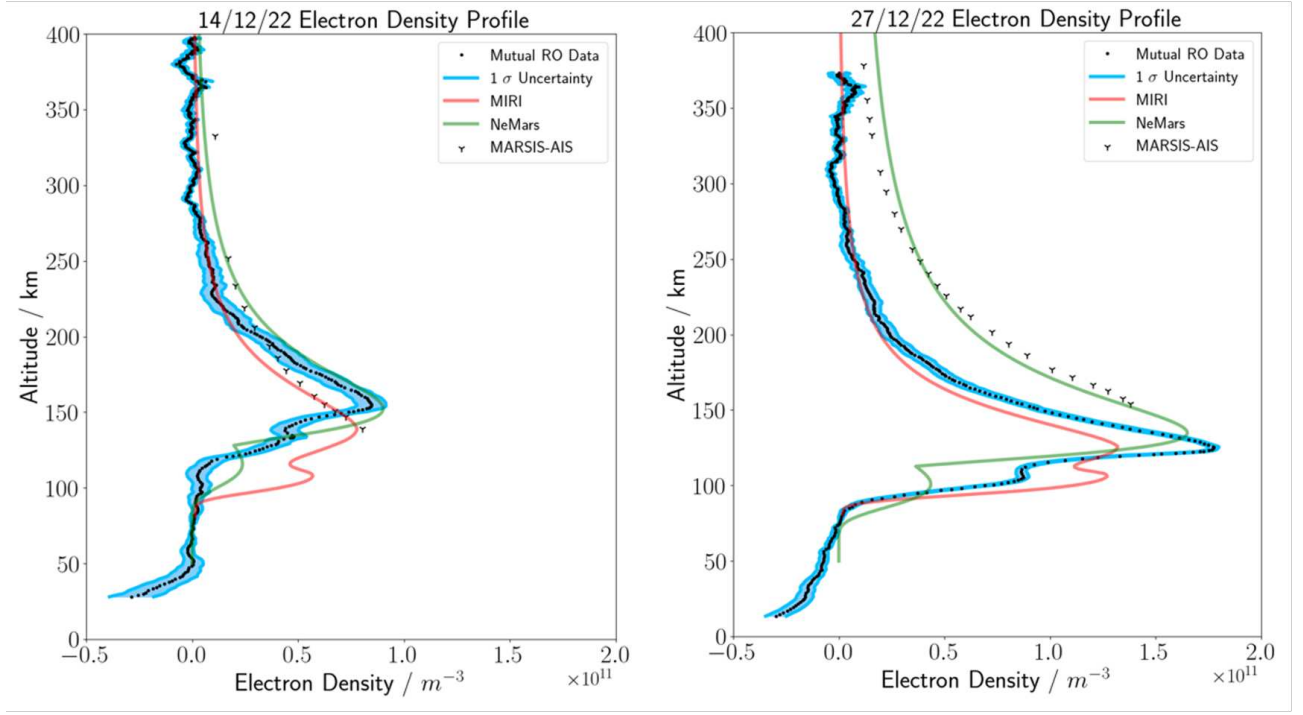


Figure 4.4: Electron density profiles for two mutual RO observations. 14/12/22 (left panel) is from an egress configuration with a high SZA value of 77° and 27/12/22 (right panel) is from an ingress with a SZA close to noon with 33° . 0 km on the y-axis indicates the average mars radii of 3389.1, not the ground. The blue envelope is the result of a numerical error-propagation with 100 iteration. There is a vertical uncertainty of 6 km for both profiles. Also included are comparisons with NeMars and Mars Initial Reference Ionosphere Model (MIRI) semi-empirical models.

4.3.1 Validation with Instruments

MARSIS

The Y-crosses in Figure 4.4 are electron density profiles from the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) onboard the MEX spacecraft in its Active Ionospheric Sounding mode (Gurnett et al., 2008), and were retrieved via the methodology described in Sánchez-Cano et al., 2012. This instrument uses a chirp signal to sound the top side of the ionosphere where the signal is reflected from an ionospheric volume when its plasma frequency is higher than the signal’s frequency. In order to determine the plasma frequency, MARSIS sequentially increases the transmit frequency until reflection ceases (Jordan et al., 2009). The altitude where this happens is determined by monitoring the time for the last echo to be received. These plasma frequencies and altitudes can be combined to infer topside electron density profiles. The altitudes below the M2 peak cannot be probed

with this method, hence the readings stop just above the M2 peak in Figure 4.4.

For the purpose of this study, the primary advantage of utilising radar sounding by the MARSIS instrument is its capability to access all solar zenith angles. However, Withers et al., 2024 highlighted that the derived vertical profiles exhibit relatively poor vertical resolution and absolute accuracy in reported altitudes. This is attributed to the 91.4 microsecond time resolution of the instrument. Radio waves travel 27 km within this time frame, resulting in altitude uncertainties of at least ± 7 km (Morgan et al., 2008). When comparing MARSIS data with mutual RO profiles, an exception must be granted for a discrepancy in altitudes, and the heights of mutual RO readings should be considered more accurate, with an uncertainty of 3.4 km ¹.

LPW

The Langmuir Probe and Waves (LPW) instrument (Andersson et al., 2015) on the MAVEN mission measures electron density, temperature, and wave power density in Mars' ionosphere. The instrument utilises two 40 cm sensors mounted on 7 m booms, and it derives temperature and density in the medium between the two probes via current-voltage (I-V) characteristics. It exploits the plasma sheath principal, which was mentioned in Section 1. When the probe is introduced, it perturbs the local plasma, which forms a sheath around the probe in a direct manifestation of Debye shielding. If no current is put through the probe, the electrons in the local plasma will be attracted to the probe, until a point where the probe is negatively charged. This, in turn, repels the rest of the local electrons, thereby forming a sheath. This voltage the passively forms across the probe is called the floating potential. If the plasma density is lower than the Debye length is greater (see Equation 1.1, so a greater current will

¹The vertical uncertainty for mutual RO is defined by a combination of spatial error from the SPICE framework ($\ll 1$ km) and the Electra/MELACOM on/off commanding time (< 1 s). If we assume the worst case scenario is a 1 s uncertainty, then this could lead to a 3.4 km in vertical uncertainty. This was calculated by realising that the geometric scenario would ascend/descend the fastest is when the orbit MEX and TGO are anti-parallel to each other (Ω differs by 180°) and they are both at the same altitude such that they go over the horizon tangentially at the same speed. MEX has a much larger range of altitudes, but the worst case scenario would involve it at the same height at TGO, so placing both at 400 km and using the equation $v = \sqrt{\frac{GM}{R}}$, where G is the gravitation constant, M is the mass of Mars and R is the 400 km altitude gives us a tangential speed of 3.4 km s^{-1} .

be required to overcome the sheath resistance. This is how varying the current across the two probes leads to density measurements.

In standard operation, one probe will sweep from -50 to +50 V in 128 steps, resting on each voltage for 7.8 ms. At each step, the other probe will measure the induced current and the I-V characteristics curve is fit to determine the density and electron temperature with an accuracy of 6-12%, depending on the ambient density and temperature. Alternately, the wave power density can be acquired via measuring the electric potential fluctuations at the probes (which is like an AC signal) and digitising this such that an FFT can be used to extract the spectral information.

The MAVEN mission was designed to explore the atmospheric escape mechanisms of Mars, its orbit was therefore created to have sporadic 'deep-dips' into the atmosphere and ionosphere to take in-situ measurements. Due to fuel limitations and safety considerations, the epoch and minimum altitude of these 'deep-dips' were carefully selected. So there is not a large selection of LPW measurements to choose from. The measurements that have comparable low SZA to our mutual RO profiles do not go to a low enough altitude. Furthermore, the measurements that go to a sufficiently low altitude do not occur at a low SZA. So, a compromise was reached by only validating our profiles from 'Deep-Dip campaign 4' from 2015. This meant that this comparison is made during different solar conditions, as all the mutual RO datasets were after November 2020. This compromise was made because altitude and SZA correlation were seen as the priority. This means that, in general, the few LPW measurements from comparable altitudes and SZA should have lower peak electron densities due to the lower solar activity. This idea is reflected in Figure 4.3, which shows the green LPW measurements being smaller than all the models and other instruments.

ROSE

The Radio Occultation Science Experiment (ROSE) on MAVEN (Withers et al., 2020) is a conventional RO experiment. It uses two-way X-band radio occultations, utilising a high-gain antenna for ingress and egress opportunities and a low-gain antenna with telemetry for just

ingress. Processed data yields vertical electron density profiles with an accuracy of $1 \times 10^{10} \text{ m}^{-3}$, a vertical resolution of 1 km, and a vertical range of 100–500 km.

ROSE is similar to our mutual RO technique, in that there is no precise lock onto the carrier frequencies. Instead, it records in open loop around the expected received X-Band frequency such that it can perform egress occultations. However, there are many differences, excluding the obvious differences in receiver position being on Earth. ROSE also does not have a USO. It addresses this by using an immensely stable 7.2 GHz carrier tone uplinked by the DSN, then retransmits this signal back down to Earth with a turn-around ratio of 880/749 such that it passes back through the Martian atmosphere with a frequency of 8.4 GHz. No oscillator is involved in this turn-around, so in effect, the ROSE re-transmission has the same stability as the hydrogen-maser oscillators of the DSN. This separation in frequencies allows scientists to parse the contribution to net refraction by the neutral atmosphere and charged ionosphere (see Equation 3.3).

With this being a conventional RO measurement, we can only validate against profiles near the terminator. Most of the ROSE profiles are above 70° SZA, with only 0.1% of the total profiles less than this. However, as this uses the same form of radio science, this should be considered the most similar to the mutual RO datasets above 70° SZA. The error introduced due to this being a conventional RO technique, and needing assimilating Earth meteorological and ionospheric parameters in the data reduction, is considered negligible (*pers comm.*, 2024, *Paul Withers*).

MaRS

The Mars Express Orbiter Radio Science (MaRS) (Pätzold et al., 2004b) is another conventional RO experiment and is onboard MEX. It uses simultaneous and coherent dual-frequency downlinks at X-band (8.4 GHz) and S-band (2.3 GHz) via the High Gain Antenna to separate contributions of the ionosphere and atmosphere.

Like ROSE, MaRS is also a conventional RO instrument, and is therefore limited to

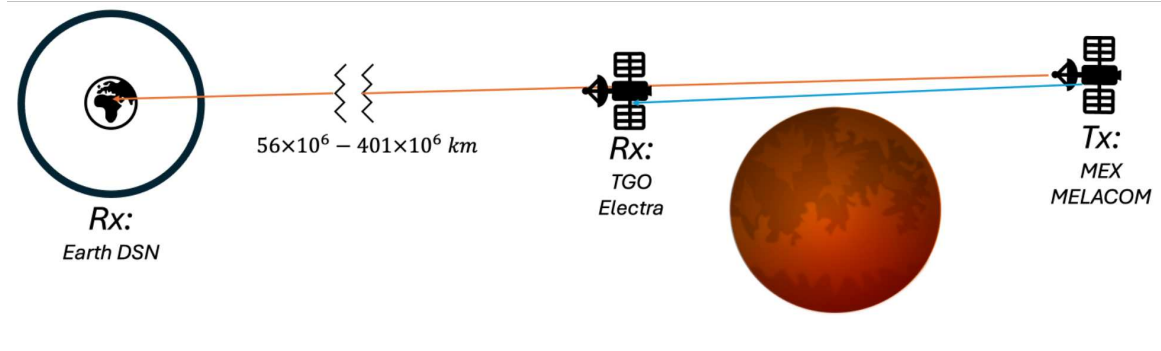


Figure 4.5: A sketch of the geometry for a mutual and MaRS calibration test. The blue line is the radio vector between MEX MELACOM and TGO Electra for mutual RO and the orange line represents the conventional MaRS RO experiment, going from MEX MELACOM to a ground station in the Earth's Deep Space Network (DSN). The black circle around Earth represents the growing annulus which increased the likelihood of this geometry occurring.

terminator regions. However, because this instrument uses a transmitter on the same spacecraft that we use for our mutual RO transmission (MEX), this allows for a unique calibration opportunity.

I saw the potential to conduct simultaneous measurements with both our mutual technique and their MaRS instrument. Both techniques share the same transmitter, but differ in that the receiver in that mutual RO is sent to TGO Electra, and MaRS is conventionally sent to a ground station on Earth. This would only be possible if I could find a moment when TGO is directly in front of the Earth's disk, as shown in Figure 4.5. To calculate this, I modified my geometry code that was part of an ESA deliverable and is available on GitHub (Parrott, 2022), as mentioned in Section 2.3.5. Of course, the Earth's disk is extremely small from the perspective of Mars. With the Earth's radius being 6,371 km and the average Earth-Mars displacement being $2.25 \times 10^8 \text{ km}$, this leads to a solid angle of approximately 8.24×10^{-6} square degrees. TGO will unlikely be directly in front of the Earth's disk a single time during its entire mission lifespan, even if the mission were to last a thousand years. Fortunately, if we allow the available annulus to grow around the Earth's disk then the likelihood of finding a moment grows exponentially ($\propto \pi r^2$). This investigation started in May 2024 when I suggested this to the Project Scientist of TGO and MEX, then I calculated the next available moment to be in December 2024. An investigation had to be carried out as there were concerns that MaRS would interfere with MELACOM, but ultimately, this was found not to be the case.

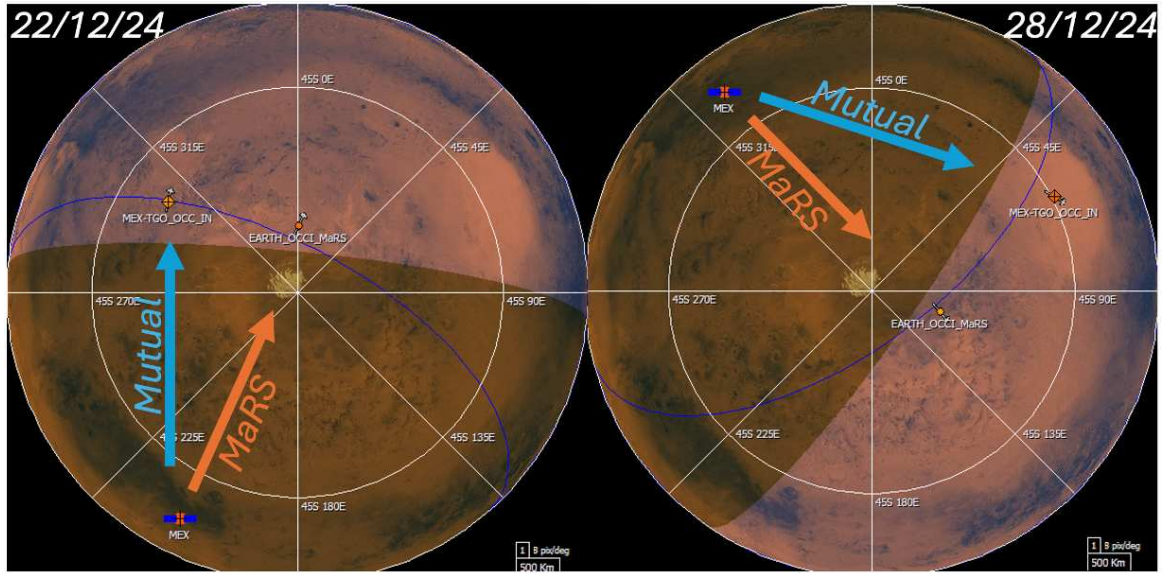


Figure 4.6: Annotated schematic of the MaRS/Mutual RO calibration test geometry, modified to show the radio propagation directions for the two measurements type. Simulation provided by Alejandro Cardesin-Moinelo in ESA’s Science Operations Centre

ESA SOC (introduced in Section 2.3.5) made the decision to go with two measurements on the 22nd and 28th of December. As previously mentioned, the requirements for conducting mutual RO measurements are restricted by the proximity to surface assets, this meant that the SZA and coordinate tolerances for similar MaRS and mutual RO measurements were loosened considerably to fit around these ‘no-go zones’. Figure 4.6 and Table 4.2 show the specification and geometry of these two measurements. At first glance, they appear to be at similar times, but the locations differ quite dramatically. This would suggest that geometric tolerances have been loosened too much. This is supported by the final results in Figure 4.7, where the M2 peak electron densities vary by $2 \times 10^4 \text{ cm}^{-3}$ and $3.8 \times 10^4 \text{ cm}^{-3}$ for the measurements on 22/12/24 and 28/12/24, respectively.

The comparison for December 22nd (in Figure 4.7) includes both frequency bands of MaRS occultation data. The instrument is capable of simultaneously broadcasting in X and S-band, enabling the separation of the net refractivity contributions from the charged ionosphere and neutral atmosphere. This capability accounts for the orange and green lines observed in the left panel, whereas only one frequency was employed during the December 28th test.

The mutual RO measurements indicate a higher density and lower altitude for the M2 peaks. This phenomenon is attributable to a 3° difference in SZA. The disparity in peak densities

		Mutual	MaRS
22/12/24	Coordinates	(305, -57)	(1, -76)
	SZA ($^{\circ}$)	82	85
	Local Time	07:55	11:33
	UTC	10:42	10:37
<i>Results</i>	M2 Density (cm^{-3})	9.3×10^4	7.3×10^4
	M2 Altiude (km)	127	132
	M1 Density (cm^{-3})	4.3×10^4	2.9×10^4
	M1 Altitude (km)	109	109
28/12/24	Coordinates	(62, -44)	(107, -76)
	SZA ($^{\circ}$)	79	86
	Local Time	07:40	10:45
	UTC	06:19	06:26
<i>Results</i>	M2 Density (cm^{-3})	11×10^4	7.3×10^4
	M2 Altiude (km)	128	132
	M1 Density (cm^{-3})	5.9×10^4	2.64
	M1 Altiude (km)	109	107

Table 4.2: Specifications of the MaRS/Mutual RO measurements

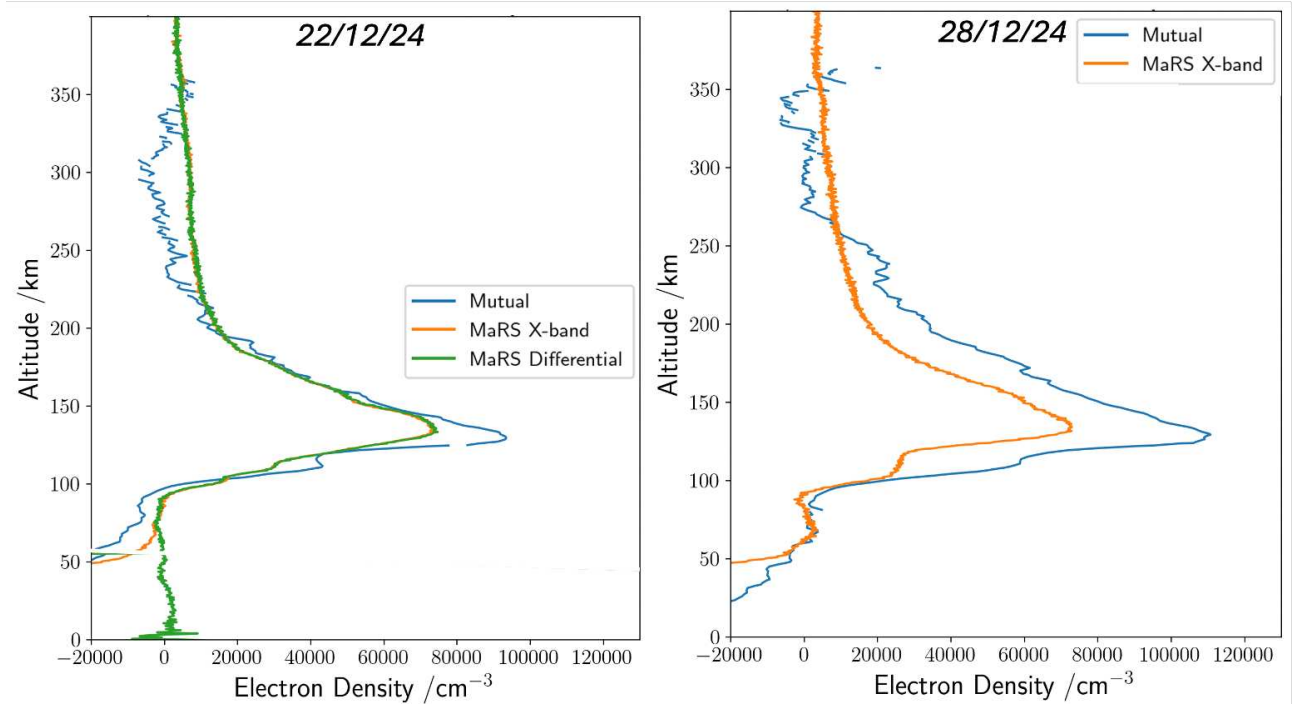


Figure 4.7: Comparison of Mutual /MaRS RO electron density profiles across two tests on Dec 22 & 28, 2024. The MaRS measurement on the 22nd used two frequencies so it can separate neutral and ionospheric layers. The difference in shape can mostly be explained by the difference in SZA.

becomes even more pronounced for the December 28th measurement, with the SZA difference now extending to a more substantial 7° .

Moreover, the 22/12/24 MaRS measurement appears to contain a subtle third peak at around 100 km, which is absent in the mutual RO readings. This is consistent with Pätzold et al., 2005, and may be the reason that they predicted a sporadic Mg^+ layer.

These observations highlight the inherent instability of the oscillator. The mutual RO measurement displays negative densities above roughly 220 km. When fitting the oscillator drift using the methodology outlined in Section 3.4, slight deviations from the fitted curve are inevitable. As the Abel transform starts from the highest altitude, even minor variations in the residuum can lead to significant changes at the top of the profile. These MaRS calibration measurements underscore the need to reduce the tolerance levels for the fit in the high-altitude regions. I would do this by further iterating step four of the processing steps described in Section 3.9.

4.3.2 Validation with Models

Figures 4.3 and 4.4 show comparisons against the NeMars (Sánchez-Cano et al., 2013), MIRI (Mendillo et al., 2018) and MCD (Millour et al., 2022) models. Finer details on NeMars and MIRI can be found in the following chapter in Section 5.2.2, where they are used to compare SZA trends. For now, they can be briefly introduced. The NeMars model is an empirical model derived from data collected by the MEX’s MARSIS experiment and by conventional RO from MGS (Sánchez-Cano et al., 2013). The MIRI model (Mendillo et al., 2013) relies on MARSIS data and incorporates some conventional RO data from MGS. Additionally, the MIRI model includes data from the MaRS experiment (Pätzold et al., 2004b). As a semi-empirical model, MIRI’s numerical parameterisations are informed by well-established physical principles governing ionospheric behaviour.

The Mars Climate Database Global Circulation Model (MCD) provides the most comprehensive profile prediction due to its inclusion of atmospheric and heliophysical

dynamics (Forget et al., 1999, Millour et al., 2022, González-Galindo et al., 2013). The inputs for this are detailed in Table 4.1, including date, time, and coordinates, these enable the calculation of SZA, solar distance, season, solar activity, and atmospheric state. It computes the reaction rates for 45 neutral and 47 ionospheric species interdependently to calculate the M2 electron density (González-Galindo et al., 2013). Because of this, this model should be regarded as the most accurate for predictions about the M2 ionospheric layer. This model ran on the web, and to speed up the data acquisition and remove the human error in the model inputs, I programmed a web bot with the Selenium python library to read Table 4.1 and input this into the web interface. The bot was designed to enter the model inputs, click through the site and download the relevant response files such that there was no human error due to the large volume of manual data input.

4.3.3 Geometry Validation with Cosmographia

While the final electron density profiles can be validated against other instruments and models, the location and other geometric parameters need to be verified. This was done with Cosmographia, which is a companion software package used by the creators of SPICE (NASA’s Navigation and Ancillary Information Facility). It allows the user to see the data from SPICE in a 3D rendered environment. This task was important for validation as it proved that the geometric parameters were correct for each RO test. For example, SPICE provide location of MEX and TGO for every second of a RO test. However, when given the geometric factors like the Martian ephemeris, solar position and curvature of the Martian ellipsoid, then custom scripts we produced to calculate what the SZA is at the tangent point. The shape of the occultation profile is even harder to understand without a visual aid. Shown on the right side of Figure 4.8, this shape needs to be visually inspected as the residuum depends on the speed at which the tangent point descends (explained with Figure 3.6.) This Cosmographia feature was achieved by customising the open-source software. Specifically, by modifying the code for the particle effects of the aurora borealis (shown on the left side of Figure 4.8) and making a python script to automate a .JSON file that Cosmographia could

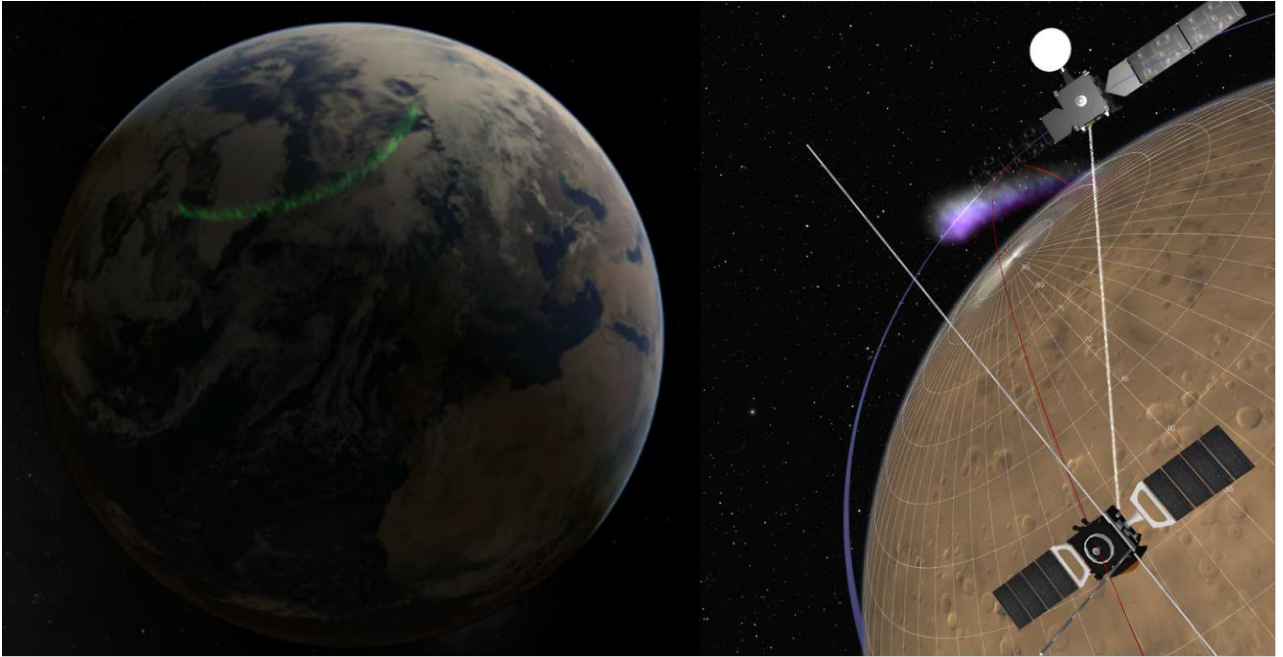


Figure 4.8: Image from SPICE-Enhanced Cosmographia showing the aurora borealis effect and how it was repurposed to create an 3D occultation trace for the purpose of visual geometry verification.

read to map the tangent point onto 3D coordinates. This modification also allows for the profile to get wider and change colour/shimmer as a function of altitude, such that ionospheric and atmospheric volumes appear different.

4.4 Summary

A comprehensive set of results has been provided, including an extensive dataset and a more detailed validation of four selected profiles. Various validation sources are employed, encompassing three models and four instruments. The validation effort has relied on multiple sources, ensuring that the extracted electron density profiles are robust.

At the time of writing, a total of 124 mutual ROs have been conducted between MEX and the TGO. Of these, 71 vertical electron density profiles have been successfully extracted and analysed. Fortunately no observational bias was introduced in the selection process as the errors were independent on geometric factors. The discrepancy between the total number of ROs and the number of viable profiles is primarily attributed to several factors. The profiles seen in this section have been structured chronologically, providing insight into how the

Martian ionosphere and lower neutral atmosphere behave under varying solar conditions.

Chapter 5

Periodic Ionospheric Drivers

The work presented in this chapter has been published in:

Parrott, J., Svedhem, H., Sánchez-Cano, B., Witasse, O., Wilson, C., & Müller-Wodarg, I. (2025). Ionospheric analysis with Martian mutual radio occultation. Journal of Geophysical Research: Planets, 130, e2024JE008854. <https://doi.org/10.1029/2024JE008854>

5.1 Introduction

With data reduction and results now presented, we can begin to explore some of the scientific implications of the mutual RO technique. This chapter will present several investigations into ionospheric forcing, including: 1) Examining how the electron density and altitudes of the ionospheric layers vary with SZA now that we have access to low-SZA regions; 2) Investigating how densities fluctuate over other longer timescale variations of solar parameters, such as heliocentric distance and solar activity; and 3) Utilising the vertical electron density profiles to investigate thermospheric neutral temperatures.

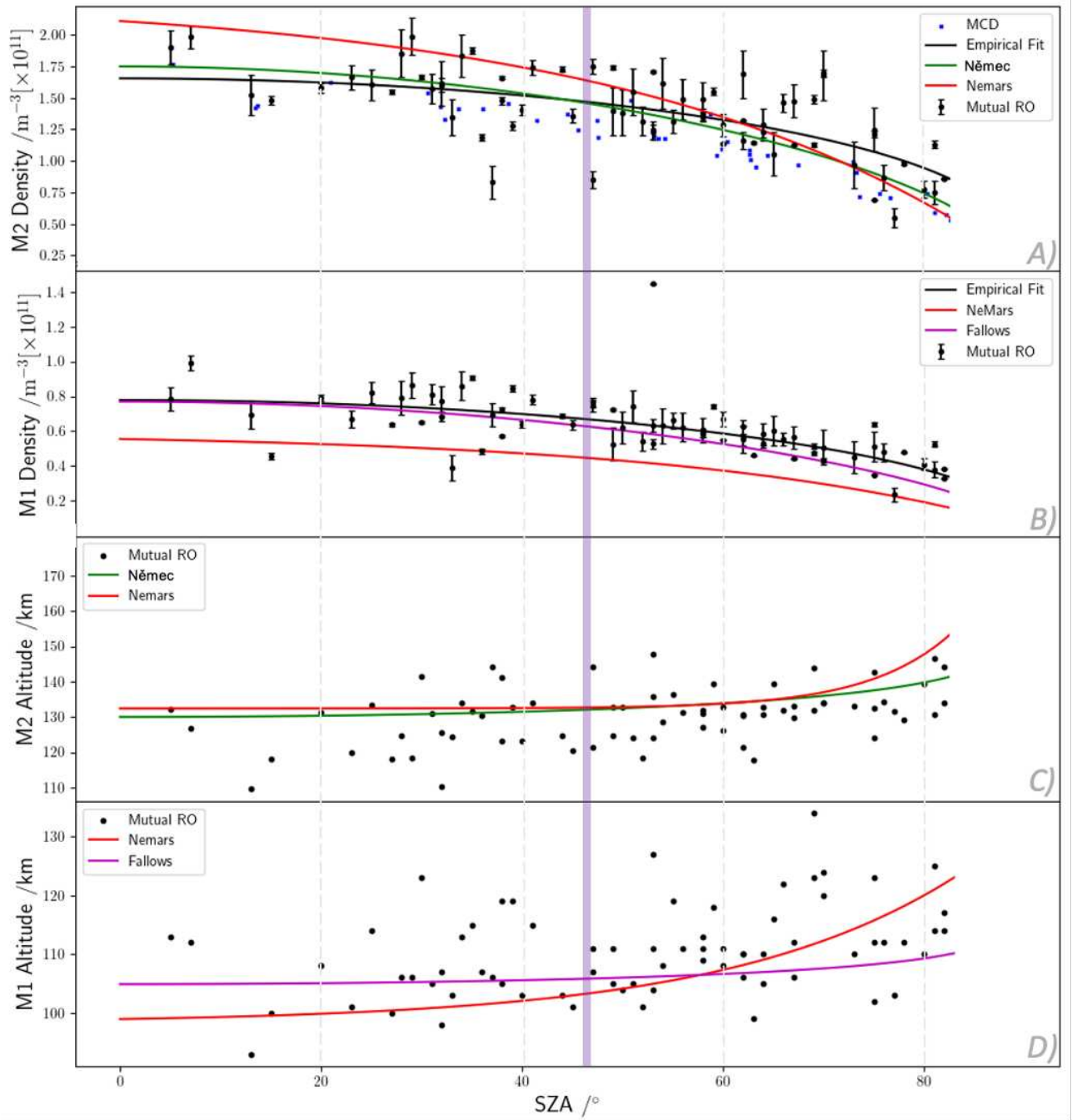


Figure 5.1: The variability of four key ionospheric parameters with increasing SZA. Panel A shows the M2 electron density, blue dots depict the density if the time and location for each measurement were input into a Mars Climate Database, the black lines are the empirical fits to the mutual RO data (black), the green line is the trend found in Némec et al., 2011, the red line is that of the NeMars model (Sánchez-Cano et al., 2013) and the purple curve is from Fallows et al., 2015. All these models use irradiance and heliocentric distance as inputs. These have been set to a constant value, which is the average for all the mutual RO profiles. Specifically, this is $F_{10.7}$ is 111 and the heliocentric distance is 1.52 AU

5.2 Solar Zenith Angle, Solar Distance & Solar Activity

The SZA trends in altitude and peak density for the M1 and M2 ionospheric layers are illustrated in Figure 5.1, derived from the profiles presented in Figures 4.1 and 4.2 from the previous chapter. As mentioned in Section 2.2, the lowest SZA that conventional RO profiles can obtain on Mars occurs at 45° , indicated by a purple demarcation in the figure. This highlights the advantage of this mutual RO method, revealing 34 measurements that would be unattainable using conventional RO techniques. The error bars represent one standard deviation, and have been calculated in the same way as described in Parrott et al., 2024, in that each dataset was processed 100 times with a 5% of the max amplitude input as stochastic noise. Error bars are not visible for panel C and D, as altitude readings in our technique are very accurate. Height-error is a combination of spatial error from the SPICE framework ($\ll 1$ km) and the Electra/MELACOM on/off commanding time (< 1 s).

The method for programmatically finding the altitude and densities also contributes little to the uncertainty. The heights and densities were found via parametrically fitting an α -Chapman profile, as seen in Equation 1.2. The variables for this minimisation are the altitude, scale height (later used for neutral temperature readings) and peak density. The method proved very affective, even for M1 readings. When the M1 appeared as subtle shoulder under the M2, the correct altitude is still found as the most vertical portion of the profile between 90 and 110 km will always be at the M1 peak (there are no other local maxima).

The first panel at the top of Figure 5.1 depicts the M2 density trend as a function of SZA, following the relation $1.6 \times 10^5 \times \cos \text{SZA}^{-0.25}$. This trend was found via a parametric fit of a cosine trend with the independent variables as the subsolar density and the cosine coefficient. All models align well with this trend, although the MCD exhibits a narrower spread, suggesting that peak densities are modulated by factors not accounted for in the MCD.

Panel B illustrates the same trend for the M1 layer. An initial conclusion can be made about the presence of the M1 ionospheric layer, which was expected to not exist during the midday

(Mayyasi & Mendillo, 2015), but was predicted recently by Segale et al., 2024.. A notable anomaly occurs at SZA is 53° , with a density of $1.51 \times 10^{11} \text{ m}^{-3}$, recorded at 08:37 on 15/05/24, shortly after a solar flare and during a coronal mass ejection disturbance. The significance of this result is such that it merits a dedicated chapter, and this will be further discussed in Chapter 6. This panel is particularly significant as it represents the first examination of the M1 layer in low-SZA regions and has not been explored in previous works.

Panel C presents the M2 altitude trend, with both models predicting an slight growth with SZA, which only begins to rise substantially around 70° SZA.

Lastly, the fourth panel focuses on M1 altitude, which exhibits the greatest variability among these trends and shows minimal correlation with SZA. The highest M1 altitude is observed at 82° , while the lowest is at 15° , which agrees with theory (Němec et al., 2011, Fox and Weber, 2012, Sánchez-Cano et al., 2013, Mendillo et al., 2013, Fallows et al., 2015 & Segale et al., 2024). This wide spread around the theoretical trend has reduced the value of showing any empirical fit. Both models are expected to perform poorly in predicting this variable, as they are partially based on MARSIS data, which, due to its radar sounder nature, cannot penetrate below the higher M2 layer. They also assimilate MGS RO data, but this is confined to high-SZA, making the low-SZA predictions speculative.

There are other periodic drivers of the Martian ionosphere that warrant investigation; specifically changes in solar activity and heliocentric distance. Panel A of Figure 5.2 shows the M2 peak after they have been normalised to subsolar values using the same trend shown above. Again, this is $1.6 \times 10^{11} \cos(\text{SZA})^{-0.25}$, and has been used here to isolate the effects of the other ionospheric drivers. This panel shows that there is a gradual increase in subsolar density values over a three year time span (a fit has not been included due to the significant spread). Panel B shows the increasing solar radio irradiance in the $F10.7$ band; correlating well to panel A and has been included as this is the standard proxy for solar activity. Panel C is the heliocentric distance, which shows the sinusoidal oscillation between 1.38 and 1.67 AU. Less correlation can be seen here with the top panel, despite the r^2 rule in solar irradiance inferring that the total flux should reduce by 31.3 % between aphelion to perihelion. The last

panel has been included to investigate the specific shorter wavelength irradiance bands known to cause the Martian ionosphere. They have been found with the Flare Irradiance Spectral Model-Version 2 (FISM-2) model (Chamberlin et al., 2020). These irradiance levels also follow the same upward trend seen in panel B, but it is evident that the different bands have slightly different responses to solar activity, with the highest short wavelength power coming from the mid-EUV (λ is 25.7 nm).

5.2.1 Normalisation via Empirical Fits

These mutual RO datasets mark a significant shift from focusing solely on high SZA values, necessitating the definition of empirical formulas to ensure their validity in low SZA regions. The following density formulas for the M1 and M2 ionospheric layers are presented, with irradiance represented by either $F_{10.7}$ or F_{mEUV} , measured in solar flux units (SFUs) and mW m^{-2} , respectively. The latter is preferred due to its higher accuracy and falls within a frequency band more relevant to ionospheric formation. The F_{mEUV} irradiance levels, derived from the 43 and 59.5 nm bands of the FISM-2 model, and were chosen because they closely match the absorption cross-sections of CO_2 (as shown in Figure 10 of Lollo et al., 2012). The F_{mEUV} values from FISM-2 utilise MAVEN LPW data and adjust Earth ground station measurements for application to Mars, accounting for solar distance, different orbital planes, and Carrington rotation (since the Sun’s EUV irradiance is not uniform across its surface; in other words, anisotropic). On the other hand, $F_{10.7}$ is included for comparability with previous empirical fits, even though it is measured for Earth at a different radio frequency 10.7 cm band. Below are the empirical fits for the M1 and M2 electron densities, expressed in terms of F_{mEUV} or $F_{10.7}$.

$$N_{M2} = 1.6 \times 10^{11} \cos(\text{SZA})^{-0.25} + 4.3 \times 10^8 F_{10.7} \quad (5.1)$$

$$= 1.6 \times 10^{11} \cos(\text{SZA})^{-0.25} + 5.3 \times 10^{10} F_{mEUV} \quad (5.2)$$

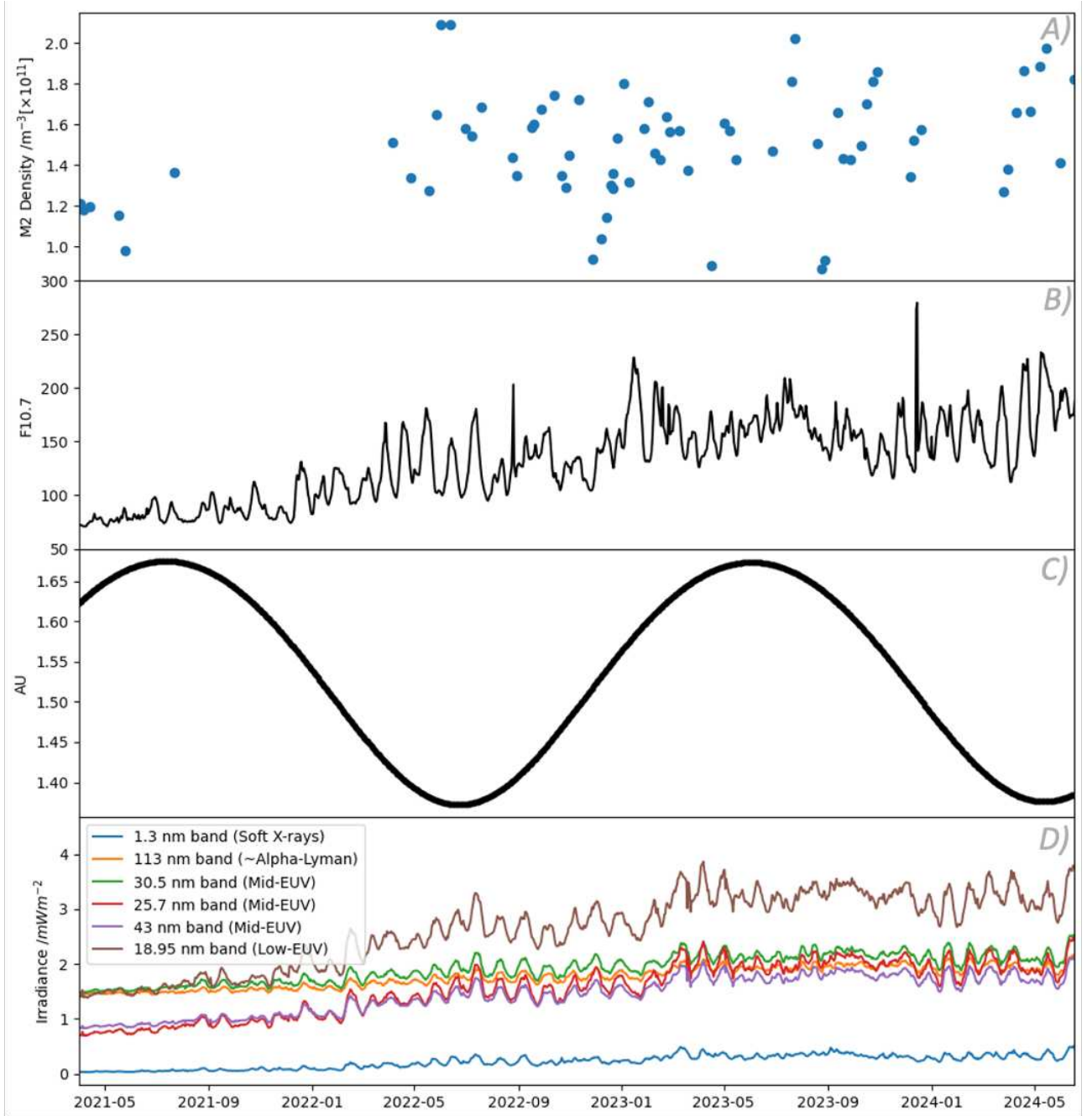


Figure 5.2: Sub-solar M2 peak electron densities (corrected using $1.6 \times 10^{11} \cos(\text{SZA})^{-0.25}$) compared with 3 major driving forces. Second panel shows the $F_{10.7}$ irradiance levels measured at Earth. Third panel is the martian solar distance measured in AU. The fourth panel is irradiance levels simulated for Earth using the FISM-2 Model.

$$N_{M1} = 7.3 \times 10^{10} \cos(\text{SZA})^{-0.34} + 2.5 \times 10^8 F_{10.7} \quad (5.3)$$

$$= 7.3 \times 10^{10} \cos(\text{SZA})^{-0.34} + 3.1 \times 10^{10} F_{mEUV} \quad (5.4)$$

Equations 5.1 and 5.3 were derived using the same methodology as Němec et al., 2011, where the largest factor (SZA) was determined first, followed by the calculation of the Spearman rank coefficient on the residuals for subsequent minor parameters until the correlation fell below 0.2. This analysis yielded a surprising result: solar distance played a negligible role in influencing electron densities, with correlations of -0.16 for M2 and -0.01 for M1. This is evident in Figure 5.2, where the effects of solar distance (shown in panel C in Figure 5.2) show no resemblance to the sub-solar peak density values. In contrast, increasing solar activity (indicated by $F_{10.7}$ and F_{mEUV} data) is correlated with rising sub-solar values. The low correlations observed are likely due to the limited sample size.

As described in Section 1, the M1 layer is primarily driven by soft X-ray photoionisation. It may therefore be more appropriate to examine with this band instead. Using the aforementioned EUV bands, the average of the 0.225, 0.6, 1.3, and 2.5 nm bands were utilised. This led to a coefficient of 2.27×10^{11} with a correlation of 0.61. This is an improvement over F_{mEUV} , which had a correlation of 0.58, i.e:

$$N_{M1} = 7.3 \times 10^{10} \cos(\text{SZA})^{-0.34} + 2.27 \times 10^{11} F_{mXRAY} \quad (5.5)$$

Empirical fits were also determined for the altitudes of both ionospheric layers. The small sample size significantly limited the confidence levels. Consequently, the fitted model was kept relatively simple, with SZA being the only significant factor. The first equation describing the altitudes of the M2 ionospheric layer was developed by Hantsch and Bauer, 1990 and follows the form $h_m = h_0 + H \ln(\sec(\text{SZA}))$, where h_0 is the sub-solar altitude and H is the scale

height. The empirical fits are as follows:

$$h_{M2} = 125.9 + 5.9 \ln(\sec(\text{SZA})) \quad (5.6)$$

$$h_{M1} = 106.2 + 5.3 \ln(\sec(\text{SZA})) \quad (5.7)$$

5.2.2 Previous Estimates

The trends above have been described in previous works, with the purpose of each study being slightly different and because the measurements occurred at different epochs, they have found different formulations, so 'apples-to-apples' comparisons are rare. The initial attempt to formulate a trend was made by Hantsch and Bauer, 1990, where they used data from the two Viking landers and Mariner 4 (minimum SZA of 42 °) to make comparisons to the then more explored Venusian ionosphere. Their first attempt was grounded in Chapman theory and led to the formula:

$$N_{M2} = N_0 \cos(\text{SZA})^{0.5} \quad (5.8)$$

$$h_{M2} = h_0 + H \ln(\sec(\text{SZA})) \quad (5.9)$$

However, they noticed that Chapman theory could not strictly be applied as the neutral scale heights and solar flux were not constant. They found a cosine coefficient of 0.57 to be more accurate. They also made an attempt to find a fit for sub-solar peak electron density as a function of solar flux, despite the limited quantity of data. They found:

$$\frac{\ln(N_0)}{\ln(F_{10.7})} = 0.36 \quad (5.10)$$

The next pertinent piece of research was done by Morgan et al., 2008, where they deployed 12,291 ionograms from MEX's MARSIS instrument to make an empirical model. They used data from 14/08/05-31/07/07, this was during the solar minimum of solar cycle 23 where the $F_{10.7}$ never reached above 105 s.f.u. They used the same formulations as the Hantsch and Bauer, 1990 study but refined the coefficients due to their larger quantity of data. They found N_0 , h_0 , H , $\frac{\ln(N_0)}{\ln(F_{10.7})}$ to be $1.62 \times 10^5 \text{ cm}^{-1}$, 128.2 km, 12.9 km and 0.3 ± 0.4 , respectively.

The next work was completed by Němec et al., 2011, where they used MARSIS data once again, but this time armed with 30,283 ionograms from August 2005 to December 2009. Much of their study was focused on the plasma distribution in the exosphere where PCE subsides and the dynamics become transport-dominated (around 10 scale heights above the M2 peak). They did, however, offer even more precise coefficients and a new formulation for $F_{10.7}$ correlation. These coefficients were N_0 , h_0 and the cosine coefficient for $1.59 \times 10^5 \text{ cm}^{-1} \pm 0.1\%$, $124.7 \pm 0.1 \text{ km}$, 0.546 ± 0.001 , respectively. Their empirical fit for solar flux was a step up in complexity when compared to previous works.

$$N_{M2} = (40,786 \pm 1\%)(F_{10.7})^{0.388 \pm 0.003} \quad (5.11)$$

Sánchez-Cano et al., 2013 wrote an article on their NeMars model and marked another advancement as it was the first to model both the M1 and M2. They did this by using a finer selection of MARSIS ionograms to equally fit varying coordinates, SZA, heliocentric distance and $F_{10.7}$ values, whilst refraining from areas near the crustal magnetic fields. In fact, just 1200 MARSIS ionograms were used to make the empirical fit, and then 500 more ionograms were used to validate it. The NeMars model could fit the M1 layer because it used 5600 MGS radio occultation datasets, but since this was a conventional radio occultation method, these profiles were only from above 70° SZA. The resultant equations also included a heliocentric distance factor (r) and had this form:

$$N_{M2} = \frac{1}{r} (4.5 \times 10^8 F_{10.7} - 1.9 \times 10^{10} \exp(\frac{SZA}{37.2}) + 2.3 \times 10^{11}) \quad (5.12)$$

$$N_{M1} = \frac{1}{r}(1.2 \times 10^8 F_{10.7} - 3.5 \times 10^9 \exp(\frac{SZA}{32.9}) + 5.9 \times 10^{10}) \quad (5.13)$$

$$h_{M2} = 0.001 \exp(\frac{SZA}{8.3}) + 132.4 \quad (5.14)$$

$$h_{M1} = 0.65 \exp(\frac{SZA}{22.8}) + 98.3 \quad (5.15)$$

These formulations changes if we are closer to the terminator, so when $SZA > 75^\circ$:

$$N_{M2} = \frac{1}{r}(4.5 \times 10^8 F_{10.7} + 2.1 \times 10^{11})\sqrt{\cos(SZA)} \quad (5.16)$$

$$N_{M1} = \frac{1}{r}(1.2 \times 10^8 F_{10.7} + 5.5 \times 10^{10})\sqrt{\cos(SZA)} \quad (5.17)$$

$$h_{M2} = 132.4 + H_0 \ln(\sec(SZA)) \quad (5.18)$$

$$h_{M1} = 98.9 + H_0 \ln(\sec(SZA)) \quad (5.19)$$

where H_0 is the scale height for that layer when SZA is 0° .

Mendillo et al., 2018 had a different approach where the fit was semi-empirical as opposed to purely empirical. This means that it was based on PCE theory as a framework for transforming observation into predictive schemes. This method was initiated in Mendillo et al., 2013 but then improved in 2018 by using a more accurate value for $F_{10.7}$ that had been corrected to the martian heliocentric distance and accounting for solar rotation ($F_{effective}$). The coefficients were also validated against MAVEN ROSE RO datasets (minumum SZA of 45°). Their semi-empirical fit followed the form of:

$$N_{M2} = 2.23 \times 10^4 \sqrt{F_{effective} \cos(SZA)} + 1.28 \quad (5.20)$$

However, 'apples to apples' comparisons can be found across various works. The following lays out the different coefficients found across the literature that can be compared with Equations 5.1-5.7. The cosine coefficient of -0.25 from our calculated Equation 5.1 produces a much flatter SZA trend for M2 densities than previous authors' calculations. Hantsch and Bauer, 1990, using Viking Lander and Mariner 4 data, predicted a coefficient of -0.57. Fox and Yeager, 2006, using MGS occultation data, found a coefficient of -0.49 for periods of high solar activity. Morgan et al., 2008 refined the coefficient to -0.476 using a large dataset from MARSIS AIS, which populated the low-SZA region. The lower coefficients obtained from mutual RO are likely because previous estimates have been primarily based on conventional RO, which lacks data for low-SZA regions and requires extrapolation to these lower SZA values. The only substantial data for midday comes from MARSIS AIS, which systematically produces higher topside density readings. Consequently, the inclusion of radar sounding data leads to an overestimation of midday density values and, overall, a steeper cosine trend with a larger SZA coefficient.

The M1 layer has been less extensively studied. However, Fox and Yeager, 2006 used MGS conventional RO measurements from high-SZA regions and found a cosine exponent of -0.55 for low solar activity and -0.53 for high solar activity.

The fact that the M1 SZA coefficient is larger than that of M2 is noteworthy. This is likely due to the greater penetration depth of soft X-rays, meaning the ionisation occurs at altitudes where the neutral atmosphere is denser. As the slant angle increases during the day, moving away from the sub-solar point, the integral density rises at a faster rate than if the flux were at the same angle at a higher altitude. This steeper rate of ionisation results in a larger SZA cosine coefficient.

Estimates of the sub-solar M2 peak density value lie in the middle range of previous estimates. The most accurate estimates are obtained via MARSIS radar sounding instruments, which

consistently access low-SZA regions and do not require extrapolation from near the terminator. However, estimates by different authors using the same instrument vary widely due to the period at which their measurements were taken, including 2.1×10^{11} , 2.0×10^{11} , 1.8×10^{11} , and $1.6 \times 10^{11} \text{ m}^{-3}$ from Safaeinili et al., 2007, Gurnett et al., 2008, Nielsen et al., 2006 & Morgan et al., 2008, respectively. Only the last estimate agree with the value obtained via mutual RO, as radar sounding tends to predict higher electron densities than RO.

Due to conventional RO only exploring regions near the terminator, there has been considerable work on the difference between the dawn and dusk ionospheric dynamics. Segale et al., 2024 used MAVEN ROSE data to show that dawn regions have a significantly higher M2 altitude and density during perihelion, as opposed to dusk, which shows less variation with solar distance. Whilst investigating the systematic difference between MAVEN ROSE and LPW measurements, Felici et al., 2022 postulated that the dawn ionosphere exhibits higher variability in general than the dusk regions. Pilinski et al., 2019 suggested this dawn/dusk asymmetry is due to diurnal variations in coupling between the ionosphere and the neutral atmosphere. The neutral atmosphere (between 150 and 300 km) is known to be at its highest density and temperatures at dusk, instead of the middle of the day (Gupta et al., 2019). This is corroborated by the simulations of Bougher et al., 2015, where they infer this is driven by winds. This suggests a higher molecular collisionality at dusk, therefore effecting the coupling in the ionosphere-thermosphere system.

5.3 Thermosphere Temperatures

Neutral temperatures at M2 altitudes can be determined through the analysis of the scale height H in vertical electron density profiles. This method assumes the region to be in photochemical equilibrium, where the timescales for transport are significantly longer than those for photochemical production and loss processes (Withers, 2009, Fox et al., 2017). The underlying logic is as follows: as the neutral atmosphere warms, it expands, causing the optical depth of unity to be reached at higher altitudes by the incident solar flux. This results

in peak photoionisation occurring at elevated heights. However, since the solar flux itself remains constant, the peak electron density does not change. Consequently, the ionospheric layers exhibit an increased scale height H , which can be readily determined.

The process begins by parametrically fitting Equation 1.2 to the M2 peak, following the approach outlined by Sánchez-Cano et al., 2016. However, regions significantly above the M2 peak are no longer in photochemical equilibrium due to the dominance of ion transport dynamics, and regions below the M2 peak coincide with the M1 ionospheric layer. After testing the sensitivity to these chosen heights, the parametric fit is performed within a range of -20 to +50 km around the M2 peak, ensuring a reliable estimation of the scale height H .

The scale height H can then be used to calculate the neutral temperature T_n using the following equation:

$$T_n = \frac{Hgm}{k} \quad (5.21)$$

where m is the molecular mass of CO_2 at 7.308×10^{-26} kg (which is still the dominant specie at this altitude), k is the Boltzmann constant, and gravity g is dependent on altitude, calculated as:

$$g = G \frac{M}{(r_m - h)^2} \quad (5.22)$$

Here, G represents the gravitational constant of $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, M is the Martian mass of 6.39×10^{23} kg, r_m is the mean Martian radius of 3.338×10^6 m, and h corresponds to the M2 altitude.

5.3.1 Observation and Validation

A trend for the neutral temperature around the M2 ionospheric peak with increasing SZA can be found in Figure 5.3, which shows a temperature gradient of around 0.46 K per degree of

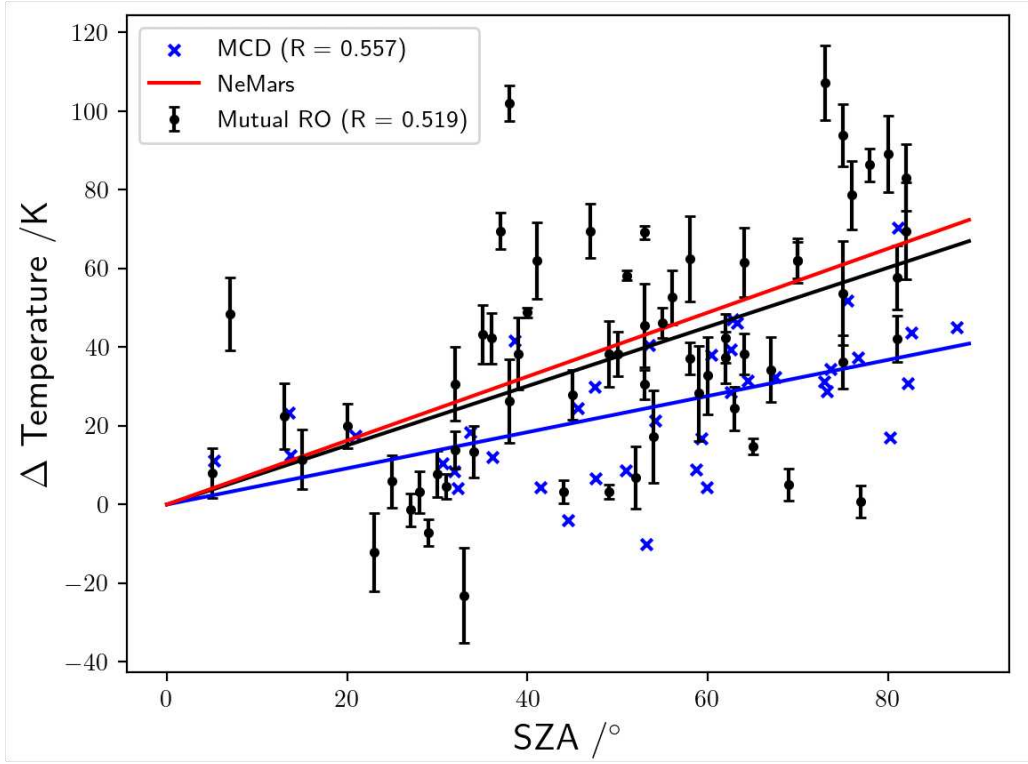


Figure 5.3: Temperature trend with solar zenith angle. Blue cross are from the same empirical Chapman fit method described in Section 5.3, but applied to the profiles found via a Global Circulation Model. The red line is the same method applied but for profiles derived from the NeMars model.

SZA.

Similar to the approach used for Figure 5.1, error bars have been calculated in the same way, and the same MCD has been employed for comparison. The inputs for this are derived from the time and coordinates of each mutual RO measurement, ensuring consistency in SZA, solar activity, and solar distance, with variations in season and atmospheric circulation. Although the NeMars model was not originally intended to provide insights into neutral temperatures, it has been included here due to its ability to explicitly output ionospheric scale height, which can then be utilised in Equation 5.21 to estimate neutral temperatures.

Both the data and the two models have been normalized by bringing the initial value to 0 K. This recognises that these models rely heavily on MARSIS data for low SZA regions, as it represents the most extensive dataset for these midday local times (Vogt et al., 2016).

However, due to the fundamentally different measurement techniques and processing, the values needed to be normalised with a temperature offset of 202 K, 139 K, and 236 K for our measurements, the MCD, and NeMars, respectively.

5.3.2 Dynamics

The results depicted in Figure 5.3 may initially seem counter-intuitive, given that conventional understanding suggests a decrease in temperature with an increase in SZA due to reduced insolation. As discussed in Section 1.0.1, the increased slant angle causes solar flux to penetrate less deeply, resulting in a reduced deposition of thermal energy in the atmosphere around the M2 peak.

One might also hypothesise that, given the M2 altitudes are situated within the lower thermosphere, temperatures would be expected to rise with altitude as SZA increases, as seen in Figure 1.6. Furthermore, as Figure 5.1 illustrates, ionospheric peak heights are anticipated to ascend with increasing SZA. Despite this, I performed an analysis of the 71 available profiles and revealed no correlation between M2 peak altitude and temperature.

A comparable trend was observed by Jain et al., 2023, using data from MAVEN’s Imaging Ultraviolet Spectrograph instrument (McClintock et al., 2015), although at a considerably higher altitude of 170-180 km. They proposed that thermospheric temperature increases steadily throughout the Martian day, with heat only reducing beyond the dusk terminator.

The temperature dynamics in this region have previously been explored through simulations by Bougher and Shinagawa, 1998 using the Mars Thermosphere General Circulation Model (MTGCM), where their simulation results showed an increase in temperature with SZA (for 120 km altitude). However, their study did not provide a detailed explanation for why this temperature trend occurred.

Using the MCD, I have simulated transport processes at various altitudes. The outcomes of these simulations are presented in Figure 5.4. The MCD was used for the Martian spring equinox (solar longitude = 0°) with the meridian set to local time 18:00, placing the sub-solar point (12:00) at approximately 90° longitude. The left column of Figure 5.4 displays temperature. It shows the warmest regions are observed near the poles and the terminator around 18:00. This temperature distribution can be employed to validate the results obtained via mutual RO in Figure 5.3, which showed that the temperature should increase as we get

further away from the subsolar point at 12:00. Please note, the local times appear to be counting backwards across the x-axis. This is to account for the rotational direction of Mars' spin. This complex dynamic has also been depicted in Figure 5.5 to aid understanding. The right column depicts the magnitude and direction of horizontal winds as a quiver map, superimposed on a map showing the scalar value of downward wind. At an altitude of 200 km, the simulation reveals divergent winds originating from approximately 19:00 local time. The divergence does not originate at the sub-solar point due to the time lag required for the low-density atmosphere to warm. These divergent winds accelerate towards the poles, becoming transpolar, crossing over to the night side, and converging on the other side of the planet. The MTGCM also found these high-altitude transpolar winds in 1998 (Bougher & Shinagawa, 1998). The convergent winds gather around 08:00 leading to downwelling. This, in turn, causes divergent winds at lower altitudes near this antisolar point. Overall, the simulation illustrates divergent winds on the night side of around 120 km due to downwelling near the anti-solar point, as well as divergent winds on the day side resulting from solar heating. These dynamics result in winds converging near the terminator, accompanied by further downwelling. The observed higher temperatures are attributed to the adiabatic heating of air as it descends to lower altitudes.

In summary, this MCD simulation explains why there are divergent winds originating from the antisolar point. When these winds coming from the nightside collide with winds from the dayside (driven by solar heating), they are diverted downwards and warm-up as the air parcels are compressed as the pressure increases with decreasing altitude.

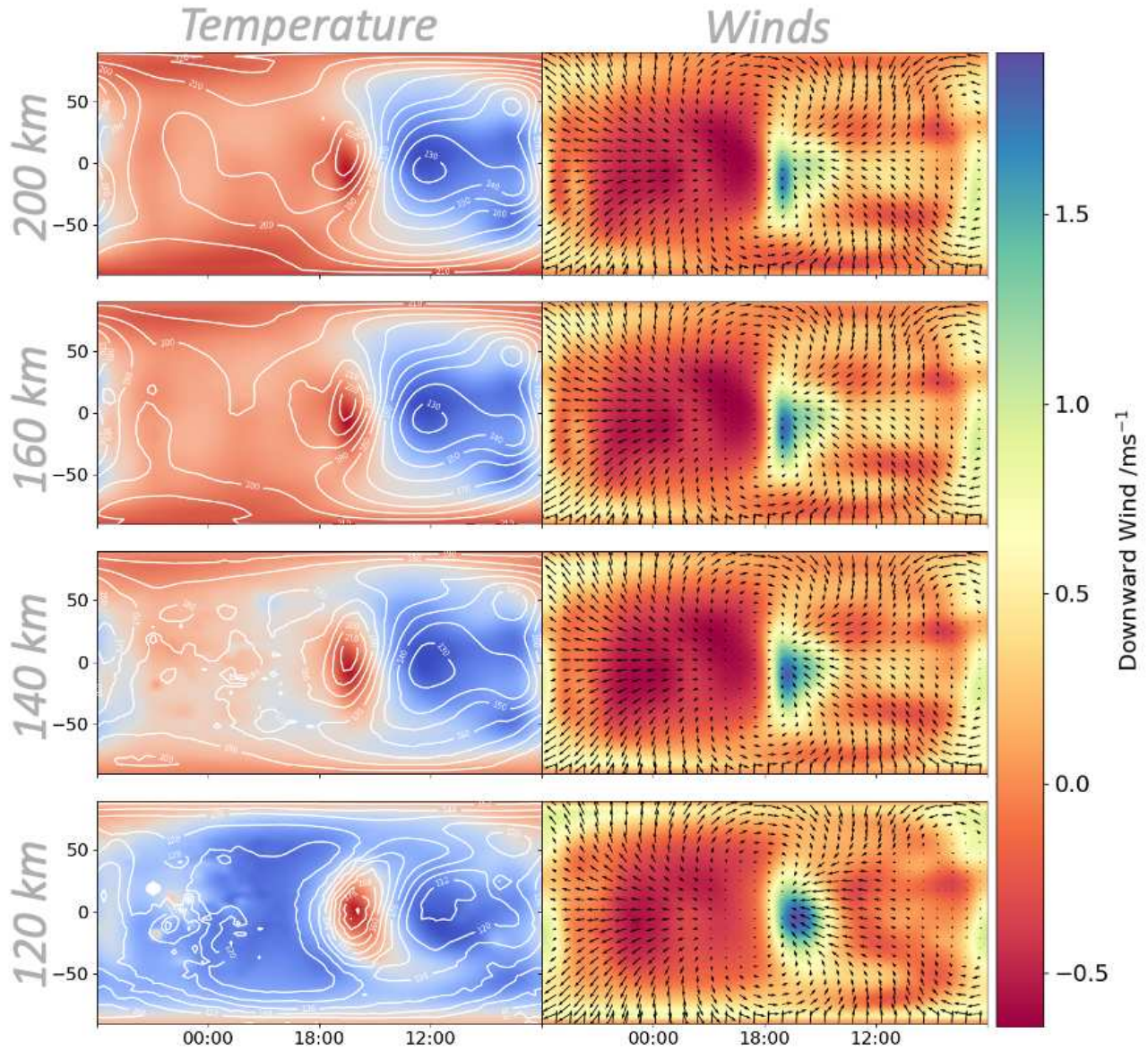


Figure 5.4: Mars Climate Database simulation results of the global thermospheric temperatures and wind at altitudes 120-200 km. Local times seem to be in reverse order, this is to match latitude with local times and to account for the direction of rotation of Mars. The dusk terminator is leading up to 18:00, and can be seen by the downwelling in the wind map and the warmer region in the temperature map.

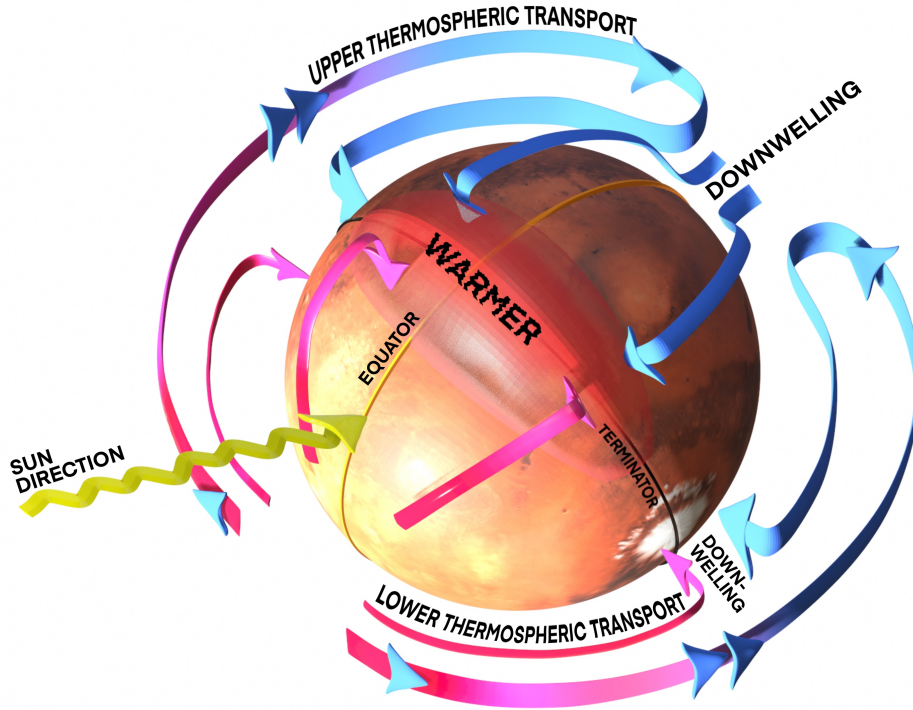


Figure 5.5: A cartoon showing the cause of the increasing temperature as the Solar Zenith Angle increases near the equator. This is due to high altitude trans-polar winds causing divergent nightside winds around 120 km. The subsolar point is intentionally 50° of the divergent region, to account for the time required for solar heating.

5.4 Summary

This chapter examined the forces influencing the Martian ionosphere, utilising data obtained from mutual RO techniques. It explores three main areas: the effect of SZA, solar distance, and solar activity on electron density and ionospheric layer altitudes; the relationship between these factors and thermospheric neutral temperatures; and how empirical fits and previous models compare with new findings.

The chapter began by examining how electron densities and the altitudes of the M1 and M2 ionospheric layers vary with SZA. The gathered data includes measurements below 45° SZA, allowing for insights unattainable with conventional RO methods. It is found that the M2 electron density aligns well with models, following the trend

$N_{M2} = 1.6 \times 10^{11} \cos(\text{SZA})^{-0.25} + 4.3 \times 10^8 F_{10.7}$. The results update previous assumptions by showing the M1 layer persisting unexpectedly during midday. Moreover, the chapter explores how these densities adjust based on long-term solar parameters, like heliocentric distance and solar irradiance.

A comparison with previous models shows how mutual RO data both aligns with and diverges from historical analyses. Differences in outcomes, particularly in flatter cosine coefficients related to densities and altitude trends across various SZAs, emphasise the unique contributions of mutual RO data.

The final section discussed thermospheric neutral temperatures. Contrary to conventional expectations, results reveal an unexpected rise in thermospheric temperature with increasing SZA, challenging the premise that greater SZA results in diminished insolation and lead to lower temperatures. I then employed MCD simulations to validate these findings, showcasing complex wind systems and temperature profiles. This offers a hypothesis that diverging winds from the night side, driven by high-altitude temperature gradients and converging at dusk, result in thermospheric warming due to adiabatic processes.

5.5 Addressed Hypotheses

Now that I have introduced novel scientific content, let's see which of the original hypotheses have been addressed.

1. **Subsolar ionospheric maximum following a $\cos\text{SZA}^{-0.5}$ trend Partially supported.** The M2 density does increase toward lower SZA, but the empirical fit of $\cos(\text{SZA})^{0.25}$ is shallower than the expected $\cos\text{SZA}^{-0.5}$ relationship. This suggests lower-than-expected peak densities at very low SZA .
2. **M1 layer absent at low SZA due to M2 absorption Disproven.** Mutual RO conclusively shows that the M1 layer persists even near local noon, directly overturning

earlier assumptions. This was not previously observable with conventional RO or radar sounders .

3. Altitude rises with slant angle

Supported for M2, inconclusive for M1. M2 altitude increases with SZA as expected. M1 altitudes, however, show large variability with no consistent trend, indicating that M1 formation is less controlled by solar geometry.

4. Thermospheric temperature peaks after midday due to thermal inertia

Disproven. Temperature increase with SZA, reaching a maximum at the terminator, modelling shows this is due to convergence-driven downwelling and adiabatic heating, not solely thermal inertia .

5. Scale height decreases with SZA due to cooling

Disproven. Surprisingly, thermospheric temperatures increase with SZA. This implies a larger or stable scale height at higher SZA, contrary to conventional expectations. Again, this is due to atmospheric circulation.

6. Crustal field effects negligible at low SZA

Not explicitly tested. However, the low-SZA observations showed smooth profiles without obvious crustal-induced structure, consistent with reduced magnetic influence during high photoionisation.

Chapter 6

Ionospheric Response to Solar Weather Events

At the time of thesis submission, the work presented in this chapter is in 2nd Review:

Parrott, J., Sánchez-Cano, B., Svedhem, H., Witasse, O., Müller-Wodarg, I., Meggi, D.
Martian Ionospheric Response during the May 2024 Solar Superstorm. Nature
Communications

6.1 Introduction

This chapter investigates the impact of the solar superstorm from early May 2024, from an intense period of geomagnetic storms not surpassed since March 1989, on the Martian ionosphere, with a specific focus on the enhancement of the M1 layer. Utilising mutual RO experiments conducted between MEX and the TGO, I captured a vertical electron density profile during a period of intense solar activity. This measurement reveals significant enhancements in the M1 layer, likely driven by increased soft X-ray flux associated with solar flares during the solar storm.

The following chapter leverages three critical aspects of the mutual RO experiments: their

cadence, their ability to probe regions with low solar SZA, and their capability to provide a complete ionospheric structure through the entire vertical electron density profile.

6.2 Origins and Typical effects of Coronal Mass Ejections, Solar Energetic Particles and Flares

Our sun is a middle-age main-sequence G2-type star that has varied its output enormously over its 4.6 billion year life (Nandy et al., 2023). Its energy source is the nuclear fusion of hydrogen and helium which drives the convective flow of plasma to its surface. This quasi-neutral proton/electron flow, in turn, produces large scale magnetic field structures that coil and twist dynamically. This magnetohydrodynamic (MHD) dynamo mechanism is what drives the sun's varying output and leads to solar weather events such as Coronal Mass Ejections (CMEs), Solar Energetic Particles (SEPs) and Flares.

These events are episodic or singular in nature, but can be analysed together to track the general activity level of the sun, which is known to be on a quasi-periodic cycle of 11-years (Schwabe, 1844). At the time of writing this thesis, we are at solar maximum; a period characterised by increased frequency and intensity of solar weather events. The simple explanation for this periodic trend is due to the internal magnetic field 'coiling-up' as the zonal transport of plasma at the solar equator is faster than that of the poles, this differential rotation leads to the magnetic field lines trailing behind as we move poleward and induce a toroidal component in a remarkably thin layer called the tachocline (Nandy et al., 2023), a process which Parker, 1955 called the mean-field α -effect. The coil becomes tighter throughout the 11-year cycle until solar maximum where magnetic tension is released via reconnection. These reconnection events can cause plasma to be violently ejected from the sun's surface in the form of a coronal mass ejection. This high energy event is often accompanied by solar flares and SEPs. The general term for this magnetic structure mechanism is the Babcock-Leighton dynamo cycle (Babcock, 1961).

The Sun's activity is more complex than an ever-repeating 11-year cycle. Originally, we tracked the solar cycle by counting sunspots. Since sunspot records began in the 17th century, we have noticed that not all solar maxima and minima are created equal. For example, the least active our star has been is in a period called the Maunder minimum between 1645-1715 (Hoyt & Schatten, 1998). Going back even further, Usoskin, 2017 used the presence of cosmogenic nucleotides in tree rings and ice cores to gauge the sun's activity over millennia. This was possible because the Earth is constantly barraged by atomic nucleotides such as ^{14}C and ^{10}Be , in the form of Galactic Cosmic Rays from sources outside our solar system. Periods of heightened solar activity are accompanied by more intense solar wind flux from the centre of our solar system at the sun. Solar wind is essentially the Sun's outer atmosphere escaping as a stream of plasma into the solar system and carrying the sun's B-field. This carrying happens because the solar wind is highly conductive so the plasma can extend the B-field from the corona out into space. The solar wind reduces the quantity of cosmogenic nucleotides coming to earth and being assimilated into organic matter or deposited into ice cores. In effect, the concentration of these nucleotides is inversely proportional to solar activity. They used these measurements to identify millennial-scale 'Eddy cycles' of 1000-1200 years and approximately 2400-year Hallstatt cycles.

As previously mentioned, sunspots serve as indicators of solar activity. The question is, how exactly do they function in this role? Sunspots appear darker than the rest of the Sun's disk because they are cooler. This cooling occurs as stray magnetic field structures, known as flux tubes, form within the Sun's convective zones and extend outward through the visible photosphere. These flux tubes impede the outward transport of plasma, resulting in localised cooling. Often, sunspots cluster together in active regions; yet, the flux tubes within these regions can possess different polarities. If they draw sufficiently close to one another, magnetic tension can be rapidly converted into kinetic energy through the process of magnetic reconnection.

The focus of this chapter is the impact of solar weather events from May 2024, associated with the same source that caused the Gannon superstorm on Earth, which is the largest geomagnetic storm since March 1989 (Thampi et al., 2025). Due to the noticeable effects on

our planet, extensive research has been carried out to identify the precise cause. The origin was traced to active region 13664, depicted in Figure 6.1. This figure illustrates the merging of three flux tubes, with areas R1 and R2 having an opposite polarity to R3, eventually separating into smaller regions where the rate of polarity inversion increases. This rising complexity in the photosphere generates intense shearing motions and strong polarity inversion lines, likely originating from the same sub-photospheric magnetic structure (Kontogiannis, I., 2024). These active regions reflect the polarity of the magnetic field at the Sun's photosphere. This measuring technique exploits the Zeeman effect in that some spectral lines will split in the presence of a magnetic field, in this case the spectral line is Fe I 6173 Å.

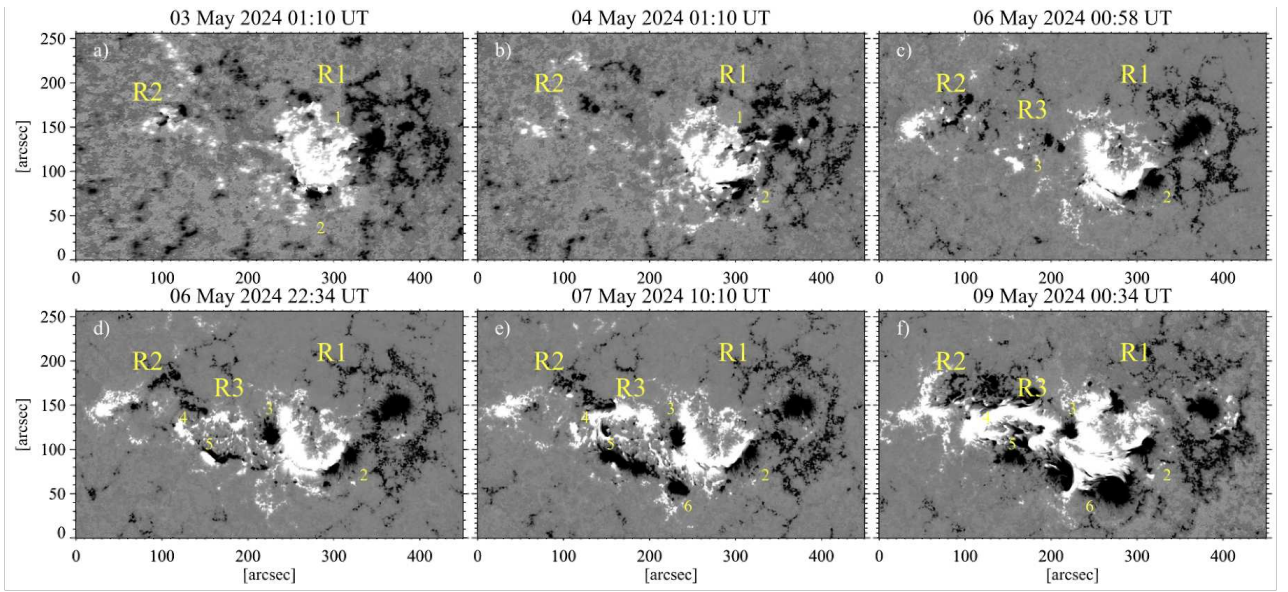


Figure 6.1: The progression of complexity in active region 13664 between 03/05/24 - 09/05/24 shown as photospheric magnetograms from the Helioseismic and Magnetic Imager on the Solar Dynamics Observatory. This shows a 6 day process where two active regions (R1 and R2) merge to produce a highly complex area consisting of three distinct regions of opposite polarity (R1, R2 & R3). Taken from (Kontogiannis, I., 2024).

In essence, Figure 6.1 can be used to show that active region 13664 contained a dense complex of many regions of opposing polarity. This maximised the magnetic tensions and triggered reconnections, leading to the excess energy in the forms of current and magnetic helicity to be converted to electromagnetic energy (solar flare) and kinetic energy (CMEs). Both these releases of energy can accelerate SEPs (mostly protons with some He and trace amounts of heavier elements such as O and Fe) to near relativistic speeds (Nandy et al., 2023). As all three space weather events are related, the intensity of all three tend to

correlate. This means a highly intense solar flare may be accompanied by a large CME.

Space weather significantly affects the ionosphere, which is the focus of this chapter. SEPs are known to produce electron density enhancements at lower altitudes, particularly between 60-90 km, and can even cause radar blackouts (Lester et al., 2022, Sánchez-Cano et al., 2019). CMEs can compress the ionosphere, resulting in a decrease in its altitude and an increase in its peak electron density (Mendillo et al., 2006). Solar flares also have a substantial impact by increasing photoionisation, which leads to higher peak electron densities. However, the extent of this effect is frequency-dependent, varying based on the specific wavelengths enhanced during the flare event (Mahajan et al., 2009).

6.3 The Event

The same May 2024 solar storm led to the event named the Gannon geomagnetic storm at Earth and was the most intense geomagnetic event since March 1989 (Boteler & D., 2019). With the former measuring -412 nT on the Disturbance Storm Time (Dst) index, and the later measuring -589 nT. Notably, it captured public attention as auroras were visible at remarkably low latitudes, including London, UK and even the Canary Islands. Occurring in early May 2024, the storm was marked by a series of solar flares, SEPs and CMEs. Among these, three solar events are of particular significance to the mutual RO measurement on May 15, 2024.

The first event of interest was an X_3 -class solar flare that erupted from [90°W, 20°S] solar coordinates, as observed by the X-ray imager on Solar Dynamic Observatory (Pesnell et al., 2012). Separately, the GOES-15 EXIS instrument (Pizzo et al., 2005) measured the same flare to have an intensity of $3.4 \times 10^{-4} \text{ mWm}^{-2}$ at Earth. It is important to note that this increased X-ray flux does not necessarily represent the same level of flux in the longer wavelength soft X-ray band. As depicted in the CME simulation in Figure 6.3, Mars was positioned at a solar longitude of 105°W when the flare occurred, which is remarkably close to the 90°W origin of the flare. These two measurements fed into a Wang-Sheeley-Argé simulation by NASA's

Moon-to-Mars (M2M) Space Weather Analysis Office which predicted the X_3 -class flare to begin on 15th of May at 08:18 UT, reaching peak intensity at 08:37 UT. Accounting for light-travel time, the Martian environment experienced the flare starting at 08:29:30 UT, with peak intensity occurring at 08:48:30 UT. At the same moment, the Extreme Ultraviolet Monitor (EUVM) instrument on the MAVEN spacecraft (Eparvier et al., 2015) recorded a significant increase in irradiance across multiple wavelengths. Figure 6.2 shows the power across two diodes in the instrument, including soft X-ray (0-7 nm), EUV (17-22 nm), and Lyman- α (121-122 nm). The results show a three-fold increase in soft X-ray at our target time of 08:48 UTC. I have chosen to show the entire day of 15/04/24 to highlight a discrepancy seen at 21:25 UTC. This shows that solar flares do not increase the irradiance linearly across the entire spectrum. Depending on the particulars of the flare origination, the power might increase more in the X-ray or the EUV, or even outside of these target bands.

SEPs are often correlated with the magnitude and direction of solar flares, particularly when there is a sharp increase in soft X-ray flux (Trottet et al., 2015). It can be inferred that a substantial burst of protons was emitted from the flare's location and propagated radially outward, accelerating along the IMF, depicted in zebra-stripe in Figure 6.3. The speed of SEPs can vary significantly (Mottl et al., 2001), ranging from relativistic speeds with energies of 1 MeV to 11 GeV. Using Equation 6.1, these energies correspond to velocities of approximately 1.4×10^4 to 2.87×10^5 kms $^{-1}$, or 4.6% to 96% of the speed of light, respectively. Given Mars' position at 1.38 AU, or approximately 2.067×10^8 km from the Sun, the travel time for SEPs would range from nearly 3 hours to just under 12 minutes. If SEPs are indeed closely correlated with X-ray flares, then the aforementioned X_3 -class flare is a strong candidate for the short-term ionospheric response observed. For responses over longer timescales (as predicted by Thampi et al., 2018), such as several hours to a day, the intense X_8 flare that occurred at 16:46 UT on the previous day is another likely candidate. The GOES-P satellite (Lemen et al., 2004) measured an X-ray irradiance of 8.7 mWm $^{-2}$ near Earth for this flare, which would likely have been associated with a significant SEP event. This SEP event could have left residual ionisation in the upper atmosphere, despite occurring 16 hours before the X_3 -flare.

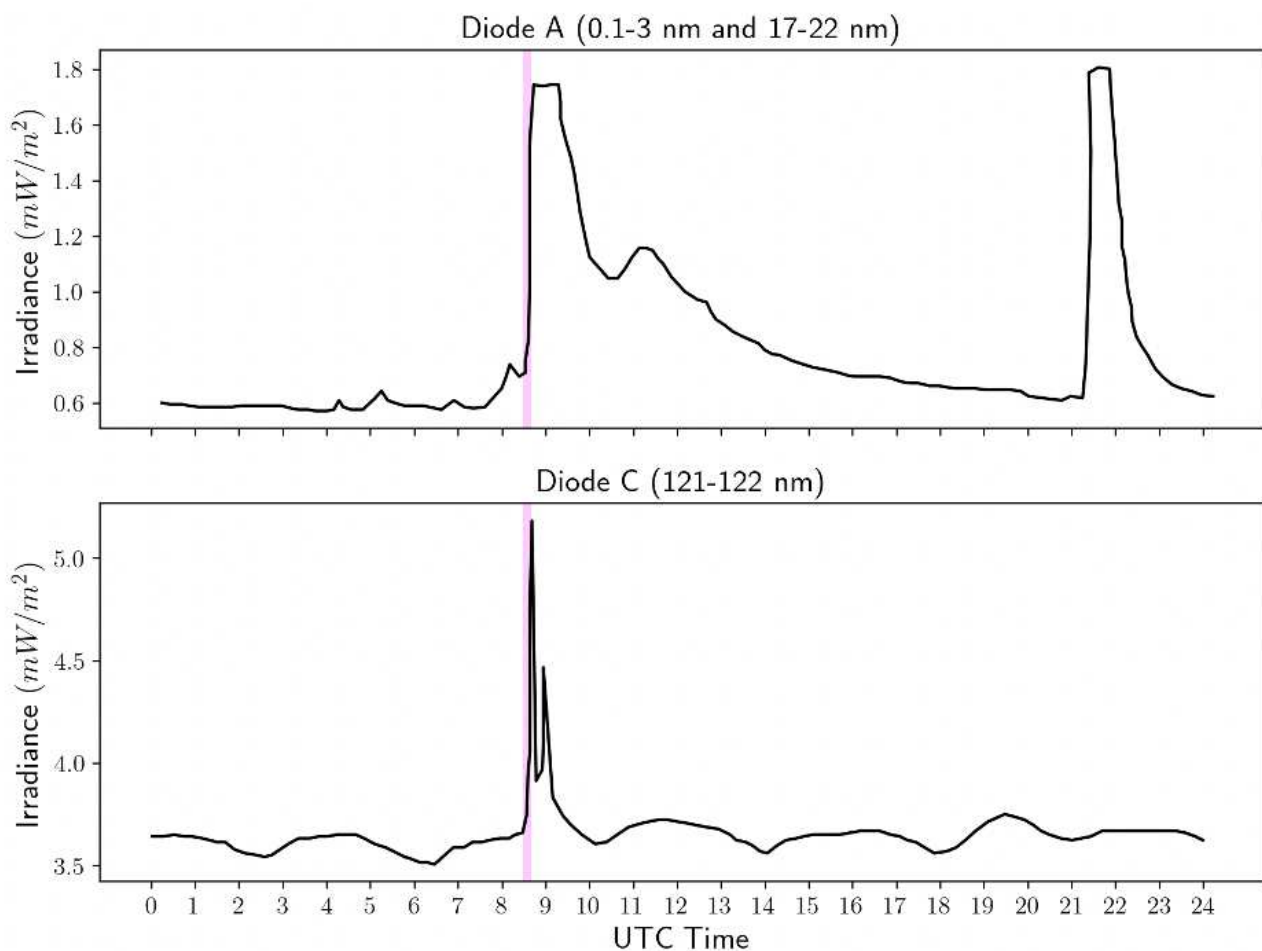


Figure 6.2: Irradiance levels recorded at Mars by the EUVM instrument onboard MAVEN for 15/05/24. The top panel is for soft X-ray which shows a three-fold increase at 08:48 UTC and a second stronger peak (albeit, shorter timescale) at 21:25 UTC. The bottom panel is the Lyman- α emission line and is a proxy for the EUV band and shows another peak at 08:48 UTC. The Magenta line indicates the mutual RO observation time. Data available at https://lasp.colorado.edu/maven/sdc/public/data/sci/euv/swx/daily-plots/2024/05/mvn_euv_20240515_0000.png

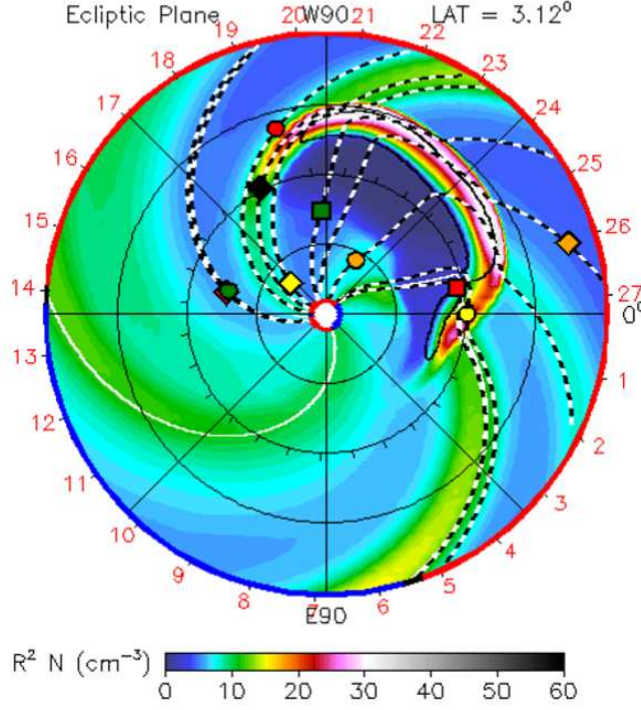


Figure 6.3: A simulation in the solar polar coordinate reference frame by the M2M office for the hour that the coronal mass ejection impacted Mars. Interplanetary magnetic field shown in zebra lines, colours correspond to particle density, circle markers indicated planets and square markers represent solar monitoring spacecraft. Specifically, the red circle found at 105°W is Mars, and the left flank of the semi-halo CME can be seen grazing the it. Simulation can be found at: <https://kauai.ccmc.gsfc.nasa.gov/DONKI/view/WSA-ENLIL/30726/1>

$$E = \left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right) m_p c^2 \quad (6.1)$$

The third event was a CME, which is shown in Figure 6.3 and Figure 6.4. According to the M2M office, this occurred at solar coordinates of [51°W, 5°N] on 11th of May at 03:12 UT. It had a broad beam width of 51° and hit Mars three days later on 14th of May at 06:18 UT, where it continued to disturb the space weather environment for 42±8 hours.

To summarise the timescales, it is estimated that the Martian ionosphere could have been affected by three solar phenomena. A CME, SEPs and a flare; these occurred 26 hours, 16 hours and at the same time as the RO measurement, respectively.

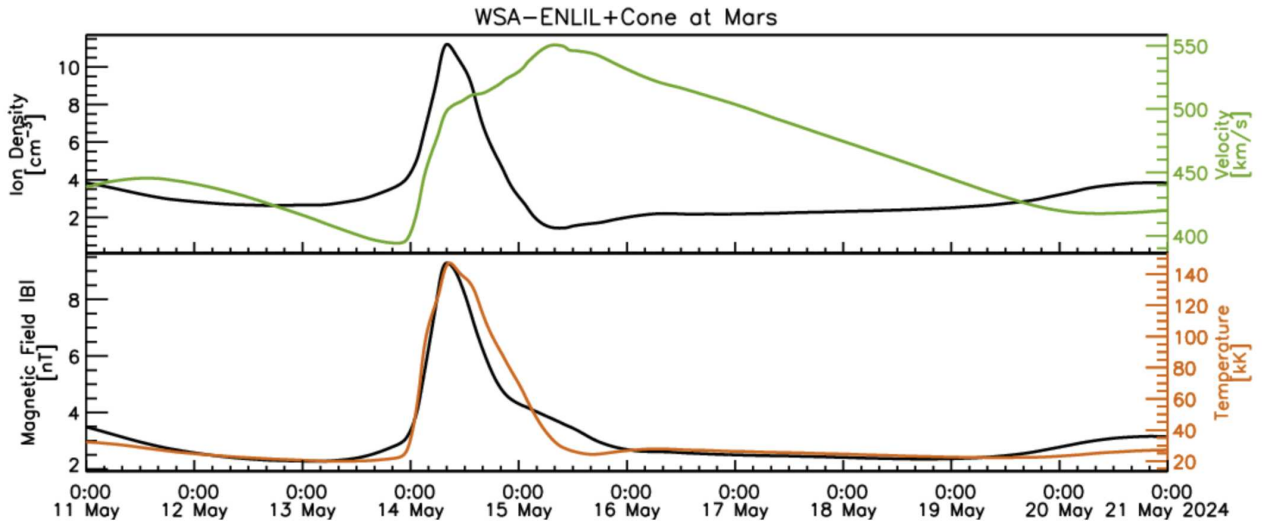


Figure 6.4: A simulation of disturbance at Mars by the M2M office, showing the ion density, velocity and magnetic field strength and temperature of the coronal mass ejection during an 10 day period between 11/05/24 and 21/05/24. Simulation can be found at: <https://kauai.ccmc.gsfc.nasa.gov/DONKI/view/WSA-ENLIL/30726/1>

6.4 The Effect on the Ionosphere

On 15 May 2024, at 08:37:11 UT, an egress mutual RO occurred between the MEX and the TGO. The spacecraft crossed the horizon and came into view of one another 45 seconds later, at 08:37:56. This event took place at coordinates $[-69.6^\circ\text{W}, 9.8^\circ\text{N}]$ over Sisyphi Planum, at a local time of 08:39, with a SZA of 53° . With a solar longitude of 255° , the observation was conducted in the middle of the northern hemisphere winter.

This measurement coincided with the solar flare’s intensity rising toward its peak, accompanied by an associated increase in SEP flux. Additionally, it can be seen in Figure 6.4 that the disturbance from the CME was approximately 60% complete, characterized by an ion density of 2 cm^{-3} and a maximum velocity of 550 km s^{-1} .

The electron density profile measured during this event is presented in Figure 6.5 (black thick line) alongside 12 other profiles obtained with mutual ROs. These profiles were selected on the basis of their similar SZA values, within $\pm 5^\circ$ of the 53° target profile. This selection was made regardless of solar distance and solar activity, which are the next biggest factors after SZA. These two elements were not considered in the selection due to the relatively small

quantity of mutual RO measurements available at the time of writing.

Notably, four key deviations from the average of the 12 other profiles are observed. First, the M1 layer peak density was enhanced by 278%, while the M2 layer exhibited a more modest growth of 45%. The altitude of both layers increased by 6.5 km which was found by calculating the derivative of the profile and then finding the minimum gradient around the key altitudes of 50-140 km. Additionally, a distinct layer with a density of $9.6 \times 10^9 \text{ cm}^{-3}$ was detected at 245 km.

There are also three notable aspects where changes were not observed. First, there was no significant compression of the topside of the M2 ionospheric layer, with the average topside electron density scale height (H_e) being 12.2 km, and the measurement during the solar storm yielding $H_e = 11.9$ km. This value for H was ascertained via a parametric fit of the α -Chapman model. Second, no major structural changes were detected in the lower neutral atmosphere below 100 km. Finally, the separation between the M1 and M2 layers increased by only 1 km, a change that is not considered significant.

The residuum for this key measurement can be found in Figure 6.6. Which shows the size of the uncertainty at this earlier stage of the processing chain. This has been calculated via the same method outlined in the previous chapter. This involves the addition of a 5% magnitude noise being added to an earlier stage of the processing chain, when the Doppler shift due to the relative motion of the spacecraft still dominates the signal. Figure 6.6 shows that the uncertainty grows around the M1 and M2 ionospheric features between 160 and 340 s. This is because a step in the processing chain involves a model fit to the oscillator drift during the vacuum portion of the signal (here, this is after 360 s), meaning the uncertainty is mostly removed for this section. A similar thing happens for a point just under the M1 layer, where the net refractivity between the neutral atmosphere and the ionosphere balances.

The observations during the May event can be put further into context by plotting the M1 and M2 peak electron densities obtained between 2021 and 2024 as a function of their SZA, as shown in Figure 6.7. This shows that the solar storm has cause an outlier in the peak density of the M1 layer and has violated the typical cosine trend seen in densities across the Martian

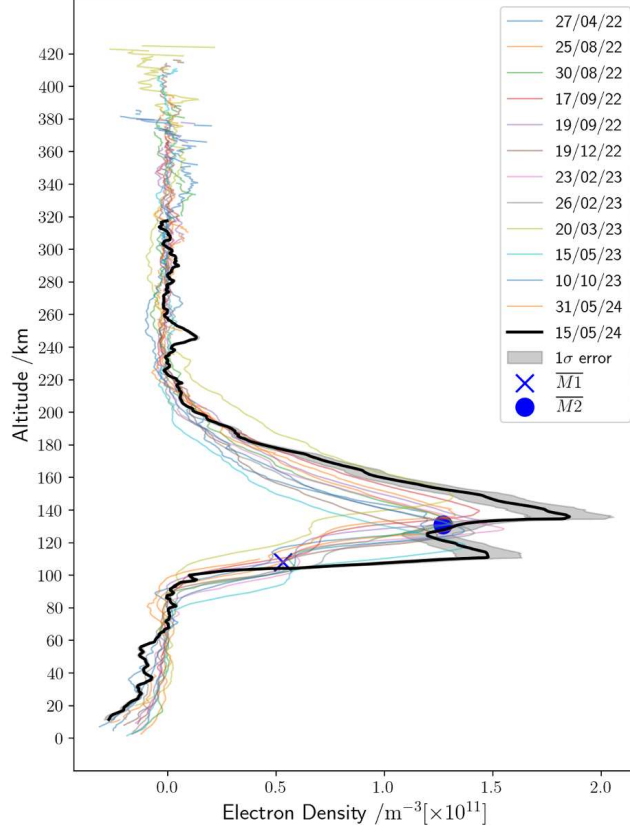


Figure 6.5: Vertical electron density profile obtains on 15/05/24 (black). 13 other profiles have been included to show that it exhibits similar morphology to other profiles from measurements with comparable SZA values (48° - 58°) . For clarity, the blue markers show the mean density and altitude values for the M1 (cross) and M2 (circle) ionospheric layers, which are $[5.32 \times 10^{10}, 108]$ and $[1.27 \times 10^{11}, 131]$, respectively.

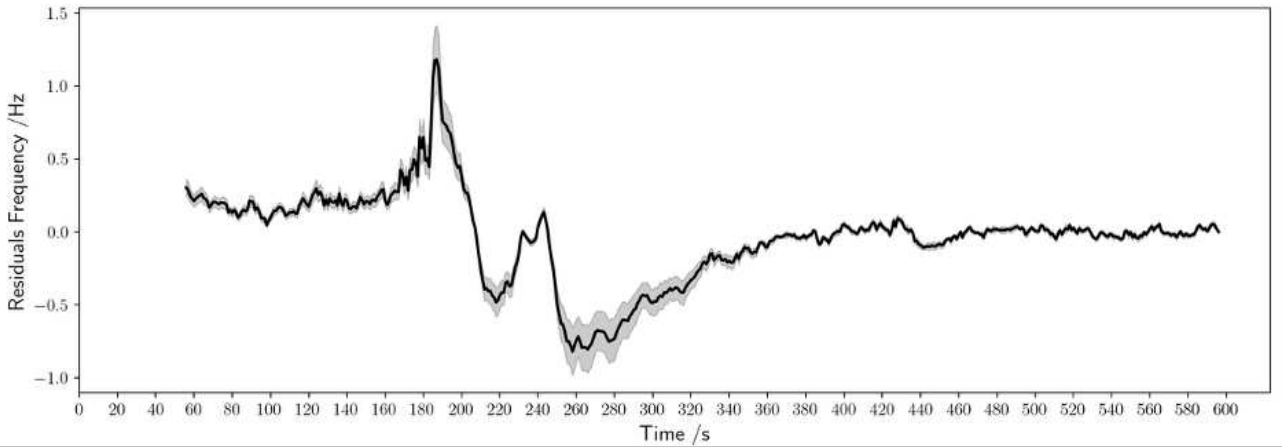


Figure 6.6: The residuum for the profile from 15/05/24. This is the residual frequency shift that is produced as the UHF radio link passes through the Martian ionosphere and atmosphere. The grey envelope is a 1σ uncertainty.

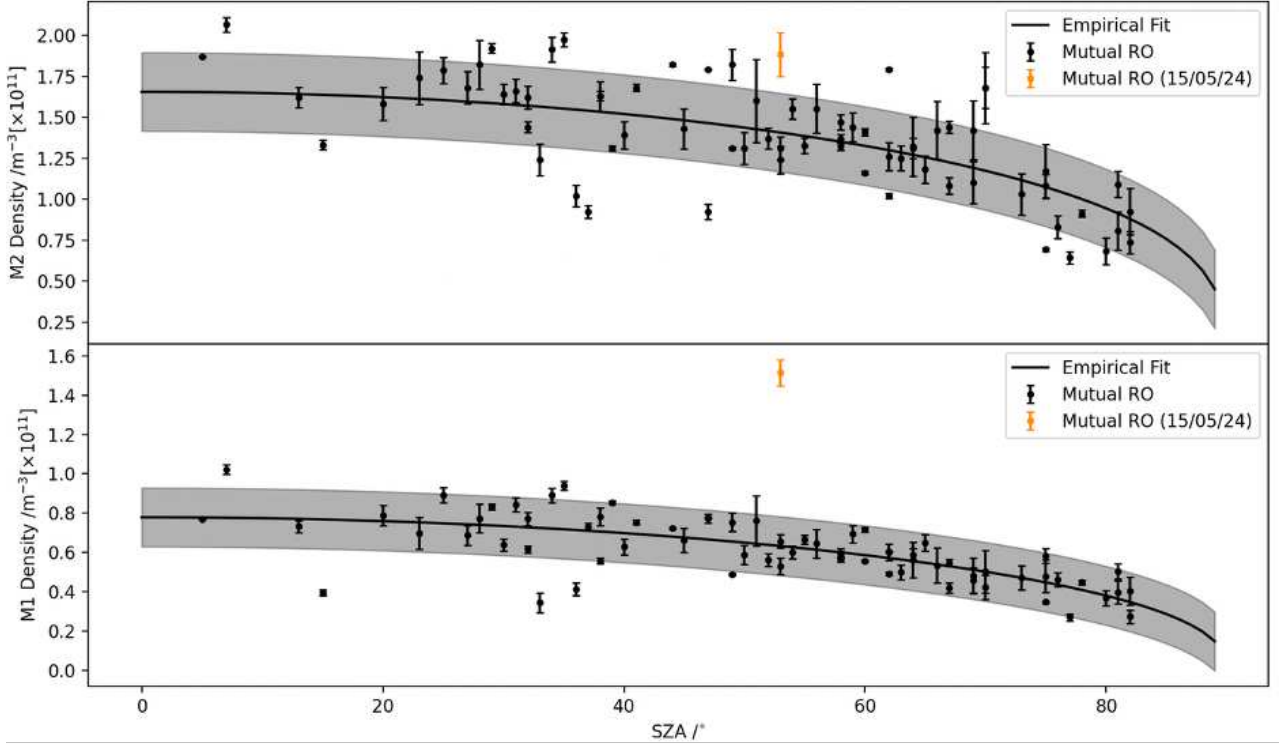


Figure 6.7: The trend of the change in peak electron density for the the M2 (top panel) and M1 (bottom panel) against solar zenith angle from the period of this mutual RO campaign (02/04/21- 17/06/24). The M2 trend is $1.6 \times 10^{11} \cos(\text{SZA})^{-0.25}$ and the grey error bar is 1σ at 2.4×10^{10} . M1 1σ fitting is 1.5×10^{10} around a $7.3 \times 10^{10} \cos(\text{SZA})^{-0.34}$ trend. The densities from the measurement on the 15/05/24 are shown as an orange cross, showing that effect of the solar storm was far greater on the M1 layer.

day as predicted with Chapman theory. However, the M2 layer's increase still fits into the typical spread caused by changes in solar distance, solar activity and other factors.

The empirical fit shown in this figure are further explained in the previous chapter. Briefly, the trend shown in the top M2 panel is $1.6 \times 10^{11} \cos(\text{SZA})^{-0.25}$, where 1σ is 2.4×10^{10} around the trend. The lower M1 panel shows 1σ fitting 1.5×10^{10} around a $7.3 \times 10^{10} \cos(\text{SZA})^{-0.34}$ trend, with both trends having units of m^{-3} . The notable part in this figure is the remarkably high M1 data point for the 15/04/24 measurement, showing it to be significantly higher than all recorded M1 measurements.

6.5 Discussion

The enhancement of the M1 ionospheric layer stands out as the primary finding from this measurement. But how does this enhancement occur? As discussed in Section 1.0.1, the

formation of the M1 layer is predominantly driven by photoionisation via high-energy soft X-ray photons. Lollo et al., 2012 demonstrated that under the typical pressure and chemical conditions at this altitude, the recombination timescale is approximately 10 minutes. Thus, we should expect the magnitude of the peak density to be directly influenced by the contemporary flux.

Previous analyses of the Martian ionospheric response to a large solar flare, such as the work by Mendillo et al., 2006 using data from the MGS radio science instrument from 20 near the nightside at a SZA of 72° . They measured a 100% M1 enhancement, which suggested that if the M1 layer is in photochemical equilibrium, the increase in flux should be proportional to the square of the M1 enhancement, i.e., $\frac{F_f}{F_0} = \left(\frac{N_f}{N_0}\right)^2$, where F_f is the flux during the flare and F_0 is the nominal flux. Therefore, an enhancement of 2.78 times would imply a 7.72-fold increase in soft X-ray flux. However, this is currently not supported by data from the GOES-15 spacecraft, which recorded a peak hard X-ray flare intensity of $3.4 \times 10^{-4} \text{ W m}^{-3}$ at Earth, and when scaled to 1.38 AU, this value becomes $1.7 \times 10^{-4} \text{ W m}^{-3}$. This measurement aligns closely with the data from MAVEN's EUV instrument, which indicated a threefold increase in soft X-rays, also to $1.7 \times 10^{-4} \text{ W m}^{-3}$, as shown in Figure 6.2. This suggests that the relationship proposed by Mendillo et al., 2006 may not be applicable in this case.

Not all solar flares are identical; Mendillo et al., 2006 analysed the effects of an enormous X_{11} -class flare, in which much of the solar spectrum was too "hard," or too energetic, to cause ionospheric enhancement. This was further complicated by the lack of solar observatories and solar flux measurements at Mars at that time. In contrast, the flare discussed in this chapters appears to have closely correlated hard X-ray and soft X-ray irradiance, resulting in an M1 density increase that follows the soft X-ray flux, which in turn correlates with the hard X-rays. Thus, the relationship can be better described as $\frac{F_f}{F_0} = \left(\frac{N_f}{N_0}\right)$.

So what would cause the flare to contribute more to the electron density than expected? We propose that the contribution of secondary ionisations to the ionosphere have been underestimated. As the spectrum becomes more 'hard' during a solar flare, the kinetic energy of the photoelectrons increases. Thus, leading to a larger cascade in secondary ionisations as

said photoelectrons thermalise. At photochemical equilibrium, the rate of production equals the rate of recombination. I.e.:

$$F\sigma\eta N_n = \alpha N_e^2$$

Where F is photon flux, σ is the absorption cross-section, η is the ion-electron pair per photon, N_n is the neutral CO_2 density, α is the dissociative recombination rate of O_2^+ . The absorption cross-section for photoionisation will reduce exponentially with increasing photon energy. Without a direct measurement of the amount of spectrum hardening, we cannot calculate the increase in secondary ionisations. Instead, if we assume that σ remained constant throughout the flare event, we can infer that η increased *at a minimum* of 2.58 times. A larger cascade of photoelectrons is the only explanation for this.

Because the M2 layer is produced via the photoionisation of lower energy EUV photons, the secondaries are less of a factor. This explains the smaller enhancement observed in the M2 layer. This difference has been predicted in previous models as a flare is known to increase the soft X-ray band considerably more than EUV. As depicted in Figure 6.5, this layer increased by a factor of 1.45. This corresponds well with the MAVEN EUVM measurements shown in Figure 1, where the EUV flux near the Lyman- α line (121-122 nm) increased from 3.75 to 5.23 mWm^{-2} , representing a 1.39-fold increase. This disparity between the effects on the M1 and M2 is clear evidence that the changes seen in the M1 are mostly due to the solar flare.

The aforementioned SEPs can be seen to have a negligible effect on the ionospheres structure. As the higher energy particles are known to ionise at much deeper altitudes when the neutral density is sufficiently high enough, typically under 100 km.

The solar storm also appears to have caused significant heating in the neutral atmosphere, as evidenced by the average elevation increase of 6.5 km in both the M1 and M2 layers. This heating is likely due to increased particle precipitation during the preceding days of CME disturbance. Thermal processes generally operate on much longer timescales than dissociative recombination, supporting the findings of Thampi et al., 2018, who observed significant

heating effects persisting up to five days after a CME. They also showed that heating in the lower atmosphere can elevate the altitude of the ionospheric layers (h_{M1} or h_{M2}) without significantly affecting their peak densities. This is similar to the heating effects observed during global dust storms, where increased IR absorption due to dust loading leads to atmospheric forcing (Withers et al., 2015).

Lastly, there is a noticeable ionospheric enhancement around 245 km, with several potential explanations for its formation. Wang and Nielsen, 2003 theoretically demonstrated that high-altitude ionospheric perturbations can result from a combination of Acoustic-Gravity Waves (AGWs) and Background-Gradient Waves (BGWs). AGWs are horizontally propagating waves that follow the compressions and rarefactions (acoustic) within any stratified medium, such as the Martian neutral atmosphere. These waves are influenced by gravitational and buoyancy forces, which induce net motion in the embedded plasma, leading to horizontal gradients in plasma density. BGWs, formed through these plasma gradients, are further amplified by increased solar pressure. The two wave modes can hybridise, propagating both horizontally and vertically, and producing plasma density perturbations at higher altitudes. A separate study by Yiğit et al., 2015 suggests that gravity waves alone can reach altitudes of 250 km, further supporting this theory. An alternative explanation, proposed by Gurnett et al., 2010, suggests that this layer could be attributed to the Kelvin-Helmholtz instability at the ionopause. During the mutual RO measurement, the tangent point's path may have traversed the crest and trough of a wave caused by this instability. The size of these waves would be amplified by the increased solar wind velocity observed in Figure 6.4. With an average solar wind incidence angle of approximately 53° on the ionopause, the majority of the velocity vector would act in the shear direction, further enhancing the instability. Although such waves do not typically form at this altitude, the heightened solar wind pressure may have compressed the ionopause down to this region.

Another hypothesis for the origin of this layer relates to the dynamics of the Martian magnetic environment. Weber et al., 2019 found that during periods of increased solar pressure, the draped IMF penetrate deeper into the atmosphere, generating streams of ion outflow. This phenomenon is also observed with closed field lines rooted in the Martian crust.

The measurement in question occurred at coordinates $[-69.6^{\circ}\text{W}, 9.8^{\circ}\text{N}]$, with a local time around 8:00, placing it north-west of the large Meridian crustal field in the southern hemisphere. At this time, the solar pressure would have been pushing these field lines toward the measurement location. Therefore, it is plausible that the increased solar pressure induced an ion outflow along the open field lines at around 250 km, which could manifest as a high-altitude electron density perturbation.

6.6 Summary

This chapter provided an analysis of the Martian ionospheric response to a large solar storm, particularly focusing on the M1 layer, which is often under explored due to limitations in traditional measurement techniques. By leveraging the advanced capabilities of mutual RO experiments conducted between MEX and the TGO, we were able to capture low-SZA vertical electron density profiles with unprecedented cadence and resolution. These measurements offer new insights into the behaviour of the Martian ionosphere during periods of intense solar activity.

The results demonstrate a clear enhancement of the M1 layer, likely driven by increased soft X-ray flux associated with the solar flares during the superstorm. These findings challenge previous assumptions about the proportionality between X-ray flux and ionospheric density enhancements, suggesting that the relationship may vary depending on the characteristics of the solar event.

Furthermore, this chapter highlights the importance of considering high-altitude ionospheric perturbations, potentially linked to hybridised AGW-BGW waves, Kelvin-Helmholtz instabilities or the plasma flow along open magnetic fields, especially during periods of increased solar wind pressure. The presence of such features underscores the complex interplay between Martian atmospheric dynamics and external solar drivers.

6.7 Addressed Hypotheses

As I did in the previous chapter, I will highlight which of the initial hypothesis have now been addressed.

1. Crustal field effects negligible at low SZA

Revised. During the May 2024 solar storm, enhanced densities at 250 km were observed even at low SZA. This suggests that crustal field-aligned flows may modulate the ionosphere under extreme conditions, though their influence is usually masked during normal midday photoionisation .

2. Electron density increases quadratically with solar flare intensity

Disproven. The X_3 -class flare on 15/05/24 caused a 278% increase in electron density, corresponding to a near threefold increase in soft X-ray flux. This indicates a roughly *linear* response, not the quadratic scaling predicted by Chapman theory.

Chapter 7

Further Work & Conclusions

7.1 Conclusions

The ionosphere of Mars is an envelope of plasma that is mostly produced by the photoionisation of CO_2 . There are two main layers; the primary M2 layer, located at approximately 120–150 km is formed from EUV photons, and the secondary M1 layer, found at around 90–110 km, is generated by soft X-ray photons and their secondaries. Its peak density and layer altitude are mostly controlled by the angle of the sun, or SZA. Both layers exhibit the largest electron density and lowest altitude layer when SZA is 0° , or at the subsolar point. These parameters then change according to Chapman theory, whereby the electron density reduces with a cosine trend and the layer altitude remains mostly constant until just before the terminator, where it then increases logarithmically. Beyond the terminator, on the nightside of Mars, the ionosphere mostly dissipates. Here, it is only sustained by day-to-night transport and electron precipitation.

This thesis uses a novel radio science technique to collect large quantities of electron density profiles for all periods of the Martian day. This technique is called mutual radio occultation, and this thesis captures the details of the first time it has been done routinely for another planet, other than Earth. This is an improvement to conventional radio occultation because it can measure all local times and latitudes during a particular season. The coordinates and

local times of conventional RO are constricted by the spacecraft-mars-ground station geometry. Instead mutual RO uses a radio link between two spacecraft orbiting *the same planet*. Specifically, I used two ESA spacecraft called MEX and TGO.

This thesis goes into detail about the development of the processing chain, as I was solely responsible for its creation. After many iterations, the final method is as follows: 1)

Decapsulate the raw bitstream from TGO to acquire the waveform encoded in in-phase and quadrature format; 2) Perform a specific sliding-FFT to extract the frequency components; 3) Increase the spectral resolution by doing a Gaussian-fit to the carrier tone's spectral peak in each periodogram; 4) Remove the dominating Doppler shift by using simulated orbits in the SPICE ephemeride framework; 5) Remove the effects of the unstable local oscillators by carrying out a iterative minimisation (inclusive of an inverse Abelian inversion) to fix a known 50-60 km point in the refractivity profile; And 6) Convert refractivity to electron density with $N_e = n f_t^2 \div \frac{e^2}{8\pi^2 \epsilon_0 m_e}$.

The results for this new method have been shown and include 71 electron density profiles, including 34 whole vertical profiles from regions that would be inaccessible by conventional RO. A number of these profiles have been compared with other instruments, including the in-situ MAVEN Langmuir probe and two quasi-simultaneous measurements from MaRS. I have also compared the profiles against the leading ionospheric models such as NeMars, MIRI and the MCD.

I then use these results to investigate trends in the ionosphere throughout the day. This was especially significant for conclusions about the lower M1 ionospheric layer because the ubiquitous midday measurements from radar sounders cannot detect this layer. Finding that the inclusion of mutual RO data makes the electron density trend much flatter than we previously thought. Most previous authors would predict a $\sim \cos(SZA)^{0.5}$ trend, but the addition of mutual RO data made this approximate to $\sim \cos(SZA)^{0.25}$ for M2 and $\sim \cos(SZA)^{0.34}$ for the M1. Longer timescale trends were also investigated, such as heliophysical parameters like $F_{10.7}$ and heliocentric distance. These more gradual trends were subtle and were likely contained by the limited volume of data.

This new mutual RO data was also leveraged to investigate the trends in thermospheric temperature throughout the Martian day. This was done by fitting a Chapman profile to the topside of the M2 ionospheric layer. This was possible because the shape of this Chapman profile is dependant on neutral scale height, which in turn, is based on neutral temperature. This revealed a counterintuitive trend where the temperatures would increase with SZA. Meaning, as the sun became less direct, it would become warmer. This was explained using MCD simulations, which showed converging winds at the terminator, causing the air to sink adiabatically and increase in temperature.

The results of a fortuitous measurement from just 10 minutes after the arrival of a solar flare was then shown. This showed the largest M1 layer ever recorded at Mars. The precise origin of the solar flare (and accompanying CMEs) were explained, including the specifics of the originating solar active region. The numerous solar weather events were then explained, as well using solar observatory data to estimate which event was most likely to have caused the large M1 layer. I then used these results to update an assumption in previous literature that the M1 peak electron density correlates to the square of the X-ray intensity. However, I hypothesised that this conclusion was made from a solar flare with a different spectrum, which had less energy in the X-ray band. With a larger volume of modern solar observatory data, I updated this assumption to $\frac{F_f}{F_0} = \frac{N_f}{N_0}$.

7.1.1 Resolution of Hypotheses

Now that this PhD thesis has come to an end, the following shall address all the hypotheses that were raised at the end of Chapter 1.

1. Subsolar ionospheric maximum following a $\cos(\text{SZA})^{-0.5}$ trend

Partially supported. The M2 electron density does increase toward lower SZA, but the observed empirical fit from mutual RO data follows a shallower $\cos(\text{SZA})^{-0.25}$, not the expected $\cos(\text{SZA})^{-0.5}$. This implies that ion production under direct solar incidence is not as strong as classical Chapman theory predicts. The flattening may be due to

dynamic transport processes and thermal expansion. This result is presented in Section 5.2.

2. M1 layer absent at low SZA due to M2 absorption

Disproven. Contrary to past expectations, the M1 layer is clearly detected in mutual RO measurements down to $\text{SZA} = 5^\circ$, including during the quiet midday sector. This demonstrates that soft X-ray and secondary electron ionisation remains effective even when the overlying M2 layer is fully formed. This overturns earlier inferences from MARSIS and Earth-based models, which lacked sensitivity to the M1 region under high illumination. These findings are discussed in Section 5.2.

3. Altitude rises with slant angle

Supported for M2, inconclusive for M1. The M2 layer peak altitude rises steadily with SZA, consistent with a Chapman-like response to the increased optical path length of ionising radiation. However, the M1 layer peak shows no clear correlation with SZA; it varies from 100 to 120 km across all solar zenith angles. This suggests M1 morphology is governed more by local composition and particle energy deposition than simple solar angle. The analysis is presented in Section 5.2.

4. Thermospheric temperature peaks after midday due to thermal inertia

Disproven. The observed temperature profiles show an increase with SZA, reaching a maximum at or near the terminator—contrary to the assumption of simple radiative heating delayed by thermal inertia. Instead, modelling with the Mars Climate Database general circulation models shows the effect is due to convergence-driven downwelling and adiabatic heating. The interpretation is detailed in Section 5.3.2.

5. Scale height decreases with increasing SZA due to cooling

Disproven. Thermospheric temperatures, and hence neutral scale heights, are found to increase with SZA in mutual RO data. This is counterintuitive, as greater SZA typically means less insolation. The explanation lies in atmospheric circulation: wind-driven adiabatic heating at higher SZA offsets radiative losses. These findings are presented in Sections 5.3.1 and 5.3.2.

6. Crustal field effects negligible at low SZA

Revised. During quiet solar conditions, mutual RO profiles show little evidence of magnetic structuring at low SZA, supporting the idea that strong midday photoionisation masks crustal field effects. However, this assumption breaks down under extreme solar forcing: the May 2024 X-class flare produced an anomalous 250 km enhancement even at low SZA, which likely involved magnetic field-aligned plasma transport from crustal sources. This is discussed in Sections 6.4 and 6.5.

7. Electron density increases quadratically with solar flare intensity

Disproven. Classical Chapman scaling predicts electron density should scale with the square of solar EUV/X-ray flux. However, the response to the X_3 -class flare on 15 May 2024 was near-linear: a threefold increase in soft X-ray irradiance led to a 278% increase in electron density. This suggests that saturation effects, loss processes (e.g., recombination), or transport limitations moderate the ionospheric response under extreme input conditions. This behaviour is examined in Sections 6.3 through 6.5.

7.2 Further Work

The last electron density profile shown in this thesis was measured on 17/06/24, yet, as of the date of handing in this thesis (07/04/25), there have been 52 new measurements. As I have been the sole processor for this mutual RO mission since its inception, I am obliged by ESA to process these final datasets before I start my next employment. The outputs to this work will be identical to my previous contributions to ESA's Guest Storage Facility, which include each mutual RO measurements at six different points in the processing chain (https://www.cosmos.esa.int/web/psa/psa_gsf). I will also need to commit some time to writing documentation and training an ESA staff member to continue this data reduction.

Apart from this imminent work, I have devised several methods to improve MEX-TGO mutual RO during my 6 years of working on this project.

7.2.1 Increase the *quantity* of Profiles via Requirements Reduction and Eavesdropping

Improving the cadence of measurements to more than two per week will help further answer the questions raised in Section 1.5. A larger dataset of midday whole profiles will help us predict the ionospheric structure throughout the day and make for easier separation of other forcing effects such as heliocentric distance and solar activity. This will be achieved by reducing the requirements of each observation.

The file size of Electra data units requiring downlink can be minimized. During this MEX-TGO RO campaign the sampling rate was reduced from 128 kHz to 64 Hz and then to 32 Hz without impacting the quality of the final data products. Currently each file is 150 MB, and further reductions could be implemented. I would estimate that this data package size can be reduced to around 35 MB with a further four-fold reduction in sampling frequency.

To further reduce the operational requirements of each mutual RO, we could implement ‘Eavesdropping’ such that the transmitting spacecraft does not need to make a bespoke transmission for every observation, completely removing any need for commanding scheduling and drains on power and attitude budgets. Reducing the requirements will lead to a higher cadence. Current mutual RO operations require a dedicated 437.1 MHz tone transmission from MEX, occupying the MELACOM antenna and utilizing power budget. However, as demonstrated by Ao et al., 2015, this process can be accomplished using ‘eavesdropping,’ where a normal data relay is used to conduct RO, filtering out modulated data in the sidebands and only utilizing the carrier tone. Mutual RO can be conducted opportunistically by extracting the carrier tone from existing radio links on the Mars Relay Network. This task is more complex than applying a filter, as RO requires sub-Hz precision and modulated data can hinder this. Methods could include ‘sinc-fitting’; where a boxcar window frequency response is dynamically fit to every periodogram after the FFT. Or this could utilise multiple passes of a digital phase locked loop, as implemented in Gurvits, 2014 where they isolated the carrier tone from MEX MELACOM with the Arecibo observatory.

7.2.2 Improve the *quality* of the Profiles for Nighttime and Lower Neutral Atmosphere Measurements

Despite there being more than 10 observations beyond 100° SZA, the deep-night has not been analysed in this thesis. Currently the noise floor is too high, and the small (but interesting) ionospheric structures are too faint, which led to the deprioritising of night RO early in the campaign. As stated in Section 2.3.3, MEX-TGO RO uses a UHF frequency of 437.1 MHz, this frequency enhances sensitivity to the ionosphere more than X/S-band conventionally used in RO. So the night is observable, but currently difficult to separate from the noise. More work is also required to make the lower neutral atmosphere reliable. This issue is because of the unconstrained oscillator drift, which produces an accumulating error throughout the RO measurement. I account for this by making assumptions which invalidate the tropospheric readings. If one could model the expected drift of the local oscillator with the help of JPL Electra engineers, then one can extract neutral atmospheric parameters for all past and future mutual RO measurements.

7.2.3 Addition of a Third Spacecraft - MAVEN

The remaining stated problems in Section 1.5 can be addressed by the inclusion of a 3rd spacecraft. This would allow for more RO measurements, increasing the cadence and global coverage. More measurements could produce quasi-collocated profiles, offering calibration opportunities or insight into short timescale ionospheric variability. This will also lead to long-term synoptic monitoring of the Martian environment as this 3rd spacecraft uses the same Electra antenna as TGO. When MEX is decommissioned around 2032, then another spacecraft can fill its vacancy, ensuring continuous long-term monitoring with the same instrument. The participation of this 3rd spacecraft could have no operational overhead due to the aforementioned eavesdropping method. So it could be transmitting to the Mars Relay Network nominally and TGO could use these signals for mutual RO.

A useful comparison can be drawn with Earth's COSMIC-2 RO constellation, which

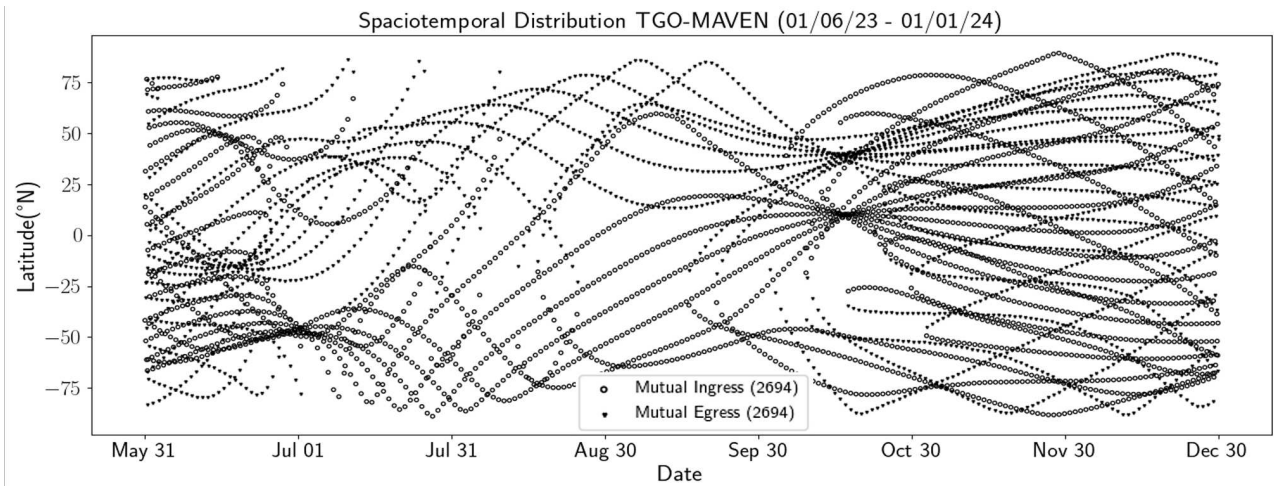


Figure 7.1: Distribution for MAVEN-TGO mutual RO produced from TGO and MAVEN SPICE kernels

comprises just six small satellites that utilise the radio links of approximately 32 GPS satellites and 24 GLONASS satellites. In 2023, COSMIC-2 produced 8 million vertical profiles. While this number is aspirational and not feasible for Mars in the near term, it provides a compelling illustration of the potential for a growing Martian satellite network to eventually support hundreds of measurements per day. MAVEN is equipped with the same Electra antenna as TGO, so it is a prime candidate for this expansion. This similarity allows lessons learned from the six-year operational experience of MEX-TGO RO to be readily applied to MAVEN. This is a significant opportunity for inter-agency collaboration, as NASA’s MRO has previously participated in the ESA mutual RO measurements on April 22, 2022. Moreover, MAVEN is projected to have sufficient fuel to remain operational for another decade, consuming only 5 kg of fuel annually with 50 kg still available. However, its mission is currently expected to continue only until 2031 due to ageing issues with other instruments. Incorporating MAVEN into the campaign does not necessarily require it to act as a receiver; it could serve as a transmitter to TGO, thus eliminating the need for a direct data downlink. This would increase the frequency of measurement opportunities. For example, during the time period of May to December 2023, MAVEN-TGO presented 5,388 RO opportunities, compared to 4,968 for MEX-TGO, demonstrating the increased capacity of MAVEN-TGO configurations. This distribution is illustrated in Figure 7.2.

In this configuration, TGO will likely remain a key player. During a recent Inter-Agency Mars Relay Coordination Working Group (IMRCWG) meeting the TGO operations manager

confirmed that TGO is expected to operate well into the 2030s. MRO is also a strong candidate for inclusion, with 130 kg of fuel remaining, potentially extending its mission until 2038. However, it's USO has shown signs of ageing, and it has already switched to its redundancy oscillator. In addition, it is less likely to be used due to stricter scheduling requirements. Odyssey, which has been used for mutual RO in the past, is now in its ninth mission extension, but with only 3.35 ± 1.9 kg of fuel remaining, it is unlikely that NASA would trial a new capability with this spacecraft. I have also reached out to the project scientist of the (yet to be launched) ESCAPADE mission, and was informed that both small satellites in this mission do not have Mars Relay Network capability.

7.2.4 Use Mutual RO to Investigate Surface Properties

The multiple peaks seen in Figure 3.10 are from surface reflections. The large spectral peak in the middle of the spectrogram is from the line-of-sight transmission from MEX, but the other two fainter peaks are from multipath scattering. Furthermore, RO has been used to probe the Martian surface before with the MEX MaRS instrument (Pätzold et al., 2004b), so this idea has heritage and would significantly increase the scientific value of MEX-TGO mutual RO.

These ground reflections can reveal two things: 1) surface roughness via the Doppler dispersion of the reflected spectral peak; and 2) the dielectric constant of the surface material via the amplitude of the reflected spectral peak or via the Brewster angle (angle at which no reflections occur). This later value could infer what the surface material is made of, such as dust or subsurface ice. After this discovery, this idea was led by Håkan Svedhem of TU Delft, The Netherlands. He found that we can expect to have a 10 m penetration depth, given our 437.1 MHz transmit frequency and we should be able to detect surface roughness at length scales around 68 cm. Bespoke mutual RO observations are now being planned to optimise for this technique. These would differ to normal mutual RO orbits by placing MEX directly above TGO (or close as possible to this) and not having any occultation. This way the signals from MEX could be transmitted near-nadir and get reflected directly upwards towards TGO, therefore maximising SNR.

7.2.5 Increase Spatial Resolution via a Machine Learning and Ray-marching Technique

The rationale for this task is to overcome some fundamental flaws in the universal radio occultation technique. In short, this flaw halves the horizontal precision of every measurement. For example, say we have a peak electron density of $2 \times 10^{11} \text{ m}^{-3}$ and the tangent point reaches the ground at coordinates $[0,0]$ at the equator and on the meridian. Because this lack of horizontal precision, this reading could actually be from $[0,5]$ or $[5,0]$, depending on the direction of the ray between the two spacecraft. On Earth, we get remarkably spatially accurate readings from RO because we can integrate many quasi-collocated readings due to the sheer quantity of RO spacecraft orbiting our planet. On Mars, we don't have this luxury, and we must make the most of every RO measurement we get.

This method is detailed in Appendix C and describes an optimised ray-marching algorithm that can simulate a residuum from spacecraft geometries and a simulated martian limb. Previous attempts by Nava et al., 2020 to do this takes about a day of processing time, but this method allows residuums to be created in less than 0.1 seconds on GPU enabled hardware. Because this is so optimised, it can then be ran thousands of times and used to train a neural net. This programme uses a type of machine learning called Deep-Operator Neural Nets (DeepONet) (Lu et al., 2019). This form of machine learning can 'learn' any form of operation (eg multiplication, Fourier transform, asymmetric Abel transform, etc) both in forward and backward directions. In summary, the new method involves creating thousands of profile-residuum pairs using the unique orbital geometry of every measurement, then feeding these pairs into a DeepONet to learn the relation (operation) between them. Then running this network backwards such that a residuum can be fed in to then produce a profile. This allows the production of electron density profiles without the use of the Abel transform and its drawbacks. It offers a doubling of horizontal precision because the simulated atmospheres can factor in horizontal gradients, such as the dramatic reduction of electron density horizontally across the terminator.

7.2.6 Using Mutual RO to Investigate Crustal Magnetic Fields

This technique could be used to investigate the crustal magnetic fields. This will take advantage of the increased frequency of possible nighttime profile made possible by mutual RO. The in-situ LPW onboard MAVEN detected regions above topologically open magnetic fields experience far higher electron precipitation and found that this precipitation is responsible for around 50% of this nighttime ionosphere below 160 km (Adams et al., 2018).

Withers et al., 2022 used MAVEN's ROSE occultation experiment to acquire nightside peak ionospheric densities of $5 \times 10^{10} \text{ m}^{-3}$ at altitudes of 60-90 km. These peaks were located specifically near strong open magnetic field lines in the Martian crust. This value of density would be clearly visible in an electron density profile, for example in Figure 4.2 , so nightside measurements should be theoretically obtainable even with the current oscillator instability.

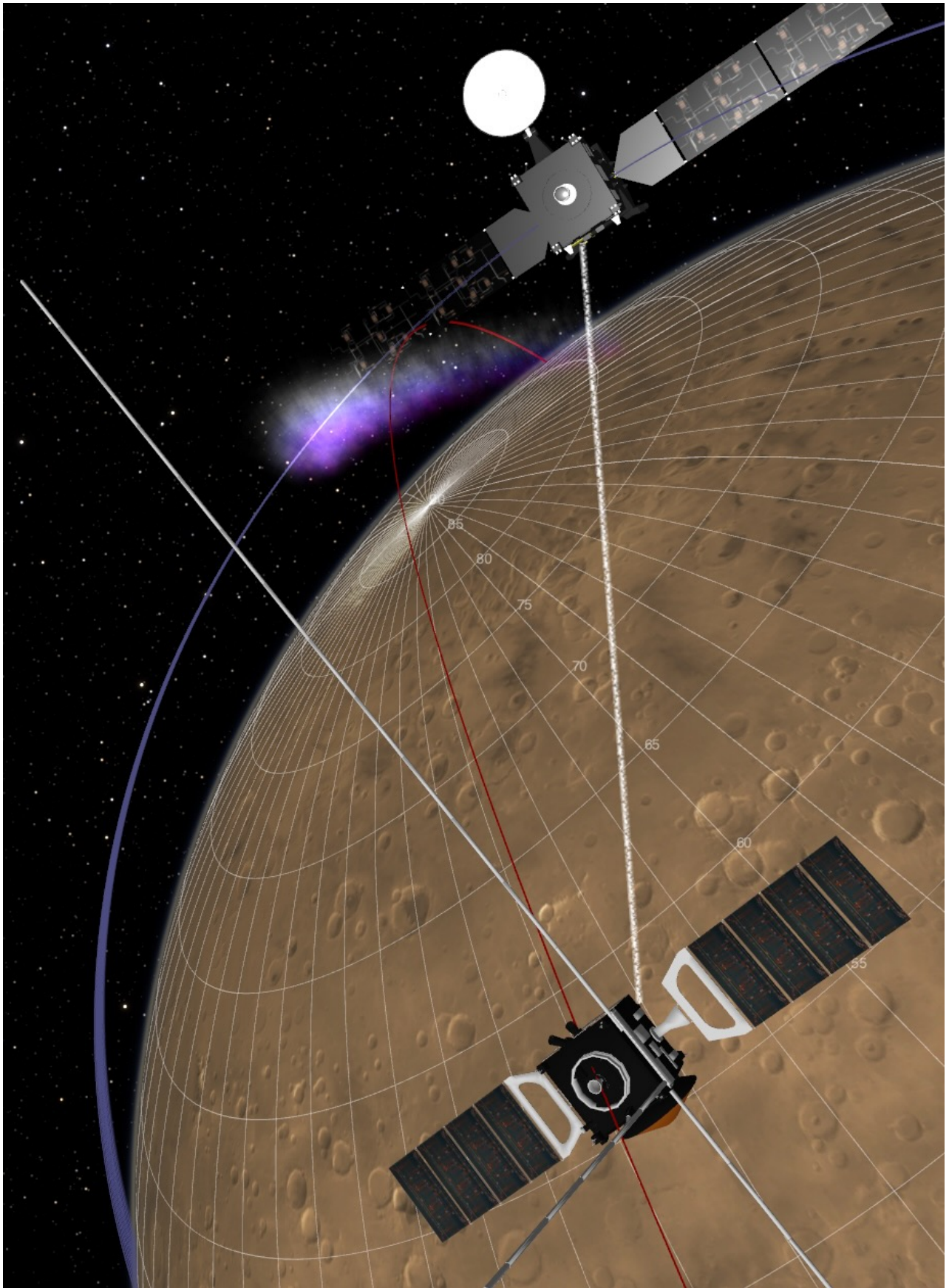


Figure 7.2: Publicity material made for the several news articles written about this mutual radio occultation campaign. MEX in the foreground and TGO in the background, with a white line representing the radio link. A purple haze shows the trace of the tangent point's movement. Made with a modified version of open-source Cosmographia.

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Appendix A

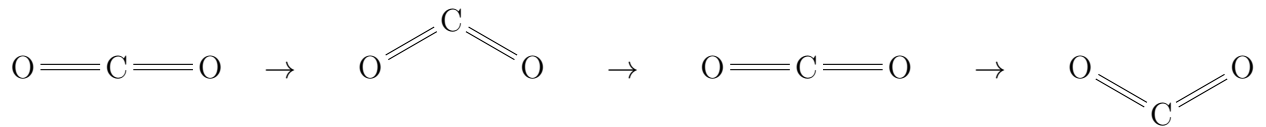
Why do CO₂ heat transfer properties depend on altitude?

Why does CO₂ have a net cooling effect at high altitudes when, at the surface, it contributes to the greenhouse effect, slightly elevating temperatures? In the troposphere, CO₂ will absorb the IR radiation from the surface and re-emit a IR photon isotropically. This means that around 50% of the heat radiated downwards. The density is also much higher here, so the collisions are far more frequent and the exchanges of kinetic energy between molecules. So CO₂ can absorb an IR photon from the surface, then exchange this energy to another non-CO₂ molecule which will not emit and IR photon, therefore increasing the local enthalpy.

At thermospheric altitudes, CO₂ will absorb IR photons emitted from the Martian surface and, in a similar vein, re-emit a IR photon into space 50% of the time. However it is different here because the rate of collisions is much lower due to the lower density, so other molecules will not receive kinetic energy from this vibrationally excited CO₂ molecule.

The core of this question is why does CO₂ have a certain time difference between emitting an IR photon and colliding with a neighbouring particle? This is because of the vibrational states of CO₂, specifically its 'asymmetric stretching,' 'symmetric stretching,' and 'bending' vibrational states. Each of these states corresponds to photon release with specific wave numbers: 2565 cm⁻¹, 1480 cm⁻¹ and 667 cm⁻¹ , respectively. Of particular interest is the

526 cm^{-1} wave number (a shorter wavelength of $15\text{ }\mu\text{m}$) photon, which falls within the infrared (IR) band and carries more thermal energy away and is emitted from CO₂ 'bending vibrational state', shown here:



Research conducted by Blauer and Nickerson, 1973 into the vibrational relaxation rate of CO₂ plumes reveals that the radiative lifetime for this particular 65 milli-electronvolt (meV) energy transition is approximately 0.3 seconds. In Earth's troposphere, where the air is characterized by high collision frequencies, one can expect CO₂ collisions to occur roughly every 2 μs . This collision frequency is significantly longer than the radiative lifetime, which means that vibrationally excited CO₂ molecules are more likely to transfer their kinetic energy through collisions (thermal conduction) than to emit it as an IR photon.

The shift in the outcome of this quantum reaction occurs at higher altitudes when the radiative lifetime (still at 0.3 seconds for Mars) becomes shorter than the collision frequency. At this juncture, a vibrationally excited CO₂ molecule is more likely to radiate IR radiation than to transfer thermal energy to neighbouring molecules through collisions. This results in a net cooling effect as CO₂ efficiently removes thermal energy from its local environment, which is then radiated out into space via IR emissions.

Appendix B

Mars Atmospheric Evolution

The ionosphere we find today is a product of its 4.5-billion-year history, over this time Mars has undergone profound transformations. Initially boasting a lush, moisture-laden atmosphere that nourished intricate river networks, the planet has evolved into the dry, frigid, and inhospitable world that we observe today. Mars, like the other inner rocky planets, formed relatively late within the protoplanetary disk, mostly made of H and He. The solid phases of these elements could not exist in close proximity to the Sun. Consequently, these inner planets lacked a substantial reservoir of solid materials with which to accelerate the accretion of additional gas and dust. This scarcity of resources resulted in the inner planets being significantly smaller and more younger than their outer gas giant counterparts. As a result, the inner planets, including Mars, predominantly accumulated heavier elements and developed into strongly oxidizing atmospheres (Rubie et al., 2015), typified by Mars' predominantly carbon dioxide (CO₂) atmosphere, comprising 95% of its composition.

A significant factor contributing to Mars' present inhospitable conditions can be primarily attributed to its lack of a significant magnetosphere, a protective shield on a planetary scale that shields Earth from the relentless barrage of solar wind. Today, Mars has an average surface pressure that is just 1% of the Earth's (Haberle & R.M., 2015). This thin gravitationally-bound gaseous envelope around Mars has less enthalpy. This combined with the greater heliocentric distance gives Mars a lower surface temperature that ranges from

-125°C to near 20°C (Jakosky et al., 2015).

Multiple theories attempt to explain why Mars possesses only a feeble magnetosphere generated by crustal magnetic fields (commonly referred to as the *intrinsic* B-field) and the ‘draping’ of the Interplanetary Magnetic Field (IMF), known as the *induced* B-field. The original theory, albeit straightforward, holds that Mars, being a mere 9.31 times less massive than Earth, lacks the abundant fissile material required to sustain a molten core. A planetary dynamo, responsible for generating magnetic fields, necessitates a fluid core where charges can freely circulate. It is estimated that Mars’ core solidified during the Pre-Noachian era (more than 4.1 billion years ago), resulting in the gradual depletion of its atmosphere over the past four billion years, driven by various mechanisms (Breuer, 2022).

However, experiments have cast doubt on this notion. The Mars Global Surveyor (MGS) conducted high-precision Doppler measurements, revealing a solar tide moving the Martian crust with an amplitude of 1.53 cm (Yoder et al., 2003). This observation strongly implied the presence of a sizeable liquid core measuring between 1520-1840 km in diameter—over half of Mars’ mean radius. This theory is supported by a recent study with an instrument called ‘Rotation and Interior Structure Experiment’ (RISE) on the lander called ‘Interior exploration using Seismic Investigations, Geodesy, and Heat Transport’ (InSIGHT) (Maistre et al., 2023), which noticed the rotational axis of Mars wobbled uncharacteristically little for a solid-cored body. This wobble is called nutation and it is larger for a body with a high density near its centre of mass. RISE measured the nutation to be well below the expected amounts for a solid core and could predict that its core density ranges from 5,955–6,290 kg m⁻³ and a diameter of $1,835 \pm 55$ km (Maistre et al., 2021).

However, a question arises: Why does this liquid core fail to generate the essential magnetic field needed to sustain a viable atmosphere? Yokoo et al., 2022 proposes that the liquid core may have become radially stratified, hindering the free flow of magma from the hot center to the cooler mantle. Analogous to oil and water, their experiments demonstrated that two types of iron compounds, Fe-S and Fe-H, become immiscible (laymans terms: unmixable) at high temperatures and pressures resembling Mars’ core conditions, which they simulated with

a diamond-anvil. This immiscibility disrupts the radial magma outflow from the core due to its stratification. The first compound, Fe-S, is pertinent because sulphur is a predominant element in Martian meteorites, while the second, Fe-H, was chosen because Mars is believed to have accumulated substantial water during its accretion, much like Earth. Ultimately, these two types of iron fluid become immiscible at high temperatures and pressures which cease radial magma flow from the core due to the core's stratification.

It would be inaccurate to claim that Mars lacks any magnetic dynamics. As previously mentioned, there are two distinct types of magnetic fields at work on Mars. Firstly, we have the intrinsic B-fields, which arise from magnetic domains within the Martian crust. As illustrated in the Figure B.1, these crustal magnetic fields exhibit varying length scales and are closely associated with the Martian dichotomy, characterized by the younger northern lowlands and the older, cratered southern highlands. It is believed that these magnetic domains originated during a period preceding the cessation of Mars' internal dipole, and the zonal bands of polarity inversions mirrors the pattern observed on planets that have undergone a reversing dynamo (Connerney et al., 2001), such as Earth, which reverses its polarity every few million years at random intervals (Banerjee, 2001).

The second type of magnetic field stems from interactions with the IMF, originating from the Sun, and is commonly referred to as induced B-fields. These fields result from the IMF's magnetic field lines effectively "draping" over the planet, leading to the generation of currents within the ionosphere. More specifically, the magnetic field is induced by the supermagnetosonic flow of the solar wind, which in turn induces currents in the highly conductive ionosphere. This process results in radial magnetic pressure, capable of shock-thermalising and shielding Mars from a portion of the oncoming solar wind (Ramstad et al., 2020).

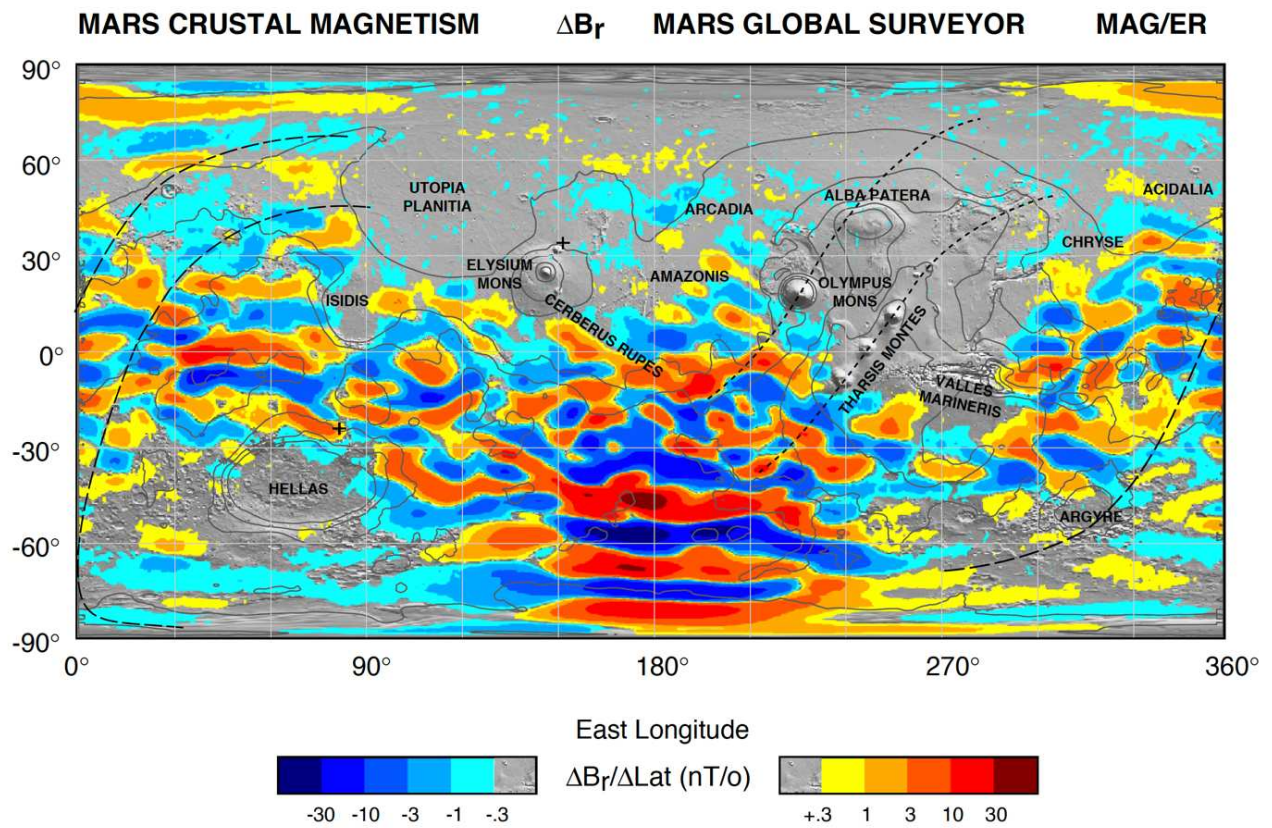


Figure B.1: A map of the intrinsic magnetic field on Mars captured by the 'Magnetic Field Experiment' on MGS from a 400 km altitude (Connerney et al., 2005).

B.1 Water Loss

The absence of a substantial magnetosphere has played a pivotal role in Mars' gradual loss of water over time. As a reminder, this is important to discuss as H_2O is an critical source of hydroxyl chaperones needed for the CO_2 reactions in the ionosphere (Equations 1.5 and 1.6). Evidence suggests that surface water existed on Mars between four to three billion years ago, during the Noachian and Hesperian eras. Even terrestrial telescopes can discern the water-etched landscape, complete with river deltas and glacial moraines near mountains. Spacecraft have found sedimentary rocks that bear the distinct markers of formation on seabeds (Burial Diagenesis), signs of recurring lake evaporation cycles (Ponding-Evaporation Karste), and the discovery of aquifers by the InSIGHT lander (Carter, 2022).

The lower water potential in the Martian atmosphere further increased surface evaporation. This phenomenon resulted from the separation of gaseous H_2O through photolysis, with the formation of O_2^+ ions, which subsequently recombined to create ozone (O_3). Simultaneously, the lighter H^+ and H_2^+ ions were stripped away through atmospheric escape. Another compelling indicator of Mars' once-humid atmosphere lies in the ratio of water to heavy water. Heavy water (HDO) occurs when one of the hydrogen atoms in an H_2O molecule possesses two neutrons, forming an isotope known as Deuterium. Mars exhibits a D/H ratio six times higher than that of Earth, suggesting that lighter H_2O molecules were preferentially lost, leaving behind the heavier HDO in a process referred to as Deuterium enrichment. Assuming that Earth and Mars initially shared the same D/H ratio because it was in the same neighbourhood of the protoplanetary disk, this observation implies that 83% of Martian water has been lost over time (Owen et al., 1988).

B.2 Atmospheric Escape

The concept of atmospheric escape plays a pivotal role in understanding the evolution of the Martian atmosphere. The MAVEN mission (Jakosky et al., 2015) was specifically launched to investigate this phenomenon, and its findings estimate the current rate of atmospheric loss to

be in the range of $2\text{-}3 \text{ kg s}^{-1}$. This current rate is estimated to be significantly lower than during the earlier epochs of Mars' history when the young solar system featured a sun emitting 30 times more UV radiation and twice the efflux of solar wind (Leblanc, 2022).

Presently, there are five distinct types of atmospheric escape mechanisms:

1. **Jean Escape/Thermal Escape** refers to a process in which the kinetic energy of a gaseous species surpasses the energy needed to break free from a planet's gravitational pull. An essential condition for this phenomenon to occur is that the volume is considered collisionless, allowing atmospheric particles to escape without obstruction. This occurs within the exosphere, where the mean free-path length exceeds the scale height of the tracers (gaseous species), in other words the distance a tracer can traverse before encountering a collision is greater than the vertical distance required for the tracer's density to decrease by a factor of e . Determining the degree of collisionality within a medium is quantified using the following equation:

$$\zeta(z) = \frac{1}{\sigma n(z) H(z)} \quad (\text{B.1})$$

Where σ is the particle cross-section, $n(z)$ is the particle density and $H(z)$ is the scale height. ζ is the collision parameter and if $\zeta \ll 1$, then the medium is considered a fluid. The bottom of the exosphere (exobase) is defined as the altitude when $\zeta = 1$. Once the collision parameter is considered then the limit for the escape (or Jean limit λ) is the ratio between the escape velocity (V_{esc}) and the mean molecular velocity (U) (assuming a Maxwellian distribution)

$$\lambda = \frac{V_{esc}^2}{U^2} \quad (\text{B.2})$$

where

$$V_{esc}^2 = \frac{2GM}{r_{exo}} \quad (\text{B.3})$$

and

$$U^2 = \frac{2kT}{m} \quad (\text{B.4})$$

Where G is the gravitational constant $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, M is the planetary mass of $6.42 \times 10^{23} \text{ kg}$, r_{exo} is the nominal exobase altitude of 200 km, k is the Boltzmann constant of $1.38 \times 10^{-23} \text{ J K}^{-1}$, T is the temperature and m is the mass of the particle.

To put this into perspective, if the mass of the body is small enough, then $\lambda \rightarrow 0$. This is the case for cometary comas, where their gaseous envelope is barely gravitationally bound. Whereas the massive gas giants which are at least 5 AU away from the sun have a jean escape value that tends to ∞ . As can be seen from Equation B.2 and B.4, if the mass of the tracer is reduced then the jean limit will reduce, hence Jean Escape for Mars is a mechanism that exclusively applies to atomic hydrogen. For larger ions, then other mechanisms need to be discussed.

2. **Ion Outflow** - In addition to being energized by thermal excitation (U) and the increasing solar wind speed, ions experience further acceleration due to Mars' open magnetic field lines. These dynamic field lines result from the interplay between the planet's intrinsic B-fields and the induced B-field. When these field lines connect to the magnetotail (on the aft side of Mars above the antisolar point), they can stream outward at velocities far surpassing the V_{esc} , allowing them to escape with energies reaching up to 1 keV (Lundin, 2011).
3. **Solar Wind Pickup** - Within Mars' exosphere, neutral particles can become ionized through interactions with UV photons or collisions with ions from the solar wind, primarily consisting of O^+ , H^+ and C^+ (Chassefière & Leblanc, 2004). Once ionized, these particles can be carried away by the convective electric field of the solar wind.
4. **Bulk Escape** - This escape mode bears similarities to the previous mechanisms, but it diverges in how the plasma reaches the upper exosphere. In this case, Mars undergoes a substantial loss of atmosphere in a single, coherent event. The term 'bulk' here signifies that the plasma is expelled into space as a coherent structure. This phenomenon arises

from the distinct reference frames of the two magnetic fields at play. While the intrinsic magnetic fields align with the planet's rotation, the induced B-fields remain fixed relative to SZA as they are following the direction of the IMF. This leads to a continuous state of magnetic reconnection (Brain et al., 2010). When the induced field reconnects with itself, the resulting magnetic tension in the field lines becomes significant, allowing for the atmospheric plasma to be transported in bulk away from the planet, which is a similar mechanism to coronal mass ejections where ions are propelled into space due to magnetic tension following magnetic reconnection (Stawarz, 2021).

5. **Sputtering** - What if the tracers are neither light enough to escape via Jeans escape nor charged for the three other types of ion escape. For instance, argon has been observed escaping from Mars due to processes like those involved in the depletion of the planet's water reserves. The Curiosity rover detected an ^{36}Ar to ^{38}Ar isotope ratio 4.2 times higher than that found on Earth (Atreya et al., 2013). As a result, the typical escape mechanisms do not readily apply to them. The prevailing theory suggests that argon is ejected from Mars' upper atmosphere following collisions with super-thermal ions transported by the solar wind.

Appendix C

Ancillary Project to Replace the Abel-Transform

The primary objective of this task was to address some fundamental shortcomings in the radio occultation technique. In essence, this flaw significantly reduces the horizontal precision of every measurement.

This method presents an optimised ray-marching algorithm capable of simulating residuums resulting from spacecraft geometries and a simulated Martian atmosphere. The program employs a novel type of machine learning known as Deep-Operator Neural Nets (DeepONet), which possesses the remarkable ability to learn any form of operation, both in the forward and backward directions. This advancement enables the generation of electron density profiles without resorting to the Abel transform and its associated limitations. Notably, this approach offers a doubling of horizontal precision by incorporating horizontal gradients, such as the dramatic reduction in electron density horizontally across the terminator.

C.1 Motivation

With the steps being shown to get to Equation 2.10 in Section 2.1.1, the specific downsides will be easier to explain. This equation will be repeated below for convenience:

$$\ln n(\beta) = \frac{1}{\pi} \int_{\beta}^{\infty} \frac{\varepsilon(a)}{\sqrt{a^2 - \beta^2}} da \quad (\text{C.1})$$

Primarily, the assumption of spherical symmetry is never strictly fulfilled. This assumption means that the refractive index only depends on distance from the center of curvature. On Earth, this is especially problematic where there are significant horizontal refractive gradients in the moist lower troposphere (Steiner et al., 1999). This problem is similar to the Martian ionosphere near the terminator, where electron density is dominated by SZA and there is a sudden drop in photoionisation longitudinally. This issue of spherical symmetry is introduced in the first step with Equation 2.6.

Second, as shown in Equation 2.8, the integrand must be evaluated from the ray parameter to an infinite height. Obviously infinity is never obtained and RO tests must start from the greatest height possible. This maximum height will be the altitude of the lowest spacecraft. In this MEX-TGO case, this maximum altitude is around 430 km. In practicality this is taken to a height where the refractivity is as close to unity as possible, but with large scale height planetary exospheres, this means there is always an approximation of unity and is never fully achieved. This drawback leads to an increased error for higher altitude measurements and often requires assimilation with simulations for heights above the M2 ionospheric peak (pers.comm Bruno Nava, ASI/CTP).

Lastly, the Abelian inversion allows for errors to propagate freely downward (Wee & Tae-Kwon, 2018). A positive drift in the local oscillator at the receiver would lead directly to an artificial increase in refractivity post-inversion and an underestimate of the electron content.

C.1.1 Possible Solutions to Increase Horizontal Resolution

This issue has been researched on for Earth based applications, to list a few:

1. Wee and Tae-Kwon, 2018 proposes a variational regularisation using an a priori from the European Centre for Medium-Range Weather Forecasting (ECMWF). Instead of using the *inverse* Abel Transform, it used the *forward* Abel Transform in an optimisation problem with the initial guess of the optimisation being a weather forecast from the ECMWF.
2. Palmer et al., 2000 suggests a nonlinear maximum a posteriori technique that can account for the effects of horizontal refractivity gradients and optimally retrieve temperature and humidity simultaneously. It does this by producing a error covariance matrix from simulated 1D data from the MET office and the results of a forward Abel Transform. They do this to model the error over specific conditions such that they can be removed with high precision. In theory, the technique can make a separate covariance matrix for temperature and humidity such that they can be removed at the same time.
3. An attempt to remove the height limitations was made by Healy et al., 2002, where they proposed putting the receiver on the planetary surface. They suggested receiving a signal from two transmitters, one from above the local horizon and one from over the horizon. Assuming spherical symmetry, the above and below rays will have the same impact parameter, so the difference in total bending (ε) for each ray can give provide them a 'space-based equivalent ε ' and the Abel Transform can be used nominally.
4. An asymmetric Abel Inversion is needed in many fields. Ma and Takeda, 2002 looked into a multi-layer neural network to reconstruct plasma densities within a fusion reactor. The training data for the network came from Magnetohydrodynamic (MHD) simulations as they were compared with interferometric measurements.

The novel technique described in the following section can be seen as a combination of solution 1, 2 & 4. Where it uses an a priori to model the SZA dominated ionosphere and

utilised a optimisation algorithm. Presently, Martian and terrestrial occultation use the same model inversion technique with no regard to the different atmospheric and ionospheric makeup. Earth’s relatively wet and dense troposphere is treated the same as the Martian ionosphere. With the drawbacks mentioned in Section C.1, these differences in water content and density can be leveraged to allow for a novel inversion technique that removes the requirement of the Abel Transform. As shown in Figure C.1, the basic premise of this method is a highly optimised ray-marching¹ simulation and a minimisation algorithm that can rapidly generate a residuum.

This method would not be possible without the speed optimisations. To put this into context, Figure C.2 took a day to produce on a high-end desktop, whereas the ray-marching in this method can produce a very similar plot in 0.1 seconds. When this system was first designed, it took approximately 30 minutes to simulate just 10 seconds of a mutual occultation residuum. The following section will show the features of the previous code and how they could be removed due to Martian specific reasons.

C.2 Ray Marching Kernel Optimisations

3D to 2D

For all RO simulations, the basic heuristic of ‘the ray’ will be used. This is classically defined by the orthogonal trajectories to the geometrical wavefronts (Born et al., 1999). Of course when we include phase delay, multi-path, scintillation and antenna patterns etc., 3D electromagnetic propagation through a limb is far more complex than joining the transmitter and the receiver with a singular ray. The bending of this line will follow the gradients of refractivity, which is always pointed towards the Martian barycenter². Here is the first key insight which led to an optimisation: the centre of the transmitter/receiver orbit and the

¹Although raytracing is more colloquially known in physics and computer graphics, there is a subtle difference in that raytracing involves light reflecting of solid surfaces. A ray can also pass through a medium and refract with a ray-marching system

²A barycenter is the location which two bodies orbit. For example, the barycentre for the Earth-Moon orbit is not the Earth centre of mass, it is offset slightly by the opposite gravitational pull of the moon

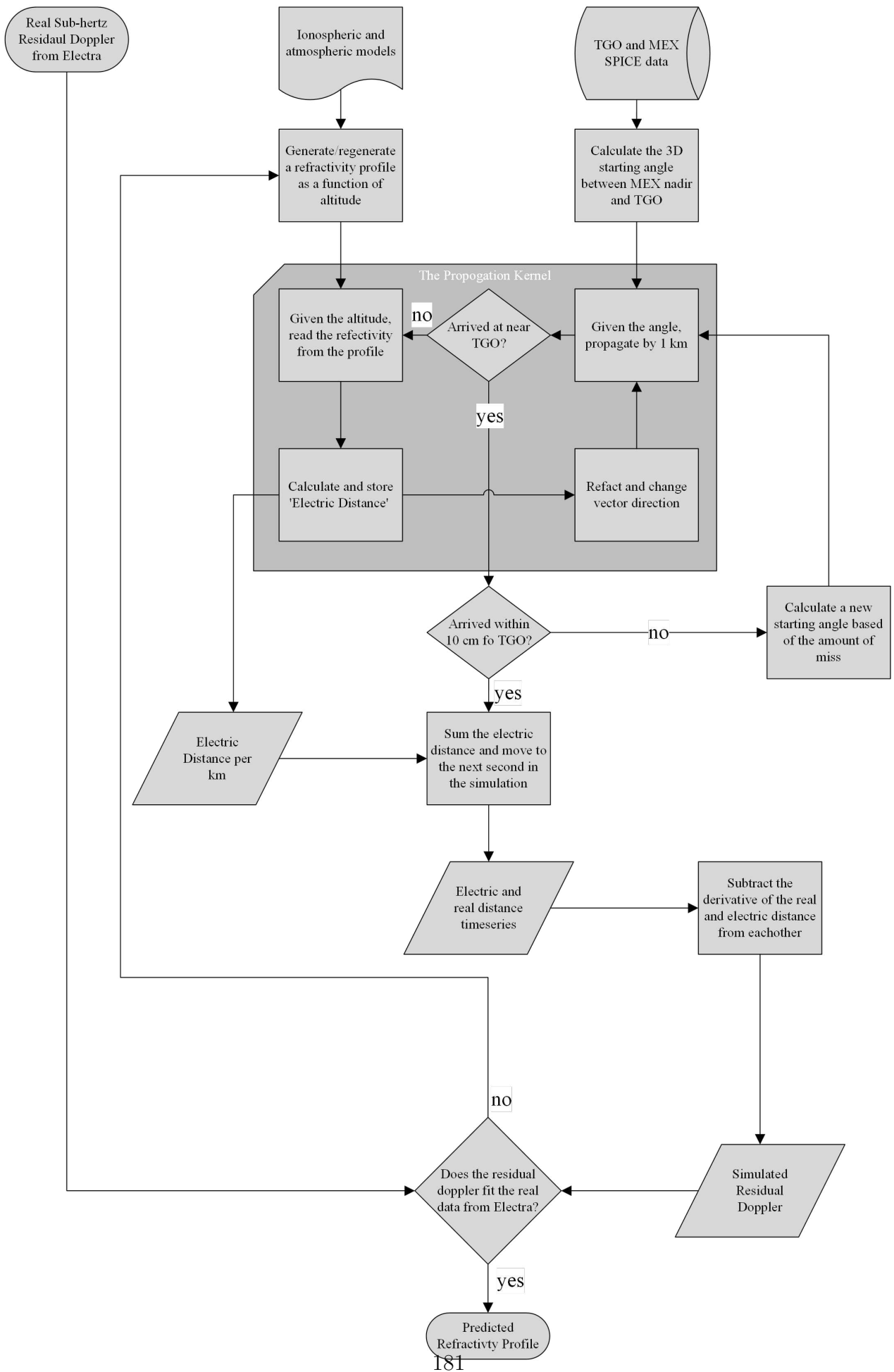


Figure C.1: Initial model inversion flowchart

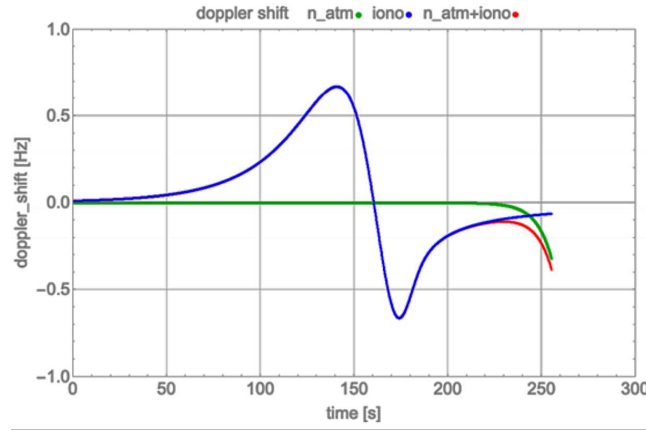


Figure C.2: A simulated residuum produced by the ASICTP. Their model did not include a M1 ionospheric peak and took over 10 hours to compute (Nava et al., 2020)

gradients of refractivity have a very similar spacial location, so can be placed in the same reference frame. This permits a reduction in dimension from a 3D to 2D and an associated computational cost reduction of $O(n^3)$ to $O(n^2)$. As shown in Figure C.3, these three points can be confined onto a single plane, with the centre of Mars being at the origin, such that the altitude can be easily found via Pythagorean addition.

This method is reliant on the out-of-plane refraction being negligible. But for Mars, the change in refractivity is dominated by gravity gradients and therefore in-plane. For example, of the neutral atmosphere, temperature and pressure are mostly altitude dependent. Both these parameters decrease as you get further away from the Martian barycentre. The ionosphere is slightly more complicated; the peak N_e is usually found near 140 km, where it steeply drops off at either side in accordance with a Chapman profile. The peak of the N_e is at an equilibrium point between there being enough molecules for ion production and height where the sun's radiation has not been attenuated. Again, this is gravity dependent as the molecular density positively follows, and the solar penetration negatively follows, the gravity gradient.

The sharpest out-of-plane refraction would be expected at the terminator. Despite this, the vertical gradient over 100-200 km altitude will have a greater magnitude than the horizontal refractive gradient over the broad terminator.

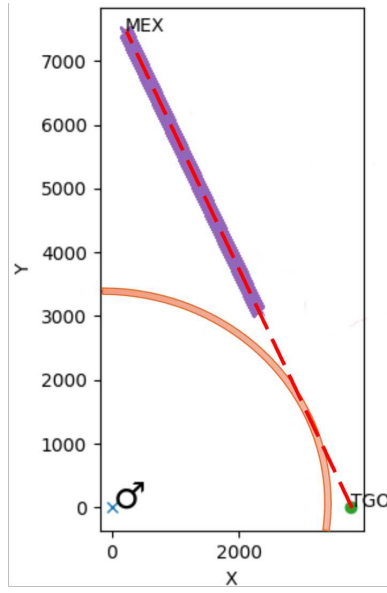


Figure C.3: An example of a 2D configuration of a mutual radio occultation between MEX and TGO, the origin is the barycenter of Mars and the red line is the surface ellipse. The purple is the portion of the ray that travels unperturbed in the vacuum of space.

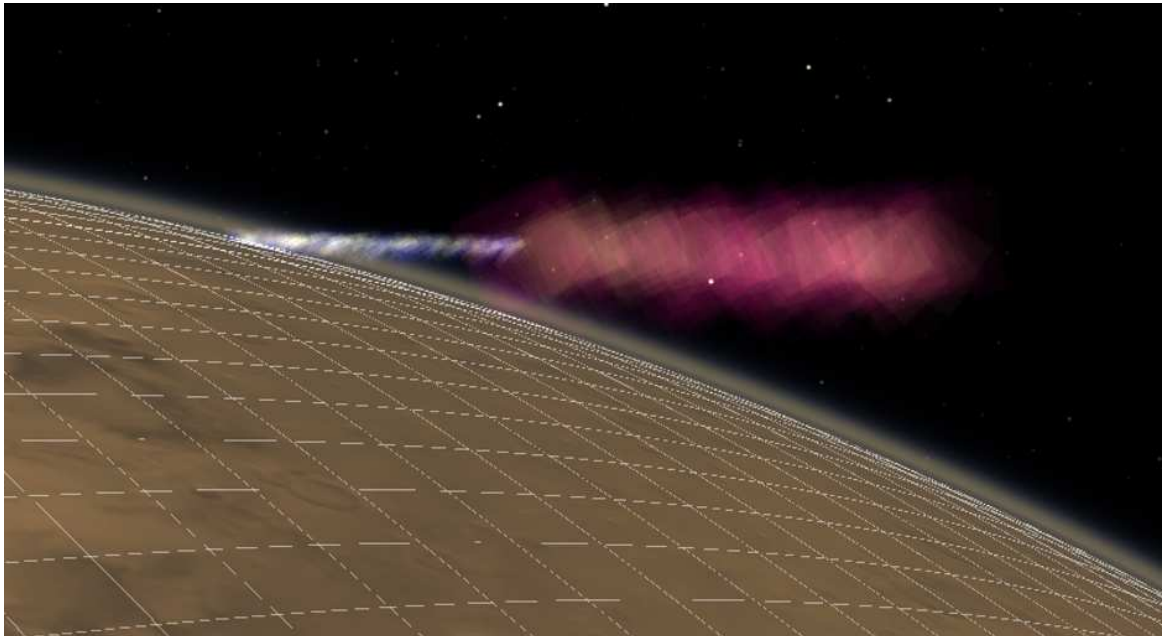


Figure C.4: The same simulation as Figure C.3, but plotted in Cosmographia using the same JSON technique in Section 4.3.3. The pink wider is the portion of the ray that travels unperturbed in the vacuum of space.

C.2.1 Straight Line Propagation

One issue with finding a ray to connect the transmitter and the receiver is that the final path is not known when the propagation begins, due to piece-wise refraction. Each time the ray changes direction, it will move through a medium of a slightly different refractivity. This will always lead to the ray initially missing the receiver, and a new propagation path needs to be recalculated with a different starting angle at the transmitter. Initially, seven full propagations would be required to find the ray between Tx and Rx. It should be obvious that if refraction was omitted from the processing then there would be a substantial time-saving, due to the thousands of refractions for a single starting angle variation. As Figure C.5 shows, it achieved the same results and fixed a problem with systematic noise.

This idea was first trailed because the initial vector would miss MEX by an extremely small amount. In the worst-case scenario, with MEX and TGO spaced 9000 km apart and where the propagation travels through the ionospheric peak³, there would be a miss of only 40 cm. This is because Mars is generally unrefractive, ranging in index from 0.999975 to 1.0000036.

In discussions with a member from the Abdus Salam International Centre for Theoretical Physics and from (Healy et al., 2002), it was discovered that on Earth it may be expected to receive a total bending angle of up to 1°. This is due to the Earth's higher water content, pressure and temperature in the troposphere, compiled with its far more refractive ionosphere. On the other hand, Mars' maximum bending angle was calculated as 2.5×10^{-6} degrees, if the peak electron density is $2 \times 10^{11} \text{ m}^{-3}$.

C.2.2 Other Programmatic Improvements

By far the largest speed improvements were due to the architectural optimizations listed in the above section. However, three other programmatic optimisations were also crucial to making the simulation time acceptable.

³The most refractive scenario is purely through the ionospheric peak because any lower would have an atmospheric effect. With an opposite refractivity, the atmosphere would correct the ray in the opposite direction

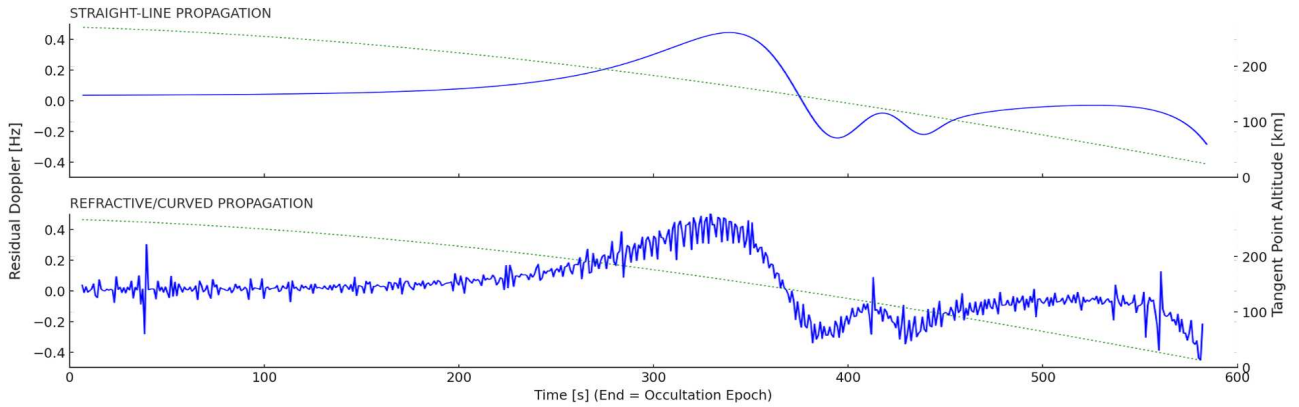


Figure C.5: Comparison between straight line (top) and refractive (bottom) propagation for the same occultation test. It is evident that the straight line propagation produces the same result, with the added benefit of fixing a systematic noise problem.

1. **Parallelisation** - Although Python was not originally designed to work like this due to its 'global interpreter lock', multicore processing is now possible with modern workarounds. The workload needed to be divided across multiple computational cores that could work in parallel. For this programme, the processing channels were separated by seconds in the occultation test. For example, the 1st second of the RO test could have its electric distance (the real distance multiplied by the refractive index) calculated simultaneously as the 4th second of the test because these two results were independent. This optimisation was completed by replacing many of the native functions for vector calculus with other tools which could work for 'CUDA core offloading'. Secondary, to synchronise the parallel processes, an effort was made to pool similar data such that shared information could be collected simultaneously. On top of the 15X speed improvement, this method is scalable. So, if this programme were to be deployed on a server with many more cores (e.g. 128 cores on a college cluster), then the performance would scale linearly.
2. **C-Compiled Kernel** - Python is a high-level programming language and this distance from the silicon can impede its processing speed. What it gains in abstraction and human readability, it loses in computation time. This is the reason why the most repeated part of the code was compiled in a different faster language. The core function for propagating the ray position from MEX to TGO in a 2D space was compiled in C

(referred to as the propagation kernel). With this language being just one layer of abstraction above assembly code and so close to the silicon, the function runs more than 100 times faster.

3. **Look-up Tables** - Previously the refractivity value for a current position would be calculated by running the altitude parameter into the atmospheric and ionospheric models. At each new position, the models would be re-trailed. This was an incredibly inefficient way of doing it. A product of the ionospheric and atmospheric models could be combined and a refractivity profile produced once per simulation. When the refractivity is required for a particular ray position, the programme only needs to check a precomputed refractivity look-up table. This prevents the models from being evaluated tens of thousands of times per simulation.

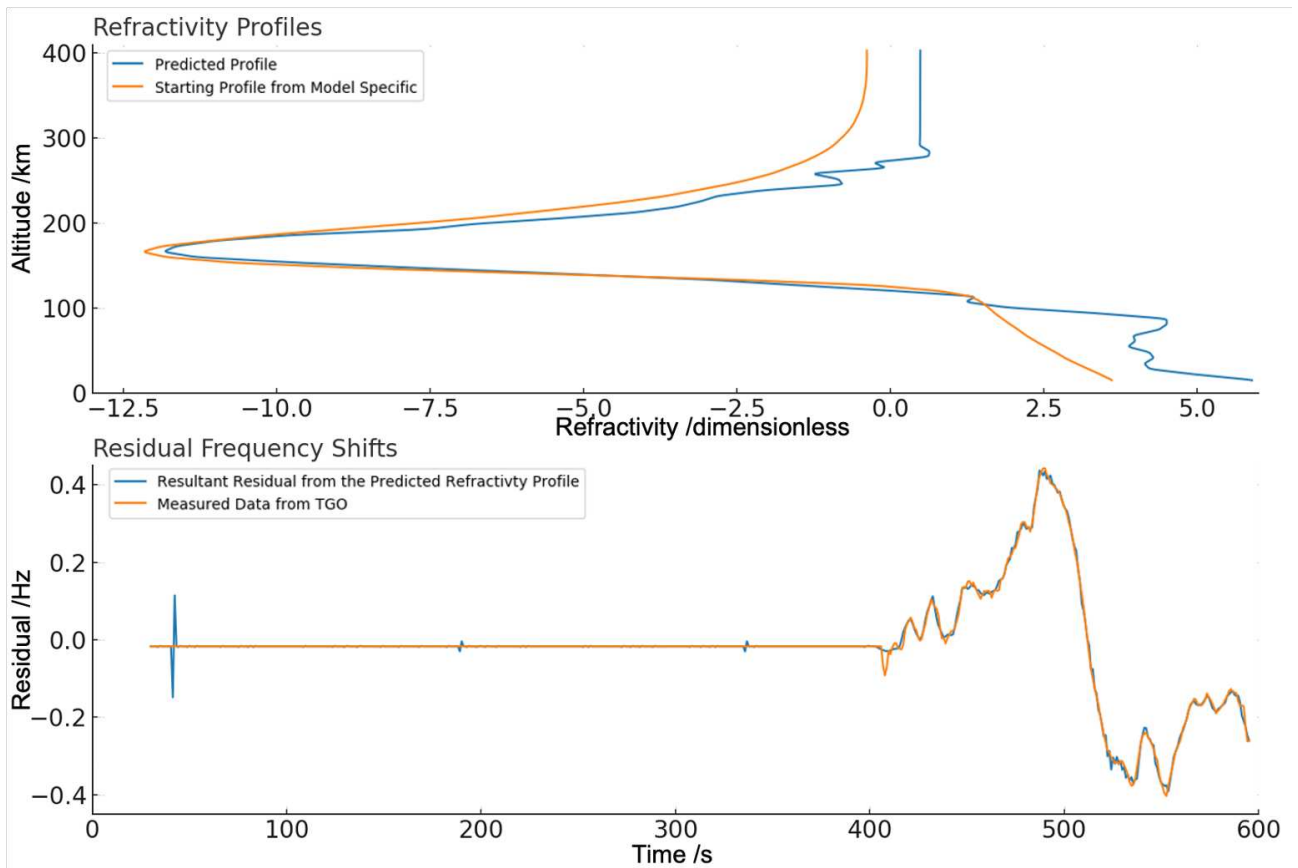


Figure C.7: Results of a prototype for non-Abelian inversion using an optimised ray-marching and an optimisation to synthesise a potential refractivity profile (blue top panel) from a received real residuum from Electra. There are two lines in the bottom panel, yellow is the real Electra data, blue is the the simulated residuum from the converged refractive profile in the top panel. The smoother yellow in the top panel is an intermediary product.

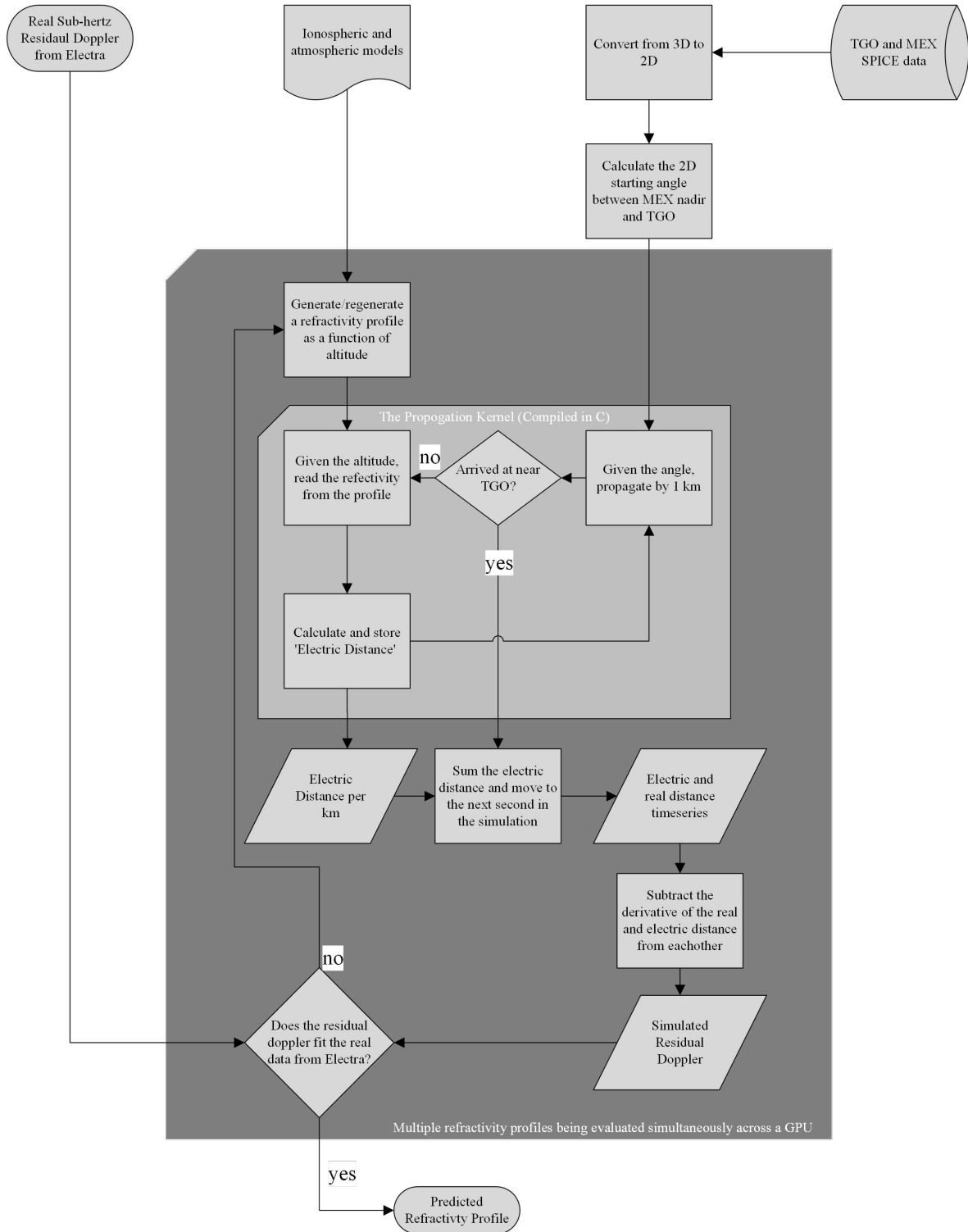


Figure C.6: Model inversion flowchart with the improvements described in Section C.2

C.3 Similar Work

A recent similar method was published by Caruso et al., 2023 in September 2023. But instead of using a straight line approximation, their method was more generalised and could theoretically work on planets with higher average refractivities, such as Titan and Venus. They extended Bourgoïn et al., 2019 work in showing that the optical path through a spherically symmetric e-folding medium is exactly a hyperbola. They extended this by stacking concentric shells of different refractivities and ray-tracing a chain of hyperbolas through a simulated atmosphere. Fortunately, they were not trying to achieve the same thing as me. They were not trying to overcome the issue of spherical symmetry and its reduction in horizontal precision. They were only tackling the problem of integrating from an infinite height. Also instead of investigating advanced Machine Learning techniques to reduce the compute/increase the spatial resolution, they simply used MATLAB's 'fsolve' function in their inversion.

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