Analysis of Ionospheric data from MARSIS

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***Abstract*—Radar remote sensing has proven to be a valuable tool for planetary observation and exploration, with several missions focused on Mars over the past few decades.This paper presents the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), a scientific instrument on board the European Space Agency's Mars Express spacecraft. Using the active ionospheric sounder, data is obtained and analysed. MARSIS has provided crucial insights into the planet's geology, climate history, and potential for life, as well as the highly variable and complex ionosphere of Mars. The ionospheric models and data from MARSIS have been used in relation to the Chapman Profile of the martian atmosphere to obtain results on its ionospheric density, scale height and with implications for communication and navigation systems for future missions to Mars.**

***Index Terms*—Ionosphere, Mars, atmosphere, analysis**

I. Introduction

Exploration of Mars is one of the most significant and ambitious endeavors of the scientific community. For centuries, the planet has captivated the human imagination, and for good reason: Mars holds answers to some of the most fundamental questions about our place in the universe. Radar systems are critical tools for Mars exploration, enabling scientists to map the surface and subsurface of the planet with unparalleled detail.

The thin atmosphere of Mars makes it an ideal candidate for radar exploration. Unlike Earth, where the atmosphere scatters and absorbs radar signals, the Martian atmosphere allows radar signals to penetrate deep into the planet's surface. This makes it possible to study the subsurface geology of Mars, including buried impact craters, subsurface water ice deposits, and even potential habitats for microbial life. Additionally, ionospheric study helps understand the effects of solar radiation on the atmosphere to improve communication and navigation systems for future missions.

Radar systems have played a critical role in past and current Mars missions, such as the Mars Reconnaissance Orbiter and the Mars Express mission. These missions have provided crucial insights into the planet's geology, climate history, and potential for life. With the help of radar systems, scientists hope to unlock even more secrets of the Red Planet and pave the way for future human exploration.

A. Mars Advanced Radar for Subsurface and Ionosphere Sounding

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) [1] is a scientific instrument on board the European Space Agency's Mars Express spacecraft, which has been in orbit around Mars since December 2003. MARSIS is a versatile instrument capable of probing both the subsurface and the ionosphere of Mars, providing important insights into the planet's geological and atmospheric processes.

There are two modes that the MARSIS instrument accomodates. The subsurface sounding mode of MARSIS uses radar pulses to probe beneath the Martian surface, providing information about the planet's geology and internal structure. The ionospheric sounding mode of MARSIS uses radar signals to probe the upper atmosphere of Mars, providing information about the planet's atmospheric composition and dynamics. Radar details is listed in Table 1. The radar signals penetrate the ionosphere and are reflected back to the spacecraft, with the echoes analyzed to determine the electron density and composition of the ionosphere. This information can be used to study the interaction between the solar wind and the Martian atmosphere, as well as the dynamics of the Martian ionosphere itself.

TABLE I
MARSIS Radar Characteristics

Operating Frequency	1.7 MHz - 5.5 MHz
Pulse Length	91.4 ms
Pulse Repetition Frequency	127 Hz

B. Mars Ionosphere

The ionosphere of Mars is an important area of study due to its influence on communication and navigation systems, as well as its potential role in atmospheric loss to space. The ionosphere is a region of the upper atmosphere where gas molecules are ionized by solar radiation, creating a layer of free electrons and ions that can affect radio signals and other forms of electromagnetic radiation. In the case of Mars, the thin atmosphere and lack of a protective magnetic field make the ionosphere particularly susceptible to the harsh solar wind, leading to the possibility of atmospheric escape. Therefore, a better understanding of its physical and chemical properties is important for predicting the evolution of Mars' atmosphere [2] [3].

The study of the Martian ionosphere has implications for a broad range of scientific and practical applications. The ionospheric models and data from MARSIS have been used to investigate the atmospheric escape rates and the evolution of the Martian climate. Understanding the ionospheric structure and dynamics is also critical for communication and navigation systems for future missions to Mars.

Observations from MARSIS have revealed a highly variable and complex ionosphere, with features such as ionospheric layers, plasma cavities, and ionospheric irregularities. These features are closely linked to solar activity and the variability of the neutral atmosphere. Their study provides insights into ionospheric dynamics and atmospheric escape processes. In this paper, ionograms from the MARSIS instrument will be used to showcase such features and observations.

II. Data and Methodology

A. Principle of Ionospheric Sounder

The principle behind the instrument used to obtain the data is based on Ionospheric sounding, whereby a short pulse is transmitted at a fixed frequency, f, and an echo is reflected from the ionosphere. There exists a limit namely the electron plasma frequency, f_p, which is a limit for free-space electromagnetic radiation to propagate causing the occurrence of reflection to occur. This quantity depends on the altitude and is represented in (1).

$$f_p(z) = \frac{1}{2 * \pi} * \sqrt{\frac{e^2 * N_e(z)}{m_e * \epsilon}} \tag{1}$$

where e is the charge of an electron, N_e is the electron number density, m_e is the mass of an electron and ϵ is the permittivity of free space.

B. Data Collection

Ionospheric measurements by MARSIS are carried out in both passive and active modes. By analyzing the time delay between the transmitted pulse and the received echo, it can determine the altitude and electron density of the ionosphere at that location. MARSIS employs radar soundings to determine the vertical range to the ionospheric reflection point as a function of frequency. This technique provides valuable information about the ionospheric structure, which is why it was chosen to use Active Ionospheric Sounding data [4] in this paper.

C. Data Interpretation

The data obtained is of every orbit of the Active Ionospheric Sounder in binary data format [5]. This file was converted to a readable format by using the provided C code included in the database. The data obtained had to run thorough the C code executable file and give the output tab-seperated. Upon conversion, the data obtained contained the begin and end time of transmission along with the parameters of the radar system including the attenuation, band number and the spectral electron density of the signal received. The data was then extracted into a CSV with the help of python code. The rest of the analysis was conducted in MATLAB.

Once the data was imported and extracted, it was found to be a dataset with constant intervals/bins. When referenced back to the website, it was found that a dataset of a particular orbit contained the electron density for 160 set of frequencies at different moments in time. Shortlisting the particular plots by manually segregating the datasets, four ionograms were chosen for this paper. These are orbit numbers 1847, 1850, 2372, 2032. The particular times were taken as well and imported.

D. Chapman Profile

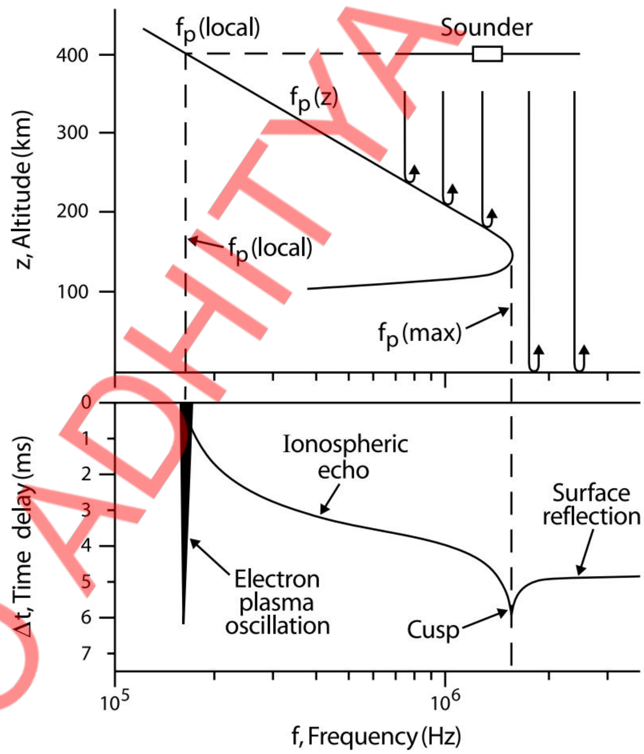

Fig. 1. Illustration of Chapman Profile

The Chapman profile is a well-established theoretical model used in ionospheric research to describe the variation of electron density with altitude in the Earth's ionosphere, shown in Fig 1. The model is based on the ionization of atmospheric gases by solar radiation, where the balance between the rate of ionization and recombination is determined by the altitude and the intensity of the solar radiation. The Chapman profile is a crucial tool for understanding the ionosphere, as it provides a quantitative description of the electron density profile. The chapman electron density profile, follows (2), is a simulated value with variable peak ionospheric density (N_0), Scale height (Z_0) and height(H_0).

$$N_e(z) = N_0 * e^{\frac{1}{2}(1 - \frac{z - Z_0}{H_0} - e^{-\frac{z - Z_0}{H_0}})} \tag{2}$$

An ionogram is a vital tool for the graphical representation of the distribution of ionospheric electron density as a function of altitude, as depicted in Fig. 2. The reflected radio signal is analyzed to obtain the electron field spectral density data necessary to construct an ionogram. In the ionogram, the ionospheric echo, which is the return signal of the radar pulse reflecting from the ionosphere, is characterized by its peak max frequency. The longer signal on the right side of the ionogram shows the subsurface reflection, while the oblique echo, a smaller echo that is similar to the ionospheric echo, originates from horizontal reflections from magnetically created bulge [6]. The presence of the electron plasma harmonics, a considerable noise on the left side of the ionogram, is due to instrument noise. the ionogram provides valuable information of the ionospheric electron density distribution as a function of altitude, which can be used to infer various physical phenomena occurring in the ionosphere.

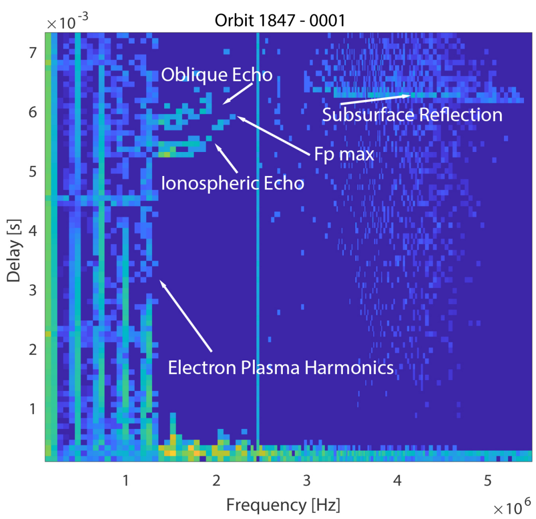

Fig. 2. Sample Ionogram depicting characteristics

RESULTS

Ionograms for four different orbits, namely 1847, 1850, 2372, and 2031 are presented in Figures 3-6, respectively. The electron density distribution is a fundamental parameter of the ionosphere and can be estimated using the Chapman profile. We have overlaid the Chapman profile on the ionograms to estimate parameters such as N_0, Z_0, and H_0. To achieve this, MATLAB was utilized to plot the ionograms and place the Chapman profile on top of them. The parameters were individually varied to fit the ionospheric echo on the ionogram. Table 2 summarizes the different parameter values and characteristics of the ionograms.

TABLE II
MARS IONOGRAM CHAPMAN MODEL CHARACTERISTICS

Orbit Number	N_0 (cm^{-3})	Z_0 (km)	H_0 (km)
1850	7e10	13	140
1864	8e10	13	140
2032	3.7e10	15	380
2372	10e10	16	720

The selected figures represent all the features necessary for a comprehensive comparison. Each of the four figures displays a subsurface reflection, an ionospheric echo, and an oblique echo. The maximum frequency peak is visible on the Chapman profile, right at the end of the ionospheric echo. As in Table 2, we see a wide range of variance for the characteristic parameters. The echoes are of different shapes and sizes as well, which depict different martian terrain. An abundance of harmonics as seen in Fig 4 represents the electro static plasma oscillations due to the reciever. In a paper by F.Duru et al [7], it says that these spikes can help determine the local plasma frequency by measuring the spacing between the vertical lines.

Similar to the oscillations, the horizontal lines in Fig 4 depict the electron cyclotron echos which when correlated with time spacings can determine the local crustal magnetic field passed by the Mars Express spacecraft. Subsurface reflections can be seen when the spacecraft is at higher solar zenith angles [6]. It is also believed that the absorption may be higher at smaller angles, only then will the surface echoes be fully absorbed and would not appear on lower ionograms. Further more, information on the altitude of echoes can be determined upon understanding the topography of Mars.

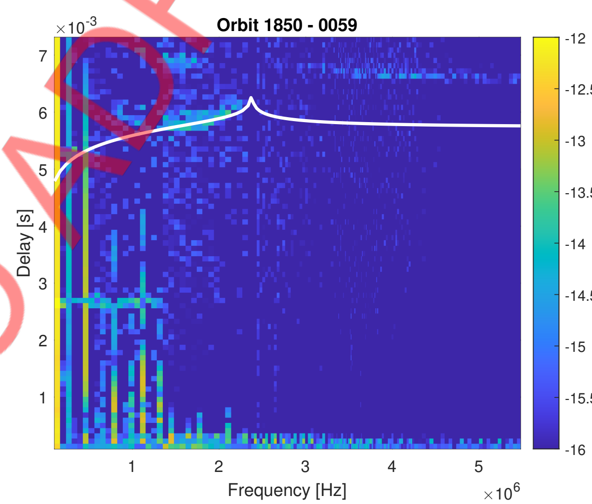

Fig. 3. Mars Ionogram at orbit 1850 (white line-chapman profile) (Lat=-21.30 ,W.Long=214.50)(Day 175)

CONCLUSION

In this study, ionograms from different Mars Express spacecraft orbits were analyzed to estimate the electron density distribution of the Martian ionosphere using the Chapman profile. The parameters N_0, Z_0, and H_0 were individually varied to fit the ionospheric echo on the ionogram. The results show a wide range of variance for the characteristic parameters and different shapes and sizes of the echoes, depicting different Martian terrain. The abundance of harmonics and electro static plasma oscillations seen in the ionograms can help determine the local plasma frequency and local crustal magnetic field passed by the spacecraft. The study also suggests that subsurface reflections can be seen when the spacecraft is at higher solar zenith angles, and information on the altitude of echoes can be determined upon understanding the topography of Mars. As a future work, comparison with the topography will provide meaningful results on the reason behind the peaks.

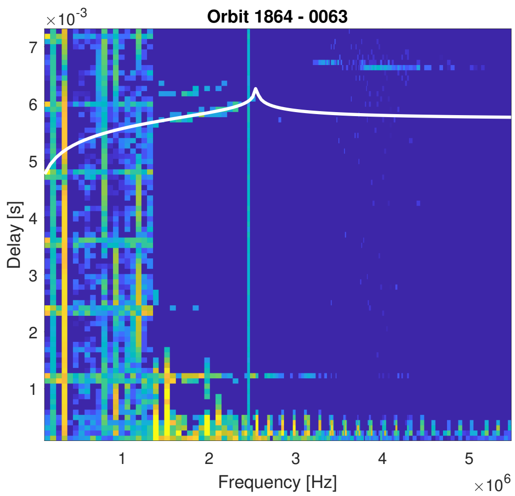

Fig. 4. Mars Ionogram at orbit 1864 (white line-chapman profile) (Lat=-23.50 ,W.Long=150.02)(Day 179)

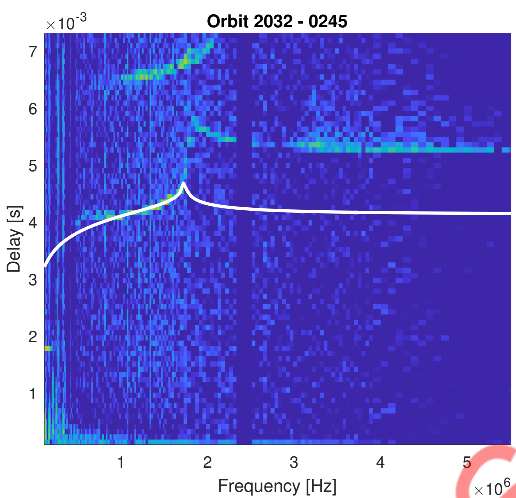

Fig. 5. Mars Ionogram at orbit 2032 (white line-chapman profile) (Lat=48.18 ,W.Long=100.55)(Day 226)

Overall, this study provides valuable insights into the structure and characteristics of the Martian ionosphere, which can help improve our understanding of the planet's atmosphere and its interactions with the space environment.

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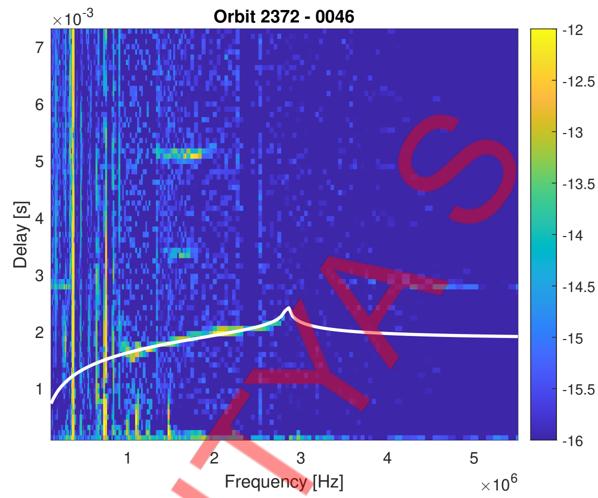

Fig. 6. Mars Ionogram at orbit 2372 (white line-chapman profile) (Lat=-83.06 ,W.Long=50.60)(Day 321)

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