Ionospheric Electron Density and Temperature Measurements with the Mars Express MARSIS Instrument[1]

by

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I. Introduction

Ionospheric measurements are an integral part of the MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) investigation that was proposed and subsequently selected for flight on the Mars Express mission. Recently a proposal was made by Dr. Jean Gabriel Trotignon and associates (copy attached) to add an antenna impedance circuit (acronym AIM) to the MARSIS instrument for the purpose of providing measurements of the ionospheric electron density and temperature. The purpose of this document is to discuss the scientific and technical integration of the antenna impedance circuit into the MARSIS instrumentation and to recommend its selection by ESA as an integral part of the MARSIS investigation.

The primary objective of the MARSIS investigation is the detection of subsurface water by radio sounding. Since the performance of the subsurface radar sounding system is strongly influenced by the ionosphere, the study of the Martian ionosphere contributes directly to the primary scientific objective of MARSIS. The ionosphere affects the subsurface sounding in two ways. First, the maximum electron plasma frequency in the ionosphere, f_p(Max), determines the lowest radar frequency that can reach the surface (see Figure 1). Since it is desirable to use the lowest possible radar frequency in order to achieve deep subsurface penetration, it is important to have good knowledge of the global distribution of the electron density. The electron density is directly related to the electron plasma frequency via the equation $f_p(\mathrm{Max}) = 8980\sqrt{n_e}$ Hz (where n_e is the electron density in cm^{-3}). It is particularly important to study the electron density on the nightside of Mars, since this is the region where the plasma frequency is the lowest and the best subsurface radar performance can be achieved. Unfortunately, very little is known about the electron density on the nightside of Mars, other than it is probably quite low due to the absence of ionizing ultraviolet radiation from the Sun. Second, because of the dispersive nature of radio wave propagation in ionized plasmas, at frequencies above the plasma frequency the radar signal suffers dispersion as it passes through the ionosphere. Dispersion occur because different frequencies propagate at different velocities. The relevant velocity is the group velocity, which is

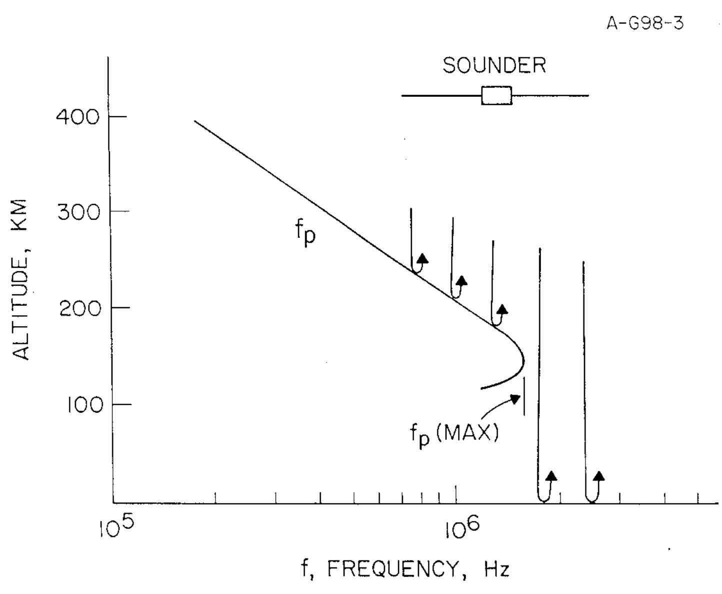

Figure 1. Radar signals from a sounder can only propagate through the ionosphere at frequencies above the maximum plasma frequency in the ionosphere, f_p(Max). Below this frequency the signals are reflected at the height where $f = f_p$.

given by $v_g = c\sqrt{1-(f/f_p)^2}$, where c is the speed of light. As can be seen, the group velocity goes to zero as the wave frequency approaches the plasma frequency. For a chirp type radar, such as used on MARSIS, this dispersive effect must be removed, otherwise the performance of the pulse compression that is used to improve range resolution can be severely degraded It is anticipated that knowledge of the ionospheric electron density profile will be of considerable help in removing the ionospheric dispersion.

In addition to the subsurface sounding, the study of the ionosphere and its interaction with the solar wind is an important secondary objective of the MARSIS investigation. Among the terrestrial planets, the interaction of the solar wind with the ionosphere of Mars is unique. At Earth it is well known that the strong internal magnetic field shields the ionospheric plasma from a direct interaction with the solar wind. Since Mars has a very weak magnetic field, the interaction with the solar wind is expected to be much different than Earth, more like Venus, which has no magnetic field. However, compared to Venus, Mars is much farther from the Sun, which greatly reduces the ionizing effect of radiation from the Sun. Also, Mars is rotating at a much faster rate, which significantly changes the recombination dynamics on the nightside of the planet. Although the ionosphere of Venus has been extensively studied by the Pioneer-Venus Orbiter spacecraft, relatively little is known about the ionosphere of Mars. The primary measurements available come from radio occultation measurements using the Mariner and Viking spacecraft. However, radio occultations are constrained by the line of sight from Mars to Earth, and are not able to adequately probe the nightside of Mars. By performing ionospheric measurements the MARSIS instrument will contribute directly to the study of the Martian ionosphere and will complement other measurements on Mars Express that are designed to study the Martian atmosphere and its interaction with the solar wind.

II. Ionospheric Measurements Contemplated in the Original Proposal

Two types of ionospheric measurements were planned in the original SSRA (now called MARSIS**)** proposal. These are based on (1) ionospheric sounding, and (2) passive spectrum measurements. Ionospheric sounding consists of transmitting a series of narrowband pulses and detecting the reflection of these signals from the ionosphere as the frequency is swept across the frequency range of interest. Ionospheric soundings have been extensively used to study the ionosphere of Earth [Franklin and MacLean, 1969]. From the delay time of the reflected signal as a function of frequency one can compute the electron density as a function of height from the spacecraft to the point of maximum plasma frequency, which on the dayside of Mars occurs at an altitude of about 150 km (see Figure 1). The frequency range planned for the MARSIS ionospheric soundings is 100 kHz to 5.4 MHz. A representative plot of the time delay as a function of frequency for the Martian ionosphere is shown in Figure 2. This type of plot is called an ionogram. No information can be obtained from the bottom side of the ionosphere (below the point of maximum plasma frequency f_p(Max), see Figure 1) since no reflection is obtained from this region. Ionospheric sounding provides a remote sensing tool that has the great advantage of giving a full two-dimensional picture of the electron density as a function of altitude along the track of the spacecraft. The cusp in the ionogram (see Figure 2) gives the maximum plasma frequency in the ionosphere, f_p(Max), at a point directly below the spacecraft, which is of direct interest to the subsurface sounding. Electrostatic plasma oscillations (Langmuir waves) are also strongly excited at the local electron plasma frequency. These oscillations appear as a vertical "spike" in the ionogram (see Figure 2). The frequency of this spike gives a very accurate determination of the local electron density.

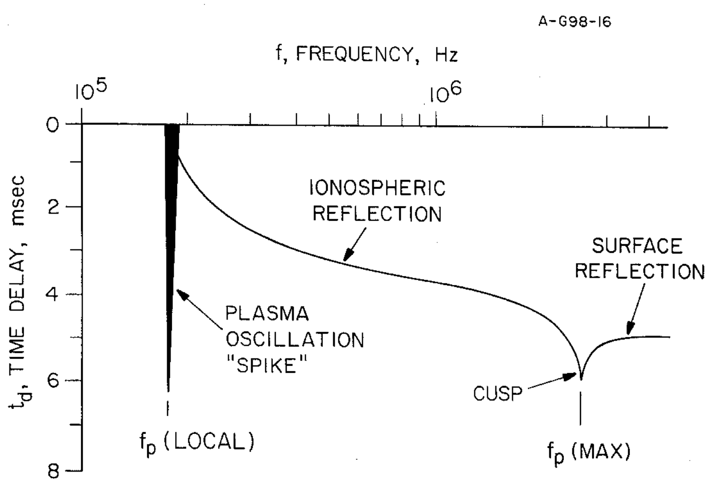

Figure 2. A plot of the time delay as a function of the transmission frequency for a radar signal reflecting from the ionosphere. The "spike" at f_p(Local) is due to the excitation of electrostatic electron plasma oscillations at the local electron plasma frequency. The "cusp" occurs at the maximum plasma frequency in the ionosphere, f_p(Max).

A crucial parameter needed by the subsurface radar to correct for the ionospheric dispersion is the electron column density through the ionosphere, $N = \int n_e ds$. Since ionospheric soundings are not able to give the electron density profile on the bottom side of the ionosphere, they cannot provide this parameter. To provide the electron column density through the ionosphere, a special sounding technique has been devised by S. Sorge of the University of Rome. This technique involves simultaneously transmitting pulses at two different frequencies above the maximum plasma frequency in the ionosphere. It is easily shown that the electron column density is directly related to the difference in the time delay between the surface return signals at these two frequencies. The methods by which this column density measurement could be used to remove the dispersion in the reflected subsurface radar signal are being explored.

The second basic method proposed for obtaining ionospheric parameters from MARSIS makes use of passive spectrum measurements, which will be acquired as a routine part of the subsurface sounder operation. For many years it has been known [Walsh et al., 1964; Mosier et al., 1973; Shaw and Gurnett, 1975] that a weak, thermally excited emission line exists at the electron plasma frequency (at the upper hybrid frequency in the case of a magnetized plasma).

Provided that the antenna length, L, is long compared to the Debye length, $l_D = 6.9\sqrt{(T/n)}$ cm (where T is the electron temperature in °K, and n is the electron density in cm^{-3}), the local plasma frequency, hence the local electron density, can be determined directly from the frequency of the thermal plasma line. Since the Debye length is typically only a few centimeters in a planetary ionospheres, the condition $L >> \lambda_D$ will almost always be satisfied in the Martian ionosphere. An example of a thermally excited plasma line is illustrated in Figure 3, which shows a frequency-time spectrogram from the Galileo spacecraft during the close flyby of the Earth that occurred on December 8, 1992. The thermal plasma line is clearly evident as the spacecraft passes through the ionosphere near closest approach, which is at about 1508 UT. Since the antenna length on

Galileo (6.6 meters tip-to-tip) is quite comparable to the antenna lengths used on MARSIS (40 meters tip-to-tip for the main dipole antenna and 5 meters for the monopole) a similar thermal plasma line will almost certainly be detectable in the Martian ionosphere. Since waveforms will be continually sampled from the two antennas during subsurface sounding, our plan is to simply Fourier transform the background noise spectrum, and present the results as a frequency-time spectrogram, similar to Figure 3. The electron density can be read directly from such a spectrogram. For this purpose it will probably be better to use signals from the monopole antenna rather the dipole antenna, since the frequency response of the dipole antenna is complicated by the impedance matching system used for transmitting the sounder pulse.

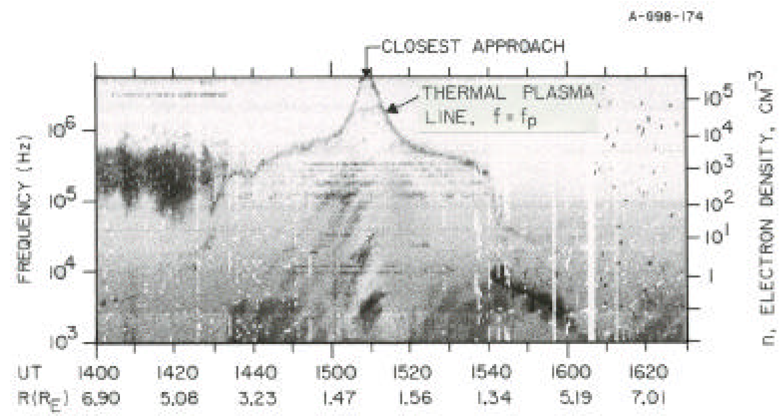

Figure 3. A frequency-time spectrogram of the electric field measurements obtained by the Galileo spacecraft during the December 8, 1992, flyby of Earth. The dark line labelled thermal plasma line is caused by thermal excitation of electron plasma oscillations at the local electron plasma frequency. The corresponding electron density is shown by the scale on the right. The passage through the ionosphere is clearly evident from the high electron densities near closest approach. The electron temperature can be determined from the shape of the plasma line.

In recent years the detailed shape of the thermal plasma line has also been exploited to give the electron temperature. The theory and detailed processing techniques involved are described in detail by Meyer-Vernet and Perche [1989]. Basically the noise originates from thermal excitation of electron plasma oscillations (Langmuir waves), which are electrically coupled to the antenna. The noise intensity at any given frequency is directly related to the real part of the antenna impedance. Since the noise is excited by thermal oscillations in the plasma, the relevant temperature is the temperature of the plasma, not the temperature of the antenna. This technique of determining the plasma temperature has the advantage that the measurement is completely unaffected by spacecraft charging and sheath effects, since the wavelength of the plasma oscillations is typically much greater than the dimensions of the spacecraft. The main disadvantage is that the thermal plasma line is very weak (typically only a few mV/m) and requires very low instrument noise levels to achieve good results. On Mars Express we expect to have low noise levels, below the cosmic noise level over most of the frequency range, so we anticipate no problem detecting the thermal plasma line. Indeed the successful operation of the subsurface radar sounder requires that the instrument noise levels be below the cosmic background. Of the two parameters that can be measured (i.e., the electron density and temperature), the temperature determination is the most sensitive to the signal-to-noise ratio. Because the electron density determination is less sensitivity to the signal-to-noise ratio, the electron density can probably be measured on very rapid time scales, 0.1 seconds or less. Longer integration times, probably several seconds or more, will probably be needed to obtain accurate temperature measurements. The main limitation of the overall technique is the Debye length. As the Debye length approaches the antenna length, the thermal emission line starts to broaden, and when the Debye length is larger than the antenna length, temperature measurements can no longer be obtained. Since the Debye length varies inversely with the square root of the ratio of the electron temperature to the electron density, the technique fails in regions where the electron density is low and the electron temperature is high, such as in the solar wind. The Debye length in the solar wind at the orbit of Mars is typically about 10 meters. The technique is expected to work well in all regions of the ionosphere with electron densities greater than about 1 to 10 cm^{-3}, with degraded resolution (particularly for the temperature) at densities from about 1 to 10 cm^{-3}, and with little or no possibility of measurements below 1 cm^{-3}. Note that the present MARSIS frequency range only goes down to a frequency of 100 kHz, which would preclude electron density measurements below about 120 cm^{-3}. However, there is no technical reason that the frequency range of the monopole receiver cannot be extended down to lower frequencies, on the order of 10 kHz, so we plan to do this. Interestingly in regions of very low density, where the thermal plasma line cannot be detected, it may still be possible to determine the electron density from the plasma frequency cutoff of various external electromagnetic emissions, such as cosmic noise and solar radio emissions.

III. Addition of Antenna Impedance Measurements

The primary objectives of the antenna impedance measurements proposed by Dr. Trotignon and associates are to measure the local electron density and temperature. These measurements rely on the same basic technique used for the passive measurements. The only difference is that the antenna impedance technique uses active measurements (i.e., an AC current injected into the antenna) to directly measure the real part of the impedance, rather than infer this quantity from the thermal noise spectrum. Since the signal voltage on the antenna can be easily made several orders of magnitude above the thermal noise level, the antenna impedance technique has a significant advantage over the passive spectrum technique in regions where the thermal plasma line is weak and hard to detect (i.e., in regions of low density and high temperature, less than 10 cm^{-3} and more than 10^4 °K). The main disadvantage of the antenna impedance technique is that it cannot be performed as often as the passive spectrum measurements, since the impedance measurement signal interferes with the subsurface sounder reception and will have to be operated on a duty cycle basis. Another potential problem is that the impedance measurement circuit may degrade the performance and/or reliability of the subsurface sounder. The potential performance degradation comes mainly from the additional base capacitance that the impedance measurement circuit adds to the relatively short monopole antenna, which has a capacitance of only about 50 pf. We have studied this problem with Bob Manning of Dr. Trotignon's group and have concluded that the impedance measurement circuit cannot be inserted permanently between the monopole antenna and the preamplifier without seriously degrading the performance. The proposed solution is to use a relay switch between the monopole and the impedance measurement circuit, wired in such a way that the preamplifier always remains connected to the antenna. This arrangement leads to a relatively low capacity (≈5 pf). To compensate for the additional capacity we propose to increase the length of the monopole antenna from 5 to 7 m. This solution has the reliability problem that if the relay were to fail in the closed position (that shorts the antenna impedance circuit to the antenna), the performance of the sounder would be degraded, by perhaps as much as 3 to 10 dB.

Another potential advantage of the antenna impedance technique over the passive spectrum technique is that due to the improved signal-to-noise ratio, more complicated models can be used to represent the ionospheric plasma. For example Meyer-Vernet [1998] has shown that the impedance measurements can be fit to a two-component electron velocity distribution function that has both a cold and a hot component (i.e., two electron densities and two temperatures). It is unlikely that such a two-component model could be obtained from the passive technique. These measurements could be of considerable value for comparison with low energy plasma measurements on Mars Express, which are specifically designed to measure the nonthermal (i. e., high temperature) part of the electron distribution function. Overall we believe that the antenna impedance measurement technique strongly complements the passive measurement techniques already planned for MARSIS and we recommend its inclusion.

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