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Reconstruction of nonmonotonic electron density profiles of the Martian topside ionosphere

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ABSTRACT

One of the problems in reconstructing the real ionosphere from an ionogram is the occurrence of a 'valley,' where electron density decreases with altitude and make a non-monotonic profile. For the case of the Earth ionosphere, the ordinary and extraordinary ray data, accompanied with an empirical model, based on the observations, are necessary to obtain a mathematical solution for a 'valley,' such as the region between the E and F layers. MARSIS/MEX is a topside sounder designed to observe the ionosphere of Mars. Some 'valley' structures were found in the ionograms measured by MARSIS. The echoes of the extraordinary ray are not available owing to the absence of the strong magnetic field on Mars. Therefore, it is difficult to have a mathematical solution for the valleys in the Martian ionosphere. In this paper, a least square method with a simple model is presented to solve the 'valley' problem in the topside ionosphere of Mars. The electron density profiles with 'valleys' observed by the Radio Occultation experiment onboard MGS are used to rebuild the virtual depths at MARSIS frequencies. The reconstructed electron density profile by the least square method with a simple model from the rebuilt virtual depth curve is compared with the original electron density profile. It is proved that this method can reproduce small valleys in the profile of the Martian ionosphere well.

1. Introduction

A low frequency radar (MARSIS=Mars Advanced Radar for Subsurface and Ionosphere Sounding) is part of the scientific package on the orbiter of the Mars Express mission to Mars (Nielsen, 2004). The radar is designed to sound the Martian cryolithosphere, primarily in search of water in solid or fluid forms. In addition, the radar is used to sound the Martian ionosphere. The study of the ionosphere is important not only as a science subject, but also because the ionosphere has a strong influence on the performance of the subsurface sounder. In order to extract information about the regolith, the radar data have to be corrected for the presence of the ionosphere.

One of the problems in reconstructing the real ionosphere from an ionogram is the occurrence of a 'valley,' that is a region of decreased electron density making the profile non-monotonic. A valley is often found in the Earth's ionosphere, for example, the region between the E and F layers. The radar cannot directly 'see' such a valley, because the lower densities in the valley are hidden behind higher densities, which prevents the lower frequency radar signals from penetrating into the valley. However, the radar signals reflected from higher altitudes (with higher densities) on the other side of the valley are affected by its presence. When adequate data are available for both the ordinary and extraordinary ray, these unseen regions can be calculated with reasonable accuracy by a mathematical solution (Titheridge, 1975, 1988). The results of rocket and backscatter radar (Lobb and Titheridge, 1977) were used to establish a physical model for the valley at Earth. In the MARSIS experiment, one cannot distinguish between the ordinary and extraordinary waves owing to the weak magnetic field at Mars. Therefore, it is difficult to apply the mathematical methods so useful in the Earth's ionosphere in the case of the Martian ionosphere.

According to the electron density profiles observed by the Radio Occultation experiment onboard MGS, there are wave-like structures in the Martian topside ionosphere (Wang and Nielsen, 2003), which form many "valleys". In this paper, we present a least square method with a simple model as a method of solving the valley problem associated with such wave activity. First, we construct a realistic ionogram of the Martian ionosphere by using the electron density profiles observed by MGS. We then rederive the electron densities from the constructed ionogram without

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making use of the knowledge of the actual electron density profiles. Finally, we discuss the validity of our method.

2. Derivation of a realistic ionogram from MGS data

In the radio occultation technique, the electron density profile, including valleys, can be derived from the observations. In this technique, a radio wave is transmitted tangential to the planet, starting at the top of the ionosphere. The phase of the signal is measured after it has passed through the ionosphere. As the 'tangent' moves closer to the planet, the phase variation is measured, and from this the electron density profile can be estimated (Fjeldbo et al., 1971). We have chosen an electron density profile measured in this way onboard Mars Global Surveyor (MGS). This profile is shown in Fig. 1.

The topside ionosphere as observed by MGS extends between ~135 and 210 km altitude. The altitude range over which MARSIS makes the sounding is from about 275 to 1200 km (Gurnett et al., 2005). When constructing the ionogram from the selected density profile, we assume that the spacecraft with the sounder is located at an altitude of 350 km. In addition, we assume that we know the local electron density at the spacecraft. When a radar signal at the plasma frequency is transmitted, it cannot propagate in the plasma but instead a standing wave at the plasma frequency is excited giving a characteristic signature in the MARSIS data (Duru et al., 2008). The spacecraft location, with the known altitude and electron density, is an 'anchor point' in the construction of the ionogram from the top side sounder data. It is further assumed that the ionosphere densities are varying exponentially between the anchor point and the first reflection point in the ionosphere with a constant electron density scale height. Using this profile and these assumptions, the virtual height of the ionosphere below the spacecraft can be calculated for each of the MARSIS frequencies.

We assume that the electron density at an altitude of Mars Express, $h0$, equals $Ne0$ (for example, $Ne0=20\#/cm^3$), i.e. that this is the measured resonance density. From this level down to a certain altitude $h_{MGS}(1)$, an altitude of the highest point in the electron density profile as shown in Fig. 1, the electron density increases exponentially to the measured value $N_{MGS}(1)$, which can be described by

$$N = Ne0\exp((h-h0)/H) \quad (1)$$

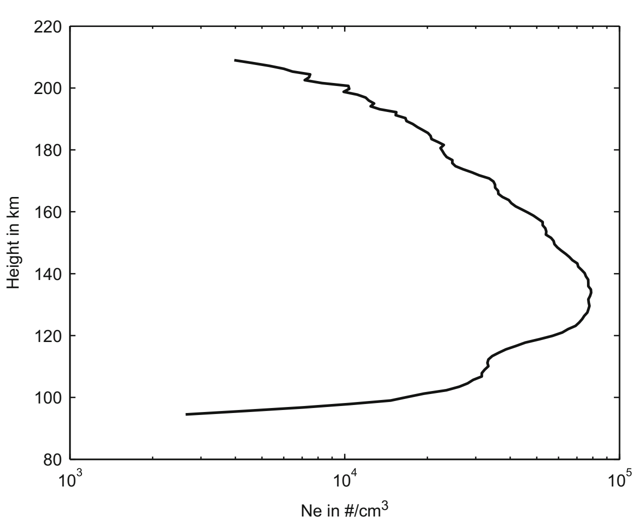

Fig. 1. Selected MGS electron density profile. The information of this profile is as following: the occultation time is 17:25:25 UT 21–December–2000, the latitude and longitude of this profile are 69.5° and 274.5°, respectively, the solar zenith angle is about 80.5° and the solar longitude is about 92.4°.

where h is the altitude, H is the electron density scale height, which is assumed to be constant between $h0$ (for example, 350 km) and $h_{MGS}(1)$. Since the radar observes the ionosphere from space, it is not the altitude of the electron density, but rather the distance from the radar downward towards the planet (the depth) that equals the radar range. The altitude profile is therefore transferred into a depth profile, using depth = 350 − altitude.

Fig. 2 shows the part of the ionosphere the radar will 'see' with the low densities at near ranges, at the top of the ionosphere, and with densities increasing with increasing depth.

It is convenient to translate the electron density depth profile into the equivalent plasma frequency profile by using Eq. (2)

$$f_p = 8.89\sqrt{N_e[\mathrm{cm}^3]}[\mathrm{kHz}] \quad (2)$$

In Fig. 3, furthermore, are shown only those frequency points, which correspond to the MARSIS frequencies. The frequency resolution of MARSIS is determined by the intervals between the neighboring MARSIS frequencies. Since an MGS depth profile has a resolution of about 1 km, the depths for the MARSIS frequencies have been obtained by interpolation in the MGS data. The (density) plasma frequency profile in Fig. 3 is derived from the topside profile shown in Fig. 2.

For MARSIS frequencies smaller than $f_{MGS}(1)$, the first frequency point of the MGS topside profile at $h_{MGS}(1)$, the real depth is determined by Eqs. (1) and (2)

$$h = 2H\ln\left(\frac{f}{f0}\right) \quad (3)$$

where h is the depth from $h0$, H is the electron density scale height assumed constant between $h0$ and $h_{MGS}(1)$. Ignoring small structures, the real depth increases almost linearly with plasma frequency for this example.

The actual depth profile is now transformed into a virtual depth profile by using Eq. (4).

$$h' = \int_0^{t_d} \frac{c}{2}\,dt = \int_{h0}^{h_r} \frac{dh}{n} \quad (4)$$

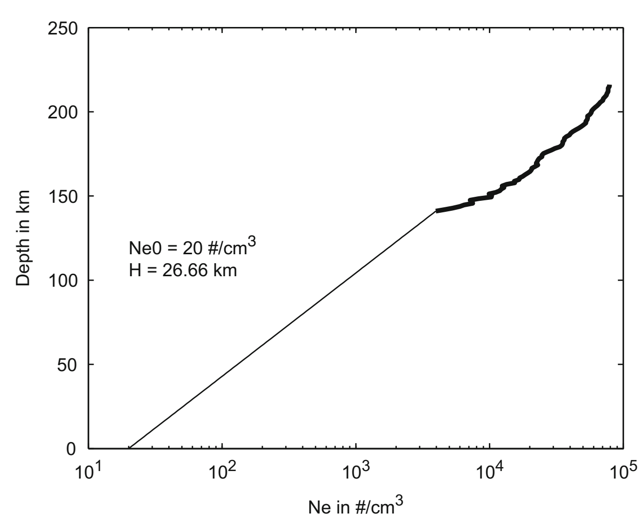

Fig. 2. Schematic model of a topside electron density depth profile. The wide line is the original observed topside profile of an MGS measurement as shown in Fig. 1, the thin line is the assumed variation between the sounder spacecraft and $Ne_{mgs}(1)$, the first point of an MGS topside profile at $h_{MGS}(1)$ and a density of ~4000 el/cm^3. The electron density at the assumed altitude of the topside sounder spacecraft (MARSIS), $h0$, is assumed to be $Ne0=20\#/cm^3$, the corresponding electron density scale height, H, between $h0$ and $h_{MGS}(1)$ is 26.66 km.