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Martian electron density profiles retrieved from Mars Express dual-frequency radio occultation measurements

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Abstract

The S- and X-band dual-frequency Doppler radio occultation observations obtained by the Mars Express Radio Science (MaRS) experiments are reduced in this study. A total of 414 Martian electron density profiles are retrieved covering the period from DOY 93 2004 to DOY 304 2012. These observations are well distributed over both longitude and latitude, with Sun–Mars distance varying from 1.38 AU to 1.67 AU, the solar zenith angle (SZA) ranging from 52° to 122°. Due to the improved vertical resolution for the MaRS experiments, the vertical structures of the retrieved profiles appear to be more complicated than those revealed by early radio occultation experiments. Dayside electron density profiles have primary peaks (M2) typically around 130 km and secondary peaks (M1) around 110 km. Nightside electron density profiles are highly variable, many of which do not have double layer structures. Both the dayside and nightside electron density profiles reveal some atypical features such as topside layering above M2 and bottom-side layering below M1. The former likely represent the plasma fluctuations in response to the solar wind (SW) interactions with the Martian ionosphere, whereas the latter is thought to be induced by the meteoric influx. We fit the peak electron density of profiles up to terminator with a simple power relation $\left(N_m = \frac{N_0}{\mathrm{Ch}^k(\chi)}\right)$, with the best-fit subsolar peak electron density being $N_0 = (1.499 \pm 0.002) \times 10^5\ \mathrm{cm}^{-3}$, and the best-fit power index being $k = 0.513 \pm 0.001$. The measured total electron content (TEC) is obtained by integrating the observed electron density profile vertically from 50 km to 400 km, which is then compared with the ideal TEC computed from the one-layer Chapman model. We find that the one-layer Chapman model can generally underestimate the measured TEC up to ~0.1 TECU ($1\ \mathrm{TECU} = 1.0 \times 10^{16}\ \mathrm{m}^{-2}$) for $55° < \mathrm{SZA} < 90°$ and up to ~0.05 TECU for $90° < \mathrm{SZA} < 120°$. The dayside TEC ($\mathrm{SZA} \leqslant 75°$) varies from 0.1 to 0.6 TECU, whereas the nightside TEC ($\mathrm{SZA} \geqslant 105°$) is usually below 0.2 TECU. Several large TEC values can be found in the terminator region. The corresponding slab thickness varies from 40 km–60 km for the dayside and 40 km–140 km for the nightside, with an average value of 61 km.

Keywords: Martian ionosphere; Radio occultation; Inversion; Differential Doppler

1. Introduction

The structure of the Martian ionosphere has been the subject of extensive research since the 1960s (Withers, 2009, and references therein). At the dayside, the Martian ionosphere contains a well-defined primary layer (hereafter M2) and a low altitude secondary layer (hereafter M1), that have been frequently drawn analogy to the terrestrial F1 and E layers (Rishbeth and Mendillo, 2004). The M2 layer is produced mainly by solar EUV ionization and the M1 layer by solar X-ray ionization along with impact ionization by photoelectrons and secondary electrons

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(e.g., Martinis et al., 2003, 2006). At the nightside, the Martian ionosphere becomes substantially more complicated, with electron precipitation from the Solar Wind (SW) and day-to-night transport being the two most likely sources of ionization (e.g., Zhang et al., 1990, 1993). Significant amounts of information on the Martian ionosphere comes from the radio occultation (RO) measurements made onboard several spacecrafts, which utilize the radio links between the orbiters and the ground telescopes to measure the signal variations caused by changes in the local refractivity of the Martian ionosphere (e.g., Fjeldbo et al., 1971, 2014).

The RO measurements of the Martian ionosphere started with Mariner 4 in 1965 (Kliore et al., 1965), followed by Mariner 9 (Kliore et al., 1972, 1973) as well as Viking 1 and 2 (Lindal et al., 1979). A total number of 443 individual electron density profiles were acquired by these early measurements (Mendillo et al., 2006). Later, this number increases substantially, with over 5600 electron density profiles collected by the RO measurements made onboard the Mars Global Surveyor (MGS) from December 1998 to June 2005 (Tyler et al., 2001). These measurements have a restricted latitude (LAT) coverage, either at mid/high northern latitudes between 60.6° N and 86.0° N or at mid southern latitudes between 64.7° S and 69.0° S. The SZA coverage is also restricted, being exclusively with a SZA range of 71°–89°. Such a large dataset has recently been complemented by the RO measurements made onboard the Mars Express (MEX) (Pätzold et al., 2005). Despite a smaller number of available electron density profiles (due to the relatively long MEX orbital period as well as the reconciliation with measurements made in the bistatic radar, gravity and solar corona modes, cf. Pätzold et al., 2004), the MEX RO measurements have a more extended distribution in both LAT and SZA, as illustrated in Fig. 1. Especially, our information on the nightside Martian ionosphere has improved significantly by these measurements, covering the SZA range up to 122° (e.g., Withers et al., 2012b).

RO measurements are not allowed to be made at the deep dayside (SZA < 44°) and the deep nightside (SZA > 136°) due to geometrical restrictions (Gurnett et al., 2008). Meanwhile, the extraction of the electron density profiles from these data is subject to the assumption of a spherical symmetric ionosphere, which is not strictly correct. However, the RO technique does have important advantages, with a better vertical resolution than the traditional in situ techniques (e.g., Hinson et al., 1999) and with a full coverage of the ionospheric electron distribution both above and below the M2 peak as compared to the radar sounding technique probing the topside ionosphere only (Picardi et al., 2005).

In contrary to a large number of research efforts that have been devoted to the MGS RO data (Withers and Mendillo, 2005; Mendillo et al., 2006; Fox and Yeager, 2009; Fox and Weber, 2012; Zou et al., 2011), the MEX RO data have been much less investigated. This is partly because the derived electron density profiles, rather than the raw measurements of radio signal frequency, are not freely accessible as are the MGS profiles at the NASA Planetary Data System (PDS) public archives. In addition, the expertise required by a proper reduction of the raw RO data is not widespreadly possessed by the majority of the planetary scientists with relevant research interests (Withers et al., 2014). In this study, we present our own efforts of reducing the MEX RO data, independent of and complementary to those of the Cologne group in Europe (Pätzold et al., 2005), as well as those of the Boston group in US (Withers et al., 2014). As stated by Muhleman (1978), existing analyses of the RO data "should be subject to independent confirmation, both to determine the reproducibility of the results and to check for systematic errors". The relevant electron density profiles have been uploaded to my homepage (http://202.127.29.4/sjzhang/) in a format similar to that of the MGS RO data to facilitate their use by different investigators.

The paper is organized as follows: The dual-frequency Doppler inversion algorithm and the detailed data analysis procedure are presented in Section 2, where the derived electron density profiles are validated with published results (e.g., Pätzold et al., 2005; Withers et al., 2012a,b). While various aspects of the Martian ionosphere based on these data are to be thoroughly investigated in follow-up studies, here only some broad characteristics

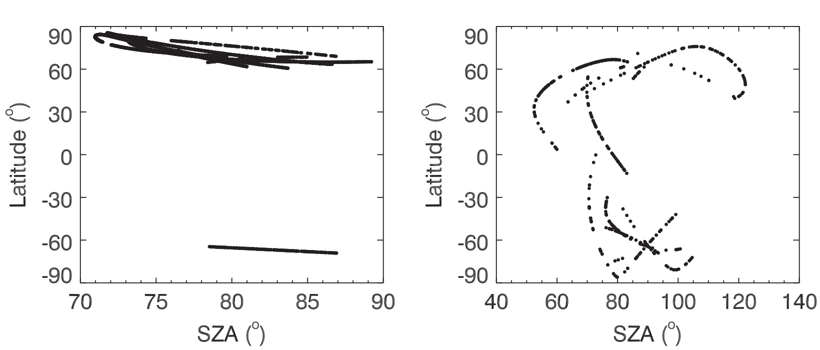

Fig. 1. MGS (left panel) and MEX (right panel) RO observation distribution against both solar zenith angle and latitude (in Mars fixed coordinate system).