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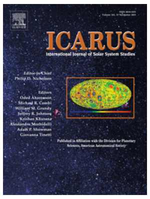

Improved estimation of Mars ionosphere total electron content

M. Cartacci[a,*], B. Sánchez-Cano[b], R. Orosei[d], R. Noschese[a], A. Cicchetti[a], O. Witasse[c], F. Cantini[e], A.P. Rossi[f]

[a] *Istituto di Astrofisica e Planetologia Spaziali (IAPS), Istituto Nazionale di Astrofisica (INAF), Rome, Italy*
[b] *Radio and Space Plasma Physics Group, Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, United Kingdom*
[c] *European Space Agency, ESTEC – Scientific Support Office, Keplerlaan 1, Noordwijk 2200 AG, The Netherlands*
[d] *Istituto di Radioastronomia (IRA), Istituto Nazionale di Astrofisica (INAF), Bologna, Italy*
[e] *Ecole Polytechnique Federale de Lausanne, Space Engineering Center, EPFL ESC, Station 13, 1015 Lausanne, Switzerland*
[f] *Department of Physics and Earth Sciences, Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany*

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ABSTRACT

We describe an improved method to estimate the Total Electron Content (TEC) of the Mars ionosphere from the echoes recorded by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al., 2005; Orosei et al., 2015) onboard Mars Express in its subsurface sounding mode. In particular, we demonstrate that this method solves the issue of the former algorithm described at (Cartacci et al., 2013), which produced an overestimation of TEC estimates on the day side.

The MARSIS signal is affected by a phase distortion introduced by the Mars ionosphere that produces a variation of the signal shape and a delay in its travel time. The new TEC estimation is achieved correlating the parameters obtained through the correction of the aforementioned effects.

In detail, the knowledge of the quadratic term of the phase distortion estimated by the Contrast Method (Cartacci et al., 2013), together with the linear term (i.e. the extra time delay), estimated through a radar signal simulator, allows to develop a new algorithm particularly well suited to estimate the TEC for solar zenith angles (SZA) lower than 95° The new algorithm for the dayside has been validated with independent data from MARSIS in its Active Ionospheric Sounding (AIS) operational mode, with comparisons with other previous algorithms based on MARSIS subsurface data, with modeling and with modeling ionospheric distortion TEC reconstruction.

1. Introduction

The Mars ionosphere is created by the ionization of the neutral atmosphere and its electron density is the result of a dynamic balance between the production and loss processes of free charged species.

The density of the free electrons N_e vary substantially with location, solar illumination, solar activity and season, due to complex interactions between solar photon fluxes and solar wind with the neutral gas. The Mars case is even more complicated due the absence of an appreciable global magnetic field and the presence of magnetic crustal anomalies, that produce a direct interaction between the ionosphere and the solar wind.

The use of a low-frequency radar sounder to analyse the surface and subsurface of Mars, such as the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on board Mars Express (Picardi et al., 2005), must take into account the dispersion caused by the ionosphere on the propagating signal, which depends on the operative frequencies adopted.

In this paper, we report about improved processing procedures, implemented in order to remove the effects of the ionosphere from the radar signal, because what was a problem for the sounding of the subsurface becomes a useful source of information in the study of the ionosphere. The outcome of this processing is a data set of high-accuracy values of the Total Electron Content (TEC) of the full atmosphere, covering about 10 years of scientific operations of the MARSIS radar.

In the following, Section 2 contains a brief description of the main effects of the Martian ionosphere on radar propagation; Section 3 describes the MARSIS instrument; Section 4 describes the methods developed to compensate the ionosphere effects, the description of the new algorithm for the TEC estimation and the

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[*] Corresponding author.
E-mail addresses: marco.cartacci@iaps.inaf.it (M. Cartacci), bscmdr1@leicester.ac.uk (B. Sánchez-Cano), roberto.orosei@inaf.it (R. Orosei), raffaella.noschese@iaps.inaf.it (R. Noschese), andrea.cicchetti@iaps.inaf.it (A. Cicchetti), owitasse@cosmos.esa.int (O. Witasse), federico.cantini@epfl.ch (F. Cantini), an.rossi@jacobs-university.de (A.P. Rossi).

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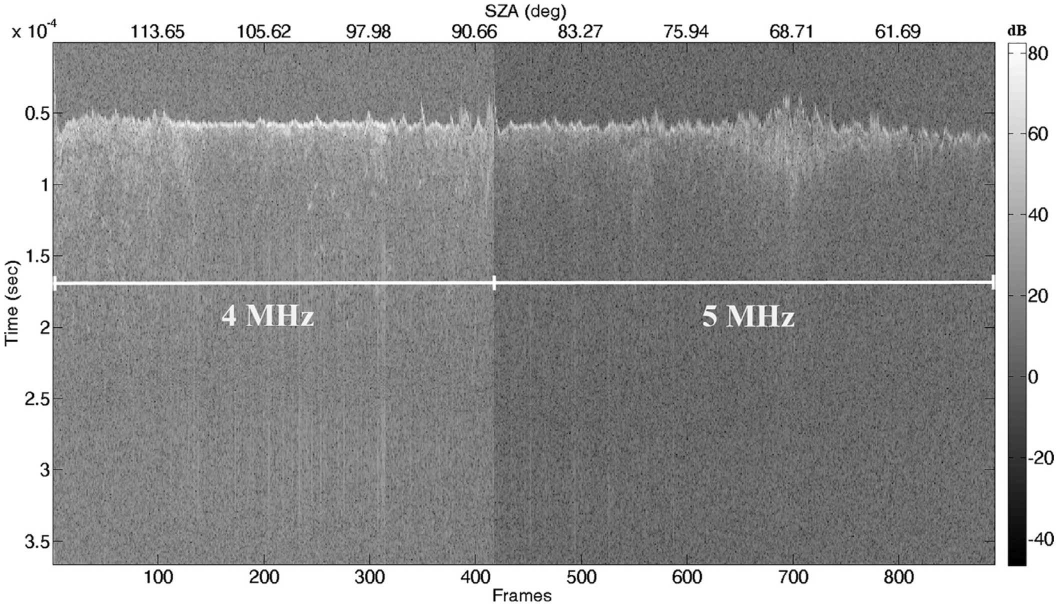

Fig. 1. Orbit 4646 radargram. The signal is range compressed with the CM, but the tracking trigger is not removed, so the surface and subsurface topography information are lost. The different brightness is related to the different gain used by the Automatic Gain Control (AGC) for each frequency.

results obtained, while Section 5 contains a discussion of the results and a brief summary and a discussion of possible future developments.

2. The effects of the Mars ionosphere on MARSIS signal propagation

The presence of the Martian ionosphere produces a variation of the refraction index with respect to vacuum. As a consequence, for an electromagnetic wave of frequency f, the propagation in the ionosphere is characterized by the following refraction index (Safaeinili et al., 2007):

$$n(z) = \sqrt{1 - \frac{f_p^2(z)}{f^2}} \tag{1}$$

where f_p is the plasma frequency and z is the altitude above ground. The plasma frequency, in Hz, can be written as

$$f_p(z) = 8.98\sqrt{N_e(z)}, \tag{2}$$

where N_e is the electron density in m^{-3}.

According to Eq. (1) all frequencies lower than f_p will be reflected, while those higher will be delayed. Moreover, since the radio wave propagation speed varies according to the refraction index and the frequency in the bandwidth, the chirp will be affected by phase dispersion (Budden, 1985). Therefore, in the presence of an ionosphere, the signals will be attenuated, delayed and defocused with different levels of severity depending on the electron density values encountered along the path (Cartacci et al., 2013). All these effects, if not compensated, can drastically reduce the quality of the data. In particular, the defocusing distorts the waveform shape, worsening the signal to noise ratio and the range resolution (see Fig. 1, Cartacci et al., 2013).

In order to remove, or at least reduce, the distortion, a dedicated algorithm was developed, called the Contrast Method (Picardi and Sorge, 2000; Cartacci et al., 2013) and was implemented in both on-board and on-ground processing. The Contrast Method (hereafter CM) does not compensate the group delay of the radar pulse. The correct arrival time of the echo can be estimated from the spacecraft altitude above the surface, or by using simulations of surface scattering of the radar pulse (see e.g. Nouvel et al., 2004; Russo et al., 2008).

3. The MARSIS instrument

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al., 2005), carried by ESA's Mars Express spacecraft, is a nadir-looking pulse-limited radar sounder, which uses synthetic aperture (SAR) techniques to achieve a higher signal-to-noise ratio and along-track resolution. MARSIS was developed by the University of Rome "La Sapienza", Italy, in partnership with NASA's Jet Propulsion Laboratory in Pasadena, California. The main task of the MARSIS experiment is to map the distribution of water, both liquid and solid, on Mars, with the secondary objective of characterizing the structure of the Martian ionosphere. In order to achieve these goals, MARSIS has two operation modes: the SS (Sub-Surface) Mode and the AIS (Active Ionosphere Sounding) Mode.

When sets in AIS Mode, MARSIS works as a swept frequency sounder, transmitting 160 spaced frequencies from 100 kHz to 5.5 MHz (Morgan et al., 2008). In this way, the radar is able to characterized the upper profile of the ionosphere estimating the topside electron density N_e. These in-situ measurements, must be considered as a reference for any study related to the Mars ionosphere.

In its Sub-Surface (SS) mode, MARSIS transmits "chirps", i.e. wave packets of duration $T = 250\,\mu\mathrm{sec}$ which are linearly modulated in frequency over a bandwidth $B = 1$ MHz, centred at 1.8 MHz, 3 MHz, 4 MHz or 5 MHz, alternating the transmission at two different frequencies, from a 40-m dipole antenna with a Pulse Repetition Frequency (PRF) of 127 Hz. MARSIS frequencies are optimized for deep penetration of the surface of Mars but are vulnerable to ionospheric effects; for this reason, the two frequencies are chosen according to the Solar Zenith Angle (SZA) at the time of observation, in order to have the transmitted bandwidth always higher than the local plasma frequency, and therefore, be able to penetrate the full atmosphere with the smallest possible degradation. As the electron density is known to be lower in the night side (Gurnett et al., 2008), this constraint implies that the MARSIS subsurface sounder is best utilized for values of SZA higher than 90° For this reason, normally during the night side (SZA >= 90°) the carrier frequencies used are 4 MHz and 3 MHz, while during the day side (SZA < 90°) the carrier frequencies used are 5 MHz and