Improved estimation of Mars ionosphere total electron content

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\textbf{A B S T R A C T}

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 Ionosphere Sounding (AIS) operational mode, with comparisons with other previous algorithms based on MARSIS subsurface data, with modeling and with modelling ionospheric distortion TEC reconstruction.

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\textbf{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
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 (Safaeeinili et al., 2007):

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

(1)

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

\[
f_p(z) = 8.98 \sqrt{N_e(z)}
\]

(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 characterize 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 \( T = 250 \mu \text{sec} \) which are linearly modulated in frequency over a bandwidth \( B = 1 \text{ MHz} \), 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...
4 MHz. The lowest frequency of 1.8 MHz is rarely used because it can only work properly during the deep night side (SZA > 115°) (see Fig. 5, Cartacci et al., 2013) and it is more vulnerable to local variation of the ionosphere than higher frequencies.

Along an orbit, the MARSIS radar performs a large number of synthetic apertures (frames). Each frame consists of about 200 radar pulses (this value depends on different parameters such as signal frequency, altitude, tangential velocity etc.), transmitted in a segment of orbit at least 5.5 km long (minimum value for a single synthetic aperture). Typically, between two frames the SZA variation is around 0.05°/0.06°, so we assumed the ionosphere as stationary within a single synthetic aperture.

The on-board processing consists of two steps: the azimuth compression, where the echoes received for each transmitted pulse are integrated together (unfocused SAR) and the range compression, which is the product, in the frequency domain, between the integrated signal and a matched filter (an ideal “chirp” used as reference function).

The next step consists in the tracking phase, where the signal position inside the receiving window is checked. It is worth noting that the signal travel time can vary considerably according to the Mars surface topography and the presence or not of an extra delay time due to the ionosphere.

For this reason, MARSIS is equipped with a tracking loop working with an Offset Center Of Gravity (O.C.O.G.) algorithm (Wingham et al., 1986).

\[
OCOG = \frac{\sum_{i=ini\_ind}^{last\_ind} P_b(i) - \sum_{i=ini\_ind}^{last\_ind} P_b(i)}{2 \times \sum_{i=ini\_ind}^{last\_ind} P_b(i)^2} \tag{3}
\]

where \(P_b\) is the signal power, while \(ini\_ind\) and \(last\_ind\) represent the range of samples where the algorithm is applied.

With the exception of the first frame of the orbit, where the spacecraft (S/C) altitude and then the receiving window position is estimated in real time using an eighth-degree polynomial function, for subsequent frames the receiving window opening time is estimated through the tracking loop. In detail, the O.C.O.G. estimates the position of the radar signal after azimuth and range compression, while the tracking loop works to align all echoes around set position inside the receiving window.

Due to data volume constraint, signals transmitted to the ground are in the frequency domain and are only compressed in azimuth. In order to complete the signal processing, the MARSIS Ground Segment performs the range compression with a dedicated processor.

The effect of the tracking algorithm is visible in the radargram of Fig. 1, related to orbit 4646, where echoes are shown after azimuth and on-ground range compression. The brightness variation is due to the frequency switch between 4 MHz and 5 MHz (for an SZA = 89.29°) and its related to the gain used by the Automatic Gain Control (AGC) of the radar.

A radargram is a representation of frames obtained by synthesizing radar pulses acquired continuously during the movement of the spacecraft as a grey-scale image, in which the horizontal dimension is distance along the ground track, the vertical dimension is the round trip time of the echo, and the brightness of the pixel is a function of the strength of the echo. It is easy to see that the tracking loop has completely removed the information related to the topography along the ground track of the radar, which hinders scientific interpretation. For this reason, the opening time of the receiving window is transmitted to the ground, together with the data, in order to allow a reconstruction of the actual signal delay with respect to a fixed altitude above the Martian ellipsoid.

In Fig. 2, the tracking trigger has been compensated before the completion of processing through range compression. Now, surface topography can be discerned, even if the ionosphere delay adds an unnatural slope to the radargram.

As discussed in Section 2, the range compression is performed using the Contrast Method.

The CM consists in iterating the correlation of the radar echoes with the transmitted signal using different phase compensation terms in order to produce a range compressed signal with the best energy concentration in a defined time interval of the receiving window.

Fig. 3 shows the same radargram of Fig. 2 obtained processing the signals without the CM. It is evident that the use of the CM yields an improvement of all the key radar parameters such as higher peak power, a better signal to noise ratio and a reduction of the main lobe width. This allows having a better range resolution increasing the capability to discriminate surface and subsurface echoes.

4. Evaluation of the TEC through the CM and radar echo simulation

4.1. A new algorithm for TEC estimation

As introduced in Section 2, the ionosphere induces a phase shift in a radar signal of frequency \(f\) that can be written as:

\[
\Delta \phi(f) = \frac{4 \pi}{c} \int_0^L [n(z) - 1] dz = \frac{4 \pi}{c} \int_0^L \left[ 1 - \left( \frac{f_\text{p}(z)}{f} \right)^2 - 1 \right] dz \tag{4}
\]

where \(L\) is the ionosphere thickness and \(c\) is the speed of light in vacuum.

If \(f_0\) is the central frequency of the radar signal band, we can perform a Taylor expansion of the integrand of Eq. (4) and then integrate each term of the expansion, so as to obtain (see Eq. (5) and Fig. 1, Cartacci et al., 2013)

\[
\Delta \phi(f) \approx a_0 + a_1(f - f_0) + a_2(f - f_0)^2 + a_3(f - f_0)^3 + a_4(f - f_0)^4 + \ldots \tag{5}
\]

where:

\[
\begin{align*}
a_0 &= \frac{4 \pi}{c} f_0 \int_0^L \left( \sqrt{f_\text{p}^2 - f_0^2} - f_0 \right) dz \quad \text{[rad]} \\
a_1 &= \frac{4 \pi}{c} f_0^2 \int_0^L \left( \frac{f_\text{p}}{f_\text{p}^2 - f^2} - 1 \right) dz \quad \text{[rad/Hz]} \\
a_2 &= -\frac{4 \pi}{c} f_0^3 \int_0^L \left( \frac{f_0}{2(f_\text{p}^2 - f_0^2)} \right) dz \quad \text{[rad/Hz^2]} \\
a_3 &= \frac{4 \pi}{c} f_0^4 \int_0^L \left( \frac{f_0^2}{2(f_\text{p}^2 - f_0^2)} \right) dz \quad \text{[rad/Hz^3]} \\
a_4 &= \frac{4 \pi}{c} f_0^5 \int_0^L \left( \frac{4f_\text{p}^3}{2(f_\text{p}^2 - f_0^2)} \right) dz \quad \text{[rad/Hz^4]}
\end{align*}
\]

In particular, we focus our attention to the terms \(a_1\) and \(a_2\).

The term \(a_2\), producing a wide main lobe signal, is responsible for the signal defocusing showed in Fig. 3, while the term \(a_1\) represents the extra delay time introduced by the ionosphere (see Fig. 1, Cartacci et al., 2013). The Contrast Method (Cartacci et al., 2013) estimates the quadratic term \(a_2\) (\(a_{2CM}\)) while comparing the received signal with the simulated one, we estimate the term \(a_1\) (\(a_{1SIM}\)), so we can assume:

\[
\begin{align*}
a_{1SIM} &= 2\pi \tau \quad \tau \equiv a_1 \\
a_{2CM} &= a_2
\end{align*}
\]
Moreover, both terms of Eq. (6), after a series expansion, can be expressed as:

\[
a_1 = \frac{4\pi}{c} \int \left( \frac{f_0}{(f_0 - f_p)^2} - 1 \right) dz \approx \frac{4\pi}{c} \int \left( \frac{f_p^2}{2f_0^2} + \frac{3f_p^4}{8f_0^4} \right) dz
\]

\[
a_2 = \frac{2\pi}{f_0^3} (8.98)^2 TEC + \frac{3\pi}{2c f_0^5} (8.98)^4 \int N_s^2(z) dz
\]

In a previous work (Cartacci et al., 2013), TEC was obtained by neglecting the \(-\frac{3\pi}{2c f_0^3} (8.98)^4 \int N_s^2(z) dz\) term from Eq. (9).

This approximation is not suitable for application to observations acquired on the day side, because it yields an overestimation of the TEC.

Indeed, during the night side, considering \(f_p = 1\) MHz and \(f_0 = 4\) MHz, the overestimation is lower than 10% (Cartacci et al., 2013), while during the day side for \(f_p = 2\) MHz and \(f_0 = 5\) MHz can be higher than 20%.

In order to solve this issue, in this work we use simulations of MARSIS surface echoes that allow to introduce Eq. (8) and consider both terms of Eq. (9) without further approximation. Simulations of surface echoes have been originally devised for the validation of subsurface interface detections, which is complicated by the so called “clutter”, that is by echoes coming from off-nadir
surface features, such as craters or mountains, and reaching the radar after the nadir surface echo. As a clutter can mask, or be mistaken for, subsurface echoes, numerical electromagnetic models of surface scattering (see e.g. Nouvel et al., 2004; Russo et al., 2008; Spagnuolo et al., 2011) have been used to produce simulations of surface echoes, which are then compared to the ones detected by the radar: any secondary echo visible in radargrams but not in simulations is interpreted as caused by subsurface reflectors. The code used in the present work was developed based on the algorithm of Nouvel et al. (2004). The MOLA topographic dataset (Smith et al., 2001) was used to represent the Martian surface as a collection of flat plates called facets. Radar echoes were then computed as the coherent sum of reflections from all facets illuminated by the radar. The computational burden of simulations was well above the capabilities of PC’s, and required the use of a supercomputer. In the present work, simulations were used to estimate the expected time of arrival of surface echoes: from the comparison between the real data and the simulated one (Fig. 4) we can estimate the ionosphere delay that is related to the $a_2$ term through Eq. (7).

In this way it is possible to solve Eqs. (8) and (9) obtaining

$$\text{TEC} = \frac{(2a_{\text{ASIM}} + a_{\text{CM}}, f_0) c f_2^2}{2\pi (8.98)^2} \quad (10)$$

The delay estimation is very accurate, because the software used the same settings of the radar. In particular, the sampling frequency $f_0 = 1.4 \text{MHz}$, is exactly the same that it is implemented in the on-board software.

The only possible source of uncertainty is related to the Spice Kernels used by the signal simulator to reconstruct the spacecraft altitude. However, in this case, the estimated error, that is typically around 20 m and always lower than 100 m (0.3 $\mu$s) (Rosenblatt et al., 2008), can be considered negligible.

4.2. Ionosphere delay evaluation

As discussed in previous sections, the signal received on ground must be processed with the range compression. The first step consists in removing the tracking trigger, that is the time shift introduced by the O.C.O.G. algorithm, from the signal phase in the frequency domain in order to obtain, after the processing, the radargram of Fig. 2.

This operation is critical, because if not well executed, the position of the signal inside the window is wrong and the extra time delay obtained comparing the real and the simulated signal is compromised.

Representing the trigger as a delay $\Delta t_{\text{track}}$, we have:

$$\Delta t_{\text{track}} = \Delta t_I + \Delta t_{\text{iono}} - \Delta t_{\text{r}} \quad (11)$$

Where:

$\Delta t_I = \text{free space travel time due to S/C altitude}$

$\Delta t_{\text{iono}} = \text{ionospheric delay}$

$\Delta t_{\text{r}} = \text{tracking error}$

At the same time, the position inside the receiving window of the simulated signal in Fig. 4 is determined only by the S/C altitude.

Comparing the first frames of the two radargrams of Fig. 2–4, where the SZA is high and the ionosphere effect is low, we can notice that there is a small bias.

This discrepancy is due to instrumental delays of about 5 $\mu$s (i.e. 5.31 $\mu$s for 1.8 MHz and 4.49$\mu$s for 5 MHz) that characterize the real signal while are absent in the simulated one. This bias is removed before the TEC estimation.

Comparing the delay of the two signals respect to a fixed reference, we have:

$$\tau = \Delta t_{\text{iono}} - \Delta t_{\text{r}} \quad (12)$$

A first result of this comparison is the possibility of obtaining a radargram aligned to the Mars topography as showed in Fig. 5.

Now, the tracking error $\Delta t_I$, is addressed.

As said in Section 3, the MARSIS on-board processing is capable of both azimuth and range compression. In particular, the range compression is performed with the CM in order to optimize the tracking phase. Unfortunately, during the commissioning phase, in 2005, the MARSIS team, together with the Thales Alenia Space company (the manufacturer of the radar), realized that the CM implemented on-board did not work properly. For this reason, the algorithm was disabled and never used again. In spite of this, the radar has performed well ever since, collecting several thousands of observations during the last eleven years.

The absence of the CM in the on-board processing has a direct impact on the tracking loop estimation of the distances involved in data acquisition.
Merging Figs. 2 and 3 in Fig. 6, it is possible to see that the tracking loop, without the CM, works on a signal that can be much wider than expected in particular during the day side.

In this condition, the O.C.O.G. of Eq. (3) estimates a signal position that is not correct.

Since the signal is badly range-compressed, it is much wider than a signal that has been compressed correctly, and for this reason, the tracking loop identifies the echo position too close to the radar.

In other words, the time delay estimated by the radar is smaller by a factor $\Delta t_{i1}$.

This value can be estimated evaluating also the delay between the simulated signal and the MARSIS data compressed, on-ground, without the CM.

From the comparison of the two delays it is possible to evaluate $\Delta t_{i2}$ and estimate correctly the extra delay time introduced by the ionosphere.

4.3. TEC estimation and validation

Once the terms $a_1$ and $a_2$ are obtained from the delay estimation and the CM respectively, it is possible to estimate the TEC along the orbit by using Eq. (10).

We highlight that, as described in the previous sections, the signal processing and, in particular the CM, are always the same. The only difference between the old TEC estimation algorithm and the new one is represented by the use of the ionosphere delay.
$\Delta T_E$ to improve the TEC accuracy in the dayside. There is not any variation in the signal processing performances in terms of width of the chirp pulse after compression and SNR.

Fig. 7, shows some examples related to consecutive orbits 4646, 4647, 4648 and 4649, where data have been processed with a low pass filter (a zero-phase digital filter that processes the input data in both the forward and reverse directions) to remove random spikes caused by signal oscillations. In detail, these spikes are produced by sudden variations of the SNR mainly due to the surface roughness. When the SNR of a frame is very low, the $a_2$ value estimated by the CM is not reliable and could vary greatly inside the range described in Appendix of Cartacci et al. (2013).

This means that between two consecutive frames, characterized by very different SNR values, the $a_2$ value, and consequently the TEC, will rise suddenly producing a spike. This is a fake value and is not considered in statistical analysis while for the figures production is filtered.

The blue line represents TEC values estimated using the algorithm described in Cartacci et al. (2013), and it shows the TEC estimated using the algorithm described in this work, which is optimized for performance on the day side.

Fig. 8 displays such averages of TEC and the difference between both estimates as a function of SZA, and clearly shows that during the night side, the difference between the two algorithms, if present, is barely visible while on the day side the difference can reach the value of $\sim 20\%$ being clear that the new algorithm greatly improves the TEC estimation, mainly for SZA $\leq 80^\circ$, removing the overestimation that affected the old one.

For lower SZA, the transmitted frequency approaches the maximum local plasma frequency, and the TEC suffers from a loss of accuracy, because the quadratic term estimated through the CM is not sufficient to fully compensate the distortion caused by the ionosphere. As a result, the scatter of TEC values above or below the average trend increases and heavy fluctuations appear for SZA $\leq 60^\circ$.

It is worth noting that the study of the TEC is influenced by the signal quality and by the SNR, which is a key parameter in order to quantify the radar performances. In some circumstances, Mars surface characteristics together with ionosphere attenuation and magnetic fields effects, can greatly reduce the radar performances. When the SNR is low, the signal processing, the CM algorithm and the ionosphere delay estimation performances are not optimal and consequently the TEC is affected by a loss of accuracy.

We wish to underline that MARSIS signals can achieve SNRs of the order of 40 dB or higher when used in flat areas during the night side. For this reason, we used a threshold of 20 dB (for lower values it is very harshly to identify subsurface layers and the signal shape is very poor) in the analysis reported in Fig. 8 to select the signals suitable for the TEC estimation.

Fig. 9a shows the comparison between the average TEC estimated for SNR $\geq 20$ dB (red points) and the one evaluated for $10$ dB $\leq$ SNR $< 20$ dB (blue points). The difference between both estimates has been plotted in form of histograms of each SZA bin range (Fig. 9b). The TEC estimated starting from signal with lower
SNR is more scattered and higher values are found with respect to the
one obtained from signals with a better SNR. The difference be-
tween both estimates is more notable during the dayside from
SZA < 85°, where it can be up to 5 times larger than during the
nightside (Fig. 9b).

The choice to utilize only signals with SNR ≥ 20 dB reduces the
amount of frames available to estimate the TEC. In particular, the
percentage of available frames varies from 97.84% (SNR ≥ 10 dB)
to 81.6% (SNR ≥ 20 dB) during the night side (SZA > 90°), while,
during the day side (SZA < 90°), the percentage falls from 89.01%
(SNR ≥ 10 dB) to 50.9% (SNR ≥ 20 dB).

This is a conservative decision but, as reported in Fig. 9, the sig-
nals with a low SNR have a negative impact on the TEC estimation,
and are not reliable.

In order to validate the new algorithm, we also compared our results
with TEC estimates produced using the Mouginit et al. (2008)
algorithm, the TEC obtained from MARSIS-AIS data (Gurnett et al.,
2008) and the TEC values from the NeMars Model (Sánchez-Canot al.,
2013 and 2016).

The comparison is focused mainly to the day side, because it is
for SZA lower than 90° that the new algorithm is expected to
improve the TEC estimation.

As a first step, we compared the average TEC estimated of the
new algorithm with the TEC obtained from the Mouginit et al.
(2008) algorithm for the year 2006 (these data are available at
the European Space Agency (ESA) Planetary Science Archive (PSA)
node). A similar comparison was done in Sánchez-Canot al. (2015)
but only with 19 orbits with different conditions, such as
year, solar activity, heliocentric distance and season. In order to
validate the algorithm presented in this paper, this study makes
a larger statistical comparison by using all the available Mars Ex-
press orbits during 2006.

Fig. 10a shows that the agreement between the two methods is
very good for SZA ≥ 110° as previously stated in Sánchez-Canot al.
(2015), while it starts to fail when the ionosphere activity be-
ties to rise and for SZA ≤ 95° the two methods diverge steadily as also
shown in the histograms of Fig. 10b.

As mentioned before, this disagreement is probably dependent
on the detected issue in the CM algorithm implemented on-board
Mars Express, because it is not considered by Mouginit et al.
(2008) (see Eq. (10)) when the constraints for the time delay es-
timation are defined (i.e. the only constraint considered is the
Spacecraft altitude).

In order to test our hypothesis, we removed from the TEC esti-
mation pipeline the term Δt_{Tr}.

Fig. 11 shows the results for the orbits 4646, 4647, 4648
and 4649, and it is clear that the agreement between our al-
gorithm (black line), without the aforementioned term, and the
Mouginit et al. (2008) algorithm (red line) is now excellent.

The next step was to compare both algorithms with the TEC ob-
tained independently from the topside electron density profiles of
MARSIS-AIS. These profiles were retrieved following the procedure
explained in Sánchez-Canot al. (2012) and Morgan et al. (2013).

At this point, we wish to underline that the MARSIS-AIS TEC,
derived from the topside profile of the ionosphere, must be lower
than the actual TEC related to the entire depth of the ionosphere.
and any TEC estimation started from subsurface data, must be higher than the MARSIS-AIS TEC, whatever the algorithm is used.

In other words, from a physical point of view, the MARSIS-AIS TEC represents the lower limit of the total TEC estimation (Sánchez-Canó et al., 2015).

For this comparison we focused our attention in the range $75^\circ \leq \text{SZA} \leq 90^\circ$ for the following reasons:

- it’s the SZA sector most sampled by all the techniques;
- it’s the part of the dayside that MARSIS in subsurface mode works better because the carrier frequency at lower SZA is very close to the maximum ionospheric frequency and therefore, there is a limit there;
- it’s the SZA sector where TEC shows less variation with solar cycle (e.g. Sánchez-Canó et al., 2016), and therefore, easier to compare.

The AIS TEC data set used in this study is smaller than both MARSIS SS techniques, as it is only composed by 7322 ionograms related to 226 orbits distributed in almost nine years of activity. Considering that 3580 ionograms (around 50%) were unsuitable, being collected for $\text{SZA} \leq 60^\circ$, the range $75^\circ \leq \text{SZA} \leq 90^\circ$ contains 3231 ionograms, which is still sufficient to have a reliable average. Since the AIS-TEC data set available is smaller than the other two, it was averaged in 0.04° SZA bins.

In Fig. 12, it is visible that the TEC of this study, estimated with the new algorithm and related to the year 2006 (black dots), is
positioned in the upper part of the AIS-TEC distribution, showing higher values for great part of the interval, while the TEC estimated by Mouginot et al. (2008) (red dots) is mostly on the lower part. This means that the TEC of this study satisfies better the physical constraint represented by the AIS-TEC, while the TEC from Mouginot et al. (2008) is probably underestimated because it is lower than the topside TEC obtained from AIS data and that is a contradiction (Sánchez-Cano et al., 2015). We note that for SZA between 86° and 90°, both subsurface algorithm gives negatives values when compared to AIS dataset, being always our estimates the closest to AIS. This can be a consequence of the terminator region, where the secondary layer of the ionosphere tends to disappear and therefore, AIS and subsurface techniques should give similar results because both are sampling only the main ionospheric layer.

Finally, we test our method with the NeMars model. NeMars is a semi-empirical model of the dayside ionosphere of Mars that calculates the electron density profile of its two main ionospheric layers for steady conditions (Sánchez-Cano et al., 2013). Both layers are based on the Chapman formulation (Chapman, 1931a,b), being both of the type alpha-Chapman (where the ions are mainly lost by recombination processes). The topside of the main layer (with peak at ∼135 km on average) is empirically based on MARSIS AIS data and the bottomside is reconstructed with the Chapman theory. The secondary layer (layer with peak ∼110 km on average and smaller than the main one), is empirically based on Radio Occultation data from the Mars Global Surveyor mission. The peak density of both layers depends on the SZA, Mars heliocentric distance and solar activity via the proxy F10.7, while the peak altitude only depends on the SZA. Regarding the shape of the main layer, the neutral scale height depends on both the SZA and on the height of the profile in relation to the peak altitude. However, the secondary layer neutral scale height is considered constant at 12 km. Finally, TEC is obtained after the integration of the electron density of both layers with altitude.

The model gives the major part of the ionization of the Martian ionosphere. Therefore, TEC from NeMars can be directly compared to the MARSIS subsurface TEC estimates, and should be higher that MARSIS AIS data that only gives information of the topside ionosphere.

Recently, the model equations (i.e. ionospheric scale height) for the topside of the main layer have been improved after considering the topside behavior with the solar cycle phases. In this work, the new topside scale height for low solar activity (Sánchez-Cano et al., 2016) has been implemented in the original model described by Sánchez-Cano et al. (2013).

Fig. 12 confirms that the new TEC estimates (black line) are always higher than the TEC from Mouginot et al. (2008) (red line). Moreover, the new TEC is significantly closer to the NeMars model (blue line). Considering that we are comparing a model of steady ionospheric conditions with respect to real data that could be influenced by many factors not considered in the model (e.g. solar wind variability, induced magnetic field, crustal magnetic fields, gravitational tides, atmospheric phenomena, electric fields, changes in ionospheric conductivities, surface roughness, topography changes, etc), the amplitude and the average shape of our TEC is in very good agreement with NeMars model.

On the contrary, the old TEC (magenta line) matches worse respect to the NeMars model, because, even if it is closer in terms of amplitude, its behavior has a different slope. This is further evaluated in the following lines with a deep analysis of the ionospheric distortion between both TEC estimations and the NeMars model.

Finally, as mentioned before, we perform a test using a simulator of ionospheric distortion to validate our results to which we apply to the new developed algorithm to evaluate the TEC. This is a kind of inverse process in which TEC from the NeMars model has been reconstructed in the same way that the MARSIS subsurface TEC is retrieved (see Section 4). In details, we compute a phase distortion using the NeMars Model, as defined by Eq. (4), for an entire orbit according to the SZA at the time of observation, and also the associated TEC.

Our goal is to verify the accuracy of the new algorithm, comparing the TEC estimated by the simulator with the one directly obtained through the NeMars Model.
The distortion, simulating the effects of the Mars ionosphere is applied to the phase of an ideal signal with the characteristics (in terms of frequency, band and sample frequency) of the actual signal transmitted by MARSIS.

In Fig. 14, the comparison between the ideal signal (blue line) and the signal affected by ionosphere distortion (red line) is shown for three different SZA related to the orbit 4646. While in the upper panels (Fig. 14a, b, c) the signal with the distortion is compressed without any compensation, in the lower panels (Fig. 14d, e, f) the signal is processed using the CM.

The effects of the ionosphere are clearly visible in the form of a wide main lobe and a delay (Fig. 14a, b, c) that get worse for lower values of the SZA (when the S/C is deeper in the dayside).

The CM removes the quadratic term (Fig. 14d, e, f), estimating the term \( a_2 \), while the delay can be easily calculated comparing the signals position.

Therefore, all the information necessary for the TEC estimation are available and in Fig. 15 the results for the orbits 4646-4647-4648-4649 are shown.

The good performance of the new algorithm is demonstrated, as the difference between the TEC estimated by the simulator and the one calculated from the NeMars Model is always under 5%, even for very low values of the SZA. The increasing gap between both TEC estimates is mainly due to the fact that for lower SZA, the related plasma frequency begins to be too close to the carrier signal frequency and the CM cannot compensate correctly the distortion.

The test also confirms that the older algorithm overestimates the TEC for this range of SZA, and that the new algorithm is an improved version for the TEC dayside.

However, the main source of error of the new method is related to the accuracy of the estimation of the ionosphere delay that can be influenced by to the presence of the surface clutter, i.e. lateral echoes produced by surface topography.

The surface clutter can introduce an error in the delay estimation influencing the correct functioning of O.C.O.G. in the tracking loop. We can quantify this error in the order of few microseconds, in worst conditions. To evaluate the impact on the TEC estimation, that can vary considerably with the SZA values, a simulated random error of maximum 5\( \mu \)sec (750m in the free space) is added to the estimated delay on a sample of 50 orbits (between orbit 4646 and orbit 4719), selected with a similar range of SZA; the results are shown in Fig. 16.

During the night side, for an SZA higher than 95°, considering the low values of the TEC involved, even a small error in the delay evaluation can lead to a large overestimation, while for an SZA lower than 95°, the error in the TEC estimation is always under 10%, and often much smaller (Fig. 17), so that it can be considered negligible.

We wish to underline that, normally, if the clutter is so heavy to introduce an error of about 10% in the time delay estimation, also the SNR is reduced. Actually, the major part of the frames where the surface features produce a relevant error in the delay estimation have a low SNR.

Adopting a conservative approach, we decided to use both methods to estimate the TEC.

The older one, which works better during the night side and it is independent from the delay, is used for SZA higher than 90°, and the new one is used for \( 50° \leq SZA \leq 90° \).

It is worth noting that, during the day side MARSIS normally operates in AIS mode for \( SZA \leq 50° \), as that operational model is specially designed for ionospheric sounding and in this SZA range is where the ionosphere is fully formed.

To conclude this section, we summarize the main findings.
Fig. 14. Comparison between the ideal and the distorted signal for orbit 4646. Both signal are range compressed. The effects of the distortion, as the delay and a wide main lobe, are clearly visible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 15. Comparison between the TEC estimated through the simulator and the TEC derived from the NeMars Model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
• The possibility to estimate both the linear and the quadratic terms of the ionosphere distortion allows developing a more precise algorithm for TEC estimation on the day side.

• The TEC estimated with the new algorithm is higher than the one estimated from MARSIS-AIS, as expected, and shows a good agreement with the NeMars model.

• Simulations demonstrate that, on the day side, the new algorithm performs with very good accuracy since the error is always under 5%.

• The new algorithm is particular well suited for the day side when the possible presence of local error in the delay estimation due to the clutter effect is negligible. The older algorithm, Cartacci et al. (2013), is still valid for the night side because it is not influenced by the clutter effects and the overestimation introduced by the approximation in Eq. (8) is under 10%.

• In the terminator region, the carrier frequency used is 5 MHz, this means that the differences between the two methods are relatively small, typically under 10%.

5. Discussion and conclusions

In this paper we have described a new algorithm that makes use of the Contrast Method and of signal echo simulations to estimate the TEC of the Martian ionosphere. We have demonstrated that the new method overcomes the limitation of the previous one (Cartacci et al., 2013) during the day side (see Fig. 7), achieving...
an improvement of about 20% in accuracy for the lowest SZA that MARIS can operate.

In order to validate the new algorithm, we have compared our results with the TEC obtained through other methods. In particular, we focused our attention to the TEC obtained using the Mouginot et al. (2008) algorithm, the TEC estimated from the MARIS AIS dataset and the predictions of the NeMars model.

We have shown that the new MARIS TEC values are in good agreement with both AIS-TEC (see Fig. 12) and the NeMars model (see Fig. 13). On the contrary, the agreement with the Mouginot et al. TEC is limited to the deep night side, while when the ionosphere activity starts to increase (lower SZA), the differences become much significant (see Fig. 10).

The TEC estimates from Mouginot et al. (2008) results too low even when compared with AIS-TEC (see Fig. 12) which is an in-situ observation (see also Fig. 11 at Sánchez-Cano et al., 2013, and statistic validation at Sánchez-Cano et al., 2015), suggesting an underestimation of the TEC values. These lower estimations can be due to the fact of an issue in the CM implemented on-board the spacecraft (see Fig. 11).

Moreover, simulations have shown (see Fig. 15) that, starting from modeled distortion, the algorithm is capable to estimate the related TEC with very good accuracy, limiting the error under 5% even for SZA close to 55°.

The comparison between the old method, using only the CM, and the new one, has shown that the two methods are complementary, performing at their best in different range of the SZA, and thus allowing an optimal estimation of the TEC along the orbits. In particular, the new algorithm performs better for SZA lower than 95°, while the older one is more robust for SZA higher than 95°.

The multi-dataset comparison shown in this paper agree with the previous study of Sánchez-Cano et al. (2015), where a critical assessment of TEC from 19 Mars Express orbits obtained with subsurface algorithms and with AIS was performed. The main conclusion of Sánchez-Cano et al. (2015) was that MARIS Mouginot et al. (2008) and Cartacci et al. (2013) subsurface data from the nightside and terminator sectors, SZA > 75°, could be used with confidence since the differences among all data sets were small. In our study, we have shown that with the new algorithm that improves the Cartacci et al. (2013) method, this is still valid, being the new algorithm more consistent than the other one when compared to AIS and to modelling. The main issue reported by Sánchez-Cano et al. (2015) was the dayside, SZA < 75°, where caution with the use of both subsurface algorithms was recommended as the TEC values were notably less accurate. In our study, we have improved these estimates by reducing the TEC uncertainty up to a 20%.

We highlight that, in general, MARIS data below SZA 55–65° (depending on solar cycle phases) should not be used for scientific purposes, simply because the MARIS carrier frequencies are of the order or lower than the actual maximum ionospheric plasma frequency. For this end, data with a poor SNR is indicated with a flag in both Mouginot et al. (2008), and Cartacci et al. (2013), files.

The new acquired capability to estimate the TEC with good accuracy during the day side, will allow us to understand and compensate better the attenuation phenomena, such as the ionosphere absorption and the Faraday rotation (Safaieinili et al., 2003), increasing the amount and the quality of MARIS data available to characterize the surface and the subsurface of Mars.

In addition, this new TEC data set will be useful to further understand the behavior and variability of the Mars ionosphere, in particular at the terminator region where there is a non-well understood dawn/dusk asymmetry, and the ionosphere does not follow the Chapman theory because of a non-spherical symmetry between day and night (e.g. Grandin et al., 2014; Ao et al., 2015).

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References


