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A new method for determining the total electron content in Mars' ionosphere based on Mars Express MARSIS data

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Abstract

We present a new method for determining the total electron content (TEC) in the Martian ionosphere based on the time delay of received radar pulses of the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) on board the Mars Express spacecraft. Previous studies of the same dataset have produced differing results for the day-side ionosphere, so it is useful to have an alternative way to compute the TEC in this region. This method iterates a model ionosphere in order to simultaneously match the ionospheric delays of the signals received by the radar's two channels by finding the model which minimizes the root mean square error (RMSE) between

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the measured and simulated delays. Topographical information is obtained from data from the Mars Orbiter Laser Altimeter (MOLA) instrument. The model parameters are held constant for a given orbit, and a very good agreement between the simulated and measured delays is obtained. The TEC can then be inverted from the ionospheric model. Matching the delays of both channels simultaneously applies an additional constraint to the model which has not been made in previous studies. The model is additionally validated by matching the simulated pulses with the raw range-compressed measurements for one orbit. Finally, typical model parameters are compared to those obtained by previous studies, which are also simulated. The method is applied to orbits during moderate solar activity, and results show very good agreement with previous studies.

Keywords:

Mars, MARSIS, MOLA, Ionosphere, Total electron content

1 **1. Introduction**

2 The ionosphere of Mars has been studied over more than 40 years, and
3 since the start of the Mars Global Surveyor and Mars Express missions, and
4 more recently with the Mars Atmosphere and Volatile Evolution (MAVEN)
5 mission, a large and continuous dataset of plasma measurements has been
6 collected. In particular, the Mars Advanced Radar for Subsurface and Iono-
7 spheric Sounding (MARSIS) instrument on board Mars Express routinely
8 provides the Total Electron Content (TEC). This is a very useful parameter
9 to characterise the ionosphere and to study its variability as a function of
10 solar illumination, Martian season, and solar and space weather activity.

11 The computation of the TEC from the processing of radar data is not
12 a straightforward process and differences have been found between different
13 works, especially on the day-side [1]. In [2] and [3], a numerical expansion
14 of the refractive index is made to model the phase distortion of the signal.
15 The expansion terms are estimated by an optimization method which tries
16 to maximize the signal-to-noise ratio (SNR) of the received signal at one
17 point in the orbit. This allows for a compensation of the distortion and an
18 estimation of the TEC. Another method which is documented in [4] and [5]
19 is based on the output from an algorithm known as the contrast method
20 (CM), which is used during processing of the raw signal to compensate for
21 higher-order distortion which causes blurring in the obtained radargram. A
22 radargram is a bi-dimensional colour-coded diagram made of a sequence of
23 echoes in which the horizontal axis is the distance along the ground track of
24 the spacecraft, the vertical axis represents the two-way travel time of the echo,
25 and brightness is a function of the received echo power. This method assumes
26 that the radar signal is narrow-banded by making a Taylor expansion around
27 the central frequency to approximate the differential phase change across the
28 band of the received signal. The expansion terms are algebraically related to
29 the TEC, which can then be solved for.

30 In this study, we show a new method in deriving the TEC, still based
31 on the same MARSIS data set. Instead of deriving the TEC by analysing
32 the high order distortion, we use the time delay recorded on both radar
33 frequencies, for the entire portion of the orbit over the planet's day side. We
34 have used the radar data that has recently become available in the European
35 Space Agency's (ESA) Planetary Science Archive (PSA). This gives us a new

36 way to obtain the TEC by analysing a different aspect of the ionospheric
 37 distortion. Grima et al. [6] describe the effects of the ionosphere’s dispersive
 38 phase shift in the time domain in the context of future radar sounders to be
 39 sent to Europa, and show how the TEC may be estimated with differential
 40 delay times by using the first expansion term of the refractive index described
 41 in [2] and [3]. Scanlan et al. [7] use the method proposed in [6] to estimate
 42 the TEC on Mars by combining MARSIS and SHARAD data.

43 Section 2 briefly describes the ionospheric effects encountered by a radar
 44 signal in the Martian ionosphere and Section 3 describes the MARSIS in-
 45 strument itself. Section 4 documents a simulation tool which is developed
 46 to model the distortion of a MARSIS radar pulse, and Section 5 describes
 47 the TEC inversion method which is developed. Results are presented and
 48 discussed Section in 6 and conclusions are drawn in Section 7.

49 **2. Ionospheric Effects on the Radar Signal**

50 The Martian ionosphere is a dispersive medium, which in the absence of
 51 a magnetic field has a refractive index n given by

$$n(\omega, z) = \sqrt{1 - \frac{\omega_p^2(z)}{\omega^2 - i\omega\nu(z)}} \quad (1)$$

52 where z is the vertical coordinate, $\omega_p(z)$ is the angular plasma frequency, ω
 53 is the angular frequency of the electromagnetic wave propagating through it,
 54 and $\nu(z)$ is the electron-neutral collision frequency. Neglecting absorption
 55 (by setting the imaginary component to zero), the wave number k of the
 56 pulse is

$$k(\omega, z) = \frac{1}{c} \sqrt{\omega^2 - \omega_p^2(z)} \quad (2)$$

57 This simplification is valid because $\nu(z)$ generally ranges from 10-60 kHz
 58 and is small compared to the frequencies of the MARSIS bands [8]. During
 59 solar storms this no longer applies and absorption has a significant effect on
 60 the signal [9]. Equation (2) can be expanded numerically for a small ω_p/ω .
 61 Keeping the first three terms gives the result

$$k(\omega, z) \approx \frac{\omega}{c} - \frac{\omega_p^2}{2\omega c} - \frac{\omega_p^4}{8\omega^3 c} \quad (3)$$

62 A detailed treatment of these equations is given in [10]. The time delay of a
 63 radar pulse is given by

$$\Delta t_{iono}(\omega) = \frac{1}{c\omega^2} \int_0^\infty \omega_p^2(z) dz + \frac{3}{4c\omega^4} \int_0^\infty \omega_p^4(z) dz \quad (4)$$

64 Note that a factor of 2 has been multiplied through the right-hand side
 65 to reflect that there are two ionospheric crossings, which corresponds to a
 66 radar pulse travelling down from the satellite, reflecting off the surface and
 67 travelling back up towards the satellite.

68 **3. MARSIS Instrument**

69 A detailed description of the MARSIS instrument can be found in [11].
 70 MARSIS can operate in multiple modes. In this work, the data collected
 71 during the subsurface sounding 3 (SS3) mode is used. The radar transmits
 72 two linear frequency modulated waveforms (chirps) with 1 MHz bandwidth
 73 in quick succession. The two chirps are each centred on a different frequency,
 74 corresponding to one of the radar's four operating bands: 1.8 MHz (band 1),
 75 3 MHz (band 2), 4 MHz (band 3), or 5 MHz (band 4). Thus it can be said
 76 that in the SS3 mode, MARSIS simultaneously collects data on two different
 77 bands.

78 The onboard processing is described in greater detail in [5]. The received
79 signal is first azimuth and then ranged compressed. Azimuth compression of
80 pulse echoes consists in artificially adding a delay, corresponding to a phase
81 shift of the complex signal, to the samples of each pulse, and then in sum-
82 ming the samples so as to allow the constructive sum of the signal component
83 whose delay (phase shift) from one pulse to the next corresponds to a de-
84 sired direction (usually nadir or close to nadir). Range processing consists of
85 computing the mathematical correlation between the transmitted pulse and
86 received echoes. Initially it was intended for the range compression to be car-
87 ried out onboard the satellite by the CM, an algorithm developed to remove
88 higher-order distortion from the signal. During the commissioning phase it
89 was found that the system implemented onboard was malfunctioning, and so
90 it was subsequently disabled. This means that the higher-order distortion
91 which the CM was meant to remove, including broadening of the signal in
92 time, is still present. This is step therefore now completed on the ground.
93 The subsequent processing step tracks the signal position inside the receiving
94 window to provide timing information about the received signal.

95 **4. Ionospheric Delay Simulation**

96 *4.1. Motivation*

97 The discrepancies between the results of different ionosphere distortion
98 correction methods motivated the development of a simulator which models
99 the effect of the Martian ionosphere on a radar pulse sent by MARSIS. This
100 allows us to find the expected time delay of a radar pulse from a theoretical
101 basis and provides a neutral starting point with which to assess the collected

102 MARSIS data. A similar tool was developed in [12] to model Martian iono-
103 spheric effects.

104 *4.2. Radar Pulse Synthesis and Propagation*

105 An ideal linear chirp with 1 MHz bandwidth and 250 μ s pulse length is
106 synthesised on one of the four MARSIS bands, corresponding to the system
107 specifications. This transmitted signal propagates from the spacecraft down
108 to the surface, is reflected, and propagates back toward the spacecraft where
109 it is received. Reflection on the ground is approximated to be specular since
110 no a priori information about the subsurface is available, and no terrain or
111 clutter is simulated. The ionospheric simulation calculates the extra time de-
112 lay caused by two crossings of the ionosphere. Since we are only interested in
113 the delay, effects such as turbulence and Faraday rotation are not considered.

114 The ionosphere is divided into layers of height $\Delta h = 500$ m each, in
115 which the electron density is constant. This number of layers ensures that
116 discontinuities between each layer are very small, such that spurious reflec-
117 tions between the layers are not significant. This corresponds to dividing
118 the simulation space into 1000 layers. The refractive index is found using
119 the unmagnetized dispersion relation given in equation (1). At the interface
120 between each layer, the transmission coefficient is determined using

$$T_{m+1} = \frac{2n_m}{n_{m+1} + n_m} \quad (5)$$

121 where n_m is the refractive index of the m th layer. The wave S is propagated
122 between layers by

$$S_{m+1} = T_{m+1} \cdot S_m e^{-i\Delta k_{m+1}\Delta h} \quad (6)$$

123 where Δk is the relative change in wave number with respect to free space,
 124 given by

$$\Delta k_m = \frac{\omega}{c} \cdot (n_m - 1) \quad (7)$$

125 Following reflection by the ground, the ionospheric layers are inverted and
 126 the signal is propagated through again. Reflection from the ground. The
 127 refractive index for a given ionospheric layer is calculated using equation (1).
 128 The electron density at a given point in the ionosphere is modelled using a
 129 Chapman layer. The model is created using the methodology described in
 130 Section 5.

131 4.3. Determining the Time Delay

132 The pulse is compressed by correlating the spectrum of the received pulse,
 133 $S_r(f)$ with a copy of the spectrum of the original, undistorted pulse, $S_t(f)$,
 134 where f is the frequency. The time delay of the signal, Δt_{iono} , is taken as
 135 the delay which corresponds to the centre of mass (COM) of the pulse [10].
 136 The correlation magnitude is given by

$$C(\tau) = \chi(\tau)\bar{\chi}(\tau) \quad (8)$$

137 where the bar indicates the complex conjugate, τ is the time delay coordinate
 138 used in the correlation, and $\chi(\tau)$ is

$$\chi(\tau) = \int S_t(f)\bar{S}_r(f)e^{-2\pi f\tau}df \quad (9)$$

139 The delay of the signal, Δt_{iono} , is then given by

$$\Delta t_{iono} = \tau_{COM} = \frac{\int \tau \cdot C(\tau)d\tau}{\int C(\tau)d\tau} \quad (10)$$

140 Additionally, the leading edge of the pulse can be estimated using the “offset
 141 centre of gravity” (OCO_G) method [13]. This method is used by MARSIS
 142 during processing of the low-level data [5]. The half-width of the pulse, $\tau_{W/2}$
 143 is estimated and subtracted from the COM position:

$$\Delta t_{OCO_G} = \tau_{COM} - \tau_{W/2} \quad (11)$$

144 where $\tau_{W/2}$ is given by

$$\tau_{W/2} = \frac{\left(\int C(\tau) d\tau \right)^2}{2 \cdot \int C^2(\tau) d\tau} \quad (12)$$

145 An example of a compressed pulse is shown in Figure 1. In this case the
 146 time delay is found to be approximately 62 μ s.

147 5. Total Electron Content Retrieval

148 5.1. Matching the Ionospheric Time Delay

149 Inverting the TEC from an ionospheric model is challenging because many
 150 assumptions have to be made, and there are not many constraints which can
 151 be placed on the model [2], [5], [14]. Therefore the objective of the simulation
 152 used in this work is to find an ionospheric model which can satisfy equation
 153 (4) for both channels simultaneously. The radar sends pulses centred on 4 and
 154 3 MHz, or 5 and 4 MHz. Due to the dispersive nature of the ionosphere, the
 155 terms in equation (4) are weighted by frequency. Therefore, finding a model
 156 which matches the delays recorded by both channels constitutes finding a
 157 solution for $\omega_p(z)$ in the system of equations

$$\begin{aligned}\Delta t_1 &= \frac{1}{c\omega_1^2} \int_0^\infty \omega_p^2(z) dz + \frac{3}{4c\omega_1^4} \int_0^\infty \omega_p^4(z) dz \\ \Delta t_2 &= \frac{1}{c\omega_2^2} \int_0^\infty \omega_p^2(z) dz + \frac{3}{4c\omega_2^4} \int_0^\infty \omega_p^4(z) dz\end{aligned}\tag{13}$$

158

159 The ionospheric delay output by the simulator is compared to the delay
 160 measured by the radar on both channels. The data used for this comparison
 161 comes from the reduced data record (RDR) dataset available in the ESA
 162 PSA. The full description of this dataset is available in [15]. This data has
 163 already been compressed in azimuth and range, and has been focused by the
 164 CM to remove ionospheric distortion, apart from the time delay. The time
 165 delay present in the signal is the sum of the free-space and ionospheric delays.
 166 The free-space delay is derived from altimetry data recorded by the MOLA
 167 instrument, and subtracted from the total delay, leaving only the ionospheric
 168 component. The total delay is extracted from the RDR radargram by finding
 169 the first sample of each frame with an SNR > 20 dB. This technique is used
 170 to minimize the effect of subsurface reflections on the time delay measured
 171 with respect to the surface [5]. The free-space delay is given by

$$\Delta t_{fs} = \frac{2 \cdot (25\text{km} - z_{MOLA})}{c}\tag{14}$$

172 where z_{MOLA} is the height of the surface above the Martian ellipsoid as
 173 defined in [16]. The 25 km in equation (14) refers to the fact that the RDR
 174 dataset has already been aligned to a reference height of 25 km above the
 175 planet's surface [15].

176 The ionospheric delay derived from the RDR dataset is compared on a
 177 frame-by-frame basis with the simulated ionospheric delay. A single-layer

178 Chapman model is iteratively tuned such that the RMSE between the sim-
 179 ulated and measured delay is minimized. The Chapman layer is defined in
 180 [17] by

$$N_e(z) = N_{e_0} \cdot \exp\left(\frac{1}{2}[1 - h - Ch(z, \chi) \cdot \exp(-z)]\right) \quad (15)$$

181 where $N_e(z)$ is the electron density in m^{-3} at a given height z . N_{e_0} is the
 182 maximum electron density with corresponding height z_0 , χ is the solar zenith
 183 angle, and $h(z)$ is given by

$$h = \frac{z - z_0}{H} \quad (16)$$

184 where H is the scale height. Finally, $Ch(z, \chi)$ is the Chapman grazing inci-
 185 dence function, given in [17] by

$$Ch(z, \chi) = d \sin \chi \int_0^\chi \exp\left(d - d \frac{\sin \chi}{\sin \alpha}\right) \csc^2 \alpha d\alpha \quad (17)$$

186 where

$$d = \frac{R + z}{H} \quad (18)$$

187 and R is the radius of the planet, equal to 3390 km.

188 The maximum density height is fixed to a typical value of 130 km. The lo-
 189 cation of the maximum density point is relatively stable and well-established
 190 [2] [18]. This assumption is required in order to constrain the degrees of
 191 freedom in the modelling problem. Since a Chapman profile is a function
 192 of 3 parameters, there exist multiple Chapman profiles which can solve the
 193 system of equations in (13). The model is then tuned by changing either
 194 the scale height or the peak electron density of the Chapman layer. How-
 195 ever in practice, both parameters have similar effects, but changing the scale
 196 height causes the TEC to “rise” faster as SZA decreases, as noted in [3]. An

197 optimum combination of parameters is found by sweeping through several
198 starting values of H and allowing the algorithm to optimize for N_{e0} .

199 The combination of scale height and peak electron density which mini-
200 mizes the RMSE is found for each orbit which is processed. The nominal
201 values for these two parameters at the sub-solar point (SZA = 0 degrees) are
202 held constant for that orbit, however, their values scale throughout the orbit
203 with SZA as per equation (15). While local variations (for instance those
204 caused by the crustal magnetic field) are lost, a very good agreement with
205 the mean delay can be found. A similar modelling approach is used in [2] to
206 derive parameters for a best-fit Chapman profile.

207 For SZAs greater than 95 degrees, the simulator does not capture the
208 effects of the night-time ionosphere, because the simulated delay tends to
209 zero as a consequence of the Chapman grazing function, but other effects not
210 taken into account by the Chapman model, such as plasma transport, become
211 significant near the terminator [19]. For SZAs below 60 degrees, distortion
212 becomes very significant and it is difficult to recover a signal. Therefore, the
213 region of SZA used to calculate the RMSE is constrained between 60 and 90
214 degrees.

215 *5.2. Reproducing the Distorted Pulses*

216 The optimum ionospheric profile obtained through the RMSE minimiza-
217 tion routine can be further validated by comparing the distorted pulses it
218 simulates to the raw range-compressed data which has not been focused by
219 the ionosphere. Multiple reflections from the subsurface can make compar-
220 ison difficult, but in these cases rising edge of the pulse shows a agreement
221 with the raw data, as can be seen in Figure 2a. In cases with a strong sur-

222 face reflection, the general shape of the raw pulse matches sufficiently well
 223 the simulation result, as is the case in Figure 2b. This step is performed as
 224 an extra check to validate the simulated pulses, but is not used to invert the
 225 TEC.

226 6. Results and Discussion

227 6.1. Ionospheric Model

228 The Martian ionosphere is modeled in the simulator using a Chapman
 229 layer whose electron density and scale height are iteratively tuned to match
 230 the observed delay of the radar pulse. The profile obtained through RMSE
 231 minimization for orbit 4646 and a SZA of 70 degrees is shown in Figure 3.
 232 The model parameters are given in Table 1. The starting iteration used
 233 for the model parameters are taken from the best-fit Chapman parameters
 234 described in [14]. The maximum density height is also taken from [14] and
 held constant.

Table 1: Best-fit ionospheric model parameters at SZA = 0 degrees (Orbit 4646)

Parameter	Value
Neutral scale height	15.2 km
Maximum electron density	$1.29 \cdot 10^{11} \text{ m}^{-3}$
Maximum density height	130 km
Vertical step size	500 m
Simulation range	0-500 km
F10.7 (measured at Earth)	67.3 sfu
Mars-Sun distance	1.42 AU

235

236 *6.2. Comparison of Measured and Simulated Delays*

237 The measured and simulated ionospheric delays of orbit 4646 for both
238 channels are plotted against SZA in Figure 4. The agreement between mea-
239 surement and simulation is very close, and the combined RMSE for both
240 channels is 4.184 μs .

241 *6.3. Total Electron Content: Orbits 4640-4649*

242 The TECs obtained by the algorithm for orbits 4640-4649 are shown in
243 Figure 5, and the mean TEC obtained for orbits 4640-4649 is compared to
244 the results of other studies in Figure 6. A moving average filter is used to find
245 the mean results of Cartacci et al. [5] and Mouginot et al. [3] in order to allow
246 for better readability in the figure. The NeMars model [20] using parameters
247 derived in [18] is plotted for a portion of the orbit, because the model is only
248 valid for the dayside. A mismatch can be found between NeMars and our
249 TEC determination. This is not surprising, first because such disagreement
250 was already identified in [1]. The NeMars TEC are closer to the values from
251 Cartacci et al. Secondly, and more generally, an agreement between data
252 and model is usually difficult to achieve, given the variability of the Mars'
253 atmosphere (e.g. see [21] section 2.2.2.). In any case, such mismatch between
254 the different data sets speak for the need of a new critical comparison of the
255 various TEC data processing pipelines, which should be discussed in view of
256 this article. A good agreement is found between our inversion algorithm and
257 Mouginot et al., and we also find a close agreement with the results of [2].

258 Data from the active ionospheric sounding (AIS) mode [14] is not available
259 while MARSIS is operating in the SS3 mode, but the best-fit Chapman profile
260 obtained from the AIS data [14] is plotted for comparison for the entire range

261 of SZA studied. The AIS mode of MARSIS allows the topside of the main
262 ionospheric layer to be probed, but it cannot collect any data on the bottom
263 side of the main layer, nor any secondary layers which may exist beneath the
264 main layer. Therefore, the AIS-fitted model should be considered as lower
265 bound on the TEC. Also note that the model is derived from measurements
266 taken during periods of solar activity with F10.7 values of 72-119 sfu, while
267 orbits 4640-4649 took place during F10.7 levels of 67.5 sfu, and so a somewhat
268 weaker ionosphere can be expected than that given by the AIS-fitted model.

269 *6.4. Total Electron Content: Orbit 8762*

270 The algorithm is run for orbit 8762 in order to provide a point of com-
271 parison during solar activity levels corresponding to the AIS-fitted model in
272 [14]. The orbit occurred during a period of moderate solar activity as defined
273 in [18]. This orbit is selected because the F10.7 measured during this time is
274 84 sfu, which corresponds to the mean value of F10.7 for the measurements
275 considered in [14]. The best-fit model parameters obtained for this orbit
276 are shown in Figure Table 2. The TEC is plotted against SZA in Figure
277 7, where it can be seen that during conditions of moderate solar activity,
278 the TEC inverted from the algorithm is greater than that obtained by the
279 AIS-fitted model, which only considers the main ionospheric layer. Due to
280 the presence of a secondary layer during moderate solar activity [20], we can
281 expect the TEC of the entire ionosphere to be approximately 10% greater
282 than the Gurnett et al. model.

283 The algorithm does not consider local variations in the TEC, and neither
284 does the Gurnett et al. best-fit model. This can be seen in Figure 7, when
285 there are local “dips” in TEC, at 80 and 85 degrees SZA in the results of

286 [5] and [3], this is not reflected in the results of our inversion algorithm.
 287 However, apart from these local deviations, a good agreement is found with
 288 [3].

Table 2: Best-fit ionospheric model parameters at SZA = 0 degrees (Orbit 8762)

Parameter	Value
Neutral scale height	14 km
Maximum electron density	$1.63 \cdot 10^{11} \text{ m}^{-3}$
Maximum density height	130 km
Vertical step size	500 m
Simulation range	0-500 km
F10.7 (measured at Earth)	84 sfu
Mars-Sun distance	1.47 AU

289 6.5. Summary

290 The TEC inverted from the best-fit model tends to agree with that found
 291 by [3] in cases of low and moderate solar activity. During low solar activity,
 292 the TEC obtained by our inversion algorithm also matches closely with TEC
 293 given by the AIS-fitted model. This can be explained by the fact that we do
 294 not expect a secondary ionospheric layer to be present during solar minimum.
 295 During moderate solar activity, our algorithm provides a TEC which again
 296 matches closely with [3], and is approximately 10% greater than the TEC
 297 given by the AIS-fitted model at 70 degrees SZA. In this case, we expect a
 298 secondary ionospheric layer to be present and to contribute to approximately
 299 10% of the TEC, and so we can conclude that here we also have results which

300 are consistent with what the AIS-fitted model provides.

301 *6.6. Sources of Error*

302 The ionospheric model derived in this work best fits the ionospheric delay
303 measurement data obtained from the level 3 data available in the ESA PSA.
304 However, the following potential sources of error may affect this result (and
305 those of other studies):

- 306 • The best-fit Chapman profile is an idealization and the true ionosphere
307 may have a different morphology. However, the simultaneous min-
308 imization on both channels of the RMSE between the simulated and
309 measured delay times ensures that the terms of the system of equations
310 in (13) are weighted correctly.
- 311 • The algorithm fits a single Chapman profile to the range of SZA under
312 consideration. Therefore, local variations in the TEC are lost, and
313 some residual error remains after an optimal ionospheric profile has
314 been found, and is visible in Figure 4. This residual RMS error is
315 approximately ± 0.03 TECu.
- 316 • The algorithm operates on level 3 data from the PSA. This data has
317 already been processed: azimuth- and range-compressed, aligned to a
318 reference altitude, and ionospheric focusing applied. Any errors intro-
319 duced by the upstream processing of this data will have an effect on
320 the final result.

321 **7. Conclusion**

322 A novel method for TEC estimation based on analysing the ionospheric
323 time delay in the MARSIS radar signals is developed. The algorithm is
324 computationally inexpensive compared to other methods, and can be used
325 with publicly available data in the ESA Planetary Science Archive. The
326 method uses an ionospheric model which is iterated in order to match the real
327 delay experienced by the signals received on both channels of the radar. The
328 dual-frequency approach is a novel one, and provides an additional constraint
329 in determining the correct model. The iterated model is further verified by
330 comparing the distorted pulse shapes it simulates with raw range-compressed
331 pulses taken from the radar measurements, and the simulated profile can
332 reproduce the raw pulses in cases of strong surface reflection. In cases of
333 moderate solar activity, the TEC obtained by this study is consistent with
334 the best-fit ionospheric model obtained from AIS data, and also agrees well
335 with previous studies using SS3 data.

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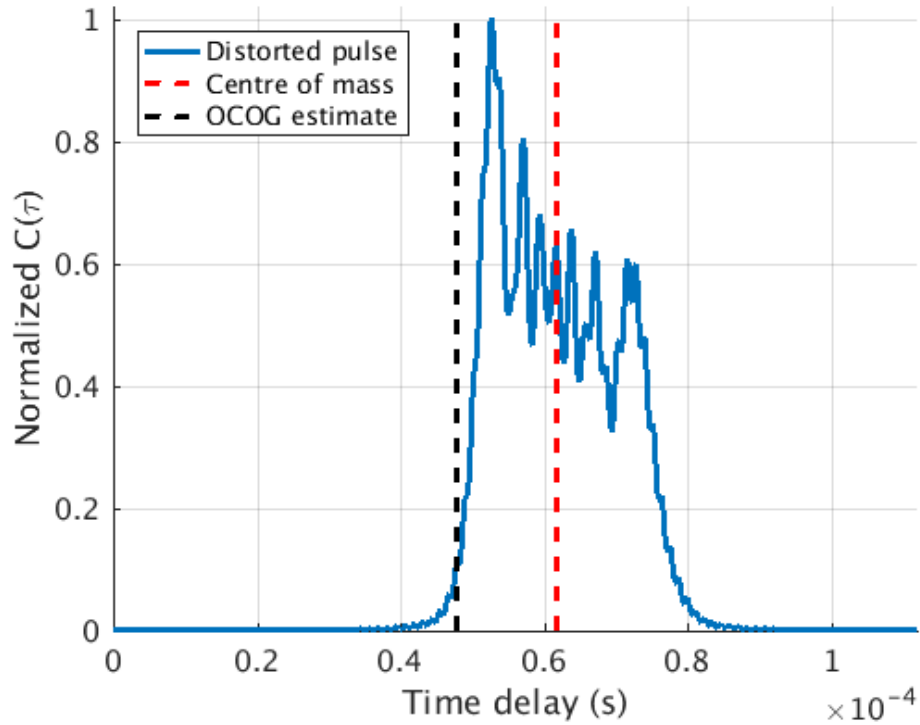
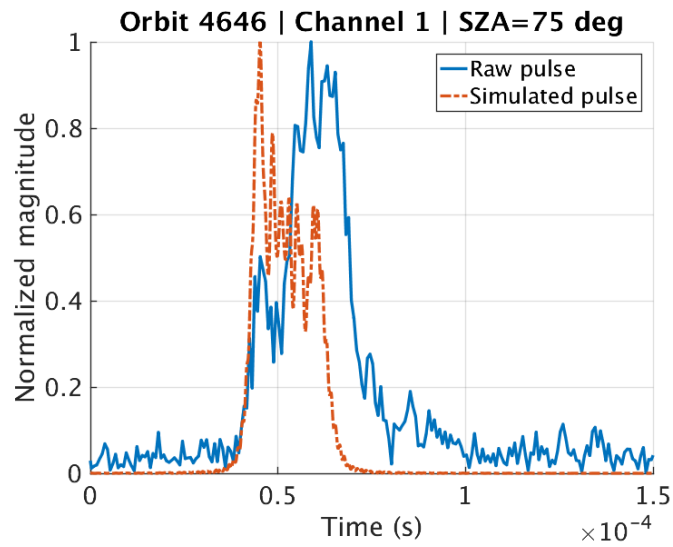
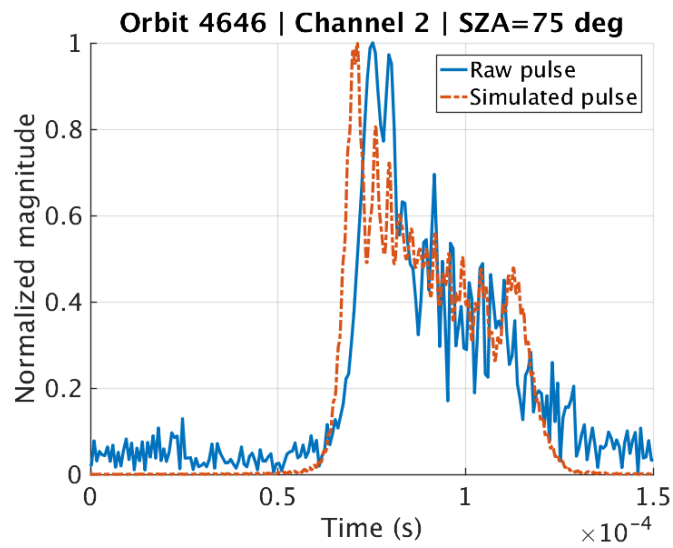


Figure 1: Determining the time delay of the radar pulse. The y-axis is the magnitude of the distorted, compressed pulse found by correlation of the transmitted and received signals. The axis is normalized such that the maximum correlation with an undistorted pulse equals unity. Red dashed line: COM delay. Black dotted line: OCOG delay.



(a) Channel 1.



(b) Channel 2.

Figure 2: Blue solid line: raw range-compressed pulses at 75 degrees SZA for orbit 4646. Purple dotted line: Simulated pulses, using parameters obtained from the RMSE routine. All pulses are individually normalized, such that the peak amplitude of each pulse is 1.

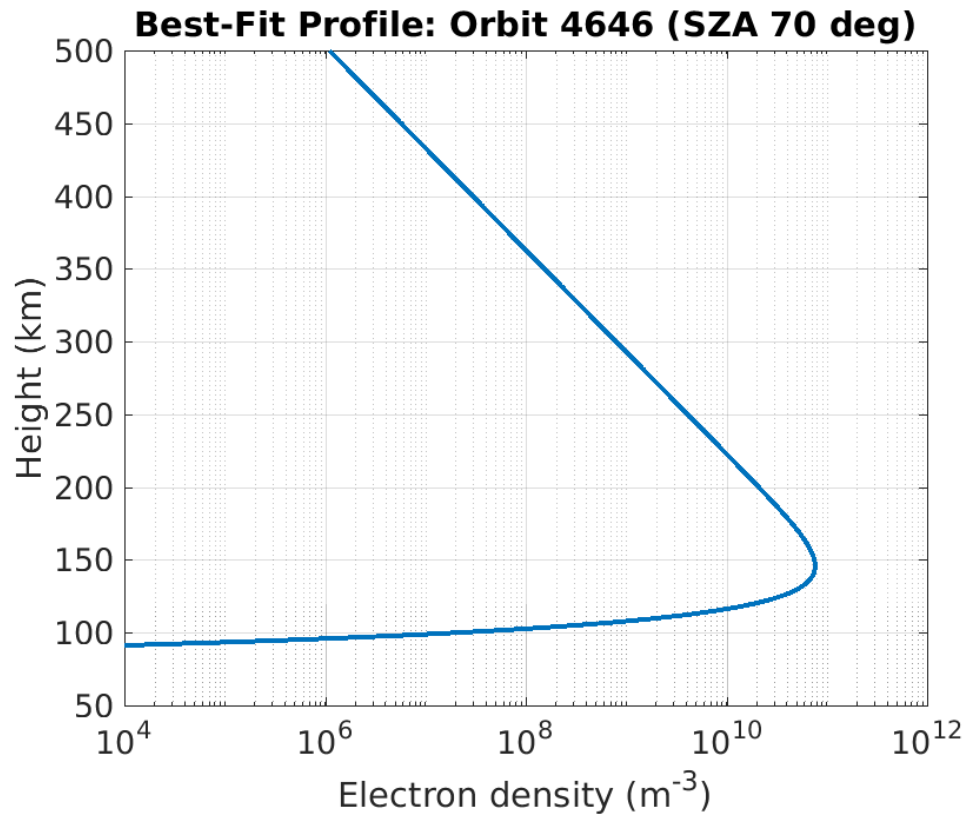


Figure 3: Best-fit electron density profile at SZA 70 degrees for orbit 4646. Note that the shape of the profile scales with SZA as given by equation (15).

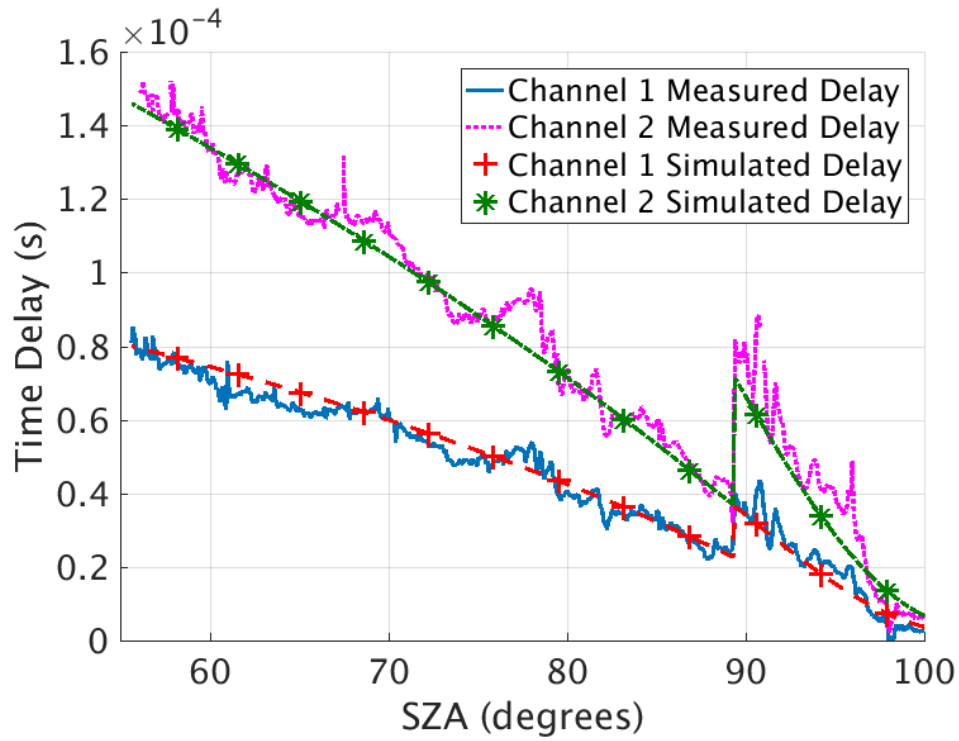


Figure 4: Comparison of measured vs simulated ionospheric delay for orbit 4646. The jump at SZA = 89 degrees is caused by the radar changing to a different set of frequency bands. Channel 1 centre frequency: 4 MHz SZA > 89 degrees, 5 MHz SZA < 89 degrees. Channel 2 centre frequency: 3 MHz SZA > 89 degrees, 4 MHz SZA < 89 degrees. Blue solid line: channel 1 measured delay. Purple dotted line: channel 2 measured delay. Red crosses: channel 1 simulated delay. Green stars: channel 2 simulated delay.

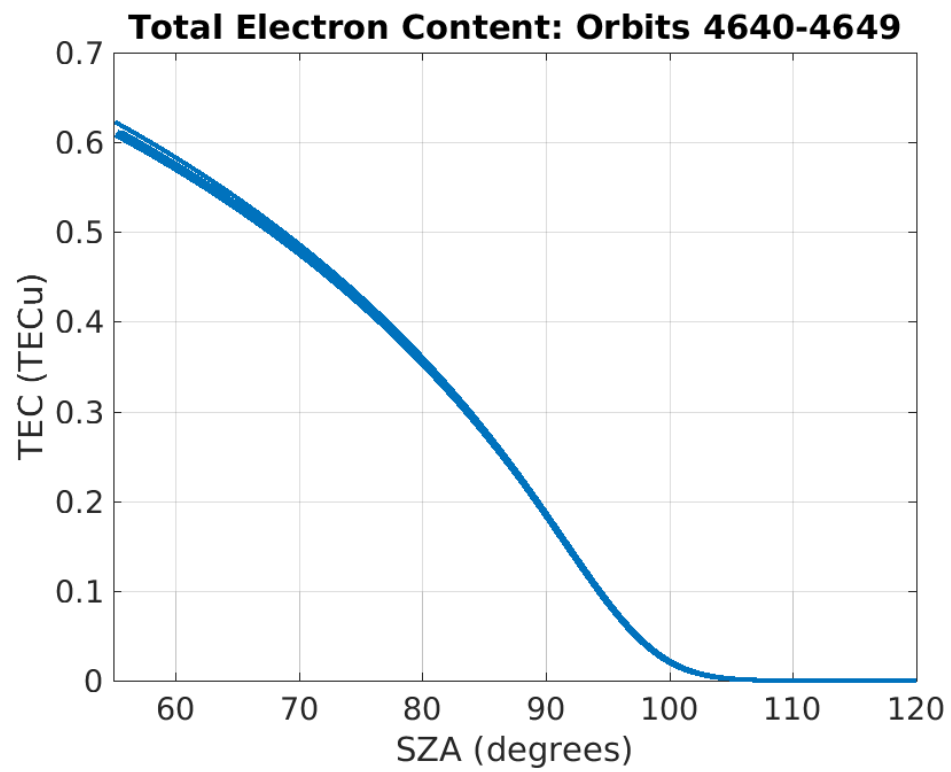


Figure 5: TEC inverted from the best-fit ionospheric profiles for orbits 4640-4649.

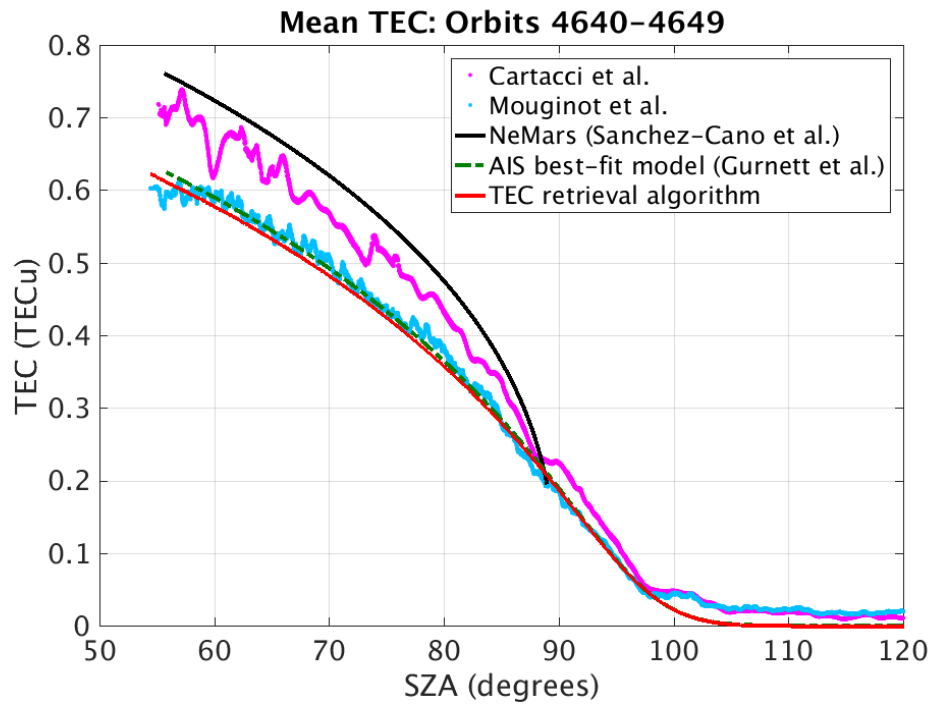


Figure 6: Mean TEC of this study compared to previous studies for orbits 4640-4649. Pink: Cartacci et al. [5]. Light blue: Mouginot et al. [3]. Black: NeMars model [18],[20]. Green: Gurnett et al. best-fit model derived from AIS data [14]. Red: best-fit model found by this study.

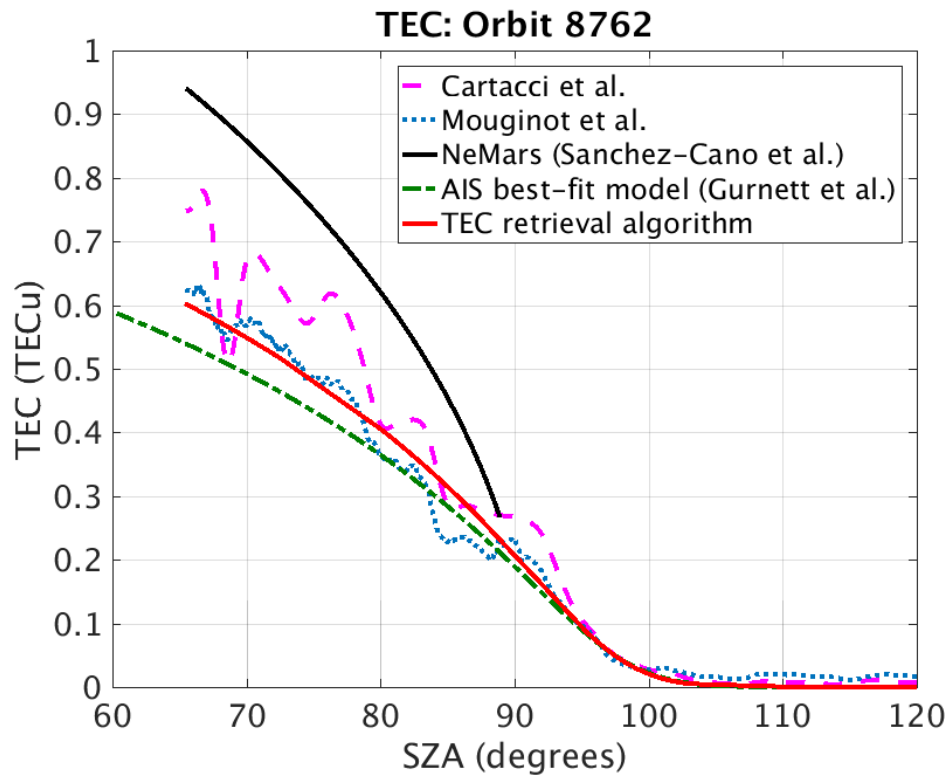


Figure 7: Pink dashed line: Cartacci et al. [5]. Blue dotted line: Mouginot et al. [3]. Black solid line: NeMars model [18],[20]. Green dot-dashed line: Gurnett et al. best-fit model derived from AIS data [14]. Red solid line: best-fit model found by this study.