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1 Mars ionosphere total electron content analysis from MARSIS subsurface data

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27 **ABSTRACT**

28 We describe a method to estimate the Total Electron Content (TEC) of the Mars ionosphere from
29 the output parameters of an algorithm, called the Contrast Method (Picardi et al. 2000, Ilyushin and
30 Kunitsyn 2004), which allows to correct the phase distortion of the echoes recorded by the Mars
31 Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al. 2005) in its
32 subsurface mode. Based on the TEC values evaluated during 6 years of MARSIS activity,
33 corresponding to about 4600 orbits, in this paper we present a global map of the night side TEC
34 variations, which correlates well with the magnetic field model derived from MGS (Mars Global
35 Surveyor) Magnetometer/Electron Reflectometer (MAG/ER) data. In particular, we demonstrate
36 that regions of enhanced TEC preferentially correspond to areas where crustal magnetic field lines
37 are quasi perpendicular to the Martian surface; moreover, we demonstrate that, in regions where the
38 magnetic field is predominantly nearly vertical, enhanced TEC values correlate with higher field
39 intensities, while in regions where the magnetic field is predominantly nearly horizontal, such
40 correlation is not observed. As already suggested in the past by other authors, we suggest that
41 increased TEC values may be related to the precipitation of electrons from the Martian
42 magnetospheric tail along vertical crustal magnetic field lines.

43 **1. Introduction**

44 It is well known that the day side ionosphere of Mars is very different from its night side
45 counterpart. The first obvious difference resides in the fact that the day side is directly hit by solar
46 EUV photons which ionize atmospheric neutrals; moreover, many different factors, external and
47 internal, are at play. As regards the day side, other factors add to photo-ionization: solar cycle, solar
48 rotation, solar flares, cosmic rays, gamma ray bursts etc. (Lillis et al., 2009). As for the night side,
49 the main factors are: neutral density, day-night plasma transport, recombination rates etc. (Lillis et
50 al., 2009) .

51
52 An important fact regarding the Martian ionosphere is that, by contrast to Earth, which has a strong
53 geomagnetic field of core origin, Mars does not possess an appreciable global magnetic field. In
54 these conditions, the solar wind can directly interact with the Martian ionosphere and induce
55 modifications of its local properties. However, the magnetometer carried by the MGS mission has
56 established that the planet has strong (up to 1600 nT at ~90 km of altitude) local magnetic fields,
57 related to properties of the Martian crust (Acuna et al., 1999; Nielsen et al. 2006). Such crustal
58 magnetic field lines close in the lower ionosphere and the associated magnetic perturbations are also
59 detected in the upper ionosphere. Magnetic field intensities exceeding 200 nT were measured
60 around 400 km above the surface, but in some regions this influence extends up to 700 Km
61 (Langlais et al., 2010). The combination of the complicated topology of crustal magnetic field with
62 the various factors influencing ionospheric conditions can produce some areas where the ionization
63 is higher and the recombination is lower, producing high values of the electron density even on the
64 night side (Safaeinili et al., 2007).

65
66 The night side ionosphere has been the object of various investigations, although its full
67 comprehension is still far from complete (see, e.g. Lillis et al., 2011, and Withers, 2009).

68 Using MARSIS AIS observations, which only respond to the top side ionosphere, Gurnett et al.
69 (2008) found that, for solar zenith angles (SZA) exceeding 100° , the ionosphere displayed
70 “irregular patches”, more dense where the magnetic field is more intense, while Němec et al. (2010)
71 found AIS ionospheric echoes in $\sim 9\%$ of cases for $SZA > 107^\circ$ and analyzed nightside MARSIS
72 airborne imaging spectrometer data, so as to find 90 cases of ionospheric echoes with $SZA > 125^\circ$,
73 all in regions of open magnetic field and with higher peak electron densities corresponding to
74 stronger magnetic fields. Complementing these observations, Leblanc et al. (2008) showed a case
75 study where three simultaneous observations were correlated: TEC increase, increase of the flux of
76 precipitating electrons, and observation of a nightside UV aurora. Moreover, for $SZA > 100^\circ$,
77 Safaeinili et al. (2007) showed that the Total Electron Content (TEC) is higher where the local
78 magnetic field is nearly vertical, while Lillis et al. (2010) showed that during solar particle events
79 TEC increases by more than a factor of 2 may take place.

80

81 In this paper, we present a night side map of TEC variations (ΔTEC) based on data collected by
82 MARSIS in its subsurface operation mode. Being based on data collected during 4600 orbits, this
83 map provides a more complete coverage of the planet and is based on a larger statistics than the
84 previous similar map by Safaeinili et al. (2007). We show that higher concentrations of ΔTEC are
85 observed at locations where the ionospheric magnetic field is nearly vertical and suggest that, when
86 such a correlation exists, the magnetic field intensity is high; on the contrary, lower concentration of
87 TEC are observed at locations where the magnetic field is roughly horizontal and has a low
88 intensity.

89

90 Section 2 recalls the main facts about MARSIS; section 3 contains a brief description of the main
91 effects of the Martian ionosphere on radar propagation; section 4 shows how TEC can be calculated
92 through the "Contrast Method" and discusses the choice of concentrating on the night side leg of
93 the orbits; section 5 compares the night side ΔTEC map with an MGS magnetic field map; section 6

94 contains a discussion of the results in relation with previous works, a brief summary and some hints
95 on possible future developments. The Appendix provides a description of the Contrast Method,
96 which has the main goal of compensating the distortions of the MARSIS subsurface data caused by
97 the Martian ionosphere.

98 2. The MARSIS instrument

99 The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Picardi et al.
100 2005) is a nadir-looking pulse limited radar sounder, which uses synthetic aperture (SAR)
101 techniques and is carried by ESA's Mars Express spacecraft. MARSIS has the main task of
102 evidencing the presence of water, both liquid and solid, on Mars, with the secondary objective of
103 characterizing the structure of the Martian ionosphere. Therefore, the MARSIS design has foreseen
104 two operation modes: the SS (Sub-Surface) Mode and the AIS (Active Ionosphere Sounding)
105 Mode.

106
107 In its SS mode, MARSIS transmits radar pulses that penetrate through the planetary surface and are
108 reflected by any dielectric discontinuity in the subsurface. MARSIS pulses consist of "chirps", i.e.
109 wave packets of duration $T = 250 \mu\text{sec}$, which are linearly modulated in frequency over a
110 bandwidth $B = 1\text{MHz}$ about a central frequency. The latter can be chosen between 4 different
111 values (1.8, 3, 4 and 5 MHz), according to the predicted SEA, so that the chirp frequency is always
112 higher than the local plasma frequency. Under such conditions, the free-space spatial resolution
113 after the so-called "range compression" (which is defined as the convolution between the received
114 chirp signal and a reference function representing the emitted chirp) is approximately 150 m, which
115 corresponds to 50-100 m in the subsurface, depending on the real dielectric constant value of the
116 subsurface layers. The SAR processing is designed so as to obtain synthetic apertures (called
117 frames) adjacent to each other, with a ground resolution of 5.5-10 km along the track and of 17-30
118 km across the track, where lower and higher resolutions pertain to higher and lower S/C altitudes,
119 respectively. The receiving window duration is $350 \mu\text{s}$ and the sampling frequency is $f_s = 1.4\text{MHz}$,
120 so that each frame contains 490 samples that increase to 512 after zero padding and FFT processing.
121 During the same SAR, MARSIS usually alternates two frequencies at PRF (Pulse Repetition
122 Frequency) steps, so as to increase the probability that at least one of them propagates above the

123 plasma frequency: the higher frequency (F01) is emitted before the lower one (F02). One additional
124 feature of MARSIS is that it is equipped with a tracking loop that allows the radar to keep echoes
125 within the receiving window regardless of the presence of any additional ionospheric delay.
126

127 As the penetration depth of radar signals in the subsurface is approximately proportional to their
128 wavelength (with the exception of ice), MARSIS operates at the lowest possible frequencies
129 capable of propagating through the Martian ionosphere, i.e. just above the local plasma frequency,
130 f_p . As the electron density is known to be definitely lower in the night side, this constraint implies
131 that the MARSIS subsurface sounder is best utilized for negative values of the SEA (Sun Elevation
132 Angle, i.e. the angle between the direction of the geometric centre of the Sun's apparent disk and the
133 horizon). However, as the ionospheric layer extends between 100 and 200 km, the true night side is
134 usually considered to correspond to $SEA < -20^\circ / -15^\circ$, so that the Sun light cannot reach the
135 ionosphere at all.
136

137 3. The effects of the Martian ionosphere on MARSIS signal propagation

138 The propagation of an electromagnetic wave of frequency f in the Martian ionosphere is
 139 characterized by the following refraction index

$$140 \quad n(z) = \sqrt{1 - \frac{f_p^2(z)}{f^2 - jf\nu}} \cong \sqrt{1 - \frac{f_p^2(z)}{f^2}} \quad (1)$$

141 where f_p is the plasma frequency, ν the electron-neutral collision frequency and z is the altitude

142 above ground. If we consider a typical MARSIS operation frequency (i.e. in the 1.3-5.5 MHz

143 range), the imaginary term in the denominator of Eq. (1) can be neglected, because $\nu \sim 10 - 60$ kHz.

144 The plasma frequency, in Hz, can be written as

$$145 \quad f_p(z) = 8.98 \sqrt{N_e(z)}, \quad (2)$$

146

147 where N_e is the electron density in m^{-3} . The maximum value of f_p obviously corresponds to the

148 maximum value of the electron density $N_{e\max}$.

149

150 As a consequence of Eq. (1) all frequencies lower than f_p will be reflected regardless of the

151 incidence angle. Moreover, if the radar signal has a wide band, the propagation speed is not

152 constant through the band and a frequency dependent phase shift arises. In other words, frequencies

153 higher than f_p will be attenuated, delayed by an average delay (group delay) in signal travel time and

154 dispersed depending on the electron density values encountered along the path.

155

156 The phase shift induced by the ionosphere in a radar signal of frequency f can be written as

$$157 \quad \Delta\phi(f) = \frac{4\pi}{c} f \int_0^L [n(z) - 1] dz = \frac{4\pi}{c} f \int_0^L \left[\sqrt{1 - \left(\frac{f_p(z)}{f} \right)^2} - 1 \right] dz, \quad (3)$$

158 where L is the ionosphere thickness and c is the speed of light in vacuum.

159 If f_0 is the central frequency of the radar signal band, we can perform a Taylor expansion of the

160 integrand of Eq. (3) and then integrate each term of the expansion, so as to obtain

$$\Delta\phi(f) \cong a_0 + a_1(f - f_0) + a_2(f - f_0)^2 + a_3(f - f_0)^3 + a_4(f - f_0)^4 + \dots, \quad (4)$$

where:

$$\begin{aligned} a_0 &= \frac{4\pi}{c} \int_0^L (\sqrt{f_0^2 - f_p^2} - f_0) dz \quad [rad] \\ a_1 &= \frac{4\pi}{c} \int_0^L \left(\frac{f_0}{\sqrt{f_0^2 - f_p^2}} - 1 \right) dz \quad [rad / Hz] \\ a_2 &= -\frac{4\pi}{c} \int_0^L \left(\frac{f_p^2}{2(f_0^2 - f_p^2)^{\frac{3}{2}}} \right) dz \quad [rad / Hz^2] \\ a_3 &= \frac{4\pi}{c} \int_0^L \left(\frac{f_0 f_p^2}{2(f_0^2 - f_p^2)^{\frac{5}{2}}} \right) dz \quad [rad / Hz^3] \\ a_4 &= \frac{4\pi}{c} \int_0^L \left(\frac{4f_0^2 f_p^2 + f_p^4}{8(f_0^2 - f_p^2)^{\frac{7}{2}}} \right) dz \quad [rad / Hz^4] \end{aligned} \quad (5)$$

The effect of the $a_0, \dots, a_4$ expansion coefficients on the MARSIS SS performance can be briefly described by recalling that the SS data are processed through the range compression. In the case of a perfect reflection at the Martian surface and of propagation in free space, the range compression would yield a time dependent signal power characterized by a central lobe and a number of side lobes (as a consequence of the linear variation of the frequency within the chirp). After range compression, the theoretical main lobe width should be 1 μ sec wide, while the difference in power between the main lobe peak and the first side lobe peak should be 32 dB. These parameters characterize the radar range resolution, that is the ability to reveal objects close to one another, and the radar dynamic range, which affects the capability to detect subsurface echoes.

Fig. 1 displays the range compression of the ideal reflected signal (i.e. in free space - blue line) and the range compressions pertaining to the a_1, a_2, a_3 , and a_4 expansion terms (blue dotted, black, red and purple lines, respectively), all evaluated through the simplified expressions given in Eqs. (A.11)

181 of the Appendix, assuming that $f_p = 1$ MHz and $\tau_0 = 533$ μ s. All lines have been normalized to their
 182 peak values. We notice that the a_1 term only introduces a time shift (group delay), while the higher
 183 terms yield phase distortions. In particular, the a_4 term smears out the side lobes, while the a_3 term
 184 enhances the lobes preceding the main lobe and reduces those following it. The most relevant
 185 effect is that due to the a_2 term, which seriously affects the received chirp slope.
 186 In conclusion, we see that the ionosphere can severely degrade the data quality, i.e. increase the side
 187 lobe levels, distort the waveform shape, and worsen the signal to noise ratio and range resolution.
 188 Moreover, the MARSIS signal is very vulnerable to ionosphere effects especially in those areas
 189 where the ionosphere and the magnetic field effects are combined together, because in these areas
 190 distortions are larger than usual. Obviously all the effects will increase steadily passing from the
 191 night side to the day side.
 192 Due to the relevance of this topic for the mission success, different methods have been proposed to
 193 correct the ionosphere distortion.
 194 Ilyushin and Kunitsyn (2004) described various methods, including a theoretical reconstruction of
 195 the signal phase, starting from its spectrum, with the use of an error function and a polynomial
 196 regression. Safaeinili et al. (2003) and Mouginot et al. (2008) proposed a recursive method to
 197 optimize the SNR with a phase correction term, considering the constraint that the measured phase
 198 after correction must be coincident with the phase obtained from the signal travel time expected
 199 from MGS-MOLA data; moreover, in order to initialize their recursive algorithm, they used a
 200 Gaussian approximation of the dependence of electron density on altitude. The core of the method
 201 used by Zhang et al. (2009) is a recursive loop to search for the best electron density N_e and
 202 electron-neutral collision frequency, neglected in Eq. (1), which optimize the SNR.
 203 The study presented in this paper is based on the Contrast Method, CM hereafter, which is briefly
 204 described in the Appendix.

205 4. Evaluation of TEC through the Contrast Method

206 4.1 TEC evaluated through the CM

207 We show in the Appendix that, when MARSIS is probing the subsurface, the CM provides an
208 estimate of a_2 for each SAR.

209

210 In the night side, usually $f_p \leq 1$ MHz, so that, excluding the lowest MARSIS SS frequency of 1.8
211 MHz, we have $f_p^2/f_0^2 \ll 1$. Therefore, we can approximate the a_2 parameter of Eq. (5) as

212

$$213 \quad a_2 \cong -\frac{4\pi}{c} \int_0^L \frac{1}{2} \frac{f_p^2}{f_0^3} dz = -\frac{2\pi}{c f_0^3} (8.98)^2 \int_0^L N_e dz \quad (6)$$

214 by keeping only the first term of the series expansion of the function $f_p^2/(f_0^2 - f_p^2)^{3/2}$, i.e. by

215 neglecting a $-\frac{3\pi}{c f_0^5} (8.98)^4 \int_0^L N_e^2 dz$ term. This approximation yields an overestimate of the

216 absolute value of a_2 of the order of $1.5(f_p/f_0)^2$, which, for $f_p=1$ MHz and $f_0=4$ MHz, is about 10%.

217 The inversion of Eq. (6) allows us to write

$$218 \quad TEC \cong -\frac{a_2 c f_0^3}{2\pi(8.98)^2} \quad (7)$$

219 where $TEC = \int_0^L N_e dz$ is the total electron content of the ionosphere, with the caveat that the

220 calculation through Eq. (7) always implies an overestimate of the TEC. In practice, as our study will

221 be limited to $SEA < 0^\circ$ and to $f_0=4$ MHz (see the summary of this section), this overestimate will at

222 generally be lower than 10% (but it can at times be higher for negative values of SEA close to 0°).

223 In Section 5 we will further comment on this issue.. The correction of this error could be the

224 subject of a future study.

225 4.2 TEC filtering and validation

226 The use of the CM over the whole MARSIS dataset has produced millions of TEC estimates for
 227 different conditions of solar zenith angle, latitude and longitude. As an example, Fig. 2a shows
 228 TEC values, as a function of the SEA, along orbit 6001, calculated from radar signals at frequencies
 229 of 3, 4 and 5 MHz (red, blue and black lines, respectively). The three lines are in good agreement,
 230 but at times they appear to be rather noisy, as many large spikes and fluctuations are superimposed
 231 to the general increase of TEC. This suggests that, before proceeding further, a filtering process
 232 should be applied to the TEC evaluated from Eq. (7). Fig. 2b displays the same data after spikes
 233 have been removed and a low pass filter (a zero-phase digital filter that processes the input data in
 234 both the forward and reverse directions) has been applied to them; hereafter, we call the result of
 235 such a process TEC_{filt} . We notice that in the night side (for $SEA < -25^\circ$) the 3 and 4 MHz lines
 236 roughly coincide. The residual differences between the two lines in that region could be due to
 237 various transient effects whose relative influences are difficult to establish quantitatively (different
 238 number of echoes collected at different frequencies, frequency dependent surface and subsurface
 239 effects, frequency dependent transmitter distortions and antenna performance). We also remark that
 240 in the range $-16^\circ < SEA < 0^\circ$ the 3 MHz TEC is generally slightly higher than the 4 MHz one. A
 241 straightforward interpretation of this result is that in that region, as the day side is approached, the
 242 plasma density increases, so that the condition $(f_p / f_o)^2 \ll 1$ starts to break down: when that
 243 happens, the value of a_2 provided by the CM is overestimated, which in turn leads to a TEC value
 244 larger than it should be. Similarly, in the day side the 4 MHz TEC is usually larger than the 5 MHz
 245 TEC.

246
 247 Before proceeding further, we compared the TEC_{filt} , obtained in the 4 MHz mode, with the TEC
 248 calculated by Mougnot et al. (2008). Figs. 3 and 4 show the comparison between the two TECs for
 249 orbits 2600 and 2640, respectively, for negative SEA values only (because, as we argue further on,
 250 the study described in this paper is focused on the night side). The TEC estimated through the
 251 Mougnot et al. (2008) method, red dotted line, has been filtered in the same way as TEC_{filt} , blue

252 dotted line. Figs. 3 and 4 demonstrate that in the night side the two TECs generally agree and
 253 display similar fluctuations and trends.
 254
 255 TEC_{filt} values were calculated from 4600 orbits between July 2005 and October 2011. In order to
 256 test such a large dataset for consistency, we first of all calculated averages of TEC_{filt} in 0.1° SEA
 257 bins for all four available frequency bands. Fig. 5 displays such averages of TEC_{filt} as a function of
 258 SEA for the four frequencies and shows that TEC_{filt} clearly and steadily increases as the SEA passes
 259 from negative (night side) to positive (day side) values.
 260 Fig. 5 shows that, in the night side, the average TEC_{filt} values, estimated for the four different
 261 frequencies, coincide, exception made for some residual peaks which seem to occur mainly for 4
 262 MHz TEC_{filt} values. However, as the SEA increases and the transmitted frequency approaches the
 263 local plasma frequency, the scatter of TEC_{filt} values above or below the average trend increases.
 264 This means that, under such conditions, TEC_{filt} suffers from a loss of accuracy, because the
 265 quadratic term estimated through the CM is not sufficient to fully compensate the distortion caused
 266 by the ionosphere. At 1.8 MHz the plasma frequency is already approached at about -20° . In fact,
 267 we see that, for $SEA > -20^\circ$, the velvet points in Fig. 5 deviate from the general trend.
 268 Consequently, above -15° we did not plot 1.8 MHz TEC_{filt} values. Similarly, we did not plot 3 MHz
 269 TEC_{filt} values above 0° . $f_0=4$ MHz is the only MARSIS operation frequency that produces a
 270 complete data set covering both the night and the day side; on the other hand, $f_0=5$ MHz provides
 271 data over the whole day side.

272 The blue solid curve of Fig. 5 displays the TEC evaluated through the Chapman model (Chapman,
 273 1931). The electron density of the Chapman model is

$$274 \quad n_e\left(\frac{h-h_0}{H}, \chi\right) = n_0 \exp\left(-0.5\left(1 - \frac{h-h_0}{H} - Ch\left(\frac{R+h}{H}, \chi\right) \exp\left(-\frac{h-h_0}{H}\right)\right)\right) \quad (8)$$

275 where h_0 is the altitude of the maximum electron density, H is the neutral scale height and Ch is the
 276 Chapman incidence function

$$277 \quad Ch\left(\frac{R+h}{H}, \chi\right) = \frac{R+h}{H} \sin \chi \int_0^\chi \exp\left(\frac{R+h}{H} - \frac{R+h}{H} \frac{\sin \alpha}{\sin \chi}\right) \text{cosec}^2(\alpha) d\alpha \quad (9)$$

278 In Fig. 5 the Chapman model has been evaluated with the following parameters: $n_0 = 2.2 \cdot 10^{11} \text{ m}^{-3}$,
 279 $h_0 = 130 \cdot 10^3 \text{ m}$, $H = 13 \cdot 10^3 \text{ m}$, chosen so as to obtain an overall acceptable fit of the experimental
 280 data. Given the nature of the Chapman model, a comparison with the experimental TEC only makes
 281 sense for $\text{SEA} > -10^\circ$. From Fig. 5 it is clear that the experimental 4 MHz TEC_{filt} values and the
 282 theoretical model match quite closely over a 10° - 20° interval roughly centered at $\text{SEA} = 0^\circ$, while
 283 they differ on the day-side, above 10° , where the model forecasts first lower, then higher values
 284 than the observed TEC_{filt} . As regards the 5 MHz TEC_{filt} values, we notice that they practically
 285 coincide with the 4 MHz ones close to $\text{SEA} = 0^\circ$, while they better agree with the model in the 10° -
 286 20° range and start deviating considerably from the model around 25° , where the plasma frequency
 287 becomes too high for the CM to produce a reliable TEC estimate.

288 *4.3 Solar activity effects on TEC*

289 The averages displayed in Fig. 5 have been obtained over a period of several years. As a
 290 consequence, all possible effects due to variations of solar activity have been probably smoothed in
 291 the averaging process. However, it is expected that the solar activity can severely degrade the radar
 292 signal propagation, mainly because of solar flares (Espley et al. 2007). Therefore, in order to briefly
 293 study the behavior of TEC_{filt} under different solar conditions, we have conducted the same analysis
 294 used for generating Fig.5 after having grouped the data according to the year. Fig. 6 shows averages
 295 of 4 MHz TEC_{filt} , calculated over 0.1° SEA bins and plotted as a function of SEA, for five
 296 subsequent years. Figs. 6a and 6b pertain to the night and to the day side, respectively, and have
 297 different ordinate scales due to the large excursion of TEC_{filt} from night to day. As regards Fig. 6a,
 298 we see that the scatter of points around the average trends is of the order of 0.1 - $0.2 \cdot 10^{15} \text{ m}^{-3}$ for each
 299 year; however, the TEC_{filt} values pertaining to the five years become more and more different as the
 300 SEA increases towards the day side, although the largest difference is roughly $0.5 \cdot 10^{15} \text{ m}^{-3}$ for
 301 values pertaining to 2007 and 2008. In the Fig. 6b, we clearly see that the average TEC_{filt} values are
 302 very different in different years; moreover, the dependence on the SEA varies a lot from year to

303 year. These results suggest that, for every statistical analysis conducted on data pertaining to distinct
304 years, these differences must be properly taken into account.

305

306 4.4 Section summary

307 To conclude this section, we summarize hereafter its main findings.

- 308 • TEC can be calculated through the Contrast Method. However, its values are generally
309 overestimated by a factor $1.5(f_p/f_0)^2$. For $f_0 = 4\text{MHz}$ and $f_p = 1\text{MHz}$, this corresponds to
310 10%, but it can attain larger values as SEA approaches 0° from the night side.
- 311 • The Martian TEC seems to depend on solar activity. This dependence shows up as a shift of
312 TEC to higher or lower values over the entire SEA range, as a function of the year in the
313 solar cycle.
- 314 • The overall dependence of the Chapman model TEC on SEA is in good agreement with the
315 experimental TEC data for $\text{SEA} > -10^\circ$, provided that the chirp frequency is well above the
316 local plasma frequency.
- 317 • When the plasma frequency gets too close to the chirp frequency, TEC values display large
318 deviations from the average TEC trend and from the Chapman model.
- 319 • The best chirp central frequency for the calculation of TEC in the night side is $f_0 = 4\text{MHz}$, as
320 confirmed by the comparison of the CM TEC with the Mouginot et al. (2008) TEC.

321

322 5. MARSIS TEC variations in relation to the Martian crustal magnetic field

323

324 5.1. General considerations

325 The conclusions drawn at the end of the preceding section clearly suggest that the day side data
326 must be treated with great care, while the night side TEC data can be used to build a map of TEC
327 covering most of the planet. Safaeinili et al. (2007) calculated for each orbit the per cent variations
328 of TEC relative to the average night side TEC, displayed such per cent variations through a
329 longitude-latitude map and compared it with a map of the crustal magnetic field, suggesting that at
330 times a correlation existed between the two. However, the map obtained by Safaeinili et al. (2007),
331 which was based on only 750 orbits and included only data from portions of the orbit for which
332 $SEA < -10^\circ$, did not fully cover all latitudes and longitudes. Based on our larger data base, we aim
333 at increasing as much as possible the longitude-latitude coverage of such a map. However, as also in
334 our case the $SEA < -10^\circ$ restriction does not allow us to obtain a continuous coverage, we have
335 devised an improved method to derive reliable per cent variations of TEC also for SEA values
336 comprised between -10° and 0° .

337 5.2. Calculation of TEC variations

338 The principle of our method can be easily explained by considering Fig. 7, in which the blue curve
339 displays TEC_{filt} values in the $(-30^\circ, 13^\circ)$ SEA range for orbit 6001 and $f_0=4$ MHz. We notice that,
340 between -32° and $-15^\circ/-10^\circ$, TEC_{filt} undergoes several humps and hollows, while it oscillates around
341 a night time average value of about $0.3 \cdot 10^{12} \text{ m}^{-2}$. As SEA increases from $-15^\circ/-10^\circ$ to 13° , TEC_{filt}
342 displays a clear positive trend over which other small oscillations are superimposed. Therefore, it
343 makes sense to calculate ΔTEC with respect to the night time average value, as done by Safaeinili et
344 al. (2007), only up to -10° of SEA, while the extension of such a calculation to the whole SEA
345 range of Fig. 7 or even just to the $(-15^\circ, 0^\circ)$ range would undoubtedly yield unreasonable results, as
346 the new average would be much higher.

347

348 We fitted the TEC_{filt} values with a 10^{th} order polynomial, plotted in purple in Fig. 7, and calculated
349 ΔTEC as the difference between TEC_{filt} and the fit function, as shown by the black curve in Fig. 7.
350 A caveat must be added at this point: as discussed in Section 4, our evaluation of TEC (see eq. 7) is
351 affected by a systematic error, which yields an overestimate of TEC roughly proportional to the
352 TEC itself through a f_p^2/f_0^2 factor. As a consequence, a similar overestimate could show up in
353 ΔTEC . In practice, however, we see from Fig. 7 that the absolute value of ΔTEC does not
354 significantly increase between $SEA = -10^\circ$ and $SEA = 0^\circ$, so that we obtain reasonable values of
355 ΔTEC for all negative SEAs. In fact, deviations from the fit function show up along the whole orbit
356 as humps or hollows with amplitudes up to $0.5 \cdot 10^{15} \text{ m}^{-2}$ which occur over orbital distances
357 corresponding to SEA excursions ranging from 2° - 3° to 5° - 7° . All other orbits show similar
358 behaviors, although the locations and amplitudes of humps and hollows vary from one orbit to the
359 other. It is interesting to remark that ΔTEC is generally much smaller than the corresponding fit
360 function value, but it can be at times of the order of the fit function for negative values of the SEA.
361

362 The definition of ΔTEC and of TEC_{filt} allows in principle to generalize the calculation of the per
363 cent ΔTEC relative to the fit function, i.e. to define $\Delta TEC_{\text{pc}} = 100(\Delta TEC/TEC_{\text{filt}})$ for any value of
364 SEA. However, Fig. 7 clearly suggest that a given absolute value of ΔTEC can be of the order of
365 even larger than the corresponding TEC_{filt} value deep in the night side, while it will result to be
366 considerably smaller than the corresponding TEC_{filt} value in the day side. As a consequence, it does
367 not make sense to calculate ΔTEC_{pc} in the day side and we limit such a calculation to negative
368 values of SEA, thus including the $-15^\circ < SEA < 0^\circ$ interval. This new definition of ΔTEC_{pc} yields an
369 increase of the available ΔTEC_{pc} values by 27%, which allows, as we will see in the following, to
370 build a map covering all longitudes and all latitudes below 54° (above 54° the map cannot be built
371 due to the fact that in the nightside MARSIS data over that region are too sparse).

372

373 Having made this choice, as a next step in our analysis, we excluded all the day side data, that is
374 those for which $SEA > 0^\circ$, and then computed ΔTEC_{pc} , point by point and for each orbit.

375 5.3. *Maps of ΔTEC_{pc} and of magnetic field inclination*

376 We binned all the night side ΔTEC_{pc} in a grid with 0.5° resolution, from -90° up to $+54^\circ$
377 geographical latitude and covering all geographical longitudes, averaging the data collected in each
378 bin. The resulting two dimensional matrix of percentages has been two-dimensionally low pass
379 filtered, in order to further reduce noise and then interpolated to achieve a resolution of 0.25° and
380 improve the quality of the maps. Fig. 8 shows the latitude-longitude map of the final ΔTEC_{pc} . The
381 data have been coded according to the scale displayed on the right, which has been chosen so, that it
382 is possible to appreciate both the spatial structure of ΔTEC_{pc} and the distribution of ΔTEC_{pc} values.
383 ΔTEC_{pc} values mostly fall between -20% and $+20\%$, but large positive and negative values are also
384 seen, as expected from the ΔTEC plot shown in Fig. 7 for orbit 6001. On the other hand, we also
385 notice that spatial structures are exhibited by ΔTEC_{pc} , similarly to what was earlier observed by
386 Safaeinili et al. (2007), who suggested a dependence of their ΔTEC_{pc} on the orientation of the
387 crustal magnetic field (in this regard, see their Figs. 3a and 3b).

388

389 In order to enhance the spatial structures exhibited by ΔTEC_{pc} , Fig. 9a shows the same ΔTEC_{pc}
390 values as shown in Fig. 8, plotted according to the new scale shown on the right. The effect of the
391 new scale is that positive values of ΔTEC_{pc} appear as whitish spots, while negative values appear as
392 blackish spots. Fig. 9b displays the corresponding latitude-longitude maps of the angle (which we
393 hereafter call α) between the ambient magnetic field vector at 200 km above the mean spherical
394 radius and the local vertical direction (taking α to be positive for both upward and downward field).
395 This angle has been computed from magnetic field predictions at a constant altitude from an

396 Equivalent Source Dipole model (ESD), based on the approach used by Langlais et al. (2004) and
 397 updated to account for more recent measurements. This new model uses magnetometer (MAG)
 398 actual rather than geographically averaged measurements of the three magnetic field components,
 399 acquired during all the phases of the MGS mission. The MAG data selection scheme was improved
 400 in order to eliminate most of the transient, time-varying, magnetic field contributions. The ESD
 401 mesh consists of a grid of 10,602 locations, with a mean spacing of 1.97° (117 km along the
 402 Martian equator). This new model therefore relies on more measurements, with an increased
 403 altitude coverage, with less contaminating external fields entering and a better lateral resolution.
 404 The constant-altitude map is computed with a 0.25° resolution both in latitude and in longitude.
 405 Areas where the field is quasi-horizontal, or with values of α close to 90° , are coded in black, while
 406 areas corresponding to a quasi-vertical field, with values of α close to 0° , are coded in white.
 407 A careful examination of Fig. 9 suggests that regions of quasi-vertical magnetic field often
 408 correspond to regions of positive $\Delta\text{TEC}_{\text{pc}}$, while regions of quasi-horizontal magnetic field often
 409 correspond to regions of negative $\Delta\text{TEC}_{\text{pc}}$. In order to highlight this, we drew two dashed lines in
 410 the lower panel: the red one along an extended region of vertical magnetic field; the yellow one
 411 along a region of horizontal field. We then copied the two lines onto the upper panel at exactly the
 412 same longitudes and latitudes. We see that, in the highlighted regions, the correlation between
 413 magnetic field orientation and $\Delta\text{TEC}_{\text{pc}}$ is strikingly good. On the other hand, it must be also
 414 remarked that in other regions of Fig. 9 the correlation between vertical (horizontal) field and high
 415 (low) $\Delta\text{TEC}_{\text{pc}}$ is blurred or not seen at all.

416
 417 A region where the correlation between the field direction and $\Delta\text{TEC}_{\text{pc}}$ appears to be particularly
 418 good is evidenced in Fig. 10, which shows blow-ups of the α and $\Delta\text{TEC}_{\text{pc}}$ maps between -64° and -
 419 7° in latitude and 104° and 194° in longitude. Again we highlight the vertical field and high $\Delta\text{TEC}_{\text{pc}}$

420 through red dotted lines and the horizontal field and low $\Delta\text{TEC}_{\text{pc}}$ through yellow dashed lines.

421 Further on in the text, we will refer to this region as to region 1 (R1 for short).

422

423 5.4. *Analysis of $\Delta\text{TEC}_{\text{pc}}$ in relation to magnetic field inclination and intensity*

424

425 The comparison between the maps of α and $\Delta\text{TEC}_{\text{pc}}$ deserves further investigation, in order to
426 quantitatively estimate the similarity of the structures which are present in each of them. Here we
427 add some statistical analysis to perform a first order quantitative assessment. The results of this
428 analysis are displayed in Fig. 11. First of all, we considered two subsets of the whole $\Delta\text{TEC}_{\text{pc}}$ map,
429 the first comprising of all $1^\circ \times 1^\circ$ pixels for which $0^\circ < \alpha < 10^\circ$ (corresponding to nearly vertical
430 magnetic field), the second comprising of all $1^\circ \times 1^\circ$ pixels for which $80^\circ < \alpha < 90^\circ$ (i.e. nearly
431 horizontal field). Panel a of Fig. 11 displays the histograms of the $\Delta\text{TEC}_{\text{pc}}$ values pertaining to the
432 $0^\circ < \alpha < 10^\circ$ subset (black solid cityscape) and to the $80^\circ < \alpha < 90^\circ$ subset (dotted cityscape), as a
433 function of $\Delta\text{TEC}_{\text{pc}}$, in 40 bins between -100 and 100. Each histogram has been normalized to its
434 peak value, being the peak value 278 for the $0^\circ < \alpha < 10^\circ$ histogram and 1793 for the $80^\circ < \alpha < 90^\circ$
435 histogram. First of all, we notice that in the vast majority of cases $\Delta\text{TEC}_{\text{pc}}$ is observed to fall
436 between -20 and 20, which is agreement with the distribution of values indicated by the grey scale
437 coding in Fig. 8. The histogram pertaining to the $80^\circ < \alpha < 90^\circ$ subset has its peak in the (-5,0) bin and
438 is nearly symmetrical with respect to 0. We also examined the histogram of all $\Delta\text{TEC}_{\text{pc}}$ values
439 displayed in Fig. 8, but, as we found that it is rather similar to the $80^\circ < \alpha < 90^\circ$ one, we do not show
440 it in order not to overload panel a. Moving to the histogram pertaining to the $0^\circ < \alpha < 10^\circ$ subset
441 (black solid cityscape), we notice that it differs from the first one, as the dotted cityscape is steadily
442 and consistently above the black solid cityscape for negative values of $\Delta\text{TEC}_{\text{pc}}$; on the contrary, the
443 quasi-vertical field histogram is steadily higher than the quasi-horizontal one for positive values of

444 $\Delta\text{TEC}_{\text{pc}}$. Moreover, its peak is shifted to the (0,5) bin. In conclusion, we may state that panel a of
 445 Fig.11 confirms the consideration we made concerning Fig. 9, insofar as regions of quasi-vertical
 446 magnetic field preferentially correspond to regions of positive and high positive $\Delta\text{TEC}_{\text{pc}}$, while
 447 regions of quasi-horizontal magnetic field preferentially correspond to regions of negative $\Delta\text{TEC}_{\text{pc}}$.
 448 The correlations between quasi vertical magnetic field and positive $\Delta\text{TEC}_{\text{pc}}$ on one side, and
 449 between quasi horizontal magnetic field and negative $\Delta\text{TEC}_{\text{pc}}$ on the other side, are further
 450 highlighted in panel b of Fig. 11, which displays the histograms for quasi vertical magnetic field
 451 (solid cityscape) and quasi horizontal magnetic field (dotted cityscape) for the region 1 highlighted
 452 in Fig. 10. We remark that in panel b the histogram pertaining to the quasi-vertical magnetic field is
 453 further shifted towards positive values of $\Delta\text{TEC}_{\text{pc}}$, while the one for quasi-horizontal field is shifted
 454 in the opposite direction: quantitatively, we find that for quasi-vertical magnetic field, 70% of the
 455 $1^\circ \times 1^\circ$ bins display a positive $\Delta\text{TEC}_{\text{pc}}$ value, while 75% of the bins corresponding to a quasi-
 456 horizontal field display a negative $\Delta\text{TEC}_{\text{pc}}$ value.

457

458 In Fig. 9 several regions can be seen where the correlation between $\Delta\text{TEC}_{\text{pc}}$ and α seems not to
 459 hold. One such a region, to which we will hereafter refer as region 2 (R2 for short) extends between
 460 5° and 25° in latitude and between 130° and 190° in longitude. Panel c of Fig. 11 displays, for R2,
 461 similar histograms as those of panel b for R1. In panel c it is evident that the two histograms are
 462 more similar than those of panel b, apart from some fluctuations which can be ascribed to the
 463 smaller extension of the region, which yields a lower statistics. As both R2 and R1 contain quasi
 464 vertical and quasi horizontal field orientations, one can look for another physical quantity, e.g. the
 465 total magnetic field intensity, which might play a role in relation to the observation of positive or
 466 negative values of $\Delta\text{TEC}_{\text{pc}}$. Panel d displays the histograms of the total magnetic field intensity for
 467 R2 (dotted cityscape) and for R1 (solid cityscape). We see that the difference between the two is
 468 strikingly clear: practically all R2 bins correspond to a weak total magnetic field, below 50 nT; on

469 the contrary, the R1 histogram displays only a few values below 10 nT and extends to hundreds of
470 nT.

471 A possible interpretation of the histogram of Fig. 11d is that a higher magnetic field intensity, B , in
472 itself favors high positive values of $\Delta\text{TEC}_{\text{pc}}$. In order to check this hypothesis, we binned and
473 averaged all $\Delta\text{TEC}_{\text{pc}}$ values of Fig. 8 in 5 nT bins of the corresponding total magnetic field. The
474 lower panel of Fig. 12 displays, as a function of B , such averages of $\Delta\text{TEC}_{\text{pc}}$ (which we call
475 $\langle\Delta\text{TEC}_{\text{pc}}\rangle_B$), while the upper panel displays the number of cases pertaining to each 5 nT bin. We
476 see that $\langle\Delta\text{TEC}_{\text{pc}}\rangle_B$ is very small for $B < 20\text{nT}$, where most of data are concentrated, and exhibits
477 larger positive or negative values for higher and less frequent values of B . The $\langle\Delta\text{TEC}_{\text{pc}}\rangle_B$
478 oscillations are even larger for the few cases of $B > 100\text{ nT}$ which we do not show in Fig. 11 due to
479 their irrelevant statistical significance. In conclusion, no prominent dependence of $\langle\Delta\text{TEC}_{\text{pc}}\rangle_B$ on
480 B can be inferred from Fig. 12.

481

482 In order to further highlight the link between $\Delta\text{TEC}_{\text{pc}}$ and the orientation of the crustal magnetic
483 field, we averaged the $\Delta\text{TEC}_{\text{pc}}$ values of Fig. 8 over $1^\circ \times 1^\circ$ pixels and then binned such averages in
484 5° bins of α by associating each average to the α value pertaining to the given latitude and
485 longitude (according to the α matrix plotted in Fig. 9b) ; finally, 16 averages were calculated
486 (covering the 0° - 90° range), which we indicate with $\langle\Delta\text{TEC}_{\text{pc}}\rangle_\alpha$. Fig. 13 displays, in its lower
487 panel, the plot of $\langle\Delta\text{TEC}_{\text{pc}}\rangle_\alpha$ as function of α , and, in its upper panel, the plot of the corresponding
488 number of cases. We see that the magnetic field appears to be close to horizontal in the great
489 majority of cases, as $\alpha < 10^\circ$ in only ~ 1400 out of $5 \cdot 10^4$ cases. However, the bottom panel clearly
490 suggests a dependence on α , as $\langle\Delta\text{TEC}_{\text{pc}}\rangle_\alpha$ is positive ($\sim 5\%$) for quasi vertical field and steadily
491 decreases to negative values ($\sim 2\%$) for quasi horizontal field, being close to 0 for $\alpha \sim 45^\circ$.

492

493 6. Discussion and summary

494 In this paper we have made use of the Contrast Method, a tool developed to compensate ionospheric
495 distortion effects on radar signals. We have demonstrated that the data collected by the MARSIS
496 radar in its subsurface mode can be processed through the CM, so as to obtain estimates of the
497 nightside TEC of the Martian ionosphere, with the caveat that they can be affected by an
498 overestimate of up to 10%. We have shown that the CM MARSIS TEC values are in good
499 agreement with the predictions of the Chapman model and with similar results described a few
500 years ago by Safaeinili et al. (2008); moreover, we have shown two examples of good agreement of
501 the CM TEC with the Mouginot et al. (2008) TEC.

502
503 As a first application of the CM auxiliary parameter a_2 , in this work we calculated TEC values for
504 the Martian ionosphere for all MARS Express orbits from 2006 to 2011: we found that large TEC
505 variations are observed from year to year as far as the day side is concerned. As such variations
506 appear to increase as the SEA increases, it is natural to ascribe them to the evolution with the solar
507 cycle of the conditions on the Sun and in the solar wind. On the contrary, the night side TEC values
508 do not seem to noticeably depend on time on a yearly scale; as a consequence, it has been possible
509 to globally analyze all the night side data and to derive from them maps of TEC as a function of
510 geographical latitude and longitude. For that purpose, we developed a new method of calculating
511 per cent variations of TEC using a 10th order polynomial function and not an average value as done
512 by Safaeinili (2007), which allowed to estimate better the TEC values for $-15^\circ < \text{SEA} < 10^\circ$, and to
513 include TEC values for $-10^\circ < \text{SEA} < 0^\circ$, so as to achieve a full and continuous coverage of a very
514 large portion of the Martian ionosphere, with the only exclusion of latitudes above 54° . In this
515 regard, our results confirm (see our Figs. 9, 10, 11 and 12), with the support of a much larger data
516 base (i.e. a total of 4600 orbits instead of the 750 orbits considered by Safaeinili et al, 2007), that
517 positive values of ΔTEC are often related to quasi vertical crustal magnetic fields, while negative

518 values of ΔTEC relate to quasi horizontal crustal magnetic fields. Moreover, we found some
519 evidence (see Figs. 11 and 12) that the intensity of the crustal magnetic field also plays a role in
520 connection with the observation of positive ΔTEC values. However, as shown in Fig. 11, the
521 magnetic field intensity alone does not seem to favor the observation of increased TEC values,
522 while we find that a quasi-vertical orientation of the field (see panel d of Fig. 11) favors increases of
523 TEC when the magnetic field intensity is higher than 10-20 nT.

524 To put the discussion of our results into context, at this point it is useful to recall that several
525 authors noticed in the past (e.g. Nemec et al., 2010 and 2011) the connection between TEC and
526 magnetic field direction. In order to explain it, it is commonly believed that, as the solar wind
527 drapes its frozen-in magnetic field around the planet, a connection might be established between
528 that field and the Martian crustal magnetic fields. Safaeinili et al. (2007) also invoked such a
529 connection, suggesting that it “can result in ionizing of the atmosphere and in the heating of the
530 ionospheric electrons that in turn, slow the recombination process and produce a higher free
531 electron content.” On the other hand, other authors observed that higher peak densities tend to occur
532 in the night side in areas of strong crustal magnetic fields. However, the magnetic field strength and
533 topology is only one of the many factors which influence the ionization of the Martian night side
534 ionosphere (e.g. Lillis et al., 2009, list 11 such factors). Still, the results we have shown in the
535 preceding section show that the influence of the crustal magnetic field is clearly detectable. The
536 $\Delta\text{TEC}_{\text{pc}}$ map that we have obtained (see Figs. 8 and 9a) confirms and strengthens the result of
537 (Safaeinili et al., 2007) about the existence, over extended geographical regions, of a correlation
538 between the orientation of the crustal magnetic field and the observed ΔTEC . In fact, it appears that,
539 in some regions, higher concentrations of TEC are associated with a quasi-vertical magnetic field
540 direction, while TEC depletions are associated with quasi-horizontal field orientations. It must be
541 remarked that such TEC increases and depletions are observed in spite of the fact that data from
542 five years have been averaged together, thus including periods of higher and lower solar activity, as
543 well as periods of quiet and disturbed solar wind conditions. Such a correlation was already

544 suggested by Safaeinili et al. (2007), where it was in particular shown for an individual track along
545 the spacecraft orbit. In this paper we have further studied it following a statistical approach, through
546 histograms of $\Delta\text{TEC}_{\text{pc}}$ calculated for quasi-vertical and quasi-horizontal local crustal magnetic
547 field line orientations, over the whole ionosphere and over two selected regions, called R1 and R2
548 in the preceding section. Moreover, we have shown (Fig. 11) that the total intensity of the local
549 magnetic field in general does not play a role in itself in favoring TEC enhancements. Nevertheless,
550 it appears that the magnetic field intensity is important when the field is predominantly nearly
551 vertical. In fact, we have found (cf. panel d of Fig. 11) that in R1, where the correlation appears to
552 be more evident than on average (as discussed in relation to panels b and a of Fig. 11, respectively),
553 the magnetic field intensity exceeds in most cases 10-20 nT and attains values of hundreds of nT,
554 while in R2, where the correlation is totally absent (as shown in panel c of Fig. 11), the magnetic
555 field intensity is clearly lower, as it is almost always lower than 50 nT, while its histogram peaks
556 between 5 and 10 nT.

557

558 To conclude this discussion and summary, we wish to outline the directions along which we intend
559 to further develop our activities on this matter: 1) investigate a possible dependence of the
560 correlation TEC-magnetic field on conditions in the solar wind and on solar activity; 2) investigate
561 the factors which favor that correlation over some regions only (in this regard, it is probably
562 relevant that the magnetic field is predicted at a constant altitude of 200 km, while the TEC values
563 pertain in general to the 200-400 km interval); 3) further extend the data base, with the objective to
564 fill the northern hemisphere gap (by including the observations of summer 2011 and 2012); 4)
565 extend the study to the day side data; 5) study the lower part of the ionosphere in conjunction with
566 the data obtained with the AIS (Active Ionosphere Sounding) Mode.

567

Appendix: The Contrast Method

As we have argued in section 3, the MARSIS SS performance is seriously hindered by the signal phase shift due to the Martian ionosphere, in particular by the a_2 term of the Taylor expansion of the phase shift, as shown in Eqs.(4) and (5) and in Fig. 2.

The ‘‘Contrast Method’’ (Picardi et al. 2000) was developed to correct, or at least reduce, the effects due to such a phase shift. In the following, we provide a concise description of the CM.

The CM consists in iterating the range compression of the radar echoes: at each step of the iteration, the following phase compensation is applied to the echoes

$$\Delta\varphi(f) = \hat{a}_2(f - f_0)^2 + \hat{a}_3(f - f_0)^3 + \hat{a}_4(f - f_0)^4 \quad (\text{A.1})$$

where the $\hat{a}_2$ term is

$$\hat{a}_2 = \hat{a}_{2\text{start}} + \left(k - \frac{n}{2}\right) \delta a_2 \quad 1 \leq k \leq n \quad (\text{A.2})$$

Here n is the number of iterations, $\hat{a}_{2\text{start}}$ is the starting value and δa_2 the iteration step. $\hat{a}_{2\text{start}}$ is set to zero for the first frame of a given orbit, while for all the following frames it is set equal to the best value of $\hat{a}_2$ estimated in the preceding frame.

In order to estimate an upper value for δa_2 , let us define the effect of the ionosphere distortion as:

$$\Phi_1(f) + \Phi_D(f) = \Phi'_1(f) \quad (\text{A.3})$$

Where $\Phi_1(f)$, $\Phi_D(f)$ and $\Phi'_1(f)$ are the square-law phase terms of the transmitted signal, of the ionosphere distortion and of the received signal. Considering Eq. (6-20) from Cook and Bernfeld (1967) and Eq. (5), we can write:

$$\Phi_1(f) = \frac{4\pi^2(f - f_0)^2}{2\mu}$$

$$\Phi_D(f) = a_2(f - f_0)^2 \quad (\text{A.4})$$

$$\Phi'_1(f) = \frac{4\pi^2(f - f_0)^2}{2\mu'}$$

589 μ is the slope of the transmitted chirp signal and can be expressed as

590
$$\mu = \frac{2\pi B}{T} \quad (\text{A.5})$$

591 where $B = 1$ MHz and $T = 0.25$ ms are the chirp bandwidth and duration, respectively, while μ' is
592 the slope of the received chirp.

593 Eqs. (A.3) and (A.4) yield

594
$$a_2 = 2\pi^2 \left(\frac{\mu - \mu'}{\mu' \mu} \right) = \frac{2\pi^2 \gamma'}{\mu} = \frac{\pi \gamma' T}{B} \quad (\text{A.6})$$

595 where the mismatching factor between transmitted and reflected chirp is

596
$$\gamma' = \frac{\mu - \mu'}{\mu'} \quad (\text{A.7})$$

597 We can define the accuracy of the phase correction as:

598
$$\Delta a_2 = a_2 - \hat{a}_2 = \frac{\pi \gamma' T}{B} - \frac{\pi \hat{\gamma} T}{B} = \frac{\pi T}{B} (\gamma' - \hat{\gamma}) = \frac{\pi T}{B} \gamma \quad (\text{A.8})$$

599 Where $\hat{a}_2$ and $\hat{\gamma}$ are the estimated correction term and the estimated mismatching factor,
600 respectively, while γ is the residual mismatching factor. From Fig. 6.27, pag. 156 from Cook C.E.,
601 Bernfeld M., 1967, we can assume, as a worst case, that:

602
$$\gamma \leq \frac{2}{BT} \quad (\text{A.9})$$

603 where B and T are the chirp bandwidth and duration, respectively.

604 In conclusion, Eqs. A.8 and A.9 yield

605
$$\Delta a_2 \leq \frac{2\pi}{B^2} = 6.28 \cdot 10^{-12} \quad \text{rad/Hz}^2 \quad (\text{A.10})$$

606 In practice, in the Eg. (A.2) iteration, it is desirable to use a step smaller than Δa_2 . Usually, $\delta a_2 = 0.1$
607 Δa_2 .

608 In order to determine the $\hat{a}_3$ and $\hat{a}_4$ terms to be used in the iteration defined in Eq. (A.1), we first
609 simplify Eqs. 5 by making use of a model ionosphere characterized by a constant plasma frequency

610 $f_{p,\max}$ and an equivalent slab thickness L_{Eq} . This assumption allows to move the integrand out of the
 611 integral, which becomes trivially equal to L_{eq} , so that we obtain

$$\begin{aligned}
 612 \quad a_1 &= 2\pi\tau_0 \left(\frac{f_0}{\sqrt{f_0^2 - f_{p\max}^2}} - 1 \right) \quad [\text{rad} / \text{Hz}] \\
 613 \quad a_2 &= -2\pi\tau_0 \left(\frac{f_{p\max}^2}{2(f_0^2 - f_{p\max}^2)^{\frac{3}{2}}} \right) \quad [\text{rad} / \text{Hz}^2] \\
 614 \quad a_3 &= 2\pi\tau_0 \left(\frac{f_0 f_{p\max}^2}{2(f_0^2 - f_{p\max}^2)^{\frac{5}{2}}} \right) \quad [\text{rad} / \text{Hz}^3] \\
 615 \quad a_4 &= -2\pi\tau_0 \left(\frac{4f_0^2 f_{p\max}^2 + f_{p\max}^4}{8(f_0^2 - f_{p\max}^2)^{\frac{7}{2}}} \right) \quad [\text{rad} / \text{Hz}^4]
 \end{aligned} \tag{A.11}$$

616 having defined $\tau_0 = 2L_{\text{eq}}/c$.

617 Assuming that $(f_{p\max}/f_0)^2 < 1$, from Eq. (A.11) we easily find that

$$\begin{aligned}
 618 \quad \hat{a}_3 &\cong -\frac{\hat{a}_2}{f_o} \left(1 - \frac{\hat{a}_2 f_o}{\pi \tau_o} \right) \\
 619 \quad \hat{a}_4 &\cong \left(\frac{\hat{a}_2}{f_o^2} \right) \left(1 - \frac{\hat{a}_2 f_o}{0.5\pi \tau_o} \right)
 \end{aligned} \tag{A.12}$$

620 The compensation term $\Delta\varphi$ that produces the range compressed signal with the best energy
 621 concentration in a defined time interval of the receiving window, is selected to perform the final
 622 range compression. In practice, the CM provides $\hat{a}_3$, $\hat{a}_3$ and $\hat{a}_4$ as best estimates of the coefficients of
 623 the expansion defined by Eq. (4).

624

625 The Contrast Method is applied to all synthetic apertures (frames) collected by MARSIS and for
 626 each frequency. Fig. A.1 shows how the CM improves the quality of the range compressed data for
 627 a given frame: the red line shows the signal after range compression without correcting the phase
 628 through the CM, while the blue line shows it after the CM optimization procedure has been applied.

629 It is evident that the CM yields a higher peak power, a better signal to noise ratio and a reduction of
630 the main lobe width, leading to a better range resolution; this allows to separate the surface and
631 subsurface echoes that without correction would be merged together.

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730 **Figure captions**

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732 Fig. 1. Simulation of the effect of phase distortion on an ideal radar signal. Blue line: convolution of
733 the ideal reflected "chirp"; blue, black, red and purple lines: convolutions pertaining to the a_1 , a_2 ,
734 a_3 , and a_4 expansion terms (see Eqs. A.11 in the appendix - assuming that $f_p = 1$ MHz and $\tau_0 =$
735 $533\mu\text{s}$). All lines have been normalized to their peak values.

736 Fig. 2. TEC evaluated through the CM at three frequencies (3, 4 and 5 MHz, as red, blue and black
737 lines) versus SEA for orbit 6001 before (2a) and after (2b) the filtering process.

738 Fig. 3. Comparison, during the night side of orbit 2600, between the CM TEC (dotted blue line) for
739 $f_0 = 4$ MHz and the TEC obtained by Mouginot et al. (2008) (dotted red line).

740 Fig. 4. Same comparison as in Fig. 3, but for orbit 2640.

741 Fig. 5. TEC_{filt} , averaged over 0.1° SEA bins, plotted as a function of SEA, for four different
742 frequencies (1.8, 3, 4 and 5 MHz correspond to purple, blue, red and black dots, respectively). The
743 Chapman model TEC is represented by the blue solid line.

744 Fig. 6: TEC 0.1° bin averages for $f_0 = 4$ MHz, calculated for five different years during the night-
745 side (6a) and day-side (6b).

746 Fig. 7. Filtered 4 MHz TEC values (blue), their fit function (purple) and ΔTEC (black) for orbit
747 6001.

748 Fig. 8. Latitude-longitude maps of $\Delta\text{TEC}_{\text{pc}}$. The latitudes range from -90° to 54° , as above 54° no
749 ΔTEC values could be deduced from MARSIS data.

750 Fig. 9. Latitude-longitude maps of $\Delta\text{TEC}_{\text{pc}}$ (9a) and α (9b). α is the angle between the ambient
751 magnetic field vector of internal origin, predicted by an ESD model, and the local vertical direction.
752 The latitudes range from -90° to 54° , as above 54° no TEC values could be deduced from MARSIS
753 data. Red dotted (yellow dashed) lines highlight quasi vertical (horizontal) field regions.

754 Fig. 10. Maps of α (left panel) and $\Delta\text{TEC}_{\text{pc}}$ (right panel) for the $-65.5^\circ/-7.5^\circ$ latitude range
 755 (vertical axis) and for the $104^\circ/194^\circ$ longitude range (horizontal axis). Red dotted (yellow dashed)
 756 lines highlight quasi vertical (horizontal) field regions.

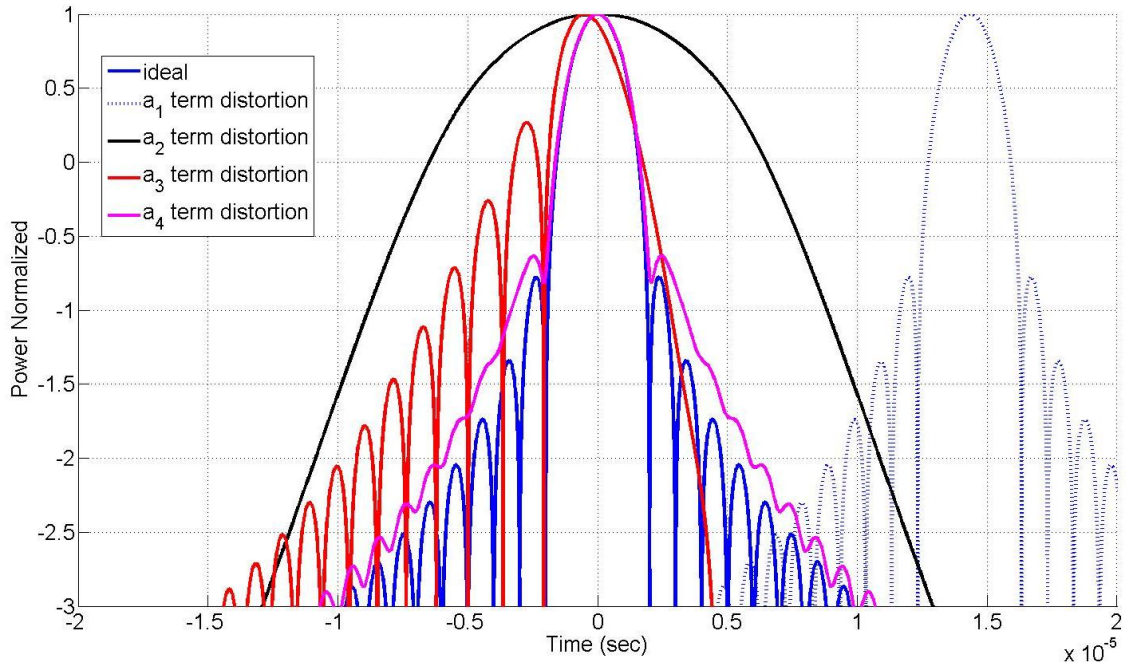
757 Fig. 11. Panel a: histograms (each normalized to its peak value) of $\Delta\text{TEC}_{\text{pc}}$ for nearly vertical
 758 magnetic field ($80^\circ-90^\circ$, dotted cityscape, peak value 1793) and nearly horizontal magnetic field
 759 ($0^\circ-10^\circ$, solid cityscape, peak value 278). Panels b and c: $\Delta\text{TEC}_{\text{pc}}$ histograms (also normalized to
 760 peak values) for nearly vertical and nearly horizontal magnetic field (coded as in panel a) for data
 761 pertaining to region 1 (R1) and to region 2 (R2) of Fig. 9 (see text for details and Fig. 10 for R1).
 762 Peak values are: 60 (solid line) and 290 (dotted line) for panel b; 45 (solid line) and 20 (dotted line)
 763 for panel c. Panel d: histograms of total magnetic field intensity for region 2 (dotted cityscape, 1464
 764 bins) and for region 1 (solid cityscape, 5278 bins, some of which not plotted as the abscissa is
 765 limited to 500 nT).

766 Fig. 12. Top panel: number of cases for 5 nT bins of B. Bottom panel: averages of $\Delta\text{TEC}_{\text{pc}}$ for 5
 767 nT bins of B.

768 Fig. 13. Top panel: histogram of α average values for the 51120 $1^\circ \times 1^\circ$ pixels of Fig. 9b, binned in
 769 α bins of 5° between 0 and 90° . Bottom panel, averages of $\Delta\text{TEC}_{\text{pc}}$ (see Fig. 8), calculated over α
 770 bins of 5° between 0 and 90° .

771 Fig. A.1. Reflected power as a function of time during frame 84 of orbit 10741. The red line shows
 772 the uncorrected received signal; the blue line shows the reflected power after correction through the
 773 Contrast Method.

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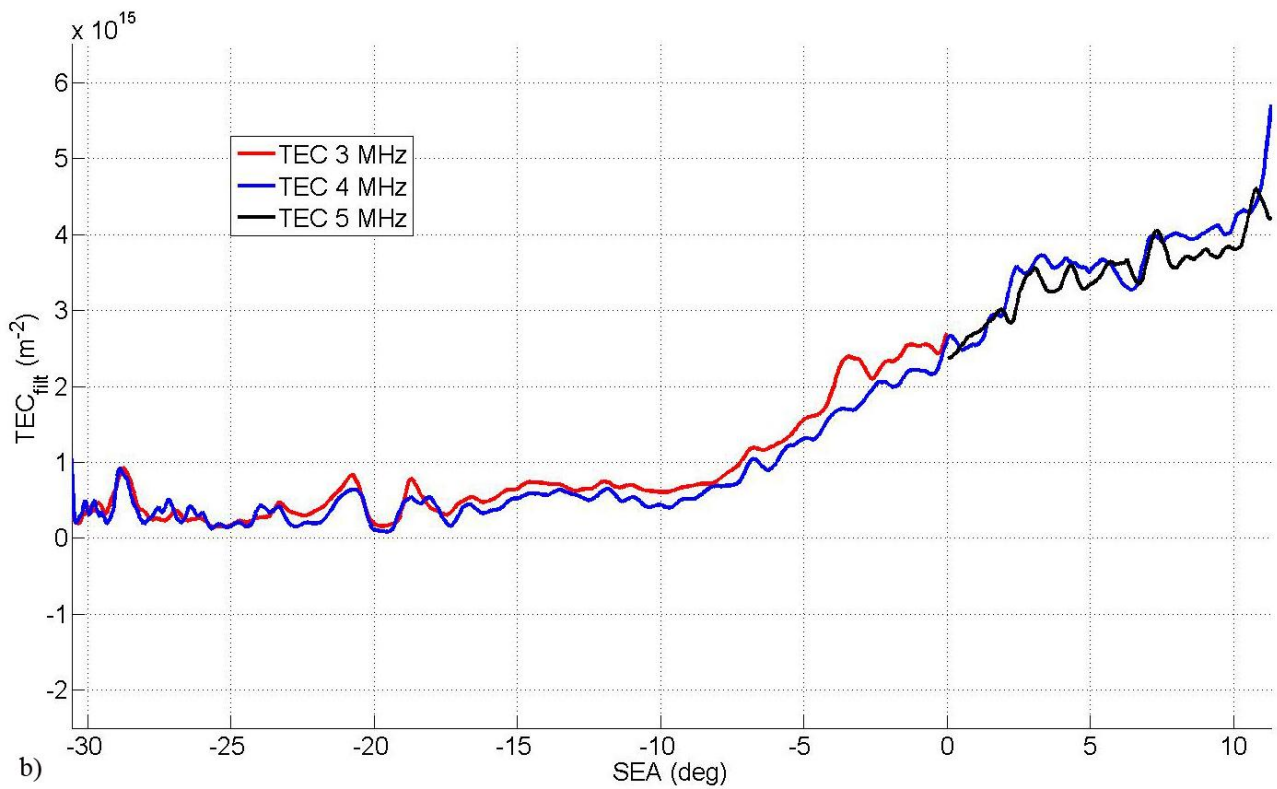
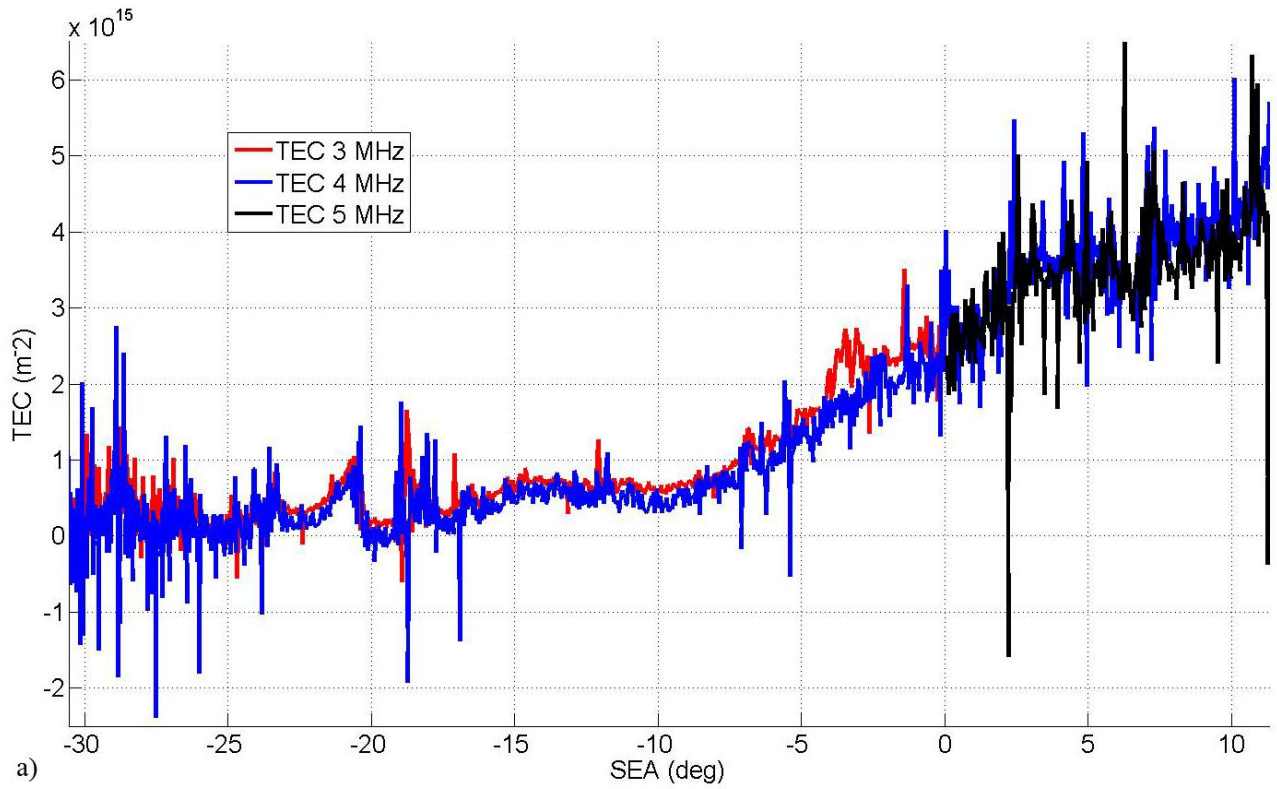
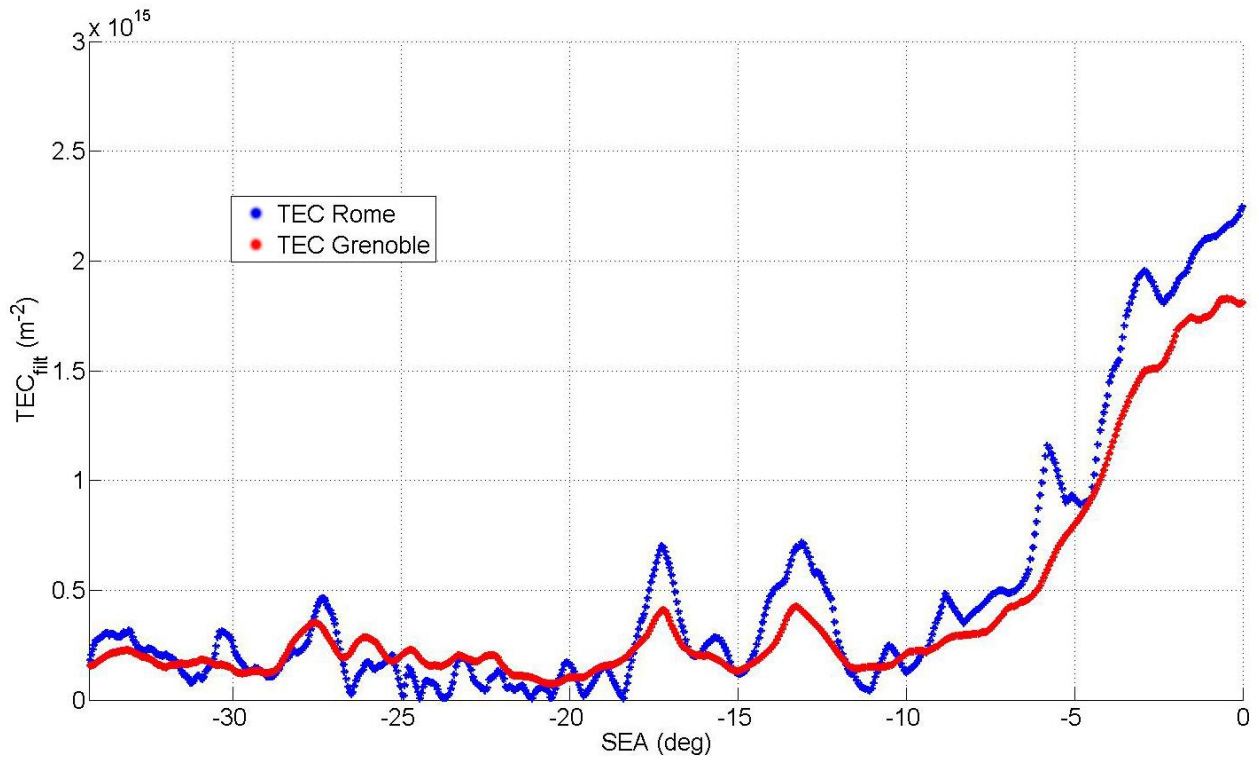


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794 for $f_0 = 4$ MHz and the TEC obtained by Mougnot et al. (2008) (dotted red line). The Mougnot

795 TEC data were downloaded from the ESA ftp server (<ftp://psa.esac.esa.int/pub/mirror/MARS->

796 EXPRESS) and were filtered in the same way as the CM TEC.

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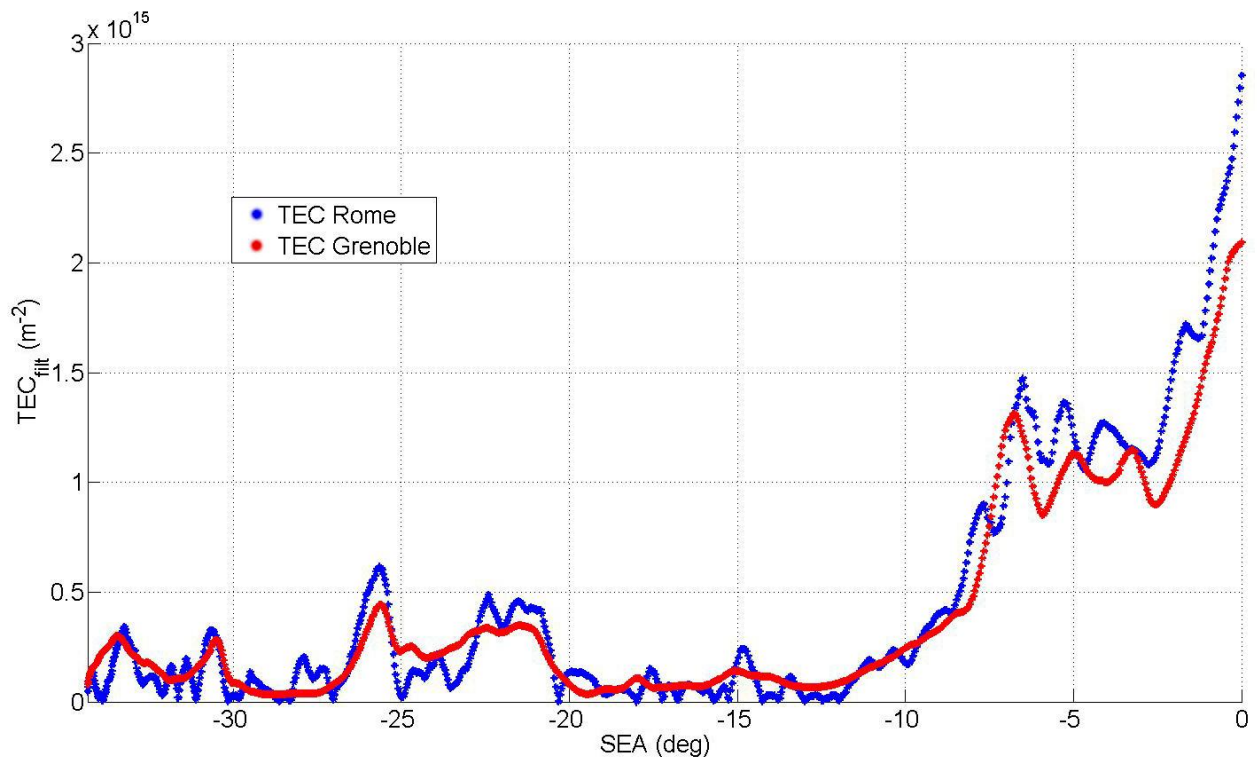
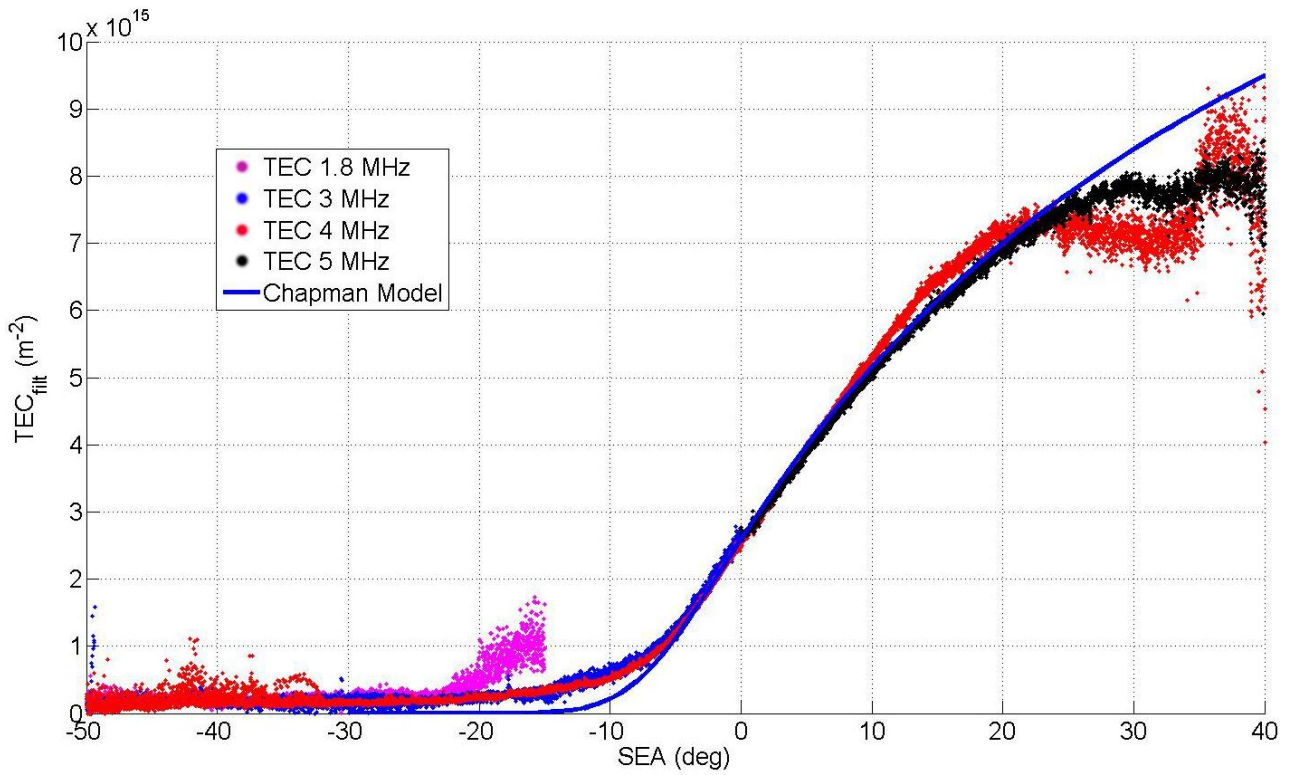


Fig. 4. Same comparison as in Fig. 3, but for orbit 2640.



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805 Fig. 5. TEC_{filt}, averaged over 0.1° SEA bins, plotted as a function of SEA, for four different
 806 frequencies (1.8, 3, 4 and 5 MHz). The blue solid line displays the TEC calculated from the
 807 Chapman model (see text for more details).

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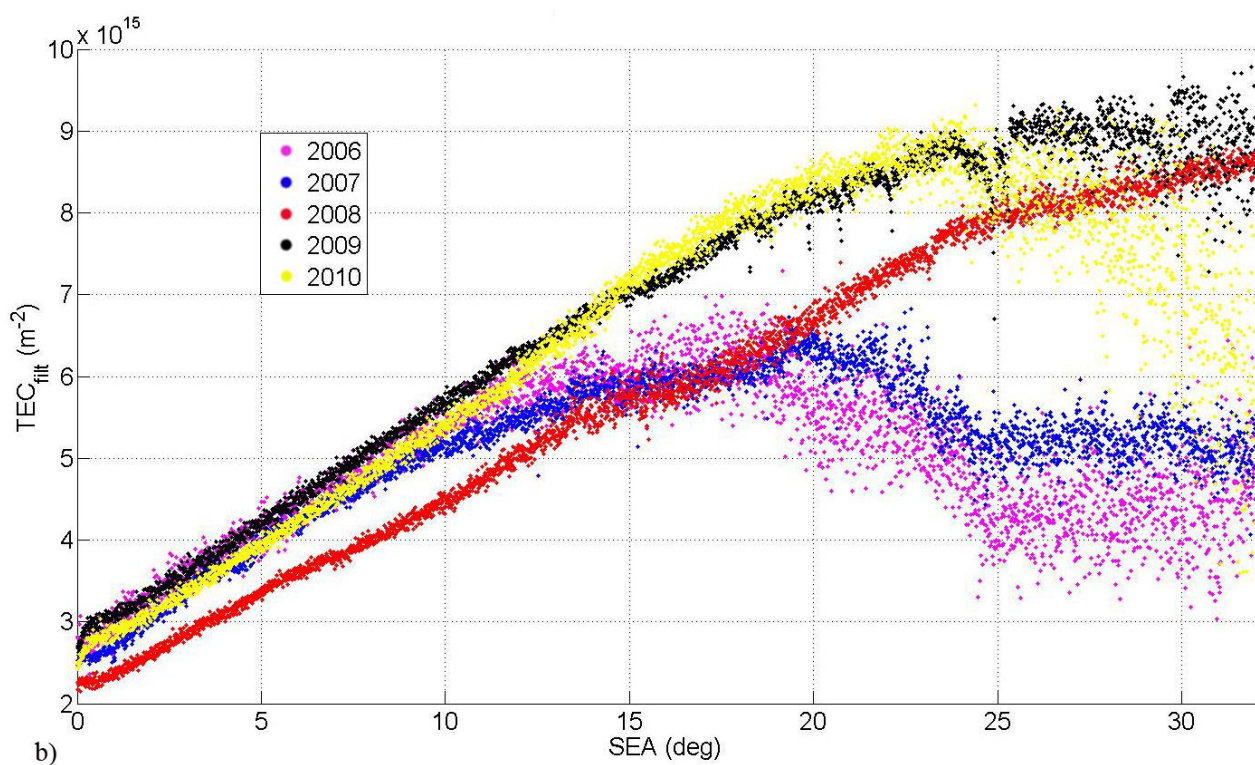
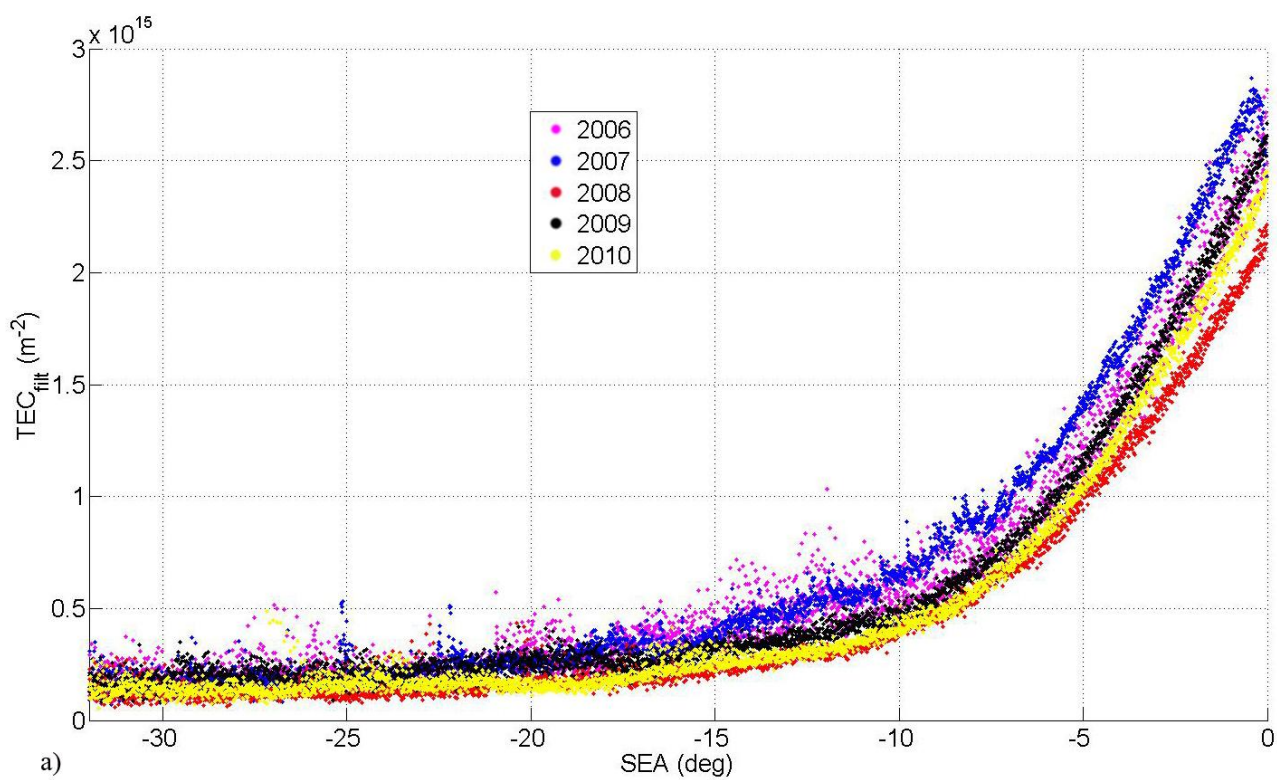
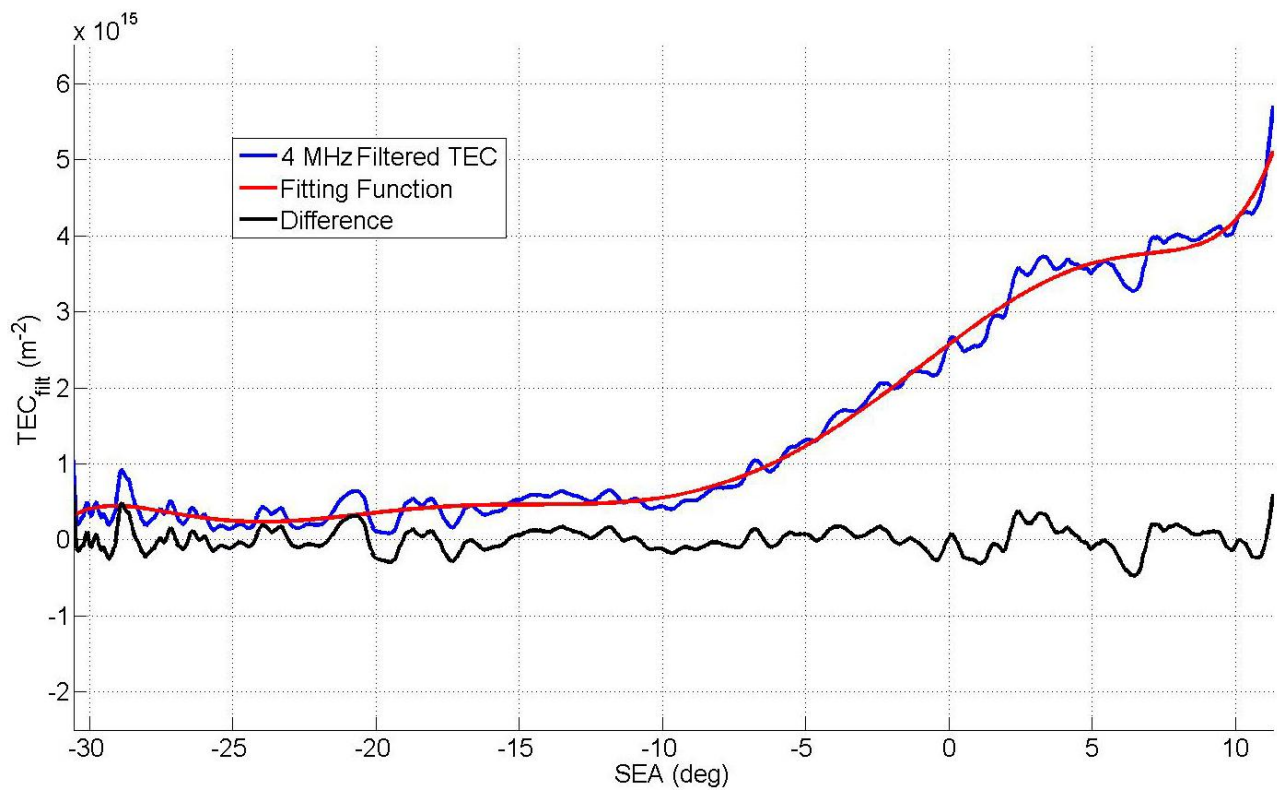


Fig. 6. TEC 0.1° bin averages for $f_0=4$ MHz, calculated for five different years during the night-side (a) and day-side (b).

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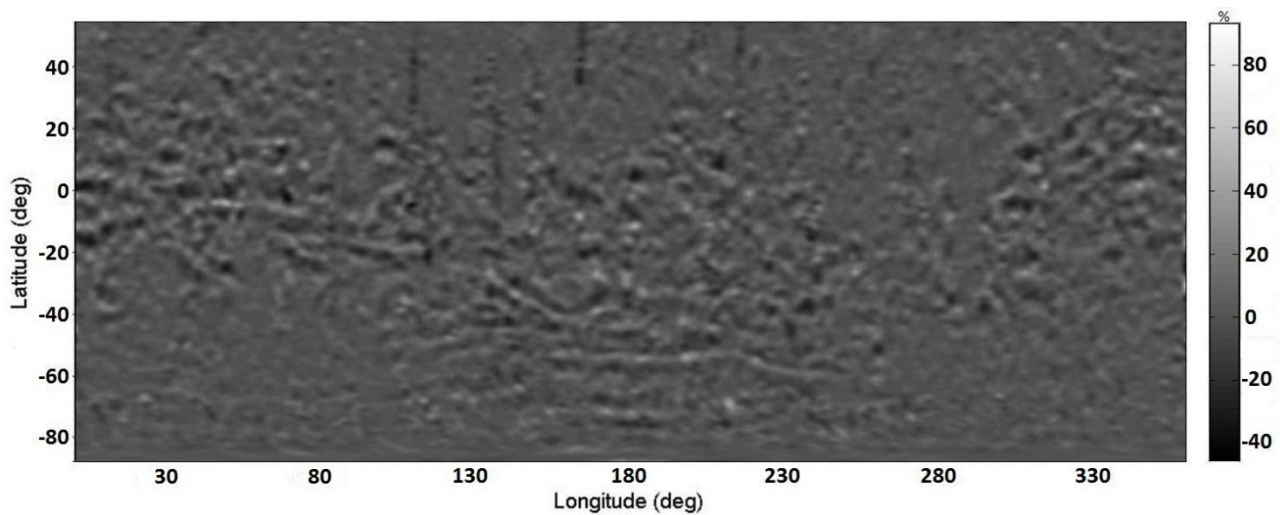
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Fig. 7. Filtered 4 MHz TEC values (blue), their fit function (purple) and Δ TEC (black) for orbit

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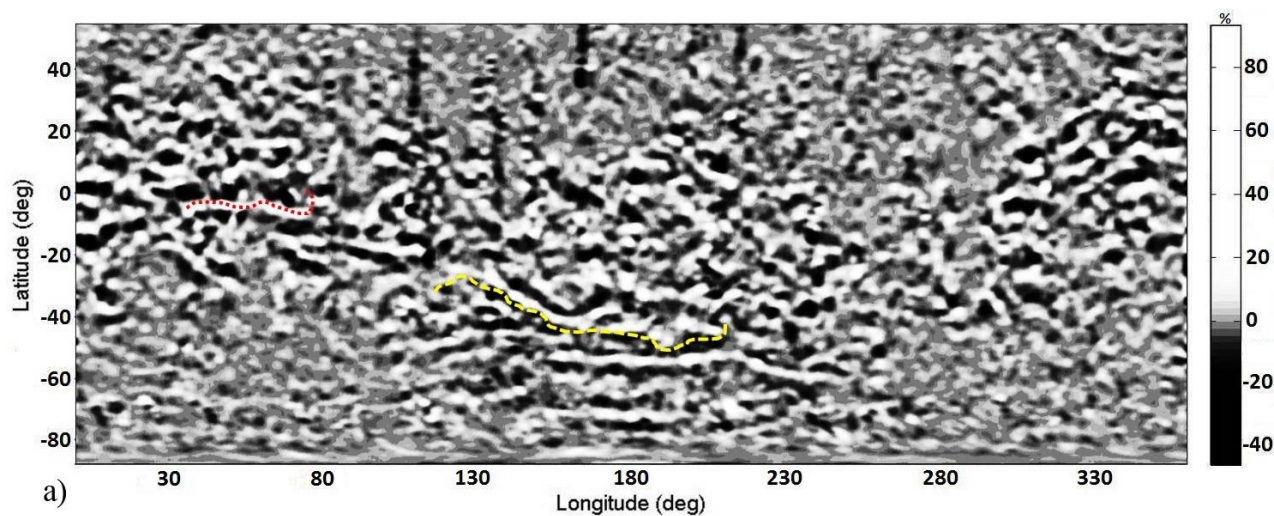
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Fig. 8. Latitude-longitude maps of Δ TEC_{pc}. The latitudes range from -90° to 54°, as above 54° no

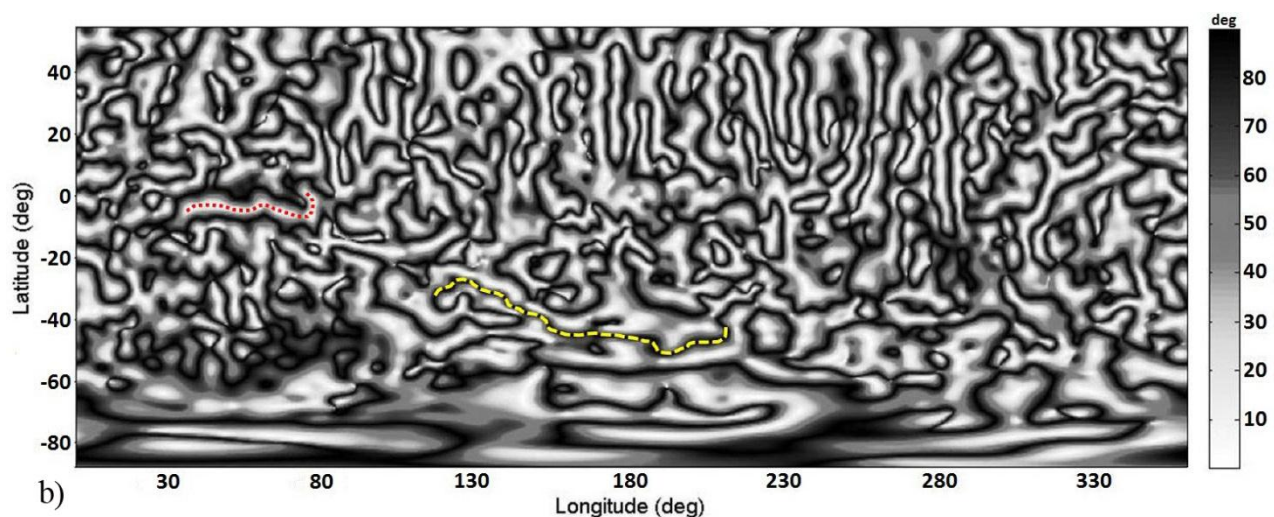
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Δ TEC values could be deduced from MARSIS data.

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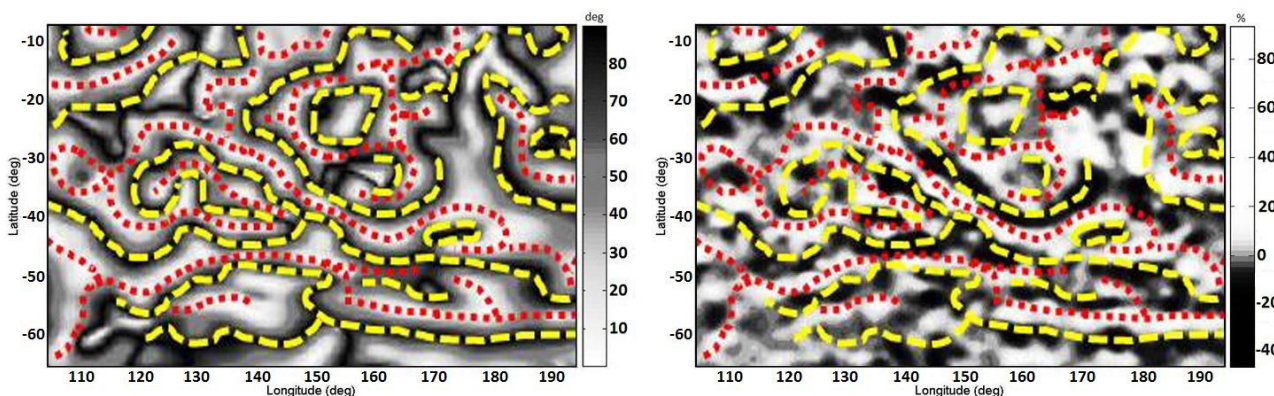


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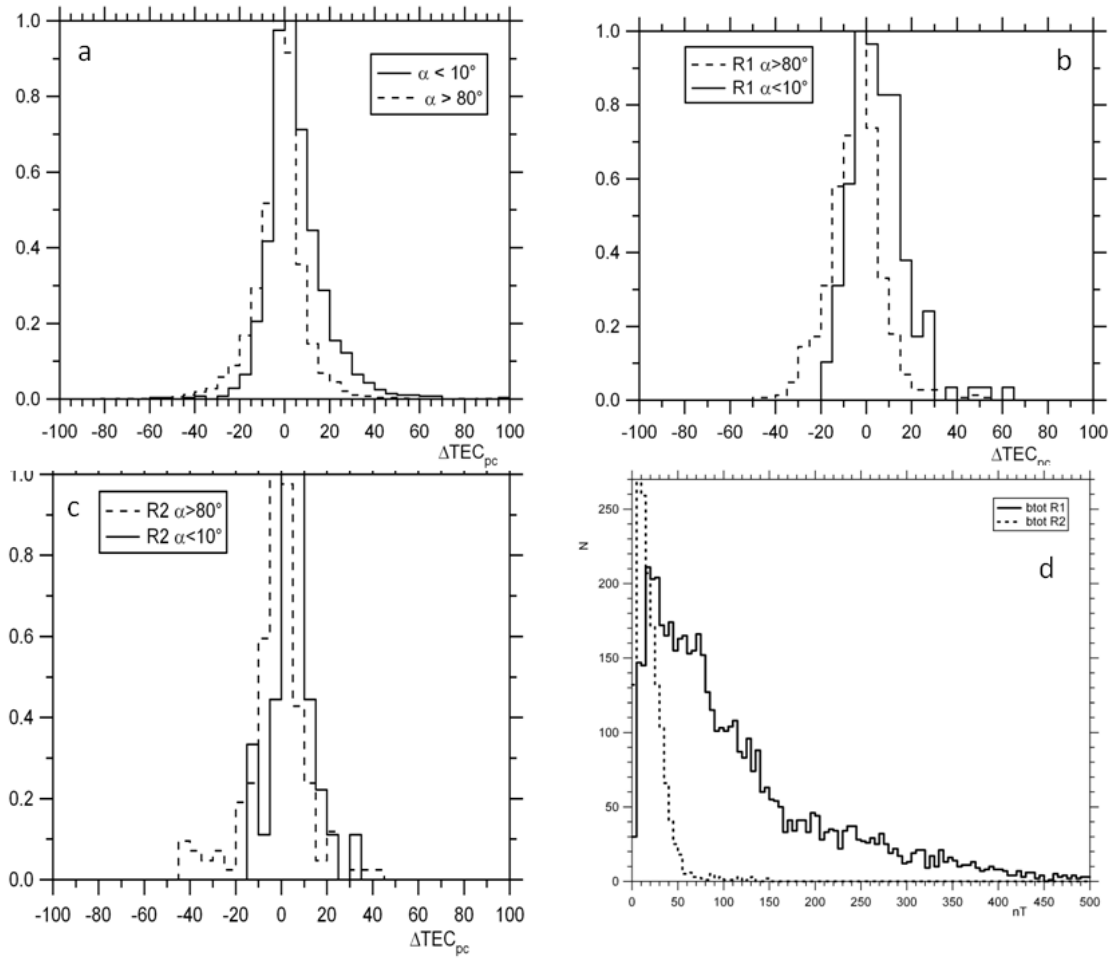
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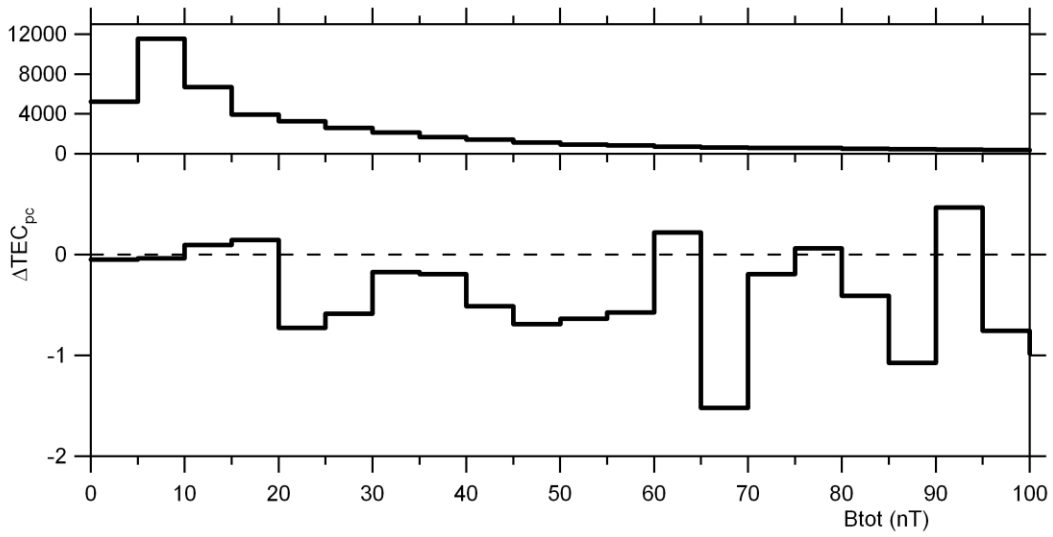
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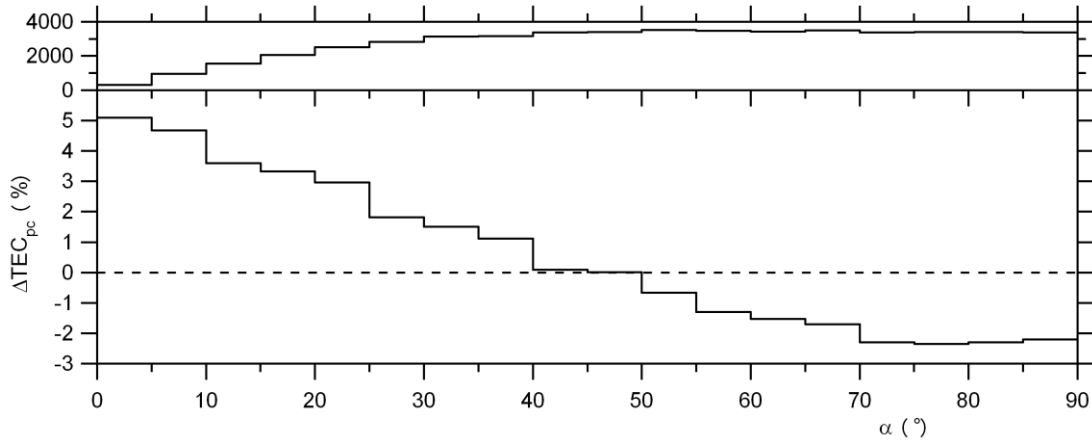
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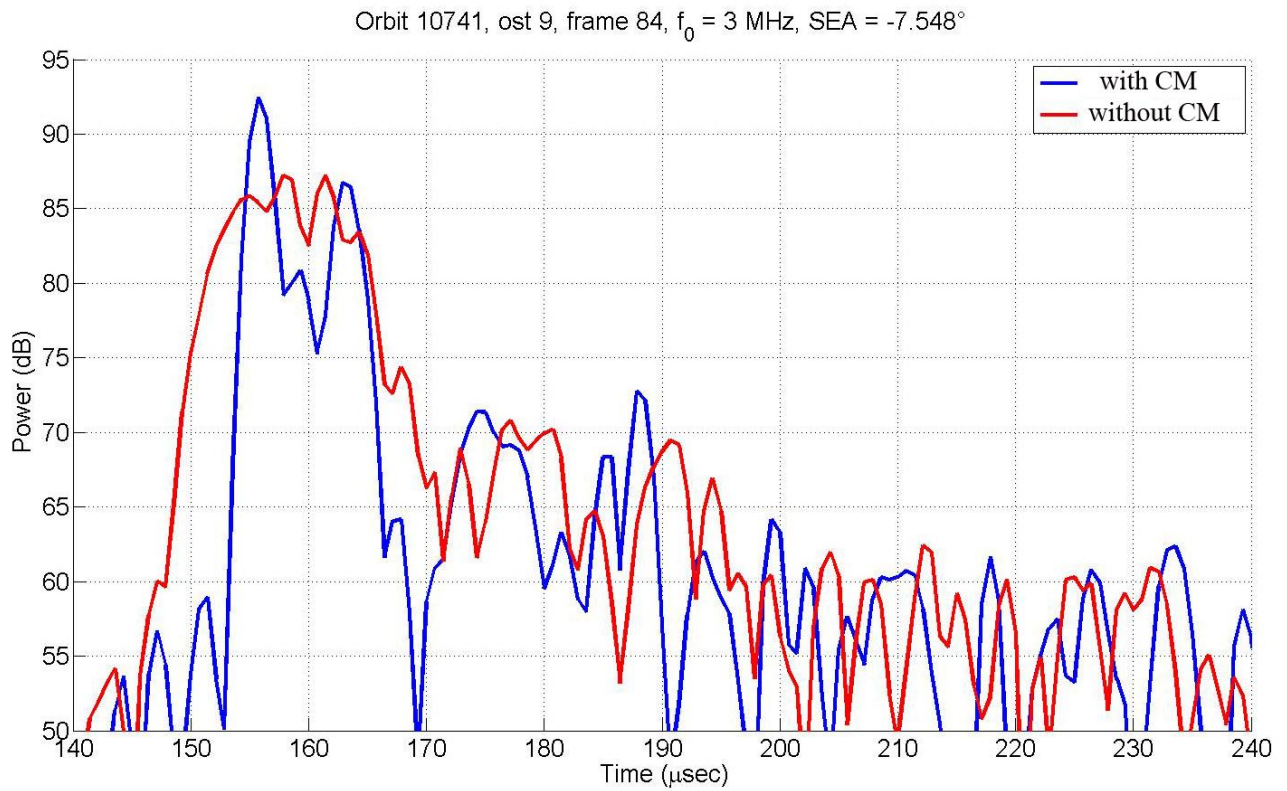


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