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Authors	CARTACCI, MARCO, Amata, E., CICCHETTI, ANDREA, NOSCHESE, RAFFAELLA, GIUPPI, Stefano, Langlais, B., FRIGERI, ALESSANDRO, OROSEI, Roberto, Picardi, G.
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6	M. Cartacci <sup>1*</sup> , E. Amata <sup>1</sup> , A. Cicchetti <sup>1</sup> , R. Noschese <sup>1</sup> ,
7	S. Giuppi <sup>1</sup> , B. Langlais <sup>2</sup> , A. Frigeri <sup>1</sup> , R. Orosei <sup>1</sup> , G. Picardi <sup>3</sup>
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12	<sup>1</sup> Istituto di Astrofisica e Planetologia Spaziali (IAPS), Istituto Nazionale di Astrofisica (INAF),
13	Rome, Italy.
14	<sup>2</sup> Laboratoire de Planétologie et Géodynamique de Nantes, CNRS and University of Nantes, France
15	<sup>3</sup> Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni (DIET), Università
16	"Sapienza", Rome, Italy.
17	
18	*Corresponding author. Fax: +39 06 4993 4383
19	E-mail address: marco.cartacci@iaps.inaf.it (M. Cartacci, Rome, Italy)
20	ermanno.amata@ifsi-roma.inaf.it (Ermanno Amata, Rome, Italy)
21	andrea.cicchetti@iaps.inaf.it (Andrea Cicchetti, Rome, Italy)
22	raffaella.noschese@iaps.inaf.it (Raffaella Noschese, Rome, Italy)
23	stefano.giuppi@iaps.inaf.it (Stefano Giuppi, Rome, Italy)
24	benoit.langlais@univ-nantes.fr (Benoit Langlais, Nantes, France)
25	alessandro.frigeri@iaps.inaf.it (Alessandro Frigeri, Rome, Italy)
26	roberto.orosei@iaps.inaf.it (Roberto Orosei, Rome, Italy)
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## 27 ABSTRACT

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

## 43 **1. Introduction**

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

51

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

65

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

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

80

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

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Section 2 recalls the main facts about MARSIS; section 3 contains a brief description of the main effects of the Martian ionosphere on radar propagation; section 4 shows how TEC can be calculated through the "Contrast Method" and discusses the choice of concentrating on the night side leg of the orbits; section 5 compares the night side  $\Delta$ TEC 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
- 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

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

106

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

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

126

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

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

where  $f_p$  is the plasma frequency, v the electron-neutral collision frequency and z is the altitude above ground. If we consider a typical MARSIS operation frequency (i.e. in the 1.3-5.5 MHz range), the imaginary term in the denominator of Eq. (1) can be neglected, because  $v \sim 10 - 60$  kHz. The plasma frequency, in Hz, can be written as

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

146

147 where  $N_e$  is the electron density in m<sup>-3</sup>. The maximum value of  $f_p$  obviously corresponds to the 148 maximum value of the electron density  $N_{emax}$ .

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

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

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 
$$\Delta\phi(f) = \frac{4\pi}{c} f \int_{0}^{L} [n(z) - 1] dz = \frac{4\pi}{c} f \int_{0}^{L} \left[ \sqrt{1 - \left(\frac{f_{p}(z)}{f}\right)^{2}} - 1 \right] dz,$$
(3)

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

161 
$$\Delta\phi(f) \cong a_0 + a_1(f - f_0) + a_2(f - f_0)^2 + a_3(f - f_0)^3 + a_4(f - f_0)^4 + ...,$$
 (4)

162 where:

**163** 
$$a_0 = \frac{4\pi}{c} \int_0^L \left( \sqrt{f_0^2 - f_p^2} - f_0 \right) dz \quad [rad]$$

164 
$$a_1 = \frac{4\pi}{c} \int_0^L \left( \frac{f_0}{\sqrt{f_0^2 - f_p^2}} - 1 \right) dz \ [rad / Hz]$$

165 
$$a_2 = -\frac{4\pi}{c} \int_0^L \left( \frac{f_p^2}{2(f_0^2 - f_p^2)^{\frac{3}{2}}} \right) dz$$
 [rad / Hz<sup>2</sup>]

166 
$$a_3 = \frac{4\pi}{c} \int_0^L \left( \frac{f_0 f_p^2}{2(f_0^2 - f_p^2)^{\frac{5}{2}}} \right) dz \quad [rad / Hz^3]$$

167 
$$a_{4} = \frac{4\pi}{c} \int_{0}^{L} \left( \frac{4f_{0}^{2}f_{p}^{2} + f_{p}^{4}}{8(f_{0}^{2} - f_{p}^{2})^{\frac{7}{2}}} \right) dz \quad \left[ rad / Hz^{4} \right]$$

The effect of the  $a_0, ..., a_4$  expansion coefficients on the MARSIS SS performance can be briefly 168 169 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 170 would yield a time dependent signal power characterized by a central lobe and a number of side 171 172 lobes (as a consequence of the linear variation of the frequency within the chirp). After range 173 compression, the theoretical main lobe width should be 1 µsec wide, while the difference in power between the main lobe peak and the first side lobe peak should be 32 dB. These parameters 174 175 characterize the radar range resolution, that is the ability to reveal objects close to one another, and 176 the radar dynamic range, which affects the capability to detect subsurface echoes.

177

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)

(5)

181 of the Appendix, assuming that  $f_p = 1$  MHz and  $\tau_0 = 533 \ \mu s$ . 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.

In conclusion, we see that the ionosphere can severely degrade the data quality, i.e. increase the side lobe levels, distort the waveform shape, and worsen the signal to noise ratio and range resolution. Moreover, the MARSIS signal is very vulnerable to ionosphere effects especially in those areas where the ionosphere and the magnetic field effects are combined together, because in these areas distortions are larger than usual. Obviously all the effects will increase steadily passing from the night side to the day side.

Due to the relevance of this topic for the mission success, different methods have been proposed tocorrect the ionosphere distortion.

194 Ilyushin and Kunitsyn (2004) described various methods, including a theoretical reconstruction of the signal phase, starting from its spectrum, with the use of an error function and a polynomial 195 regression. Safaeinili et al. (2003) and Mouginot et al. (2008) proposed a recursive method to 196 197 optimize the SNR with a phase correction term, considering the constraint that the measured phase after correction must be coincident with the phase obtained from the signal travel time expected 198 from MGS-MOLA data; moreover, in order to initialize their recursive algorithm, they used a 199 200 Gaussian approximation of the dependence of electron density on altitude. The core of the method used by Zhang et al. (2009) is a recursive loop to search for the best electron density  $N_e$  and 201 202 electron-neutral collision frequency, neglected in Eq. (1), which optimize the SNR. The study presented in this paper is based on the Contrast Method, CM hereafter, which is briefly 203 204 described in the Appendix.

## **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

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

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

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 neglecting a  $-\frac{3\pi}{c f_0^5}$  (8.98)<sup>4</sup>  $\int_0^L N_e^2 dz$  term. This approximation yields an overestimate of the 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%. The inversion of Eq. (6) allows us to write

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

where  $TEC = \int_0^L N_e dz$  is the total electron content of the ionosphere, with the caveat that the calculation through Eq. (7) always implies an overestimate of the TEC. In practice, as our study will be limited to SEA < 0° and to  $f_0$ = 4 MHz (see the summary of this section), this overestimate will at generally be lower than 10% (but it can at times be higher for negative values of SEA close to 0°). In Section 5 we will further comment on this issue.. The correction of this error could be the subject of a future study.

## 225 4.2 TEC filtering and validation

The use of the CM over the whole MARSIS dataset has produced millions of TEC estimates for 226 227 different conditions of solar zenith angle, latitude and longitude. As an example, Fig. 2a shows TEC values, as a function of the SEA, along orbit 6001, calculated from radar signals at frequencies 228 of 3, 4 and 5 MHz (red, blue and black lines, respectively). The three lines are in good agreement, 229 but at times they appear to be rather noisy, as many large spikes and fluctuations are superimposed 230 to the general increase of TEC. This suggests that, before proceeding further, a filtering process 231 232 should be applied to the TEC evaluated from Eq. (7). Fig. 2b displays the same data after spikes have been removed and a low pass filter (a zero-phase digital filter that processes the input data in 233 both the forward and reverse directions) has been applied to them; hereafter, we call the result of 234 235 such a process TEC<sub>filt</sub>. We notice that in the night side (for SEA  $< -25^{\circ}$ ) the 3 and 4 MHz lines roughly coincide. The residual differences between the two lines in that region could be due to 236 various transient effects whose relative influences are difficult to establish quantitatively (different 237 238 number of echoes collected at different frequencies, frequency dependent surface and subsurface effects, frequency dependent transmitter distortions and antenna performance). We also remark that 239 240 in the range  $-16^{\circ}$  < SEA <  $0^{\circ}$  the 3 MHz TEC is generally slightly higher than the 4 MHz one. A straightforward interpretation of this result is that in that region, as the day side is approached, the 241 plasma density increases, so that the condition  $(f_p/f_0)^2 \ll 1$  starts to break down: when that 242 243 happens, the value of  $a_2$  provided by the CM is overestimated, which in turn leads to a TEC value larger than it should be. Similarly, in the day side the 4 MHz TEC is usually larger than the 5 MHz 244 TEC. 245

246

Before proceeding further, we compared the  $\text{TEC}_{\text{filt}}$ , obtained in the 4 MHz mode, with the TEC calculated by Mouginot et al. (2008). Figs. 3 and 4 show the comparison between the two TECs for orbits 2600 and 2640, respectively, for negative SEA values only (because, as we argue further on, the study described in this paper is focused on the night side). The TEC estimated through the Mouginot et al. (2008) method, red dotted line, has been filtered in the same way as TEC<sub>filt</sub>, blue

dotted line. Figs. 3 and 4 demonstrate that in the night side the two TECs generally agree anddisplay similar fluctuations and trends.

254

TEC<sub>filt</sub> values were calculated from 4600 orbits between July 2005 and October 2011. In order to test such a large dataset for consistency, we first of all calculated averages of TEC<sub>filt</sub> in 0.1° SEA bins for all four available frequency bands. Fig. 5 displays such averages of TEC<sub>filt</sub> as a function of SEA for the four frequencies and shows that TEC<sub>filt</sub> clearly and steadily increases as the SEA passes from negative (night side) to positive (day side) values.

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  $\text{TEC}_{\text{filt}}$  values. However, as the SEA increases and the transmitted frequency approaches the

local plasma frequency, the scatter of  $\text{TEC}_{\text{filt}}$  values above or below the average trend increases.

This means that, under such conditions,  $\text{TEC}_{\text{filt}}$  suffers from a loss of accuracy, because the

quadratic term estimated through the CM is not sufficient to fully compensate the distortion caused

by the ionosphere. 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<sub>filt</sub> values. Similarly, we did not plot 3 MHz

TEC<sub>filt</sub> values above  $0^{\circ}$ .  $f_0$ =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,  $f_0$ =5MHz provides

271 data over the whole day side.

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

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

277 
$$Ch\left(\frac{R+h}{H},\chi\right) = \frac{R+h}{H}\sin\chi\int_{0}^{x}\exp\left(\frac{R+h}{H} - \frac{R+h}{H}\frac{\sin\chi}{\sin\alpha}\right)\operatorname{cosec}^{2}(\alpha)d\alpha$$
(9)

In Fig. 5 the Chapman model has been evaluated with the following parameters:  $n_0 = 2.2*10^{11} \text{ m}^{-3}$ , 278  $h_0 = 130*10^3$  m, H =  $13*10^3$  m, chosen so as to obtain an overall acceptable fit of the experimental 279 data. Given the nature of the Chapman model, a comparison with the experimental TEC only makes 280 sense for SEA >  $-10^{\circ}$ . From Fig. 5 it is clear that the experimental 4 MHz TEC<sub>filt</sub> values and the 281 theoretical model match quite closely over a  $10^{\circ}-20^{\circ}$  interval roughly centered at SEA =  $0^{\circ}$ , while 282 they differ on the day-side, above 10°, where the model forecasts first lower, then higher values 283 284 than the observed TEC<sub>filt</sub>. As regards the 5 MHz TEC<sub>filt</sub> values, we notice that they practically coincide with the 4 MHz ones close to SEA =  $0^{\circ}$ , while they better agree with the model in the  $10^{\circ}$ -285 20° range and start deviating considerably from the model around 25°, where the plasma frequency 286 287 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 consequence, all possible effects due to variations of solar activity have been probably smoothed in 290 the averaging process. However, it is expected that the solar activity can severely degrade the radar 291 signal propagation, mainly because of solar flares (Espley et al. 2007). Therefore, in order to briefly 292 study the behavior of TEC<sub>filt</sub> under different solar conditions, we have conducted the same analysis 293 294 used for generating Fig.5 after having grouped the data according to the year. Fig. 6 shows averages of 4 MHz TEC<sub>filt</sub>, calculated over 0.1° SEA bins and plotted as a function of SEA, for five 295 296 subsequent years. Figs. 6a and 6b pertain to the night and to the day side, respectively, and have different ordinate scales due to the large excursion of TEC<sub>filt</sub> from night to day. As regards Fig. 6a, 297 we see that the scatter of points around the average trends is of the order of  $0.1-0.2 \ 10^{15} \text{ m}^{-3}$  for each 298 year; however, the TEC<sub>filt</sub> values pertaining to the five years become more and more different as the 299 SEA increases towards the day side, although the largest difference is roughly  $0.5 \ 10^{15} \ m^{-3}$  for 300 values pertaining to 2007 and 2008. In the Fig. 6b, we clearly see that the average TEC<sub>filt</sub> values are 301 very different in different years; moreover, the dependence on the SEA varies a lot from year to 302

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

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## 306 4.4 Section summary

307 To conclude this section, we summarize hereafter its main f	indings.
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- TEC can be calculated through the Contrast Method. However, its values are generally overestimated by a factor  $1.5(f_p/f_0)^2$ . For  $f_0 = 4$ MHz and  $f_p = 1$ MHz, this corresponds to
- 310 10%, but it can attain larger values as SEA approaches  $0^{\circ}$  from the night side.
- The Martian TEC seems to depend on solar activity. This dependence shows up as a shift of
   TEC to higher or lower values over the entire SEA range, as a function of the year in the
   solar cycle.

# • The overall dependence of the Chapman model TEC on SEA is in good agreement with the experimental TEC data for SEA>-10°, provided that the chirp frequency is well above the local plasma frequency.

- When the plasma frequency gets too close to the chirp frequency, TEC values display large
   deviations from the average TEC trend and from the Chapman model.
- The best chirp central frequency for the calculation of TEC in the night side is  $f_0 = 4$ MHz, as confirmed by the comparison of the CM TEC with the Mouginot et al. (2008) TEC.

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

323

## 324 5.1. General considerations

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

## 337 5.2. Calculation of TEC variations

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

348	We fitted the TEC <sub>filt</sub> values with a $10^{th}$ order polynomial, plotted in purple in Fig. 7, and calculated
349	$\Delta TEC$ 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	$\Delta$ TEC. In practice, however, we see from Fig. 7 that the absolute value of $\Delta$ TEC does not
354	significantly increase between SEA = $-10^{\circ}$ and SEA = $0^{\circ}$ , so that we obtain reasonable values of
355	$\Delta$ TEC 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 $0.5 \ 10^{15} \ m^{-2}$ which occur over orbital distances
357	corresponding to SEA excursions ranging from $2^{\circ}-3^{\circ}$ to $5-7^{\circ}$ . 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 $\Delta TEC$ 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	

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

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

375 5.3. Maps of  $\Delta TEC_{pc}$  and of magnetic field inclination

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

388

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

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

416

417 A region where the correlation between the field direction and  $\Delta TEC_{pc}$  appears to be particularly 418 good is evidenced in Fig. 10, which shows blow-ups of the  $\alpha$  and  $\Delta TEC_{pc}$  maps between -64° and -419 7° in latitude and 104° and 194° in longitude. Again we highlight the vertical field and high  $\Delta TEC_{pc}$  420 through red dotted lines and the horizontal field and low  $\Delta TEC_{pc}$  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 $\Delta TEC_{pc}$ in relation to magnetic field inclination and intensity

424

The comparison between the maps of  $\alpha$  and  $\Delta TEC_{pc}$  deserves further investigation, in order to 425 quantitatively estimate the similarity of the structures which are present in each of them. Here we 426 427 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  $\Delta TEC_{pc}$  map, the first comprising of all  $1^{\circ}x1^{\circ}$  pixels for which  $0^{\circ} < \alpha < 10^{\circ}$  (corresponding to nearly vertical 429 magnetic field), the second comprising of all  $1^{\circ}x1^{\circ}$  pixels for which  $80^{\circ} < \alpha < 90^{\circ}$  (i.e. nearly 430 horizontal field). Panel a of Fig. 11 displays the histograms of the  $\Delta TEC_{pc}$  values pertaining to the 431  $0^{\circ} < \alpha < 10^{\circ}$  subset (black solid cityscape) and to the  $80^{\circ} < \alpha < 90^{\circ}$  subset (dotted cityscape), as a 432 function of  $\Delta TEC_{pc}$ , in 40 bins between -100 and 100. Each histogram has been normalized to its 433 434 peak value, being the peak value 278 for the  $0^{\circ} < \alpha < 10^{\circ}$  histogram and 1793 for the  $80^{\circ} < \alpha < 90^{\circ}$ histogram. First of all, we notice that in the vast majority of cases  $\Delta TEC_{pc}$  is observed to fall 435 between -20 and 20, which is agreement with the distribution of values indicated by the grey scale 436 coding in Fig. 8. The histogram pertaining to the  $80^{\circ} < \alpha < 90^{\circ}$  subset has its peak in the (-5,0) bin and 437 is nearly symmetrical with respect to 0. We also examined the histogram of all  $\Delta TEC_{pc}$  values 438 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 439 it in order not to overload panel a. Moving to the histogram pertaining to the  $0^{\circ} < \alpha < 10^{\circ}$  subset 440 (black solid cityscape), we notice that it differs from the first one, as the dotted cityscape is steadily 441 and consistently above the black solid cityscape for negative values of  $\Delta TEC_{pc}$ ; on the contrary, the 442 quasi-vertical field histogram is steadily higher than the quasi-horizontal one for positive values of 443

 $\Delta TEC_{pc}$ . Moreover, its peak is shifted to the (0,5) bin. In conclusion, we may state that panel a of 444 445 Fig.11 confirms the consideration we made concerning Fig. 9, insofar as regions of quasi-vertical magnetic field preferentially correspond to regions of positive and high positive  $\Delta TEC_{pc}$ , while 446 regions of quasi-horizontal magnetic field preferentially correspond to regions of negative  $\Delta TEC_{pc}$ . 447 The correlations between quasi vertical magnetic field and positive  $\Delta TEC_{pc}$  on one side, and 448 between quasi horizontal magnetic field and negative  $\Delta TEC_{pc}$  on the other side, are further 449 highlighted in panel b of Fig. 11, which displays the histograms for quasi vertical magnetic field 450 (solid cityscape) and quasi horizontal magnetic field (dotted cityscape) for the region 1 highlighted 451 in Fig. 10. We remark that in panel b the histogram pertaining to the quasi-vertical magnetic field is 452 further shifted towards positive values of  $\Delta TEC_{pc}$ , while the one for quasi-horizontal field is shifted 453 in the opposite direction: quantitatively, we find that for quasi-vertical magnetic field, 70% of the 454  $1^{\circ}x1^{\circ}$  bins display a positive  $\Delta TEC_{pc}$  value, while 75% of the bins corresponding to a quasi-455 horizontal field display a negative  $\Delta TEC_{pc}$  value. 456

457

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

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

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

481

In order to further highlight the link between  $\Delta TEC_{pc}$  and the orientation of the crustal magnetic 482 field, we averaged the  $\Delta TEC_{pc}$  values of Fig. 8 over  $1^{\circ}x1^{\circ}$  pixels and then binned such averages in 483 5° bins of  $\alpha$  by associating each average to the  $\alpha$  value pertaining to the given latitude and 484 longitude (according to the  $\alpha$  matrix plotted in Fig. 9b); finally, 16 averages were calculated 485 (covering the 0°-90° range), which we indicate with  $\langle \Delta TEC_{pc} \rangle_{\alpha}$ . Fig. 13 displays, in its lower 486 panel, the plot of  $<\Delta TEC_{pc}>_{\alpha}$  as function of  $\alpha$ , and, in its upper panel, the plot of the corresponding 487 488 number of cases. We see that the magnetic field appears to be close to horizontal in the great majority of cases, as  $\alpha < 10^{\circ}$  in only ~1400 out of 5  $10^{4}$  cases. However, the bottom panel clearly 489 suggests a dependence on  $\alpha$ , as  $\langle \Delta TEC_pc \rangle_{\alpha}$  is positive (~5%) for quasi vertical field and steadily 490 decreases to negative values (~2%) for quasi horizontal field, being close to 0 for  $\alpha$ ~45°. 491

### 493 **6. Discussion and summary**

In this paper we have made use of the Contrast Method, a tool developed to compensate ionospheric 494 495 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 nightside TEC of the Martian ionosphere, with the caveat that they can be affected by an 497 overestimate of up to 10%. We have shown that the CM MARSIS TEC values are in good 498 agreement with the predictions of the Chapman model and with similar results described a few 499 500 years ago iby Safaeinili et al. (2008); moreover, we have shown two examples of good agreement of the CM TEC with the Mouginot at al. (2008) TEC. 501

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

values of  $\Delta$ TEC relate to quasi horizontal crustal magnetic fields. Moreover, we found some evidence (see Figs. 11 and 12) that the intensity of the crustal magnetic field also plays a role in connection with the observation of positive  $\Delta$ TEC values. However, as shown in Fig. 11, the magnetic field intensity alone does not seem to favor the observation of increased TEC values, while we find that a quasi-vertical orientation of the field (see panel d of Fig. 11) favors increases of 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 authors noticed in the past (e.g. Nemec et al., 2010 and 2011) the connection between TEC and 525 magnetic field direction. In order to explain it, it is commonly believed that, as the solar wind 526 527 drapes its frozen-in magnetic field around the planet, a connection might be established between that field and the Martian crustal magnetic fields. Safaeinili et al. (2007) also invoked such a 528 connection, suggesting that it "can result in ionizing of the atmosphere and in the heating of the 529 530 ionospheric electrons that in turn, slow the recombination process and produce a higher free electron content." On the other hand, other authors observed that higher peak densities tend to occur 531 in the night side in areas of strong crustal magnetic fields. However, the magnetic field strength and 532 topology is only one of the many factors which influence the ionization of the Martian night side 533 534 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  $\Delta TEC$  pc map that we have obtained (see Figs. 8 and 9a) confirms and strengthens the result of 536 (Safaeinili et al., 2007) about the existence, over extended geographical regions, of a correlation 537 between the orientation of the crustal magnetic field and the observed  $\Delta TEC$ . In fact, it appears that, 538 in some regions, higher concentrations of TEC are associated with a quasi-vertical magnetic field 539 direction, while TEC depletions are associated with quasi-horizontal field orientations. It must be 540 remarked that such TEC increases and depletions are observed in spite of the fact that data from 541 542 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

suggested by Safaeinili et al. (2007), where it was in particular shown for an individual track along 544 545 the spacecraft orbit. In this paper we have further studied it following a statistical approach, through histograms of  $\Delta TEC_pc$  calculated for quasi-vertical and quasi-horizontal local crustal magnetic 546 field line orientations, over the whole ionosphere and over two selected regions, called R1 and R2 547 in the preceding section. Moreover, we have shown (Fig. 11) that the total intensity of the local 548 magnetic field in general does not play a role in itself in favoring TEC enhancements. Nevertheless, 549 550 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, while in R2, where the correlation is totally absent (as shown in panel c of Fig. 11), the magnetic 554 field intensity is clearly lower, as it is almost always lower than 50 nT, while its histogram peaks 555 between 5 and 10 nT. 556

557

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

## **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.

572 The "Contrast Method" (Picardi et al. 2000) was developed to correct, or at least reduce, the effects 573 due to such a phase shift. In the following, we provide a concise description of the CM.

574

575 The CM consists in iterating the range compression of the radar echoes: at each step of the iteration,

576 the following phase compensation is applied to the echoes

577 
$$\Delta \varphi(f) = \hat{a}_2 (f - f_0)^2 + \hat{a}_3 (f - f_0)^3 + \hat{a}_4 (f - f_0)^4$$
(A.1)  
578

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

579 
$$\hat{a}_2 = \hat{a}_{2\,start} + \left(k - \frac{n}{2}\right)\delta a_2$$
  $1 \le k \le n$  (A.2)

Here n is the number of iterations,  $\hat{a}_{2\text{start}}$  is the starting value and  $\delta a_2$  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.

583 In order to estimate an upper value for  $\delta a_2$ , let us define the effect of the ionosphere distortion as:

584 
$$\Phi_1(f) + \Phi_D(f) = \Phi_1'(f)$$
 (A.3)

585 Where  $\Phi_1(f)$ ,  $\Phi_D(f)$  and  $\Phi_1(f)$  are the square-law phase terms of the transmitted signal, of the 586 ionosphere distortion and of the received signal. Considering Eq. (6-20) from Cook and Bernfeld 587 (1967) and Eq. (5), we can write:

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

588  $\Phi_D(f) = a_2(f - f_0)^2$ 

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

(A.4)

589  $\mu$  is the slope of the transmitted chirp signal and can be expressed as

590 
$$\mu = \frac{2\pi B}{T} \tag{A.5}$$

where B = 1 MHz and T = 0.25 ms are the chirp bandwidth and duration, respectively, while  $\mu$  is the slope of the received chirp.

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

where the mismatching factor between transmitted and reflected chirp is

596 
$$\gamma' = \frac{\mu - \mu'}{\mu'} \tag{A.7}$$

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

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

599 Where  $\hat{a}_2$  and  $\hat{\gamma}$  are the estimated correction term and the estimated mismatching factor,

600 respectively, while  $\gamma$  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:

$$602 \quad \gamma \leq \frac{2}{BT} \tag{A.9}$$

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

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

605 
$$\Delta a_2 \le \frac{2\pi}{B^2} = 6.28 \cdot 10^{-12}$$
 rad/Hz<sup>2</sup> (A.10)

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

- 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
- <sup>609</sup> 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

612 
$$a_1 = 2\pi\tau_0 \left(\frac{f_0}{\sqrt{f_0^2 - f_{p \max}^2}} - 1\right) \quad [rad / Hz]$$

613 
$$a_{2} = -2\pi\tau_{0} \left( \frac{f_{p\,\text{max}}^{2}}{2(f_{0}^{2} - f_{p\,\text{max}}^{2})^{\frac{3}{2}}} \right) [rad / Hz^{2}]$$
(A.11)

614 
$$a_3 = 2\pi\tau_0 \left( \frac{f_0 f_{p\max}^2}{2(f_0^2 - f_{p\max}^2)^{\frac{5}{2}}} \right) \quad [rad / Hz^3]$$

615 
$$a_{4} = -2\pi\tau_{0} \left( \frac{4f_{0}^{2}f_{p\max}^{2} + f_{p\max}^{4}}{8(f_{0}^{2} - f_{p\max}^{2})^{\frac{7}{2}}} \right) \quad [rad / Hz^{4}]$$

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

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

$$\hat{a}_3 \cong -\frac{\hat{a}_2}{f_o} \left( 1 - \frac{\hat{a}_2 f_o}{\pi \tau_o} \right) \tag{A.12}$$

619 
$$\hat{a}_4 \cong \left(\frac{\hat{a}_2}{f_0^2}\right) \left(1 - \frac{\hat{a}_2 f_0}{0.5\pi \tau_0}\right)$$

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

624

The Contrast Method is applied to all synthetic apertures (frames) collected by MARSIS and for

each frequency. Fig. A.1 shows how the CM improves the quality of the range compressed data for

- a given frame: the red line shows the signal after range compression without correcting the phase
- 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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- Fig. 1. Simulation of the effect of phase distortion on an ideal radar signal. Blue line: convolution of
- 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  $\tau_0 =$
- 533µs). All lines have been normalized to their peak values.
- Fig. 2. TEC evaluated through the CM at three frequencies (3, 4 and 5 MHz, as red, blue and black
- lines) versus SEA for orbit 6001 before (2a) and after (2b) the filtering process.
- Fig. 3. Comparison, during the night side of orbit 2600, between the CM TEC (dotted blue line) for
- $f_0 = 4$  MHz and the TEC obtained by Mouginot et al. (2008) (dotted red line).
- Fig. 4. Same comparison as in Fig. 3, but for orbit 2640.
- Fig. 5. TEC<sub>filt</sub>, averaged over  $0.1^{\circ}$  SEA bins, plotted as a function of SEA, for four different
- 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.

- Fig. 6: TEC 0.1° bin averages for  $f_0$ = 4 MHz, calculated for five different years during the nightside (6a) and day-side (6b).
- Fig. 7. Filtered 4 MHz TEC values (blue), their fit function (purple) and ΔTEC (black) for orbit
  6001.
- Fig. 8. Latitude-longitude maps of  $\Delta TEC_{pc}$ . The latitudes range from -90° to 54°, as above 54° no ATEC values could be deduced from MARSIS data.
- Fig. 9. Latitude-longitude maps of  $\Delta TEC_{pc}$  (9a) and  $\alpha$  (9b).  $\alpha$  is the angle between the ambient
- magnetic field vector of internal origin, predicted by an ESD model, and the local vertical direction.
- The latitudes range from  $-90^{\circ}$  to  $54^{\circ}$ , as above  $54^{\circ}$  no TEC values could be deduced from MARSIS
- data. Red dotted (yellow dashed) lines highlight quasi vertical (horizontal) field regions.

Fig. 10. Maps of  $\alpha$  (left panel) and  $\Delta TEC_pc$ (right panel) for the -65.5°/-7.5° latitude range

(vertical axis) and for the 104°/194° longitude range (horizontal axis). Red dotted (yellow dashed)
lines highlight quasi vertical (horizontal) field regions.

Fig. 11. Panel a: histograms (each normalized to its peak value) of  $\Delta TEC_pc$  for nearly vertical

magnetic field (80°-90°, dotted cityscape, peak value 1793) and nearly horizontal magnetic field

 $(0^{\circ}-10^{\circ}, solid cityscape, peak value 278)$ . Panels b and c:  $\Delta TEC_pc$  histograms (also normalized to

peak values) for nearly vertical and nearly horizontal magnetic field (coded as in panel a) for data

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)

for panel c. Panel d: histograms of total magnetic field intensity for region 2 (dotted cityscape, 1464

bins) and for region 1 (solid cityscape, 5278 bins, some of which not plotted as the abscissa is

765 limited to 500 nT).

Fig. 12. Top panel: number of cases for 5 nT bins of B. Bottom panel: averages of  $\Delta TEC_pc$  for 5 nT bins of B.

Fig. 13. Top panel: histogram of  $\alpha$  average values for the 51120 1°x1° pixels of Fig. 9b, binned in  $\alpha$  bins of 5° between 0 and 90°. Bottom panel, averages of  $\Delta \text{TEC}_{pc}$  (see Fig. 8), calculated over  $\alpha$ bins of 5° between 0 and 90°.

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

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



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



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Fig. 3. Comparison, during the night side of orbit 2600, between the CM  $\text{TEC}_{\text{filt}}$  (dotted blue line)

- for  $f_0 = 4$  MHz and the TEC obtained by Mouginot et al. (2008) (dotted red line). The Mouginot
- 795 TEC data were downloaded from the ESA ftp server (ftp://psa.esac.esa.int/pub/mirror/MARS-
- EXPRESS) and were filtered in the same way as the CM TEC.





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



Fig. 5. TEC<sub>filt</sub>, averaged over  $0.1^{\circ}$  SEA bins, plotted as a function of SEA, for four different

frequencies (1.8, 3, 4 and 5 MHz). The blue solid line displays the TEC calculated from the

<sup>807</sup> Chapman model (see text for more details).



Fig. 6. TEC  $0.1^{\circ}$  bin averages for  $f_0 = 4$  MHz, calculated for five different years during the nightside (a) and day-side (b).









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

 $\Delta$ TEC values could be deduced from MARSIS data.



Fig. 9. Latitude-longitude maps of ΔTEC<sub>pc</sub> (9a) and α (9b). α is the angle between the ambient
magnetic field vector of internal origin, predicted by an ESD model, and the local vertical direction.
The latitudes range from -90° to 54°, as above 54° no TEC values could be deduced from MARSIS
data. Red dotted (yellow dashed) lines highlight quasi vertical (horizontal) field regions.



- Fig. 10. Maps of  $\alpha$  (left panel) and  $\Delta TEC_pc$ (right panel) for the -65.5°/-7.5° latitude range
- 829 (vertical axis) and for the  $104^{\circ}/194^{\circ}$  longitude range (horizontal axis). Red dotted (yellow dashed)
- 830 lines highlight quasi vertical (horizontal) field regions.



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832 Fig. 11. Panel a: histograms (each normalized to its peak value) of  $\Delta TEC$  pc for nearly horizontal magnetic field (80°-90°, dotted cityscape, peak value 1793) and nearly vertical magnetic field (0°-833 10°, solid cityscape, peak value 278). Panels b and c: ΔTEC pc histograms (also normalized to 834 peak values) for nearly vertical and nearly horizontal magnetic field (coded as in panel a) for data 835 pertaining to region 1 (R1) and to region 2 (R2) of Fig. 9 (see text for details and Fig.10 for R1). 836 Peak values are: 60 (solid line) and 290 (dotted line) for panel b; 45 (solid line) and 20 (dotted line) 837 838 for panel c. Panel d: histograms of total magnetic field intensity for region 2 (dotted cityscape, 1464 839 bins) and for region 1 (solid cityscape, 5278 bins, some of which not plotted as the abscissa is limited to 500 nT). 840



Fig. 12. Top panel: number of cases for 5 nT bins of B. Bottom panel: averages of ΔTEC\_pc for 5
nT bins of B.

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