ESA STUDY CONTRACT REPORT

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ABSTRACT:

A planetary ionosphere is a perturbing environment for radar waves. Unfortunately, it is an unavoidable obstacle along the propagation path of signals emitting by orbiting radar sounders. The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) is an instrument onboard the European Space Agency's Mars Express spacecraft. In order to deeply penetrate the surface, MARSIS operates at MHz frequencies for which the perturbations due the Martian ionosphere can be significant. Therefore, prior to any analyze, MARSIS data need to be corrected from the ionospheric effects.

The aim of this document is to describe an approach to correct the impact of the ionosphere on MARSIS radar data. Among the three effects caused by the ionosphere, two (global absorption and Faraday rotation) can be easily avoided by choosing wisely the MARSIS band and the observation place. The impact of the third (phase distortion) is too important whatever the conditions of observation. A method is proposed to do a systematic correction of the phase distortion. The method is enhanced by using the digital elevation model MOLA as a reference for the position of the surface echo.

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1. Introduction

The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) is an instrument of the Italian Space Agency (ASI) [*Picardi et al.*, 2005]. It is orbiting onboard the Mars Express (MEX) spacecraft of the European Space Agency (ESA). MARSIS is getting data since its unfolding in the early summer 2005. Its primary science objective is to study the subsurface of Mars at a low-frequency regime to penetrate deep under the soil. The orbit of MEX is highly elliptical with a periapsis of 270 km and an apoapsis of 11600 km, thus always above the ionosphere. The ionosphere is a plasma which disturbs radio waves passing through it. Since MARSIS is an active instrument, it emits its own signal, which is backscattered by surface and subsurface structures before to be collected back. That is, along is propagation path, a MARSIS signal is two times disturbed by the ionosphere.

In a first document [*Grima and Kofman*, 2008] we characterized the impact of the ionosphere by describing its main effects on the MARSIS radar signal. The phase distortion is the only one that should be corrected because of a significant effect on the signal, whatever the conditions of observation. The phase distortion is summarized before to present the optimization method to correct it. The correction is enhanced by using different constraints as the use of an accurate digital elevation model (MOLA) to fix the position of the surface. The total electron content (TEC) is a by-product of this ionospheric correction, and will be briefly presented as well.

2. The MARSIS instrument

MARSIS can operate in 2 different sounding modes. The first is a passive mode (receive only) called 'active ionospheric sounding' (AIS) [*Gurnett et al.*, 2005]. It sounds the ionosphere with a quasi-wave tone by swapping 160 frequencies in the range of 0.1 to 5.5 MHz. Of course, for the purpose of this document the ASI mode is not valuable. We will only focused on the second sounding mode, which study the subsurface with the active component of the radar (transmit and receive). MARSIS can use this subsurface sounding mode when the spacecraft is lower than 900 km. This represents 26 minutes of operation by orbit. It uses 4 different frequency bands centered to 1.8, 3, 4, and 5 MHz. Each band is 1 MHz wide. MARSIS operates in two bands simultaneously, in order to get the backscattered echoes as a function of the frequency. The choice of the two operating bands aims to minimize the impact of the ionosphere. It depends of the solar zenith angle (SZA) which is directly linked to the ionosphere activity. The MARSIS signal is emitted at a rate of 127.27 pulses per second. The returned pulses are integrated over 1 s to increase the signal-to-noise ratio (SNR). This final process gives an along-track resolution in the range of 5 to 9 km, varying with MEX altitude and speed. At this time the MARSIS coverage of Mars is almost complete.

3. The ionospheric impact

3.1. Presentation

The impact of an ionosphere on a radar signal has been detailed in a previous work [*Grima and Kofman*, 2008] for the Martian case. It can be summarized in three effects: Global absorption, phase distortion, and Faraday rotation. Avoiding or correcting those effects is required to study the surface and the subsurface information enclosed within the data. The global absorption as well as the Faraday rotation can be avoiding by choosing carefully the conditions of observation. The global attenuation can be neglected in the night side, or by using the three higher MARSIS bands on the day side of the planet. The Faraday rotation is significant only over known places where magnetic anomalies occurred, representing 20 % of the whole surface area [*Acuña et al.*, 1999].

The phase distortion is the only significant effect of the ionosphere that disturbs the radar signal at all MARSIS bands, especially on the day side. It cannot be avoided and need to be corrected.

3.2. The phase distortion

In the time domain, the phase distortion generates two effects: A delay of the pulse, and a spreading of the pulse. Thus, the surface and the subsurface echoes are broadened, while their absolute time position is miss-estimated. This is well represented by the Fig. 1.

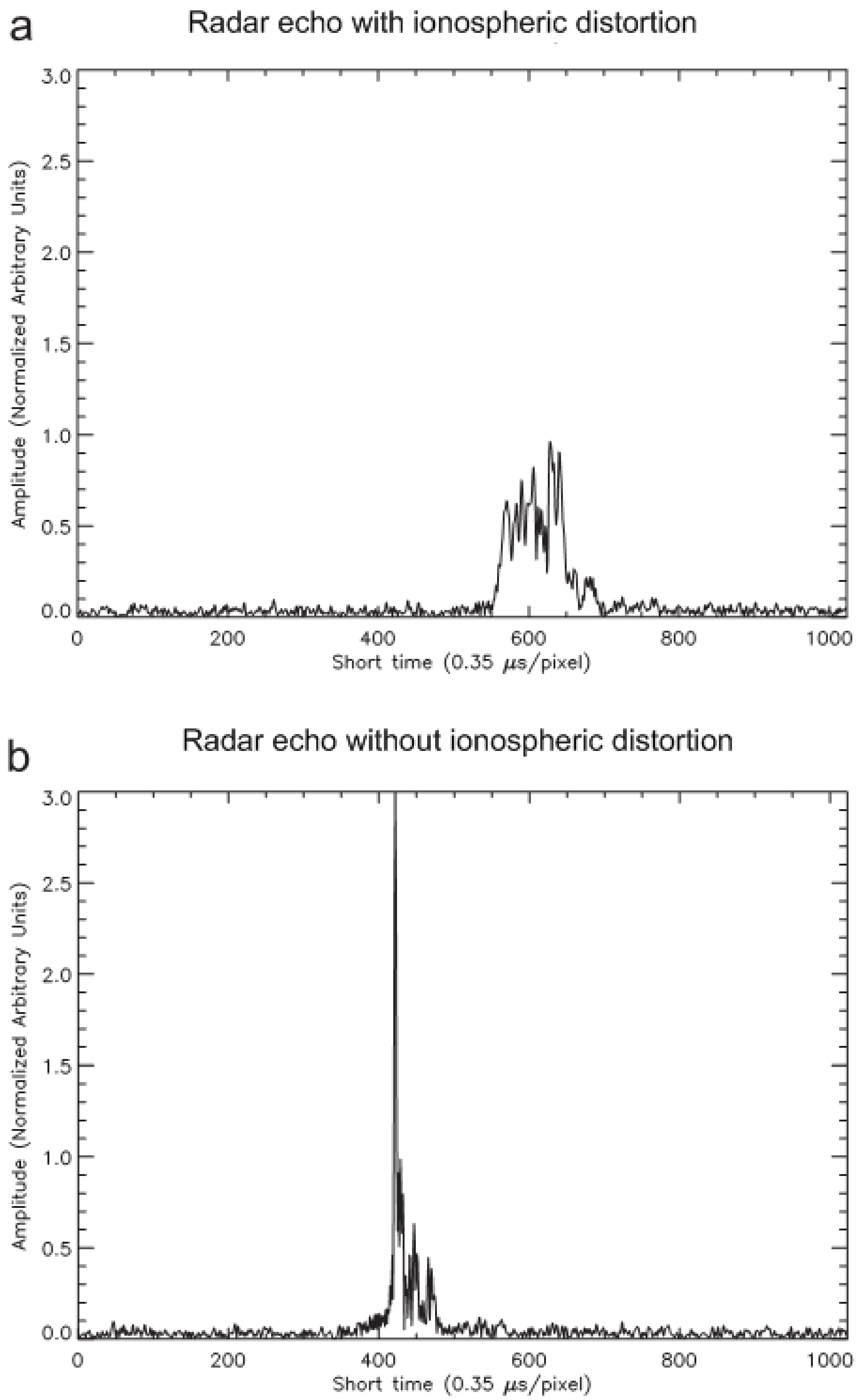

Fig. 1. (a) MARSIS pulse after ionospheric two-way propagation represented in time domain. One can see the spreading and the delay of the echo compared to (b) same pulse without ionospheric distortion [adapted from *Mouginot et al.*, 2008].

The ionospheric distortion can be described by the addition of a phase term to the expression of a radar wave propagating in vacuum:

$$\varphi = \varphi_0 + \Delta\varphi \tag{1}$$

where φ is the phase of the signal and φ_0 is the phase of a wave in vacuum. $\Delta\varphi$ is the phase distortion due to the ionosphere and can be expressed for a two-way propagation as [*Budden*, 1964; *Safaeinili et al.*, 2003]

$$\Delta\varphi(\omega) = \frac{2\omega}{c}\int_{h1}^{h2} \Re(n-1).dz \tag{2}$$

where $\omega=2\pi f$ is the wave pulsation of the radio signal with f its frequency, c is the light velocity in vacuum, h_1 and h_2 are the lower and upper altitude crossed in the ionosphere, and n is the ionospheric refractive index. *Mouginot et al* [2008] rewrote this expression

$$\Delta\varphi(f) = \frac{a_1}{f} + \frac{a_2}{f^3} + \frac{a_3}{f^5} \tag{3}$$

defined by the terms

$$a_1 = 40.32 \times \int N_e^1(z).dz \times \frac{4\pi}{c} \tag{4}$$

$$a_2 = 812.851 \times \int N_e^2(z).dz \times \frac{4\pi}{c} \tag{5}$$

$$a_3 = 32774.2 \times \int N_e^3(z).dz \times \frac{4\pi}{c} \tag{6}$$

where $N_e(z)$ is the electron density at the altitude z. Therefore, since the TEC defines the "total electron content in a column of atmosphere" [see *Grima and Kofman*, 2008], one can introduce the following equation:

$$TEC = \int N_e(z).dz \tag{7}$$

4. Method to correct the ionospheric impact

4.1. Presentation

Before to be processed, the received signal should be correlated with the emitted one (the chirp). This operation is called the signal compression. It is made in order to emphasize the contribution of the surface and the subsurface reflections enclosed within the received signal. The correction of the ionospheric impact consists in modifying the received signal by introducing the phase term developed in equations (2) - (6), before to do the compression:

$$S_{corrected}(f) = C^{*}_{chirp}(f).S_{received}(f).\exp(j\Delta\varphi(f)) \tag{8}$$

To do so, $\Delta\varphi(f)$ needs to be deduced. The method is to investigate the parameters [a_1, a_2, a_3] (Equations (4) - (6)), in order to get $\Delta\varphi(f)$ with the best SNR. As initial conditions for this optimization, we use the parameters fitting with a simplified gaussian density-profile of the ionosphere. Then, the optimization is done by using the following constraints:

- A constraint on the vertical position of the surface echo estimated with the digital elevation model MOLA [*Smith et al.*, 2001].

- A constraint on the SNR. The signal amplitude must be maximal after correction.

4.2. Determining the initial conditions

The aim of this part is to find approximated values for the parameters [a_1, a_2, a_3], in order to start the optimization and to do it as fast as possible. Such initial conditions can be determined by using a model for the density of the ionosphere. The radio signal crosses the ionosphere in its vertical dimension. Therefore, a simplified gaussian profile for the ionospheric density can be used. Using a Gaussian profile as initial conditions, instead of a more accurate Chapman model, does not affect the result of the optimization. From this, a Gaussian profile was preferred because it is faster to implement.

$$N_e(z) = N_0 \exp\left[-\frac{(z-z_0)^2 \sec\chi}{2H^2}\right] \tag{9}$$

where N_0 is the maximum of the electron density, H is the scale height, and χ is the sun zenith angle (SZA). The set of z_0 is not important, since only the electron content of a column of atmosphere will be considered. From this profile and equation (7), the solutions of the integrals of $N_e(z)$, $N_e^2(z)$, and $N_e^3(z)$ can be easily derived, in order to get the solutions for the parameters a_1, a_2, and a_3 (Equations (4) – (6)):

$$\int N_e^i(z).dz = \frac{1}{\sqrt{i}}\left(\frac{\sec\chi}{2\pi}\right)^{(i-1)/2}\frac{TEC^i}{H^{i-1}} \tag{10}$$

where TEC is the total electron content. Then, the phase distortion (Equation (3)) can be rewritten as

$$\Delta\varphi(f) = \frac{2}{c}\left[\frac{253.34}{f}.TEC + \frac{1440.76\sqrt{\sec\chi}}{f^3}.\frac{TEC^2}{H} + \frac{18922.4\sec\chi}{f^5}.\frac{TEC^3}{H^2}\right] \tag{11}$$

This equation is a simplified model to estimate *$\Delta\varphi(f)$*. Those two free parameters (TEC and H) have a minor impact on the quality of the estimation. In practice H is in the range of 8 to 30 km, that is the expected values for Mars [*Krymskii et al.*, 2004; *Gurnett et al.*, 2005; *Nielsen et al.* 2007]. The use of this approximated model is obviously suboptimal. However, it will provide a good estimation of the phase distortion to start the optimization.

4.3. The altitude constraint (with MOLA)

The digital elevation model of the Martian surface MOLA (Mars Orbiter Laser Altimeter) has a spatial resolution of 128 pixels/° (~ 0.463 km) and a vertical resolution of 1 m [*Smith et al.*, 2001]. That is well lower than MARSIS characteristics in free space (respectively 10 km and 150 m [*Picardi et al.*, 2005]). Since one effect of the ionospheric distortion is a delay of the MARSIS signal, we will use MOLA data to estimate where the surface radar echo should be and to derive the corresponding $\Delta\varphi$. However, this is not sufficient to get the correct phase distortion itself, because there are uncertainties on the altitude of Mars Express leading to a miss-estimation of the absolute position of the surface echo. But this method will help to determine a phase range that reduces the domain of values where the optimization will be made. In practice, we impose that the wanted $\Delta\varphi$ should modify the position of the surface radar echo of the initial MARSIS signal in order to match the MOLA surface at $\pm$ 0.6 km:

$$\Delta\varphi_{MOLA+0.6km} < \Delta\varphi < \Delta\varphi_{MOLA-0.6km} \tag{12}$$

4.4. The signal to noise constraint (SNR constraint)

Within the phase range determined by the altitude constraint, we look for the best SNR. Typically, for each $\Delta\varphi$ in the phase range, a Fast Fourier Transform (FFT) is applied to compute the SNR of the surface echo in the time domain.

The surface echo is defined as the brightest one. Thus, an error on the correction could arise in the few cases where some subsurface echoes are more powerful than the surface. This error is avoided since we defined the noise as the mean of the signal preceding the brightest echo. That is, in the configuration of a brighter subsurface, the surface echo will be included in the range defined as noise. The resulting SNR will be weak and the corresponding $\Delta\varphi$ rejected.

4.5. The optimization method

The correction factor $\Delta\varphi$ is defined by the terms [a_1, a_2, a_3] (see equations (3) – (6)). The optimization method consists to explore this set of parameters in order to match the best SNR, using the constraints explained before. To enhance the optimization, another condition is added: The SNR must be optimum in the two highest MARSIS bands, since [a_1, a_2, a_3] depends only of the electron density.

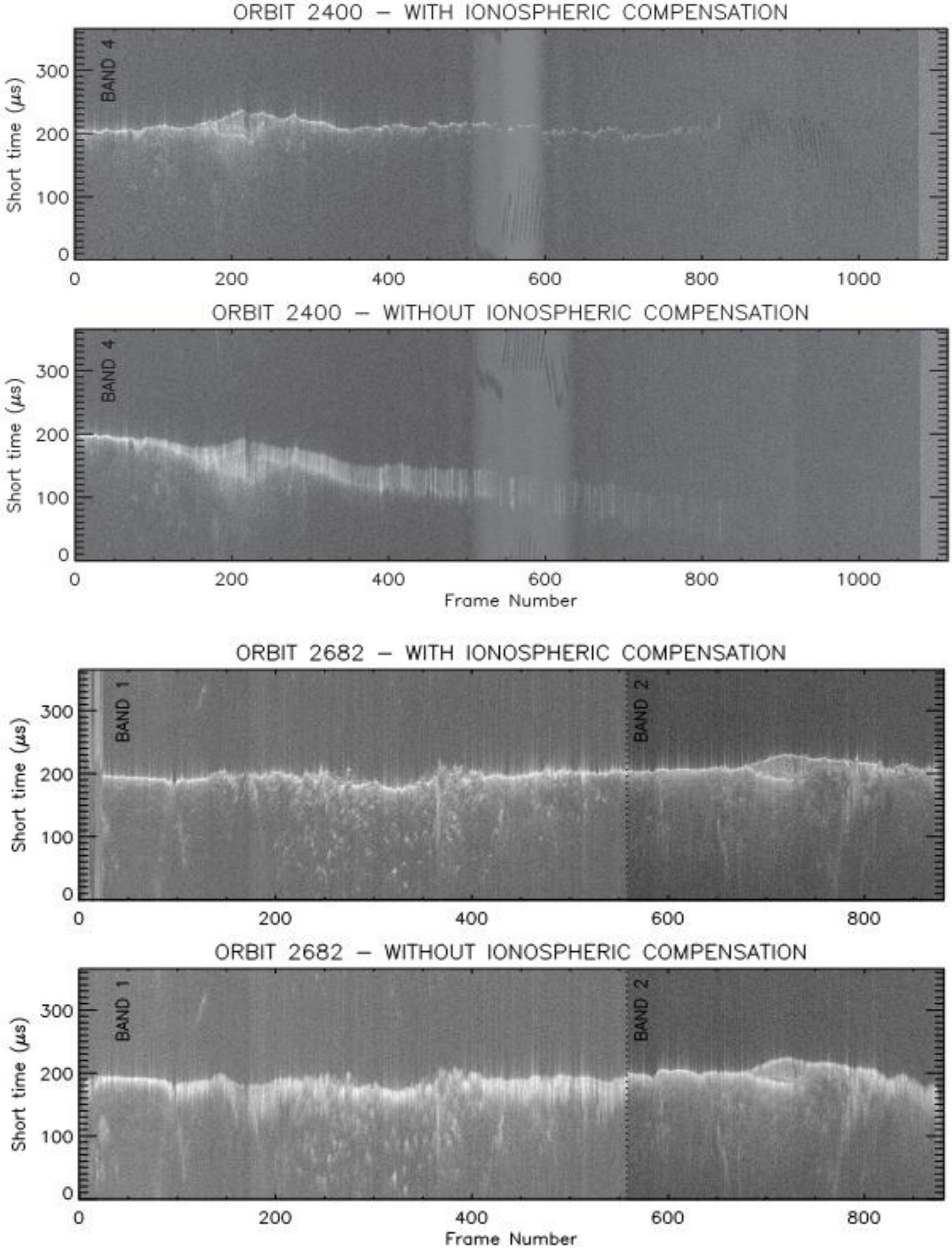

Fig. 2. Two MARSIS radargrams (orbit 2400 and 2682) corrected by our compensation method, and with the ionospheric impact. A radargram is the concatenation of several radar pulses as the one presented in figure 1 (see text for detailed) [from *Mouginot et al.*, 2008].

The first iteration of the optimization uses the determined initial conditions to find a new set of parameters [a_{11}, a_{21}, a_{31}], set as the new starting point of the next iteration. The optimization is considered accomplished when the difference between the SNR products of the two MARSIS bands stops to evolve significantly.

Since the determined initial conditions should be close to the optimum solution, the searching field is limited to enhance the rapidity of the optimization. Thus, a computation space is built, covering $\pm$ 20% of a_{1i} and $\pm$ 50% of a_{2i} and a_{3i}.

The figure 2 shows this optimization applied on two MARSIS radargrams (concatenation of pulses). The orbit 2400 begins on the night side of the planet (SZA = 100°), and finishes on the day side (SZA = 20°). One can observes the progressive impact of the growing electron density of the ionosphere. The method is efficient to correct the delaying and the spreading of the pulses, giving narrow and bright echoes. Likewise, the correction applied on the orbit 2682 enable to distinguished accurately subsurface echoes of the south polar layered deposits of Mars (between echoes 700 and 800).

5. The TEC as a by-product

This document aims to achieve the description of a method to correct the impact of the ionosphere on MARSIS radar signal. However, it will be incomplete if the by-product of the ionospheric correction is not mentioned. The TEC is a direct result deduced from a_1 parameter. The determination of the TEC from MARSIS data has been investigated by *Safaeinili et al.* [2007], and *Mouginot et al.* [2008]. It can easily derived from equation (4) and (7):

$$TEC = \frac{a_1 . c}{161.28\pi} \tag{7}$$

Figure 3 shows the derived TEC of some MARSIS orbits compared with other datasets. This figure is the opportunity to see the correlation between the derived TEC of MARSIS with those from measured with other space instruments. It is a confirmation on the reliability of the correction method.

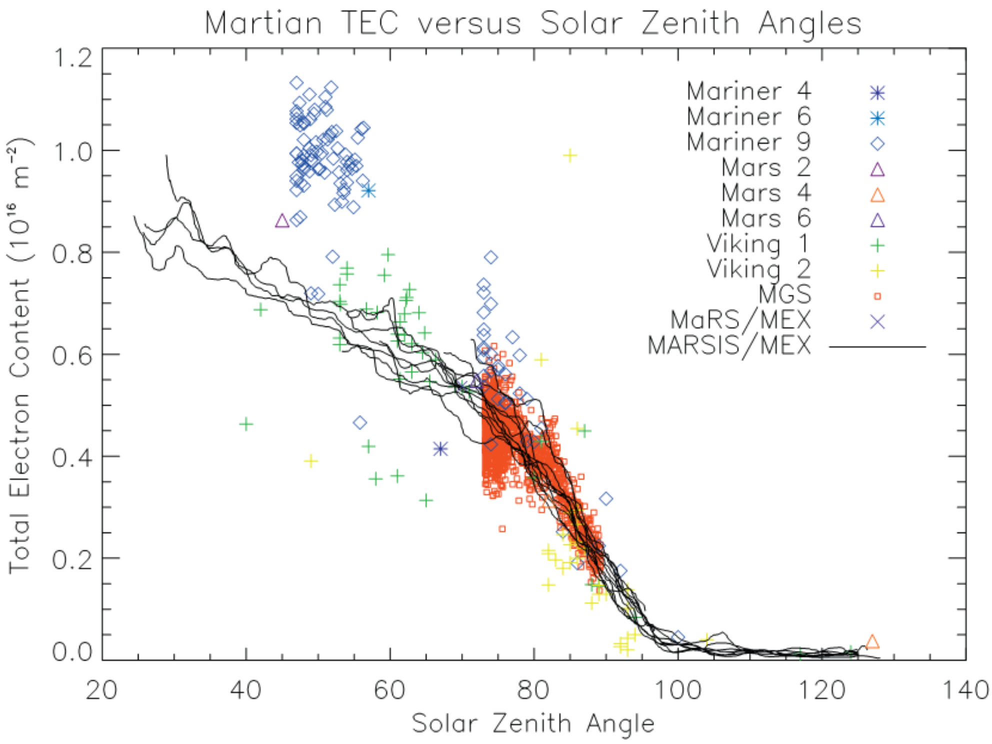

Fig. 3. Total electon content as a function of the solar zenith angle. Each dots corresponds of TEC measurements by other instruments, and solid lines to derived TEC of some MARSIS orbits. The altitude ranges of the measurements changes with the altitude of MarsExpress. However, since the spacecraft is no less at 270 km above the suface and the the main electron density is between 100 and 150 km, the error is small [from *Mouginot et al.*, 2008].

6. Conclusion

The phase distortion is an important effect of the ionosphere affecting the MARSIS radar signal. It prevents the users from correctly analyzing the surface and subsurface information enclosed within the data. A correction method of this impact has been achieved and explained in this document. The optimization method is enhanced by using the digital elevation MOLA to set the surface echo. The reliability of the correction is verified by comparing the TEC by-product with other datasets. As a result, we get radargrams with narrow and bright echoes, allowing the accurate study of the surface of Mars.

7. References

Acuña, M.H., Connerney, J.E.P., Ness, N.F., Lin, R.P., etal. 1999. Global distribution of crustal magnetization discovered by Mars global surveyor MAG/ER experiment. *Science 284*, 790-793.

Budden, K.G. 1964. Lectures on magnetoionoc theory. Gordon & Breach Publishing Group, London.

Grima, C., and Kofman, W. 2008. Ionospheric impact on MARSIS radar signal. *ESA study contract report* No 21646/08/NL/NR, volume 1.

Gurnett, D.A., Kirchner, D.L., Huff, R.L., Morgan, D.D., et al. 2005. Radar soundings of the ionosphere of Mars. *Science 310*, 1929-1933.

Krymskii, A.M., et al. 2004. Solar win interaction with the ionosphere/atmosphere and crustal magnetic fields at Mars: Mars Global Surveyor Magnetometer/Electron Reflectometer, radio science, and accelerometer data. *J. Geophys. Res. 109,* 11306.

Nielsen, E., Morgan, D.D., Kirchner, D.L., Plaut, J.J., Picardi, G. 2007. Absorption and reflection of radio waves in the Martian ionosphere. *Planet. Space Sci. 55*, 864-870.

Picardi, G., Plaut, J.J., Biccari, D., Bombaci, O., et al. 2005. Radar soundings of the subsurface of Mars. *Science 310*, 1925-1928.

Safaeinili, A., Kofman, W., Nouvel, J-F, Herique, A., and Jordan, R.L. 2003. Impact of Mars ionosphere on orbital radar sounder operation and data processing. *Planet. Space Sci. 51*, 505-515.

Safaeinili, A., et al. 2007. Estimation of the total electron content of the Martian ionosphere using radar sounder surface echoes. *Geophys. Res. Lett. 34*, L23204.

Smith, D.E., et al. 2001. Mars Orbiter Laser Altimeter : Experiment summary after the first year of global mapping of Mars. *J. Geophys. Res. 106,* 23689-23722.