IONOSPHERIC CORRECTION FOR MARSIS ON MARS EXPRESS AND TOTAL ELECTRON CONTENT (TEC) ESTIMATION.
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Introduction: MARSIS/MEX instrument is now working since 2 years and brings many measurements from the ionosphere, the surface and the subsurface. MARSIS is using two modes of sounding, one for ionosphere and the other for surface and subsurface [1][2]. Here we work only with the surface/subsurface mode and more especially on the technique to reduce this data. In this subsurface/surface mode, MARSIS is working simultanously with 2 of 4 available frequency bands (1.8, 3, 4, 5 MHz). The band-width is always 1MHz. Using these low frequencies allow the radar to penetrate deeply in the ground as 3.5 km in ice of the south polar layered deposits [3]. The vertical resolution of MARSIS is 60-160 m and the footprint size is about 6 to 16 km.

These frequencies are close to plasma frequency of the ionosphere, especially during Martian day. Indeed the radar waves, which pass through the ionosphere, are delayed and distorted. We show here our technique to correct these effects. The compensation technique works well and provide a powerfull tool to derive the Total Electron Content (TEC) on a large range of Solar Zenith Angles (SZA). Using a Chapman model, we fit these derived data and therefore estimate n0 the peak of electron for solar zenith and H the neutral height scale.

Ionospheric Distortion: As described above the radar waves of MARSIS are distorted. The refraction indice of the ionosphere depends on the frequency. As the bandwidth is very large compared to the central frequency, all frequencies don't travel at the same velocity. So ionosphere doesn't only induce a global shift but also a distortion of the signal. The phase shift due to the ionosphere can be described by the equation [4]:

$$\Delta\varphi(\omega) = \frac{2\omega}{c}\int_{h_1}^{h_2} \Re(n-1)dz$$

where ω is the pulsation of the radio wave signal, c the speed of light in a vacuum, h1 and h2 the lower ad upper altitude traversed in the ionosphere and R means the real part .

The refraction index of the ionosphere and the plasma frequency are given by:

$$n = \sqrt{1 - \frac{f_p^2}{f^2}} \text{ and } f_p = \frac{q_e}{2\pi\sqrt{\varepsilon_0 m_e}}\sqrt{n_e} \approx 8.98\sqrt{n_e}$$

We expand n until the third order to make the correction. It can be easily shown that this development is necessary to correct the data. Indeed the second and third order of the expansion can be respectively high as 30 and 15% of the first order.

Here we neglect the attenuation and the Faraday rotation due to the ionosphere [5]. And finally the phase shift is corrected by the equation:

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

where a1 is proportional to $\int n_e(z)dz$ (TEC), a2 to $\int n_e^2(z)dz$ and a3 to $\int n_e^3(z)dz$. Where n_e is the electron density profile.

Technique of Correction: In a first step of correction, in order to simplify the treatment, we consider that the density profile is like a Gaussian. The electronic density as function of altitude is given by:

$$n_e(z) = n_0 \exp\left[-\frac{(h-h_0)^2 \sec\chi}{2H^2}\right]$$

This equation depends on three parameters n0 the electron density at SZA equals to 0, H the neutral height scale and SZA. The phase shift in this case can be easily written only as function of TEC and H. In changing these two parameters, we check the quality of the compression of the signal (Signal to Noise Ration SNR) and the position of the surface echo compared to MOLA altitude and finally chooses the best one. However this model is not exact and don't represent the real parameters.

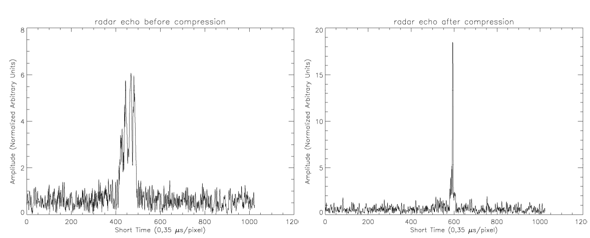

***Figure 1**: MARSIS pulse before and after compression.*

In a second step, we have chosen to vary separetly the tree parameters a1, a2, a3. As initial conditions, we use the values given by the first step of the correction. Experimentally we have checked that this gives very good initial condition. We use the same approach to choose the best correction: SNR and MOLA altitude constraints. MARSIS is working simultaneously with two bands of frequency, therefore the solution for a1, a2, a3 is searched for two bands at the same time. This process work well as we can see on figure 1 and 2. And we apply this process on all MARSIS/MEX orbit.

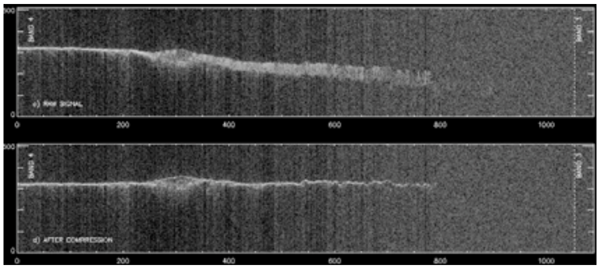

***Figure 2**: MARSIS radargram for the orbit 2455 before and after the compression. SZA increases on the radargram and we can see that the signal is more and more spread and delayed. MARSIS looses the signal below 50° of SZA.*

Results: As a1 parameter is directly proportional to TEC, this technique gives a powerfull tool to estimate TEC every 2 seconds. And so we can systematically follow the behaviour of the ionosphere (figure 4) for a large range of SZA (~ 50-120°). So these derived data allow to caracterize a global behaviour but also small variation as spatial variations during the night and waves.

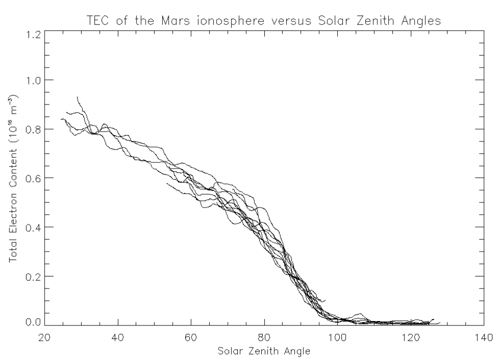

***Figure 4**: TEC from MARSIS ionospheric correction as function of SZA. Here are about 10 orbits, which cover together the maximum range of SZA. Generally as we said previously, the signal is lost below 50°.*

To explore in more detail the Martian ionosphere, we fit a1, a2, and a3 parameters using a Chapman model. The Chapman of a density profile is generally defined [6] as:

$$n_e(z,\chi) = n_0 \exp(-0.5(1 - z - Ch(x,\chi)\exp(-z)))$$

where z=(h-h0)/H, x=(h+R)/H, R the radius of Mars, h altitude, h0 altitude of maximum of production of ionization, χ the solar zenith angle and Ch the Chapman incidence function [6] defined by:

$$Ch(x,\chi) = x\sin\chi \int_0^x \exp\left(x - x\frac{\sin\chi}{\sin\alpha}\right).\mathrm{cosec}^2(\alpha).\mathrm{d}\alpha$$

In this model, we compute the integrated values corresponding to a1, a2, and a3 as function of SZA. The fit depends of course on n0 and H and we use a range of 5-30 km for H and 0-4.10^{11} m^{-3} for n0. We search the best solution in minimizing the three parameters as sum of:

$$\varepsilon_i^2(n_{0,}H) = \left(a_i - \int n_e^i(z)dz\right)^2$$

We take into account by normalizing the fact that the order of magnitude for a1, a2, and a3 is not the same. The figure 5 represents the fit for the orbit. One can see the good agreement between the Chapman model and the measurement realized by MARSIS.

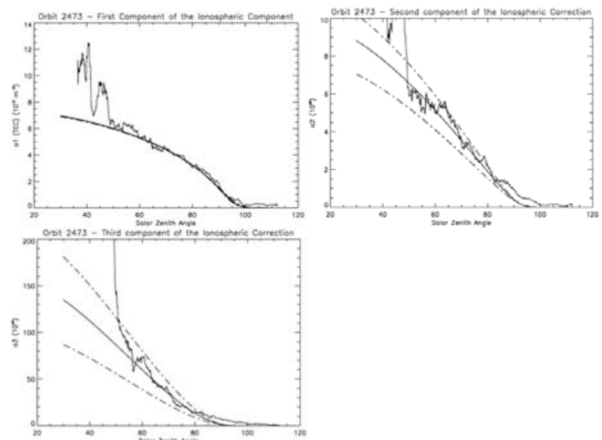

***Figure 5**: MARSIS fits for the orbit 2473. The first graphic corresponds to TEC or a1 values, the second one to a3 values and the third to a5. We can see as on figure 3 that the signal is lost below SZA~50° and therefore values for a1, a3, a5 aren't good.*

On figure 5, we plot also in dot-dashed lines the fit for $\min(\varepsilon) + \Delta\varepsilon$. It shows the sensitivity of the fit for n0 and H. We apply this fit for all orbits. Typical values of n0 and H are respectively 2.10^{11} m^{-3} and 9.5 km. The deviation on n0 and H, which corresponds to dot-dashed lines, is about 0,3.10^{11} m^{-3} and 1.2km.

MARSIS results compared to others: Many missions have measured electron density profiles since 30 years. Each of these profiles provides a value of TEC. We put together all of these results, in the figure 6.

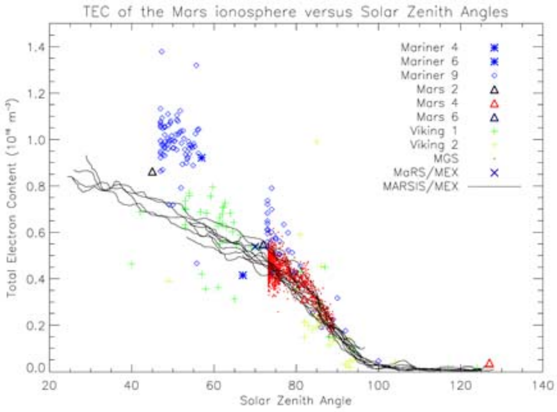

Figure 6: *TEC as function of SZA. In addition to MARSIS TEC, we plot Mariner 4, 6, 9 values [7][8], Mars 2, 4, 6 [9], Viking 1,2 [10][11], MGS [12]and MaRS/MEX values [13]*

We take into account for the MGS data only profiles measured after January 2005. Therefore MARSIS and MGS TEC are close in time and so in global solar flux (low solar activity). We see the good agreement between MGS and MARSIS. Mariner 9 provides another important set of measurements. The Mariner 9 values are larger than MARSIS ones. This phenomenon corresponds probably to the difference in solar wind flux during solar cycle : low activity for MARSIS and moderate for Mariner 9.

Conclusion: We show the way how we correct MARSIS/MEX and that this correction is necessary. The good analysis of surface/subsurface necessarily needs a good correction of ionosphere distortion.

We show also that the correction provides a powerfull to study the behaviour of the Martian ionosphere in time and space.

We derive from the parameter of the correction typical values of n0 and H.

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