Discussions

Geoscientific
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Data Systems

Retrieval of ionospheric profiles from the Mars Express MARSIS experiment data and comparison with radio-occultation data

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Abstract

Since 2005 the Mars Advanced Radar and Ionospheric Sounding experiment (MARSIS) aboard Mars Express has acquired a unique data set on the ionosphere of Mars made up of ionospheric soundings taken by the instrument working in its Active Ionospheric Sounding (AIS) mode. These soundings play a role similar to those of modern Terrestrial digisondes in the analysis of our planet ionosphere and have allowed us to dramatically improve our knowledge about the Martian ionosphere. This paper describes this kind of data, which are available from the public Planetary Science Archive, and introduces the MAISDAT tool developed by the European Space Agency to analyze and derive the vertical profile of electron density. Comparisons with radio-occultation profiles obtained from Mars Express Radio Science instrument are performed to validate the procedure used in this study.

1 Introduction

Our current understanding of the ionosphere of Mars has been mostly gained through the radio-occultation technique. However, in 2005, Mars Express mission put into operations a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) that is designed to sound the subsurface and ionosphere of Mars (Picardi et al., 2004). This technique, in the case of the ionospheric mode, is similar to the method used by digisondes on Earth and compared with previous radio-occultation measurements allows us to improve the horizontal spatial resolution and to obtain data at solar zenith angles for which radio-occultation cannot be obtained (Gurnett et al., 2008). With this instrument, it has been possible to study and understand the behaviour of the Martian ionosphere and its similarities and differences with the Earth ionosphere as never done before. To analyze the Martian ionosphere, MARSIS uses the Active Ionospheric Sounding (AIS) mode and his basic unit of data is the AIS ionogram which, as will be explained in the next section, is a graph of the delay time

(time between the MARSIS radar pulse transmission and its echo reception) versus carrier frequency. Ionograms can be easily converted into electron density profiles.

The knowledge of the ionosphere of Mars has dramatically changed recently thanks to the huge amount of new data. In general terms, the Martian dayside ionosphere is a plasma characterized by two main layers: the M2 layer which corresponds to the maximum ionization area of the ionosphere and it is produced by the solar EUV photons and the M1 layer which corresponds to the layer below the maximum of ionization and is mainly produced by the soft X-ray photons. In both cases, the dominated ions are the O_2^+. Occasionally, below the M1 layer, a third layer appears sporadically, created by the ablation of meteoroids (Paetzold et al., 2005; Withers, 2009). A significant part of the new information on the Mars ionosphere is due to the harvest that the Mars Express MARSIS radar has produced. One of the most important discoveries by MARSIS instrument has been the finding of the Martian ionopause. Duru et al. (2009) clearly show that the ionopause exists and the average altitude of the boundary, where the magnetic fields change from open to closed, is almost constant and for solar zenith angles of 60° is located at approximately 500 km. Some other important discoveries have been reached. One of them is the presence of oblique echoes. These kinds of echoes are very common in the MARSIS ionograms and they are associated with the crustal magnetic field of Mars. It is thought that in these regions there exist bulges in the ionosphere due to the vertical magnetic field. In these areas the sounder detects two different echoes, one due to the vertical reflexion from the ionosphere and the other due to the oblique reflection from the bulge (Gurnett et al., 2005). Another important finding has been the detection of the enhanced electron density over regions where the crustal magnetic field is strong and nearly vertical. This enhanced zone can reach 50 km above the surrounding ionosphere and it is believed that the increase in density can be caused by the heating of the electron gas which leads to a decrease of the recombination coefficient and an increase of the electron density (Duru et al., 2006; Nielsen et al., 2007 and Gurnett et al., 2008). Finally, another phenomenon that recently has been revealed is the existence of a new layer at altitudes above about

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200 km. Although only one topside layer is usually observed with MARSIS ionograms, sometimes it is possible to detect an additional layer above the maximum ionization. This layer is transitory and lasts about 60 % of the time near the sub-solar point. Their transient nature suggests that is originated by a dynamical process, most likely involv-
5 ing an interaction with the solar wind in the upper levels of the ionosphere (Kopf et al., 2008 and Gurnett et al., 2008). Furthermore, a "third layer" has been observed in the 1 % of MARSIS AIS mode observations at even higher altitudes (Kopf et al., 2008). Presently, the ionosphere of Mars is much better known and a very large number of MARSIS ionograms is available in the ESA's Planetary Science Archive (PSA).
10 The main purposes of this study are (1) to describe how the archival data of Active ionospheric Sounding (AIS) of MARSIS instrument are processed in order to derive the vertical profile of the electron density and (2) to check the correctness of our approach. To achieve the first objective, a description of MARSIS, of the AIS dataset and of the shape and structure of the AIS ionograms is given. Besides, the MAISDAT tool that
15 the European Space Agency has developed to analyze these data and the method to retrieve the ionospheric trace are introduced. To get the second objective, comparisons with radio-occultation profiles obtained from Mars Express Radio Science instrument are performed.

2 Acquisition and processing of the MARSIS AIS data

20 The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) is a low-frequency radar instrument on board Mars Express mission. This instrument consists of a 40-m tip-to-tip electric dipole antenna, a transmitter, a receiver and a digital data processing system (Picardi et al., 2004). Although its primary objective is to observe the distribution of water in the upper Martian crust, it can also operate in three
25 different secondary modes. In particular, the Active Ionospheric Sounding (AIS) mode is used to analyze the Martian ionosphere. In this mode the sounder of the spacecraft sends through the topside of the ionospheric plasma a vertical radio wave of the

frequency f_w. The waves are propagated through layers of increasing electron density while its frequency is greater that the plasma frequency of the surrounding plasma. When it reaches the layer with $f_w = f_p$ (f_p is the plasma frequency) the wave is reflected and goes back to the sounder which measures the delay time between the signal emis-
5 sion and its echo reception. This cycle is repeated step by step for a range of wave frequencies covering the whole spectrum between the local plasma frequency at the altitude of the spacecraft and the maximum plasma frequency of the topside (Bauer, 2008). In particular, in this mode, the instrument transmits a 91.4 µs short monochromatic radio pulse and then listens for the echoes during 7.3 ms recording 80 samples
10 of the electric field spectral density at a sampling rate of 91.4 µs. MARSIS can emit RF signals in a frequency range between 0.1 and 5.5 MHz at a maximum radiated power of 15 W. The maximum plasma frequency peak in the ionosphere of Mars is located at an altitude around 150 km. To record one complete ionogram this procedure is repeated for a set of 160 different frequencies taking 1.26 s in total. An ionogram is recorded
15 every 7.54 s. The acquisition of MARSIS data is strongly controlled by the spacecraft orbit. Mars Express goes over a highly eccentric orbit with a periapsis altitude of about 275 km, an apoapsis altitude of about 11 000 km and a period of 6.75 h (Chicarro et al., 2004). Because of signal-to-noise limitations, ionospheric sounding data are only collected when the spacecraft is near periapsis. A typical MARSIS ionospheric sound-
20 ing pass starts at an altitude of about 1200 km, continues through periapsis at about 275 km, and ends at an altitude of about 1200 km. The total duration of an ionospheric sounding pass usually is about 40 min (Gurnett et al., 2005) and around 280 ionograms can be recorded. However, as the instrument has other modes of operation, it is very common to find AIS for 10 min, then subsurface mode around the pericenter, and then
25 AIS again.

An AIS ionogram (Fig. 1) is a two-dimensional plot of time delay and frequency. It represents the echo delay time for a series of signals with varying frequency. The frequency varies along the x-axis in the image and the signal delay along the inverted y-axis. The echo is visualized by a colour coded spectral density of the E-field component

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of the returning electro-magnetic wave. Starting at zero, the response delay increases with frequency. This part of the response trace is called "ionospheric echo" and corresponds to frequencies reflected in the ionosphere. When the frequency approaches the maximum plasma frequency $f_p(\text{max})$ the delay increases dramatically due to the decreasing slope of the function $f_p(z)$. At the frequency just above $f_p(\text{max})$, a cusp indicates when the signal frequency is high enough to pierce the ionospheric layer. This feature comes because as the frequency increases together with the electron density the pulse velocity decreases almost to zero at the critical frequency of the layer. If frequency keeps increasing, the waves reach the surface of the planet and experiment the reflection on the surface (Bauer, 2008). In the ionograms recorded close to the periapsis, almost always appear vertical lines at different frequencies called "plasma oscillation harmonics". They come from the electro static plasma oscillations which are detected by MARSIS receiver due to specific technical characteristics. These harmonics can actually be used to derive the local plasma frequency by measuring the spacing between the vertical lines (Duru et al., 2008). Other important features that appear sometimes in the AIS ionograms are the horizontal lines located in the left side of the ionograms and equally spaced in delay time. They are known as "electron cyclotron echoes" and their time spacing can be correlated with the cyclotron frequency of the local crustal magnetic field crossed by Mars Express (Gurnett et al., 2008).

The MARSIS AIS Dataset is available in the ESA's Planetary Science Archive (PSA). This type of data is written in binary files, where everyone contains all received records from the AIS operation phase of one orbit, i.e. they contain every ionogram. The data files are named FRM_AIS_RDR_XXXX.DAT where XXXX is the orbit number. All the geometrical information concerning the sounding events (coordinates of the spacecraft above Mars, altitude, solar angle conditions...) is contained in one single file, GEO_MARS.TAB, for all data files. There is also a C-program to read the binary file format. The currently available data corresponds to the period: June 2005–July 2010, in particular between the orbits 1844–8319 (although not in every orbit AIS data have been recorded).

In order to process these data, the European Space Agency has developed a MAT-LAB software, called MAISDAT (Bauer, 2008). With this software it is possible, among other many options, to perform the inversion of the ionospheric trace in order to obtain the electron density profiles (Fig. 2) which is the most important information that can be retrieved from the AIS data. To perform this operation, also known as "ionogram reduction", MAISDAT uses a method based on an inversion of the integral Eq. (1):

$$\Delta t(f_w) = \frac{2}{c}\int_{z_{refl}}^{z_{sc}} \frac{dz}{\sqrt{1 - (f_p(z)/f_w)^2}} \tag{1}$$

whose formal solution is the Abel's Eq. (2):

$$\tilde{z}(f_p) = \frac{c}{\pi}\int_{\alpha_0}^{\pi/2} \Delta t(f_p \sin\alpha)d\alpha \tag{2}$$

Δt is the delay time, f_w is the used frequency, f_p is the plasma frequency, c is the light speed, z_{sc} is the spacecraft altitude, z_{refl} is the altitude of the ionospheric reflexion, $\sin\alpha = \frac{f_w}{f_p}$ with $f_w \le f_p$ and $\sin\alpha_0 = \frac{f_p(z_{sc})}{f_p}$ (Gurnett et al., 2008).

When MAISDAT is initiated, the main window that appears is a spectrogram (a sounding frequency versus time plot) which is composed by stacking all the ionograms contained in the data file along their delay axis. The spectral density of the sounding echo for delay time and frequency values is displayed colour coded in the units: $V^2\,m^{-2}\,Hz^{-1}$. This window offers several options: selecting a data file, opening an ionogram display, opening a time series display or setting the range of spectral density values to be mapped to the colour scale. To analyze the ionospheric trace, it is necessary to start selecting an orbit and an ionogram. Then, a new window with the ionogram tool display described above is shown.

To start with the inversion, it is necessary to know the plasma density in the vicinity of the spacecraft because the corrected range for each data point depends on the plasma density profile of the sounding wave path (Fig. 1). This information can be obtained from the harmonics of the local plasma frequency. These harmonics (vertical

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lines) are easily measured from their average frequency separation by digitizing the plot. Then, to determine the ionospheric trace it is possible to follow either an automatic or a manual procedure. In the first case, it is usually complicated to select the correct trace due to several strong interferences at frequencies below 1 MHz. In the second case, this difficulty can be overcome by the user's visual inspection. We propose to select a clear ionogram with a well-defined vertical signature of the trace in the highest frequencies, and to click on the bottom of this part of the trace because the corresponding frequency is the $f_p(\text{max})$ which is directly proportional to the maximum ionization in the ionosphere. To select and digitize the rest of the trace until the lowest frequency, where is no longer distinguishable from noise, we propose to click on the top of the trace because it is the first record of the refection signal. Then, the digitized information is analyzed by MAISDAT, who gives the corrected and uncorrected electron density profiles of the ionogram. The corrected profiles use the true height in the ionosphere corrected by the oscillation harmonic in the frequency, and the uncorrected profiles use the virtual height. It is important noting that these profiles only explore the top of the ionosphere, i.e. the plasma that exists from the place where Mars Express spacecraft is located to the region of maximum electron density.

The top of Fig. 2 shows a typical profile from MARSIS radar with the corrected and uncorrected profiles obtained from the 178 ionogram of the orbit 2405. For comparisons, this figure also includes another corrected profile from the same ionogram obtained by the Iowa University team. The results match pretty well.

3 Comparison with Mars Express radio-occultation data

Mars Express spacecraft carries on board another instrument that is able to take measurements of the Martian ionosphere, the Mars Radio Science (MaRS) instrument. This experiment uses the Radio-Occultation technique to sound the ionosphere and to derive vertical electron density profiles. These profiles are different from those given by MARSIS because MaRS technique allows obtaining the full profile of the ionosphere.

Radio-occultation measurements are remote sensing techniques used for measuring physical properties of a planetary ionosphere. When the spacecraft is going to be occulted to the Earth by Mars, the spacecraft sends radio signals in the X and S bands which go across the Mars's ionosphere. The propagation path of these signals changes as soon as they reach deeper layers in the atmosphere, and the bending angle informs about the electron density distribution in this path of ionosphere. Those ionospheric profiles were retrieved from archival data, using the standard scheme for processing radio-occultation data (Paetzold et al., 2005).

Radio-science is a well-known technique which has been used widely in the study of the Earth and other planets ionospheres. Therefore, in this study we consider these data as a reference to compare and validate the electron density profiles obtained from MARSIS soundings. To this end, different profiles from both kinds of experiments under similar conditions in term of solar zenith angle, solar longitude, Martian latitude and solar activity ($F_{10.7}$ index) have been selected. Most of the time, these data show similar results especially in the region of maximum ionization where the value of the altitude and the electron density of the maximum peak are practically the same. The biggest differences appear close to the topside of the ionosphere (about 180 km) where the presence of other physical processes like vertical transport due to diffusion or penetration of an induced magnetic field can play a significant role.

A typical example of this very good agreement is shown in Fig. 3 where the MARSIS profile matches with the radio-occultation profile in the altitude range 130–190 km. The remaining of the MARSIS profiles is similar in electron density but with a small shift in altitude (by about 10 %). Close to the maximum peak of ionization the results are practically the same in both cases with a deviation of about 11 % in altitude and of about 5 % in electron density. With respect to the electron density, the greatest differences reach almost the 50 % of the radio-occultation profile at 160 km. As for the altitudes, they can amount to the 40 % of the radio-occultation profile and appear close to the topside. Figure 4 is another example of this kind of comparison where the results are practically the same.

However, when the difference in some of the considered parameters increases, the degree of similitude in the comparison decreases. Figures 3 and 5 show the same radio-occultation profile which is compared with MARSIS profiles from the same orbit. The only differences between these last profiles are the values of solar zenith angle and latitude which have increased in the second case. It is possible to observe that in Fig. 5 both kinds of profiles do not match as well as in Fig. 3 where the conditions of every parameter are more similar. This last result indicates that if similar conditions of solar zenith angle, season, latitude and solar activity are not considered, large differences in the adjustments can appear.

This good agreement between the profiles obtained from two different instruments give us confidence in our data analysis methodology.

4 Discussion

In order to describe the ionospheric soundings obtained by MARSIS instrument working in the Active Ionospheric Sounding (AIS) mode, the paper presents the main characteristics of this equipment, the shape and location of the AIS dataset and the structure and particularities of the AIS ionograms. In the same way, the methodology adopted to produce the inversion of these ionograms is described by introducing the MAISDAT tool. This MATLAB utility uses the Abel equation as base for processing and is able, among other many options, to obtain the electron density distribution.

To start with the inversion routine in MAISDAT following the Bauer (2008) procedure, the first step is to calculate the plasma frequency at the spacecraft altitude using the harmonic lines (vertical lines in the left part of the ionogram). So, it is important to choose ionograms not only with a good ionospheric trace (especially in the highest frequencies) but with good harmonics too. The next step is to select and digitize the ionospheric trace in a manual way starting with the highest frequencies. In the vertical part of the trace is advisable select the bottom zone and in the rest of the trace the upper part of the pixel because this part corresponds to the first record of the reflection

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signal. The manual fitting goes on until the lowest frequency, where the trace is no longer distinguishable from noise. Finally, MAISDAT processes the digitized data to calculate the electron profile of the ionogram.

A comparison between AIS electron density profiles and MaRS radio-science electron density profiles from the Mars Express Radio-occultation experiment has been accomplished to validate the ionospheric profiles obtained. As the radio-occultation technique is well-known in the study of the Earth and planetary ionospheres, can be considered as a reliable reference. In this study, different profiles from both kinds of experiments with similar conditions of solar zenith angle, solar longitude, Martian latitude and solar activity, have been compared. In a large number of cases, the comparison shows similar results, especially in the maximum region of ionization where the value of the altitude and the electron density of the maximum peak are practically the same for both kinds of data. These comparisons give us confidence that the MAISDAT processing is correct.

One of the most important goals of this current research is to develop a global empirical model for the maximum ionization peak of the dayside ionosphere of Mars. With this purpose the full dataset of MARSIS AIS ionograms is being used. Using MAISDAT software to analyze these data, a sample of ionograms that offers a representative number of profiles in different conditions of latitude, longitude, solar zenith angle, solar activity, solar longitude and Mars-Sun distance has been chosen. This set of data has allowed us to develop an empirical model for the main ionospheric peak. A detailed paper on this model will be sent for publication soon.

The α-Chapman expression is the basis of this model. It means that the main ionospheric layer is dominated by loss of ions due to radiation and dissociation processes (Sánchez-Cano et al., 2010). In order to obtain and represent mathematically a more realistic behavior for the ionosphere of Mars, the contribution of different parameters has been gradually introduced. The first of these parameters is the Sun-Mars distance. Mars has the most eccentric orbit in the Solar System, therefore this characteristic is very important to consider because the radiation that arrives at Mars depends a lot on

the position of Mars with respect to the Sun. With this purpose in mind, and following the Ionosphere formation given by the Chapman theory, every AIS ionogram has been normalized to the mean orbit distance (1.52 AU). The second parameter considered is the solar zenith angle which physically is the most important factor that dominates the formation of the ionosphere with respect to the altitude and electron density of the main peak. The results show a clear exponential tendency in both cases. The third parameter is the solar activity, in particular, the $F_{10.7}$ index.

So far, we have noticed that although the main density peak is affected linearly by the variation of the solar flux, the dependence of the height with respect this parameter is being studied. There are also other important parameters that, in a lesser extent, can affect the ionosphere. One of them is the crustal magnetic field in the southern hemisphere of Mars that seems to affect the shape of the biggest and smaller layers at Mars ionosphere (Nielsen et al., 2007). The effect of this magnetic field, as stated in a previous section, can be clearly observed in the left part of the ionograms, which suggests that the effect of the crustal magnetic field can be important at the spacecraft altitude (Zou et al., 2010).

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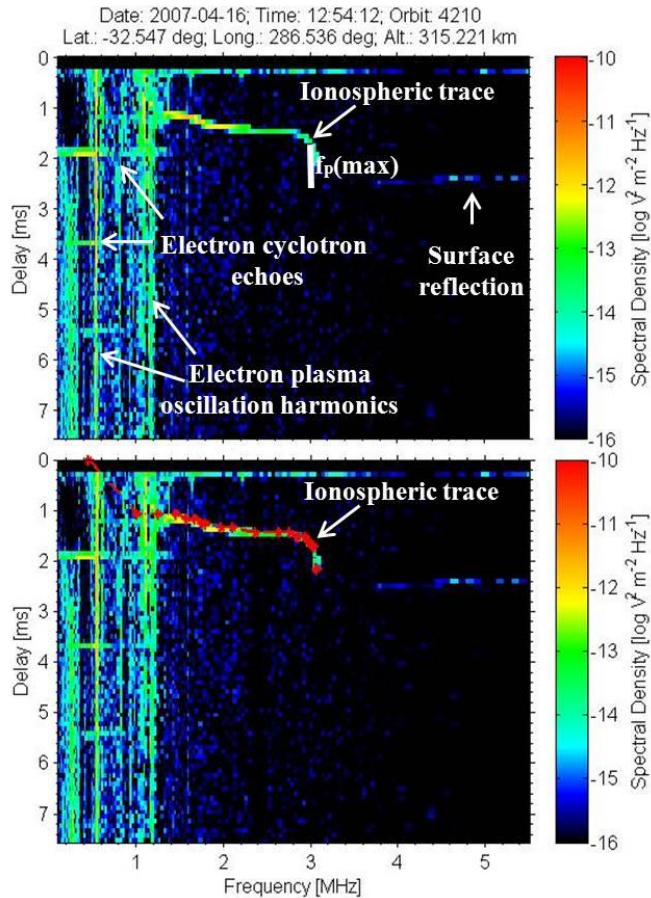
Fig. 1. The top panel shows a typical example of an ionogram obtained from MARSIS instrument using MAISDAT tool. The bottom panel emphasizes the identification of the trace for the ionogram reduction. In red it shows the identification of the trace as it is described in this paper.
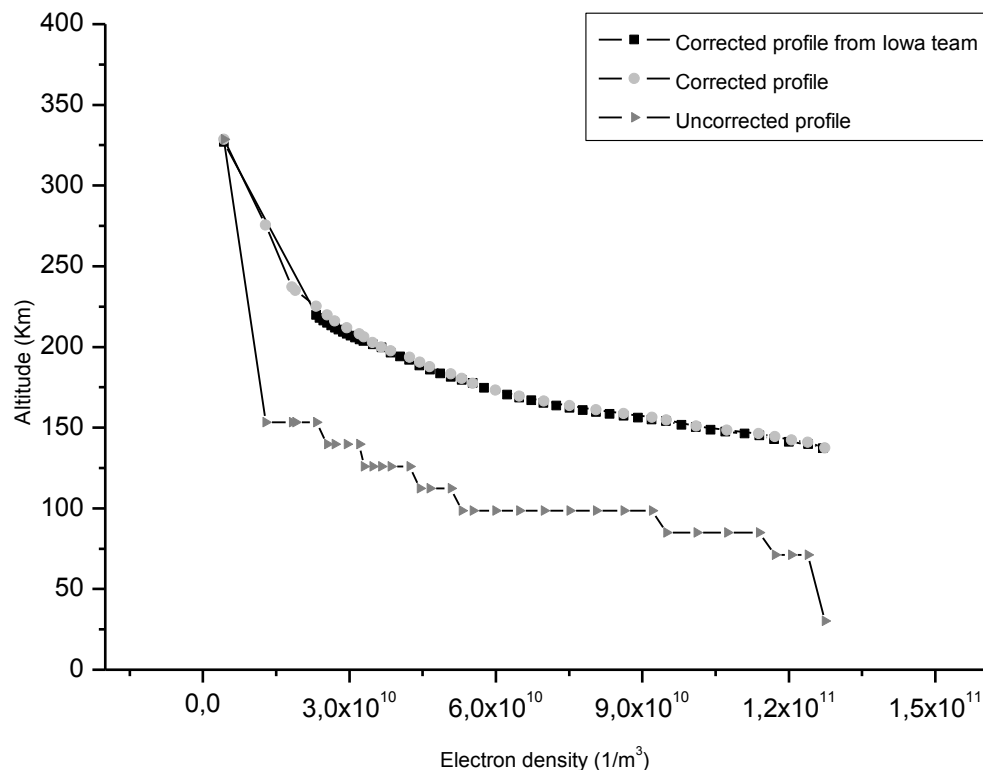
Fig. 2. Example of topside ionospheric profiles obtained from the ionogram 178 in the orbit 2405 of Mars Express. There are two different kinds of profiles: the corrected profile where the true height corrected by the oscillation harmonic in the frequency is used and the uncorrected one where the virtual height is considered. Another corrected profile, obtained at Iowa University by the MARSIS team, is also displayed. The agreement with the ionogram corrected by our team is very remarkable, and confirms that the same method is applied to obtain the electron density.

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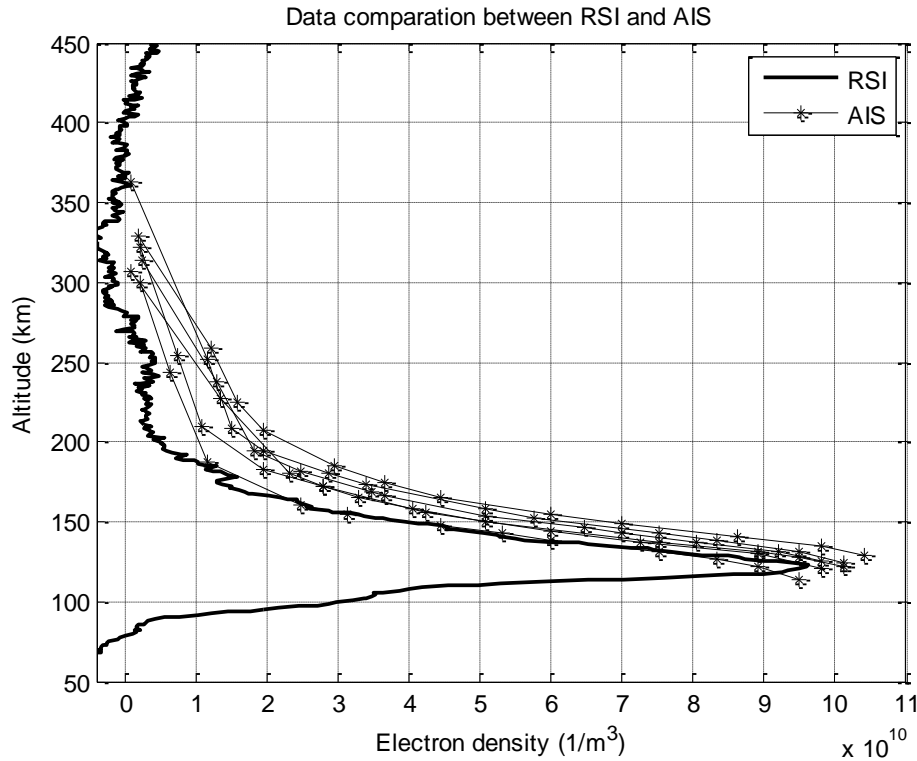
Fig. 3. First Comparison between a profile obtained from Mars Express Radio Science (Year: 2004, DOY: 180, Latitude: 10.2471°, SZA = 74.6059°, Ls = 53.21°, $F_{10.7}$ = 85) (bold line) and some topside profiles obtained from MARSIS instrument with similar conditions of location, solar zenith angle, solar activity and solar longitude (Orbit: 3065, ionograms: 20–40, SZA = 61–65°, Latitude = 11–1°, Ls = 59.65°, $F_{10.7}$ = 80) (light lines).

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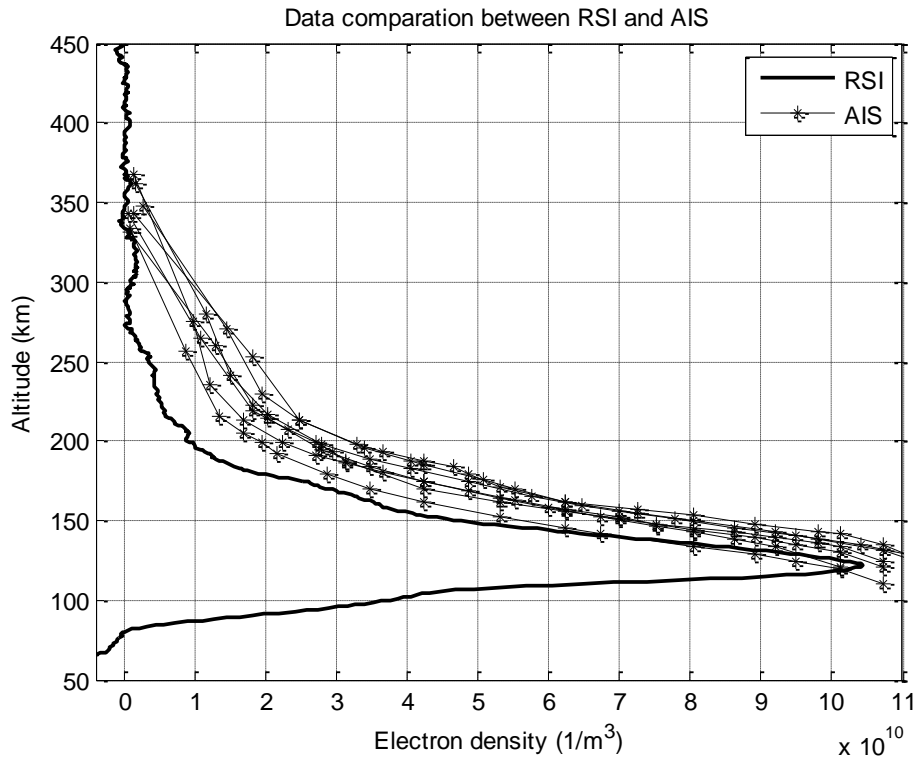
Fig. 4. Second Comparison between a profile obtained from Mars Express Radio Science (Year: 2006, DOY: 084, Latitude: 16.6432°, SZA = 54.3843°, Ls = 30.15°, $F_{10.7} = 76$) (bold line) and some topside profiles obtained from MARSIS instrument with similar conditions of location, solar zenith angle, solar activity and solar longitude (Orbit: 5240, ionograms: 155–186, SZA = 50–51°, Latitude = 26–11°, Ls = 25.14°, $F_{10.7} = 73$) (light lines).
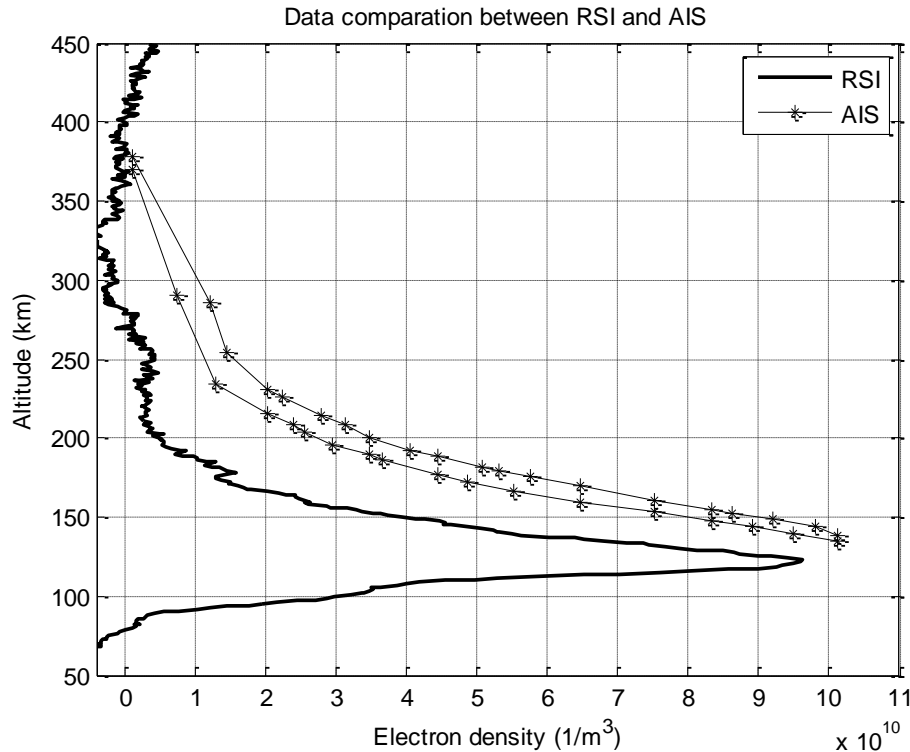
Fig. 5. Third Comparison between a profile obtained from Mars Express Radio Science (the same profile that in Fig. 3, Year: 2004, DOY: 180, Latitude: 10.2471°, SZA = 74.6059°, Ls = 53.21°, $F_{10.7}$ = 85) (bold line) and two topside profiles obtained from MARSIS instrument with similar conditions of location, solar activity and solar longitude but different conditions for solar zenith angle (Orbit: 3065, ionograms: 2–4, SZA = 57–58°, Latitude = 19.9–18.9°, Ls = 59.65°, $F_{10.7}$ = 80) (light lines).

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