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Vertical sheets of dense plasma in the topside Martian ionosphere

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[1] The low-frequency radar, Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), on board the Mars Express spacecraft is used to sound electron densities in the topside Martian ionosphere. The radar records the delay times to echoes of reflected radio waves as a function of frequency, yielding spectrograms with traces of radar echoes. At times, two traces are present in spectrograms of the Martian ionosphere. One of these traces corresponds to reflections from the direction to nadir. The other trace originates in a localized reflector in the ionosphere. The local reflectors can be associated with the cusplike regions of near-vertical crustal magnetic fields. The apparent nadir angle of reflection can occasionally increase to 90°. This suggests that steep gradients of the altitude of the electron isodensity exist in the Martian ionosphere and indicates rapid horizontal spatial variations of vertical diffusion of Martian plasma. Such gradients may arise owing to preferential access of solar wind to the cusplike regions or to precipitation of energetic electrons from acceleration regions located on cusp magnetic field lines high above the ionosphere.

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1. Introduction

[2] The Martian plasma environment is increasingly attracting attention as a laboratory for studying an ionosphere immersed in a complex magnetic field. The crustal magnetic field on Mars with its spatial variations of cusplike and closed magnetic field lines is a configuration very different from the large-scale dipole field within the Earth's ionosphere [*Acuna et al.*, 1998, 1999, 2001]. The scale length of the crustal magnetic field is small, which can lead to significant variations of the ionosphere over short horizontal distances. In the cusplike regions the ionosphere has been observed to extend to higher altitudes than in regions with nearly horizontal magnetic fields [*Ness et al.*, 2000; *Mitchell et al.*, 2001, 2002]. *Krymskii et al.* [2004] showed that the atmosphere/thermosphere is heated by the solar wind above crustal magnetic field anomalies. *Lundin et al.* [2006] reported acceleration events producing energetic electrons streaming toward crustal magnetic field anomalies. The altitude profile of electron densities sometimes shows a narrow valley (a few kilometers wide in altitude) in locations preferentially near-horizontal magnetic field lines over crustal magnetic field anomalies [*Withers et al.*, 2005].

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[3] The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on Mars Express (MEX) is a topside ionosphere sounder [*Picardi et al.*, 1999]. It provides information on variations of the ionosphere electron density with distance from the sounder. The sounder is based on the property of radio waves, that they can propagate in a plasma with a plasma frequency less than the signal frequency, and are reflected where the local plasma frequency equals the signal frequency [*Budden*, 1966]. A sounder measurement consists in transmitting a narrow pulse at a discrete frequency and to measure the reflected signal intensity as a function of time following transmission (the delay time). The measurement is repeated for many discrete frequencies. In this way the received signals are used to build up a spectrogram in a coordinate system of frequency versus delay time. The sounder transmits in a broad angular interval centered on nadir. Specular reflections occurring in off nadir directions are therefore also detected.

[4] Spectrograms typically exhibit a single echo trace of reflections from the direction of nadir [*Gurnett et al.*, 2005]. The nadir trace can be inverted to yield the electron density profile [*Nielsen et al.*, 2007]. However, quite often is observed more than one echo. In this work we specify the ionosphere structures which may be responsible for the dual echo.

2. Dual Traces

[5] The secondary trace is observed in addition to the nadir trace, but for larger delay times (larger virtual distances). The reflecting layers in the nadir ionosphere are therefore closer to the spacecraft than the reflecting surfaces

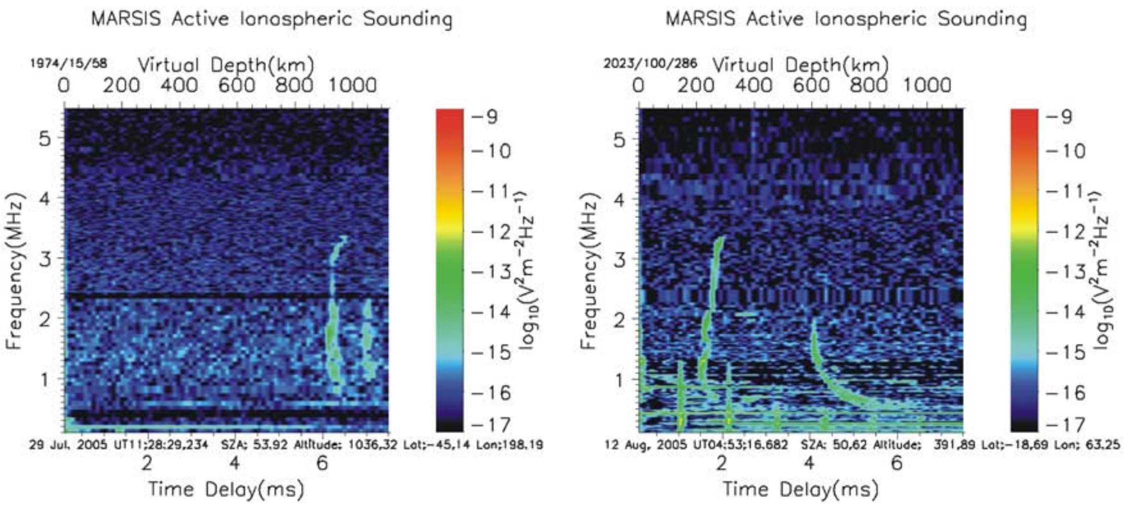

Figure 1. Examples of dual-trace spectrograms for (left) a high-altitude event during orbit 1974 and (right) a low-altitude event during orbit 2023.

associated with the secondary trace. This implies that secondary echoes arrived at the spacecraft from off nadir directions. Secondary echoes are observed at spacecraft altitudes between 280 and 1050 km, which are close to the altitude interval in which measurements have been made. Here we discuss two types of dual-echo events. One type occurred when MEX was at high altitudes from 700 to 1050 km. These events last up to 120 s and the apparent nadir angle estimated from the difference in time delay of the echoes is from 5° to 50° (the nadir angle is the angle between nadir and the direction to the reflection region). Another type of event was observed when MEX was at low altitudes between 280 and 400 km. The events of the second type last up to 20 s and the nadir angle of the reflections estimated can be as large as 90°. Figure 1 shows a typical spectrogram for each type of event. The left- and right-hand panels are for high- and low-altitude events, respectively. The leftmost trace (short delay times) in a spectrogram corresponds to echo signals from the nadir ionosphere. For a high-altitude event the right (secondary) trace sometimes approximately copies the frequency dependence of the echo with a shorter delay time, so that the two traces are practicable parallel. The secondary trace occasionally seems like a copy of the nadir trace in the whole frequency interval, but it appears more typically only at lower frequencies. In Figure 1 (left) a typical example of such a spectrogram is shown. In Figure 1 (right) a typical spectrogram for a low-altitude event is shown where the delay time of the second echo significantly increases when the signal frequency decreases. It is shown here that near-horizontal propagation can be responsible for that.

[6] The nadir trace shown in Figure 1 (left) is analyzed, as outlined by *Nielsen et al.* [2007], to yield the electron density altitude profile during the dual-trace event, and it is displayed in Figure 2. The profile of the electron densities giving rise to reflections. Following *Budden* [1966], the solid curve is fitted by a Chapman layer function (dash curve). The fit yields a realistic scale height of the neutral air. Above the Chapman layer the plasma scale height increased (dash-dotted curve). Figure 2 represents the nadir ionosphere during the dual-trace event described in the following. The spacecraft was at a high altitude (near 1036 km) and moved in its orbit downward toward the nadir ionosphere. The delay times for the nadir trace were therefore decreasing during the event. The secondary trace seemed to separate from the nadir trace in the frequency interval from 1.2 to 2.4 MHz. The secondary trace remained at a near-constant delay time. This resulted in an increasing

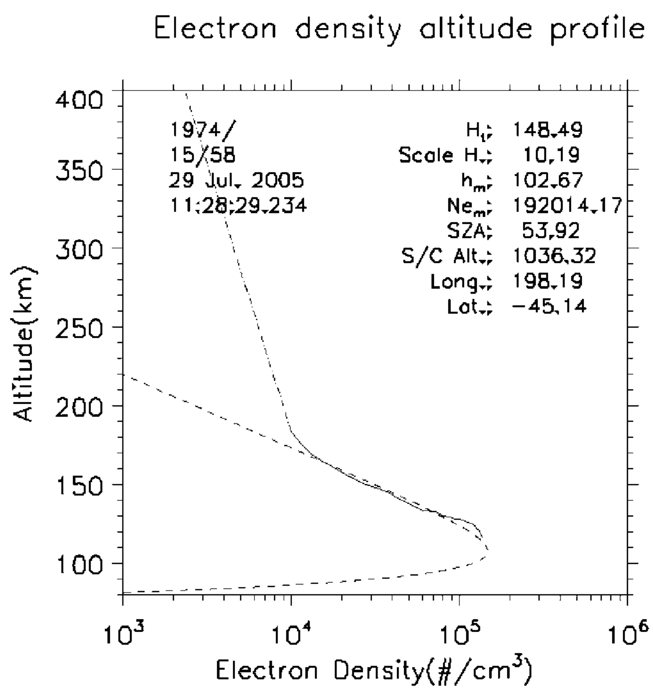

Figure 2. Inverted spectrogram of the nadir trace during a dual-echo event (orbit 1974; Figure 1, left). Shown is the altitude profile of electron densities in the nadir ionosphere. The Chapman layer ionosphere is characterized by typical values of the parameters peak electron density, scale height, and peak altitude for observations at this solar zenith angle of ~54°. The scale height in the topside ionosphere is large, 149 km.

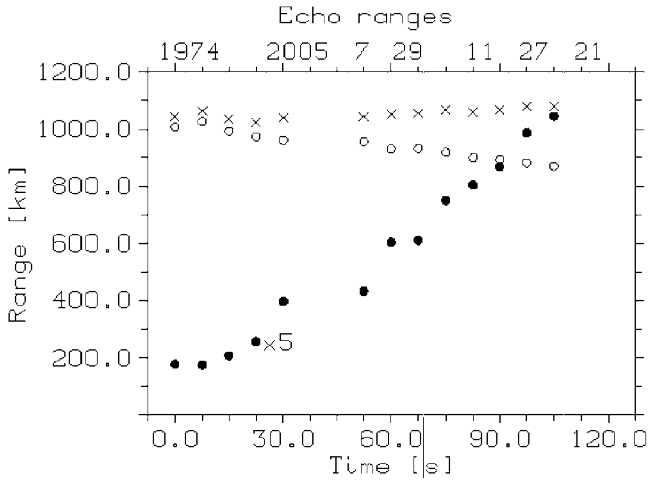

Figure 3. Range from the spacecraft to the secondary trace (crosses), altitude of the spacecraft (open circles, D_{nadir}), and difference between these two traces (solid circles, Δ) shown as a function of time (at the top of the figure the universal time (1127:21 UT) is given for the start of the plot) for the dual event in orbit 1974. The difference range between the two traces has been multiplied by a factor of 5 in the figure.

separation of the traces with time. To illustrate the dynamics of the traces with time the width of the interval separating the traces is plotted in Figure 3 together with the echo distance from the second trace to the spacecraft and with the altitude of the spacecraft over the Martian surface. At some point in its orbit (time = 0 in Figure 3) the radar picked up reflections from a second surface, and the distance to that surface remained nearly constant during the event. We argue that the constancy to the reflection region can only be understood by considering the dynamics of the spacecraft, its vertical and horizontal velocity components. The continuity in time of the secondary trace strongly suggests the echoes are from the same reflecting surface throughout the event. It therefore appears that the spacecraft moved relative to the surface in such a way that the distance to the structure remained nearly constant (the geometry happened to be this way for this event). The distance to the second reflecting surface could stay constant because the spacecraft moved simultaneously downward and horizontally away from the structure.

[7] Since it is realistic to assume that the distribution of electrons in the ionosphere remained unchanged during the measurement session, these considerations of the observed echo traces imply that their dynamics is a result of the dynamics of the MEX spacecraft, of its vertical and horizontal velocity. In this interpretation the evolution of the right-hand trace in the spectrogram suggests that the second echo is associated with a fixed localized reflection region in the ionosphere. To further explore this possibility an attempt is made to qualitatively determine the location of the secondary reflector.

[8] MARSIS ionosphere sounding is active when the spacecraft altitude is less than 1200 km. During that part of its orbit the spacecraft orbital speed is from 3 to 5 km/s, i.e., in a few seconds the spacecraft passes distances which are significant compared to the apparent distances to the reflection points. For a known spacecraft altitude of D_{nadir} and for an assumed reflection altitude of 150 km, the apparent nadir angle, Θ, to the reflection region can be estimated as follows: $\Theta \sim \mathrm{acos}((D_{nadir} - 150)/(D_{nadir} - 150 + \Delta))$. Here Δ is the difference between the apparent distance to the surface of the fixed reflector and to the nadir reflecting surface. For $D_{nadir} = 1038$ km and $\Delta = 100$ km we have $\Theta = 26.0°$. For a reflection altitude of 200 km, we have $\Theta = 26.7°$. Provided the apparent distance to the reflection region is significantly larger than the altitude of the reflection region, as is a good assumption for this event, the uncertainty on the reflection altitude does not have a strong influence on the nadir angle to the reflection region. The sounder measures the apparent distance to the reflection regions, but not the azimuth. Thus the apparent reflection region is located on a circle. The coordinates of the center of the circle are in the reflecting altitude at the current longitude and latitude of MEX. The radius of the circle is determined by the nadir angle. As the spacecraft moves in its orbit the apparent nadir angle to the localized reflector varies and so does the center and radius of the nadir circle containing the reflection region. Since the reflection region is localized, the nadir circles will cut or touch each other where the fixed reflector is located.

[9] For the event in orbit 1974 the nadir circles have been determined and plotted on four maps each displaying a parameter of the crustal magnetic field in latitude versus longitude (in Figure 4): magnitude (top left panel), radial component (bottom left panel), horizontal component (bottom right panel), and inclination (top right panel). The inclination is 90° for a vertical field and zero for a horizontal magnetic field. These magnetic fields represent the crustal fields in ~400 ± 30 km altitude [*Connerney et al.*, 2001]. It is striking that the nadir circles cluster in a region where the horizontal component of the crustal field is near zero. This is the same region where the magnetic field is vertical with an inclination near 90°. These crustal fields represent the best current experimental estimates of the magnetic fields for our measurements. In order to minimize influence of solar wind induced magnetic fields on the observed crustal component, the crustal magnetic field model is based on nightside measurements. We are interested in the field at the altitude of the assumed reflections (from 150 to 200 km), i.e., about half the altitude at which the model fields were measured. This is unlikely to be a problem. Generally, magnetic field lines expand with increasing distance from the source, in such a way, that, along a vertical altitude line, the inclination of the field decreases with increasing altitude. If there is high magnetic field inclination in the model data at 400 km, then the inclination at 200 km is likely to exceed that at the higher altitude. The total magnetic field is the sum of the crustal field and of the solar wind induced field components. At this time we cannot estimate the magnitude and direction of the solar wind induced field with an accuracy required for the analysis. For our dayside observations we assume that the crustal field component is dominating. Flaring of the magnetic field flux tubes also imply that the magnitude of the field in the reflection altitude is larger than in the model. Thus we argue that the magnetic field in the reflection region has larger inclination and is less sensitive to solar

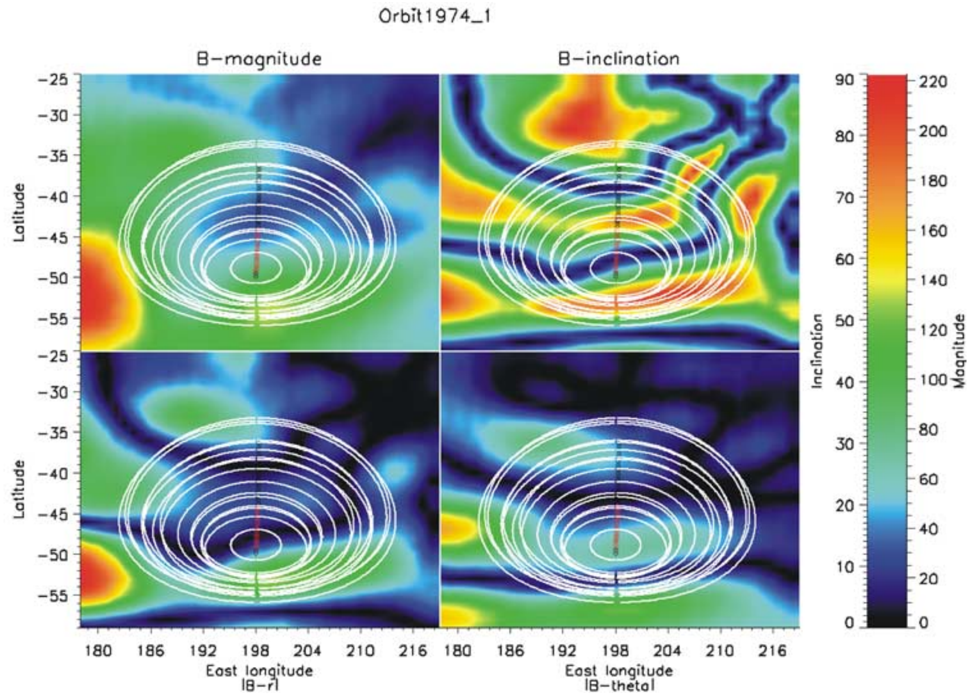

Figure 4. Four maps of the crustal magnetic field (magnetic magnitude, inclination, radial component, and horizontal component) with nadir circles for the secondary trace in orbit 1974. The circles tend to cluster closely in a region centered near 198°E and 53°S, marking that location as the region of a localized ionosphere reflector. The reflector is in a region of near-vertical magnetic fields. The magnetic fields are from *Connerney et al.* [2001].

wind effects than the model fields. The fact that the nadir circles cluster in a high-inclination area (not only for this event but in general; see below) is good evidence that the above arguments for using the 400 km altitude magnetic measurements in the analysis are realistic.

[10] That the described dynamics of the double traces represent a general pattern, and not quirks in an individual event, is illustrated by four more examples, in Figure 5. In two of the events the distance between the two traces increased (as in the previous example), and in two other events the separation decreased. The separation between traces increased/decreased with time, because the spacecraft moved away from/toward the reflector. These events are therefore not in principle different but results from the spacecraft dynamics relative to the reflector. The nadir circles have been drawn on a map of the magnetic field inclination, in Figure 6. It is clear that the fixed reflectors are located in regions with large magnetic inclination. Within the duration of each event the radar signal intersects regions with a large variation in inclination, from 0° to 90°. It is therefore significant that for all events the nadir circles cluster in a high-inclination region, excluding regions of more horizontal magnetic field lines as location for the fixed reflector. Placing the fixed reflector in a low-inclination region by modifying the apparent nadir angle would require unrealistic (either small or high) reflection altitudes.

[11] For the type of events described so far the spacecraft altitude varied from 1050 to 700 km, and the nadir angles from 5° to 50°. There is however evidence that fixed reflectors can occur for even larger nadir angles, up to 90°. In Figure 1 (right) such an example of a secondary trace is shown, which we will argue is likely to be reflected from a vertical “wall” of electron densities with a large horizontal gradient aligned with the direction between the radar and the reflection region.

[12] In Figure 7 the nadir trace has been inverted to yield the electron density profile (following *Nielsen et al.* [2007]). Note that the ionosphere density profile for this event is quite similar to the profile for the high-altitude event presented earlier. The events are different owing to the difference in the altitude of the spacecraft. For this event the spacecraft is at an altitude of 391 km, at a local electron density of 2000 el/cm^3. In Figure 1 (right) there is a resonance line at 0.4 MHz indicating excitation of the local plasma frequency. That means the spacecraft is immersed in a plasma with density about 2000 el/cm^3, consistent with the densities derived from the nadir trace. Thus the local plasma density is consistently derived in two independent ways from the observations: by inversion of the ionogram, and by the occurrence of oscillations at the local plasma frequency.

[13] When transmitting at the local plasma frequency there is no propagation of energy away from the radar but only excitation of oscillations at the local plasma frequency. At frequencies slightly larger than the local plasma frequency there is propagation but with large delay times. Actually, the secondary trace delay times tend toward infinity when the frequency approaches the local plasma frequency. The group velocity of a radio wave propagating in a plasma depends on the ratio of the plasma frequency and the radio frequency. There is only propagation if the ratio is less than one. As the ratio approaches one the group velocity

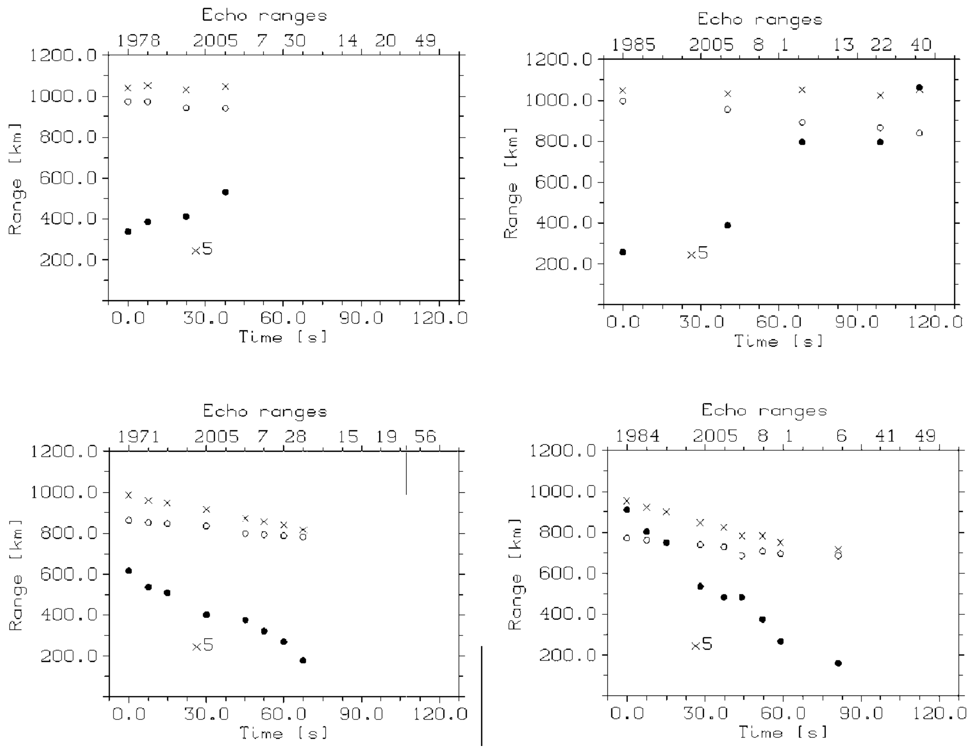

Figure 5. Same format as in Figure 3: ranges and trace separation distances versus time.

approaches zero, and the delay time increases toward infinity (see equation (1) below). These findings therefore strongly suggests that the radio wave signal has propagated either a certain distance in a plasma with electron density close to the one measured at the spacecraft, or propagated a much longer distance through lower electron densities (larger group velocities). We deem the latter possibility to be unrealistic since the lower densities imply that the propagation path would have to be located at larger distances from the planet than the altitude of the spacecraft. It

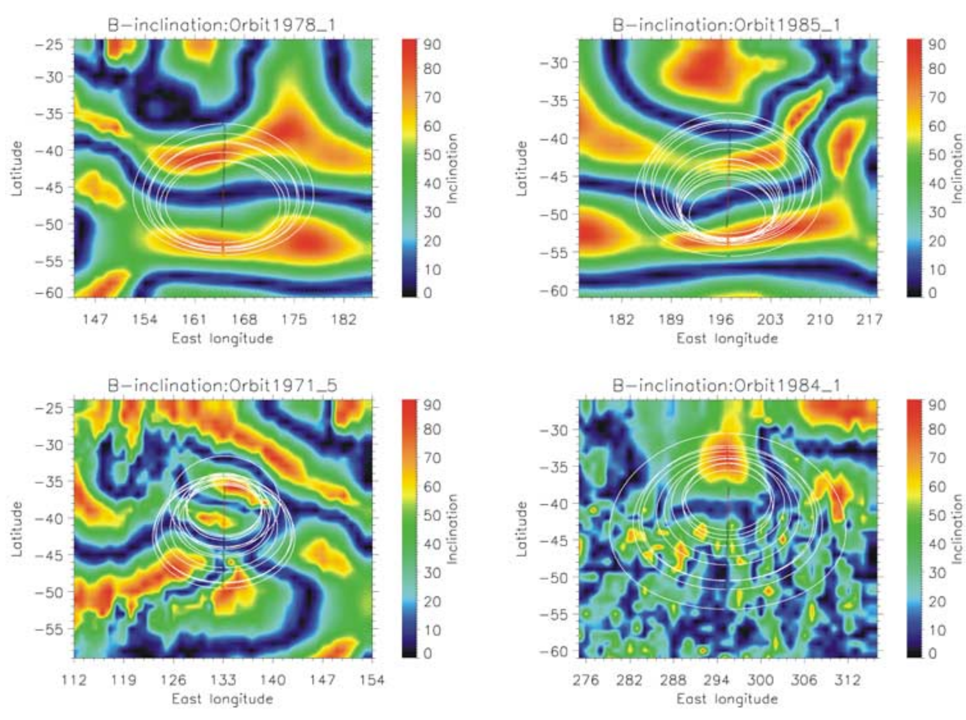

Figure 6. Four maps of magnetic inclination with superimposed nadir circles (as in Figure 4) for secondary trace events in orbits 1978, 1985, 1971, and 1984. The circles tend to cluster in a region of large magnetic inclination.

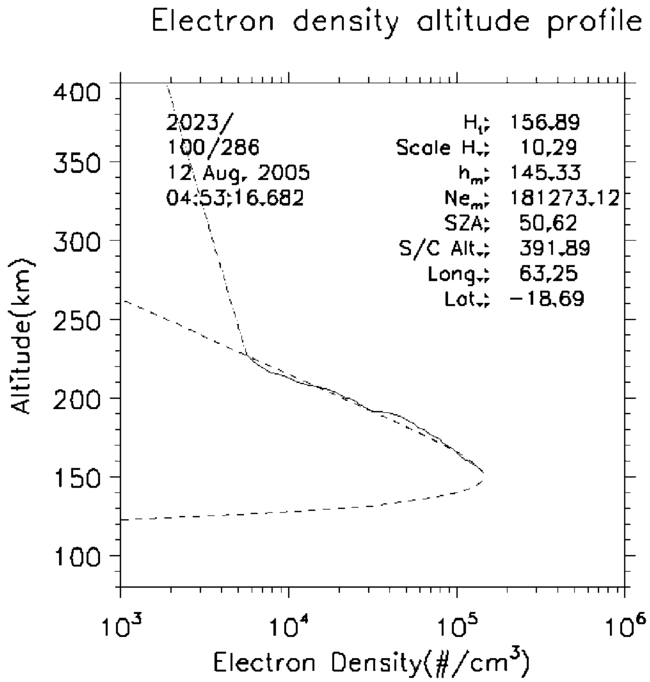

Figure 7. Altitude profile of electron densities in the nadir ionosphere at the time of a dual-trace event (Figure 1, right). The Chapman layer ionosphere is characterized by typical values of the parameters peak electron density, scale height, and peak altitude for observations at this solar zenith angle of ~51°. The scale height in the topside ionosphere is large, 142 km.

is difficult to imagine a geometry that could account for such a propagation path. The observations rather imply nearly horizontal propagation to and from a reflector, which is nearly vertical and the nadir angle of reflection is nearly 90°. Here, near spatial homogeneity along the signal path is assumed; that is, it is assumed that the nadir ionosphere along the signal path is as shown in Figure 7.

[14] In this scenario the distance to the reflector closely equals the travel distance for the high-frequency part of the secondary trace, i.e., about d = 600 km (for a delay time of 2 ms, and a group velocity equal to the speed of light). For a hard target the delay time for a signal with frequency f propagating in a plasma with plasma frequency f_p is given by *Budden* [1966]

$$t_d = \frac{2d/c}{\sqrt{1-\left(\frac{f_p}{f}\right)^2}} \tag{1}$$

where c is the speed of light. The delay times estimated this way are compared to the measured delay times in Figure 8. The delay times calculated from equation (1) are marked by red points in the figure, and represent a good approximation to the measurements. Clearly, the interpretation of horizontal propagation, with 90° nadir angle in the reflection region, yields a good approximation to the observation. Note that calculation of the apparent nadir angle to the reflection region as described earlier in this section is not possible owing to break down of the assumption for those calculations. A further reason is that these events are short-lived, lasting for a few frames. It is therefore not possible to determine the geographic location of the localized reflector with accuracy.

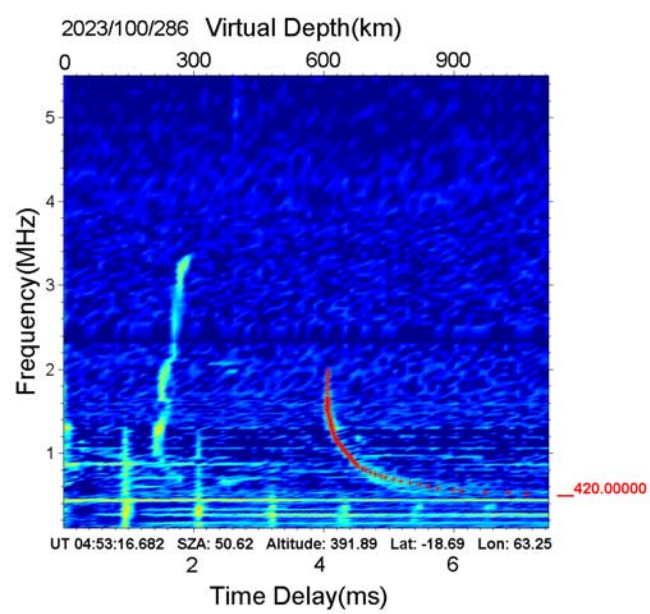

Figure 8. Secondary event characterized by a strongly increasing delay time as the frequency decreases toward the local plasma frequency of ~0.4 MHz. The red data points are the estimated delay time for a signal propagating horizontally to and from a vertical reflector (equation (1)). The very good agreement between observed and predicted variation of the delay time with changing frequency is a strong argument for near-horizontal propagation and therefore for the existence of a near-vertical reflecting structure in the ionosphere.

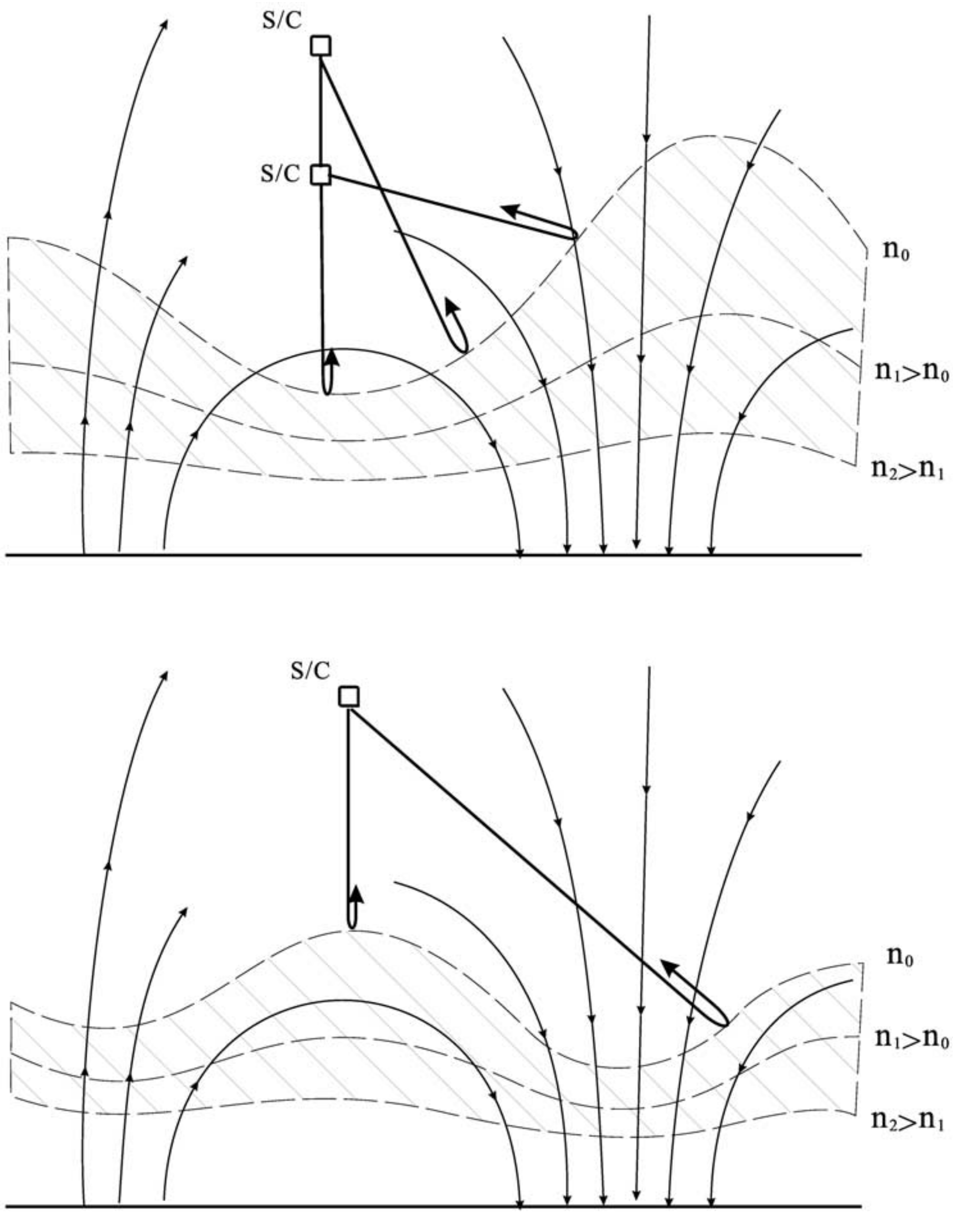

Figure 9. Schematic of crustal magnetic field lines (solid curves) and an ionosphere with spatially varying iso-electron-density ($n_0 < n_1 < n_2$) altitude contours (dashed curves), which on occasion can allow reflections for nadir angles up to $\sim 90°$. (top) Upwelling and (bottom) downwelling of the ionosphere is assumed.

[15] The above calculations were made for a hard target. The good agreement with observations implies that reflection at all frequencies occurred at nearly the same surface in space. The vertical sheet of dense plasma is characterized by a large horizontal density gradient. That the hard target is a good approximation means that the density gradient may be very large.

[16] In this analysis rectilinear propagation of the radio waves in the ionosphere has been assumed. Bending of the ray path occurs because of refraction of the radio signal in the Martian ionosphere/atmosphere [*Budden*, 1966]. According to Snell's law the ray bends away from the direction to the electron density gradient. When the signal penetrates into the dense ionosphere, the current nadir angle increases with distance from the spacecraft. Thus Snell's law further enhances the argument for vertical sheets reflecting the sounder signal.

[17] The dual-trace event can be interpreted as results of reflections from regions in the ionosphere in which the density gradient makes a large angle with the vertical, and lines up with the direction to the radar. A rotation of the gradient away from the normal generally vertical direction, can qualitatively in principle occur in two different ways: either through an upwelling or a downwelling of the ionosphere.

[18] For the case of an upwelling ionosphere the observations are summarized schematically in Figure 9 (top). Closed and open magnetic field lines are shown with an

ionosphere superposed (cross hatched), which extends to higher altitudes in the cusplike magnetic field regions. Shown are also three isodensity contours. Assume the Chapman layer is constant across the magnetic field regions, and that the scale height in the topside ionosphere increases going from a closed field line region to a cusplike region. Then the slope of the isodensity surface in going from closed to open field lines increases with decreasing frequency. This suggests that reflections for non zero nadir angles are more likely for the lower frequencies where the density gradient is tilted the most away from vertical (toward the radar). This is consistent with our observations. Instead of an upwelling of the isodensity contours we may assume a downwelling of the ionosphere associated with the formation of a "hole" or a "trough," as illustrated in Figure 9 (bottom). Also in that case a strong gradient could appear (in one side of the "hole") to reflect the radar signal back toward the spacecraft from off nadir directions. The significant difference between the two interpretations is that the altitude of the reflecting surface in the center of the cusplike region should be higher/lower in the upwelling/downwelling ionosphere compared to the surrounding ionosphere. *Gurnett et al.* [2005] found a tendency for the height of the ionosphere to peak when the spacecraft moved across the fixed reflector, thus favoring the upwelling interpretation.

3. Discussion

[19] A topside ionospheric sounder measures the delay times for radio waves propagating from the sounder to a reflection region and back, as a function of frequency. The sounder transmits in a broad angular interval centered on the nadir. Specular reflections occurring in off nadir directions are therefore also detected. The sounder provides information on variations of the ionosphere electron densities with distance from the sounder.

[20] Sometimes there are dual traces in a spectrogram. One of the traces has its origin in reflections from nadir. The second trace occurs always at larger delay times. The secondary trace approximately copies the frequency dependence of the nadir echo, so that the two traces are practicable parallel. The second trace is not always visible in the whole frequency range of the nadir trace. It is preferably visible in the lower frequencies. This may be partly a result of sounder sensitivity and strength of reflection, but could also be a result of the physics of the reflecting target. Evidence is presented that suggests that the process causing a tilt of isodensity contours, required for off nadir returns, may be most efficient at low densities (at low plasma frequencies).

[21] When two traces appear the first to examine is whether they can be understood as ordinary (O) and extraordinary (X) radio wave propagation in a magnetized plasma. The ordinary wave is reflected in a region where the signal frequency equals the plasma frequency. The extraordinary wave is reflected in the same region, but at a higher signal frequency. The increase in reflection frequency is controlled by the magnitude of the magnetic field. As a consequence of this the O and X traces in the spectrogram would be parallel shifted in the direction of the frequency axis. However, the observations show a displacement of the traces best described as a displacement in delay time. Mars Global Surveyor measurements have shown that a magnetic field in ~400 km altitude of 250 nT can be considered a strong field. Stronger fields, ~1000 nT, have been observed at much lower altitudes. The electron gyro frequency in a 1000 nT field is 28 kHz, a good deal smaller than the lowest frequency of the sounder (100 kHz) and even smaller compared to the lowest frequency for which echoes were observed in the events presented (~1000 kHz). In order to have a large difference in the reflection levels of the O and X rays, and therefore a large difference in delay times as observed for the two kind of rays, one would have to require a very large scale height, much larger than we have observed. It is therefore not to be expected that there will be large delay time differences between the two types of waves. For the events presented the difference in delay times for the O and X waves is calculated to be at least 2 orders of magnitude less than the measured difference delay time between the two traces. It is concluded that wave propagation in a magnetized plasma does not play a primary role in these events. The observed difference in delay times point to a spatial difference in ranges to the reflecting surfaces.

[22] These events are mostly observed (though not exclusively [*Gurnett et al.*, 2005]) in the Southern Hemisphere, where most of the Martian crustal magnetic fields are located. Furthermore, most of the events are in the longitude and latitude range where the crustal fields are most pronounced.

[23] For one class of events the spacecraft was at high altitudes and the nadir angles varied between 5° and 50°. The events lasted from 40 to 120 s, which means that as a rule several soundings were made during an event (one sounding lasts 1.2 s and is repeated with 7.5 s interval). For each sounding the apparent nadir angle to the localized reflector was determined. Then the radius and the latitude and longitude of the center of the nadir circle could be determined, which demarks the possible locations of the localized fixed ionosphere reflector. Superposing all the nadir circles for an event the location of the fixed reflector could be identified as the region where the nadir circles cluster together. It was found that the reflectors are located in cusplike regions with near-vertical magnetic field lines.

[24] In addition to the rather long-lived events we also observed a class of events at low altitudes with a short lifetime of 20 s. The observations were consistent with horizontal propagation from spacecraft to reflector and back to the sounder. This implies a horizontal electron density gradient aligned with the line of sight to the radar and perpendicular to a near-vertical surface of dense plasma in the reflection region. It means that a vertical reflecting sheet of enhanced plasma densities can be present in the Martian ionosphere.

[25] For reflections from a surface to be directed back toward the spacecraft, the spacecraft has to be located within a small angle from the normal to the reflecting surface. The velocity of the spacecraft increases as it decreases in altitude toward perigee, and thus the lower the altitude the shorter the time when reflections are possible (for the same surface). This may explain why the typical duration of events observed from high/low altitude is long-lasting/short-lasting, respectively.

[26] Observations made at high and low spacecraft altitudes have been presented. If the interpretation of near-horizontal to vertical sheets is real, then one would expect also to make observations at all spacecraft altitudes, also between 300 and 700 km. It is expected that characteristics of such events are a mix of the events at high and low altitudes. Analysis of such events is under way.

[27] That the two echo traces sometimes appear to be parallel means that the two reflection regions must have quite similar electron density profile along the line of sight to the sounder. For a spacecraft altitude of 850 km over the reflection region and a trace separation of 100 km, this means that the vertical electron density gradient in nadir must have been tilted by about 26°. The required tilt of 26° is quite large, especially when one considers that all the horizontal slabs of the whole ionosphere, from the top down to the maximum density, must be equally tilted in order to produce the occasionally observed parallel traces.

[28] In which way could cusplike magnetic field regions contribute to modify the ionospheric plasma distribution, or rather refractive index distribution, to form localized reflectors with density gradients pointing at zenith angles varying between 5° and 90° as shown in this report? *Ness et al.* [2000] analyzed Martian electron density profiles obtained by the radio occultation technique [*Hinson et al.*, 1999] and found the plasma scale height in the topside ionosphere to be larger inside cusplike regions than outside (schematic in Figure 9 (top)). This implies an increase of the altitude of the iso-electron-density contours in moving from a region of horizontal magnetic fields to a region of vertical fields. It also implies that the increase in altitude of the isodensity contours is most pronounced for low densities (low frequencies). *Mitchell et al.* [2001] showed that ionospheric plasma is more likely to extend to high altitudes in cusplike regions than in closed loop magnetic fields (schematic in Figure 9 (top)). This is equivalent to stating that the scale height in the topside ionosphere is larger in cusplike regions than in closed loop magnetic field regions in agreement with *Ness et al.* [2000]. Qualitatively, it is conceivable that the difference in scale height in closed and open field line regions is large enough to tilt the reflecting surfaces in the ionosphere (the iso-electron-density contours) enough to allow reflections back to the spacecraft from even large nadir angles. It was suggested that the scale height difference is caused by larger influx of solar wind energy in the cusp regions, whereas the closed magnetic field loops prevents access from interplanetary space. The added energy increases the plasma and neutral air temperatures with resulting increased plasma scale height in the cusp regions.

[29] The analysis showed that the vertical sheet of dense plasma appeared as a hard target, i.e., as if all frequencies between 2 and 0.4 MHz were reflected in the same region of space. It means that the horizontal density gradient in the dense plasma is very large. Very large horizontal gradients in the Earth's ionosphere are associated with auroral arcs, precipitation of energetic charged particles and field aligned currents. It is a too large jump to suggest that large gradients in the Martian ionosphere may be similarly associated. However, recent observations of acceleration and precipitation of energetic electrons on Mars may be relevant. *Lundin et al.* [2006] reported observations of plasma acceleration above Martian magnetic anomalies on the nightside, at solar zenith angles near 180°. It appears that an acceleration process, which is known to work in the Earth's magnetosphere: inverted-V events [*Frank and Ackerson*, 1971, 1976; *Evans*, 1974] may also be operating at Mars. If there are inverted-V events at Mars it could cause sheets of dense plasma in cusplike crustal magnetic regions, associated with energetic electrons, auroral arcs and field aligned currents. However, it remains to be shown that charged particle acceleration in inverted-V events can occur over magnetic anomalies on the dayside where dual echoes are observed.

[30] We are not aware of other observations or theories that suggest occurrence of "holes" or "troughs" in the dayside Martian ionosphere (schematic in Figure 9 (bottom)). Contrary to an upwelling ionosphere this electron density configuration cannot easily be brought into agreement with horizontally propagating radio waves being reflected from density gradients in a "hole" or "trough" in the ionosphere.

[31] Precipitation of solar wind energy into the ionosphere along vertical magnetic field lines and acceleration of electrons above magnetic anomaly regions could cause the ionosphere plasma to extend to higher altitude in magnetic cusp regions and tilt the electron density surfaces sufficient to allow reflections in off vertical directions, maybe up to an angle of 90°.

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