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Overlapping ionospheric and surface echoes observed by the Mars Express radar sounder near the Martian terminator

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[1] Radar soundings from the Mars Express spacecraft occasionally show ionospheric and surface echoes that overlap in frequency. For specular reflection from a horizontally stratified ionosphere such a frequency overlap is not possible, since ionospheric and surface reflections can only occur at frequencies below and above the maximum ionospheric plasma frequency, respectively. In this paper we show that such overlapping echoes are only observed near the terminator where strong horizontal gradients are present in the ionosphere. Using a simple ionospheric propagation model we show that the observed frequency overlaps are consistent with current estimates of the horizontal gradients near the terminator. **Citation:** Duru, F., D. D. Morgan, and D. A. Gurnett (2010), Overlapping ionospheric and surface echoes observed by the Mars Express radar sounder near the Martian terminator, *Geophys. Res. Lett.*, *37*, L23102, doi:10.1029/2010GL045859.

1. Introduction

[2] The Mars Express spacecraft [*Chicarro et al.*, 2004] carries a low-frequency radar called MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) that is designed to perform subsurface and ionospheric soundings [*Picardi et al.*, 2004]. For a horizontally stratified ionosphere, reflection can only occur at frequencies below the maximum electron plasma frequency in the ionosphere, f_p(Max). The plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}. Conversely, since radio waves cannot propagate through the ionosphere at frequencies below f_p(Max), surface reflections can only occur above the maximum plasma frequency in the ionosphere. Thus, for this idealized situation there should never be any overlap in frequency for the ionospheric and surface echoes. However, ionospheric and surface echoes that overlap in frequency are sometimes observed for extended periods, particularly near the terminator. The purpose of this paper is to study these overlapping echoes and develop a simple model that explains their basic characteristics.

2. MARSIS Radar Sounder

[3] The MARSIS radar sounder consists of a 40 m tip-to-tip dipole antenna, a radio transmitter, and a digital signal processing system [*Jordan et al.*, 2009]. Remote sounding is performed by sending a short radio pulse of frequency f and then measuring the time delay of the returning echo. The frequency is sequentially stepped through 160 quasi-logarithmic steps from 100 kHz to 5.5 MHz, once every 7.54 seconds. Although the pulse is emitted in all directions, only those waves that are incident normal to a reflective surface are reflected back to the sounder. The reflection at the ionosphere occurs because the free-space electromagnetic mode cannot propagate at frequencies below the electron plasma frequency. For normal incidence the reflection occurs at the altitude in the ionosphere where the wave frequency is equal to the electron plasma frequency.

[4] MARSIS data are often displayed as an ionogram, which is a plot of echo intensity as a function of frequency, f, and time delay, Δt. An idealized sketch of an ionogram is shown in Figure 1a. Electron plasma oscillations excited by the sounder cause an intense spike at the local electron plasma frequency, f_p(Local). An ionospheric echo is detected between f_p(Local) and f_p(Max) and is followed by the reflection from the surface of Mars at greater frequencies than f_p(Max). This ordering occurs because at frequencies higher than f_p(Max), the radio pulse passes through the ionosphere, all the way to the surface of Mars, whereas, at frequencies below f_p(Max), the radio pulse is reflected by the ionosphere. At f_p(Max), the ionospheric echo and surface reflection form a cusp. This cusp is formed because, as the wave frequency approaches f_p(Max), the group velocity ($v_g = c\sqrt{1-(f_p(z)/f)^2}$) is very small, thereby causing a large increase in the time delay.

[5] In Figure 1b an actual ionogram from November 11, 2007 is shown. The equally spaced vertical lines at low frequencies are harmonics of the local electron plasma frequency, and are caused by the excitation of electron plasma oscillations by the radar sounder [*Duru et al.*, 2008]. The equally spaced horizontal lines on the left side of the ionogram are electron cyclotron echoes. The time difference between these horizontal lines is the inverse of the local electron cyclotron frequency [*Gurnett et al.*, 2008; *Akalin et al.*, 2010]. As expected, at lower frequencies, between 1.0 and 1.85 MHz, an ionospheric echo is observed. At frequencies greater than 1.85 MHz, the surface reflection is detected. Between the ionospheric echo and surface reflection a cusp, centered at f_p(Max) (1.85 MHz) is formed. All these features are consistent with the sketch of the idealized ionogram shown in the top panel. In this ionogram, as in many others, the surface reflection starts at a frequency just above the maximum frequency of the ionospheric echo, and does not overlap the ionospheric echo.

3. Overlapping Surface Reflections and Ionospheric Echoes

[6] Investigation of 3509 MARSIS orbits, between August 4, 2005 and September 9, 2009, showed that there

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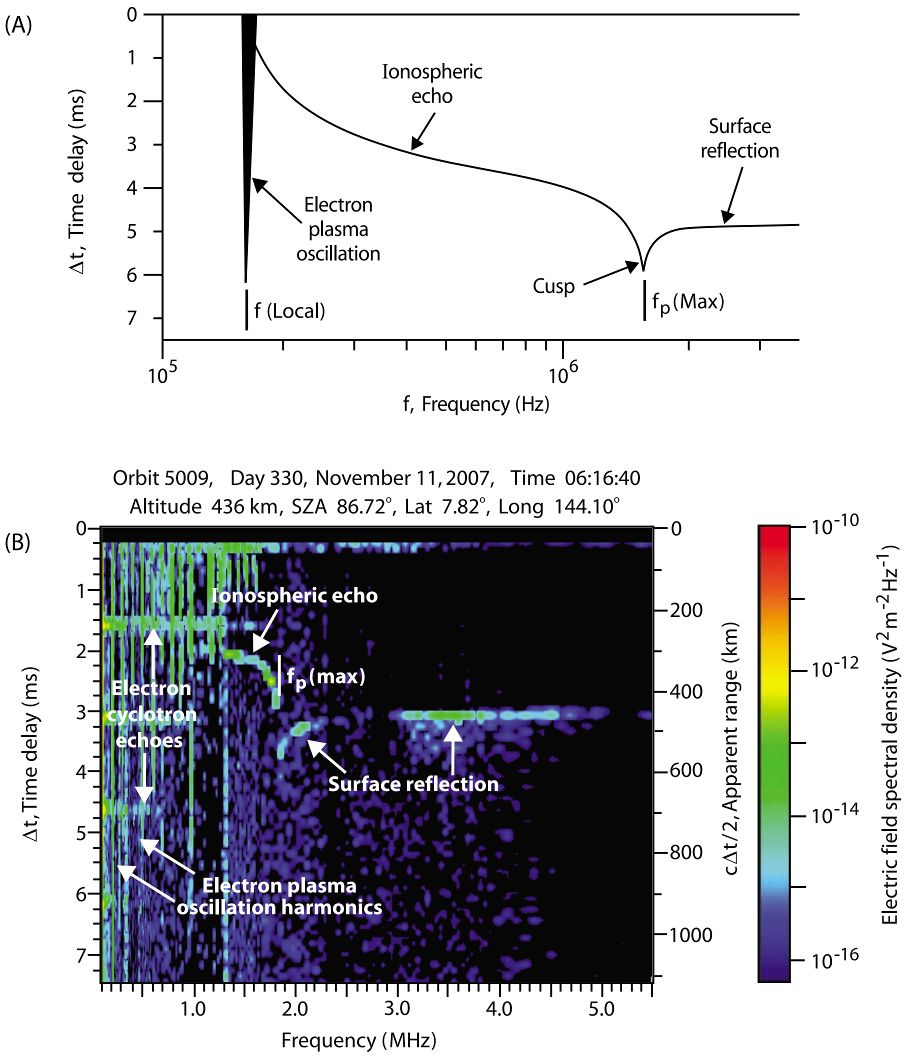

Figure 1. (a) A schematic representation of an ionogram, which is a plot of echo intensity as a function of time delay (Δt) and frequency (f). (b) An actual ionogram from November 11, 2007, 06:16:40 UT where the color code provides the echo intensity, as a function of time delay (y-axis) and frequency (x-axis).

are exceptions to the situation seen in Figure 1. In some ionograms there is a frequency range where the ionospheric echo and surface reflection overlap. An example is given in Figure 2. This ionogram is from July 01, 2009, and is expanded around the overlap region. As can be seen, the ionospheric echo starts at a frequency of approximately 0.9 MHz, and extends to a maximum plasma frequency of 1.84 MHz. The surface reflection starts at a frequency of 1.6 MHz and extends to the highest frequency observed, which is 5.5 MHz. Between 1.6 MHz and 1.84 MHz, these two echoes overlap, implying that in this frequency range there are two echoes for each frequency value. As explained before, for perpendicular reflection from a horizontally stratified ionosphere two distinct echoes at the same wave frequency cannot occur.

[7] Figure 3 provides another example of overlapping echoes. This is a 40 minute pass from April 25, 2009. The top panel shows the ionogram at 23:32:40 UT. The ionospheric echo starts at about 0.8 MHz and ends at 1.8 MHz. The surface reflection starts at 1.56 MHz. The two echoes overlap between 1.56 MHz and 1.8 MHz. At this time the solar zenith angle (SZA) value is 89.87°. For this pass, overlaps of the surface and ionospheric reflections are observed in 11 consecutive ionograms, in the SZA range between 87.65° and 92.09°. An echogram for the same pass, is shown in Figure 3b. Echograms are plots of echo intensity as a function of universal time (UT) and apparent altitude at a fixed frequency. Apparent altitude is presented in the y-axis and is defined as cΔt/2, where c is the speed of light. The x-axis shows the universal time (UT), with altitude (alt), longitude (long), latitude (lat) and solar zenith angle (SZA) given below. The frequency for this echogram is chosen to be 1.6 MHz, which is within the overlap region. The picture is very clean. Surface reflections are shown by the horizontal line at the apparent altitude of 0 km. Towards the end of the echogram, at about 23:32:10 UT, the surface reflections become dispersed due to slowly increasing plasma frequency in the ionosphere. The ionospheric reflection starts around 23:31:55 UT, as the horizontal line at about 130 km. For 1.6 MHz, surface reflection and ionospheric echo are observed simultaneously between 23:31:55 UT and 23:32:10 UT. The crustal magnetic fields (from the model of

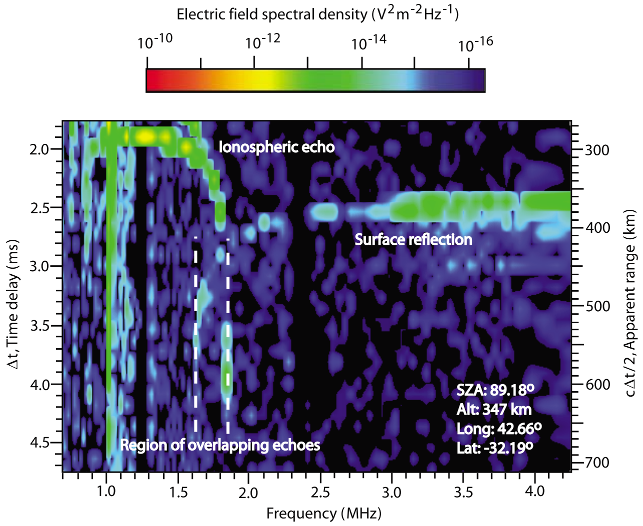

Figure 2. An ionogram from July 01, 2009, 15:11:08 UT. The ionospheric echo and surface reflection are observed simultaneously for the frequency interval between 1.6 and 1.84 MHz.

Cain et al. [2003]) are shown in the small panel below. The magnetic field magnitude (black line), and all the components of the magnetic field are very small, almost zero. Among the overlapping cases studied, we chose to investigate only those with almost no crustal magnetic fields, such as the example shown in Figure 3, to exclude the possibility of oblique echoes due to a bulge in the ionosphere. In the southern hemisphere, where strong crustal magnetic fields exist, oblique echoes due to a bulge in the ionosphere at high vertical magnetic field regions are also observed around the terminator region. As shown by *Duru et al.* [2006], oblique echoes often can have a normal incidence with respect to an upward bulge in the ionosphere formed due to near-vertical crustal magnetic fields. Such oblique echoes result in two or more distinct echoes at the same frequency. There were 10 such orbits. With detailed analysis of the echograms, ionograms and crustal magnetic field data from *Cain et al.*'s [2003] model, we were able to identify and exclude these cases from our study.

[8] Out of 3509 orbits, only 22 of them display overlaps of the type shown in Figures 2 and 3. The total number of ionograms is 52. All of the observed cases occur near the terminator region, in the SZA range between 86.2° and 95.6°.

4. Interpretation

[9] In analogy with the explanation of multiple ionospheric echoes due to oblique ray propagation, it is possible to explain overlapping surface reflection and ionospheric echoes as the result of a nadir-directed reflection from the surface of Mars and an oblique reflection due to the ionosphere which has slowly increasing density around the terminator. To verify that this model can reproduce the overlapping traces, we have created a model of the ionosphere for the pass in Figure 3. The model is based on Chapman layer fits [*Chapman*, 1931a, 1931b] to the electron density profiles obtained by the standard inversion [see *Morgan et al.*, 2008] in this series of 11 ionograms. However, note that, because nadir-direction propagation is always assumed in the standard processing of ionograms, a model based directly on these fits cannot confirm our hypothesis. Of the ionograms in this series, we have chosen the Chapman layer fit with the lowest value of the subsolar peak density. We have retained the peak altitude and the scale height, but reduced the value of the subsolar peak density in order to allow a nadir-directed ray to penetrate to the surface of Mars at the minimum frequency of the surface reflection. Density contours from Chapman layer model resulting from this process are seen in Figure 4a. In Figure 4, contours with the same density, corresponding to 1.0, 1.6 and 1.7 MHz, are shown. They have a nose shape around the terminator and then they become more flat at lower SZA values. Two rays at the same frequency are also shown in Figure 4. The first such ray propagating in the nadir direction is reflected from the surface of Mars. The second ray shown propagates oblique to the nadir direction and is reflected normally from the "nose" of the ionospheric contour where plasma frequency is equal to the sounding wave frequency.

[10] Figure 4b provides the ionogram obtained by applying the straight ray tracing shown in the top panel. The retrieved ionogram has the ionospheric echo at low frequencies and surface reflection starting at around 1.58 MHz. There is a frequency region, between 1.58 and 1.74 MHz, where the ionospheric echo and surface reflection overlap. Figure 4b, although very simplified, is a proof of the hypothesis that a nadir-directed reflection from the surface and an oblique reflection due to a pulse incident normally to the ionosphere of Mars could form a region of overlapping echoes.

[11] We see cases of overlapping ionospheric echo and surface reflections only around the terminator region. One reason for this fact could be that at low SZAs, the horizontal gradients are too small to produce a resolvable overlap. Also, well-defined cusps for both ionosphere and surface reflections are only seen in the range between 80° and 100°, due to another effect. For SZA less than about 80° the surface reflection is subject to strong absorption due to collisional damping of the sounding wave, first starting at frequencies near f_p(Max) and extending to higher frequencies until the entire frequency range above f_p(Max). At SZAs below about 60° the ground reflection is hardly observed [*Nielsen et al.*, 2007]. Also, ionospheric echoes are rarely observed for SZAs above about 100°, because the electron density in the nightside ionosphere becomes too low.

[12] We have sorted the overlap cases according to their altitudes, longitudes and latitudes. It is seen that the altitude of the spacecraft during these overlap cases varies between 304 and 932 km and the overlaps occur at all longitudes, suggesting that there is no relationship between the overlaps and the altitude and longitude of the spacecraft. The latitudes of these cases range between −77.9° and 55.4°. The majority of the cases, 39 ionograms out of 52, are from the southern hemisphere. However, in most cases, the magnitude and the components of the crustal magnetic field at the location of overlap cases are too small to cause an oblique reflection.

[13] Another issue is the frequency range where the overlapping cases are observed. The initial frequency where we start to observe the overlap changes between 1.08 and 1.89 MHz. The final frequency, where the overlap ends varies between 1.28 and 2.02 MHz. The frequency interval

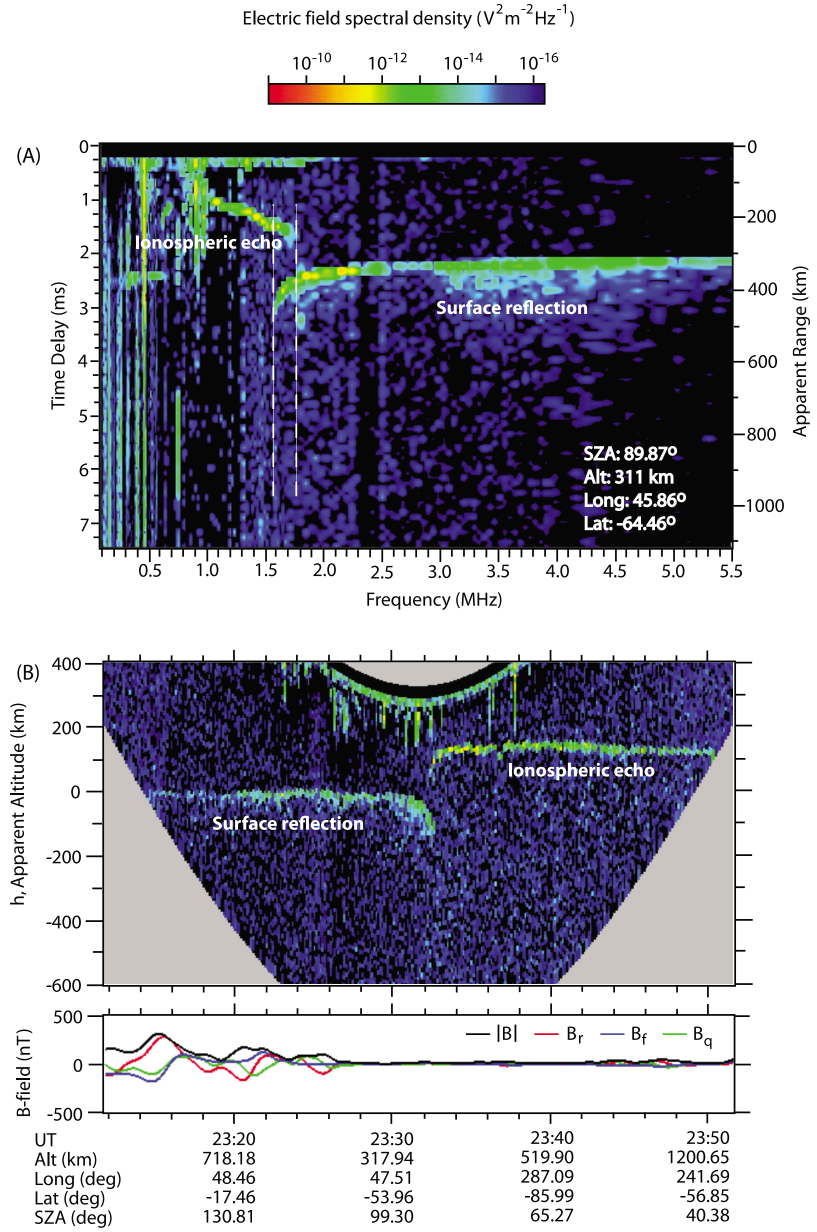

Figure 3. (a) An ionogram from April 25, 2009, 23:32:40 UT, showing overlapping ionospheric echo and surface reflection between 1.56 and 1.8 MHz. (b) The echogram for the same pass, at the frequency value of 1.6 MHz. Between the times 23:31:55 UT and 23:32:10 UT, the surface and ionospheric echoes are observed simultaneously. At the bottom, the magnitude and components of the magnetic field, from *Cain et al.* [2003] model at an altitude of 150 km are shown.

of the observed overlap is usually small, between 0.04 and 0.29 MHz.

5. Conclusion

[14] Radar soundings from the Mars Express spacecraft show that occasionally the ionospheric echo and surface reflections overlap in frequency. This overlap is observed in 22 orbits, all near the terminator region. Overlap cases can be observed when both ionospheric echo and surface reflection can be seen simultaneously. This condition can be satisfied around the terminator. On the ionograms, at SZAs lower than about 60°, only ionospheric echoes are observed most of the time. The surface reflection is almost always absorbed at lower SZAs because of high total electron content. As the SZA approaches 90°, the surface reflection appears at lower frequencies and gets closer to the ionospheric echo. The two echoes take the form seen in Figure 1 and in some cases they overlap, as in Figure 2. Although the total number of orbits investigated is 3509, the number of orbits which pass around terminator, between 85° and 95°, is 960. However, 660 of these orbits have large data gaps and contain only a few ionograms from the terminator region, which, because of the orbit configuration through

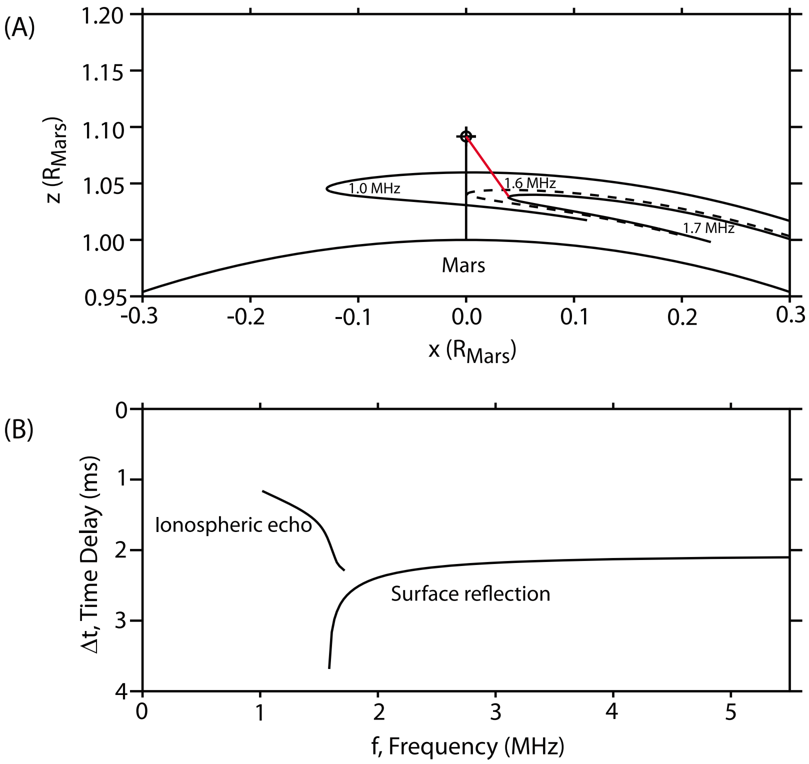

Figure 4. (a) A model of the ionosphere for the pass in Figure 3, obtained using a sequence of MARSIS ionograms and resulting Chapman model with the subsolar peak electron density reduced to allow a nadir-directed ray at frequency to propagate to the surface. (b) A very simple ionogram reconstructed from the model using straight ray tracing. The ionospheric echo and surface reflection overlap between 1.58 and 1.74 MHz.

most of the mission, tend to occur at very high altitudes, above about 1000 km, making observation of the surface reflection at low frequencies marginal. Out of 300 remaining orbits, only 22 of them display overlap cases, corresponding to 7.3%. The ratio is small, suggesting overlaps are very infrequent. Any roughness and irregularities in the ionosphere can destroy the oblique reflection preventing the overlap.

[15] Earlier studies show that it is possible to have more than one echo for a given frequency if there is an oblique reflection in addition to a nadir-directed one. We conclude that an oblique echo from the ionosphere in addition to nadir-directed reflection from the surface is the most likely mechanism for creating such an overlap. This assumption has been verified by creating a model ionosphere using an inversion technique and Chapman model for one of the overlap cases. To have an oblique reflection from the ionosphere it is necessary to have big enough horizontal gradients which can produce resolvable overlap. This kind of gradient is expected to be found around the terminator region.

[16] Overlapping echoes are observed for a wide range of altitude, longitude and latitude. No relationship between the occurrence of the overlaps and their geographic location has been observed. The SZA range is between 86.2° and 95.6°. Overlaps are observed between 1 and 2 MHz, changing from case to case. The frequency width of the overlap is usually small with an average of 0.13 MHz.

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