8. Summary and Conclusions

8.1 Ionospheric Effects

Because Mars has almost no intrinsic magnetic field, the solar wind can directly interact with the upper atmosphere. The height of the ionopause is controlled by the solar wind pressure. The dayside Martian ionosphere may be described using a simple Chapman layer model. The Martian dayside ionosphere has stable peak height and peak density. The peak height is between 120 and 130 km. On average, the Martian ionospheric plasma density is one order lower than Earth's and its TEC value is 50 times lower than Earth's ionospheric TEC. The Martian ionosphere is almost transparent to radio waves with frequencies above 450 MHz. For frequencies below 450 MHz, there is a progressive degradation of signal until the 4.5-MHz cut-off frequency where waves cannot pass through the ionosphere. Because the Martian ionosphere is similar to that of Earth in some aspects, we have used 0.5 dB for VHF-band signal and smaller losses for higher frequency bands. There is a comet-like structure to the nightside ionosphere extending several thousand kilometers in the antisolar direction. The plasma density in the nightside ionosphere is very low ($\leq 5\times10^3$ cm^{-3}). The nightside ionospheric profile often shows no dominant density peak and has large variations.

Recommendation: The Martian ionosphere may be used as a reflector for global communication. This is crucial for future Mars ground-to-ground communication. The Martian dayside ionosphere has a critical frequency of ~4.0 MHz for vertical incidence. This frequency is high enough to carry information. The stable condition in the dayside ionosphere also favors oblique incidence communication. Reflection off the Mars ionosphere can also provide trans-horizon (or beyond line of sight) communication for future Martian colonies, rovers, vehicles, and robots released from Mars landers. However, because of low usable frequency and very unstable condition, the nightside ionosphere has serious limitations for global communication.

Suggestions: We do not yet have any nightside ionosphere model. This is mainly because very few nightside ionospheric measurements are available. Thus, we suggest a detailed nightside ionosphere study. The MGS spacecraft is performing dayside ionospheric occultation and in-situ measurements. It will take some time to shift to the nightside. Previous occultation measurements showed that often no density peak was seen in the nightside ionosphere. We propose to drop a digital ionosonde to the Mars surface at a low latitude. The ionosonde will transfer daily ionospheric sounding data either to an orbiter or directly to Earth. We can have daily ionospheric data on peak height, critical frequency, etc. Through this study, we can assess stability of the nightside ionosphere for use as a radio wave reflector. Eventually, a model for the nightside ionosphere will be developed.

We still need to discover many things about the overall for the entire Martian ionosphere. To calculate low-frequency radio wave attenuation, we need to measure the ionospheric collision frequency. Ionospheric scintillation will be related to plasma irregularities and turbulence. For Earth during an ionospheric storm, absorption of VHF waves is enhanced. We are not sure that the same thing can happen in the Mars ionosphere. The ionospheric refractive index fluctuation and gradients will cause radio wave ray bending. We need to perform an accurate calculation of these effects.

8.2 Tropospheric Effects

The Martian troposphere is so thin that we expect it to have very little effect on radio wave propagation. The refractive index of the Martian troposphere at the surface is about two orders of magnitude smaller than that of Earth. Attenuation due to clouds and fog depends largely on their water content. So far we have little knowledge about such attenuation because these measurements are not yet available. Martian clouds are expected to have relatively less water liquid content than terrestrial clouds because measurements show that the clouds have low optical depth. At most, the Martian clouds are similar to terrestrial high-level cirrus clouds. Martian fog and aerosols (haze) also have a small optical depth. The total attenuation due to Martian clouds and fog should be less than 0.3 dB at Ka-band. There is a plasmasheath effect on communication during Martian atmospheric entry phase due to spacecraft impact ionization.

Recommendation: Even though the Martian tropospheric radio refractivity has a small value, it can still cause ray bending and multipath effects. We recommend performing an accurate calculation on excess phase and group delays (range and time delays). Other effects (such as range rate errors, appearance angle deviation, and defocusing loss on Mars) should also be estimated. Ice depolarization effects due to Martian clouds on radio waves are still unknown, but they are expected to be small because of the lower optical depth and the thinner cloud layer. Thus, the Martian atmospheric environment is also good for optical communications, except during dust storms. Even though Mars aerosols can cause some attenuation to a laser beam, this effect is very small, as compared with Earth.

For the communication blackout during Martian atmospheric entry phase, three solutions are recommended:

1) Place the antenna where the plasma is diluted, e.g., on the lee side; or communicate by a relay orbiter.

2) Inject some electron-absorbing liquid chemicals into the flowfield to neutralize the plasma.

3) Increase the frequency of transmission signals from X-band to Ka-band.

Future Martian atmospheric entry and manned landing programs should experimentally test to decide the best of these three options.

Suggestions: In the future, the amount of water or condensed CO_2 in the clouds should be measured accurately. Also, dust amounts in the atmosphere should be monitored, and the height in the atmosphere to which the dust extends should be determined. Absorption by water vapor, and the size and shape of the dust particles, should be measured. To study tropospheric scattering and scintillation, the tropospheric turbulence needs to be measured. We also need to estimate the effects of the plasma sheath due to the impact ionization on radio wave propagation during atmospheric entry. As on Earth, the entry blackout can temporarily shut down communications between the spacecraft and ground.

8.3 Gaseous Attenuation

Mars has an atmospheric gaseous attenuation of less than 1 dB in the microwave band, because the Martian atmosphere has very low concentrations of gaseous H_2O and O_2. Martian gaseous absorption is at least three orders of magnitude lower than at Earth. An accurate calculation for zenith opacity requires information about scale heights of H_2O and O_2. The ratio of total zenith absorption in the Earth atmosphere relative to Mars should be equal to the ratio of column number densities of H_2O and O_2 of Earth relative to Mars. We also do not know how high the gaseous attenuation can be in the infrared and optical frequency ranges because there are so many complicated absorption spectral lines in these frequencies.

Because the Mars troposphere consists of almost entirely dry air and the surface atmospheric water content is 3000 times lower than at Earth, the water absorption peaks in the spectrum are very low. Thus, the windows that on Earth are bounded by water lines become much wider. From 60 GHz to 300 GHz there is almost no attenuation. This feature is obviously in contrast to the Earth's situation, in which heavy rain and water vapor dominate the attenuation. The Martian atmosphere is dominated by CO_2 and N_2 gases. Under normal conditions, these gases do not have electric or magnetic dipoles, so they do not absorb electromagnetic energy. However, they may generate dipoles through collision and interaction with waves under a high-density condition. We often see that both gases have many absorption lines in the infrared and visible bands in the Earth atmosphere. It will be a research topic whether CO_2 and N_2 gases at the Martian surface can generate such dipoles. In our gaseous attenuation calculation, we have used an average surface value (300 ppm) for Martian water vapor, instead of a maximum value (400 ppm), which corresponds to the worst case. Actually, the exact amount of gaseous H_2O is still debatable. An accurate water vapor altitude profile at Mars is not available yet. A conservative estimate for the worst situation of Martian atmospheric attenuation is an increase by a factor 1.5.

8.4 Dust Storm Effects

Dust storms are the dominant factor in radio wave attenuation at Mars. A large dust storm can cause at least a 3-dB loss to Ka-band waves. For a normal dust storm, the attenuation is about 1 dB. The attenuation depends largely on dust mass loading, dust size distribution, etc. Currently we still have little information about these factors. Most large dust storms occur in the southern hemisphere during later spring and early summer when the southern hemisphere becomes suddenly hot.

Suggestions: In future missions, a number of dust storm parameters need to be further measured: Occurrence frequency, size, altitude, dust mass loading, dust size distribution, etc. Using this information, we will be able to accurately estimate dust storm effects on the wave attenuation. When the spacecraft lands in the southern hemisphere, at least a 3-dB margin should be considered for lander and rover communication.

8.5 Surface Geomorphologic Structures

Low-elevation-angle multipath fading due to surface rocks and terrain is another important impairment factor in wave propagation. Mars has a very complicated surface geomorphologic structure. When terrain or rocks block direct radio wave rays, a lander can sometimes still keep communication with a satellite through a diffracted or reflected ray. Diffracted wave signals will reduce intensities by at least a factor of 5 relative to direct signals. Reflected signal intensity strongly depends on the reflectivity of materials. Multipaths can also cause signal amplitude fading and attenuation due to phase shifts. Some studies of multipath effects for terrestrial canyon and hilly environments have been done. For an 870-MHz wave, attenuation is in a range of 2–7 dB, while for L-band (1.7 GHz), the attenuation is 2–8 dB. At higher frequencies, higher losses should be expected. Thus, surface rock attenuation will be potentially a significant attenuation source. We need to perform a similar multipath study on the Mars.

Suggestions: Low-elevation-angle fading is a potential communication problem for future Mars colonies and land vehicles. We need to study the fading due to rocks and terrain and to find their distributions in various scales. Currently we have very limited information regarding the surface and rock properties. We recommend that such types of measurements and experiments be included in future Mars missions.

8.6 Links between Mars and Earth

The minimum and maximum distances between Mars and Earth are, respectively, 55×10^6 and 400×10^6 km. Free space losses are 277 and 294 dB corresponding to these distances. In addition to free space loss, radio wave signals propagating from Mars to Earth suffer additional atmospheric losses at both planets. These combined atmospheric losses are about 8 dB under normal conditions. At Earth, for 99% of the time, weather conditions are such that total tropospheric attenuation for Ka-band is about 5 dB for a vertical propagation, while the comparable attenuation at Mars is about 3 dB. We have ignored medium loss in the interplanetary space because its effects are so small.

Finally, based on the Martian atmospheric environment, we strongly recommend using optical links for future Mars communications. Because of the thinner Martian atmosphere and the almost transparent Martian clouds, optical communication is almost perfect for links between Mars orbiters, between orbiters and landers, and even between Mars surface robots. Laser beams in the Martian atmosphere will have much less attenuation relative to those used in the Earth environment. We also suggest using low frequency (4.0 MHz) radio waves for Martian surface communication because the Martian ionosphere can effectively reflect these waves forward to areas beyond the line of sight. This will make Martian surface global communication possible.

8.7 Recommendations for Telecommunication Systems Engineer

8.7.1 Martian Ionospheric Effects

The Martian ionosphere only effects low-frequency waves (less than 450 MHz) and is almost transparent for high-frequency bands (S, X, and Ka). It has a loss of ~ 0.5 dB for the VHF (including UHF) band and negligible losses for higher frequency bands. The ionosphere has a critical frequency of ~4 MHz for vertical incidence. A wave with a 90-degree incidence angle and with frequency higher than the critical frequency will pass through the ionosphere unattenuated. The ionosphere can be used for future Mars surface trans-horizon communication. Martian ionospheric effects on one-way radio waves are summarized in Table 2-3 and plotted in Figure 8-1.

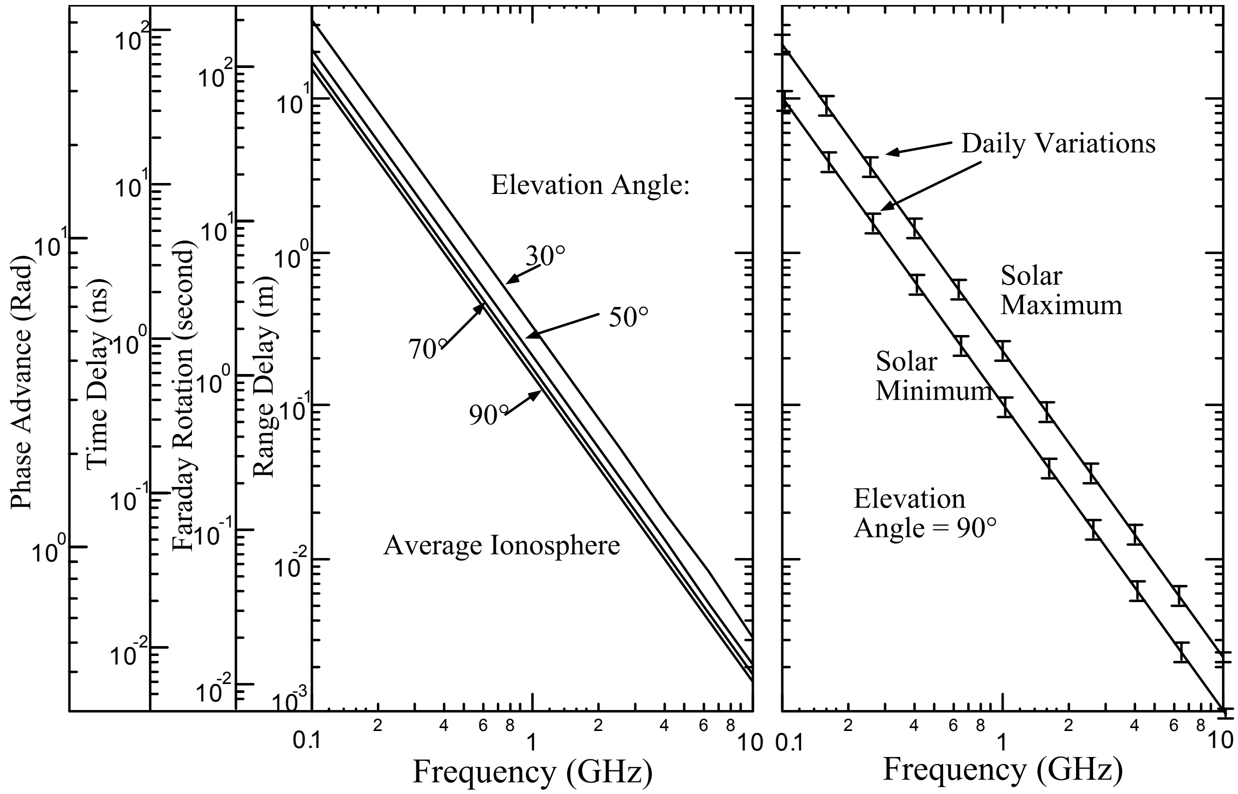

Figure 8-1. Martian Ionospheric Effects on One-Way Radio Wave Propagation of Various Frequencies. These effects include range delay, Faraday rotation, time delay, and phase advance. The left panel shows elevation angle effects for propagation through an average Martian ionosphere (between the solar maximum and minimum). The right panel shows solar cycle effects on the propagation with a zenith path. Daily variations (about ±15%) are also shown.

8.7.2 Martian Atmospheric Effects

The Martian atmosphere (or troposphere) is very thin and can be expected to have very little effect on radio wave propagation. Because Mars has a very low atmospheric pressure (less than 1% of Earth's), the Martian atmospheric radio refractivity is about two orders of magnitude smaller than that of Earth. Lower frequencies (UHF band) are expected to have very little refractive and scattering effects in the Martian troposphere. A high-frequency wave (above 1 GHz) may be bent or trapped by the vertical refractivity gradient when the wave incident angle is very close to the horizon.

8.7.3 Martian Cloud Effects on Wave Propagation

Optical depth is a measure of propagation loss. A transparent object has a small optical depth; an opaque object has a large optical depth. The optical depths of Martian clouds and fogs are about 1.0 at visual wavelengths. Thus, it is expected that they have little attenuation for microwave propagation. In the limiting case, the Martian clouds are expected to be similar to terrestrial high-level cirrus clouds. Martian aerosols (haze) have also been found to have a small optical depth (less than 0.5). The total attenuation due to Martian clouds, fog, and aerosols should be less than

0.3 dB at Ka-band. For lower frequency bands, the attenuation is almost negligible. All information about cloud attenuation is summarized in Tables 3-2, 3-3, and 3-4.

8.7.4 Martian Atmospheric Gaseous Attenuation

The atmospheric gaseous attenuation at Mars is greater at higher frequencies than at lower frequencies. However, the worst-case loss (at Ka-band) is still less than 1 dB. This is because the Martian atmosphere has very low concentrations of gaseous H_2O and O_2. Martian gaseous absorption is at least three orders of magnitude lower than that at Earth. Even though in the Martian atmosphere there is very little water vapor, it still dominates the entire gaseous attenuation, because compared to the Earth Mars has a much lower ratio of oxygen than water vapor. An accurate water vapor altitude profile at Mars is not yet available. Figure 8-2 shows gaseous attenuation for one-way radio wave path with two different elevation angles. We have used a 10-km scale height and a 300-ppm water vapor density, which may range from 100 to 400 ppm and represents an upper limit.

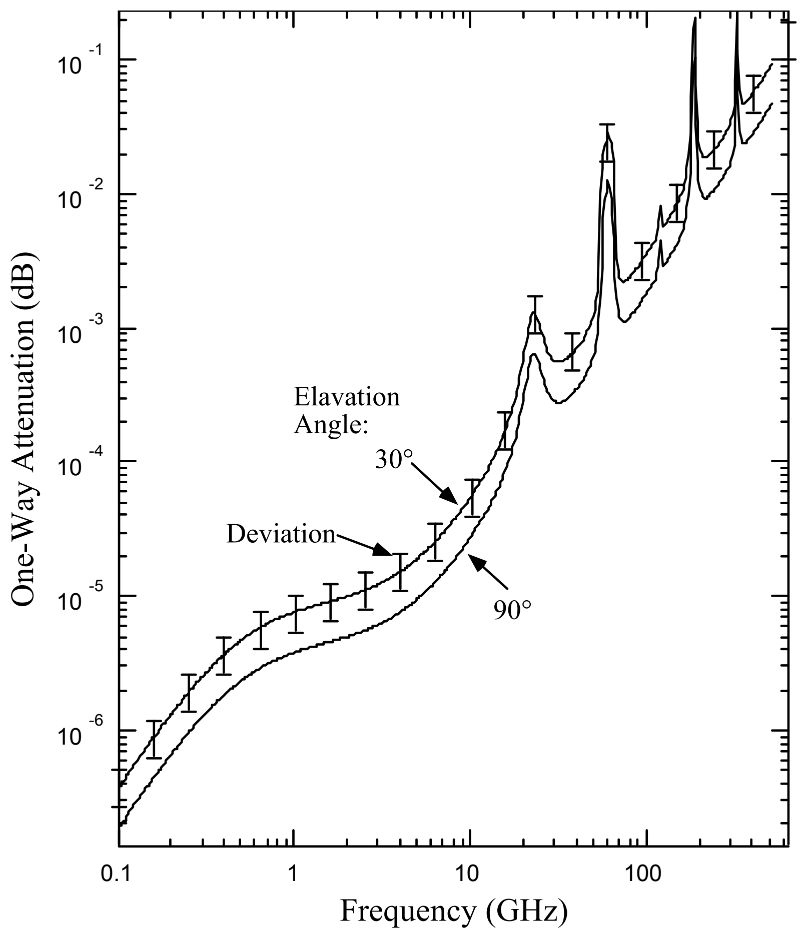

Figure 8-2. Martian Gaseous Attenuation for a One-Way Radio Wave Path through the Atmosphere for Two Different Elevation Angles (30° and 90°). The total attenuation showed here is mainly due to water vapor, even though the oxygen effect is also included. To calculate the attenuation, a 10-km scale height and a 300-ppm water vapor density have been used. The attenuation deviations for possible water vapor variations (about ±30%) are also shown.

8.7.5 Martian Dust Storm Effects

Dust storms on Mars can significantly affect a communication link. A large dust storm can cause at least a 3-dB loss at Ka-band. Lower frequency bands (UHF, S, and X bands) suffer less dust storm attenuation, which has a linear relationship with frequency and depends on the cube of particle size. Figure 8-3 shows Martian dust attenuation for a one-way radio wave path through a dust cloud with 10-km scale height for various elevation angles and particle sizes. The dust cloud parameters used for the calculation are summarized in Table 5-3. Most large storms occur in the southern hemisphere during later spring and early summer.

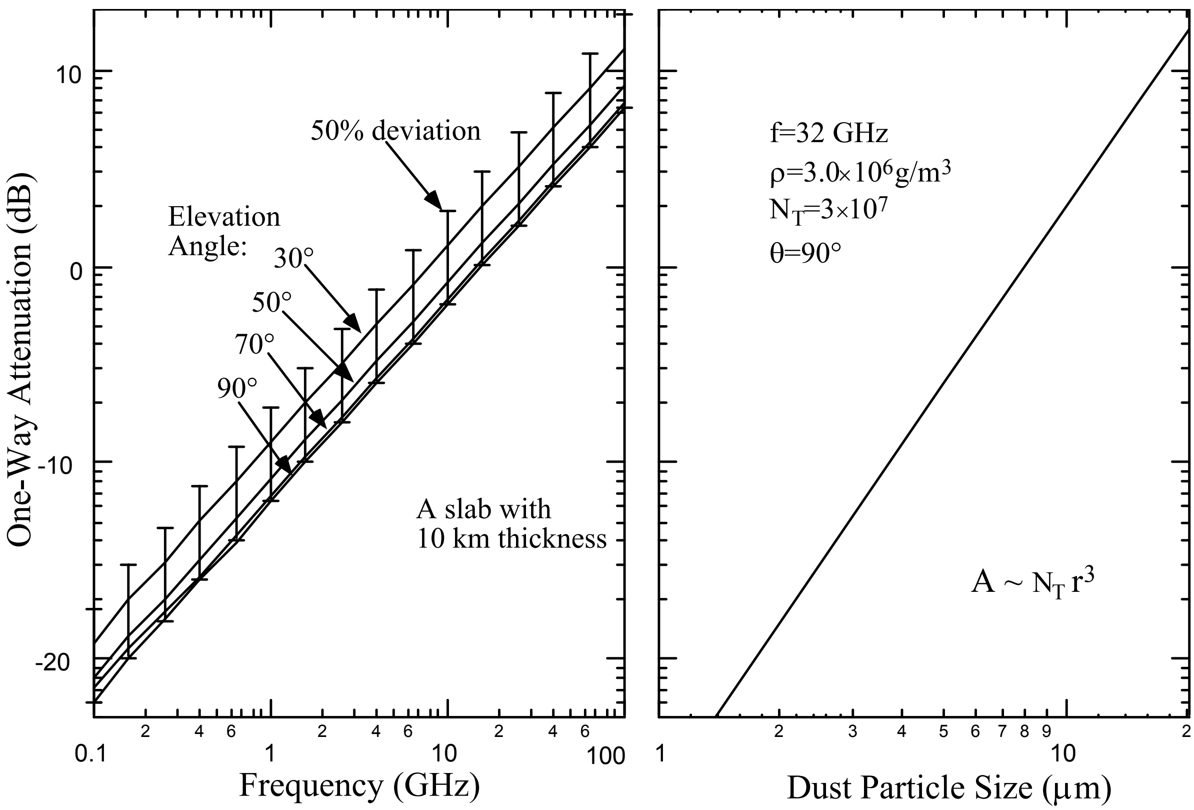

Figure 8-3. Martian Dust Attenuation for One-Way Radio Wave Path through a Dust Cloud for Various Elevation Angles and Dust Particle Sizes. To calculate the attenuation in left panel, a 10-km scale height and a 10-μm particle radius have been used. The attenuation deviations due to possible particle size variations (about ±50%) are also shown. Right panel shows the attenuation dependence on dust particle size for a 32-GHz radio wave signal with a zenith path.

8.7.6 Communication Blackout during the Martian Atmospheric Entry Phase

When a high-speed spacecraft enters the Martian atmosphere, a plasma sheath is formed in the front of the spacecraft due to the impacting ionization. This can cause a communication blackout, the extent of which depends on the communication frequency. A 30-s communication disruption was observed with the Mars Pathfinder (X-band), and a 1-minute blackout was experienced by both Viking Landers (UHF). If the frequency of a communications signal is higher than the critical frequency of the surrounding plasma, a radiowave can pass through the plasma sheath freely, and there will be no communication disruption. It is believed that this is the case at Ka-band.