

## 4. Martian Atmospheric Gaseous Attenuation

### 4.1 Introduction

When radio waves pass through an atmosphere, the waves suffer molecular absorption and scattering at centimeter and millimeter wavelengths [CCIR, 1986; Crane, 1981; Liebe, 1981; Waters, 1976]. At Earth, the gaseous absorption is due primarily to atmospheric water vapor and oxygen. There are 29 absorption lines for H<sub>2</sub>O (up through 1097 GHz) and 44 lines for O<sub>2</sub> (up through 834 GHz). Relatively narrow and weaker ozone (O<sub>3</sub>) lines are above 100 GHz. Between 120 GHz and 1097 GHz, water vapor plays a serious role in the radio wave attenuation. For frequencies greater than 70 GHz, other gases can also contribute an attenuation in the absence of water vapor; however, their spectral lines are usually too weak to affect propagation [Waters, 1976; Ulaby et al., 1981; Smith, 1982; Liebe, 1985].

The principal interaction mechanism between radio waves and gaseous constituents is molecular absorption from molecules. Accurate predictions of atmospheric attenuation can be determined from radiative transfer calculations. Absorption attenuation of radio waves results from a quantum level change in the rotational energy of molecules. Spectral line absorption occurs when a quantized system, such as a molecule, interacts with an electromagnetic radiation field and makes a transition between two quantum states of the system. The resonant frequency  $f_{lm}$  is [Waters, 1976; Ulaby et al., 1981]

$$f_{lm} = (E_l - E_m) / h \quad (4-1)$$

where  $E_l$  and  $E_m$  are energy levels of final and initial rotational energy state, and  $h$  is Plank's constant.

The general expression for the absorption coefficient  $\kappa(f, f_{lm})$  may be written as

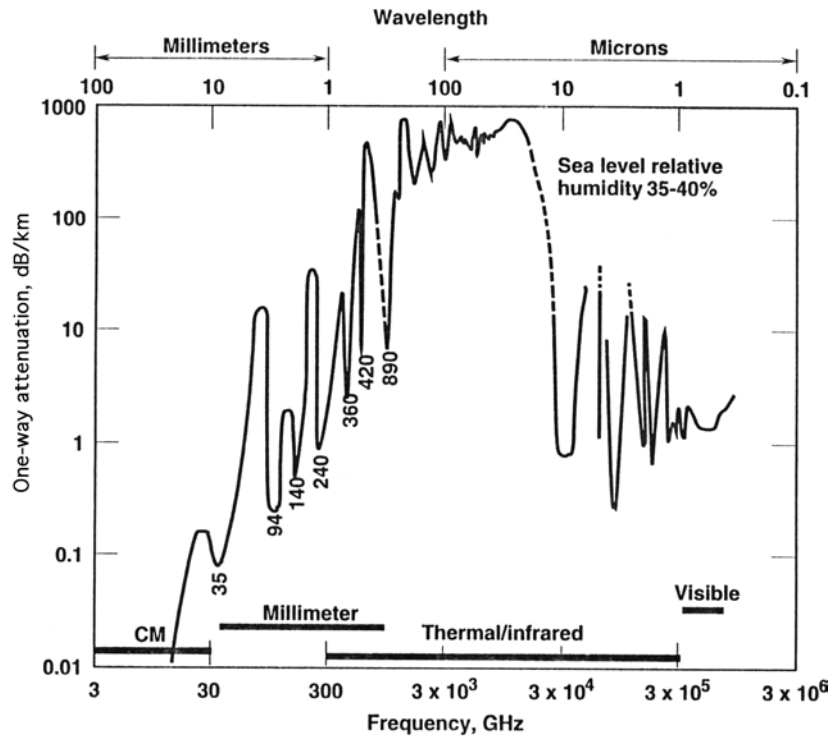
$$\kappa(f, f_{lm}) = \frac{8\pi^3 n_i f \mu^2}{3hcQ} \left\{ e^{-E_l/kT} - e^{-E_m/kT} \right\} g_l |\phi_{lm}|^2 L(f, f_{lm}) \quad (4-2)$$

where  $n_i$  is the number of absorbing molecules per unit volume for  $i$ th species,  $\mu$  the total dipole moment,  $g_l$  the statistical weight of the lower state,  $\phi_{lm}$  the transition matrix element,  $L(f, f_{lm})$  a function describing the line shape, and  $Q$  the partition function.

The volume absorption coefficient  $\kappa$  describes the interaction of radiation with the absorbing matter.  $\kappa$  is a function of the density of the absorbing substance, the atmospheric temperature, and the pressure. The coefficient has units of  $\text{cm}^{-1}$ . There is a relation of  $1 \text{ cm}^{-1} = 10^6 \log_{10} e \text{ dB/km} = 4.34 \times 10^5 \text{ dB/km}$ . Optical depth is an integration of the absorption coefficient  $\kappa$  along the path, which is dimensionless and can be expressed in a unit "neper" (logarithms to base  $e$ ) or dB (logarithms to base 10).  $1 \text{ Np} = 4.34 \text{ dB}$ .

Absorption of electromagnetic energy by gaseous molecules usually involves the interaction of electric or magnetic field-of-incident waves with an electric or magnetic dipole. H<sub>2</sub>O and O<sub>2</sub> are

the two major atmospheric constituents for radio wave absorption in the microwave band. The oxygen molecule has a permanent magnetic moment arising from two unpaired electron spins. Magnetic interaction produces a family of rotation lines around 60 GHz and an isolated line at 118.8 GHz. Water vapor is a molecule with an electric dipole. Through an electric interaction with the incident electric field, Water vapor produces rotational lines at 22.2, 183.3, and 323.8 GHz and at several frequencies in the far-infrared band. Each of the absorption spectral lines has a certain width because the energy levels vary when molecules are in motion. Among the various factors causing line broadening, atmospheric pressure broadening is the most important in the microwave band.



**Figure 4-1. Specific Gaseous Attenuation for a One-Way Horizontal Earth's Atmospheric Path in the Frequency Ranges from Microwave to Visible Light.**

Figure 4-1 shows the atmospheric attenuation at Earth surface as a function of frequencies (3 GHz to  $3 \times 10^6$  GHz) in a range from microwave to visible light (wavelength from 100 mm to 0.1  $\mu\text{m}$ ). Below 890 GHz, there are seven attenuation peaks, which are caused by  $\text{H}_2\text{O}$  and  $\text{O}_2$ . Between these absorption maxima, a number of low attenuation atmospheric windows exist for radio wave propagation. The center frequencies of the windows have been marked under each trough. The broad peaks between 890 GHz and 10,000 GHz are mainly due to water vapor. Above 10,000 GHz ( $\lambda > 30 \mu\text{m}$ ) from infrared to the optical range, there are some absorption lines due to  $\text{CO}_2$  and  $\text{N}_2$ .

Argon is a heavy, chemically inert gas. Both  $\text{CO}_2$  and  $\text{N}_2$  are also very stable gases. Because these molecules do not have an intrinsic electric or magnetic dipole, they do not absorb electromagnetic energy in the microwave frequency range. However, through collisions among themselves when the neutral density is reasonably high,  $\text{CO}_2$  and  $\text{N}_2$  can generate dipoles and

interact with radio waves. Other constituents (such as O<sub>3</sub>, SO<sub>2</sub>, and N<sub>2</sub>O) can also produce absorption lines. However, because their concentration is so small their contribution can be neglected in comparison with effects of H<sub>2</sub>O and O<sub>2</sub>.

## 4.2 Martian Gaseous Composition and Comparison With Earth Atmosphere

Attenuation from atmospheric molecules is heavily dependent on atmospheric structure, including its temperature, pressure, composition, abundance, etc. Because the gaseous attenuation for the Earth's atmosphere has been well studied and documented, we should compare the Martian atmospheric structure with Earth's. This comparison can help us understand Martian gaseous attenuation.

The atmosphere of Mars is quite different from that of Earth in composition, abundance, and altitude profiles [Hanson et al., 1977; Owen, 1992; Nier and McElroy, 1977; McElroy et al., 1977]. It is composed primarily of carbon dioxide, with small amounts of other gases. Some basic parameters are:

Surface Pressure: ~6.1 mb (variable)

Surface Density: ~0.020 kg/m<sup>3</sup>

Scale height: ~11.1 km

Average temperature: ~210 K

Diurnal temperature range: 184 K to 242 K

Mean molecular weight: 43.34 g/mole

Atmospheric composition (by volume):

Major:

carbon dioxide (CO<sub>2</sub>) — 95.32%

nitrogen (N<sub>2</sub>) — 2.7%

argon (Ar) — 1.6%

oxygen (O<sub>2</sub>) — 0.13%

carbon Monoxide (CO) — 0.08%

Minor (units in parts per million [ppm]):

water vapor (H<sub>2</sub>O) — ~100–400 (variable)

nitrogen Oxide (NO) — 100

neon (Ne) — 2.5

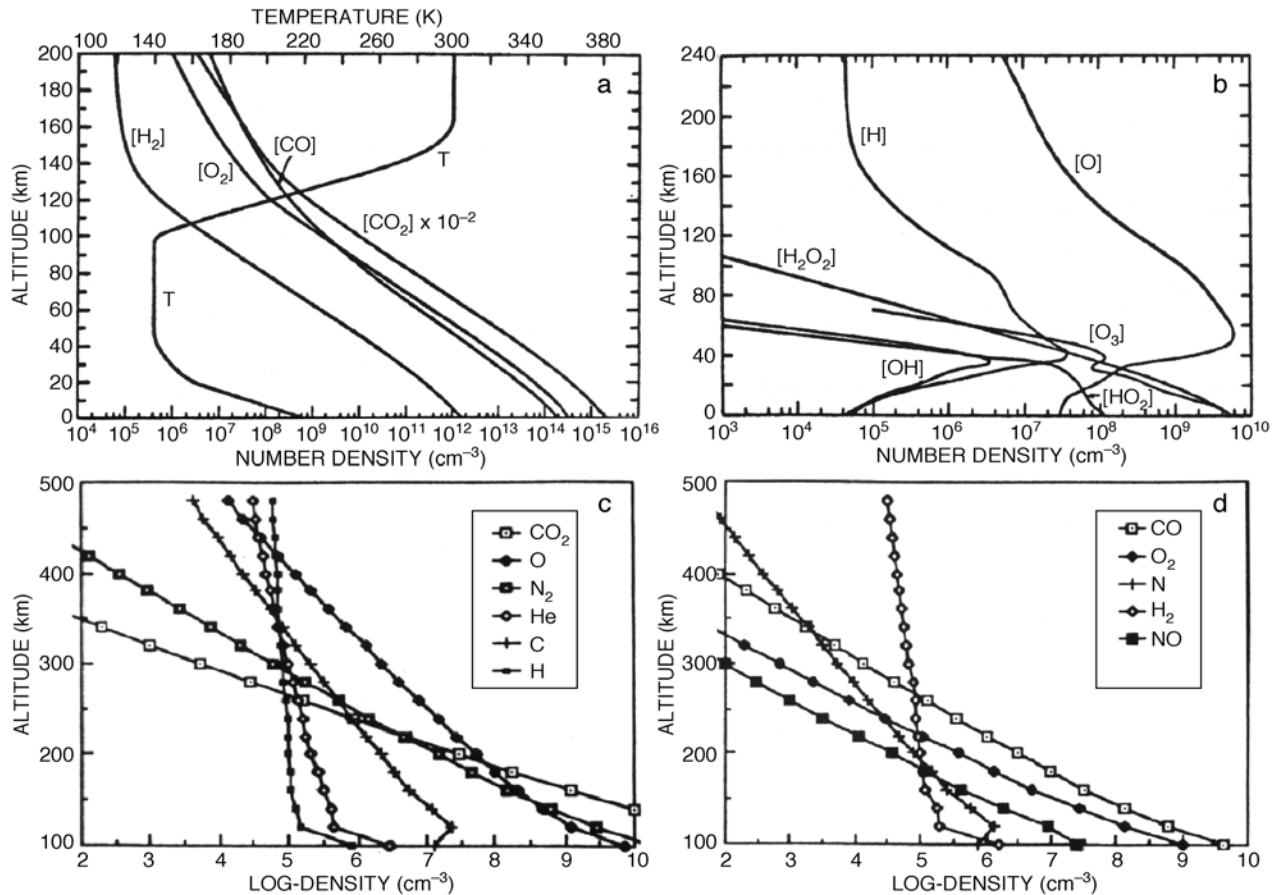
hydrogen-deuterium-oxygen (HDO) — 0.85

krypton (Kr) — 0.3

xenon (Xe) — 0.08

ozone (O<sub>3</sub>) — 0.04–0.2.

In Figure 4-2a, b, c, and d, we show altitude profiles of the Martian atmospheric density for all compositions in various altitude ranges [McElroy and McConnell, 1971a and b; Anderson, 1974; Chen et al., 1978; Fox and Dalgarno, 1979; Yung et al., 1977]. Most gases decrease in density with increasing altitude, although some light gases (such as atoms of O, H, N) have peak concentrations at higher altitudes.



**Figure 4-2. Martian Atmospheric Density Profiles for Various Constituents. a)  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{O}_2$ , and  $\text{H}_2$  in an altitude range between 0 and 200 km, b)  $\text{O}$ ,  $\text{H}$ ,  $\text{OH}$ ,  $\text{H}_2\text{O}_2$ , and  $\text{O}_3$  from 0 to 240 km, c)  $\text{CO}_2$ ,  $\text{O}$ ,  $\text{N}_2$ ,  $\text{He}$ ,  $\text{C}$ , and  $\text{H}$  between 100 and 500 km and d)  $\text{CO}$ ,  $\text{O}_2$ ,  $\text{N}$ ,  $\text{H}_2$ , and  $\text{NO}$  between 100 and 500 km.**

As a comparison, we also list parameters of the Earth atmosphere below [NOAA, 1976; Jursa, 1985]. The Earth's atmosphere consists of  $\text{N}_2$ ,  $\text{O}_2$ , and several minor gases. Their composition profiles are shown in Figure 4-3 [Junge, 1963].

Surface Pressure: 1013 mb (average)

Surface Density:  $\sim 1.29 \text{ kg/m}^3$

Scale height:  $\sim 9.5 \text{ km}$

Average temperature:  $\sim 300 \text{ K}$

Diurnal temperature range: 210 K to 320 K

Mean molecular weight: 28.61 g/mole

Atmospheric composition (by volume):

Major:

nitrogen ( $N_2$ ) — 78.09%

oxygen ( $O_2$ ) — 20.95%

argon (Ar) — 0.93%

carbon Dioxide ( $C O_2$ ) — 0.03%

Minor (units in ppm):

water vapor ( $H_2O$ ) — ~40–40,000 (variable)

neon (Ne) — 20

helium (He) — 5.2

methane ( $CH_4$ ) — 1.5

krypton (Kr) — 1.1

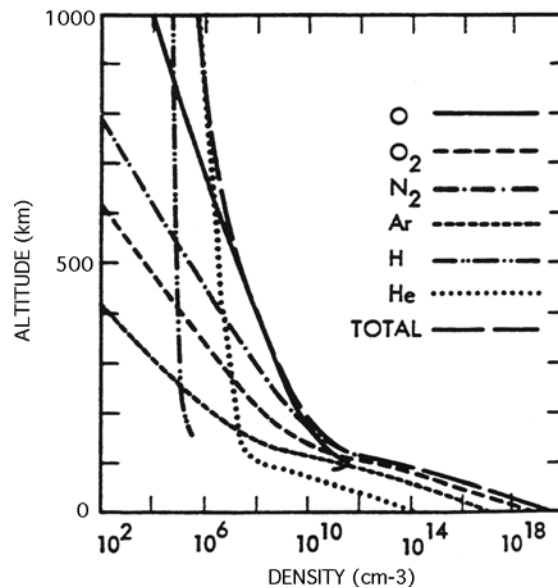
hydrogen ( $H_2$ ) — 1.0

nitrous oxide ( $N_2O$ ) — 0.6

carbon Monoxide (CO) — 0.2

ozone ( $O_3$ ) — < 0.05

xenon (Xe) — 0.09



**Figure 4-3. Earth Atmospheric Number Density Profiles for Individual Species. Above 120 km in altitude, scale heights are different for each species.**

From Figures 4-2 and 4-3, we can note that each constituent has a different scale height above the homopause. For example, at Mars, the scale height for  $CO_2$  is ~8 km, for oxygen ( $O_2$ ) is

~9 km, and water vapor has a variable scale height. Average scale height for all gases below the homopause is 11.1 km. At Earth, below 120 km, all constituents have similar scale heights ( $N_2$  ~8.7 km;  $O_2$  ~9.0 km; Ar ~9.2 km). Above 120 km (in the thermosphere), scale heights almost double for these gases. The atomic gases O and H occur as larger concentrations at 100 km altitude. In this study, because we are interested in the surface atmospheric attenuation, we only consider gaseous density and scale heights near the surface of planets.

To calculate Martian atmospheric attenuation, we need various atmospheric parameters. In Table 4-1, we have listed all surface average values for both Mars and Earth.

From Table 4-1, we can see that the Martian surface atmospheric pressure is only about 6/1000 of Earth's pressure. The Martian atmospheric average molar weight (gram/mole) is larger than at Earth's because the dominant gas,  $CO_2$ , has a larger mass than  $N_2$  at Earth. However, the Martian atmospheric mole volume is much larger (by three orders) than Earth's. Because of low pressure at Mars, the mass density of the Mars atmosphere is 61 times less than that of Earth. Thus, the average number density is also smaller by about 2 orders of magnitude. The scale heights at both planets are only slightly different.

**Table 4-1. Surface Atmospheric Parameters at Mars and Earth**

Planets	$P$ , pressure (mb)	$T$ , temperature (K)	$M$ , mean molecule weight	$\rho$ , mass density ( $kg/m^3$ )	$N$ , number density ( $m^{-3}$ )	$V_m$ , mole volume ( $m^3/kmole$ )	$H$ , scale height (km)
Mars	6.1	210	43.34 g/mole	0.021	$2.85 \times 10^{23}$	$2.1 \times 10^3$	~11.1
Earth	1013	300	28.61 g/mole	1.29	$2.7 \times 10^{25}$	22	~9.5

In order to make a more accurate parameter comparison, we have defined:

$F_i$ : fraction by volume for  $i$ th species (air mix ratio)

$\beta_i$ : fraction by mass for  $i$ th species

$p_i$ : pressure for  $i$ th species;  $P$ : pressure for all species (mb)

$n_i$ : number density  $i$ th species ( $cm^{-3}$ );  $N$ : sum for all species

$\rho_i$ : mass density  $i$ th species;  $\rho$ : mass density for all species ( $gram/m^3$ )

$M_i$ : molar weight (i.e., gram/mole) for  $i$ th species;  $M$ : mean molecule weight for all species (gram/mole)

$V_m$ : air volume for one kilomole at surface ( $m^3/kmole$ )

$N_A$ : Avogadro constant;  $k_B$  Boltzmann constant;  $R_A$ : Universal gas constant

$T$ : temperature (K);  $H$ : scale height (km), which is defined as  $N=N_0e^{-z/H}$

On the basis of gas dynamic theory, the following fundamental relations exist between these parameters in a multi-species atmosphere:

$$p_i = n_i k_B T, P = N k_B T, P = \sum_i p_i \quad (4-3)$$

$$F_i = \frac{p_i}{P} = \frac{n_i}{N}, N = \sum_i n_i \quad (4-4)$$

$$\beta_i = \frac{\rho_i}{\rho} = \frac{F_i M_i}{M}, M = \sum_i F_i M_i, \quad (4-5)$$

$$\rho_i = \frac{n_i M_i}{N_A} = \frac{F_i M_i N}{N_A} = \frac{F_i M_i \rho}{M} = \beta_i \rho, \rho = \frac{NM}{N_A}, \rho = \sum_i \rho_i \quad (4-6)$$

$$n_i = \frac{\rho_i}{k_B T} = \frac{F_i \rho N_A}{M} = \frac{\rho_i N_A}{M_i}, \quad (4-7)$$

$$V_m = \frac{N_A}{\sum_i n_i} \quad (4-8)$$

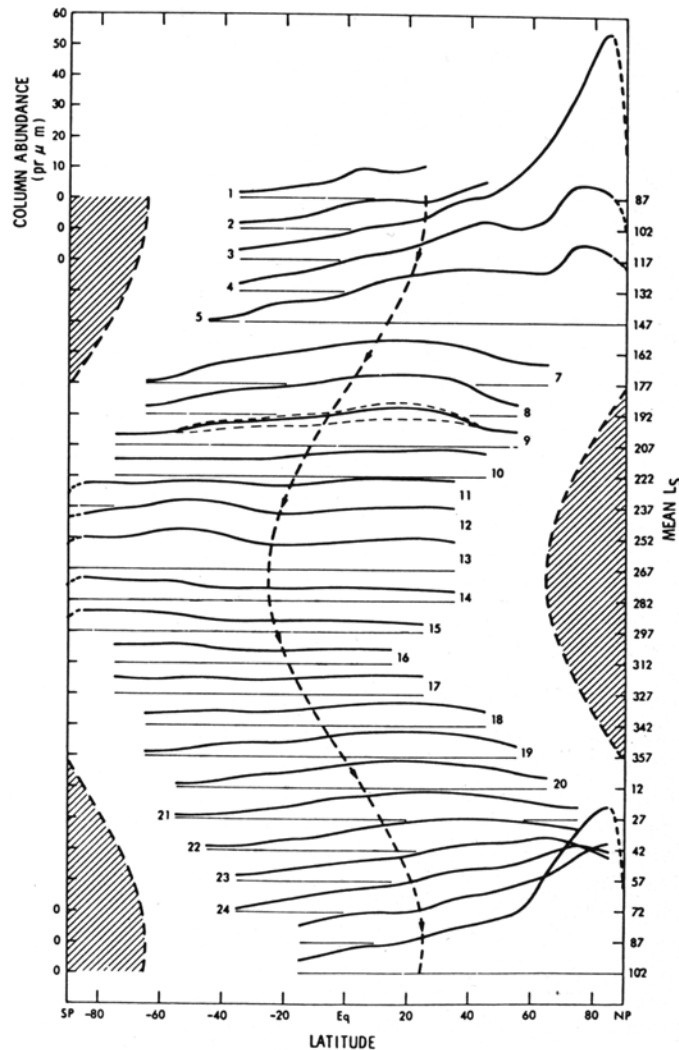
Starting from parameters  $F_i$ ,  $M_i$ , and  $\rho$ , we have derived parameters,  $M$ ,  $\beta_i$ ,  $\rho_i$ , and  $n_i$ . These parameters for six main compositions are listed in Table 4-2. In the table, for each species, the second to sixth columns are, respectively, molecular weight (gram molecule),  $M_i$ ; atmospheric mixing ratio by volume,  $F_i$ ; fraction by weight,  $\beta_i$ ; gaseous mass density,  $\rho_i$ ; and number density,  $n_i$ .

**Table 4-2. A Comparison of Atmospheric Compositions Near the Surfaces of Mars and Earth**

Gaseous Composition		Mars Surface (6.1 mb, 210 K)				Earth Surface (1013 mb, 300 K)			
mole- cule	$M_i$ , Weight (g/mole)	$F_i$ , mix ratio (by volume)	$\beta_i$ , fraction in mass	$\rho_i$ , mass density (g/m <sup>3</sup> )	$n_i$ , number density (cm <sup>-3</sup> )	$F_i$ , mix ratio (by volume)	$\beta_i$ , fraction in mass	$\rho_i$ , mass density (g/m <sup>3</sup> )	$n_i$ , number density (cm <sup>-3</sup> )
CO <sub>2</sub>	44.02	95.32%	96.77%	20.32	2.8x10 <sup>17</sup>	400ppm	615ppm	0.8	1.1x10 <sup>16</sup>
N <sub>2</sub>	28.02	2.7%	1.74%	0.365	7.8x10 <sup>15</sup>	78.09%	76.5%	986.9	2.1x10 <sup>19</sup>
Ar	39.96	1.6%	1.48%	0.311	4.7x10 <sup>15</sup>	0.93%	1.3%	16.8	2.6x10 <sup>17</sup>
O <sub>2</sub>	30.00	0.13%	900ppm	0.02	3.8x10 <sup>14</sup>	20.95%	21.97%	283.7	5.7x10 <sup>18</sup>
CO	28.00	800ppm	517ppm	0.011	2.3x10 <sup>14</sup>	0.2 ppm	0.2ppm	2.6x10 <sup>-4</sup>	5.6x10 <sup>12</sup>
H <sub>2</sub> O	18.02	300ppm	125ppm	0.0026	8.8x10 <sup>13</sup>	1.0%	0.63%	8.1	2.7x10 <sup>17</sup>

\* ppm = part(s) per million.

From Table 4-2 we can see that except for CO<sub>2</sub> and CO, all gaseous densities at Mars are less than that at Earth. Even though CO<sub>2</sub> is the dominant gas at Mars, its density is only 25 times more than at Earth. Water vapor abundance is much more variable at both planets. At Mars water vapor abundance ranges from 100 to 400 ppm with an average of 300 ppm, varying with season and latitude as shown in Figure 4-4 [Doms, 1982; Farmer and Doms, 1979]. The dominant feature was found to be the large amount of water vapor over the residual northern cap in the northern summer. At Earth the water vapor abundance is from 40 to 40,000 ppm with an average value of 10,000 ppm.



**Figure 4-4. Distribution of Water Vapor in the Martian Atmosphere by Latitude and Season (Planetocentric Longitude). The scale of water vapor abundance is shown in the left top. The dashed line through the center of the figure indicates the latitude of the subsolar point. The main feature is the large amount of water vapor over the residual northern cap in the northern summer (from Farmer and Doms, 1979).**



Finally, as a comparison, Table 4-3 lists various ratios of atmospheric compositions between Earth and Mars. These ratios are important scale factors related to atmospheric attenuation at both planets.

Ratios for  $\beta_i$  for all species are 1.51 times greater than ratios for  $F_i$  because Earth's mean molecular weight is less than Mars' by 1.51. Ratios of Earth relative to Mars for  $\rho_i$  (gaseous mass density) are the same as for  $n_i$  (number density) because  $\rho$  is proportional to  $n$ . There is much more  $N_2$ ,  $O_2$ , and  $H_2O$  at Earth than at Mars (by factors of  $10^3$ – $10^4$  in density). We have more interest in the ratios of  $\rho_i$  and  $n_i$ , in oxygen and water vapor between Earth and Mars because both gases have strong absorption on Earth. At Mars the amounts of  $O_2$  and  $H_2O$  are very small, and the question is how much smaller the atmospheric attenuation can be compared to Earth.

**Table 4-3. Ratios of Atmospheric Constituents between Earth and Mars**

<b>Ratios (Earth/Mars)</b>	<b>CO<sub>2</sub></b>	<b>N<sub>2</sub></b>	<b>Ar</b>	<b>O<sub>2</sub></b>	<b>CO</b>	<b>H<sub>2</sub>O</b>
for $F_i$ (fraction by volume)	$4.2 \times 10^{-4}$	28.9	0.58	161	$2.4 \times 10^{-4}$	33.3
for $\beta_i$ (fraction by weight)	$6.4 \times 10^{-4}$	44	0.88	244	$3.9 \times 10^{-4}$	50.4
for $\rho_i$ and $n_i$ (density)	0.04	2704	54	$1.4 \times 10^4$	0.024	3068

### 4.3 Martian Atmospheric Absorption Effects on Microwaves

CO<sub>2</sub> and N<sub>2</sub> are the dominant gases in the Martian atmosphere, and these gases have little absorption in the microwave range. Consequently, O<sub>2</sub> and H<sub>2</sub>O cause most of the attenuation. There are 10 strong absorption lines for H<sub>2</sub>O below 450 GHz and 39 lines for O<sub>2</sub> between 50 and 70 GHz. Below 300 GHz, ozone (O<sub>3</sub>) has 65 weak and narrow absorption lines. There are more than a thousand spectral absorption lines in the microwave and infrared frequency bands for all species. Precise measurements in frequencies and intensities for these lines have been well documented in both the Earth atmosphere and the laboratory [Liebe, 1981; U.S. Department of Commerce, 1968; Waters, 1976; Crane, 1981; Gordy and Cook, 1984].

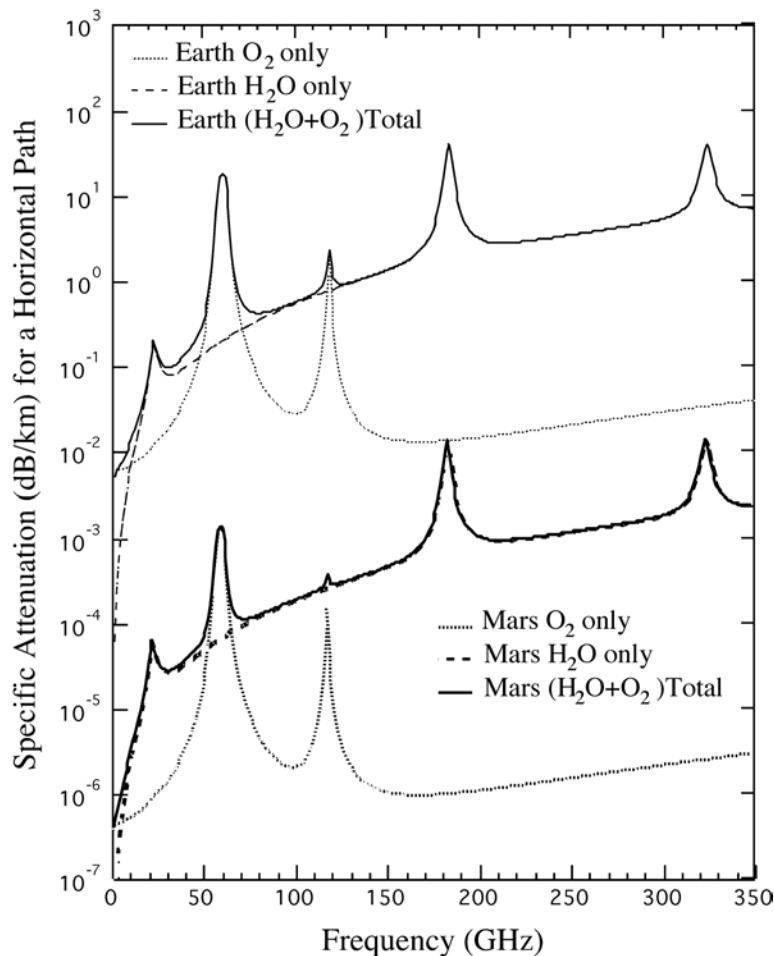
We have calculated the total atmospheric attenuation, using equations and procedures developed by Waters [1976], Liebe [1981], and Ulaby et al. [1981]; using planetary atmospheric parameters listed in Tables 4-1, 4-2, and 4-3; and using standard spectral intensity measured in the laboratory. The total Martian atmospheric absorption coefficient is a combination of both H<sub>2</sub>O and O<sub>2</sub>.

$$\kappa_a(f) = \kappa_{H_2O}(f) + \kappa_{O_2}(f), \text{ dB/km} \quad (4-9)$$

Figure 4-5 shows the calculated specific atmospheric attenuation for a horizontal path at the Earth surface and the Mars surface. The plots only give a microwave frequency range (<350 GHz). Above 350 GHz, absorption spectral lines from all species are so complicated that we do not describe them. The dotted lines are for O<sub>2</sub> absorption only. There are two peaks at 60 and

118.8 GHz. The dashed lines are for water vapor only. The absorption peaks are at 22.2, 183.3, and 323.8 GHz. The solid lines are for both combined.

We found that the attenuation values due to oxygen at Mars are reduced by a factor of  $1.4 \times 10^4$  relative to Earth. This is the ratio  $\rho_{O_2}$  (oxygen density ratio) between the Earth's atmosphere and the Mars atmosphere at the surface. The water vapor attenuation at Mars is lower by a factor of 3068 than at Earth. This calculation is also dependent on the types of spectral-line shape function chosen [Van Vleck, 1987; Waters, 1976]. There are several types of line shape functions, such as Lorentzian, van Vleck-Weisskopf, and kinetic-line (Gross) shape. Here we have used a kinetic-line shape. We have also not considered the Zeeman effect of the spectral line of the  $O_2$  molecules because Mars has a very weak magnetic field.



**Figure 4-5. Gaseous Specific Absorption Attenuation by Water Vapor, Oxygen, and Both at the Surface of Earth and Mars. The upper three thin lines are for attenuation at Earth, while the lower three thick lines are for Mars.**

The optical depth (or opacity) along the zenith,  $\tau_0$ , is defined as an integration of the absorption coefficient over a vertical path from the surface to infinity:

$$\tau_0 = \int_0^{\infty} \kappa(z) dz \quad (4-10)$$

This is equivalent to integrating all resonant particles along a column because the absorption coefficient is proportional to the particle number density. Actually, the column number for each species is equivalent to a slab with a density of  $N_0$  and a thickness  $H_0$ , where  $H_0$  is the scale height of the species, because

$$\int_0^{\infty} N dz = \int_0^{\infty} N_0 e^{-z/H_0} dz = N_0 H_0 \quad (4-11)$$

Thus, for each species, the total zenith attenuation (dB) is the product of the surface specific attenuation (dB/km) plotted in Figure 4-5 and the scale height,  $H_0$ (km), for an isothermal atmosphere.

At Ka-band (32 GHz), the total zenith attenuation of the Martian atmosphere is estimated to be less than 0.01 dB, assuming that water vapor has a scale height of 10 km. In comparison, in the Earth's atmosphere the attenuation is about 0.3 dB. At higher frequencies, (for example, 100 GHz) the Martian atmospheric attenuation increases to 0.1 dB. Such a small attenuation is negligible for telecommunication.

For an oblique path with zenith angle  $\theta$ , when  $\theta < 70^\circ$ , the opacity may be expressed as

$$\tau(\theta) = \tau_0 \sec \theta \quad (4-12)$$

Thus, an oblique path will have greater attenuation.

On the other hand, gaseous absorption also can be used as a remote-sensing tool to study Martian atmospheric structures. In the near-infrared and infrared regions there are many absorption lines caused by CO, CO<sub>2</sub>, and H<sub>2</sub>O. The infrared spectrometer (ISM) on board the Soviet Phobos 2 spacecraft made spectral measurements of the Martian atmosphere [Combes et al., 1991]. There are strong absorption lines at 1.14, 1.84, and 2.55  $\mu\text{m}$  for H<sub>2</sub>O; at 2.35 and 5  $\mu\text{m}$  for CO; and at 2.0 and 2.72  $\mu\text{m}$  for CO<sub>2</sub>. These results will help us to determine the atmospheric constituents. One application is to use measurements of the column density of CO<sub>2</sub> between the spacecraft and the Martian surface to derive surface pressure and topography maps [Combes et al., 1991].

#### 4.4 Summary and Recommendations

Mars has a much lower atmospheric gaseous attenuation than Earth in the microwave frequency band because of much lower abundances of uncondensed H<sub>2</sub>O and O<sub>2</sub> in its atmosphere. Preliminary calculations show that Martian gaseous absorption is at least a factor of 3000 lower than at Earth. For a radio wave with a frequency of 100 GHz through a vertical atmospheric path, the attenuation is estimated to be less than 0.1 dB. However, this calculation is only based on Martian surface composition values. An accurate calculation requires scale heights for each species at different altitudes in the Martian atmosphere. So far we do not have such information. We also do not know how severe the gaseous attenuation can be in the infrared and visible frequency range because of the very complicated spectral lines in these frequencies.

The Martian atmosphere is dominated by CO<sub>2</sub> and N<sub>2</sub>. Under normal conditions, these gases do not have electric or magnetic dipoles, so they do not absorb electromagnetic energy from radio waves. However, they may generate dipoles through collisions and interact with waves in the higher frequency range. We often see that both gases having many absorption lines in the infrared and visible ranges in the Earth atmosphere. It should be researched whether or not CO<sub>2</sub> and N<sub>2</sub> at Mars can generate such dipoles.

In this calculation, we have used an average surface value (300 ppm) for Martian water vapor. We have not used a maximum value (400 ppm) that corresponds to the worst case. The error bars can be as large as 33%. Actually, the exact amount of Martian atmospheric water vapor is still controversial, although it is known to depend strongly on latitude and season. 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 of two.

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