Comparative Analysis of Communication Links Between Earth-Moon and Earth-Mars

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Abstract. Deep space exploration is one of the three major aerospace activities of mankind in the new century, and deep space exploration is inseparable from the research on technologies of deep space communication. In the future, the goal of human space exploration will be extended to more and farther stars, analyzing the basic characteristics of the deep space communication link channel, and studying the specific communication problems of the nearer stars will be the necessary basis for the research of deep space communication. Focus on the characteristics of the communication channel between Earth-Moon and Earth-Mars. According to the influential parameters of different communication link, the impact of the communication link of Ka frequency band and below is simulated and analyzed to clarify each range of loss and the effect of each parameter, and the relevant channel characteristics of deep space communication link are obtained.

Keywords: Deep space communication · Channel modeling · Link budget · The lunar environment · Martian environment

1 Introduction

The communication between the probe in deep space and the earth ground station is called deep space communication. At present, deep space exploration is one of the three major human activities in the aerospace field. It integrates many high-tech technologies in the aerospace field. It is of great significance for mankind to explore deeper space, as well as to learn and use the cosmic resources. The United States is the first country to carry out deep space exploration activities, which is currently the only country that has successfully probed the sun and the eight planets of the solar system. In recent years, its exploration activities have continued to develop. The Curiosity successfully landed on the surface of Mars in 2012, and the New Horizon in 2015 flew over Pluto for the first time, NASA announced the evidence of liquid water in Mars in the same year; India successfully achieved the first Mars exploration in 2013, and launched a moon exploration project in 2019; in 2016, China's Mars exploration mission was officially established. The

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achievements of the major aerospace nations and organizations and the planning of the new era signify that international deep space exploration has entered a new stage [1].

Deep space communication are essential for the deep space exploration missions, 1 many space agencies and researchers have been making efforts in the long distance weak signal transmissions enhancement, such as the free space optical communications, 2 large scale antenna array. 3 Because of the slowly development and great difficulties of such physical solutions, it is important for us to pay more attention on the interplanetary networking. 4 Derived from the needs of national development strategy, there might be more and more robot/manned spacecraft to explore further space in the Solar System, which would gradually construct the sparse interplanetary networks to provide end-to-end wireless communications with high quality of service [2].

Deep space exploration is inseparable from deep space communication technology. When humans extend the scope of aerospace activities to the moon and Mars, there will be many technical difficulties in the communication channel, such as low coverage and huge losses due to the distance and the impact of the cosmic environment. The deep space exploration mission marked by the exploration of moon and Mars has greatly improved the requirements for the reliability and real-time performance of the ground-air communication, the adjustment capability of the multimedia type service, the processing capacity of the transmitted data, and the throughput rate. Analyzing the basic characteristics of the link channel, and studying the specific problems of nearer astral communication will be the necessary foundation for the development of deep space communication research.

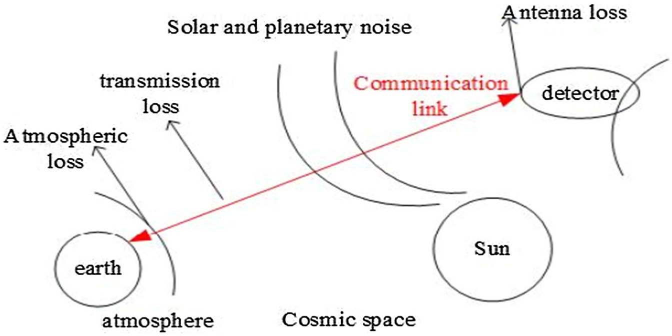

Fig. 1. The conceptual diagram of the deep space communication link

The conceptual diagram of the deep space communication link is shown in Fig. 1. Compared with the daily mobile communication, the radio signal of deep space communication has to traverse a longer distance, the path loss of the link is very serious, and the environmental impact of the surface of the star and the surface of the earth must also be considered. Here we focus on the characteristics of the communication channel between the Earth-Moon and the Earth-Mars. According to the different communication link impact parameters, the impact of the communication link in the Ka frequency band and lower frequency bands are simulated and analyzed. Clarify the value range of each loss and the effect of each parameter, and obtain the characteristics of the deep space communication link channel represented by the Earth-Moon and Earth-Mars links.

2 Similarities and Differences in the Communication Environment Between Earth-Moon and Earth-Mars

The distance between the earth and the moon is much shorter than the distance between the earth and Mars. The distance between the earth and Mars is nearly 6 * 107 km, but the distance between the earth and the moon also reaches 105 km. The communication delay between the earth and the Mars has reached several minutes or even more than ten minutes, but between the earth and the moon it is relatively small, only about one second at the maximum. At the same time, there is planetary convergence between Earth and Mars, which can be divided into superior conjunction and inferior conjunction [3]. During the superior conjunction, the communication link between Earth and Mars reached the longest. At this time, the distance between the signal transmission path of the communication link and the sun is the shortest, and the charged particles ejected by the solar wind are the most affected, which will increase the noise temperature of the communication system, causing the spectrum spread of the signal and the fluctuation of the phase and amplitude, sometimes will cause the link to be interrupted. But during the inferior conjunction, the distance between Earth and Mars is the shortest, the loss caused by space transmission is minimal, and the influence of solar activity is also small, the communication quality is the best.

In addition, the surface of moon is not covered by the atmosphere, so there will be no atmospheric fading during the transmission of radio waves. There are moon seas and land on the surface of moon, and there are no mountains, lakes and oceans, the environment is relatively simple; and compared to earth, the radius of moon is small, the curvature is bigger. The radius of Mars is about half that of the Earth, and the rotation period is similar to that of the Earth. The surface of Mars is covered by the atmosphere, but the composition is very different from the earth and relatively thin, which makes the dust difficult to fall, so it is easy to cause large-scale sandstorm and have a great impact on the quality of communications.

3 Analysis and Simulation of Mars Channel Fading Characteristics

3.1 Atmospheric Loss in the Mars Channel

Mars has an atmosphere with a composition that differs greatly from that of Earth. Table 1 compares the composition parameters of the atmosphere of Mars and the atmosphere of Earth [4]. It can be seen from the table that the water vapor content in the Martian atmosphere is extremely low, most of which is carbon dioxide. Therefore, when the communication link signal is transmitted through the Martian atmosphere, the fading is mainly caused by the absorption of radio wave energy by water vapor and oxygen molecules. Since the calculation method is similar to the earth's atmospheric loss, here we can refer to the model of the earth's atmospheric loss, and refer to the ITU-R recommendation for the atmospheric loss calculation method for the frequency band below 350 GHz to analyze the characteristics of the Martian atmosphere. For frequency below 54 GHz, the formula for calculating the loss coefficient (dB/km) of dry air is:

$$\gamma_0 = \left[\frac{7.2 r_t^{2.8}}{f^2 + 0.34 r_p^2 r_t^{1.6}} + \frac{0.62\xi_3}{(54-f)^{1.16\xi_1} + 0.83\xi_2}\right] f^2 r_p^2 \times 10^{-3} \tag{1}$$

Where f is frequency, the unit is GHz; p is pressure, the unit is hPa; t is temperature, the unit is °C; $r_p = p/1013$, $r_t = 288/(273 + t)$; ρ is water vapor density, the unit is g/m^3.

Table 1. Parameters of the atmosphere between Mars and Earth

Star	Temperature/K	Mean atmospheric pressure/Pa	Ingredient content (%)				
			O_2	N_2	H_2O	CO_2	Ar
Earth	300	101300	20.95	78.09	0.25	0.04	0.93
Mars	210	610	0.14	1.9	0.021	95.9	2.0

For frequency below 350 GHz, the calculation formula for the water vapor loss coefficient (dB/km) is:

$$\begin{aligned}\gamma_w = & \Big[\frac{3.98\eta_1 e^{2.33(1-r_t)}}{(f-22.235)^2 + 9.42\eta_1^2} g(f,22) + \frac{11.96\eta_1 e^{0.7(1-r_t)}}{(f-183.31)^2 + 11.14\eta_1^2} \\ & + \frac{0.081\eta_1 e^{6.44(1-r_t)}}{(f-321.226)^2 + 6.29\eta_1^2} + \frac{3.66\eta_1 e^{1.6(1-r_t)}}{(f-325.153)^2 + 9.22\eta_1^2} \\ & + \frac{25.37\eta_1 e^{1.09(1-r_t)}}{(f-380)^2} + \frac{17.4\eta_1 e^{1.46(1-r_t)}}{(f-448)^2} \\ & + \frac{844.6\eta_1 e^{0.17(1-r_t)}}{(f-557)^2} g(f,557) + \frac{290\eta_1 e^{0.41(1-r_t)}}{(f-752)^2} g(f,752) \\ & + \frac{83328\eta_2 e^{0.99(1-r_t)}}{(f-1780)^2} g(f,1780)\Big] f^2 r_t^{2.5} \rho \times 10^{-4}\end{aligned} \tag{2}$$

For each parameter appearing in formula (1) and formula (2), there are:

$$\xi_1 = \varphi\left(r_p, r_t, 0.0717, -1.8132, 0.0156, -1.6515\right) \tag{3}$$

$$\xi_2 = \varphi\left(r_p, r_t, 0.5146, -4.6368, -0.1921, -5.7416\right) \tag{4}$$

$$\xi_3 = \varphi\left(r_p, r_t, 0.3414, -6.5851, 0.2130, -8.5854\right) \tag{5}$$

$$\varphi(r_p, r_t, a, b, c, d) = r_p^a r_t^b \exp[c(1 - r_p) + d(1 - r_t)] \tag{6}$$

$$\eta_1 = 0.955 r_p r_t^{0.68} + 0.006\rho \tag{7}$$

$$\eta_2 = 0.735 r_p r_t^{0.5} + 0.0353 r_t^4 \rho \tag{8}$$

$$g(f, f_i) = 1 + \left(\frac{f - f_i}{f + f_i}\right)^2 \tag{9}$$

The atmospheric temperature of Earth stays constant at 300K and that of Martian remains stable at 210K. Referring to the parameters in Table 1, the characteristic loss coefficient of the Martian atmosphere can be calculated through the above formulas. Fig. 2 shows the relationship between atmospheric loss coefficient and frequency.

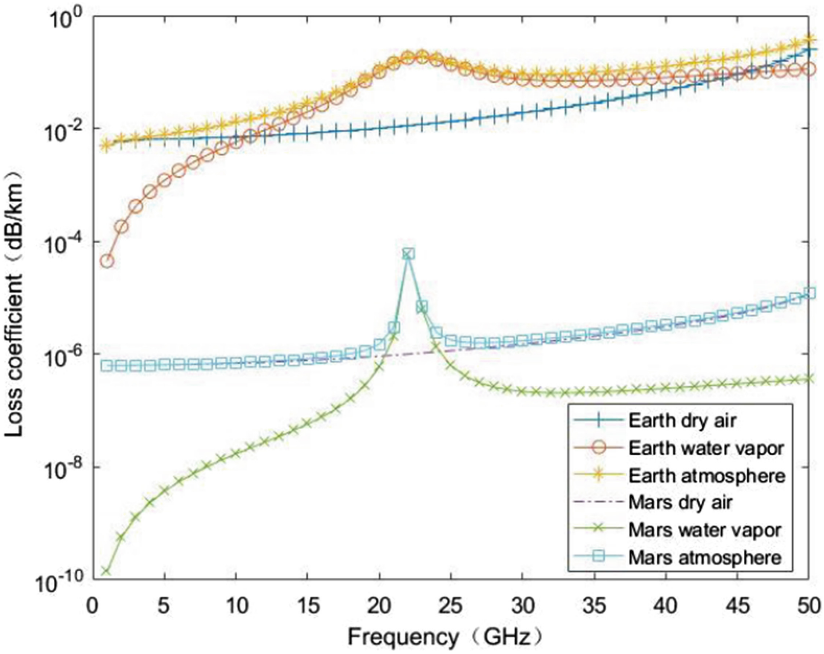

Fig. 2. Relationship between atmospheric loss coefficient and frequency on earth and Mars

It can be seen from the graph that the loss coefficient of the Martian atmosphere is small compared to the earth's atmospheric loss coefficient, and the loss caused to the communication link is basically relatively smaller. At the same time, the curve of the Martian and the earth's atmospheric fading coefficient has reached an extreme value around 22 GHz. By observing the changes of the dry air loss coefficient and the water vapor loss coefficient in the earth and Mars atmospheric fading coefficient, it can be found that around 22 GHz, the loss coefficient of dry air does not produce any special changes, and the loss coefficient curve of water vapor rises sharply to the extreme value.

3.2 Sandstorm Loss in the Mars Channel

Sandstorms are a significant feature of the weather environment on the surface of Mars. When sandstorms occur, the visibility on the surface of Mars is usually only about 4 m–10 m. Table 2 gives a comparison of the parameters of the sandstorms between the earth and Mars [5].

Table 2. Parameters of sandstorms between Earth and Mars

Star	Sand density/m^{-3}	Mass density/ (g/m^3)	Average size of sand particles/μm	Maximum size of sand particles/μm	Path length/km
Earth	10^8	$2.6 * 10^6$	30–40	80–300	10
Mars	$3 * 10^7$	$3 * 10^6$	1–10	20	10

According to the relevant parameters in Table 2, the average size of the particles can be used to calculate the characteristic decline of the dust on the surface of Mars. Let the average radius of the dust particles be r, the unit is m; Ld is the characteristic fading of the dust on the surface of Mars, the unit is dB/km, there is a calculation expression:

$$L_d = \frac{1.029 \times 10^6 \varepsilon''}{\lambda[(\varepsilon' + 2)^2 + (\varepsilon'')^2]} N_T r^3 \tag{10}$$

Where λ is the wavelength of the radio wave, the unit is m; ε' and ε'' are the real and imaginary parts of the average dielectric constant of the dust particles; N_T is the density of the sand particles in the dust, the unit is m^{-3}. According to the relevant measured results, the values of and are 4.56 and 0.251 [6]. If we take several special frequency points: 1 GHz, 5 GHz, 10 GHz, 20 GHz and 40 GHz, and change the value of the dust particle radius, then the relationship between the characteristic dust fading and the dust particle radius and frequency can be obtained, as shown in Fig. 3.

It can be seen from the curve in the Fig. 3 that as the frequency increases, the loss caused by the Martian sandstorm will also increase, and when the frequency is kept constant, for larger sand particle radius, the sandstrom characteristic fading value will also be bigger. At the same time, the change of the communication distance will also affect the value of the sandstorm fading.

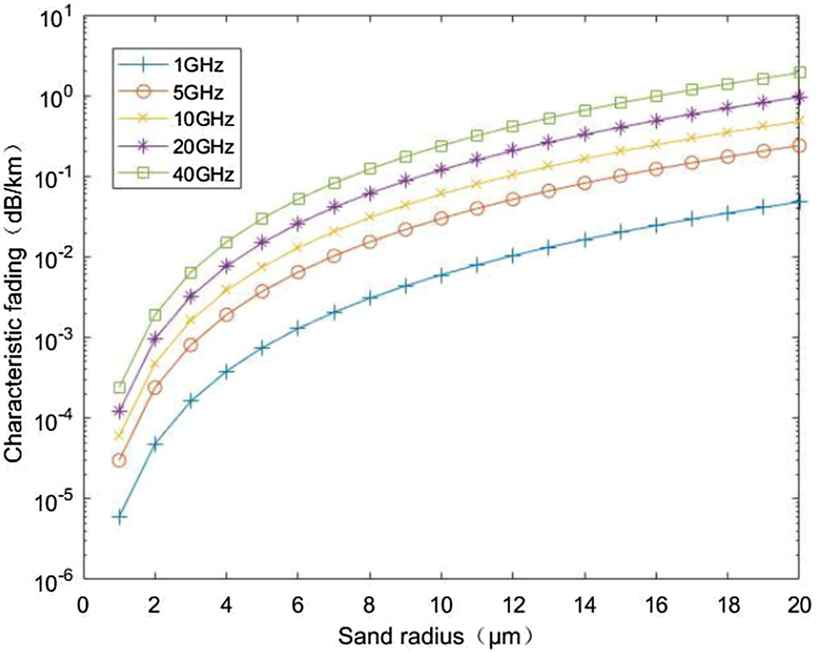

Fig. 3. Relationship between the characteristic fading of Martian sandstorm and the size of sand particles or frequency

4 The Characteristics of Radio Wave Transmission on the Surface of Moon and Mars

Compared with earth, the radius of Mars and moon has a small curvature and a large radius, and the problem of long-distance diffraction needs to be considered. At the same time, the Moon has large undulating terrain such as the moon valley, and there are obstacles of various shapes on the surface of Mars. In addition, because there is a thin atmosphere on the surface of Mars and moon has no atmosphere, so the influence of the refraction of the atmosphere during the transmission of radio waves is small or almost none. Due to the actual terrain conditions and the complex shape of obstacles, the transmission loss analysis of surface waves is divided into three stages: free transmission loss, surface reflection loss and diffraction loss. The simplified segmented model is used to study the radio wave transmission characteristics in the surface of the star [7, 8]. Here we mainly analyze the loss changes of reflection and diffraction.

When there is a signal on the reflection path on the surface of the star, for the reflected signal, the rough surface of the star will scatter part of the signal, and the reflection coefficient can be corrected by introducing the scattering loss coefficient. Let a be the scattering loss coefficient, with the expression:

$$a = \exp\left[-8\left(\frac{\pi\sigma_H \sin\psi}{\lambda}\right)^2\right] J_0\left[8\left(\frac{\pi\sigma_H \sin\psi}{\lambda}\right)^2\right] \tag{11}$$

Where σ_H is the standard deviation of the undulations on the surface of the star, and $J_0[\cdot]$ is the first kind of zero-order Bessel function, and Ψ represents the glancing angle. If the glancing angle is set to 10°, the value of the scattering loss coefficient can be estimated. The relationship between the standard deviation of the surface fluctuation of the star and the communication frequency is shown in Fig. 4. It can be seen from the curve that as the frequency increases, the scattering loss coefficient decreases to near zero; at the same time, for a larger surface fluctuation standard deviation, the terrain is not flat, and the energy of radio wave scattering is more.

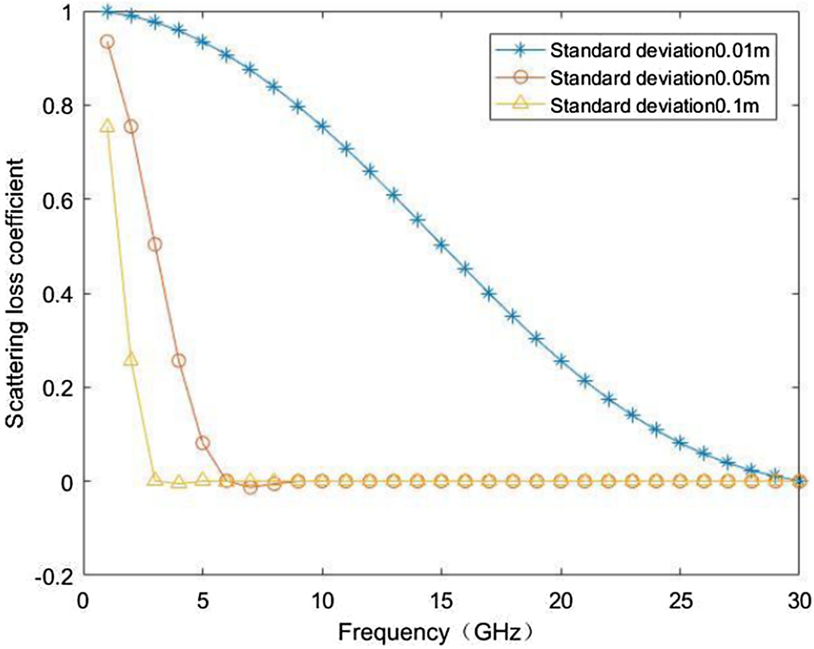

Fig. 4. Relationship between scattering loss coefficient and frequency and standard deviation of surface fluctuation

When the communication distance *d* does not exceed the sum of the maximum line-of-sight propagation distance and half of the half-shadow width, the loss of long-distance propagation and diffraction can be expressed as:

$$L = F[X(P)] + G[Y(r,P)] + G[Y(t,P)] \tag{12}$$

Where *F(X)* is the distance gain term, and *G(Y)* is the height gain term, the expressions are:

$$F[X] = \begin{cases} 11 + \log(X) - 17.6X & X \geq 1.6 \\ -20\log(X) - 5.6488X^{1.425} & X < 1.6 \end{cases} \tag{13}$$

$$G[Y] = \begin{cases} 17.6\sqrt{B-1.1} - 5\lg(B-1.1) - 8 & B > 2 \\ 20\lg(B + 0.1B^3) & 10\text{K} < B \leq 2 \\ 2 + 20\lg K + 9\lg(B/K)(\lg(B/K)+1) & K/10 < B < 10K \\ 2 + 20\lg K & B \leq K/10 \end{cases} \tag{14}$$

Among them, the calculation formula of X and Y is:

$$X = \beta\left(\frac{\pi}{\lambda r_e^2}\right)^{\frac{1}{3}} d \tag{15}$$

$$Y = 2\beta\left(\frac{\pi^2}{\lambda^2 r_e}\right)^{\frac{1}{3}} h \tag{16}$$

Where r_e is the equivalent radius; d is the transmission distance; σ is the ground conductivity; h is the corresponding height; K is the normalization factor, $B = \beta Y$, and for horizontal polarization, the parameters β and K have expressions:

$$K = \left(\frac{2\pi r_e}{\lambda}\right)^{-\frac{1}{3}} \left[(\varepsilon_r - 1)^2 + (60\lambda\sigma)^2\right]^{-\frac{1}{4}} \tag{17}$$

$$\beta = \frac{1 + 1.6 \times K^2 + 0.67 \times K^4}{1 + 4.5 \times K^2 + 1.53 \times K^4} \tag{18}$$

If the height of the transceiver is 2 m, the equivalent radius is 100 km, and the frequency of the communication wave is 1000 MHz. Taking the lunar surface as an example, under horizontal polarization conditions, the lunar surface conductivity is 3×10^{-4}, relative permittivity is 3, lunar radius is 1738 km, and in the diffraction range of 1000 m–8000 m, the long-distance propagation around the lunar surface can be obtained. The relationship between the radiation loss and the propagation distance is shown in Fig. 5.

As can be seen from Fig. 5, as the transmission distance increases, the loss of the diffraction section will gradually increase. At the same time, by comparing the curve changes of the diffraction loss at several different frequencies, it can be found that the low frequency radio waves are affected when the distance is closer. The loss is greater, and when the distance continues to increase far enough, the loss of higher frequency waves will exceed that of lower frequencies.

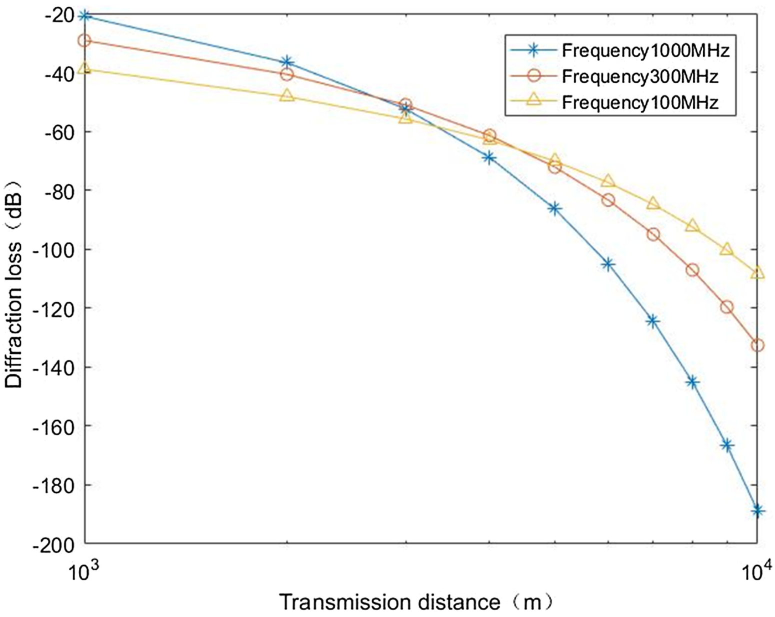

Fig. 5. Relationship between diffraction loss and transmission distance and frequency

5 Conclusion

Recently, deep space communication technology is developing rapidly, and the analysis of the channel characteristics of deep space communication links is the basis of research. This paper mainly considers the characteristics of the moon and Mars channels, gives the performance simulation results of the communication links in the Ka frequency band and lower frequency bands, and summarizes the relevant characteristics of the deep space channel. The atmospheric loss of Mars is nearly a hundred times lower than that of the earth, but similarly, there are peaks in the frequency band of 20–25 GHz; when the radius of Martian sand is large, the characteristic loss can reach nearly 1 dB/km for the radio waves of higher frequency bands; the simulation results using a simple segmented model show that uneven terrain will greatly increase the harmful scattering on the transmission path, and the diffraction loss in transmission over several kilometers can reach more than 20 dB, and at the same time, take a lower frequency can help to reduce the loss caused by scattering and diffraction.

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