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Factors affecting the choice of frequency bands for space research service deep-space (space-to-Earth) telecommunication links

SA Series

Space applications and meteorology

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REPORT ITU-R SA.2167

Factors affecting the choice of frequency bands for space research service deep-space (space-to-Earth) telecommunication links

(2009)

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1 Introduction

There are a number of primary space research service (SRS) allocations that can be used by deep-space missions for telecommand, telemetry, and radiometric data collection. Some of these allocations are designated specifically for deep-space SRS missions and are not available to non-deep-space SRS missions, while other allocations are available to both deep-space and non-deep-space SRS missions. The deep-space SRS allocations are given in Table 1.

TABLE 1

Primary SRS (deep-space) allocations

Earth-to-space	space-to-Earth
2 110-2 120 MHz	2 290-2 300 MHz
7 145-7 190 MHz	8 400-8 450 MHz
34.2-34.7 GHz	31.8-32.3 GHz

The above primary SRS allocations are restricted to deep-space missions and are not available to non-deep-space missions. These allocations together provide a total of 555 MHz in the Earth-to-space direction and 560 MHz in the space-to-Earth direction.

In addition to these primary deep-space allocations in Table 1, there are two other general primary SRS allocations of 37-38 GHz (space-to-Earth) and 40-40.5 GHz (Earth-to-space). Since the 37.5-38 GHz part of the 37-38 GHz band is shared with FSS, it is not especially usable for deep-space missions, especially for manned planetary missions.

The use of the 2 110-2 120 MHz (Earth-to-space) band will be limited in the future at NASA’s Madrid Deep-Space Communication Complex due to potential interference to IMT-2000 users. The 8 400-8 450 MHz (space-to-Earth) band is very congested, since it is being extensively used by all deep-space missions. The 34.2-34.7 GHz (Earth-to-space) and 31.8-32.3 GHz (space-to-Earth) allocations are not yet crowded, but deep-space missions have started using these bands. Currently, there are no known deep-space missions planning to use the 37-38 GHz (space-to-Earth) and the 40-40.5 GHz (Earth-to-space) allocations, and the ground infrastructure needed to support these frequencies has yet to be developed.

2 Spectrum requirements for future deep-space missions

The amount of spectrum needed to support the space-to-Earth links of deep-space missions is expected to increase within the next 15 to 30 years, as the number of future missions and the data rate of each mission are expected to increase. More and more space agencies are expected to send missions to explore the solar system and beyond. Furthermore, all these future deep-space missions are expected to send the data collected by the on-board instruments using a much higher data rates, perhaps in excess of hundreds of megabits per second. On-board instruments require very high data rates. For example, a radar may require a data rate of 100 Mbit/s and a hyperspectral imager may require data rates between 150 Mbit/s and 600 Mbit/s (EO-1, Moon Mineralogy Mapper, EnMAP). These instruments can be flown on both robotic and human missions. Examples of possible future spacecraft flying these high-rate science instruments are shown in Table 2.

TABLE 2

Users of science instruments requiring high downlink data rates

User spacecraft	Instrument	Data rate (Mbit/s)
Robotic rovers	Surface radar Hyperspectral imaging	100 150-600
Science orbiters	Orbiting radar Hyperspectral imaging	100 150-600
Human transports	Hyperspectral imaging	150-600

The return of science data from deep-space missions is limited by the capacity of the space-to-Earth links. Often, the amount of science data returned to Earth from a deep-space mission during its lifetime is only a small fraction of what it is capable of producing. A deep-space mission sometimes may take months or years to reach its destination, but may have only a limited time, measured in weeks or even in days, to explore its target. Increasing the amount of data returns is important scientifically and economically. This increase is already taking place in the planned deep-space missions, which have started taking advantage of the 31.8-32.3 GHz (space-to-Earth) band capability to increase data returns. The Mars Reconnaissance Orbiter (MRO), for example, has a 32.2 GHz downlink capable of sending telemetry at 6 Ms/s. While this link is experimental, the MRO project plans to use it to return science data once it has been successfully demonstrated. The data rate of MRO is about 5 times higher than the telemetry rates of all existing deep-space missions, except SIRTF, which has a downlink rate of 4.4 Ms/s. Another planned Mars mission, Mars Telecom Orbiter (MTO) would have an even higher downlink rate. In one option, the MTO telecom system was designed to support a telemetry data rate of 40 Ms/s using a 34-m ground antenna. MTO was initially planned for launch in 2009, but had recently been postponed due to budgetary constraints.

Two developments considered by NASA will enable to increase the downlink data rate and accelerate the trend towards higher and higher data returns. First, NASA is considering to implement a large array of antennas with a G/T 10 times higher than the existing 70-m antennas in the NASA's Deep-Space Network (DSN). This will enable spacecraft to transmit at a much higher rate than they presently can, without requiring a large EIRP from the spacecraft. Second, NASA is also considering to use nuclear power technology to power the spacecraft, making ample power available for sending data to the Earth. The Prometheus programme has studied large EIRP missions to Jupiter. The requirement for the Jupiter Icy Moons Orbiter (JIMO) mission is a data rate of 10 Mbit/s at a range of 6.5 AU into a 70-m equivalent aperture. To achieve this data rate, the current design has a 3 m 32 GHz band high-gain antenna with a 1 kW 32 GHz band transmitter. A similar spacecraft at Mars range would support a data rate of 62 Mbit/s at Mars maximum range (2.6 AU) and 1.1 Gbit/s at Mars minimum range. The supportable data rate would be 10 times higher using the full antenna array.

These developments together will enable future deep-space missions to send science data to the Earth at a much higher data rate than they presently can. Previous studies indicated a possible 1 000 fold increase in mission data reception throughput by 2030 for deep-space missions based on a JPL analysis. A 2009 internal JPL study estimated a downlink throughput data rate of 125 Mbit/s, 150 Mbit/s, and 1500 Mbit/s for the highest data rate user in the 2010, 2020 and 2030 time-frame, respectively. While there is a large uncertainty in these estimates, they do point to a trend toward higher and higher data rates for deep-space missions. They indicate that the bandwidth required to support future deep-space missions will far exceed the capacity of all existing allocations, even after accounting for possible use of bandwidth-efficient modulation schemes. Interests among various space agencies in exploring Mars through robotic or human missions increase the likelihood that there may be multiple spacecraft operated by different space agencies exploring Mars at the same time. This will further increase the needed spectrum because the frequency used by one Mars mission cannot in general be reused by another. Factoring the needs for future Mars missions and allowing some spectrum for non-Mars missions, a total allocated spectrum of 2 to 3 GHz in addition to existing allocations appears to be sufficient to meet the anticipated long-term spectrum needs. For example, with 3 GHz of additional spectrum, two spacecraft at Mars would be able to send data simultaneously to Earth at the highest anticipated data rate.

3 Factors considered in the choice of frequency bands

There are many factors that can constrain the choice of frequency bands for future high-rate deep-space missions. In allocating appropriate spectrum and identifying suitable frequency bands, we need to consider the following factors. Note that some of these factors are more constraining than the others.

3.1 Link applications

The intended application of a telecommunication link can have an impact on the choice of its operating frequency. A link operating at a frequency not suitable for its application can experience poor link performance. In general, a communications link having a broadbeam antenna at both ends of the link would perform better at a lower frequency than at a higher one. Links with a broadbeam antenna perform much better at 400 MHz, 1 GHz, or 2 GHz bands than, for example, at 32 GHz or 79 GHz bands. A broadbeam antenna has the advantage of not requiring accurate antenna pointing, making it best for certain mission events such as propulsive maneuvers, landing, or loss of spacecraft attitude. On the other hand, a link with a narrow-beam antenna at both ends would perform better at a higher frequency than at a lower frequency, assuming that the antennas can be accurately pointed. For the specific application of sending data to Earth at extremely high rates, it is not suitable to use a broadbeam low-gain antenna at either end of the link. Instead, a highly directive narrow-beam antenna is needed at both ends of the link. Everything else being equal, a higher frequency would be preferable over a lower frequency.

3.2 Propagation impairments

A space-to-Earth link is adversely affected by the atmosphere and weather conditions on Earth, due to increased system noise temperature, signal attenuation, scintillation, and depolarization. Figure 1 gives the zenith atmospheric gaseous absorption up to 100 GHz for a water-vapour density of 12 g/m^3, exceeded approximately 1% of the time for the area around Goldstone, California. The attenuation generally increases with increasing frequency. For any other elevation angle (θ), the attenuation will be higher by a factor of $1/\sin(\theta)$ than the attenuation at zenith.

For receiving systems such as the deep-space receivers operating with a very low system noise temperature, increased atmospheric noise temperature due to water vapour and light clouds (without rain) can degrade the link performance significantly. Figure 2 gives the zenith atmospheric noise temperature as a function of frequency for various elevation angles. The noise temperature was calculated for a rainfall region with a moist atmosphere and light clouds. The curves are derived assuming a water-vapour density of 15 g/m^3 and moderate cloud columnar liquid-water content of 0.5 kg/m^2 (both are exceeded 1% of time). Figure 2 shows that the noise temperature generally increases as the operating frequency increases. Note that Fig. 2 is applicable to the DSN site at Goldstone, California. The noise temperature for the DSN site in Canberra, Australia is somewhat higher.

FIGURE 1

Zenith gaseous absorption due to oxygen and water vapour as a function of frequency

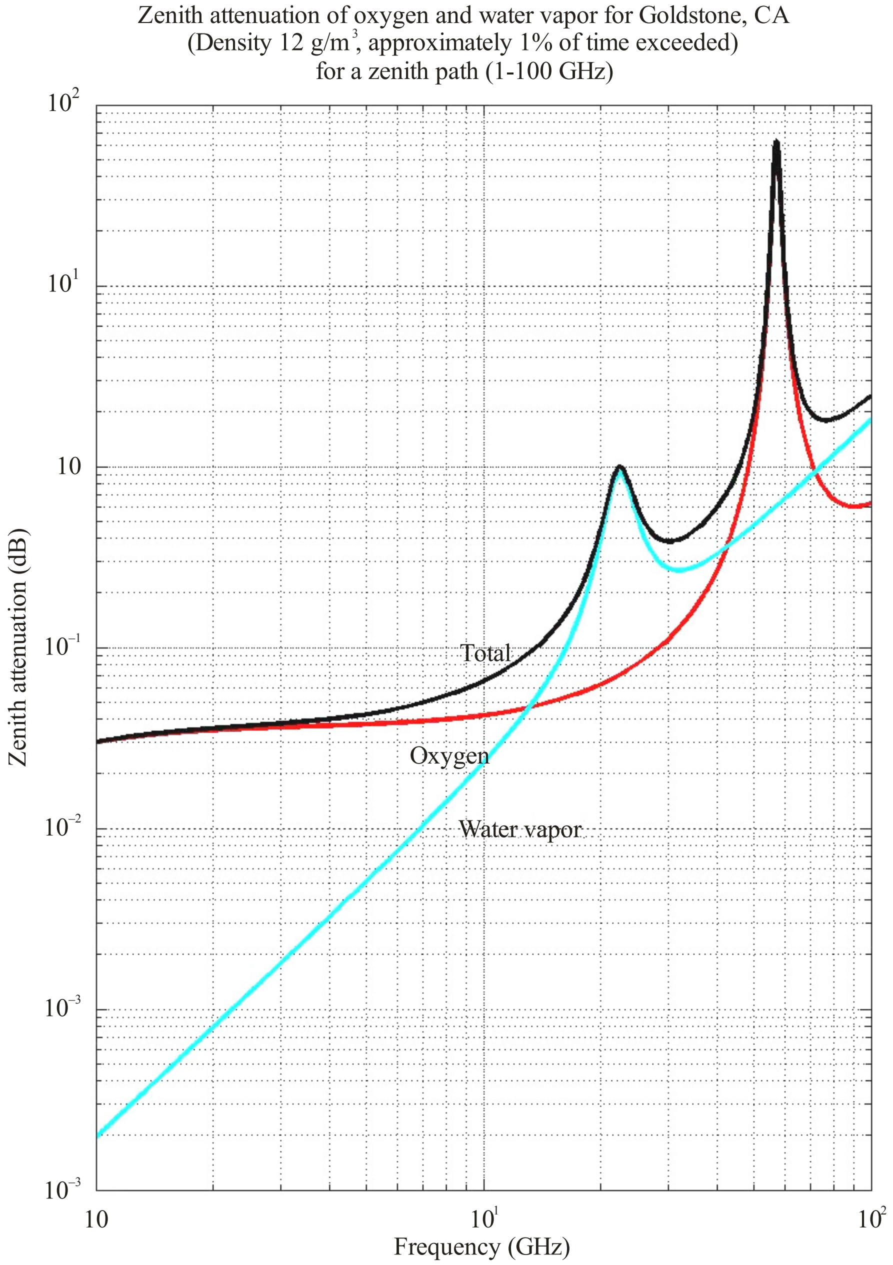

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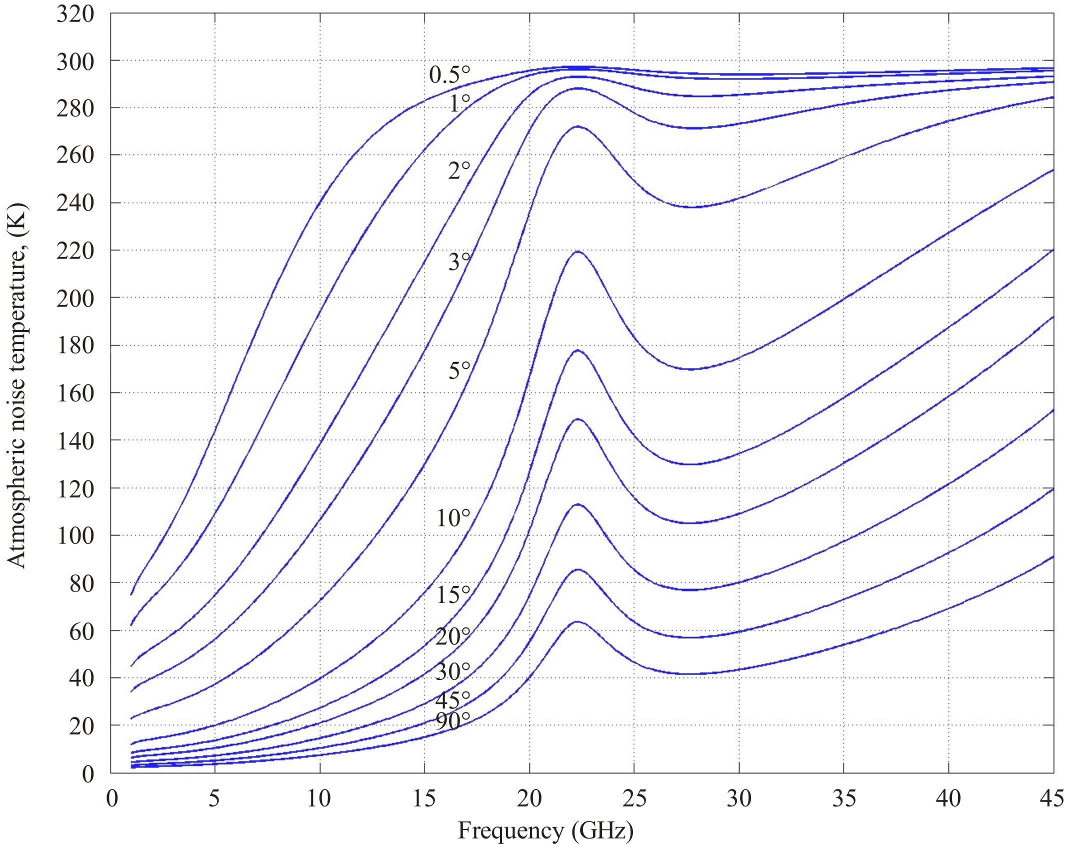
FIGURE 2

Atmospheric noise temperature as a function of frequency

CLOUD + CLEAR AIR, AH = 15 g/m³, BASE = 1 km, TOP = 3 km, LWC = 0.25 g/m³,
COLUMNAR LIQUID = 0.5 kg/m²



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The rain, which does not happen often, can severely impair the link performance by attenuating the received signal and increasing the system noise temperature. Deep-space communication links require higher than 99% availability, thus these rain impairments must be appropriately accounted for in the choice of frequencies. These rain impairments depend on the elevation angle and the percentage of time exceeded. They are, in general, more severe at higher frequencies than at lower frequencies. As an example, the rain attenuation at zenith is given in Fig. 3 as a function of the percentage of time that a given attenuation is exceeded. The curves are derived assuming a zenith rain path of 4 km. For example, the rain attenuation at 45 GHz would exceed 4 dB for 0.4% of the time, and 8 dB for 0.1% of the time.

Figure 4 shows the atmospheric noise temperature at zenith due to the rain as a function of percentage of time exceeded for various frequencies for the area around the Goldstone SRS earth station.

The curves in Figs 3 and 4 clearly indicate that a lower frequency is more favourable than a higher one.

FIGURE 3

Rain attenuation at zenith as a function of percent of time exceeded

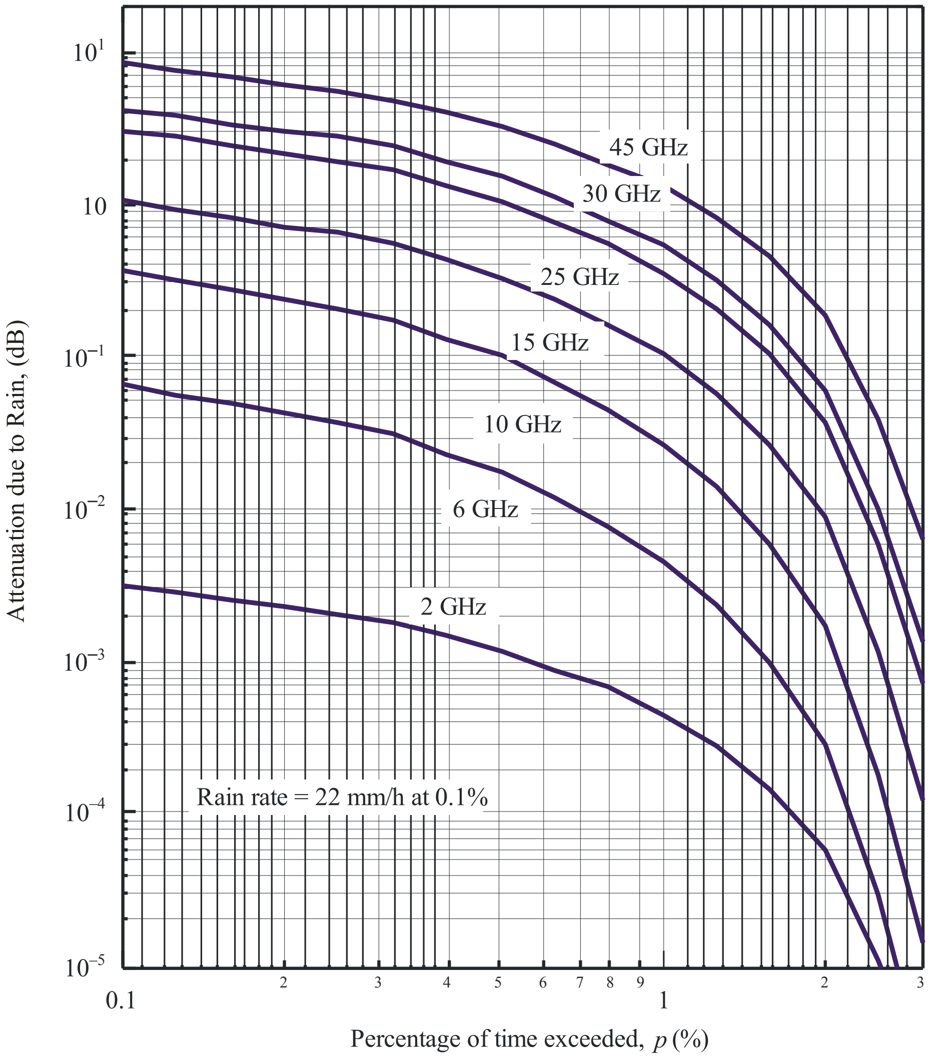

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FIGURE 4

Atmospheric noise temperature due to rain at zenith

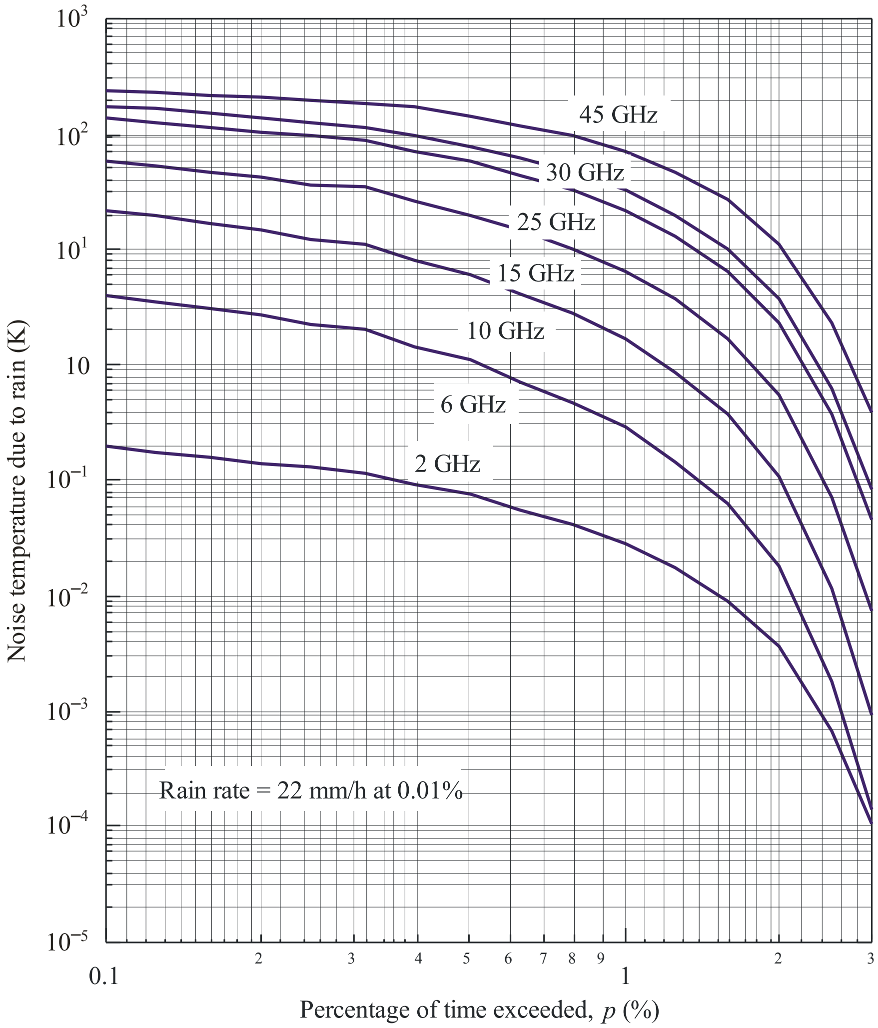

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Table 3 compares the various propagation impairments for the Goldstone area for 14-16 GHz, 27.5-29.5 GHz and 78-79 GHz bands with link availability (or exceeding probability) of 95% and 99%. The table shows that rain attenuation dominates. Rain attenuation at the Goldstone and Madrid DSN sites is similar, but at the Canberra DSN site it is much higher. Because deep-space links generally require 99% or higher link availability, it is clear that a 78-79 GHz band link will have a much more severe link degradation than a 27.5-29.5 GHz band link, even without considering its immature space technology including a much lower high-power-amplifier efficiency. Although there is ample spectrum above 75 GHz, it should be avoided if possible.

TABLE 3

Atmospheric attenuation around the Goldstone area for a 20° elevation angle

Percentage of link availability	Frequency band (GHz)	Atmospheric absorption, (water-vapour density = 12g/cm^3) (dB)	Rain attenuation (dB)	Cloud, fog attenuation (dB)	Scintillation (dB)
95%	14-16	0.4	0.7	0.4	0.2
	27.5-29.5	1.2	3.0	0.8	0.4
	78-79	7	18.0	4.0	2.4
99%	14-16	0.4	0.8	0.6	0.3
	27.5-29.5	1.2	4.0	1.2	0.5
	78-79	7	24.0	5.5	3.0

3.3 Available bandwidth

As mentioned previously, approximately 2 to 3 GHz of additional allocated spectrum is needed to provide sufficient bandwidth to support the high-rate downlinks anticipated for future deep-space missions. There are two possible approaches to obtain the needed wideband spectrum: one single allocation, or multiple small allocations.

With a proper design, it is possible for a spacecraft to aggregate several segmented allocations to obtain the needed spectrum for sending high-rate data to the Earth. One simple way is to send the data on different carriers, each in one of the allocated spectrum segments. This approach, however, can severely impact both the spacecraft and the ground station, especially, if numerous small spectrum segments are aggregated over widely separated frequency bands. For this approach to be practical, each allocation should be sufficiently wide (about 500 MHz) and sufficiently close to each other, such that they can easily be aggregated to provide the bandwidth to support a user spacecraft operating at the highest rate of 1 500 Mbit/s.

Because of the congestion in the 2 290-2 300 MHz (space-to-Earth) and 8 400-8 450 MHz (space-to-Earth) bands, only spectrum above the 8 450 MHz should be considered for possible allocations.

3.4 Technology maturity and equipment availability

Considerations of technology maturity and spacecraft-equipment availability generally favor lower frequencies already having extensive space applications instead of the very high frequencies with little or no relevant space applications. There are many commercial satellites operating in spectrum below 30 GHz. Commercial satellites offer high-power, high-data-rate equipment that could be easily modified to work in the nearby frequency bands.

Many commercial satellites operate at frequencies in the 12-18 GHz band. Space technology in this band is very mature and there is plenty of space-qualified equipment that is applicable to deep-space missions with little or no modifications.

There are also 18-40 GHz band commercial satellites, typically operating in the 20 GHz (space-to-Earth) and 30 GHz (Earth-to-space). Technologies in this band are already mature, although space equipment in this band is not available as readily as in 12-18 GHz band. Developing flight hardware in the 18-40 GHz band for deep-space applications is only an engineering development, not a technology development.

Because of many years of technology development in the deep-space 31.8-32.3 GHz band, the technology around 32 GHz is mature. 32 GHz band equipment is available although not as fully implemented as technologies in 8 GHz and 15 GHz bands. Equipment that is currently being developed in the 32-GHz band for deep-space missions could be modified to work in nearby frequencies, such as the 28-30 GHz band. Operational experience gained in the 32 GHz band and operational techniques developed for this band can also be extended to the nearby frequency bands.

Above 32 GHz, there are governmental satellites operating in around 40 GHz, making technology in this frequency region relatively mature. Beyond this, there are not much known space applications.

There are no known commercial satellites in 75-110 GHz band and space technology in this band is much less developed than in 15 GHz and 32 GHz bands. There is no flight hardware in this band for deep-space missions. A serious and costly technology development effort will be needed if this band is to be used for deep-space missions. A new operations technique may have to be developed specifically for this band due to the severe weather effects.

3.5 Ground infrastructure considerations

NASA is considering to implement a new antenna system for future deep-space missions by arraying a large number of small antennas to form a large aperture antenna array. When fully implemented, this antenna array will have 400 small antennas of 12 m diameter and will be capable of supporting existing primary deep-space allocations in the 8 400-8 450 MHz, 31.8-32.3 GHz and 37-38 GHz bands. An allocation between 8 GHz and 37 GHz would ensure maximum compatibility with this ground infrastructure, lower the implementation cost, and greatly benefit space agencies in general and NASA in particular.

3.6 Compatibility with the recommended frequency plan for the Mars region

The space frequency coordination group (SFCG) adopted a frequency usage plan for missions operating in the Mars region (Table 4). A spacecraft operating in the Mars region could have many different links in additional to the traditional space-to-Earth and Earth-to-space links. These links include orbit-to-surface, surface-to-orbit, surface-to-surface, and orbit-to-orbit links. It is important for the new allocated spectrum to be compatible with the Mars Frequency Plan to avoid incompatible operations in the Mars region.

It is noted that the current Mars frequency plan is primarily for robotic missions. Although all proximity-link frequencies are available to human missions as well as robotic missions, future human Mars missions should use the 37-37.5 GHz band for space-to-Earth links.

TABLE 4

Summary of frequency bands for communications in the Mars region

	Frequency bands (MHz)
Orbit-to-surface:	435-450 2 025-2 110 7 190-7 235 14.5-15.35
Surface-to-orbit:	390-405 2 200-2 300 8 400-8 500 16.6-17.1
Surface-to-surface:	435-450 390-405 2 025-2 120 2 200-2 300
Orbit-to-orbit:	435-450 390-405 2 025-2 120 2 200-2 300 7 190-7 235 8 450-8 500
Approach navigation and atmospheric radio science	8 400-8 450

3.7 Incompatible services

To minimize regulatory issues between services, it is important to avoid spectrum already allocated to services that are incompatible with the deep-space (space-to-Earth) links. In general, the following are considered incompatible operations:

a) Deep-space space-to-Earth links cannot use the spectrum allocated for radio astronomy and passive sensors because of the potential for interference.

b) Deep-space missions cannot share the same space-to-Earth frequency with satellites in the Earth-exploration satellite (EES), fixed-satellite (FS), mobile-satellite (MS), and broadcasting-satellite (BS) services. This is because the signal received from a spacecraft in the deep-space is extremely weak and is very susceptible to interference from the space-to-Earth links of the near-Earth orbiters.

c) For the same reason stated above, it is also not feasible for deep-space missions to share the same space-to-Earth frequencies with other non-deep-space SRS missions that use earth stations having a small *G/T*.

Compliance with these constraints will limit the choices of frequency but will reduce regulatory objections. More importantly, it will avoid in the future complicated and costly operational coordination necessitated by incompatible allocations and operations.

3.8 Feasibility of frequency sharing

While deep-space missions generally cannot share the same space-to-Earth frequency with Earth orbiters, it is possible for deep-space missions to use the Earth-to-space frequencies allocated to Earth orbiters in the reverse direction. The downlink signal of a deep-space mission is extremely weak and is not expected to cause interference to near-Earth satellites. The peak of the power spectral density (PSD) of a deep-space downlink received by a deep-space antenna is very close to the noise floor of the deep-space receiver. The received symbol-energy-to-noise-spectral-density ratio (E_s/N_0) is 0 dB for BPSK, 3 dB for QPSK, and about 4 dB for GMSK. Existing deep-space missions can operate at E_s/N_0 of −3 to −5 dB using error-correcting codes with a large coding gain. Assuming a concatenated Reed-Solomon plus 7-1/2 convolution code, the required E_b/N_0 is 2.3 dB for a bit-error rate of 1.0e-5, corresponding to an E_s/N_0 of about 0 dB. The received peak PSD is thus the same as the receiver noise floor. For a 400 × 12-m array with a system noise temperature of 40 K, the noise spectral density is about −213 dB(W/Hz) and the equivalent aperture area is about 44 dB(m^2). The peak PSD received by the array is −213 dB(W/Hz), corresponding to a peak spectral power flux-density of −257 dB(W/m^2/Hz). This signal when received by an Earth orbiter would be far below the noise floor of its receiver.

A simple link analysis is given in Table 5 for a specific scenario: a hypothetical link from Mars at a Mars-Earth range of 1 AU operating at 30 GHz with a fully deployed antenna array. The spacecraft has 1 kW transmit power and a 3 m high-gain antenna. The ground antenna array has a gain of 90 dBi. At a rate of 1 Gs/s, the link analysis shows a received E_s/N_0 of 19 dB, much more than what is needed. Even with this high EIRP from the spacecraft, the amount of interference received by an Earth orbiter is almost 87 dB below the noise floor of the receiver. It is assumed in the link analysis that the deep-space downlink signal is received by a near-Earth satellite through the side lobe of its antenna with 0 dBi gain. Even in the extremely unlikely event when the interference enters the satellite through the main beam of its antenna, the peak PSD would still be far below the noise floor of the satellite receiver.

Significant interference from Earth orbiter uplinks to the deep-space downlink is not expected due to the high directivity of the antenna of the deep-space earth stations.

4 Spectrum that could be considered for possible allocations

Consideration of propagation characteristics, technology maturity, space equipment, and ground infrastructure suggests that the spectrum most suitable for future wideband deep-space missions is in the 8-40 GHz range.

One way to obtain the needed spectrum is to upgrade the existing allocations from a secondary status to a primary status. For example, a review of the Table of Frequency Allocations in the ITU Radio Regulations shows that there is a SRS (deep-space) secondary allocation in the 12.75-13.25 GHz band. Upgrading this allocation to primary status would only provide part of the needed spectrum. Additional allocations however would be needed, preferably also in the same 12-18 GHz band. There are several secondary SRS allocations in the 12-18 GHz band. Because of the difficulties in sharing the space-to-Earth frequencies between deep-space and non-deep-space missions, it may not be feasible to obtain a primary deep-space allocation from any of these SRS allocations. In addition, several 12-18 GHz band frequencies are being used by NASA's tracking and data relay satellite system (13.775 GHz (forward), 15.0034 GHz (return), 13.4-14.05 GHz (space-to-Earth) and 14.6-15.25 (Earth-to-space)).

Another possibility is to obtain a primary deep-space allocation in spectrum that is allocated to services compatible with the SRS (deep-space). As previously stated, it is feasible for deep-space downlinks to share the Earth-to-space frequencies for EESS and FSS. Spectrum allocated for these services in the Earth-to-space direction could be a viable candidate.

TABLE 5

Interference from a deep-space downlink to an Earth orbiter

Desired signal path		
Transmitter power	1 000 W	30 dB(W)
Circuit loss		3 dB
Transmit antenna diameter	3 m	
Transmit antenna gain		57 dBi
EIRP		84 dB(W)
Symbol rate	1 000 Ms/s	90 dB(sym/s)
Frequency	30 GHz	
Range	150 Mkm	
Range	1.0 AU	
Space loss		286 dB
Equivalent receive antenna diameter	240 m	
Equivalent receive antenna gain		95 dBi
Received signal power (P_t)		–107 dB(W)
Receiver system noise temperature	40 K	16 dB(K)
Receiver noise spectral density (N_0)		–213 dB(W/Hz)
Received P_t/N_0		106 dB(Hz)
E_s/N_0		19 dB
Interference to the receiver of an Earth orbiter		
EIRP		84 dB(W)
Symbol rate	1 000 Ms/s	90 dB(sym/s)
Peak interference PSD (I_0)		–3 dB(W/Hz)
Range	150 Mkm	
Space loss		286 dB
Receive antenna gain		0 dBi
Received interference peak PSD		–289 dB(W/Hz)
Receiver system noise temperature	500 K	27 dB(K)
Receiver noise spectral density (N_0)		–202 dB(W/Hz)
Peak I_0/N_0		–87 dB

Table 6 summarizes the frequencies between 8-40 GHz that could be considered for possible future deep-space applications.

TABLE 6

Frequencies between 8-40 GHz for possible deep-space applications

Frequency band (GHz)	**Existing compatible services** (E-s = Earth-to-space, s-E = space-to-Earth)
12.75-13.25	FS, FSS(E-s), MS, srs(deep-space)(s-E)
24.25-24.45	RADIONAVIGATION, FS, MS
24.75-25.25	FS, FSS(E-s), MS
27.5-28.5	FS, FSS(E-s), MS
28.5-29.1	FS, FSS(E-s), MS, eess(E-s)
29.1-29.5	FS, FSS(E-s), MS, eess(E-s)
29.5-29.9	FS(E-s), MSS(E-s), mss(E-s), eess(E-s)
29.9-30	FS(E-s), MSS(E-s), eess(E-s)
30-31	FSS(E-s), MSS(E-s), standard freq. and time signal-sat (s-E)
33-33.4	FS, RADIONAVIGATION

It appears that the 27.5-31 GHz band is most desirable and meets the various constraints previously discussed, including technology maturity, propagation characteristics, and the amount of available spectrum.

5 Conclusions

The anticipated spectrum usage of future deep-space missions far exceeds the capacity of all existing allocations. Therefore, SRS will need additional spectrum allocations. This report provides information on the amount of needed spectrum and discusses various constraints in selecting a suitable frequency band for a possible allocation by ITU in the future. Considerations of many constraints, such as technology maturity, ground infrastructure, and propagation characteristics indicate that the additional allocated spectrum should be within the range 8 GHz to 40 GHz. It appears that the 27.5-31 GHz band is the most desirable to meet the requirements for deep-space research.