Frequencies for Mars Local High-Rate Links

D. Hansen,[1] M. Sue,[1] T. Peng,[2] and F. Manshadi[2]

This article considers the options for frequency choice for high-data-rate links at Mars during the next 10 to 20 years. Current Mars local links use UHF (400 MHz) for data rates up to 2 Mb/s. Higher data rates will require a wider bandwidth and improved link performance. A frequency higher than UHF will more easily achieve the improved performance. The selected frequency should also be available on a non-interfering basis with the direct-to-Earth links for existing and future Mars spacecraft, allow for reuse of hardware on the spacecraft, and support near-Earth testing of the relay-link hardware. The chosen frequency should also support approaching spacecraft navigation. Based on these considerations, a list of possible candidate frequency bands has been identified. The candidate frequency bands are presented here along with their strengths and weaknesses.

I. Introduction

Current Mars missions use the UHF (390- to 450-MHz) band for local links between landers, rovers, and orbiting spacecraft. UHF equipment has been designed for these links for relatively low data rates (8 to 512 kb/s). The links typically use wide-beam, low-gain antennas that do not require active pointing control. There is a desire to provide for higher-data-rate local links for future missions. These links will require more bandwidth and higher effective isotropic radiated power (EIRP) and gain/temperature (G/T) values. The higher-gain antennas will be more easily realized at a higher frequency than UHF. This article looks at the options for frequency bands for higher-rate links for the next 5 to 10 years.

II. Bands of Interest

Several different bands have been considered: S-band, X-band, Ku-band, and Ka-band. Table 1 provides a summary of the bands.

S-band (2.1 to 2.3 GHz) is attractive because of the availability of commercial components, the existing frequency allocations for near-Earth and deep space, and the fact it could be used without interfering with most future deep-space missions, which will primarily use X-band or Ka-band for their direct-to-Earth (DTE) links.

---

[1] Communications Systems and Research Section.

[2] DSMS Plans and Commitments Program Office.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Table 1. Summary of frequency bands for communications in the Mars region.

Link	Frequency range
Space-to-Earth	2290 to 2300 MHz
	8400 to 8450 MHz
	31.8 to 32.3 GHz
Earth-to-space	2110 to 2120 MHz
	7145 to 7190 MHz
	34.2 to 34.7 GHz
Orbit-to-surface	435 to 450 MHz
	2025 to 2110 MHz
	7190 to 7235 MHz
	14.5 to 15.35 GHz
Surface-to-orbit	390 to 405 MHz
	2200 to 2300 MHz
	8400 to 8500 MHz
	16.6 to 17.1 GHz
Surface-to-surface	435 to 450 MHz
	390 to 405 MHz
	2025 to 2120 MHz
	2200 to 2300 MHz
Orbit-to-orbit	435 to 450 MHz
	390 to 405 MHz
	2025 to 2120 MHz
	2200 to 2300 MHz
	7190 to 7235 MHz
	8450 to 8500 MHz
Approach navigation and atmosphere radio science	8400 to 8450 MHz

X-band (7.2 to 8.5 GHz) is attractive because of the existing near-Earth and deep-space frequency allocations and because onboard hardware could be shared for both the deep-space and local links. The biggest concern is potential self-interference during simultaneous DTE and local-link communication passes.

Ku-band (14.5 to 17.1 GHz) is attractive because of the availability and technology maturity of components from the commercial satellite industry and because it will not cause any interference with the DTE links. Close to the commercial satellite band there is a band at 15 GHz allocated to Space Research Service (SRS) downlink and another band at 16 GHz allocated to SRS uplink.

Ka-band (32 to 34 GHz) was briefly considered. It provides a very high bandwidth and potentially a large EIRP and G/T, but it requires fine-antenna-pointing control, making this appear to be a less viable option at this time. Also, there is not the hardware maturity and availability of the other frequency bands.

III. Considerations for Selecting a Higher-Frequency Band

In determining the best option for a frequency band for higher data rates, several requirements and/or desirable features are considered. They are as follows:

(1) Feasibility of sharing (or reuse) of existing onboard equipment. This would include using some or all of the transceiver/transponder, power amplifier, diplexer, and antennas on the spacecraft (primarily on the landed element; may be able to share antennas on the orbiter) for both the DTE link and the local link. This is highly desirable from the project point of view because it would provide for a reduction in mass and cost.

(2) Support of near-Earth testing. Many missions desire the ability to conduct an in-flight test of the local-link hardware on spacecraft when they are still close to Earth. This provides confidence that the hardware will work when it is on station. It also serves as an in-flight calibration. Frequently, future missions are relying on the just-launched spacecraft for communications support during their landed missions. Getting early assurance that the hardware works and how well can shape the design of the next spacecraft. It is desirable that the near-Earth testing be performed on a non-interfering basis with local users of the chosen frequency.

(3) Compatibility (no interference) with the DTE spacecraft frequency. The concern is that the onboard transmitter could cause self-interference between the local link and the DTE link. The spacecraft transmission in the same band could overwhelm its own receiver and preclude receiving an intended signal. A lesser concern is that a nearby spacecraft at Mars, while communicating to Earth, could interfere with the local link. Providing sufficient filtering to overcome the interference might cause too much insertion loss to be practical.

(4) Technology maturity and hardware availability. In choosing a band for the local link, it is important to consider the availability of components for designing and fabricating the hardware.

(5) Approaching spacecraft navigation. A new goal for future orbiters is to provide a capability to perform radio navigation for incoming spacecraft from an orbiting Mars spacecraft. This would be performed at the incoming spacecraft's DTE frequency, most likely X-band.

(6) Other issues. These include link performance, antenna coverage of Mars, propagation, and evolution of the Mars communications frequencies.

IV. Analysis of Requirements for Frequency Selection

A. Feasibility of Sharing Equipment

The first issue is the feasibility of sharing the equipment for both the DTE and local links. X-band and Ka-band are the deep-space bands of choice for future missions. Ka-band was previously considered for the local links but has not been pursued further because of the difficulty in pointing the antennas. While this limitation can be overcome by advanced antenna technology in the future, this leaves X-band as the choice for sharing hardware, at least for the near term.

For an X-band local link, the existing deep-space spectrum could be used. This would allow for using the current DTE transponders for the return link. From a spectrum point of view, using the near-Earth spectrum (7190 to 7235 MHz, Earth-to-space; 8450 to 8500 MHz, space-to-Earth) would be better—no interference with other spacecraft at Mars. The near-Earth band is adjacent to the deep-space spectrum (7145 to 7190 MHz and 8400 to 8450 MHz). The current deep-space allocation is crowded. Using the near-Earth band for the local link would allow for sharing the X-band power amplifier, diplexer, and antennas on the landed element. All of these devices should be able to cover the expanded bandwidth. The current transponders are not frequency agile and would not work in the near-Earth spectrum. Also, the modulation scheme for the deep-space uplink is much different from what the local link would use. A future transceiver/transponder might be able to accommodate both the DTE and local-link modulation schemes and radio navigation signals. Another possibility is to add a capability to the local-link transceiver (now operating at UHF) to allow it to receive/transmit X-band signals via the DTE X-band antenna and receiver front end. Either way, there would be a reduction in hardware, with the benefits of reducing mass, simplifying the design, and lowering overall cost.

The effect would be significant for a landed spacecraft. A rover or lander is generally mass- and power-limited. It is unlikely that there would be sufficient power for simultaneous links back to Earth and to a local orbiter. The lander could support a very high data rate back to an orbiter with a small high-gain antenna (HGA) and a moderate-sized X-band power amplifier, like the Mars Exploration Rovers (MERs) have. MER uses a 0.28-m X-band HGA with a 15-W X-band solid-state power amplifier (SSPA).

The orbiter will not really get the advantage of sharing hardware because the local link will be at the reverse frequencies of the DTE link. It may be able to share some antennas, depending on the spacecraft design and attitude. The orbiter is no worse off than using a non-shared frequency.

B. Support of Near-Earth Testing

The next desire is support of near-Earth testing. As noted before, there is a need for missions to conduct in-flight tests on the local-link hardware onboard the spacecraft when they are still close to Earth. Near-Earth testing poses regulatory and technical problems. The main problem is the high-power uplink from an Earth station that is needed to conduct some of the tests. The uplink signal can cause interference to other users. The downlink is generally not a problem because it is weak and, hence, is not likely to interfere with other users.

The Mars Odyssey spacecraft is flying a UHF local-link payload for support of future landed missions. The Mars program requested that the equipment be tested post-launch in support of the MER 2003 mission, which will rely on Odyssey for much of its data return. MER wanted to be confident that the UHF equipment was working to maintain their current mission design. Testing the UHF equipment in flight with a ground station is problematic because the band is allocated for other services around the Earth. JPL had to overcome many hurdles to support the in-flight testing, and it may be more difficult to perform this type of testing in the future. Testing the downlink is not really an issue because the received power from Odyssey is so low. The real concern is a high-power uplink, which could interfere and even damage a satellite with a UHF receiver.

Testing with a UHF uplink from an Earth station is extremely difficult and should be minimized. Testing with an uplink in a suitable band can be accommodated subject to possible constraints.

1. Suitable Frequency Bands. From an in-flight testing point of view, it would be better to choose frequencies with an existing deep-space frequency allocation so as not to intrude on other bands when conducting in-flight tests. S-band and X-band are the two choices. They have existing allocations for deep-space applications.

There are factors, however, that may prevent use of the deep-space SRS frequencies for Mars local links. Compatibility with the DTE link is an example. One possible approach to mitigate this problem is to employ frequencies that are in the SRS allocations and are also adjacent to the deep-space allocations. With a frequency-agile radio that can operate in both the deep-space frequencies and the adjacent near-Earth frequencies, the local-link equipment can first be tested near Earth using the deep-space frequencies and later switched to the adjacent bands for Mars local operations. There are SRS allocations (i.e., near-Earth allocations) in both S-band and X-band:

(1) Earth-to-space: 2025 to 2110 MHz (S-band); 7190 to 7235 MHz (X-band)

(2) Space-to-Earth: 2200 to 2300 MHz (S-band); 8400 to 8500 MHz (X-band)

In addition, Ku-band is a possibility because of the existing SRS frequency allocations.

2. Near-Earth Testing Scenarios. There are two different scenarios for near-Earth testing if S-band or X-band (either the deep-space or the near-Earth allocations) is used. The landed element and the orbiter will have reverse frequency pairs for the uplink and downlink. The landed element can test most of its local-link hardware within the existing deep-space (or near-Earth) allocated spectrum. At X-band, the landed element will transmit at 8.4 GHz and receive at 7.2 GHz. The orbiter will have the reverse—transmit at 7.2 GHz and receive at 8.4 GHz. To test the orbiter's local-link hardware, the mission would have to request a waiver to operate out of band in the Space Research Service. (Coordinating with SRS users is believed to be easier that coordinating with other services.)

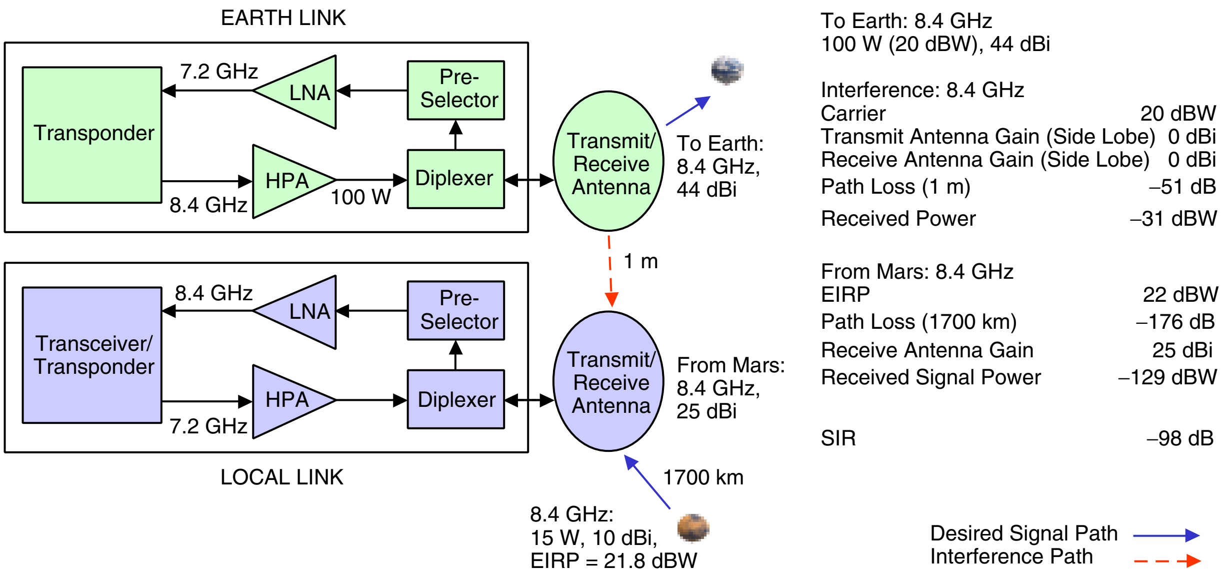
In addition, this requires that there be ground hardware that can operate at these frequencies. A simpler solution is to perform onboard self-testing between the DTE link hardware (7.2 GHz up and 8.4 GHz down) and the local-link hardware (8.4 GHz up and 7.2 GHz down). If one of the transceivers is frequency agile and can cover the whole band, this should be easily accommodated.

3. Onboard Self-Testing. The alternative to performing in-flight testing, with a ground station, is to have the spacecraft carry an onboard self-test capability. This can test the local-link electronics but not the complete system, including the antenna. The Deep Impact mission has an onboard self-test capability because it is carrying both halves of the radio link before release of one of the spacecraft just prior to encounter. The Electra UHF radio that NASA is developing will have some form of self-test capability as well. The receive capability of the spacecraft's local link can be tested with a continuous wave (CW) carrier signal from the ground. This would prove to be much less of a problem on an interference basis than transmitting wideband modulated data. If the local link has a frequency-agile transceiver, an uplink carrier can more easily be chosen that will not interfere with local users.

C. Compatibility with Existing DTE Equipment

The third issue is compatibility with the existing DTE equipment. The main issue is self-interference during simultaneous DTE and local-link communications. If the local-link frequency is at S-band or Ku-band, then there is no problem. These frequencies will not interfere with the DTE link, because all known Mars missions use X-band for the DTE link, although some also use S-band. This is an issue if both the local link and the DTE link are in the same frequency band, e.g., X-band. Even if the local link is in the adjacent near-Earth allocation and is 50 MHz away from the DTE channel, the power from the transmitted signal of an orbiting or landed element can saturate the front end of its receiver. This signal then would capture the receiver, preventing reception of the intended signal. This is the case for very strong signal interference. Figure 1 presents a diagram showing an example of this type of self-interference. Also shown in the figure is a rough estimate of the signal-to-interference ratio (SIR) and a specific set of assumptions used in the calculation. If the interference is not too strong, such as in the case when the interfering signal is from another spacecraft, then the receiver front end can pass both the desired and interfering signal, and filtering at intermediate frequency (IF) can filter out the unintended signal. Figure 2 shows this scenario.

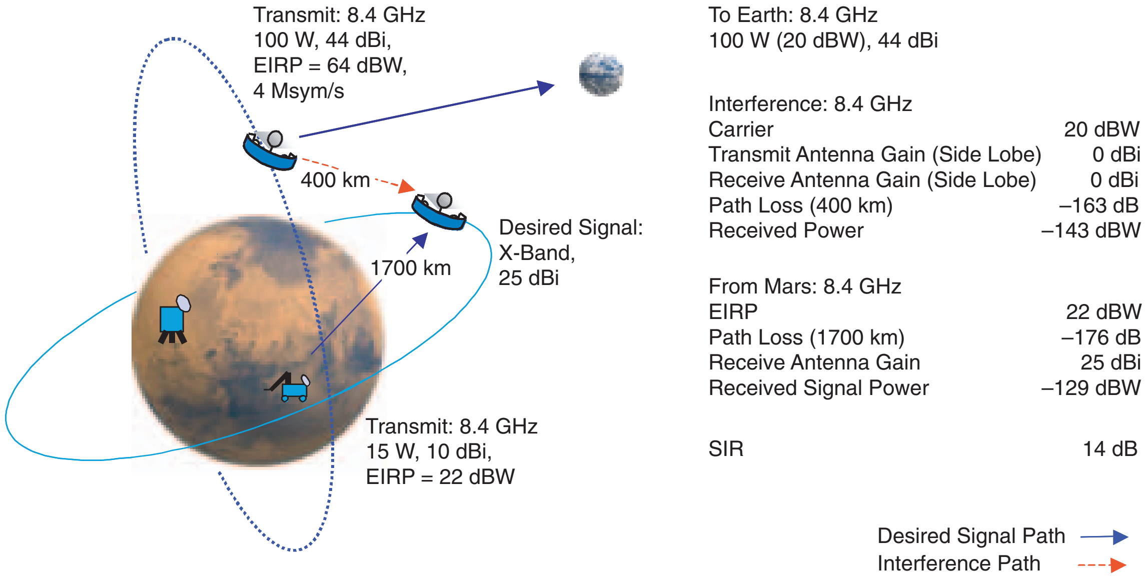
Self-interference is not a concern for a landed element. The forward and return frequencies are aligned, for both the local and DTE links, such that the lander will not transmit near either receive frequency. Also, it is unlikely that the landed element will have sufficient power to support transmitting both the DTE downlink and the local return link simultaneously. In addition, its sequence can be planned to preclude this from occurring.



To Earth: 8.4 GHz
100 W (20 dBW), 44 dBi

Interference: 8.4 GHz	
Carrier	20 dBW
Transmit Antenna Gain (Side Lobe)	0 dBi
Receive Antenna Gain (Side Lobe)	0 dBi
Path Loss (1 m)	–51 dB
Received Power	–31 dBW
From Mars: 8.4 GHz	
EIRP	22 dBW
Path Loss (1700 km)	–176 dB
Receive Antenna Gain	25 dBi
Received Signal Power	–129 dBW
SIR	–98 dB

Fig. 1. An illustration of self-interest (internal) when transmitting and receiving in the same frequency band. (Conclusion: The 8.4-GHz downlink (to Earth) will interfere with the 8.4-GHz local return link; similarly, the 7.2-GHz local forward link will interfere with the 7.2-GHz Earth uplink.)



To Earth: 8.4 GHz
100 W (20 dBW), 44 dBi

Interference: 8.4 GHz	
Carrier	20 dBW
Transmit Antenna Gain (Side Lobe)	0 dBi
Receive Antenna Gain (Side Lobe)	0 dBi
Path Loss (400 km)	–163 dB
Received Power	–143 dBW
From Mars: 8.4 GHz	
EIRP	22 dBW
Path Loss (1700 km)	–176 dB
Receive Antenna Gain	25 dBi
Received Signal Power	–129 dBW
SIR	14 dB

Fig. 2. An illustration of external (inter-satellite) interference when the same frequency band is used for Mars local links and DTE links. (Conclusion: Depending on geometry, antenna orientation, and other link parameters, potential interference may exist.)

The concern is for an orbiter, which is simultaneously communicating with Earth and a landed element. There are two possible scenarios for interference: transmitting to the Mars surface and receiving from Earth (at 7.2 GHz) and transmitting to Earth and receiving from the Mars surface (at 8.4 GHz). The first option may not be allowed. Some missions may choose not to transmit from an orbiter to a landed element at 7.2 GHz. (Note that for Consultative Committee for Space Data Systems (CCSDS) Proximity-1 protocols to work, there must be real-time acknowledgment packets transmitted from the orbiter down to the surface element.) Doing so could prevent both the orbiter and lander from receiving commands from Earth. This is true for the orbiter because of self-jamming and for the lander because its receiver is locked to the orbiter's forward link. These missions may choose to have the forward link from the orbiter to the lander at UHF. Although this requires having UHF equipment onboard, it will not have an adverse impact because most landed elements are expected to continue to carry UHF equipment in the future for low-rate links. The data rate in the forward direction typically is much lower than the return-link data rate and can be readily supported by the UHF local link. If the mission chooses to have the orbiter–lander forward link at 7.2 GHz, the resulting interference problem can be solved through operational coordination or planning. Depending on the orbiter's trajectory, the possible interference time may be relatively short.

Filtering could be employed to reduce the signal from the transmitter going into the receiver front end, but the receiver would suffer from a large insertion loss (5 to 10 dB). This might be acceptable for the local link because it may have very large margins, even for high data rates, but this would clearly be unacceptable for the deep-space link. A simple solution, achieved operationally, is to not support simultaneous communications for the two links. This probably is acceptable for a low-altitude orbiter where passes are typically less than 10 minutes in duration. Ceasing communications to Earth during this brief outage would not significantly impact the mission, although this will complicate mission operations. But at a higher altitude, e.g., 4350 km, orbiters can have pass durations of 2 hours or more. That is too big a bite to take out of the Earth-link schedule. The higher altitude is what is being considered for Mars Telesat, which also plans to use the higher-data-rate schemes.

The alternative is to choose S-band or Ku-band for the local link. They will not interfere with the orbiter's DTE link, most likely X-band. Of course, if the orbiter's DTE link is Ka-band, then there is no issue for any of the possible frequency choices. This assumes use of a Ka-band uplink to the orbiter or no X-band uplink during local-link communications.

D. Availability of Hardware

The fourth factor to consider is the availability of hardware in the respective bands. S-band and Ku-band are both popular commercial bands. X-band currently is used on many deep-space spacecraft. All of these are active bands, and the availability of components should not weigh heavily in deciding the best option for a high-rate Mars local-link frequency band.

E. Support of Approaching Spacecraft Navigation

The last desire is support of approaching spacecraft navigation. This would require that the orbiter have the capability to receive at the incoming spacecraft's DTE frequency, presumably 8.4 GHz. For now, this is envisioned as a one-way link. The approaching spacecraft would require a decent oscillator to provide reasonable Doppler data.

F. Other Issues

1. Performance. S-band is not that much higher in frequency than UHF. It requires a sizable antenna to achieve the necessary gain to overcome the increased space loss at S-band relative to UHF. The improvements in EIRP and G/T will be greater at X-band and Ku-band without requiring precise antenna pointing. The MERs will have an X-band EIRP of about 62 dBm and a G/T of −10 dB/K. Typical UHF values are an EIRP of 40 dBm and a G/T of −27 dB/K.

2. Mars Coverage. One of the downsides of increasing the frequency is that the antenna beam from the orbiter down to the surface will be smaller. The antenna will not cover the entire Mars disk. This precludes the possibility of having simultaneous return links from geographically separated landed elements. This is a minor drawback because of the small number of landed elements that will exist in the same region in the near future as well as the small number of simultaneous links that could be supported by the orbiter's relay-link electronics.

3. Propagation. Various propagation effects on a radio wave in the Mars region have been studied, and preliminary results indicate that the total zenith attenuation on a signal is about 0.5 dB for both UHF and S-band, 1 dB for X-band, and 3.5 dB for Ka-band. The study took into account effects of the ionosphere (absorption and scintillation), gas, fog, aerosol (haze), and dust in the Mars region. Although UHF and S-band have a lower attenuation, they are not suitable candidates for high-rate links.

4. Evolution. Figure 3 shows the current frequency scheme for Mars local links. The orbiter uses X-band up and down for its DTE links. The lander also has X-band DTE links. The local link is done with a single UHF frequency pair. Figure 4 shows a possible next step in the frequency scheme at Mars. The orbiter uses X-band and Ka-band for the DTE links. The lander has an X-band DTE link. The local links are done at UHF with high-rate X-band links. Either the deep-space X-band or the near-Earth X-band can be used. In the near-term, it is likely that missions will use the deep-space X-band. From spectrum management, missions operations, and interference avoidance considerations, missions should migrate to the near-Earth X-band when it is practicable. A possible far-future frequency scheme is shown in Fig. 5. It shows the orbiter using X-band up and Ka-band down for its DTE links. The landed element uses X-band up and down and Ka-band down for its DTE links. The local links use separate Ku-band equipment to support high rates for both the forward and return links. Future missions may continue to use UHF for low-rate local links (not shown in the figure).

V. Conclusion

All of the frequency bands considered in this study would provide adequate performance for Mars high-data-rate local links. Table 2 lists the pros and cons for each of the frequency bands. None of the bands is perfect, but based upon the discussion above, the recommendation at this time is to use the near-Earth X-band allocation for the high-data-rate local-link frequency for the near term. Using this band would provide a much wider bandwidth for high-rate communications. It would allow for reusing DTE radio equipment for a reduction in mass and cost. It would provide for greatly improved data throughput performance. It would not interfere with other spacecraft operating in the X-band deep-space frequency band. It also provides a better solution for performing near-Earth in-flight testing post-launch on a non-interfering basis.

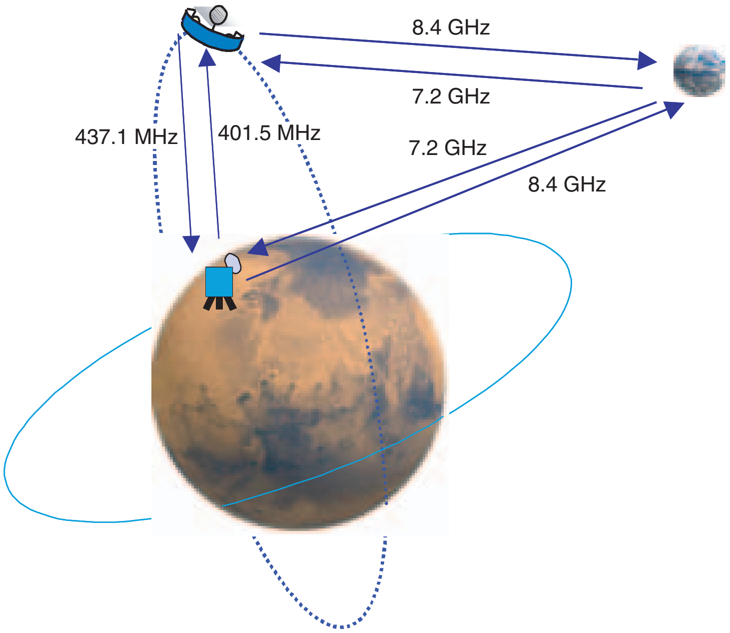
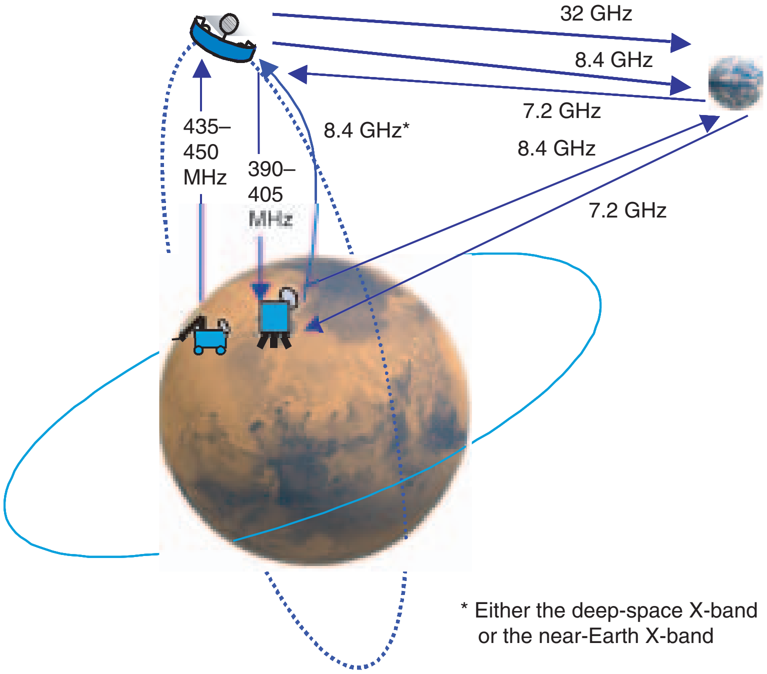


Fig. 3. Current frequency scheme at Mars: X-band DTE links and UHF local links.



* Either the deep-space X-band or the near-Earth X-band

Fig. 4. Near-future frequency scheme at Mars: X-band and Ka-band DTE links, UHF and X-band* local links.

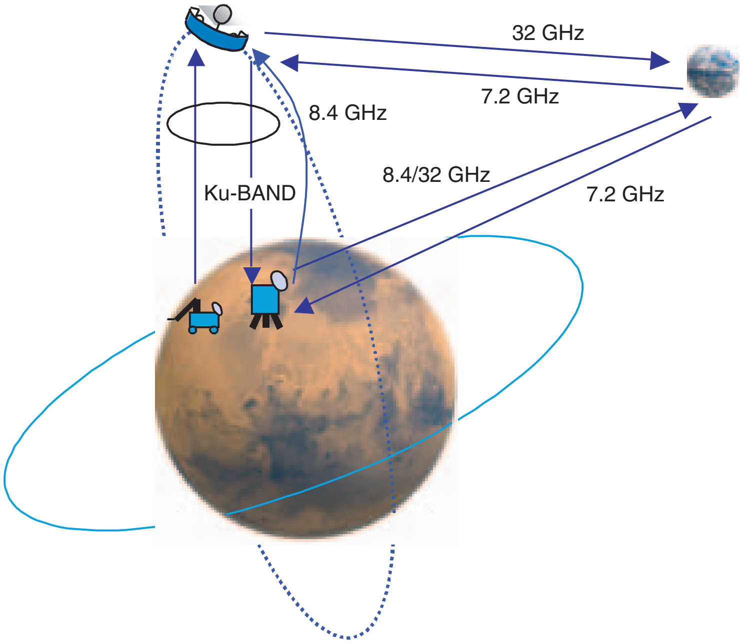


Fig. 5. Potential future Mars frequency scheme: uses X-band and Ka-band for DTE links and a dedicated Ku-band high-rate local link (mission may continue to use UHF for low-rate links).

The biggest downside to using X-band is the potential self-interference issue since X-band also is used for the DTE links. This can be overcome with filtering at a cost of increased insertion loss into the local-link receiver on the orbiter. The simplest solution is to avoid simultaneous DTE and local-link communications through mission planning.

The best option for a high-rate local link in the near future (beyond 2010) is to fly landers and rovers that work at X-band for both DTE and local-link communications and to fly orbiters that are dual-frequency—X-band and Ka-band capable. The orbiter can use X-band for cruise and emergency communications and Ka-band for high-rate science and relay data return at Mars. The orbiter should have a frequency-agile X-band capability to receive data from and transmit to the Mars surface. The orbiter then would be able to support simultaneous X-band local-link communications and a high-rate Ka-band downlink to Earth.

Table 2. Pros and cons for each of the frequency bands.

Parameter	S-band	X-band	Ku-band
Reuse of onboard equipment.	No reuse of electronics, possibly share antenna with second feed.	Landed element could share power amplifier, diplexer, and antennas. No reuse in orbiter other than antennas.	No reuse of electronics, possibly share antenna with second feed.
Support of near-Earth testing.	Use S-band deep-space/ near-Earth allocation.	Use X-band deep-space/ near-Earth allocation.	May be able to use SRS allocation at Ku-band.
Compatibility with DTE spacecraft frequency.	Fully compatible.	Potential interference issues if DTE link is at X-band. No concern if DTE is at Ka-band.	Fully compatible.
Technology maturity.	No issue.	No issue.	No issue.
Approaching spacecraft navigation (assume incoming spacecraft has X-band or Ka-band DTE frequency).	Does not support.	Does support with orbiter receiving at 8.4 GHz.	Does not support.
Link performance.	Only slightly better than UHF, need big antenna to support high rates.	Much better link performance with good pointing of HGA/medium-gain antenna (MGA)	Much better link performance with good pointing of HGA.
Propagation.	Low attenuation, same as UHF.	Slightly higher attenuation than S-band.	Slightly higher attenuation than X-band.