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1. Introduction

The Future Mars Communications Architecture report is the first part (Volume 1) of the two-volume deliverable from the IOAG working group on Mars and Beyond Communications Architecture. A separate report (Volume 2) will be produced, concerning the extension of the architecture to other deep space scenarios beyond Mars, including probes flying to inner and outer planets of the solar system, cometary missions, missions to the interstellar medium etc.

The overarching objective of the Volume 1 report is to define the communications architecture(s) that will serve as the framework for the IOAG member agencies, individually or collaboratively, to develop their communication assets that will be interoperable with each other as a minimum at the network, data link, and physical layers, to support all flying and future Mars missions.

The Mars region is the target of innumerable future missions, as illustrated in section 2, either of exploratory or scientific nature, with Agencies' exploration roadmaps ultimately heading towards human exploration in a collective effort towards the establishment of human presence at Mars beyond today's Earth low orbit and the coming Lunar outpost. Such global initiative requires an unprecedented level of international collaboration, in order to guarantee the fulfilment of challenging communications performance, in terms of system availability and latency, data rates and data volume, navigation accuracy, and at the same time to manage the system complexity that the steadily expanding missions set will determine, in terms of operations and exploitation.

In defining the Mars Communications Architecture, the study has taken into account the following drivers:

(1) The communication needs of all Mars missions planned by the member agencies for the next two decades, i.e., the period of 2020s through 2040s: as reported in section 2, toward 2030s there will be a mix of robotic science, robotic exploration, and human crewed missions. Mission trend analyses conducted so far have all indicated that a communications architecture, dramatically different than the one that has been in place since early 2000s, will have to be established in order to fulfill the unprecedented communication needs.

(2) The architectural "requirements" as envisioned for the international Moon-to-Mars exploration initiative: the Lunar exploration initiative currently planned and executed by IOAG space agencies is only part of the journey towards the end destination, i.e., the human exploration to Mars. In view of the above, an effort was made to re-use, wherever feasible and appropriate, solutions already defined in the frame of the Lunar Communication's Architecture working group.

(3) The advancement of communications technology: The sustained advancement in communications technology from the past decade to the next should spur many "tipping point technologies" to be infused during the next two decades for supporting the scientific investigations and human and robotic exploration. Consequently, this study has placed a heavy emphasis on the infusion of beneficial technology into the future Mars communications architecture, even for those of low technology readiness level (TRL) for the time being, taking into account the long term realization of the architecture.

(4) The commercial providers of communication services: it is expected that by the end of 2020s some companies will have succeeded in providing communications services to the Lunar exploration missions. Moving into the next two decades, it is conceivable that such commercial providers, as participants of the Moon-to-Mars initiative, will set their sights on the Mars, and be prepared for planning to deliver relay satellites/vehicles/platforms to its orbit and surface. When business cases permit, extending and augmenting their commercial Earth stations, originally used for Lunar communications, into the assets viable for Mars communications will be a reality. Taking into account the above, the study has, to the degree possible, investigated the commercial-friendly aspect of the architecture.

(5) The CCSDS and industry standards: in view of the underlying interoperability requirements, it has been imperative for this study to pick and choose the suitable standards as the solutions to the future Mars communications architecture. The convergence of multiple options from the rich repertoire of the standards produced and evolved by the CCSDS over the years was a key to the viability of the architecture. Furthermore, to accommodate fast, low-cost, commercial-enabled missions, the study has investigated areas where industry standards could be applied, like for example for the Mars surface network.

(6) The ITU-R and SFCG frequency band allocations: the study has taken into account the frequency and spectrum allocations plus the recommended use.

(7) The existing and planned new communication assets, capabilities, and services, at all space agencies and potential commercial providers, that are relevant to Mars communications.

The Mars Communications Architecture defined in this report encompasses the following elements, in terms of communications-related interfaces: Mars science orbiters, Mars exploration orbiters, Mars surface mobile vehicles and stationary platforms, Mars Transfer/Descent/Ascent & Return modules, and associated Earth ground stations and mission operations centers.

Communications links covered by the architecture include: Earth-Mars link, Mars proximity link, Mars cross link, Mars surface vicinity link, Earth orbiting relay link, and Earth space link extension.

The study has also addressed the Space Internetworking aspect of the architecture, i.e., the decomposition of the end-to-end architecture into the following networks: Mars relay network, Mars surface network, and Earth network. The interconnections between them has also been elaborated.

The study defines the specific services provided by the network communication assets within the Architecture to user missions, including not only communications services, but also tracking, navigation, and timing services, which will be of high interest to missions to be involved in future Mars exploration. In addition, the definition of relay service(s) has been formalized.

The study has focused on the interoperability among elements within the network, data link, and physical layers.

The physical layer of the Architecture has considered both RF and optical communications including specific frequency/wavelength bands.

Finally, the study has addressed user missions in three categories, robotic science, robotic exploration, and crewed exploration, covering the timespan from 2020s to 2040s.

The report is organized as follows: after the introduction constituted by the present section, the set of missions to Mars from the 2020s to the 2040s, and from the involved IOAG agencies, is presented in section 2, including a trend analysis based on the most important features and drivers of such missions. The following section 3 gives highlights about the communication system and capabilities employed by each Mars-faring agency to support their Mars missions. The section 4 is devoted to down-selecting standardized solutions, in terms of Frequency, Modulation, Coding, Ranging, and Link Protocol (FMCRL), from the large repertoire available in CCSDS, and also to identify potential gaps of CCSDS in specific areas deemed essential for the new architecture. In the same section key issues requiring further resolution are also presented, reflecting cases where different opinions across the various agencies could not be entirely resolved in the frame of the trade-off. The proposed Mars communications architecture is presented in section 5, based on tradeoffs and elaborations reported in the previous sections. The architecture includes Mars Communications, Mars Relay Networks, Mars Surface Networks, involved Earth Networks, a preliminary PNT Architecture for Mars Communications and Cross Support Services, including Mars end-to-end network management. Conclusions are reported in section 6, together with programmatic recommendations for follow-on.

2. Mars Mission Set – Towards ~ Early 2040s

2.1 Mars Missions per Space Agencies

Based on inputs from IOAG member agencies, Appendix A lists current Mars missions and spacecraft and also provides projections for future Mars missions and spacecraft for the next two decades. In total, there are about 40 missions and 63 spacecraft/vehicles. They cover a wide spectrum of mission types, i.e., science orbiters, science landers, science rovers, sample return vehicles, robotic precursors for human exploration, infrastructure platforms, dedicated relay satellites, crewed surface vehicles, and human habitats in Martian space and surface.

2.2 Trend Analysis of Mars Mission Set

An analysis on this mission set has led to a few important observations that have ramifications to the Mars communications architecture:

- The significant increase in mission launches: There would be about 15 missions with 22 spacecraft to be launched during this coming decade, i.e., 2022 – early 2030s. As compared to the last decade, i.e., 2010 – 2020, when 9 missions with 15 spacecraft were launched, this represents a remarkable increase. Looking back over the various past decades since 1960, it may be worth noting that there have been significant number of successful and failed spacecraft intended for Mars exploration (see Figure 2.2-1).

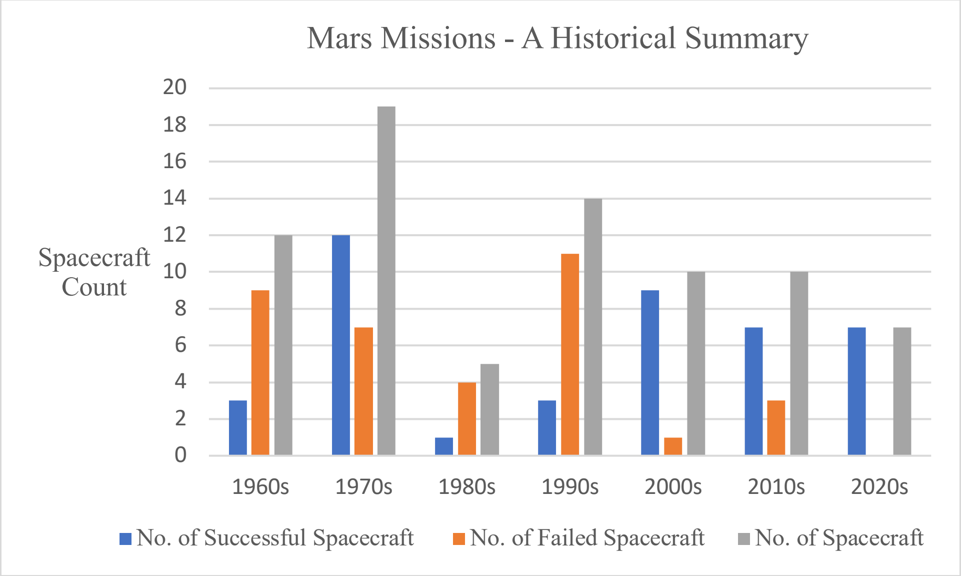


Figure 2.2-1. Historical Summary of the Number of Mars Spacecraft
(The graph is created based on data in https://en.wikipedia.org/wiki/List_of_missions_to_Mars)

- Science missions will continue to dominate the Mars exploration activities until late 2030s when the set of robotic precursor missions for human Mars exploration will begin to roll out.

- The trend toward Mars surface exploration: At least 7 missions have been planned to deploy a lander, a rover, or both during the next decade. In comparison, there were only 4 in the last decade. Sample return as a new type of Mars science missions seems to contribute to the trend.

- Inter-agency cross support: The decade-old practice of leveraging the services provided by other space agency's communication assets will be carried forward into the next decade almost by all 15 new Mars missions.

- The advancement of new technology through Mars exploration: Predictably, the wave of Mars missions will spur many "tipping point technologies" to be infused for supporting the scientific investigations and human exploration.

- The emerging Mars relay orbiters:

  Perhaps, most notable in the mission set table of Appendix A are the International Mars Ice Mapper mission and the Small demonstrator Mars Areostationary Relay Network. They would provide the first opportunity to begin developing a dedicated Mars communications relay infrastructure. If implemented, such infrastructure would reduce the cost and risk of future Mars missions and increase the return on investment, as measured by vastly greater data return. It would provide reliable, near-continuous support to surface and in-orbit users, providing essential capacity for the next decade that scales toward a human and robotic missions thereafter.

3. Mars Communications – Current and Future as Envisioned by Individual Space Agencies

3.1 CNSA's Mars Communication Capabilities

The TianWen-1 mission is the China Mars mission to implement orbiting Mars, landing and roving on Martian surface in one mission; it was launched in July 2020 and landed on Mars in May 2021. The TianWen-1 probe consists of an orbiter and an entry module including a stationary lander and a surface rover, Zhurong. The scientific objectives of the mission are to study Martian topography and geology, characterize the surface soil and water-ice distribution, analyze composition of the surface material, profile the Martian ionosphere, climate, and environment on Martian surface, and derive the physical fields (electromagnetic, gravitational) of the interior structure. There are 13 scientific instruments onboard the TianWen-1 probe, including 7 instruments on the orbiter and 6 instruments on the rover. The scientific instruments on the orbiter include the medium resolution camera, the high resolution camera, subsurface penetrating radar, magnetometer, ions and neutral particle analyzer and energetic particles analyzer. The scientific instruments on the rover include the topography camera, multispectral camera, subsurface composition analyzer, surface magnetic field detector and meteorological instrument.

3.1.1 Overview of TianWen-1 mission's Communication Architecture

The orbiter communicates directly with Earth in X-band, while serves as telecommunication relay for the entry module, the stationary lander and the surface rover, in both UHF-band and X-band. During the Entry, Descent, and Landing (EDL) phase, the entry module communicates with Earth through the orbiter relay in UHF-band. After landing, the lander and the rover communicate directly with Earth in X-band, or through the orbiter relay in both UHF-band and X-band. The communication architecture of TianWen-1 mission is illustrated in Figure 3.1-1.

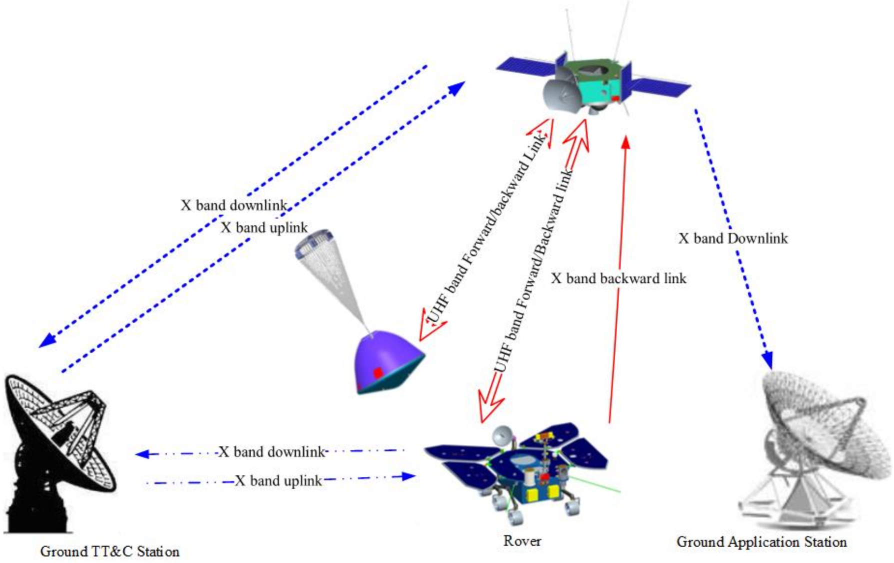


Figure 3.1-1. The communication architecture of the TianWen-1 mission

3.1.2 Description of TianWen-1 Mission’s Communication Capabilities

The TianWen-1 Mission’s Communication capabilities are summarized in Table 3.1-1.

Table 3.1-1. TianWen-1 space communications links

Space communications link	Frequency band /antenna	Uplink data rates	Downlink data rates
Communications between Orbiter and Earth	X-Band HGA	2000 bps	16384 bps for telemetry 16 kbps - 4096 kbps for data
	X-Band LGA	7.8125 bps	32 bps
Communications between Lander or rover and Earth	X-Band HGA	125 bps	32 bps - 4096 bps
	X-Band LGA	7.8125 bps	
Communications between entry module, lander or rover with Earth through the orbiter	UHF	1 kbps - 6.4 kbps Forward link	1 kbps - 2048 kbps Return link

3.1.3 Description of TianWen-1 Mission’s Communication Capabilities of Ground System

The global layout of China's deep space TT&C network includes a 66m deep space station in Jiamusi, northeast China, a 35m deep space station in Kashi, northwest China, and a 35m deep space station in Zapala, Neuquen Province, Argentina. The three antennas are shown in Figure 3.1-2.

Figure 3.1-2. Jiamusi 66m, Kashi 35m and Neuquen 35m deep space stations

The China's deep space TT&C network uses S, X and Ka frequency bands which are suggested by ITU, CCSDS and SFCG, and reported in Table 3.1-2. Up to date, both S-band and X-band have uplink and downlink capability, and Ka-band can be used for downlink, which has the capability to extend the uplink in the future. China's deep space TT&C network, summarized in Table 3.1-3, is suitable for lunar and deep space exploration missions, compatible with international mainstream TT&C systems for deep space missions, and capable of delta-DOR measurement.

Table 3.1-2. Frequency bands of China's deep space TT&C network

FREQUENCY BAND	UPLINK(MHz)	DOWNLINK(MHz)
S band	2025 ~ 2120	2200 ~ 2300
X band	7145 ~ 7235	8400 ~ 8500
Ka band	34200 ~ 34700	31800 ~ 32300

Table 3.1-3. Main characteristics of China's deep space stations

		Jiamusi	**Kashi**	**Neuquen**
Diameter		66m	35m	35m
EIRP	S band	>97.3dBW@10kW	>93dBW@10kW	>83dBW@1kW (solid state amplifier)
	X band	>108.3dBW@10kW	>104 dBW@10kW	>104dBW@10kW
G/T	S band	>41.8 dB/K@10°EL	>33dB/K@10°EL (without cryogenically cooled LNA)	>37dB/K@10°EL
	X band	>53.3 dB/K@10°EL	>49dB/K@10°EL	>50.2dB/K@10°EL
	Ka band	—	>56dB/K@10°EL	>56dB/K@10°EL

China's 35m/66m deep space TT&C equipment consists of antenna, servo and feed subsystem, transmitting subsystem, high frequency receiving subsystem, multi-functional digital baseband subsystem, time-frequency subsystem, and Delta-DOR raw data acquisition and recording subsystem:

1) The antenna, servo and feed subsystem uses large-aperture shaped Cassegrain antenna and beam waveguide feed mode, which can meet the requirements of multi-frequency bands operation, high system G/T value and high pointing accuracy.
2) The transmitting subsystem uses an S/X band 10kW klystron transmitter with a bandwidth greater than 95MHz (-1dB).
3) The high frequency receiving subsystem can perform low noise amplification and conversion of received S/X/Ka RF signals using cryogenically cooled LNA.
4) Multi-functional digital baseband subsystem is mainly used for command, telemetry, ranging and Doppler measurements. CCSDS PN ranging is also supported. The supported modulation systems include PCM/PSK/PM, PCM/PM, BPSK, QPSK, OQPSK, GMSK. The supported coding systems include convolutional codes, Reed Solomon (RS) codes, RS+Convolutional concatenated codes, Turbo codes and Low Density Parity Check (LDPC) codes in accordance with CCSDS standards.
5) The time-frequency subsystem is equipped with two active hydrogen masers to provide high-precision frequency reference signals and timing pulses required by other subsystems. It can also receive time code signals from external input or generate time reference signals required by the entire system through GPS or Beidou timing receiver inside the sub-system.

In addition, high-precision GPS common view receiver is configured to achieve high-precision time synchronization between stations.

6) Delta-DOR raw data acquisition and recording subsystem supports CCSDS standard and VLBI Mark5B standard raw data formats.

3.2 ESA's Mars Communication Capabilities

3.2.1 Overview of Agency's Mars Communications Architecture

ESA's current operational Mars missions include ExoMars Trace Gas Orbiter and Mars Express, which provide UHF proximity link data relay services to assets on the Mars surface. The current communications architecture is depicted in Figure 3.2-1.

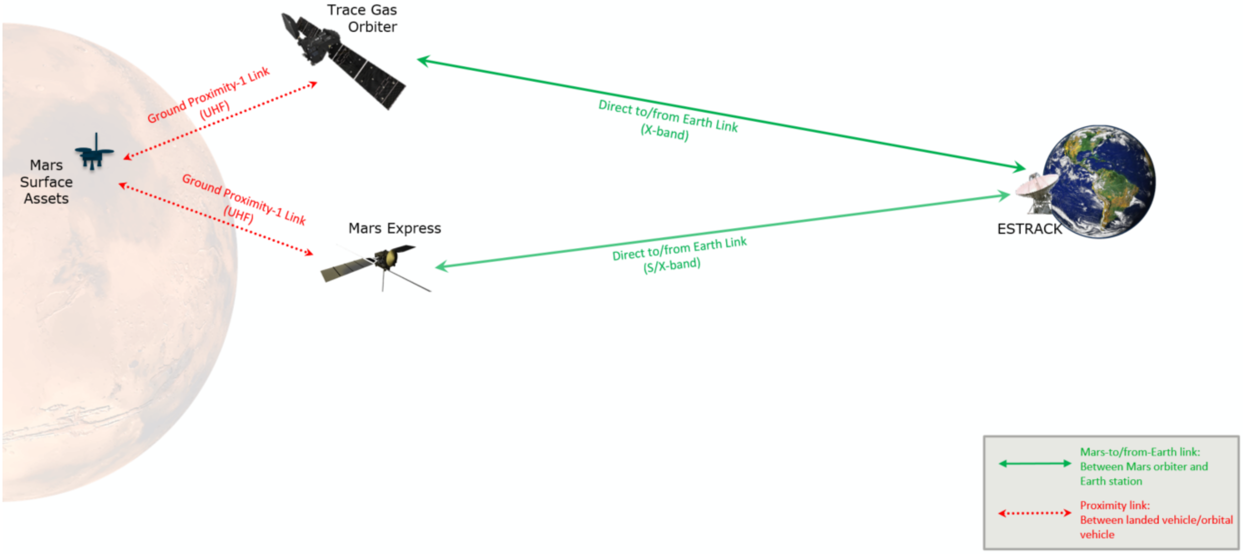


Figure 3.2-1: ESA's current Mars communications architecture

In the coming decade ESA's Mars missions will be supplemented by the upcoming ExoMars Rosalind Franklin Rover, the Sample Fetch Rover and the Earth Return Orbiter missions. The augmented communications architecture for this future near term scenario is depicted in Figure 3.2-2.

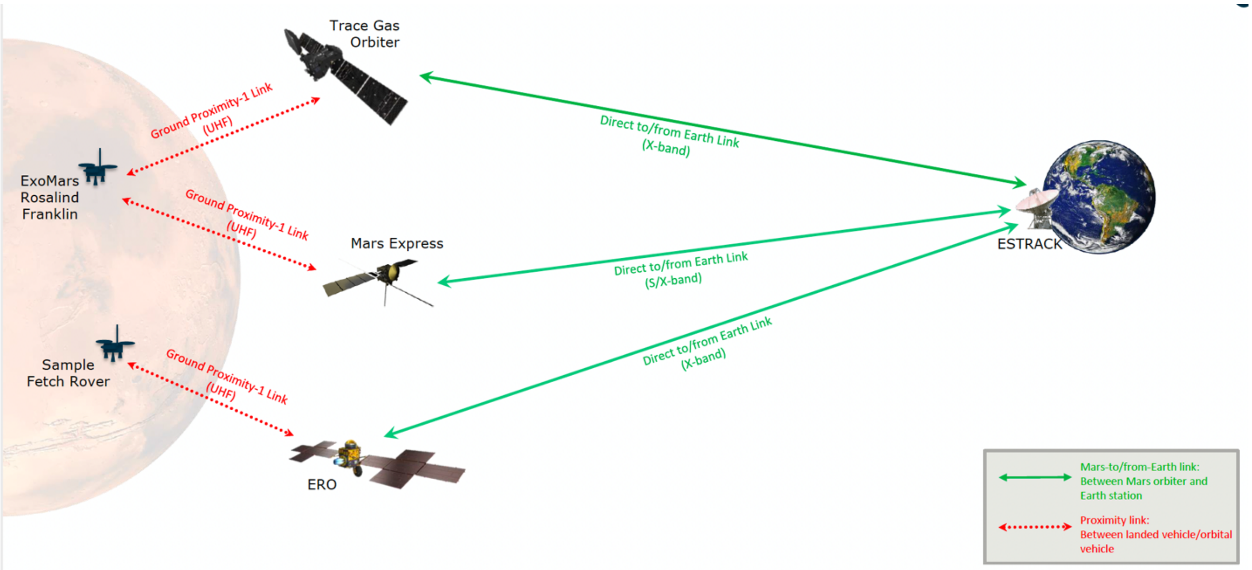


Figure 3.2-2: ESA's future near term Mars communications architecture

Looking to the future, ESA anticipates a significant role as a provider of a Mars communications and navigation service and will work alongside other agencies to realize a significant communications capability, using both RF and optical technologies, that will not only serve ESA missions but will also be made available for the international community.

3.2.2 Description of ESA's Mars Communication Capabilities of Flight System(s)

This section describes the ESA capabilities which are either existing (heritage), or are under development or planned for the Mars communications scenario, in the domains of radio frequency and optical communications. In the following, the main focus is on the core of the communication system, i.e., the transponder/transceivers, however several improvements on microwave equipment like amplifiers and antennas are ongoing. Among those, for the Mars scenario it is worth mentioning the development of a Ka-band TWT with the goal to reach 150 W of RF output power.

3.2.2.1 ESA heritage flight equipment for Mars

The heritage European flight equipment for Mars scenario include the following equipment:

Orbiters: X band deep space transponders

The reference European deep space transponder includes the following characteristics in a 3 kg mass:

- Integrated TC, TM & Ranging functionalities;
- Configurability of TC and TM data rates (up to 4 ksps in uplink and 5 Msps in downlink) and modulation schemes;
- Digital synchronization loops ensure robust tracking down to -154 dBm and in presence of large Doppler/Doppler rate;
- Extremely low phase noise (less than 2 deg-rms in X-Band integrated from 1 Hz to 1 MHz);
- Autonomous radio capabilities PN ranging as per [8];
- Simultaneous GMSK and PN ranging in downlink as per [2].

Orbiters/Martian assets: S band transponders

European equipment in S-band include units with high flexibility regarding uplink and downlink modulation schemes, uplink and downlink data rates, RF output power, frequency channels, Spread Spectrum codes and housekeeping interfaces making it suitable for most missions and platforms, up to ~8 Msps.

The heritage include specific S-band transceivers designed for intersatellite links with a reduced number of assets.

S-band equipment is also developed in Europe for smallsats/cubesats applications, typically employing Software Defined Radio (SDR) receivers.

Landers: UHF Proximity-1 transceivers

UHF CCSDS proximity-1[13][14][15] transceiver for Martian landers and rovers is available, compatible with all existing orbital assets at Mars (ESA and NASA). It supports the adaptive data rate, as well as the low power consumption - wake on hail mode. Data rates up to 2048 sps are available for the return link.

3.2.2.2 ESA flight equipment under development, which are of interest for Mars applications

For the Mars scenarios, the following development activities are on-going at ESA:

Orbiters: Development of IDST

The IDST (Integrate Deep Space and Radio Science Transponder) is a new Transponder unit that integrates the functionalities of the classical TT&C for deep space applications with new digital signal processing techniques w.r.t. current state-of-art represented by BepiColombo and Solar Orbiter communication systems. The new features are:

- dual band front end supporting X- and Ka-band;
- On-Board Radio-Science;
- advanced radiometric techniques (Enhanced or Wide-Band DDOR);
- autonomous receiver capabilities (Autonomous recognition of modulation format and symbol rate);
- demodulation at very low bit rates;
- subcarrier acquisition with large Doppler via FFT;
- MFSK tones transmitter;
- high data rates transmission in Ka band (up to 300 Msps).

The IDST is suitable for medium and large Mars orbiters that need to transfer high data volumes via Ka-band and to perform radio science. Its receiver in Ka-band will enable Mars missions to be operated down to 1 deg Sun-Earth-Satellite separation angle.

Orbiters: Development of UHF Proximity-1 transceiver for orbiters

The development of a UHF transceiver compatible with Proximity-1 protocol to be flown on-board Mars orbiters is on-going, to provide an European capability equivalent to the US-built unit on-board ExoMars TGO and NASA orbiters. The key requirement is that the new unit shall be based on a SDR design, to guarantee high degree of flexibility and adaptability to future needs and possible changes in the Proximity-1 protocol. The unit will be backward compatible with existing missions since it will implement the Proximity-1 protocol features defined in the standard. But it will also include new functionalities which may be useful in new missions, such as:

- higher data rates (>4096ksps);
- LDPC coding;
- QPSK/GMSK modulation;
- higher Tx output power;
- multiple channels to support simultaneous operation with more landers;
- emergency beacon detection;
- full Packet Utilization Service (PUS) compliance;
- on-board recording of demodulated or raw data for longer duration;
- in-flight full re-programmability.

As the unit will be based on state-of-the art technologies, an improvement in terms of SWaP characteristics with respect to existing products is also foreseen. The goal is to reach a TRL of 4 to 5 through an engineering breadboard manufacturing and validation. A follow-up will be required to reach higher TRL level.

Orbiters and landers: Development of dual mode (CDMA and standard) X/X or X/X-Ka band transponder breadboard

A deep space, dual standard transponder breadboard is under development at ESA, able to make use of both classical TT&C modulations and CDMA uplink and downlink. The CDMA mode supports the Multiple Spacecraft per Aperture architecture and enables the use of such device both for orbiters and landers, tuning the signal processing algorithms to the expected received powers in the uplink. In the downlink it works with coherent CDMA retransmission enabling thus also ranging. A follow-up to reach higher TRL is included in the technology roadmap.

Orbiters: Optical Communications - Mars-Earth links

A Mars-Earth optical link typically will require transmitted laser power at the range of 5-10 watt limited primarily by the availability of the electrical power. Such power levels are provided by optical amplifiers operating at the two wavelength bands of interest around the 1064 nm and 1550 nm. Such amplifiers have been already developed by ESA at 6Watt (at 1064 m) and at 10 Watt (at 1550nm). UK industry has also developed a 5W optical amplifier.

From the optical waveform point of view, the solution for supporting a direct Mars-Earth link shall rely on the so-called High Photon Efficiency (HPE) standard included in [4] and [5]. The HPE standard foresees maximum allowable data rate of 2.1 Gbps. Realistic simulations reveal that depending on conditions (the actual link distance, the telescopes diameters and weather conditions on the earth OGS) a Mars link will run at rates between few Mbps and hundreds of Mbps.

Orbiters: Optical Communications - Long range Inter-satellite links in Mars Orbit

Such links (e.g., with spacecraft in the areostationary orbit of 17600 km altitude and some tens of thousands of km link distance) can be supported by existing products of European industry that serve the relevant applications in Earth orbit. Such links can reach rates of several Gbps and require tens of Watt (with optical output power of some Watts). The exact figures can be tailored to the particular link requirements in order to ensure optimized power consumption.

Orbiters: Optical Communications - Proximity inter-satellite links between Mars orbiters

Such links can be supported by the products currently released by the same European industry that serve the small platforms and cubesat market. Such links can reach rates of several Gbps and require tens of Watt (with optical output power of 0.3 to 2 Watts) The exact figures can be tailored to the particular link requirements in order to ensure optimized power consumption.

Orbiters: Optical Communications - Proximity links between Mars orbiters and Mars surface assets
Such links, if relevant, can be served by products currently released by the European industry for similar DTE applications. They can reach rates of several Gbps and require less than 10Watt (with optical output power of less than 1Watt). The exact figures can be tailored to the particular link requirements in order to ensure optimized power consumption

Landers/Habitats: Optical Communications
ESA has been developing for several years Optical Wireless solutions for short distance intra-spacecraft and extra-spacecraft, for example in solar panels applications. This technology can serve Habitats or other landers in case there are concerns of RF interference. The technology can be based on either diffused transmission using reflections or line of sight. LEDS are usually employed instead of laser sources. Data rates are usually at the range of some Mbps of lower for the diffused transmission and can reach Gbps for the direct line of sight transmission.

3.2.2.3 ESA flight equipment in development for Moon, adaptable to Mars

The following developments of lunar flight systems can also be adapted for Mars scenario:

Orbiters: Development of UHF and S-band Proximity-1 transceiver
The Lunar Pathfinder relay spacecraft will be equipped with a Moon link payload, currently under development, capable of operating 2 full duplex channels simultaneously:

- S-band (2025-2110 MHz (forward 0.5 - 128 kbps), 2200-2290 MHz (return 0.5 kbps to 2 Mbps)
- UHF (390-405 MHz (forward 0.5 - 128 kbps), 435-450 MHz (return 0.5 kbps - 2 Mbps).

The Moon link payload is used to send (and receive) to (from) the lunar user assets using a Proximity1 protocol. The Earth link is realized in X-band, 7190-7235 MHz (forward up to 30 kbps), 8450-8500 MHz (return ≤ 5 Mbps). The Proximity-1 protocol is designed to work with multiple assets in the same coverage area, and with a variety of assets of various performances. The communication service works on a “store and forward” architecture, allowing flexibility regarding to relative position of the lunar assets, the data-relay spacecraft, and the Earth ground station. Data is stored in the payload until links are available.

Orbiters: HLCS K-band transceiver and S-band transceiver for the Lunar Gateway (orbit to orbit and orbit with surface)
The development of the HALO Lunar Communications System (HLCS) is managed by European industry on behalf of ESA. HLCS is a single module encompassing Lunar communications for Surface and Orbiting Assets. The system follows the ICSIS standard[37] and provide RF links from Gateway to the Lunar Systems from the Moon Surface up to 70000 km and down to few tenths of km in S-Band and from 400 km up to 70000 km in K-Band. In both bands it features variable data rates and modulations to adapt to variable link qualities. Return link supports up to 50 Msps in K-band and 200 ksps in S-band. It features an automatic HGA tracking function for K-Band HGA and supports ranging in S-Band.

Moon assets: Development of K-band high data rate transceivers
A K-band high speed receiver unit breadboard is currently under development. Features include:

- Operating frequency tuning to support any 100 MHz bandwidth within the full band from 22.55 GHz to 23.55 GHz.
- Demodulation of SRRC-OQPSK signal at information data rates ranging from 10 Mbps up to 100 Mbps.
- Decoding of LDPC encoded uplink signal (using AR4JA codes[3]).
- Autonomous receiver capabilities:
    - Autonomous acquisition of uplink signal (not-ground aided approach). Ground-aided acquisition approach also supported.
    - Autonomous data rate detection (from a pre-configured set of 4 rates).
    - Autonomous detection of presence of either uncoded or coded (out of 4 possible code rates) signal.
- Ability to withstand signal fades up to 2 seconds.

Orbiters: Optical communications
Studies are in progress at ESA about the needs of the lunar communications where existing products of the European industry can be readily adapted communicating with a 1m optical ground station (OGS), e.g. the one available at Tenerife. The telescope size and available optical power are adequate to support such links up to the HPE protocol maximum data rate of 2.1 Gbps. Higher data rates up to 10 Gbps have been shown also to be feasible with a 1 1-2meters OGS but the reception scheme has to be different from the HPE protocol.

There has not been a dedicated Optical Communication Terminal developments for the lunar links yet. Currently ESA has in its work plan developments for the receiver detectors (photon counting technology) as well as the transmitter beacon to equip the OGSs. Such technologies can be adapted for use in the Mars-Earth links.

3.2.2.4 ESA flight equipment development to be started

The following development activities, interesting for Mars, are extracted from the ESA's TT&C technology roadmap for potential future funding and implementation. They are just mentioned here for sake of completeness:

Orbiters: High data rate Ka-band transceiver for DTE/DFE link
The digital processing part of the earth to moon K-band transceiver can be leveraged to build a high data rate Ka-band transceiver for Mars.

Orbiters and landers: Development of miniaturized X band transponder
To reduce the mass and power consumption, a miniaturized X band DST is an appropriate solution for small to medium orbiters with moderate data volume needs, as well as for landed assets with DTE link.

Mars assets: S-band and K-band transceiver for Lunar or Mars user asset (orbit<->orbit, orbit<->surface and surface<->earth)

Such transceivers will follow the ICSIS standard[37] and are meant to communicate either to the Gateway or to Earth in K band and with the Gateway in S-band. Such development can be adapted to the Martian scenario.

Mars assets: Development of UHF and S-band Proximity-1 transceiver for landers
Such transceiver will follow the Proximity-1 standard and possibly could be extended as a dual standard Proximity-1 + ICSIS[37] in S-band to increase the interoperability.

Orbiters: Optical Communications - Mars-Earth link
Higher power amplifier assemblies up to 100 Watts both at 1064nm and at 1550 nm are planned to start in Q1 2022, to be delivered by 2024. Such amplifiers can increase the data throughput for the Mars-Earth link.

Furthermore, recent studies on the ESA HYDRON concept have highlighted the potential need for telescopes up to 40cm diameter. Similarly size telescope is suited for the Mars-Earth link. Developments of telescopes of this size may be initiated in the coming years depending on the utilization

3.2.3 Description of Agency's Mars Communication Capabilities of Ground System(s)

ESA tracking network (ESTRACK)
The European Space Agency owns and operates a network of antennas with diameter ranging from 5m to 35m (ESA tracking network, ESTRACK, see Figure 3.2-3), for supporting ESA and third parties' spacecraft during both critical and routine mission phases. ESTRACK provides the space-ground radio frequency communication link for data acquisition, command and tracking services, and includes a network of deep space antennas located at New Norcia (Western Australia), Cebreros (Spain) and Malargüe (Argentina). Their strategic locations uniformly distributed on Earth provide around-the-clock coverage to space missions. The combination of southern and northern hemispheres sites represents an optimum configuration for interferometric measurements of spacecraft positions in the plane of the sky. These measurements enable very precise orbit determination during critical mission phases (e.g., Mars orbit insertions, asteroids fly-bys) as well as during routine operations, as required.

Figure 3.2-3. ESTRACK core and cooperative networks
(ESA deep space antennas sites are shown in orange background)

As far as Mars communications scenarios are concerned, and neglecting the obvious need of supporting early mission phases close to Earth and during cruise, the key ESTRACK resources are the 35m antennas located in the above mentioned sites (see Figure 3.2-4). Each site currently hosts one 35m antenna, however a new terminal is under construction at New Norcia, to be completed by 2025, and feasibility studies are on-going in cooperation with JAXA, related to the buildup of a new terminal in Malargüe. All existing antennas over the three sites support X-Band uplink and downlink according to the allocations reported in Table 4.2-1 for links with Earth. Ka-Band downlink is also supported at Cebreros and Malargüe, and will be available at New Norcia after completion of the new antenna. Ka-Band uplink is available at Malargüe for radio science applications, currently used for BepiColombo, and to be used for JUICE. S-Band is supported only by the existing terminal in Norcia, however it will not be available in the new terminal under construction. The antennas support additional frequency bands for Category A missions (in X-Band and K-Band), however not of interest within this report.

Figure 3.2-4. Existing ESA 35m antennas at New Norcia (left), Cebreros (middle) and Malargüe (right)

The ESA deep space antennas are being upgraded, by installation of cryo-feeds at X-Band and Ka-band, to enhance their downlink performance. After the completion of the cryo feeds upgrade, to be completed by 2025, the G/T in clear sky and at high elevation of the deep space antennas will be around 55.5 dB/K at X-Band and around 63 dB/K at Ka-band, with slight differences depending on the site. The EIRP exceeds 108 dBW (including a pointing loss) in the three sites, and is achieved by use of 20 kW klystron-based high power amplifiers (HPA, lower EIRPs are achievable with 2 kW HPAs and 500 W solid state amplifiers). Along the current decade it is planned to install 80 kW transmission in at least one deep space site (likely New Norcia) thus leading to 6 dB improvement for the EIRP for the involved antenna. Together with the planned and progressive introduction of LPDC codes for the on-board telecommand systems, reliable commandability will be achievable at Mars largest distance as well as in the outer solar system up to the "ice giants", even when confronted with contingency commanding through low gain antenna. All deep space sites host accurate and stable clocks based on hydrogen maser technology, with ADEV below 1E-15 over several thousands of seconds, ensuring reliable Doppler tracking for all interplanetary missions. Concerning modulation, coding and data link layer, the ESA backend has a very large coverage of CCSDS recommendations.

Optical Ground Stations for the Mars Earth link
ESA works currently towards equipping the 2.1 m diameter ARISTARCHOS telescope in Greece for use for Optical Communications. Among others, a demonstration is expected to be performed with the NASA PSYCHE spacecraft at distances beyond the orbit of Mars. Hence the Tx/Rx equipment at the OGS facility of ARISTARHCOS could be readily used for the Mars-Earth link.

Furthermore, ESA owns an OGS in Tenerife with 1m diameter and is about to equip the Astronomical telescope in Crete, Greece also with 1 m aperture.

As part of the efforts to engage ESA into the NASA PSYCHE mission the Agency plans to develop a 5000 watts transmitter at 1064 nm to be used as a transmission beacon. Similarly, there is a number of activities looking at very sensitive detectors (see developments for the Moon adaptable to Mars in section 3.2.2.3) which will equip the OGS and shall be used for the Mars-Earth links since they represent the state of the art.

3.3 ISRO's Mars Communication Capabilities

3.3.1 Overview of ISRO's Mars Communications Architecture

ISRO's Mars Communication Architecture is demonstrated and proven in its first maiden mission to Mars, the Mars Orbital Mission (MOM) also called as Mangalyaan Mission. The MOM entered Mars orbit in the year 2014 with one of the many objectives of proving the indigenous capability of planning & executing the deep space communication architectures for performing many mission critical operations in Earth bound, Martian transfer and Mars insertion orbits.

MOM carried five payloads: IR spectrometers, Alpha-photometers, Composition Analyser, a methane sensor for proving the evidence of existence of life on Mars and a colour camera to picture out topology and topography of Mars surface. The successful operations of the science payloads till date, generating enormous data on Mars is an evidence of robustness of system engineering design, mission planning and well proven communication architecture that was put in place to enable India in joining the club of Mars faring nations and reaching a unique position of reaching the Mars in its very first attempt.

The communication architecture of MOM had been configured into three phases namely the launch and early phase of operations, which are Earth bound maneuvers, the second being cruise phase and partially the Mars insertion phase, the third being the post Mars injection phase. The initial phase of communication operations (TTC) right from the launch to a distance of 400000 km is supported by an on-board S-band, Low Gain Antenna (LGA). For the ground communications, a network (of 11m, 18m and 32m diameter antennas) of deep space network (DSN's), JPL and Global ground stations including ship bound terminals for the continuity of visibility coverage is planned.

The communication in the cruise phase was supported by the on-board S-band Medium Gain Antenna (MGA). The MGA is also designed to support Mars insertion phase. For the injection and post injection communications operations of the Mars orbiter an S band High Gain Antenna (HGA, see Figure 3.3-4) is utilized with two coherent transponders powered with two high power Travelling Wave Tube Amplifiers (TWTA) to support the EIRP requirements with good link margins. Aiding the link is a highly sensitive receiver with -135 dBm carrier acquisition signal threshold that is programmed with sequential ranging. This arrangement, shown in Figures 3.3-1 and 3.3-3, is put in place to ensure robust communication management for distances of 214 million kilometers and beyond with good Delta-DOR, Ranging and Orbit determination accuracies which altogether helped ISRO in precision insertion of MOM in its orbit of 365 x 80000 km.

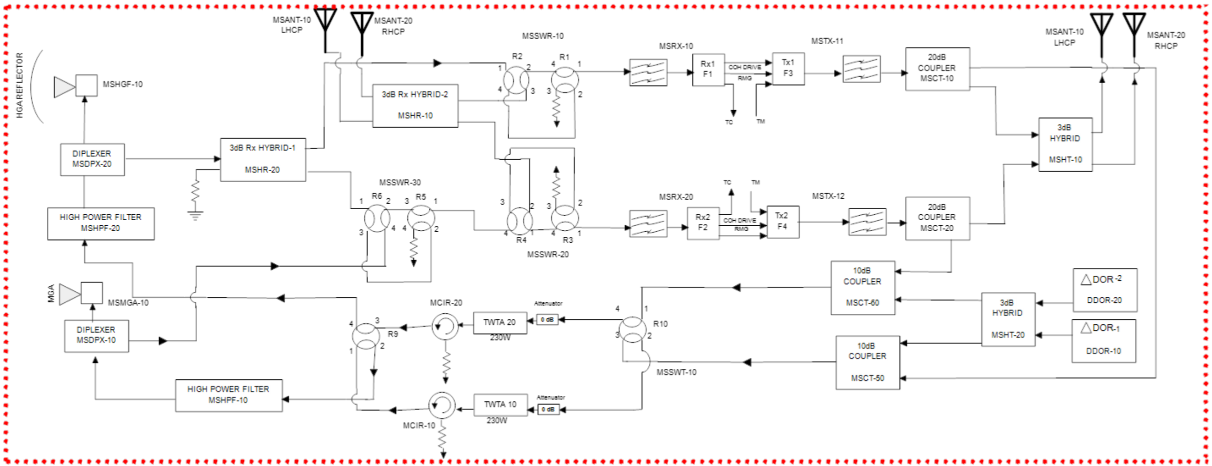


Figure 3.3-1. S-band TT&C, data handling and ΔDOR system

The full Mars Orbiter Mission Communication Architecture, comprising S-Band uplink and downlink over multiple links is shown in Figure 3.3-2.

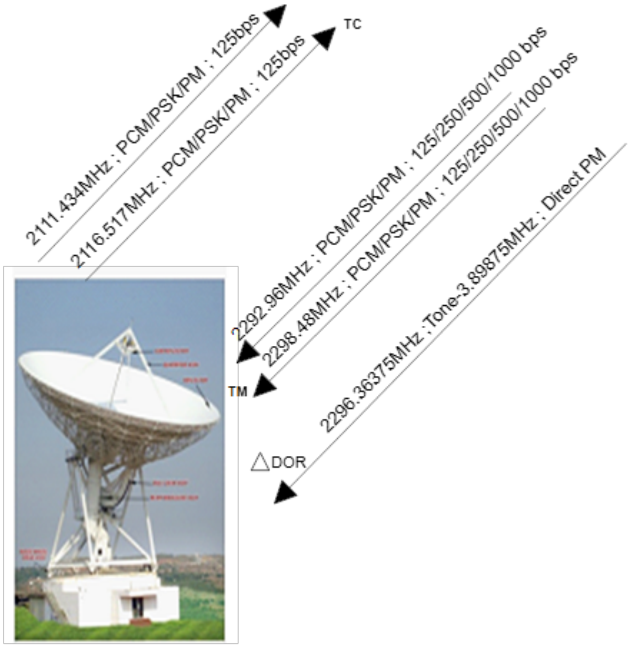


Figure 3.3-2. Mars Orbiter Mission (MOM) Communication Architecture

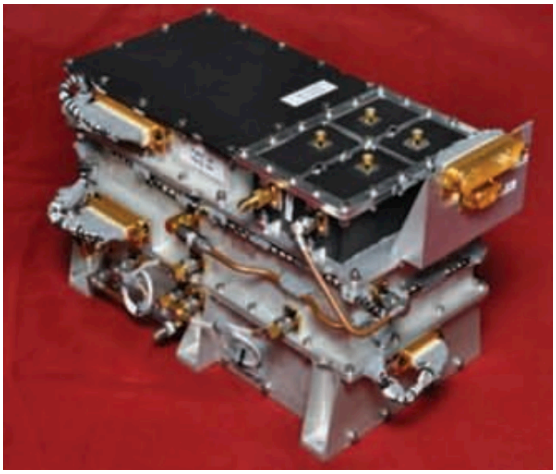


Figure 3.3-3. Highly sensitive receiver of MOM

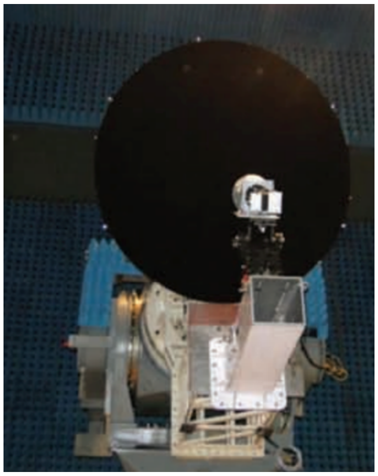


Figure 3.3-4. The HGA antenna of MOM

The TTC link in S-band is programmed to have a data rate of 125 bps. The commanding scheme adopted is fully compatible to CCSDS standards. The, ISRO Telemetry and Tracking center in Bangalore, India & JPL/NASA ground networks are used for TTC using PM/PSK modulation schemes. Telemetry and payload data is transmitted in S-band using time division multiplexing. Data transmission rates are designed to be selectable with options of 5/10/20/40 kbps based on the link requirements. Coding used is turbo rate 1/2, modulation is BPSK, data formats compatible with CCSDS TM format.

The following Figure 3.3-5 provides an overview of some of the ground stations used for Mars orbiter communication. The Table 3.3-1 summarizes the uplink and downlink frequencies used for TTC, Ranging etc. in the frame of the Mars communication architecture.

Figure 3.3-5. Network off Ground Stations used in MOM communication

Table 3.3-1 Frequencies and Modulation adopted for Mars Communication Architecture

Phase	**Frequency Band**		**Modulation**	
	Uplink	**Downlink (TM & Data)**	**Uplink**	**Downlink**
Earth Bound, Cruise phase and Insertion phases	2110 MHz to 2120 MHz	2290 MHz to 2300 MHz	PCM/PSK/PM	PCM/PM for transponders and BPSK for data transmission
Frequency used for Delta-Differential One-Way Ranging for OD accuracy improvements				
Carrier	2296.36375 MHz	**Tone**	3.89875 MHz	
Turn Around Ratio for TTC				
240/221				

3.3.2 Description of ISRO Mars Communication Capabilities of Ground System(s)

ISRO's Mars Orbiter Mission's, ground systems capabilities are controlled and monitored by the ISRO Telemetry Tracking and Command Network (ISTRAC) which is the master control center by providing centralized communications support to all the TTC ground station network and Indian Space Science Data Center (ISSDC). The ground segment systems are designed and established to form an integrated system supporting both launch phase, and orbital phase of the mission.

The Indian Deep Space Network (IDSN) at Bylalu, a campus near Bangalore, India, is an extension of ISTRAC, and is equipped with 18-m and 32-m diameter terminals. In addition, one 18-m antenna is coming up at the IDSN campus to support India's first lagrangian Solar Mission, called Aditya-L1.

The IDSN D32 station is a 32-meter antenna with S/X beam wave-guide composite feed. The Antenna has surface accuracy in the range between 0.1 and 0.3 mm rms, and has composite beam-wave guide feeds, one in S-band and the other in X-band. Both feeds are capable of supporting right and left circular polarizations for respective receive and transmit bands. The beam wave-guide feed is part of the configuration in order to have the advantage of higher efficiency, higher power handling capability in uplink and low losses in uplink and downlink chains. The antenna is fully steerable in azimuth +/-270^0 and 5^0 to 89.5^0 in elevation. Maximum tracking velocity is 0.4^0/second and can be accelerated to 0.01^0 /seconds^2 in both axes. MOM has adopted a minimum tracking velocity of 0.1 millidegrees per second to take care of deep space mission requirements.

The 11-meter, 18-meter and 32-meter antennae supported the Mars Orbiter Mission in the TTC requirements in following ranges of the mission.

- 11-meter Ground Stations
  - Telemetry support up to 400000 km using LGA.
  - Tele-command support up to 2.7 million km for Tele-command using LGA.
- 18-meter Ground Stations
  - Telemetry support up to 40 million km using MGA.
  - Tele-command support up to 23 million km for Tele-command using MGA.
- 32-meter Ground Stations
  - Telemetry support up to 400 million km using HGA.
  - Tele-command support up to 400 million km for Tele-command using HGA.
- Δ-DOR: for OD accuracy improvements

MGA and HGA were used for accurately determining the Orbit accuracy along with TT&C transponders during the important phases of the mission.

The following are the major characteristics of the existing 18-m and 32-m DSN network used for MOM.

Dual band (S/X) uplink and downlink capability: Both, IDSN 28-m antenna & IDSN 32-m antennae (Figure 3.3-6 and 3.3-7 respectively) are equipped with uplink and downlink capability in S-band and only downlink in X-band. The new D18 station will have X-band uplink capability also.

Carrier acquisition capability: Acquisition can be achieved with very low signal level (low C/No) by employing receiver phase locked loop (PLL) with tracking bandwidths as small as 100 mHz.

Very low demodulator threshold: The downlink systems operate down to the demodulator/decoding Es/No threshold, which helps in recovering of complex coded data.

Multi-Decoding: The baseband systems support all kind of de-coding like Viterbi, RS, concatenated, turbo de-coding (down to rate 1/6) required for typical deep space missions.

High end server class computers: To support high speed Payload data acquisition.

Cryogenically cooled LNAs: D32 is equipped with cryogenically cooled LNAs for achieving extremely low system temperature (Tsys) of the antenna.

Beam Waveguide S/X feed System: The D32 is equipped with a beam waveguide system (BWG) to take the advantage of higher efficiency, higher power handling capability and very low loss in downlink and uplink chains.

20-KW S-band uplink: The D32 high power system enables very high station EIRP.

Gravity Deflection Correction: Five-axis sub-reflector control system (D32) is used for gravity deflection correction.

Multiple Ranging : In addition to standard tone ranging, ESA code / PN ranging standards required for typical deep space missions are supported. Very low Range PLL threshold is achieved by having PLL bandwidth down to 1 mHz.
Full CCSDS compatible. Supports SLE gateway for cross support requirement for any missions.
Very High Frequency Stability :Extremely stable station clocks like cesium and Active Hydrogen Maser are used for achieving very high frequency stability and phase noise performance.
Pointing Accuracy : Good Station Pointing Accuracy (15 mdeg.) required for supporting mission in both S & X band.

Figure 3.3-6. The IDSN-18m antenna

Figure 3.3-7. The IDSN-32m antenna

The following Table 3.3-2 and 3.3-3 depict the detailed specifications of the existing 18-m and 32-m DSN network used for MOM.

Table 3.3-2. D18 Major specifications

Parameter	Unit	Specification
Antenna Diameter	Meter	18.3
Antenna Mount		EL over AZ
Antenna Azimuth Coverage	Deg.	+/- 270
Antenna Elevation Coverage	Deg.	2 – 89.5
Receive Frequency band (S-band Receive) Transmit Frequency band (S-band Transmit) Receive Frequency band (X-band receive only)	MHz	2200 – 2300 2025 – 2120 8025 – 8500
Receive G/T (at 10^0 El.) S-band X-band	dB/K	 31.0 40.0
Antenna Beamwidth S-band X-band	Deg.	 0.46 0.12
Receive Polarization		RCP and LCP

Parameter	**Unit**	**Specification**
No. of D/L carriers supported in S-band		Two
No. of D/L carriers supported in X-band		One
Transmit EIRP (S-band)	dBW	80
Transmit Polarization		RCP or LCP - selectable
Antenna Tracking Rates (max.) Azimuth Elevation	Deg./sec	 10.0 1.0
Tracking Acceleration Rates (max.) Azimuth Elevation	Deg./sec^2	 5.0 0.5
Tracking Modes		Manual, Slew, Program, Star Track, Standby
Antenna Pointing Accuracy	Deg.	0.02
Frequency Standard		Highly accurate atomic clock based time / freq. information from NaVIC timing center
Allan Deviation 1 Sec 10,000 sec		 5x10^{-12} 8.5x10^{-14}
Phase Noise (10 MHz) 1 Hz offset 100 Hz offset		 -115 dBc -145 dBc
Telemetry Processing		
TTC Processor		Cortex CRT DS
Receiver IF Frequency	MHz	70 MHz +/-4
Dynamic Range	dBm	-20 to –120 dBm
Modulation types		CCSDS Compatible PM / BPSK / QPSK / OQPSK
Demod Sub-Carrier Freq	KHz	5 – 1024
Data Rates		NRZ: 100 bps – 10 Mbps Bi-Φ: 100 bps – 5 Mbps
Coding Supported		CCSDS: RS, Viterbi, concatenated code Turbo code down to rate 1/6
Telecommand Encoder		As per CCSDS
Modulator IF Frequency	MHz	230 MHz +/-4
Ranging Standards		ESA-100, ESA User, ESA Code, CCSDS PN sequence,

Table 3.3-3 D32 Major specifications

Parameter	**Unit**	**Specification**
Antenna Diameter	Meter	32
Feed type		Beam Waveguide architecture
Antenna Mount Configuration		Wheel & track
Antenna Azimuth Coverage	Deg.	+/- 270
Antenna Elevation Coverage	Deg.	5 – 89.5

Parameter	**Unit**	**Specification**
Frequency band S-band Receive S-band Transmit X-band Receive X-band Transmit	MHz	 2200 – 2300 2025 – 2120 8400 – 8500 7145 – 7235
Receive G/T (at 10^0 El.) S-band X-band	dB/K	 36.5 47.0
Antenna Beamwidth S-band X-band	Deg.	 0.28 0.07
Receive Polarization		RCP and LCP
No. of D/L carriers supported in S-band		Two
No. of D/L carriers supported in X-band		One
Transmit EIRP (S-band 2 KW / 20 KW)	dBW	84 / 94
Transmit EIRP (X-band)	dBW	98 dBW
Transmit Polarization		RCP or LCP - selectable
Antenna Tracking Rates (max.) Azimuth & Elevation	Deg./sec	0.4
Tracking Acceleration Rates (max.) Azimuth & Eelvation	Deg./sec^2	0.01
Tracking Modes		Manual, Slew, Program, Standby
Antenna Pointing Accuracy	Deg.	0.015
Frequency Standard		Highly accurate atomic clock based time / freq. information from NaVIC timing center
Allan Deviation: 1 Sec 10,000 sec		$1.5\text{x}10^{-13}$ $2.0\text{x}10^{-15}$
Phase Noise (10 MHz) 1 Hz offset 100 Hz offset		 -120 dBc -145 dBc
Telemetry Processing		
TTC Processor		Cortex CRT DS
Receiver IF Frequency	MHz	70 MHz +/-4
Dynamic Range	dBm	-20 to –120 dBm
Modulation types		CCSDS Compatible PM / BPSK / QPSK / OQPSK
Demod Sub-Carrier Freq	KHz	5 – 1024
Data Rates		NRZ: 100 bps – 10 Mbps Bi-Φ: 100 bps – 5 Mbps
Coding Supported		CCSDS: RS, Viterbi Concatenated code, Turbo code down to Rate 1/6
Telecommand Encoder		As per CCSDS
Modulator IF Frequency	MHz	230 MHz +/-4
Ranging Standards		ESA-100, ESA User, ESA Code, CCSDS PN sequence,

3.3.3 Future Infrastructure Expansion OF Communication Infrastructure in ISRO

ISRO is planning to have next succession mission to Mars in the near future. The mission configuration, communication architecture and payloads are now in the study phase. For these missions, the communication is planned in X band and Ka bands.

To support future Ka-band requirement, ISTRAC has initiated upgrade of D32 station for Ka-band. ISRO is also exploring possibilities of positioning some ground stations including Deep Space Antennae in the hemisphere in collaboration with the other space agencies

3.4 JAXA's Mars Communication Capabilities

Japan Aerospace Exploration Agency (JAXA) has an interest in the exploration and science around Mars. These activities are coordinated with international collaborations.
The Martian Moons eXploration (MMX, 2024-2029 sample return) for returning the surface materials of the Martian satellite Phobos, and the Mars Ice Mapper (MIM, 2026-) for observing the underground of Mars with L-band Synthetic Aperture Radar (SAR), are the near future Mars missions in JAXA's plan.

3.4.1 Overview of JAXA's Mars Communications Architecture

Direct communications between the ground stations and the Mars orbiters including landing phases are the baselines. Table 3.4-1 shows the main characteristics of Mars communication with the main *Misasa* 54 m station (MDSS54) described in Secion 3.4.3, including the period when MMX described in Section 3.4.2 is in the vicinity of Mars.

JAXA deep space stations are located only in Japan, and overseas stations are used by agreements with international partners during long-hour mission operation sequences, the period when the spacecraft on the ecliptic plane is invisible from the Northern Hemisphere and DDOR data acquisition for precision orbit determination. Figure 3.4-1 shows JAXA Mars mission communications diagram.

Table 3.4-1: MMX Communications Specification summary

	Bitrate (minimum)	Distance (max)	Spacecraft	Ground
X-band Uplink	1 kbps	2.5 AU	HGA, MGA	MDSS54
	8 bps	2.5 AU	LGA	MDSS54
X-band Downlink	32 kbps	2.5 AU	HGA (Earth pointing)	MDSS54
	4 kbps	2.5 AU	MGA	all stations
	8 bps	2.5 AU	LGA	MDSS54
Ka-band Downlink	128 kbps	2.5 AU	HGA (Earth pointing)	MDSS54

Reed-Solomon & Viterbi Convolutional concatenated coding or Turbo coding (Rate=1/2, 1/3, 1/4 and 1/6) can be used for error correction *etc.* of Mars communications. USLP is not supported.

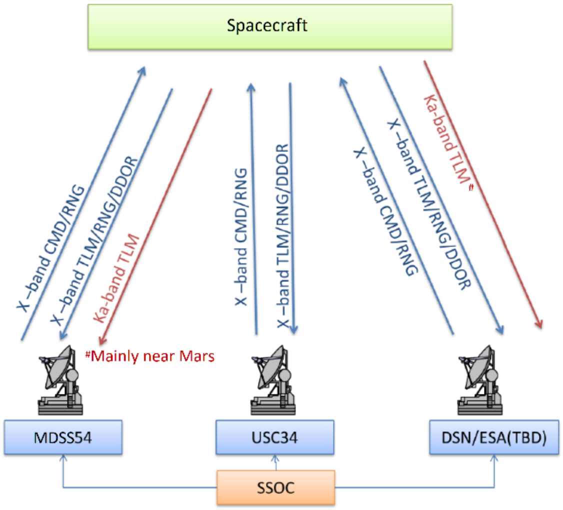


Figure 3.4-1: JAXA Mars mission communications diagram. Picture Credit: JAXA

3.4.2 Description of Agency's Mars Communication Capabilities of Flight System(s)

Mars missions have not been carried out for about 20 years, but communication technologies have evolved thanks to asteroid and other deep space missions, so these heritages will be used for Mars communications.

In addition to the X-band TT&C, 32 GHz Ka-band direct communication link enables large-volume data transmission including 8K high definition images. In addition to three LGAs (Low Gain Antenna), MMX, shown in Figure 3.4-2, communicates through X-MGA (Medium Gain Antenna) or Ka/X-HGA (High Gain Antenna).

The X-band Transponder (X-TRX) for TT&C is under development in other missions and Ka/X-band Deep Space Transponder (DST) are flight-proven by international partners.

There is some overseas equipment onboard on MMX. The proximity link capability of MMX Rover developed by DLR and CNES is described in the respective sections of the agencies.

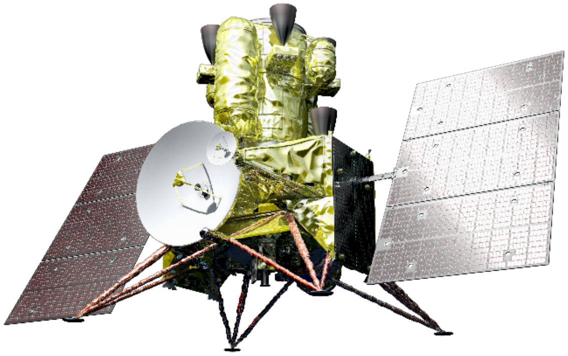


Figure 3.4-2: MMX. Picture Credit: JAXA

3.4.3 Description of Agency's Mars Communication Capabilities of Ground System(s)

There are two antennas for deep space missions in Japan shown in Figures 3.4-3 and 3.4-4. *Misasa* 54 m station (MDSS54) is capable of X-band uplink and X/Ka-band (simultaneous in preparation) downlink, and *Uchinoura* 34 m station (USC34) is capable of X-band uplink and downlink. Table 3.4-2 shows MDSS54 and USC34 Communications Capabilities.

Figure 3.4-3 (Left): *Misasa* 54 m (MDSS54), Figure 3.4-4 (Right): *Uchinoura* 34 m (USC34).
Picture Credit: JAXA

Table 3.4-2: JAXA *Misasa* 54 and *Uchinoura* 34 Communications Capabilities

	Freq. bands	MDSS54	USC34	Remarks
EIRP	X 7.145-7.235 GHz	> 142.6 dBm (20 kW & 69.6 dBi)	> 138.7 dBm (20 kW & 65.7 dBi)	(Tx Power & Gain)
G/T	X 8.4-8.5 GHz	> 53.3 dB/K	> 47.7 dB/K	EL > 15 deg, Cryo feeds, 8.2-8.7 GHz for geodetic VLBI
	Ka 31.8-32.3 GHz	> 59.3 dB/K		
Lat. Lon.		36°08'27" N 138°21'08" E	31°15'16" N 131°04'42" E	

Figure 3.4-5 shows the block diagram of MDSS54 X/Ka-band ground station. The antenna adopts beam waveguide mirrors and there are several options for Mirror #6: "no mirror" only for Ka-band reception without X-band uplink, "solid metal mirror" only for X-band, and "Dichroic mirror (FSR: Frequency Selective Reflector)" for both X/Ka-bands. Mirror #5 can be rotated allowing future extensions to other frequency bands. X-band SSPA consists of GaN HEMT solid-state devices. 125 W from each power amplifier is coupled into eight 48-way power combiners to input 20 kW to the X-band feed.

At present, external users communicate with the SLE gateway at SSOC (Sagamihara Space Operation Center) Operation LAN after protocol conversion, but near future TT&C operation will be possible via the SLE gateway at the station to communicate with TLM/CMD Processor directly.

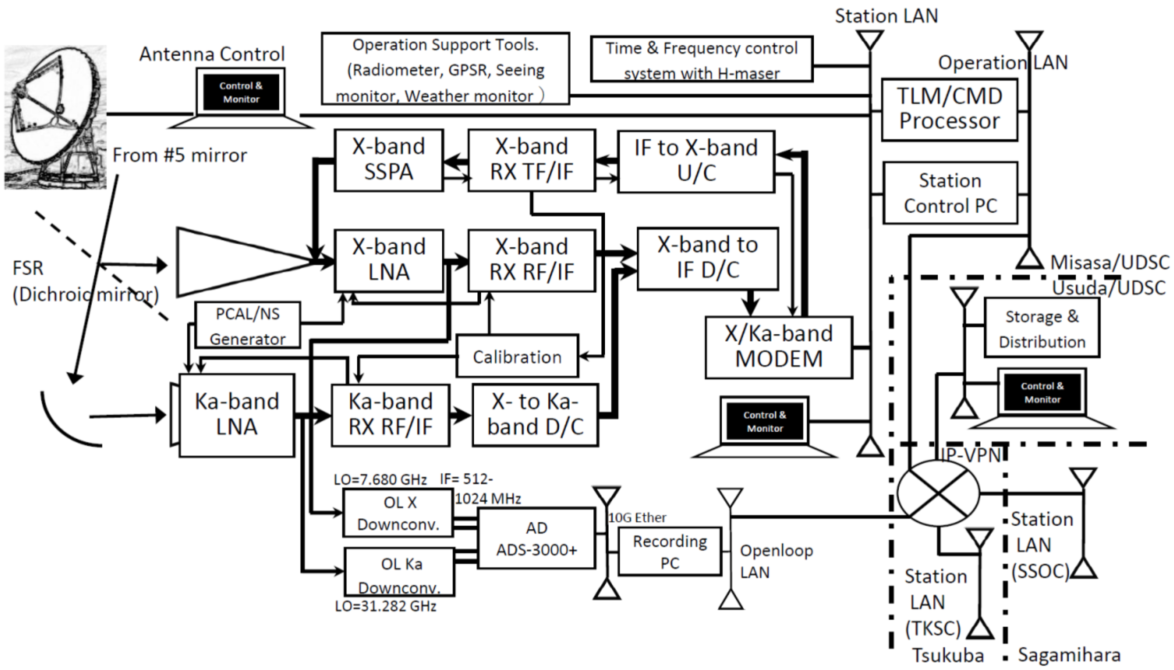


Figure 3.4-5: Block diagram of JAXA *Misasa* 54 m (MDSS54) X/Ka-band station. Picture Credit: JAXA

3.5 Roscosmos' Mars Communication Capabilities

The space agency of the former Soviet Union started the first Mars mission in 1960. After several attempts in a decade, the agency successfully conducted the world's first Mars orbiting mission, the Mars 2, in 1971. Most notably, the Mars 2 mission achieved a flight record of 362 orbits. Roscosmos has inherited a set of deep space communication assets and continued to performs activities in preparation for its future Mars exploration.

The Roscosmos owns antennas which are suitable for Mars communications, in particular the 64m antennas at Kalyazin and Bear Lake exhibit a X-Band G/T of 58.2 to 58.5 dB/K at high elevation and in clear sky. Such antennas currently support ExoMars TGO during its routine mission phase. The nominal EIRP is 113.5 dBW, for the X-Band uplink capability currently available at Kalyazin.

The Roscosmos is supporting, in collaboration with ESA, the ExoMars program, both in terms of ground antennas well as with the provision of the Kazachok lander, which will deliver the ESA's Rosalind Franklin rover on the surface of Mars.

3.6 NASA's Mars Communication Capabilities

3.6.1 NASA's Present Mars Communications Architecture - Overview

At present, NASA's operational Mars missions include three Mars orbiters, i.e., the Mars Odyssey (launched 2001), the Mars Reconnaissance Orbiter (MRO, launched 2005) and the Mars Atmosphere and Volatile EvolutioN (MAVEN, launched in 2013), and three landed vehicles, i.e., the Curiosity rover (launched 2011), the InSight lander (launched 2018), and the Perseverance rover (launched 2020) plus the Ingenuity helicopter. They are supported by a communications architecture which has the following key characteristics:

- Maximum commonality exists in the communications systems of the various missions. Communication assets and capabilities for an individual mission tend to inherit those from the previous mission(s) with minimum adaptations. Most ostensibly are the Small Deep Space Transponder (SDST), as the radios for direct-with-Earth communications, and the Electra which is a software defined radio (SDR) for proximity link communications. SDST direct to Earth radios are used on all six operational spacecraft, and for proximity UHF links, the Electra radio is used on four with older CE505 proximity link radios used on InSight and Odyssey.
- All six missions are supported by the Deep Space Network (DSN). They benefit from the multi-mission services provided by the DSN.
- The three lander/rover missions rely on relay capabilities provided by the three NASA orbiters as well as ESA's Trace Gas Orbiter (TGO) spacecraft, which also carries Electra relay radios. In the past, Mars Express has also provided some relay services.. In fact, all NASA and ESA science orbiters, past and present since 1996, have carried proximity radios and antennas to provide relay services to Mars surface missions as "additional duty." The science orbiters, as a results, in fact behaves as service-providing elements.
- Inter-agency cross support has been extended from ground assets to flight assets. Not only do all NASA's Mars missions benefit from the cross support services provided by ESA's ESTRACK and JAXA's ground networks (GN), but also, on the flight side the relay services provided by ESA's science orbiters, i.e., the Trace Gas Orbiter (TGO) and Mars Express, have played a pivotal role for data return from NASA's lander/rover missions.

Figure 3.6-1 gives an overview of NASA's present Mars communications architecture. Forming the backbone of the end-to-end system are the direct-with-Earth (DWE) link using X-band and proximity link based on UHF-band. Table 3.6-1 summarizes the key attributes of the DWE link. [Note: The DWE links include both the downlink, i.e., the DTE link, and the uplink, i.e., the DFE link.]

Table 3.6-1 Key attributes of direct-with-Earth (DWE) links of NASA's Mars missions

Mission	Frequency band	Maximum downlink data rate (ksps)	Maximum uplink data rate (ksps)	Spacecraft antenna diameter (m)	Spacecraft antenna gain (dB) (transmit)	Spacecraft transmit Power (W)
Odyssey	X-band	221.2	4	1.3 (HGA)	38.3	15
MRO	X-band	6,000	4	3 (HGA)	46.7	100
MAVEN	X-band	936	4	2 (HGA)	42.35	100
Curiosity	X-band	20	4	0.28 (HGA)	25.5	15
InSight	X-band	0.02	4	MGA	6.8	15
Perseverance	X-band	20	4	0.28 (HGA)	25.5	15

(Note: The MRO is equipped with 32 GHz Ka-band capability as well. The capability was demonstrated during cruise phase. But due to a hardware anomaly later, the plan to switch to yet-to-be used redundant Ka-band hardware was considered too risky. So, Ka-band is unlikely to become operational for such mission.)

In addition, almost uniformly among them the various Mars missions apply a set of common, standard methods/techniques for the communications over DWE links. These include those identified in Table 3.6-2.

Table 3.6-2 Communication parameters of direct-with-Earth (DWE) links of NASA's Mars missions

Modulation	Ranging	Coding	Space data link protocol	Application layer protocol
Uplink: PCM/PSK/NRZ & PCM/PSK/PM Downlink: PCM/PSK/PM, BPSK, QPSK	Sequential ranging, delta-DOR	Uplink: BCH; Downlink: Reed Solomon-Convolution Concatenated code, Turbo code	Telecommand (TC), Telemetry (TM), Advanced Orbiting System (AOS) for return link	Downlink: CCSDS File Delivery Protocol (CFDP) [* Mars Odyssey is an exception*]

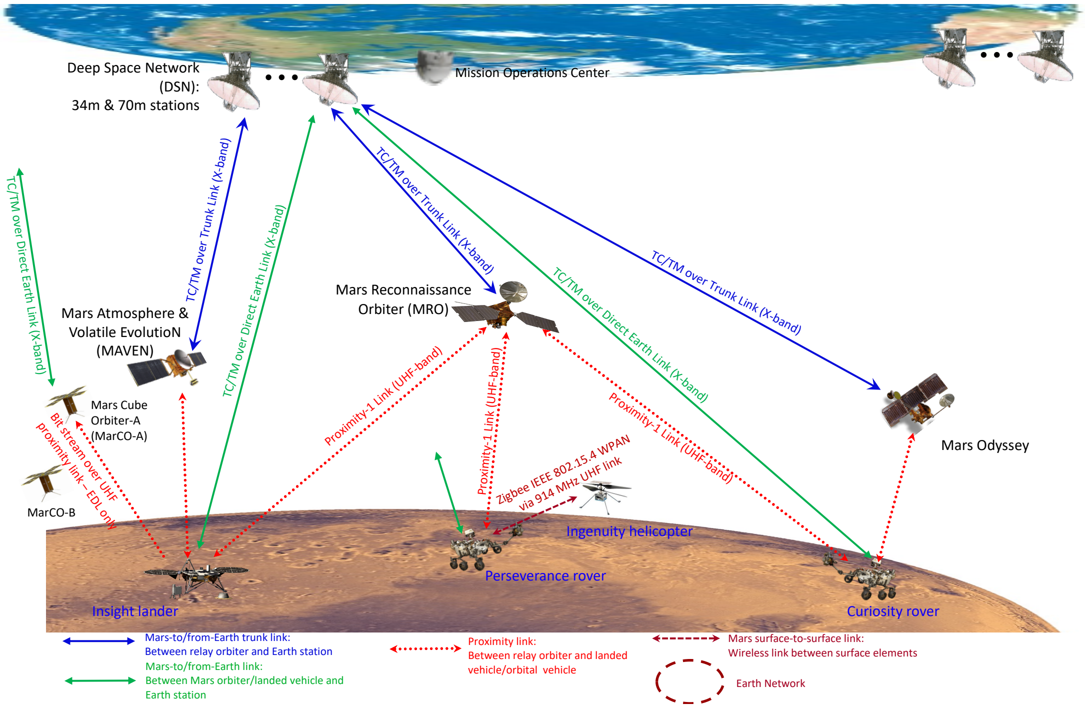


Figure 3.6-1. Overview of NASA's Present Mars Communications Architecture

The relay services enabled by the UHF link have been key to the success of NASA's Mars lander/rover missions. The UHF link for relay has been used by them for the entry, descent, and landing (EDL) and surface operations phases. During the EDL phase, through the UHF link with a science orbiter in view they were able to provide extensive information about the spacecraft critical events. For instance, the Mars Cube Orbiters (MarCO) managed to capture the EDL data from the InSight lander through their open-loop recording capability. The data were then transmitted to the DSN for post-processing to recover valuable carrier and telemetry data. During the surface operations phase, Curiosity, InSight, and Perseverance all rely on the relay orbiters of

NASA and ESA to return large volume of science data at very low-energy-per-bit. In fact, the InSight lander was designed to be a UHF-only mission since, like its predecessor the Phoenix lander, it is not equipped with HGA and is not capable of any meaningful direct-to-Earth communications.

Although the five science relay orbiters are not interconnected, the fact that they are interoperable to support the landed vehicles qualifies them as a collective entity, the Mars Relay Network. The present-day Mars Relay Network routinely acquires and returns 3-4 Gb/sol science data. Figure 3.6-2 shows the total data volumes, from the NASA's landers/rovers, returned by the Mars Relay Network over the period of 4 January 2004 to 20 March 2021. As shown on the graph, Perseverance returned 2.3 Gbits of data within its first 48 hours on the surface of Mars through orbiting relays to DSN. Most recently, in mid-2021, the relays have provided ~1.0 Gb/sol for Curiosity, and ~250 Mb/sol for InSight, and 2 Gb/sol for Perseverance, for a total about roughly 3.25 Gb/sol. Since the current lander and rovers can typically send data to Earth at rates that are more than 1000x faster (typically ~ 1 Mbps) via relay links, compared to the very slow direct to Earth rates from the Mars surface (typically < 0.5 kbps), only a tiny fraction of the data have been sent directly from the surface.

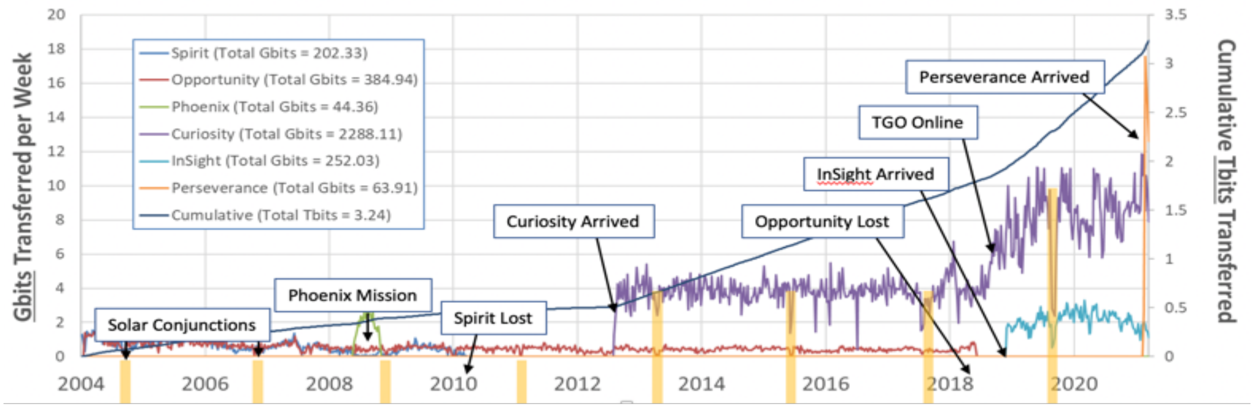


Figure 3.6-2. Total data volume returned by Mars Relay Network (4 January 2004 to 20 March 2021)
(Provided by Steve Lichten and Roy Gladden, May 2021)

Communications over the UHF link between a landed vehicle and a relay orbiter are in compliance with the CCSDS Proximity-1 protocol[13][14][15], which covers both physical and space data link layers, including the MAC sub-layer and coding/synchronization sub-layer. The link design can achieve a maximum data rate at 2 Mbps. Coding scheme is primarily the convolutional code as defined by the Proximity-1 standard. Perseverance, however, recently has also started using the LDPC code (at the coding rate 1/2) for its return proximity link. So far, NASA's relays have offered only the data delivery service, no tracking, navigation, or time service. However, measurements of the Doppler shift on the UHF signal during a relay pass provides a precise determination of the position of a landed vehicle in the Martian reference frame. Such Doppler measurements have been used by the navigation team to improve the position knowledge of the lander/rover after EDL (in a non-real-time, non-in-situ fashion). It takes a few UHF relay passes to acquire sufficient Doppler measurements to reduce the position uncertainty down to < 30m. To that end, the use of Doppler and ranging measurements acquired over the proximity link to enable the real-time navigation appears quite promising in the future Mars relay network.

At space data link layer, the UHF interface abides by the Proximity-1 protocol. The “sequence controlled” (reliable) link is the nominal protocol. Bit stream (unreliable) mode that bypasses the Proximity-1 protocol is available for off-nominal cases and for EDL. The adaptive data rate mode (ADR) takes advantage of the ability of the Proximity-1 protocol to control different data rates on the fly.

3.6.2. Description of NASA’s Mars Communication Capabilities of Flight System(s)

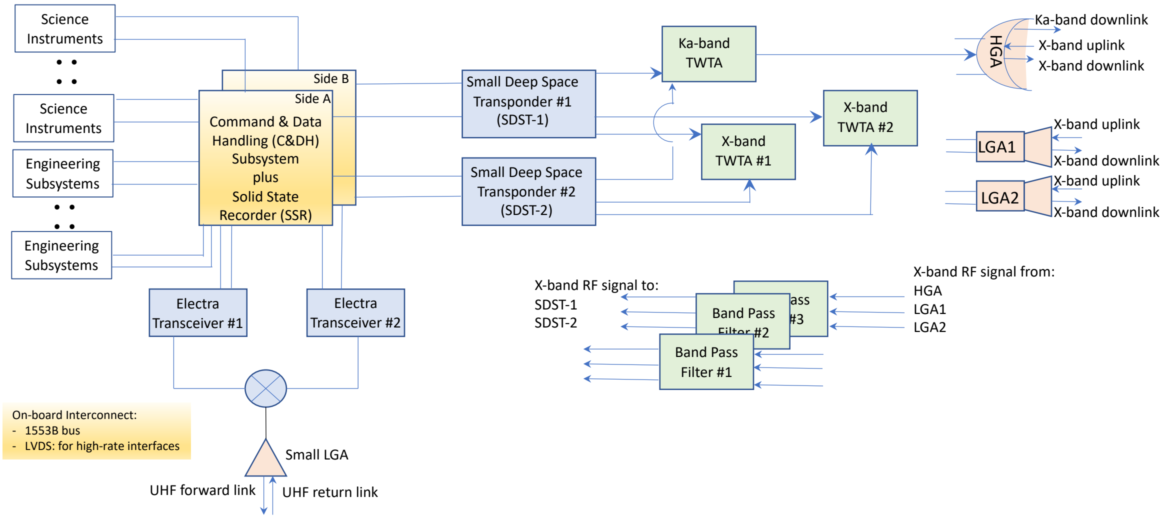


Figure 3.6-3. Description of Spacecraft Communications System for NASA’s Mars Missions

<u>Communication capabilities on a Mars orbiter:</u>

The following points summarize the Mars communications capabilities on the flight system of a typical Mars orbiters:

(a) X-band capability: The Mars orbiter provides X-band (~8 GHz) uplink, downlink, and radiometric tracking (two-way Doppler, turnaround ranging, and delta DOR) with the Earth stations. The direct-from-Earth uplink can also carry data destined for relay to a surface vehicle, and the direct-to-Earth downlink can also carry data relayed to the orbiter from a surface vehicle.

(b) UHF-band capability: The Mars orbiter provide UHF-band data relay and tracking services to landers/rovers during their entry, descent, and landing (EDL) phase, and subsequently provide UHF forward-link relay services to the landed surface vehicles and return-link services back from them.

(c) Significant telecom redundancy is provided. The redundant active elements are SDSTs, Electra radios, USOs, and X-band TWTAs. Only one is powered on at a time. The HGA has no redundant unit.

(d) Antennas - HGA and LGAs: The gimbaled high-gain antenna, deployed shortly after launch, serves as the primary means of communications to and from the orbiter. Two LGAs are present for lower-rate communication during emergencies and critical events, such as launch, Mars obit insertion (MOI), or safe mode. The data-rate capability when using these antennas is lower because they focus the radio beam much more broadly than does the HGA.

(e) Small Deep Space Transponder (SDST): Currently operating NASA orbiters carry two small deep-space transponders (SDSTs)[50]. The SDSTs provide identical functions, and only one is powered on at a time. It is responsible for tracking the uplink carrier, demodulating commands from the carrier, generating the downlink carrier (coherent or non-coherent with the uplink frequency), performing convolutional coding, producing different subcarrier frequencies, modulating telemetry on the subcarrier or directly on the downlink carrier, demodulating and modulating turnaround ranging signals, and generating delta-DOR tones.

(f) Electra radio for UHF proximity link: As shown in the above Figure 3.6-3, the Electra radio[51] on a science orbiter is a network node in the Mars Relay Network that provides efficient relay of high-rate in-situ mission science and engineering data. It interfaces with the Command and Data Handling (C&DH) and Solid State Recorder (SSR) for transferring the data to and from the landers/rovers. Table 3.6-3 gives a summary on the communication capabilities of the Electra radio. The older relay radio on Odyssey serves the same basic relay function as does Electra, but its data rates are lower and it does not provide all the capabilities as Electra does.

Table 3.6-3. A summary of Electra's communication capabilities:

Parameter	Capability & Value
Protocol	CCSDS Proximity-1 (reliable bit-stream and expedited unreliable service)
Frequencies	UHF: Transmit 435-450 MHz; Receive: 390-405 MHz
Modes of operation	Half-duplex for Rx and Tx; Full-duplex
Carrier modulation modes	Suppressed carrier, residual carrier
Modulation types	Residual carrier binary phase-shift keying (BPSK) with bi-phase-L (Manchester). Suppressed-carrier BPSK.
Receive/Transmit symbol rates	1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 ksps. Adaptive data rate mode is available.
Encoding	Uncoded, (k = 7, r = 1/2) convolutional, differential symbol coding
Decoding	Uncoded, (k = 7, r = 1/2) convolutional (3-bit soft decode)
Tracking range and rate	±20 kHz, ±200 Hz/s
Hailing mechanism	Implemented for signaling. But has not been used for concurrent access.

Communication capabilities on a Mars lander or rover:

(a) Significant telecom redundancy. For example, the system includes a small deep space transponder (SDST) and a transmitter (a 100W output TWTA on the descent stage and a 15W output SSPA on the rover) for X-Band. Being able to use either the TWTA or the SSPA (albeit at a significantly lower link performance, with the extra line losses and the reduced power from the SSPA) provides functional redundancy during cruise. After reaching the surface of Mars, only the SSPA is available for surface operations.

(b) Different telecom equipment and configurations are provided for the various stages of the lander/rover mission, e.g., the cruise, descent, and surface operations.

(c) During cruise stage, at any given time, one antenna (MGA or LGA) is selected to receive X-band uplink from the DSN and transmit downlink to the DSN. During the EDL phase, X-Band LGAs are used and downlink only.

(d) The surface telecom system includes LGA and HGA antennas for X-band DWE links and a UHF antenna for relay to a science relay orbiter.

(e) Electra-Lite Transponder: The UHF link is used throughout the EDL phase, after cruise stage separation. The radio for communications over UHF links is the Electra-lite. During surface operations phase, UHF is the primary means of returning large volumes of data to the Earth via relay of science orbiters. The UHF relay includes dual-redundant Electra-lite radios. It has the functions for relay communications with all NASA's science relay orbiters (plus compatible orbiters such as ESA's TGO and MEX). The Electra-lite, is a software defined radio (SDR), a stripped down version of the Electra radio (as shown in Figure 3.6-3) that demands lower power and less mass, and is intended for use in landed vehicles. It has an integrated transponder, power amplifier, and diplexer.

- The Electra-lite for return link: The ELT is capable of downlink rates from 2 kbps to 2048 kbps. Along with a compatible relay orbiter, it could use suppressed carrier modulation with adaptive data rates (ADR) during a relay overflight. (Note: InSight's older radio can support return links of 256 kbps.)

- The Electra-lite for forward link: For forward link, i.e., the link to a relay orbiter, both residual and suppressed carriers are supported. And the forward link data rates are from 2 to 256 kbps.

3.6.3. Description of NASA's Mars Communication Capabilities of Ground System(s)

On the ground side, the system responsible for communicating with the Mars spacecraft is the deep space network (DSN). A suite of antennas deployed at three Deep Space Communications Complexes (DSCC) are the primary assets for providing communications and tracking support to Mars missions. The three DSCC facilities are located near Barstow in Goldstone, California; Madrid in Spain; and Canberra in Australia. Each complex has a Signal Processing Center (SPC) and a number of antennas, including a 70m antenna and multiple 34m Beam Wave Guide (BWG) antennas. Madrid complex has an additional 34-m High Efficiency (HEF) antenna. The HEF antennas at Goldstone and Canberra have been decommissioned. Each complex also has the support infrastructure and personnel needed to operate and maintain the antennas.

Figure 3.6-4 shows the antenna sizes and types available at each of the locations. These stations communicate with and track Mars spacecraft at X-band (and Ka-band for MRO during cruise phase).

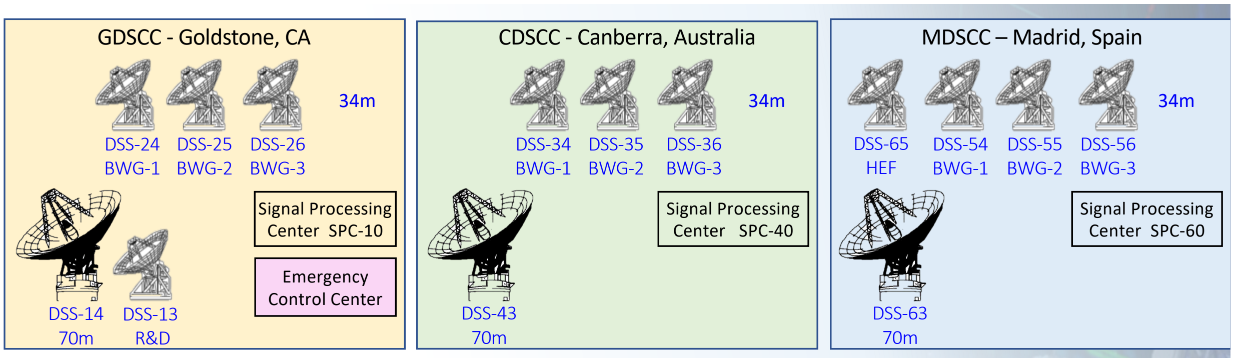


Figure 3.6-4. NASA's DSN antennas

The DSN is a service-providing system[48]. It supports approximately three dozen missions above geosynchronous distance including the set of Mars missions. A variety of capabilities is provided to enable a broad range of mission functions. DSN-provided data services are accessed via well-defined, standard data and control interfaces. "Standard interfaces" in this usage include those formally established by standards organizations (e.g., the Consultative Committee for Space Data Systems (CCSDS), the Space Frequency Coordination Group (SFCG), the International Telecommunication Union (ITU), the International Organization for Standardization (ISO), de facto standards widely applied within industry, and common interfaces specified by the DSN. Consistent with the definitions of IOAG cross support services, the types of standard services currently employed by all the Mars missions are:

- Forward Data Services: Command Radiation Service
- Return Data Services: Telemetry Frame Service, Telemetry Packet Service, Telemetry File Service, Beacon Tone Service, and Relay Service
- Tracking Services: Radio Metric Data Service and Delta-DOR Service
- Radio Science Services

There are other service types offered by the DSN that have not been used by any Mars missions. An example is the reliable forward file delivery per CFDP protocol. Some attributes of the forward and return data services are identified in Table 3.6-4 and Table 3.6-5, respectively.

Table 3.6-4. Attributes of DSN Forward Data Services[48]

Parameter	Value
Frequency Bands Supported	Deep space X (*Note: Ka-band uplink has been only used for DSN radio science support for deep space mission; no present Mars mission is using it.)*
EIRP and Transmitting Power	X-band: 34m BWG/HEF 110 dBW at 20 kW 70m 116 dBW at 20 kW
Polarizations Supported	RCP LCP No RCP/LCP simultaneity
Modulation Types	BPSK on subcarrier for uplink rate ≤ 4 kbps
Modulation Formats	NRZ: L, M, S Bi-phase L or Manchester, M, S

Parameter	Value
Carrier/Subcarrier Waveform	Subcarrier: 8 or 16 kHz
Uplink Acquisition Types	CCSDS Physical Link Operations Procedure-2 (PLOP-2)
Uplink Data Rate	Minimum 7.8 bps
Channel Coding	None
Data from MOC to DSN	Stream of CLTUs over a TCP/IP interface
Data from DSN To Spacecraft	CLTU per CCSDS TC Space Link Protocol[12]
Data Unit Size	Maximum CLTU size: 32,752 bits Minimum: 16 bits A series of CLTUs can be contiguously radiated.
Transaction Rate	600 CLTU/s (max.)
Data Retention Period	No data retention other than buffer staging for radiation
Data Delivery Methods from MOC to DSN	CCSDS Space Link Extension (SLE) Forward CLTU[26] on-line delivery mode
Radiation Latency	≤ 125 milliseconds per CLTU
Service Operating Mode	Automated
Service Availability	Nominal 95% Mission critical event 98%
Data Quality	Bit error rate: 10^{-7} CLTU error rate: 10^{-4}
Accountability Reporting	SLE command radiation status report

It must be noted that certain uplink capabilities offered by the DSN are not identified in the above table because they have not been used by any Mars missions. Chief among them are maximum uplink data rate at 10 Mbps using BPSK direct carrier modulation and LDPC coding.

Table 3.6-5. Attributes of Return Data Service[48]

Parameter	Value
Frequency Bands Supported	Deep space X (*Note: Ka-band has been a DSN capability for deep space missions. But presently, no Mars mission is using it.*)
G/T @ 45 Degree Elevation, diplexed	X-Band G/T (dB) 34m BWG 54.2 34m HEF 53.2 70m 61.5
Polarizations Supported	RCP LCP RCP/LCP simultaneity at some stations
Modulation Types	BPSK on residual carrier (with or without subcarrier) BPSK on suppressed carrier QPSK, OQPSK* (no ranging)
Modulation Formats	NRZ: L, M, S; Bi-phase L or Manchester, M, S
Carrier/Subcarrier Waveform	Residual carrier: sine or square wave
Downlink Data Rate	Maximum: 6 Mbps Minimum: 10 bps (> 40 bps recommended for timely acquisition)

Parameter	Value
Forward Error Correction	Convolutional codes: (k=7, r=1/2), without punctured code Reed-Solomon (RS) interleave = 1 to 8 Reed-Solomon (outer) concatenated with convolutional (inner) code Turbo codes: 1/2, 1/3, and 1/4 (1.6 Mbps max) Turbo code: 1/6 (1 Mbps max)
Data Format, from Spacecraft to the DSN	CCSDS TM Synchronization and Channel Coding[3] Transfer frame format conforming to CCSDS TM Space Data Link Protocol[16] For MRO only, transfer frame (VCDU) format conforming to CCSDS AOS Space Data Link Protocol**Error! Reference source not found.**
Data Format, from DSN to MOC	Stream of frames
Data Unit Size (information bits only)	TM frame or VCDU: 8920 bits (nominal), 1760 bits (safing and critical events), 16 kbits (maximum).
Maximum Number of Virtual Channels Supported	64 (16 virtual channels can be processed at a given time)
Data Delivery Methods from the DSN to the MOC	CCSDS Space Link Extension (SLE) RAF/RCF [24][25]
Data Delivery Latency (DSN to MOC)	Engineering telemetry: Typically, on-line timely (seconds) and on-line complete (hours) Science telemetry: Typically, off-line (hours to 24 hours).
Service Operating Mode	Automated
Service Availability	Nominal: 95% Mission critical event: 98%
Data Quality	Frame rejection rate: 10^{-4} to 10^{-5} typical
Time Tagging Accuracy	10-50 microseconds in Earth Receive Time (ERT) relative to UTC, depending on downlink data rate
Accountability Reporting	SLE RAF/RCF status report

It must be noted that certain downlink capabilities offered by the DSN are not identified in the above table because they have not been used by any Mars missions. Chief among them are maximum downlink data rate at 13 Mbps for deep space link, LDPC coding, and the AOS space data link protocol.

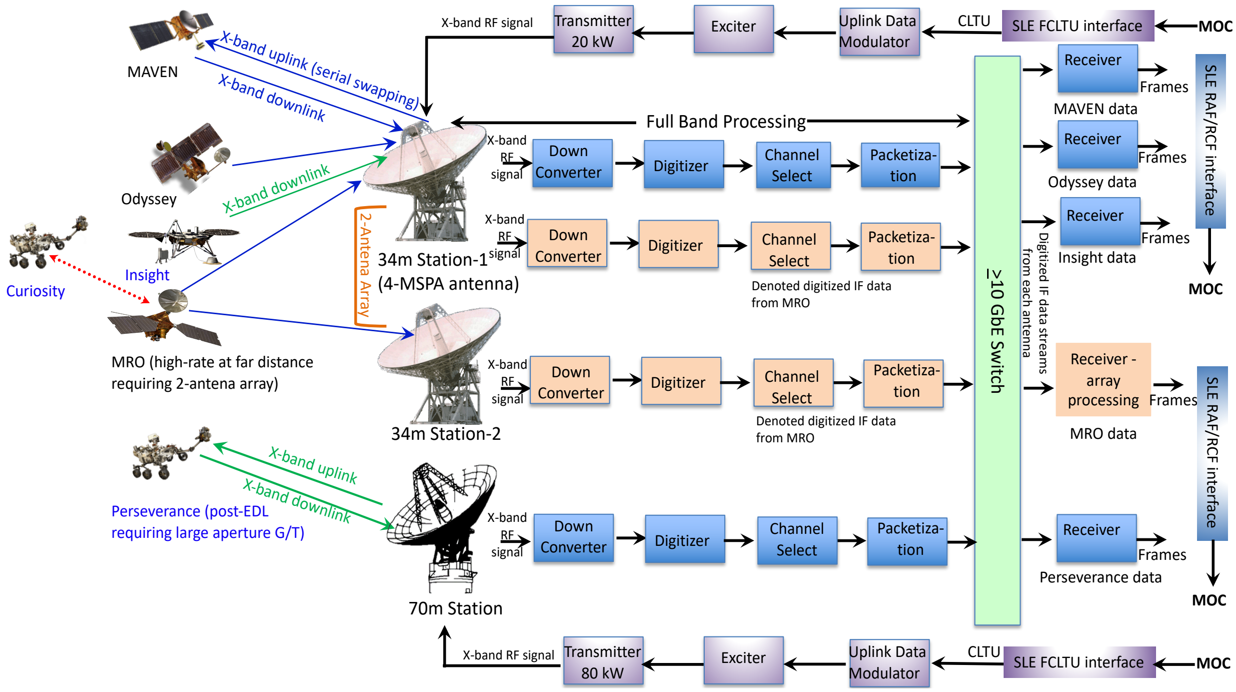


Figure 3.6-5. Description of Ground Communications System for NASA's Mars Missions

Figure 3.6-5 above depicts the signal processing flows for both uplink and downlink paths. The processing flows also encompass all the functions, albeit at a high level, involved in executing the forward data, return data, radiometric tracking, and radio science services.

For maximizing the antenna utilization efficiency and in the meantime extending signal capture threshold, the DSN has supported the Mars mission set through a few different station-operating modes by optimizing its antenna and signal processing parameters. In addition to the standard one-station configuration, the alternative operating modes prevalently applied are Multiple Spacecraft Per Antenna (MSPA), antenna arraying, interferometry tracking, and site diversity.

(a) Multiple Spacecraft Per Antenna (MSPA)

The MSPA is a special configuration wherein multiple receivers are connected to a single DSN antenna permitting the simultaneous reception of signals from two or more spacecraft. MSPA makes more efficient use of DSN facilities by enabling simultaneous data capture services to several spacecraft, provided that they are all within the Earth station's beam width (which is the case for Mars missions). MSPA is not a service; it is a capability for resolving some schedule conflicts.

Presently, the DSN can receive signals from four spacecraft simultaneously in a 4-MSPA configuration. MSPA design limits uplink transmissions to a single spacecraft at a time. Thus, only one spacecraft can operate in a two-way coherent mode, all others must be in one-way non-coherent. As illustrated in Figure 3.6-5, three Mars orbiters and a lander are tracked by a single 34m BWG antenna.

(b) Antenna Arraying

Antenna Arraying is another special configuration wherein the signals from two or more DSN antennas are combined to create the performance of an antenna larger than either. Arraying is also available for combining signals with different polarizations (RCP and LCP). Combining is performed at an intermediate frequency (IF) resulting in improved performance of both the carrier and data channels. Arraying 34m antennas with a 70m antenna improves the performance of the 70m antenna. At X-band, four 34m antenna arraying would achieve within 0.5 dB of the 70m performance due to aperture and system noise difference plus some array processing loss. A case example shown in Figure 3.6-5 is a 2-MSPA operating mode where the MRO is at a far distance demanding a G/T higher than a single 34m can provide.

(c) Interferometry Tracking

Interferometry Tracking is an operating mode in which two stations, each at a different DSN site, are configured to perform spacecraft tracking using a Very Long Baseline Interferometry (VLBI) technique, i.e., Delta-DOR. It allows determination of the angular position (or plane-of-sky position) of a deep space spacecraft relative to a natural radio source by measuring the geometric time delay between received radio signals at the two stations. Almost all NASA's Mars missions have used this mode during cruise and for their mission-critical events such as MOI.

(d) Site Diversity

Site diversity is a special configuration in which multiple sites are scheduled to improve the certainty of achieving the desired service availability. This is normally done for critical events (e.g., orbit insertions, landings, etc.) This can be done deterministically (sites are scheduled without reference to equipment or weather conditions), or adaptively (sites are scheduled on short notice only when needed).

Mars Relay Operations Service (MaROS)

Separate from the DSN is another multi-mission system, the Mars Relay Operations Service (MaROS) operated by NASA's Mars missions. It provides needed capabilities to the various missions participating in the Mars Relay Network. As mentioned in Section 3.6.1 "Overview", each NASA's Mars science orbiters are in fact a service-providing system, and like the DSN, there exists a service provider - service user relationship between each orbiter and the landed vehicles. In that service paradigm, the MaROS becomes the focal point for service management activities on behalf of the Mars Relay Network. Operationally, MaROS functions[48] as a centralized entity that coordinates when and how the orbiters at Mars communicate with the vehicles on the surface of Mars:

- Relay service planning: define a baseline plan for relay service to be provided to landed assets.
- End-to-end forward data delivery: orchestrate the processes needed to transfer lander/rover command data sets from the lander/rover MOC to an orbiter's MOC to the relay orbiter and then ultimately to the lander/rover itself.
- End-to-end return data delivery: Orchestrate the processes of transferring lander/rover telemetry data from a lander/rover to a designated relay orbiter to that orbiter MOC and then ultimately to the lander/rover MOC themselves.

- Accountability reporting: provide to the lander/rover/orbiter MOC the relevant reports on the performance of relay passes.

3.6.2 NASA's Future Mars Communications Architecture

Looking forward into the future, NASA's Mars communications architecture will continue to grow in terms of its assets and capabilities both on Earth and in flight. It will evolve according to the policy and guidance of the Mars explorations program and the tenets established by the IOAG. The architecture, therefore, is expected to follow a few fundamentals during the next two decades:

- Increase the communications performance of the flight and ground assets to support the science and human exploration missions. This includes the operational use of Ka-/K-band and optical communication capabilities for high-rate links.

- Develop a next generation infrastructure with dedicated high-availability, on demand communications, timing, and positioning services for users, compared to the present-day utilization of science orbiters for occasional communications passes with timing and positioning provided by long-distance DSN tracks, augmented by limited onboard imaging and inertial sensors for local in situ navigation.

- Move forward to a new level of internationally interoperable communications architecture.

- Infuse the communication systems provided by the industry to accommodate the provision of commercial Mars communication services.

- Create an open communications framework to spur the participations by all parties in the Mars internetworking system.

- Deploy NASA's elements for the international Mars Relay Network and Mars Surface Network towards the build-up of the Mars internetworking system.

To that end, the future Mars communications architecture as described in Section 5 will be "reflected" in the NASA's architecture.

3.7 UAE's Mars Communication Capabilities

The Mars Hope orbiter of the United Arab Emirates (UAE) Space Agency was launched on 19 July 2020, and went into orbit around Mars on 9 February 2021.

The UAE Mars Mission (EMM) has been operated by the Mohammed bin Rashid Space (MBRSC) in Dubai.

The orbiter uses a 1.5-m parabolic high-gain antenna (HGA) and three omni-directional low-gain antennas (LGA) for the direct-with-Earth link communications with NASA's DSN. Services provided by the DSN are command radiation service, telemetry frame service, telemetry file service (per CFDP), radiometric data service, and Delta DOR service. In addition, the platform and media calibration services are used by the EMM for navigation and science analysis purposes. Key telecommunications parameters are summarized in Table 3.7-1:

Table 3.7-1. EMM Telecommunications Parameters

Uplink (X-band)		Downlink (X-band)	
Parameters	Value	Parameters	Value
Receive gain	> 39.5dBi	Transmit gain	> 41.5dBi
Spacecraft receiver G/T	16.8 dB/K	Spacecraft EIRP	91.16 dB
EIRP (from station)	129.22 dB	Ground G/T	53.2 @ 45 Deg Elevation
Uplink Polarization	LCP	Downlink Polarization	LCP
Uplink Modulation	BPSK, on subcarrier frequency @16,000 Hz	Downlink Modulation	BPSK
Uplink Data Rates	Minimum 7.8125 bps; Maximum 2000 bps	Downlink Data Rates	Minimum 2 Kbps; Maximum 240 Kbps
CMD Coding	None	TLM Coding	Turbo rates 1/2 and 1/6
		DDOR Tones	15 MHz (Major) and 0.9375 MHz (Minor)

3.8 UK Space Agency's Mars Communication Capabilities

The UK Space Agency is a member state of ESA and has a keen interest in the exploration and science around Mars. These activities are coordinated with industry and universities in the UK through its delegation to ESA. The UK Space Agency controls the development of Mars instrumentation for both ESA and international bilateral missions. In addition, the UK Space Agency is an active member of CCSDS and participates at both a technical and management level in its own right.

3.8.1 Overview of UK Space Agency's Mars Communications Architecture

Through its participation in CCSDS, the UK Space Agency has worked alongside their international partners in the development of the standards required to support the Mars Communication Architecture. This started with the development of the Proximity-1 standard used by landers and orbiters currently around Mars.

This support has continued with the development of new standards. The UK Space Agency has worked on bringing USLP from a CCSDS white paper to a published Blue Book, and saw the Agency develop a prototype during this process.

3.8.2 Description of UK Space Agency's Mars Communication Capabilities of Flight System(s)

The UK Space Agency, through UK Industry, has been developing flight communications systems for the Mars Exploration since 2000 with its work on ESA's Mars Express and Beagle-2. These systems were based on the current draft version of CCSDS Proximity-1 available at the time. The development of these Mars Express systems also allowed the lessons learnt to be fed into the CCSDS standardization process to enhance the published version of Proximity-1 recommendation.

Moreover, the Mars Express unit (MELACOM) is still being used today in support of Mars landed assets, with the latest performed in support of the CNSA Tianwen-1 lander in May 2021.
These developments have continued in support of the ESA/ROSCOSMOS ExoMars program. Figure 3.8-1 (below) shows the flight unit used for the ESA ExoMars 2016 Schiaparelli lander. This unit will also be used for the 2022 ESA Rosalind Franklin Rover and ROSCOSMOS landing system.

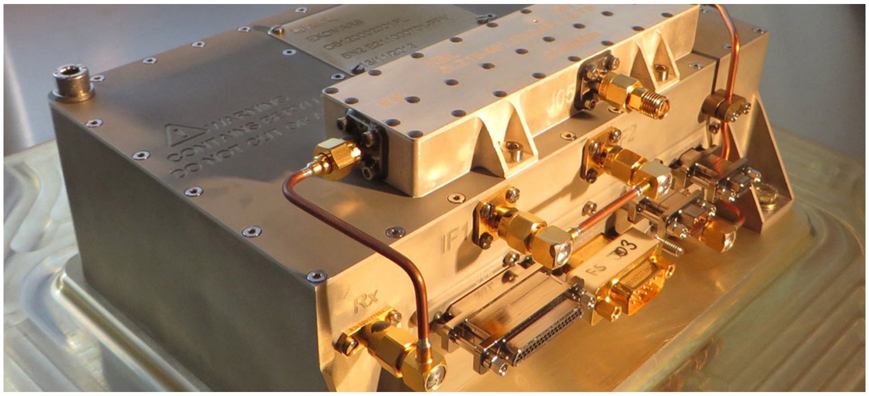


Figure 3.8-1. ESA ExoMars Lander and Rover UHF Proximity-1 system. Picture Credit: QinetiQ

3.8.3 Description of UK Space Agency's Mars Communication Capabilities of Ground System(s)

During 2018, the UK Government contracted Goonhilly Earth Station to modify its 32m antenna (GHY-6) to support Lunar and Deep Space communications at both S- & X-band. The contract was delivered through ESA to ensure that the upgraded antenna was able to support current and future ESA and other agencies missions. The design has been based on the ESA Deep Space Antennas and supports all the modulations, coding, ranging and SLE services as offered by a DSA station. For this reason, ESA treat this antenna as an augmented station on their ESTRACK Network. Further plans are already underway to implement AOS & USLP on both the up and downlink as well as DTN. This antenna is shown in Figure 3.8-2 below.

During the commissioning phase of the GHY-6, it was used to record the X-Band tones from NASA Mars Perseverance during its entry, descent and landing (EDL) in February 2021.

Figure 3.8-2. Goonhilly's GHY-6 32m S- &X-band antenna. Picture Credit: Goonhilly Earth Station Ltd

Goonhilly has also self-funded the conversation of their 30m antenna (GHY-3) into a dual use radio telescope and receive only X-band deep space antenna. It has been designed with a super-cooled front end leading to a system noise temperature of ~25K at zenith. The antenna is capable of receiving signals between 4 GHz and 8.5 GHz. The baseband I&Q stream can be either routed to the on-site high compute data center or demodulated using the GHY-6 systems. In the I&Q

stream mode, the complete Deep Space Frequency allocation is received and stored with the individual channels extracted and processed depending on the current supported mission. This antenna is shown in Figure 3.8-3 below.

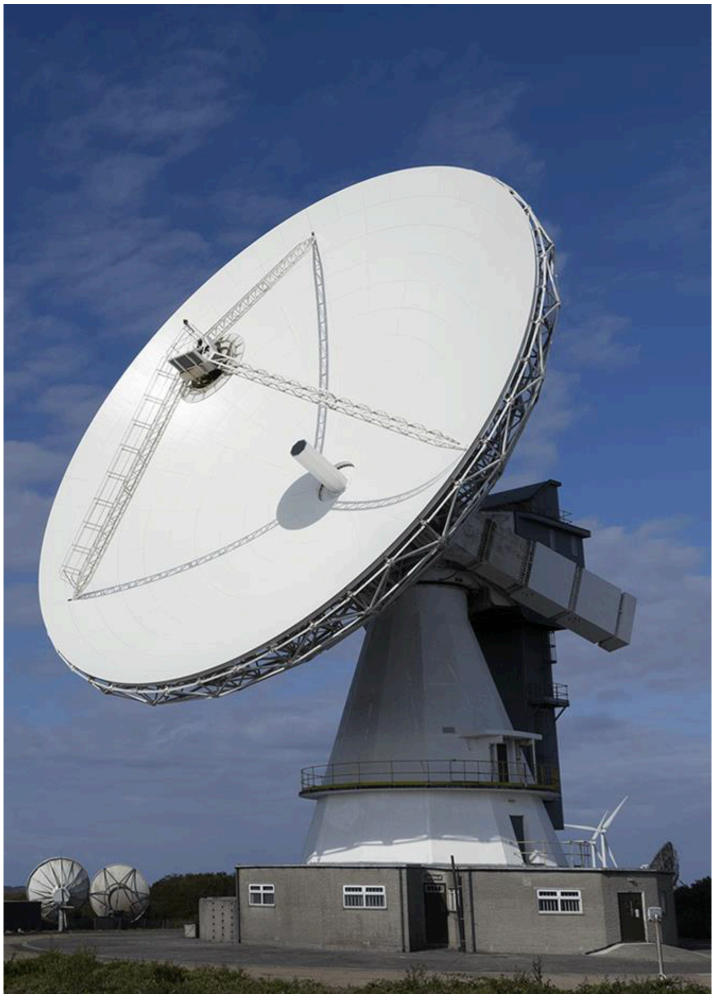


Figure 3.8-3. Goonhilly's dual use radio telescope / deep space antenna.
Picture Credit: Goonhilly Earth Station Ltd

3.9 ASI's Mars Communication Capabilities

3.9.1 Overview of ASI's Mars Communications Architecture

ASI has been actively participating for some time in some Mars exploration programs such as ESA's "ExoMars" and is working in the recently announced "Ice Mapper" program in partnership with NASA, JAXA and CSA.

ASI also actively participates in the work of the international CCSDS committee called for the definition of international space communication standards.

For future Mars exploration missions, ASI's capacity is based on the 64 m antenna called “Sardinia Deep Space Antenna” (SDSA) that is described below in its current and future characteristics.

3.9.2 Description of ASI’s Mars Communication Capabilities of Ground System

The 64-m fully steerable Sardinia antenna (Figures 3.9-1 and 3.9-2) is a formidable ground instrument operated both by the Italian Space Agency (ASI) for space activities /deep space operations) and by the Italian National Institute for Astrophysics (INAF) as a radio astronomy telescope. It is located on a mountain valley at 600 m above the sea level in the territory of S. Basilio, a village 35 km away in the northern of Cagliari (Lat. 39°29’34’’ N - Long. 9°14’42’’ E) in the territory of the Sardinia Island.

The ASI/INAF antenna optical design consists of a shaped Gregorian configuration equipped with an active control of the main reflector surface and of the sub-reflector position. The uniqueness of its optical design allows to meet the requirements for the services to Spacecraft and Radio Science in the bandwidths of Near Earth and Deep Space and to the radio astronomy in the frequency range 0.3-116 GHz. Six different focal positions are available (Figure 3.9-3): one in the parabolic primary focus (F1), one in the Gregorian secondary focus (F2) and four in the tertiary foci (F3, F4, F5, F6) inside the beam waveguide (BWG) and Elevation Equipment (EE) rooms. The focus and receiver can be quickly selected by means of electro-mechanical positioners operating in the primary, Gregorian and BWG focal area, accomplishing the so-called antenna frequency agility. To date the antenna hosts 4 receivers operating in the frequency range 0.3-26.5 GHz.
ASI and INAF share the antenna usage (20% and 80% of the available time respectively), part of its instrumentation and the site infrastructures, but with different missions. INAF operates the antenna in the radio astronomy configuration (a.k.a. Sardinia Radio Telescope, SRT), in order to study the universe in the whole antenna frequency range, by means of the P-, L-, K- and C-band receivers hosted in F1, F2 and F3 foci respectively. ASI operates the antenna in the deep space configuration (a.k.a. Sardinia Deep Space Antenna, SDSA), for the space communications and space science experiments, at the moment by means of a X-band receiver hosted in F4. In addition, SDSA has been testing services employing the P-band receiver, to offer a UHF communication link during the Entry, Descent and Landing (EDL) phase of the Martian missions (InSight, Perseverance).

Figure 3.9-1. ASI-INAF dual use radio telescope/deep space antenna.

Figure 3.9-2. ASI-INAF dual use radio telescope/deep space antenna.

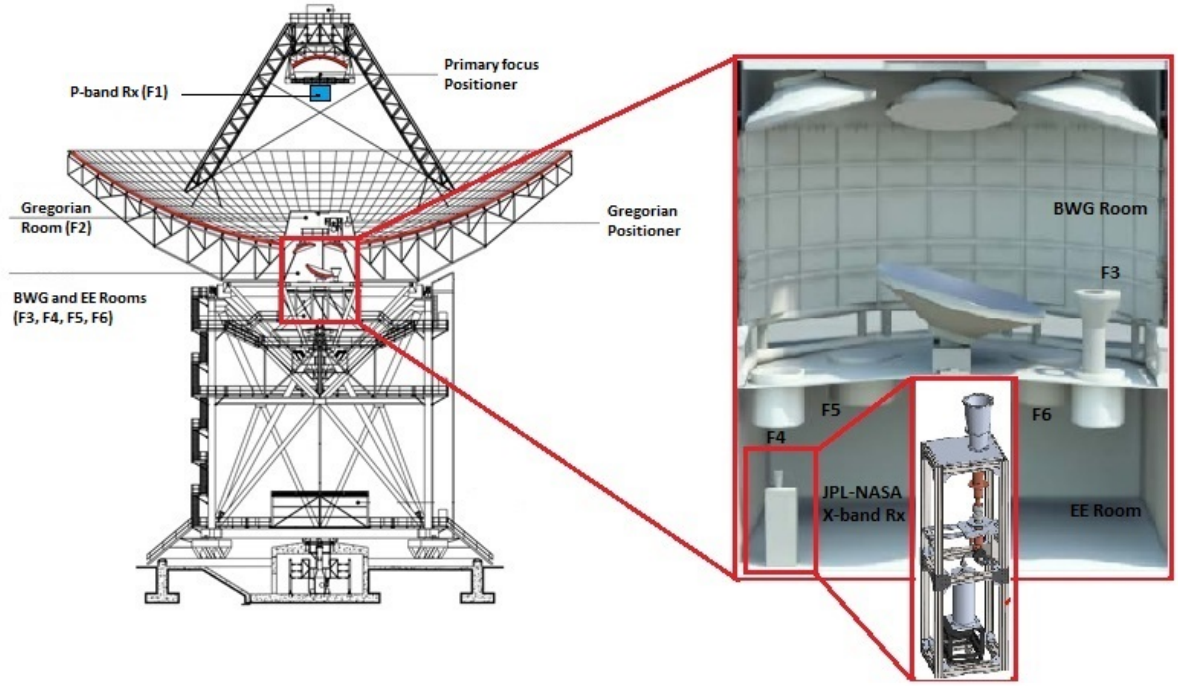


Figure 3.9-3 Antenna overview and actual SDSA capabilities for deep space communication (X-band and P-band receivers)

3.9.2.1 Present ASI SDSA deep space communication architecture

At the present (Figure 3.9-3 above and Figure 3.9-4 below), SDSA communication architecture consists of: a cryogenic single-circular-polarization receiver (by NASA-JPL), working in the frequency range 8.2-8.6 GHz; a commercial frequency downconverter providing a 28 MHz bandwidth signal centred at 70 MHz. Both systems are installed in EE room, and connected by a fibre optical link to the digital backend (Intermediate Frequency and Modem System - IFMS by ESOC-ESA) hosted in the shielded room of the ground station site. At the end, the IFMS output provides telemetry, tracking and open-loop data to the users via LAN.
Among the instrumentations shared by ASI and INAF, it is worth mentioning those essential for radio astronomy and deep space communications: a time and frequency laboratory equipped with an active hydrogen maser (by T4Science, i-MASER option LN) providing high-precision frequency reference signals and timing pulses at the backend and the antenna receivers; a weather station and a microwave radiometer (by Radiometrics, mp-series) for an atmosphere nowcasting; a radio frequency interference laboratory for a routine monitoring of the receivers frequency bands.

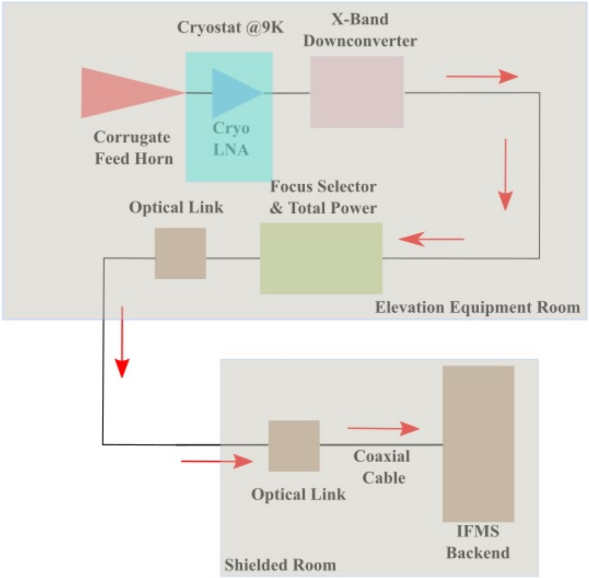


Figure 3.9-4. X-band Receiver Chain Block Diagram

Thanks to the actual communication architecture, since 2017 several tests have been performed to characterize the SDSA X-band capabilities for space communication. Up to now, SDSA has been successfully taking part to many three-way links to different spacecraft orbiting on Saturn (Cassini, in August-September 2017), on the Earth-Sun Lagrangian points L4 (STEREO-A, several passes through 2018-2020), on Mars (MAVEN, MEX some passes in 2019), on Jupiter (JUNO, several passes in 2020-2021) and beyond the solar system (Voyager 1, some passes in 2021). These tests show satisfactory performances of the actual downlink configuration, in terms of Gain-over-System Equivalent Noise Temperature (*G/Ts*), it means at least 56.5 dB/K @ 15 deg antenna elevation. Moreover, the SDSA-SRT primary focus P-band receiver was successfully tested for deep space communication by accomplishing the UHF Mars-Earth link during the InSight EDL in November 2018.

The SDSA capabilities and performances will be increased adopting a new architecture and equipment for Near-Earth (X and K-band) and Deep Space (X and Ka-band) communication. The latter is described in the following section.

3.9.2.2 Future SDSA Deep Space communication architecture

With regard to the future deep space communication architecture, ASI is planning to provide SDSA with new X- and Ka-band capabilities for TT&C and Radio Science activities.

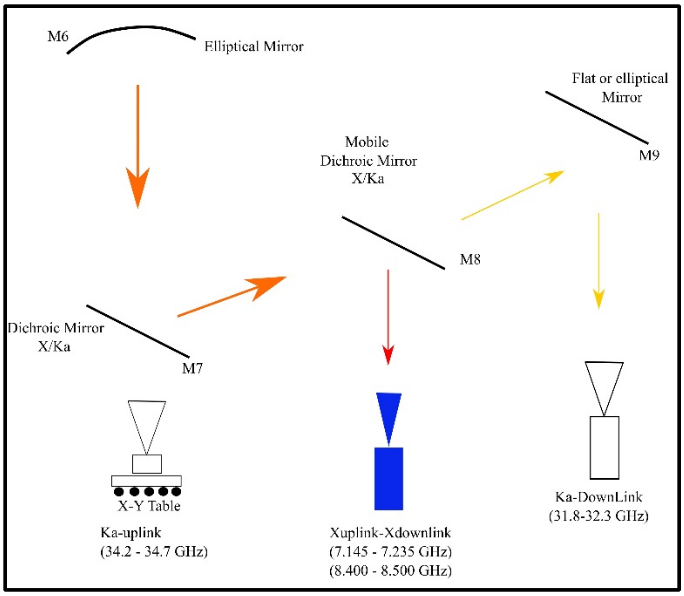


Figure 3.9-5. SDSA deep space preliminary optics configuration

The future deep space chain will be installed in the EE room on the F6 and will consist of: cryogenic X- and Ka-band receivers, all together providing the so-called X/X, X/Ka and Ka/Ka "triple link", i.e., the capability of receiving and transmitting in X- ad Ka-band simultaneously.

Figure 3.9-5 above shows a preliminary configuration of the SDSA "triple link" optics suitable for the installation into EE room. Of course, the performances of the SDSA triple link will strongly depend on the antenna *G/Ts* and the Equivalent Isotropic Radiation Power (EIRP) resulting from the final design not still ready. However, some preliminary performance evaluations resulting from electromagnetic simulations of the configuration shown in Figure 3.9-5, are summarized in Table 3.9-1.

Although an accurate value of *G/Ts* for X- and Ka-band downlink communication is not still defined (the electromagnetic analysis is still ongoing), the SDSA performance will be able to fulfil the Mars communication requirements. The theoretical transmitter power values and the resulting EIRP in Table 1 are derived from an analysis of the requirements for the present and, above all, of the more challenging future missions as BepiColombo, JUICE. However, they still need to be confirmed.

Moreover, such a performance should make SDSA able to communicate to multiple spacecraft or cubesats (Multiple Spacecraft for Aperture Antenna mode, MSPA) orbiting around Mars, and to provide high data rate communication in the Mars-Earth link.

With regard to the future SDSA backend, the IFMS backend will be replaced by two new Telemetry, Tracking and Command Processor (TTCP) back ends (Master and Slave configuration) to be installed in the shielded room to provide telemetry, tracking, open-and closed-loop data to the users via LAN, and commands to the spacecraft/cubesat. Of course, the SDSA communication architecture will be provided with all the services, i.e., time and frequency standard references, weather and atmospheric site characterization, already mentioned above, and their redundancy systems, needed to meet the mission requirements for deep space communication.

Frequency bands	Downlink freq. range [GHz]	Expected G/T [dB/K]	Uplink freq. range [GHz]	Maximum	Maximum Expected

				Theoretical Tx Power [kW]	EIRP [dBW]
X	8.4-8.5 (Cryo Rx)	>56.5 dB/K @15 deg*	7.145-7.235	20 TBC (Klystron Tx)	>112**
Ka	31.8-32.3 (Cryo Rx)	TBD	34.2-34.7	1 TBC (Klystron Tx)	>112**

Table 3.9-1. Expected future SDSA deep space TT&C capabilities

**This G/T value refers to the performances of the SDSA provisional optical configuration to be updated in a near future*

*** EIRP values resulting from a theoretical analysis, still to be confirmed*

3.10 CNES' Mars Communications

3.10.1. Overview of CNES's Mars Communications Architecture

Representing its member state (France) at ESA, CNES is relying on ESA for the European participation in the Mars communication architecture. CNES also has participations in NASA and ROSCOSMOS Mars communication architectures, and, as mentioned in Section 3.10.2, CNES is conducting its own studies and observations to contribute to reflection on the subject and to sensitize to the respect of the ITU Radio Regulation applicable on the Moon and on Mars, due to the importance of this subject for French radio astronomers, and also for international radio astronomy community which contacted CNES on this issue. Representing the French radio astronomy community, CNES has been involved in Phase 0 and Phase A projects for the Shielded Zone of the Moon (SZM) to protect radio astronomy observations. The French Ministry of Research is the stakeholder of this study. The findings and CNES observations will guide future CNES contributions to Mars communication architectures.

As part of the study, CNES is currently performing received power and PFD level studies in the 300 MHz - 2 GHz band to check Mars communications or navigation links assumptions versus expected levels in the SZM. These computations shows, for instance, that an L-band GNSS-like Martian navigation system is not compatible with Radio Astronomy expectations in the SZM.

3.10.2 Description of CNES's Mars Communication Capabilities of Flight System(s)

CNES, as an ESA delegation, has participated in ESA Martian projects, and in some of the Martian projects of its international partners, by providing payloads and sometimes communication equipment also (*the equipment of the communication chain procured directly by ESA to French industry is not mentioned here*):

CNES provided UHF data relay on board equipment for 3 Mars probes in the past:

- To NASA, for "Mars Observer"; the cruise tests of the equipment were successful, but the injection of the probe into a Martian orbit failed.
- To Roscosmos, for" Mars 1996", but the launch failed

- To NASA, for “Mars Global Surveyor”; the equipment worked properly till the end of the mission, and relayed data during descents and surface operations.

CNES also developed a UHF data relay prototype equipment for the “Mars Premier” NASA/CNES project, which was later canceled. CNES continued this development by coding PL-1 protocol in one FPGA.

CNES is currently developing an S-band Inter Satellite Link (ISL) (transponder and antennas) between the JAXA MMX Probe (Mars Moon eXplorer) and a CNES/DLR Rover dedicated to the exploration of Phobos. For MMX, the ISL will be used in transceiver mode. This S-band ISL is a next generation technology compared to the one delivered by CNES to ESA for the Rosetta ESA/DLR/CNES comet mission. A further post-MMX new generation of nano-ISL for exploration (COMs and relative PNT), compatible with links between multiple spacecraft, is also under development.

CNES is currently pre-developing and testing a 32 GHz Ka-band TWTA (65 Watts minimum end-of-life) for the VERITAS NASA/ASI/CNES/DLR Venusian probe. Such a TWTA could later be used for a Martian probes requiring high data rate telemetry. The manufacturer is also currently developing with ESA a 120 Watts 32 GHz TWTA with 200 MHz of instantaneous bandwidth for the EnVision Venusian probe of ESA.

CNES is also involved in the customization of mass market technologies for COMs+PNT and PNT-only flight hardware prototypes, using notably the SFCG lunar and Martian orbit-to-surface band, i.e., the 2483.5-2500 MHz band, compatible with applications in the lunar and Martian regions.

CNES pre-developed prototypes of X-band and Ka band small transponders and of Ka-band deployable reflect array antennas, to be used on small satellites for exploration, like the Martian MarCOs of JPL.

CNES also studied a local Martian wireless surface network to study Martian winds, using the SFCG 902-928 MHz Martian surface band[1][36], thanks to a local light wireless technology in that band. However, CNES gave up this study when it was realized that a proliferating wireless network using such frequencies could be incompatible with Radio Regulation applicable to the SZM.

3.10.3 Description of CNES’s Mars Communication Capabilities of Ground System(s)

As one of the ESA delegations, CNES is relying on ESA ESTRACK ground systems. CNES is also relying on the Ground Systems of its international partners for supporting Martian probes.

4. Frequency, Modulation, Coding, Ranging, and Link Protocol (FMCRL)

4.1 Key Considerations for Down-Selection of FMCRL

The overarching initiative of down selecting from the existing solutions' portfolio in SFCG (frequency bands) and CCSDS (modulation and coding schemes including ranging, data link protocols and upper layers) is motivated primarily by the need of interoperability for future Mars missions. Indeed, by identifying a subset of solutions from the above normative and advisory frameworks will ensure a high degree of interoperability for the various programs across institutional space agencies and commercial service providers. The key factors which have been considered for the down-selection are the following:

- adherence as much possible to SFCG and CCSDS, with identification of situations where extensions of the existing recommendations, or creation of new ones, may be required;
- use of bandwidth efficient modulations, including possible use of Variable Modulation and Coding, suitable for the to-be RF-congested Mars environment;
- use of coding schemes approaching the ideal channel capacity as much as possible, however leaving design parameters free (e.g., the block length for LDPC and Turbo codes) in order to optimize the link vs. error rate performance as well as latency and on-board complexity;
- application of homogenous solutions across the different links between Earth and Mars assets (orbiter, landers, rovers), in terms of modulation, coding, data link layer and security protocols;
- adoption of the Unified Space Link Protocol (USLP) as common space data link protocol solution across the whole architecture, leaving the optional use of TC and TM only for legacy missions, or missions with low data rates and not requiring networking;
- synergy with solutions adopted for the Lunar environment, wherever feasible and appropriate;
- introduction of optical communications as a viable option for all spacelinks, with the potential of a step increase of data rates for the Mars to Earth link.

The identified communications standards are presented in Table 4.2-1 in Section 4.2, and are organized according to the various types of links that are relevant for the current and future Mars communications architecture. These links types are defined as follows:

- Earth-to-Mars link: The uplink from the Earth to Mars orbit and Mars surface.
- Mars-to-Earth link: The downlink from Mars orbit and Mars surface to the Earth.
- Cross link: The link between two relay spacecraft around Mars.
- Proximity link: The link between a relay satellite and its relay service user. Relay service users can be orbital spacecraft, descent/ascent vehicles, lander, rovers, and, potentially, astronauts equipped with portable communication device, communication stations/towers on surface, and human habitats.
- Mars surface to surface link: The communication link between a landed asset and another landed asset.

In various cases multiple options are included, e.g., when it is perceived that heritage solutions can still play a role in the future Mars communications architecture, and co-exist with more performing solutions. In such cases, where appropriate, a preferred option has been identified with a $^{(*)}$.

4.2 Recommended FMCRL According to Down-Selection

Table 4.2-1: Down-Selected Standards for the Physical and Data Link Layers of the Mars Communications Architecture

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Earth to Mars link	7145 - 7190 MHz[1]	• Spacecraft critical TT&C, special event/emergency/contingency or very low rate commanding: < 4 ksps • Nominal commanding: ≤ 256 ksps				
		• Option 1: PCM/PSK/PM Modulation on subcarrier (up to 4ksps)[2] • Option 2: PCM/PM/bi-phase-L (filtered) Modulation on residual carrier (up to 256 ksps) [2] • Option 3: CDMA (for MSPA) [2],[33]	• Option 1: BCH[10] • Option 2(*): LDPC (n=128, k=64) or (n=512, k=256)[10]	• Option 1: TC[12] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging (also enabling telemetry ranging if adopted on-board)
		Forward direct with Earth communications at moderate-high data rate (few Msps)				
		• Option 1(*): GMSK[2] • Option 2: filtered OQPSK[2]	• Option 1(*): LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3] • Option 2: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: Simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3: CCSDS VCM (DVB-S2, SCCC, or LDPC) for bandwidth constrained link [32]				

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Earth to Mars link (cont.)	34.2 – 34.7 GHz[1]	• During superior solar conjunctions, spacecraft critical TT&C or low rate commanding: < 4 ksps. • During superior solar conjunctions, nominal commanding: ≤ 256 ksps • Radio science				
		• Option 1: PCM/PSK/PM Modulation on subcarrier (up to 4ksps) [2] • Option 2: PCM/PM/bi-phase-L (filtered) Modulation on residual carrier (up to 256 ksps) [2] • Option 3: CDMA (for MSPA) [2],[33]	• Option 1; BCH[10] • Option 2(*): LDPC (n=128, k=64) or (n=512, k=256) [10]	• Option 1: TC[12] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging (also enabling telemetry ranging if adopted on-board)
		Forward direct with Earth communications at high data rate (tens of Msps)				
		• Option 1(*): GMSK[2] • Option 2: filtered OQPSK[2]	• Option 1(*): LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3] • Option 2: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3: CCSDS VCM (DVB-S2, SCCC, or LDPC) [32]				
	Optical 1030 nm, 1064.15 nm, 1070 nm[4]	Nominal: up to tens of kbps (without sub-symbol modulation)				
		OOK (2PPM)[4] (modulation is optional, beyond the primary need of establishing a beacon used for accurate on-board pointing)	LDPC[5]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: • Optical Telemetry Ranging[4]

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Mars to Earth	8400 – 8450 MHz[1]	• Spacecraft critical TT&C, special event/emergency/contingency or very low rate telemetry: ~ tens ksps • Entry, Descent and landing (EDL) or support to survival mode with direct-to-Earth link • Nominal telemetry: ~ hundreds ksps				
		• Option 1: PCM/ PSK/PM Modulation on subcarrier (tens ksps)[2] • Option 2: PCM/PM/bi-phase-L (filtered) Modulation on residual carrier (up to hundreds ksps)[2] • Option 3: MFSK (for EDL or survival mode) • CDMA (for MSPA) [2], [33]	• for power constrained links: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3] • for bandwidth constrained links: LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3]	• Option 1: TM[16] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging Telemetry Ranging if adopted on-board Delta DOR ([2] or future extensions, e.g. for wide band DDOR), without TM transmission.
		Return direct with Earth communications at moderate-high data rate (tens of Msps)				
		• Option 1(*): GMSK [2] • Option 2: filtered OQPSK[2]	• for power constrained links: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3] • for bandwidth constrained links: LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3]	• Option 1: TM[16] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3 CCSDS VCM (DVB-S2, SCCC, or LDPC) for bandwidth constrained link[32]				

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Mars to Earth (cont.)	31.8 - 32.3 GHz[1]	• During superior solar conjunctions, spacecraft critical TT&C, special event/emergency/contingency or very low rate telemetry: ~ tens kbps, • During superior solar conjunctions, nominal telemetry: ~ hundreds ksps • Radio science				
		• Option 1: PCM/ PSK/PM, modulation on subcarrier (tens ksps) [2] • Option 2: PCM/PM/bi-phase-L (filtered), modulation on residual carrier (up to hundreds ksps)[2] • CDMA (for MSPA)[33]	• for power constrained links: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3] • for bandwidth constrained links: LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3]	• Option 1: TM[16] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging Telemetry Ranging if adopted on-board Delta DOR ([2] or future extensions, e.g. for wide band DDOR), without TM transmission.
		Return direct with Earth communications at high data rate (up to ~ 300 Msps)				
		• Option 1: GMSK[2] • Option 2: filtered OQPSK (below 20 Msps)[2]	• for power constrained links: Turbo codes, coding rates 1/2, 1/3, 1/4, 1/6[3] • for bandwidth constrained links: LDPC, coding rates 1/2, 2/3, 4/5, 7/8[3]	• Option 1: TM[16] • Option 2(*): USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3 CCSDS VCM (DVB-S2, SCCC, or LDPC) [32]				
	Optical	Nominal: tens to hundreds Msps				

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
	1530.33 nm – 1567.13 nm[4]	OOK[4] Note: SC-PPM coding gives rise to OOK in physical layer	SC-PPM[5]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: • Optical Telemetry Ranging[4]

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Cross link (orbiter to orbiter) Communications for docking system not covered	22.55-23.55 GHz[1] 25.5-27.5 GHz[1]	RF high rate link between relay satellites (tens of Msps)				
		• Option 1(*): GMSK[2] • Option 2 Filtered OQPSK[2]	LDPC Coding rates 1/2, 2/3, 4/5, 7/8[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
	1530.33 nm – 1567.13 nm[4]	Optical high rate link between relay satellites (up to 10 Gbps)				
		OOK[4]	Reed Solomon (no soft decision required) [3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: • Optical Telemetry Ranging[4]

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Proximity link (Orbit to Mars surface or orbit to low Mars orbit)	435-450 MHz[1](**) 2025-2110 MHz[1] 2483.5-2500 MHz[1] could be considered for accurate PNT in the long term	RF TT&C link from orbit to surface (up to 2 Msps)				
		• Option 1: PCM/PM/bi-phase-L, Modulation on residual carrier (for FDMA) [2] • Option 2: CDMA, for multiple access[33] (CCSDS reference currently applicable to S-Band only)	LDPC: Coding rates - 1/2, 2/3, 4/5, 7/8[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging, only applicable to the 2025-2110 MHz allocation
		Option3: Proximity 1[13], [14], [15] (CCSDS reference currently applicable to UHF only)				
	7190-7235MHz[1], (++) 22.55-23.55 GHz[1]	RF high rate link from orbit to surface (tens of Msps)				
		• Option 1(*): GMSK[2] • Option 2: Filtered OQPSK[2]	LDPC Coding rates 1/2, 2/3, 4/5, 7/8[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3 CCSDS VCM (DVB-S2, SCCC, or LDPC) for bandwidth constrained link[32]				
	1530.33 nm – 1567.13 nm[4]	Optical high rate link from orbit to surface (up to 10 Gbps)				
		OOK[4] O3K standard, defined as pink sheet, will be included as a standard in [4]	(*) preferred: Reed Solomon (no soft decision required) [3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: Optical Telemetry Ranging[4]

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Proximity-Link (Mars surface to orbit or low Mars Orbit to Orbit)	390-405 MHz[1](**) 2200-2300 MHz[1]	RF TT&C link from surface to orbit (up to 2 Msps)				
		• Option 1: PCM/PM/bi-phase-L, Modulation on residual carrier (for FDMA) [2] • Option 2 CDMA, for multiple access[33] (CCSDS reference currently applicable to UHF only)	LDPC: • Coding rates - 1/2, 2/3, 4/5, 7/8[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	CCSDS PN[8], regenerative (recommended) or non-regenerative, simultaneous data and PN ranging, only applicable to the 2200-2300 MHz allocation
		Option3: Proximity 1[13], [14], [15] (CCSDS reference currently applicable to UHF only)				
	8450-8550MHz[1] (***), (++) 25.5-27.5 GHz[1]	RF high rate link from surface to orbit (tens of Msps)				
		• Option 1(*): GMSK[2] • Option 2 Filtered OQPSK[2]	LDPC Coding rates 1/2, 2/3, 4/5, 7/8[3]	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: simultaneous transmission of PN ranging and data using GMSK [2]
		• Option 3 CCSDS VCM (DVB-S2, SCCC, or LDPC) for bandwidth constrained link[32]				
	1530.33 nm – 1567.13 nm[4]	Optical high rate link from surface to orbit (up to 10 Gbps)				
		OOK[4] O3K standard, defined as pink sheet, will be included as a standard in [4]	(*) preferred: Reed Solomon (no soft decision required) [3] PBRL LDPC ARA LDPC Protograph based raptor codes	USLP[6]	CCSDS Space Data Link Security Protocol[22] CCSDS Cryptographic Algorithms[21]	For links where ranging is needed: Optical Telemetry Ranging[4]

Source/Destination	Frequency band	Modulation	Coding	Space Data Link Protocol	Space Link Security	Ranging and Delta DOR
Mars surface to Mars surface (access point based networks - same allocation can be used for direct client-client communications)	390 - 405 MHz[1](**) 410 - 420 MHz[1](**) 435 - 450 MHz[1](**) 902 - 928 MHz[1](**) 2025-2120 MHz[1] 2200-2300 MHz[1] 2400-2480(*) MHz[1] 2503.5-2620 MHz[1] 5150-5835MHz[1](+) 25.25 - 25.5 MHz[1] 27.225 -27.5 MHz[1]	Depending on scenario (ref. section 5.4) IEEE 802.11[11] 3GPP LTE[30] 3GPP 5G[31]	Depending on scenario (ref. section 5.4) IEEE 802.11[11] 3GPP LTE[30] 3GPP 5G[31]	Depending on scenario (ref. section 5.4) IEEE 802.11[11] 3GPP LTE[30] 3GPP 5G[31]	IEEE 802.1111] 3GPP LTE[30] 3GPP 5G security[31]	None

(*) Preferred option.

(**) Use in the Mars region is on a non-interference basis to Radio Astronomy and other passive services in the Shielded Zone of the Moon

(***) Use of the 8500 – 8550 MHz for Mars surface-to-orbit and orbit to orbit communications is on a non-interference basis to Radiolocation Service

(+) Use of the 5250-5570 MHz band for Mars surface-to-surface communications is on a non-interference basis to Space Research Service (active)

(++) A guard band will have to be defined between X-Band proximity links and X-Band links with Earth, to avoid interference between signals transmitted and received at the same spacecraft

4.3 Key features of the Recommended FMCRL

The set of solutions reported in Table 4.2-1 is consistent with the guidelines already anticipated in section 4.1, namely

- Adherence to SFCG frequency allocations and CCSDS recommendations is ensured at a large extent, with only few issues to be resolved in the future, e.g. extending the applicability of downlink modulations to all spacelinks.
- Use of bandwidth efficient modulations is ensured by adopting GMSK (enabling simultaneous PN ranging, the preferred solution) or filtered O-QPSK, especially for high rate links. Proposed use of VCM families also goes in the direction of reducing or controlling the use of the frequency spectrum.
- Adoption of LDPC and turbo codes ensures high efficiency in the use of the communications channel, with a wide set of coding rates allowing to properly design the link in power constrained as well as in bandwidth constrained link scenarios.
- Synergies are exploited in terms of re-use of solutions across different links from the Earth-Mars to the local Mars region, e.g., in terms of modulation, channel coding and data protocol, as well as in the re-use of solutions from the Lunar region, also opening the way to a Moon-to-Mars communications roadmap.
- Ka-Band uplink (34.2 – 34.7) is introduced as a potential TT&C solution beyond its current use for radio science, due to the larger immunity of Ka-Band to solar plasma effects than X-Band.
- Optical communications all included for all spacelinks
- USLP is proposed uniformly though all the various links leaving the TM and TC option only for low rate missions without strong needs for interoperability and networking.

4.4 Key Issues Requiring Further Resolutions

<u>Issue 1: selection of a unique frequency bands pair for high rate communications at RF</u>

The extension of the frequency allocations 37-37.5 GHz and 40-40.5 GHz from cis-lunar environment to Mars environment (contemplated by SFCG[1]) was discussed in the frame of the Lunar Communications Architecture working group[35]. Indeed, a single frequency allocations pair valid for the two contexts (Moon and Mars) would allow unifying hardware solutions for spacecraft spending their life operational life in each environment for a large amount of time. However the allocations pair 31.8 – 32.3 GHz (downlink) and 34.2 – 34.7 GHz (uplink) is available according to [1] for links with Earth, and has been tentatively selected as the unique choice for high data rates with RF, with the understanding that one frequency pair should be sufficient for the purpose, and that optical communications would be available for even larger data rates with more relaxed availability and latency constraints, if required. Such approach mirrors the one followed for the Lunar Communications Architecture, by endorsing the same motivations as described in the related report[35].

<u>Issue 2: Mars in SZM of the Moon</u>

CNES has raised an issue concerning the design of Mars communications links in view of the regular visibility of the Mars from the Shielded Zone of the Moon (SZM)[57]. For protecting Radio Astronomy observations from any RF interference, it is important for Mars missions to abide by the ITU recommendation RA.479-5[58]which has reserved the 300 MHz to 2 GHz range for radio astronomy observations. The point has been addressed in the latest revision of the SFCG document [1] which is applicable to the present report.

Regarding Surface to Surface links CNES suggested that the terrestrial wireless 2400-2480 MHz standard band be used as a future Mars surface-to-surface band. (Note, this band is now listed in the latest SFCG recommendation[1].) Using 2400-2480 MHz for the mid and long term would help solve the "Mars in SZM" issue with UHF band, and avoid interference issues with 2025-2110 MHz/2200-2300 MHz bands.

Issue 3: co-existence of residual carrier and suppressed carrier modulations
Whereas a prevalent use of bandwidth effect modulations is envisaged for the "to-be-congested" RF spectrum in the Mars environment, the availability of residual carrier modulations for low rates scenarios linked to e.g., critical TT&C or spacecraft emergency is deemed necessary.

Issue 4: co-existence of GMSK and O-QPSK
Even though GMSK has better spectral efficiency than O-QPSK and can be operated simultaneously with PN ranging, it is recognized that legacy hardware is available implementing O-QPSK for high data rate transmission, and therefore both options are tentatively retained.

Issue 5: need of variable coding and modulation
The need for variable coding and modulation may arise in those cases where spectral efficiency is important (e.g., small bandwidth at S-Band or X-band), or when the link signal-to-noise ratio is expected to change significantly during a pass (e.g. for proximity links). Accordingly, the use of ModCods from CCSDS families [32] has been proposed as option in various scenarios, complementing the wide use of GMSK or OQPSK.

Issue 6: need of MFSK modulation
Although the majority of missions landing on Mars has used, and will use, relay communications via a Mars orbiter in UHF to support the Entry Descent and Landing (EDL) phase, the use of Direct To Earth communications during EDL cannot be excluded in the future, especially to cope with potential situations where no relay obiter would be available. Such scenarios may rely on MFSK modulation as a reliable and robust method for conveying critical information to Earth. Use of MFSK is also being investigated for support to survival mode, in a severely SNR constrained scenarios as well as in communications links affected by solar plasma induced scintillation (e.g. during superior solar conjunctions).

Issue 7: Coexistence of S-Band and X-Band for proximity links
Whereas it is recognized that UHF may be required for low rate TT&C, also because it is the unique frequency allocations currently used for proximity links, and K-Band is an appealing option for high data rates in RF, the question was posed whether either S-band or X-Band could be down-selected. Currently both frequency bands are maintained for proximity links, the S-Band oriented to complement UHF for TT&C, and X-Band targeting higher rate applications together with K-Band. The preservation of S-Band is highly motivated by the need of re-using hardware employed in the Lunar environment.

Issue 8: Need of O3K complementing PPM for cross-links or proximity links

PPM/SC-PPM (downlink) and PPM/LDPC (uplink) are proposed as baseline for optical communications links with Earth. Whereas the transposition of such solution to cross links and proximity links has clear benefits in terms of re-use of on-board hardware, it is recognized that O3K can serve the purpose as baseline, also considering the heritage from Earth applications. It is also remarked that optical telemetry ranging could be employed in optical link, however work in CCSDS is required, e.g., as extension of [5], for which a pink sheet is already available

Issue 9: Need of AOS on top of USLP
USLP is tentatively proposed as ubiquitous solution Space Data Link Protocol, with the exception of legacy missions with low complexity, or not requiring networking for which TM and TC are left as options. The added value of incorporating AOS on top of USLP is unclear for Mars scenarios, as both data link protocols offer largely overlapping services, and therefore USLP is kept as the preferred choice.

Issue 10: Considerations about coding schemes
LPDC and turbo codes are proposed, offering very good performance for a broad range of coding ratios, from 1/6 to 7/8. Indeed, Turbo codes should be selected for power-constrained links, and LDPC codes should be used when bandwidth is constrained. Differently from the Lunar Communication Architecture[35] however, the block lengths are not prescribed and left as design parameter for the links optimization.

Issue 11: Possible inputs to SFCG for adoption of K-Band allocations in the Mars context
In the frame of a “Moon to Mars” concept the allocation 25.5 – 27 GHz for Mars surface to Mars orbit and Mars orbit to orbit cross-links has been extended up to 27.5 GHz, enabling the possible re-use of Ka-Band hardware, operating in the Moon for proximity links, at Mars

Issue 12: Need of Ku-Band for proximity links
Due to the use of the 22.55/26 GHz allocations pair for proximity links, largely justified by Lunar heritage, it is tentatively proposed to de-scope the Ku-Band allocations (14.5 – 15.35 GHz and 16.6 – 17.1 GHz) which would be allowed according to [1].

Issue 13: Adequacy of current CDMA CCSDS blue book for Mars region
The current CDMA standard[33] focused on near Earth applications at 2 GHz, is not adequate for MSPA and may be not adequate to a Mars communications architecture. ESA is running a study with European industry to define and prototype a different CDMA approach vs. the one described in [33]. The results of that study will be an input to the definition of a new CCSDS standard, covering uplink, downlink, forward, return links.

Issue 14: Use of telemetry ranging.
Telemetry Ranging[34] could represent an alternative to GMSK+PN[2] for simultaneous ranging and high rate telemetry transmission, especially when O-QPSK is adopted instead of GMSK as high rate modulation. In the present report GMSK+PN has been baselined in view of its high maturity (e.g., flying with the ESA mission Solar Orbiter), however in the future the Telemetry Ranging option could be added, once it has been operationally demonstrated and included in a CCSDS blue book.

Issue 15: Potential use of PCM/PM/NRZ-L modulation.

While PCM/PM/bi-phase-L, as the modulation on residual carrier, is identified in Table 4.2-1, in practice the PCM/PM/NRZ-L has been used by many missions for years. This is because the former is not as bandwidth efficient. The down side of the PCM/PM/NRZ-L scheme is it is not yet a CCSDS standard. Perhaps, this issue should be brought to the CCSDS for resolution.

Issue 16: Departure from Reed Solomon/convolutional codes towards LDPC.
Ostensibly missing from Table 4.2-1 is the concatenated Reed Solomon/convolutional codes that has served space missions ubiquitously well over the past four decades. As more and more new missions are adopting the LDPC codes, the burden now is on the new and currently existing service providing assets, e.g., the Earth stations and relay orbiters, to provide LDPC encoding/decoding capabilities while still maintaining the concatenated coding capability for supporting many current missions.

5. Description of the Mars Communications Architecture

Since 1960, about 47 missions have been launched (and attempted to be launched) by the various space agencies in a vast effort to expand the sphere of human presence to the Mars. Among them, 17 successfully conducted their science objectives and 11 missions are still operational today. In the next decade, a score of missions will be launched to orbit or land on the Mars and establish a new chapter of robotic science and exploration activities there. Entering the era of late 2030s – 2040s when human Mars exploration would gradually unfold, it is expected there would be a marked rise in the number of missions, space vehicles and platforms. Future Mars missions planned by the various space agencies will benefit from an interoperable architecture sufficiently flexible to provide a phased approach for essential communications, navigation and other services.

5.1 Communications Architecture of Currently flying Mars missions

As shown in Appendix A, 11 Mars missions are currently in flight. These include 8 orbiters, 3 rovers, 1 lander plus a helicopter. Key characteristics of the communications architecture for current Mars missions can be summarized as following:

(1) Multiple communication paths: Except for two of the orbiters and the helicopter, all other vehicles have the capability of communications over the Direct-with-Earth (DWE) link and proximity link. The existence of multiple communication paths is nothing unique. Dating back to the 1970s, the Soviet Union's Mars-3 and NASA's Viking-1 and Viking-2 missions all had this feature. What is significant is the number of the alternative end-to-end communication paths available to a lander/rover due to the available combinations of relay satellites and Earth stations.

(2) Cross support by communication assets: All Mars missions at present rely on cross support by communications assets owned or operated by other space agencies. The communication assets involved in cross support are Earth stations and, for some missions, the relays as well. The degree of dependency on cross support services varies from mission to mission and very often fluctuates by mission phases and mission events. On average, cross support services represent ~30% [TBC] of the total service utilization. For instances, at present, NASA's InSight,

Curiosity, and Perseverance are getting about two-thirds of their data back through ESA's TGO relays, and TGO and MEX as well as ISRO's MOM get a lot of DSN time through cross-support.

(3) Science orbiters serving as relays: The relay services are provided exclusively by the "opportunistic" telecom relay payloads on science orbiters. These relay assets are considered opportunistic payloads because the primary purpose of their host spacecraft is for science observations. This approach has been very successful in providing low-cost relay assets and keeping the user burden to a minimum level, e.g., low SWaP terminals carried by the landed vehicles. A negative side effect is that the lower Mars orbits, optimized for achieving best science values by the science orbiters, have limited the relay coverages for surface user vehicles. Today's science orbiters also lack certain relay capabilities:

- They can only relay data from one surface asset at a time. When there are multiple surface assets operating in the same general region, there may be a need for relays that can simultaneously communicate with more than one asset at once (i.e., multi-beaming).
- They do not typically relay data from any user vehicles except surface assets. An exception to this is EDL coverage through one or more relay orbiters as exemplified in Perseverance's EDL coverage by MRO (bent pipe) and MAVEN (open loop recording) and by InSight's EDL coverage by MRO (open loop recording) and the two MarCO CubeSats (bent pipe). But currently there are no orbiter to orbiter relays. In the future, that will likely need to change.
- The access by landed vehicles to relay links is largely pre-scheduled manually. User-initiated service mode similar to that suggested for Lunar relays is desirable in the future architecture.

(4) Constrained communication links: The capabilities of all the communication links, DWE and proximity links, are rather limited due to the SWaP constraints of the flight systems. X-band is solely used for the DWE links. Till this date, the maximum data rate for the end-to-end return links is ~12 Mbps (at Mars near distances) and ~0.6 Mbps (at Mars far distances). For the relay links, the data rate of the UHF bands is limited at ~2 Mbps. At present, no high-rate links, e.g., Ka-band or optical links, are operational. While the MRO was equipped with a 32 GHz Ka-band capability that was successfully tested on the way to Mars, there has been no follow-up plan for migrating to Ka-band. As a result, the HiRISE camera, given its powerful imaging ability for covering vast areas of Martian terrain and seeing high-resolution features as small as a kitchen table, has only managed to return a small fraction of the data sets needed to globally map Mars. The constraints in communication links are not a problem resolvable by each individual mission. The real solution lies in the infrastructure inherent in the Mars communications architecture.

(5) Temporary surface-to-surface communications: No persistent communications link between surface vehicles exists in the current mission architecture. The Perseverance mission, however, has successfully applied a 900 MHz UHF link to conduct a few short-lived communication sessions between the helicopter and rover. Mars surface communications is nothing new. In 1997, Mars Pathfinder became the first Mars mission employing a surface link between the lander and rover to conduct the operations of the Sojourner rover throughout the 2.5 month mission life. Undoubtedly, beyond the present state, more persistent utilization of surface

communication capabilities will emerge as an important aspect of the future Mars communications architecture.

(6) Communication layers: The fundamental communications services now offered are based on the capabilities enabled by the space data link and physical link layers. No end-to-end networking functionality exists in the communications architecture. Transfer of application data end-to-end relies on either certain application layer protocols such as CFDP or stitching together a series of point-to-point data link interfaces. Often data streams from landed assets are treated as a bitstream and transferred as a "bag of bits". No effective comm architecture using networking or higher level reliable protocols has been applied in any consistent way

(7) Downlink beam sharing: To maximize the use efficient use of Earth stations, a downlink beam sharing technique has been employed to simultaneously support multiple Mars spacecraft by a single antenna. So long as two or more spacecraft lie within the half-power beamwidth of a single Earth antenna, acquiring data from them simultaneously using the Multiple Spacecraft Per Antenna (MSPA) system is feasible. MSPA decreases loading demands on the Earth networks and reduces Mars mission's operating costs. However, on the uplink side during the MSPA downlink, a "serial uplink swap" approach is taken which allows each spacecraft to "occupy" a portion of the uplink pass for two-way Doppler and ranging as well as commanding. Since only a single uplink frequency can be transmitted at a time, only one spacecraft at a given time can operate in a two-way coherent mode, while the remainder must be in a one-way mode. This imposes some undesirable inflexibility in the provision of radiometric data to the missions participating in beam sharing.

(8) Standard radiometric tracking services: Radiometric observables, i.e., ranging, Doppler, and DDOR, are part of the standard radiometric services provided by the network infrastructure. Like the forward and return data services, they are multi-mission in nature. Notably, almost all Mars missions at present make use of DDOR to obtain precise plane-of-sky measurements of spacecraft position that complement the line-of-sight ranging and Doppler measurements.

(9) Mission-specific navigation: Navigation capabilities are provided by individual missions. They rely heavily on radiometric observables acquired over the Mars-Earth links and on on-board navigation cameras (usually when on the surface; they also rely on IMUs and wheel rotation counters).

(10) Present-day architecture severely limits present-day Mars relay capabilities. Multiple constraining factors exist in the relay communications architecture. First, the proximity relay operation consumes a significant amount of available power to the rover/lander. Second, the low-altitude geometry of the existing relay orbiters means only 2 or 3 relay passes of ~ 10 min duration are typically available from the science orbiters providing relay. The third constraint is the frequency band. UHF throughput is constrained to 2048 kbps or less. One or more orders of magnitude increase in Mars Relay data volume can be realized with modern architectural and design advancements that could include higher frequency directional proximity links to dedicated higher altitude relay orbiters that support both rovers and orbiters and utilize higher frequency DTE links to the deep space antennas on Earth.

5.2 Communications Architecture of Future Mars Exploration Eras

Our analysis of the Mars mission set covered in Appendix A has led to some observations and findings and about the evolution of the future Mars communications architecture. In general, the architecture will evolve over four distinct, but overlapping eras for the missions:

- Current Flying Missions: Present
- Future Near-Term Missions: Starting 2022 launch
- Future Mid-Term Missions: Starting 2026 launch
- Future Long-Term Missions: Starting 2037 launch

Figure 5.2-1 illustrates the mission eras and the overall complexion of driving missions in each era.

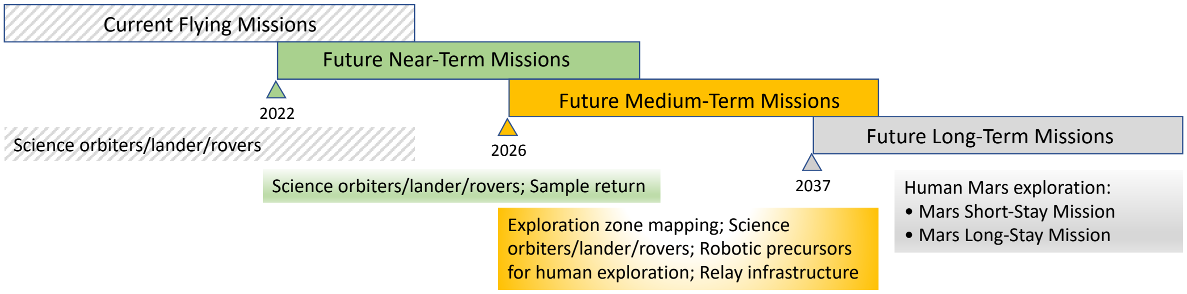


Figure 5.2-1. Mars mission eras for communications architecture evolution

Figures 5.2-2 – 5.2-4 illustrate the Mars communications architecture as it evolves over the three eras.

5.2.1 Communications Architecture of Future Near-Term Missions

The existing communications architecture, given its key characteristics as discussed in Section 5.1, will persist well into the rest of 2020s. However, for the era of Future Near-Term Missions starting 2022, it is expected that a few new capabilities will gradually emerge. These include:

(1) A step towards high-rate link: The JAXA's MMX mission (launch 2024) has planned to use the 32 GHz Ka-band, in addition to the X-band, for its Mars-to-Earth return link. This may be a significant step in the migration to high-frequency bands for deep space communications, taking into account not only the increased return link capacity but also the better immunity of Ka-Band to amplitude and phase scintillation effects at low Sun-Earth-Satellite separation angles. During this era, other Mars missions that probably will fly a Ka-band capability are the two NICT's CubeSat missions, the TEREX-1 lander (launch 2022) and TEREX-2 orbiter (launch 2024). So, it is fair to conclude that the traditional SWaP constraints are being resolved and the infusion of Ka-band capability into flight systems is gaining some momentum, also taking into account the better immunity of Ka-Band to amplitude and phase scintillation effects at low Sun-Earth-Satellite separation angles.

(2) PN ranging techniques: As discussed in Section 4, the preferred approach to ranging is the PN ranging based on the CCSDS standards. Convergence towards PN ranging offers the advantage

of maximizing cross supportability between Earth networks and simplifying radiometric tracking services for mission support. It gives missions the added freedom to adjust their measurement performance in real time since PN ranging has the advantage of modifying its integration time in real time, whereas sequential ranging integration time is fixed by the code definition. This approach has been recommended in the IOAG LCAWG report and the ICSIS document. As more Lunar missions and Earth networks will provide and use PN ranging measurements for radiometric tracking, the same approach will also be taken by future Mars missions.

(3) Ka-band PN delta-DOR: Delta-DOR technique uses interferometry to directly measure spacecraft angular position in the radio reference frame. It complements line-of-sight range and Doppler measurements. Since 1981 the delta-DOR using X-band has been used by almost all deep space missions for navigation purpose and has supported Mars missions including the prediction of landing position accuracy for landers and rovers. In view of the potential use of Ka-band by Mars missions, the time is ripe for the introduction of a new delta-DOR approach that makes use of Ka-band and PN DOR tones. The Ka-band PN delta-DOR offers an Improvement in angular accuracy from current X-band delta-DOR at 2 nrad (300m plane-of-sky at Mars encounter distance) to a targeted 0.5 nrad accuracy. This is achieved by the combined contribution of Ka-band and PN ranging, e.g., the DOR bandwidth increased from 50 MHz at X-band to 500 MHz at Ka-band to reduce quasar coordinate error and the PN DOR signals to reduces dispersive phase error, among other error budget components.

(4) LDPC coding schemes: A family of LDPC codes was standardized by the CCSDS about a decade ago. Recently, the Perseverance rover successfully executed a UHF session with the MAVEN orbiter using LDPC code, enabling significantly higher data return than with traditional convolutional code. This was the first application of LDPC coding by a Mars mission. Given its performance advantage over the concatenated Reed-Solomon/convolutional codes at coding rate 1/2, the adoption of the LDPC codes for downlink will also occur during this era. And this may signify the gradual departure from the concatenated Reed-Solomon/convolutional codes that have been used by space missions for more than four decades.

(5) Cross Support Service Management (CSSM) capabilities: In the continued striving to make it easier for the collaborating Earth ground networks to cross support each other's Mars missions, the infusion of the CSSM capabilities standardized by the CCSDS will be critical. For more than two decades, the standard approach to cross support services using SLE data transfer services has benefited most Mars missions, but the processes for planning, preparing, and articulating/configuring these services have been conducted in a network-specific manner. To that end, the use of Simple Schedule Format (SSF), Planning Information Format (PIF) and Service Management Utilization Request Formats (SMURF) by all Earth networks would promote a higher level of interoperability. Both SSF and PIF are considered low-hanging fruits among the suite of CSSM capabilities because they are easy and low-cost to implement.

(6) Solid State Power Amplifier (SSPA): On the flight side, the ultra-high-efficiency SSPA based on gallium nitride semiconductor technology that will enable higher transmitted power, hence higher data rate, particularly at X-band and Ka-band.

Some capabilities will be carried forward from the previous era with changed use profile, for example, the increased reliance on the Multiple Spacecraft Per Antenna (MSPA) and more prevalent use of Turbo codes for downlink. Figure 5.2-2 depicts the Mars communications architecture for the Future Near-Term mission era.

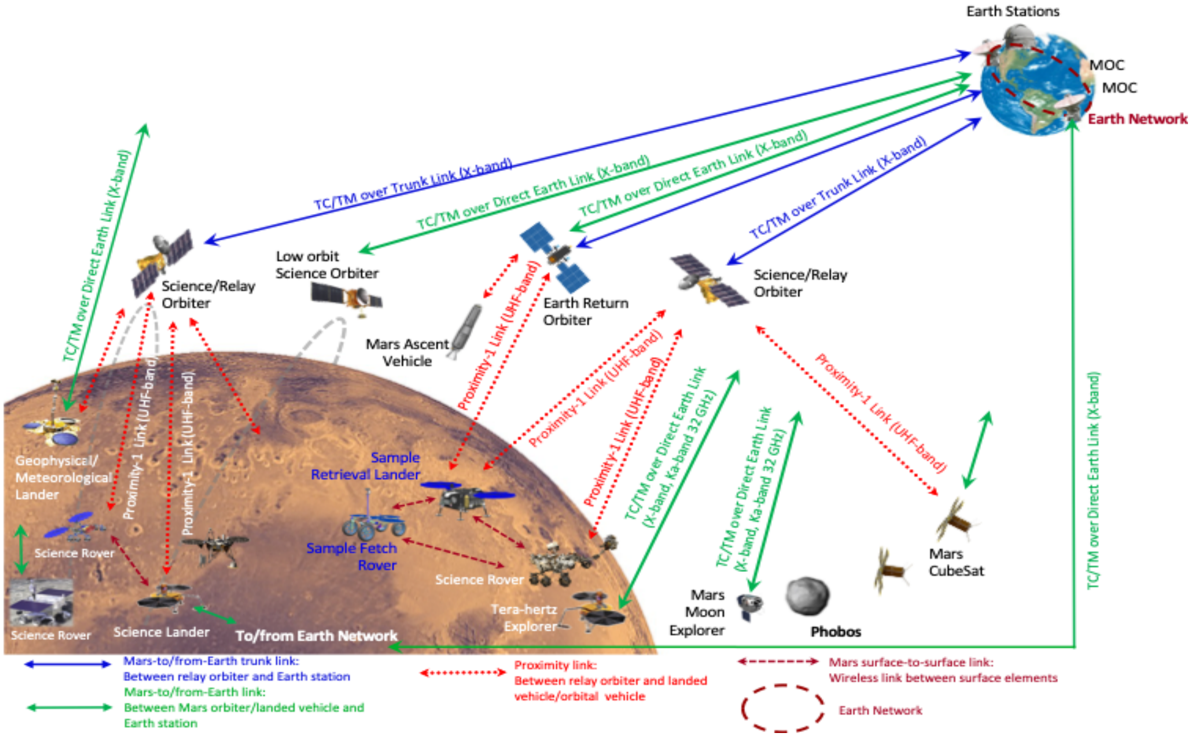


Figure 5.2-2 Mars Communications Architecture – Future Near-Term Mission Era

5.2.2 Communications Architecture of Future Medium-Term Missions

Moving into the era of Future Medium-Term Missions, i.e., during the late 2020's – 2030's, some significant advancements in communication and navigation capabilities will likely occur:

(1) Ka-band for high-volume/high-rate data return: The international Mars Ice Mapper mission, currently being planned by NASA, JAXA, CSA, and ASI, would detect the near-surface ice deposits and perform reconnaissance zone mapping for human landing site selection. Driven by the SAR instrument, the average data rate estimated for the DTE link would be about 16.7 Mbps on a 24x7 persistent basis.

(2) Mars relay network dedicated to communications: Two potential relay networks have been envisioned for this era. They are ESA's Mars Communication and Navigation Infrastructure Network and NASA's commercial relay network for servicing the Mars Ice Mapper and other missions. If either of the two occurs, it will mean the start of the build-up of "local" Mars infrastructures dedicated to communications. This would represent a departure from the eras where relay capabilities were a secondary function on science orbiters. The dedicated relay satellites can typically be deployed on orbits at higher altitude to provide longer coverage

period for surface vehicles, hence higher data returns. Additional functionalities would become available with service behavior exhibiting more powerful attributes, for example:

- The relay satellites can relay data from multiple surface assets at a time. This would provide the capability that allows simultaneous, multiple access to the proximity link.
- They can relay data from both surface and orbital vehicles.
- The access by user vehicles to relay proximity links would be on-demand, i.e., no longer being pre-scheduled manually. A user-initiated service (UIS) mode similar or identical to that suggested for Lunar relays would be the norm. The pre-scheduled initiation mode would still be available, but only for exceptional use cases.
- Ranging and Doppler measurements can be acquired over the proximity link by user vehicles, thus enabling a form of radiometric services.

(3) An early form of Mars Network (MarsNet): During this era, starting from the Lunar environment where an early form of relay network would be emerging due to dedicated relay orbiter(s), the use of surface-to-surface links for the interface between ExoMars Kazachok lander and Rosalind Franklin rover and that between MSR's Sample return lander and Sample fetch rover would also indicate the existence of a limited Mars surface network. Architecturally, analogous to the terrestrial internet, the three types of networks, i.e., the Mars relay network, the Mars surface network, and the Earth networks, when interconnected together would create an early form of Mars space internet or the Mars Network (MarsNet). Figure 5.2-3 shows the scope of the Mars Network end-to-end and its boundary with the network user elements. The internal connectivity, i.e., that between the three types of networks, and external connectivity, i.e., that between the network and the user elements are also identified.

(4) DTN: In order for the MarsNet to provide even a basic space internet service, it will have to provide some rudimentary network layer functionality, i.e., the space internetworking services as defined in the IOAG Service Catalog – Volume 2. The DTN will provide the protocol suite that is applied to the MarsNet. That means DTN nodes would be deployed throughout the end-to-end data path. Each relay orbiter, its user vehicles (in orbit or on surface), the relevant Earth stations, and the various Mission Operations Centers (MOCs) will all potentially serve as DTN nodes to achieve reliable, robust, efficient end-to-end communications path.

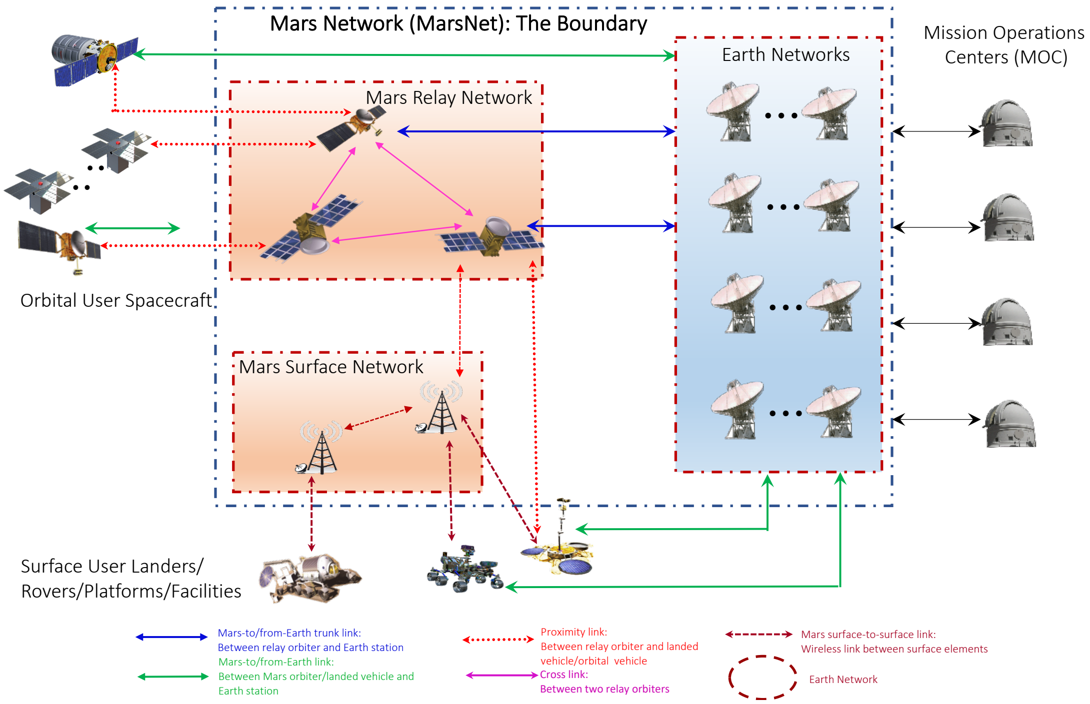


Figure 5.2-3. Mars Network (MarsNet) – Scope and Boundary

(5) Unified Space Link Protocol (USLP): For decades, the application of multiple space data link protocols, i.e., the TM protocol for downlink, the TC protocol for uplink, and the Proximity-1 for proximity link, has been the practice of all Mars missions. For future missions requiring high-rate links, and in order to maximize the link efficiency through using large frame length and codewords, there will be the need to move to either the AOS or USLP. As discussed in Section 4 and the LCA report, the USLP is the preferred option. A fundamental issue is whether the multiplicity of space data link protocols should perpetuate into the eras of future Mars exploration. Since the USLP can be operated regardless of link directionality (unlike TM and TC) and link rates (it supports all data rate regimes, RF and optical, unlike TM, TC, and Proximity-1 protocols), as the single protocol at space data link layer it would offer the advantages of enhanced interoperability, reduced implementation cost, and reduced operational complexity for communications.

(6) Optical downlink demonstrations: Looking into future eras, both demands on RF spectrum and growth in data demand will motivate deploying optical communication capability for supporting Mars missions. This is particularly critical in view of the such demands during the Future Long-Term Mission era because of human Mars exploration. Since the infusion of optical communications, like any new major technology infusion, will take long lead time, e.g., two decades in the case of deep space Ka-band, it is prudent for all Mars-faring space agencies to undertake operational demonstrations of optical communications during this era. A logical initial deployment is the direct-to-Earth link. As part of such demonstrations is the smart use of RF and optical communications, in combinations or separately. While optical communications has the potential to bring multiple benefits to users including higher data rates, shorter contact times, improved security, more precise navigation, and smaller flight terminals relative to traditional RF equipment, optical link is more vulnerable than Ka-band link during

or near superior solar conjunction when the SEP angle is less than 10 degree. Even for uplink, in time of narrow SPE angles, optical is more problematic than Ka.

(7) GMSK for simultaneous data and PN ranging: GMSK and its less-performing variant, OQPSK, have been used by some Mars missions for downlink signal modulation to maximize X-band spectral efficiency. As always, the design of the link must take into account the trade-off between power efficiency and bandwidth efficiency. In view of the ever-increasing number of Mars missions, allocations of X-band bandwidth will be more challenging than they are today. And optimization for link efficiency will be leaning more toward maximizing bandwidth efficiency, hence GMSK for both uplink and downlink appears to be a right solution. The new GMSK method, defined by the CCSDS, that allows for simultaneous transmission of data and PN ranging (for accommodating radiometric tracking on suppressed carrier) is therefore the preferred modulation approach for X-band and other congested bands.

(8) Potential demand on stand-by contingency links: Persistent connectivity with flight operations personnel in mission control center for some critical cargo deployment activities may be needed. This would lead to the potential demand on maintaining some stand-by contingency links.

(9) Potential use of ModCod families for bandwidth constrained links: Venturing into this era is the significant growth of the overall Mars mission set. By this time, the number of spacecraft accumulated from late 2010's could reach ~34. The severe over-subscription of X-band bandwidth will become a very daunting issue. It would be even worse for the next era unless a coordinated effort involving all Mars-faring agencies is taken. That means, in addition to moving to Ka-band and GMSK, the use of ModCod should start to happen.

Carried forward from the Future Near-Term Missions era are the prevalent use of PN ranging, LDPC/Turbo codes, MSPA, and autonomous navigation. Figure 5.2-4 depicts the conceptual Mars communications architecture for the Future Medium-Term mission era.

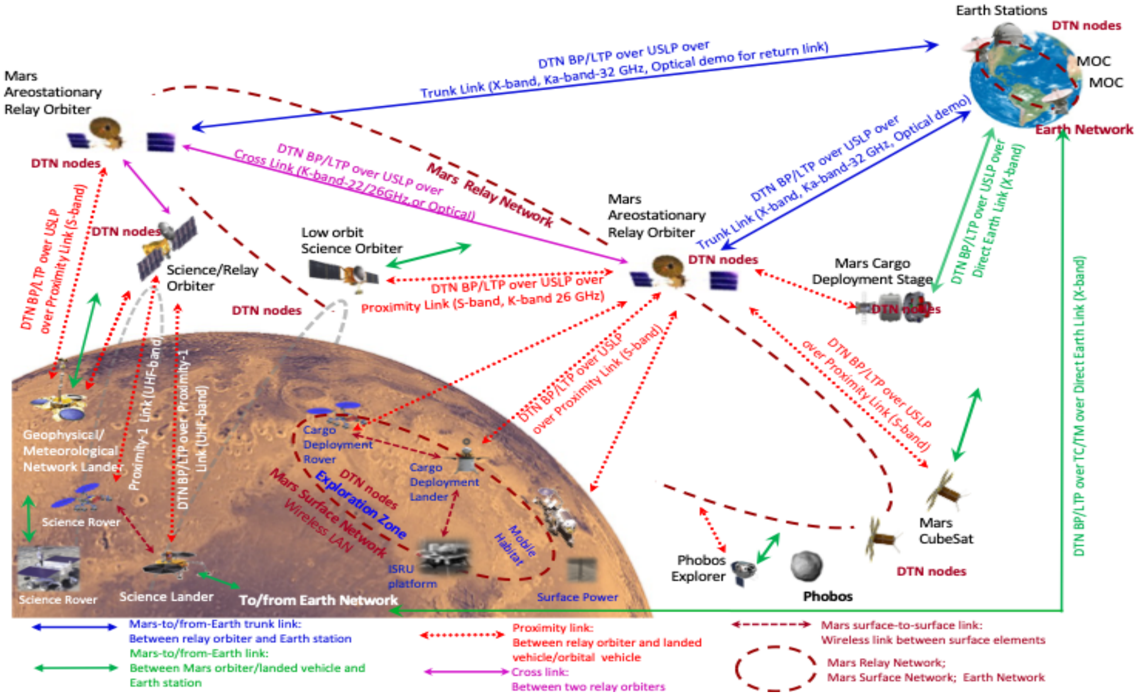


Figure 5.2-4 Mars Communications Architecture – Future Medium-Term Mission Era

5.2.3 Communications Architecture of Future Long-Term Missions

Marked by the activities conducted in orbits and on surface for the human Mars exploration under the orchestration of an international program, the period of the late 2030's – 2040's is the era of Future Long-Term Missions. Leveraging the architecture defined and implemented for the human Lunar exploration, the Mars communications architecture during this era (See Figure 5.2-5) would be imbued with additional advancements in communication & navigation capabilities:

(1) Mars Relay Network: Evolving from the version built in the previous era, a more complete, more powerful, and more robust Mars relay network would be in place. It is envisioned that the expansion of the network would involve: (a) the addition of more dedicated relay satellites to a total of three forming a constellation; (b) the deployment of the telecommunications payload on the DSH and Cargo Relay; (c) the establishment of crosslinks to interconnect the dedicated relay satellites, the DSH, and the Cargo Relay.

(2) Mars Surface Network: In this era, the human habitat and a multitude of landers, rovers and ISRU platforms, clustered in one (or multiple) exploration zones near equator or mid-latitude region, would be deployed to conduct exploration and science activities. This would lead to the formation of a full-fledged Mars surface network. Such a network, potentially using WiFi or 3GPP/LTE wireless devices, would be needed to facilitate vicinity wireless communications between the various landed elements including astronaut's hand-held/body-mounted devices.

(3) Mars Network (MarsNet): Given the full-grown Mars relay network and Mars surface network plus the participating Earth networks, the Mars Network would evolve into a more encompassing end-to-end space internet (see Figure 5.2-3 for the Mars Network scope and boundary). Patterned after the DTN's architecture model, it is a network of networks that

facilitates definition and delivery of services essential for all Mars missions. Participating networks will be owned and operated by an international set of space agencies, commercial companies, and academic organizations, all governed by a coordinating body and capable of seamless interoperation. Since the DTN-based architecture is inherently organic, the Mars Network is flexible and open, being able to adjust itself in accordance to changes in mission needs. All key network assets, in Mars region or on Earth, will be treated as DTN nodes in this end-to-end space internet, thereby compatible with each other regardless of the providing organizations.

(4) Space internetworking: as implied in Section 5.1 "Communication Layers", current relay operations at Mars provide crude multi-hop relaying without true internetworking. There is no true end-to-end network protocol, no network-wide addressing scheme, no provision for different classes of data, and no common, fully automated, accountable, data delivery. These deficiencies would inhibit operations as more elaborate missions involving orders-of-magnitude-more systems and communication links, as well as human crews, are developed.

The Mars communications architecture defined in this document features a full space internetworking functionality. At the network layer and above, data bundles are routed and transferred over the end-to-end path(s) using the DTN protocol suite. By end-to-end path, it is to mean a path through which data are transferred between a Mars user vehicle and an Earth-based ground system. Similar to the IP nodes on terrestrial internet, all elements on the end-to-end path(s) between (and including) the source and destination are DTN nodes. However, for data transfer localized in Mars region where neither the end source nor the end destination of the data is an Earth system, both IP and DTN protocols can be used. In that regard, the full TCP/IP protocol suite, should be considered as a viable alternative to the DTN protocol suite for Mars surface network, but it should only be thought of as an intranet protocol for local surface-to-surface communications. Any DTN/IP mixed protocol architecture for cross-network communications should be avoided as it will require a specialized "protocol matching gateway" architecture to be developed and deployed (these two different protocol suites operate very differently from end-to-end).

(5) DTN Network Management: In order to support the multitude of Mars missions, the combination of relay orbiters, surface network hub(s), and Earth stations must be orchestrated in a coherent and efficient manner to provide the fully integrated, interoperable services. Differing from previous eras, the nature of this network-of-networks, composed of different contributions from different agencies, inevitably will introduce some additional complexity to the network management function for the Mars Network. This network management function can no longer be performed as a set of monolithic processes by one agency. A federated peer-to-peer model involving network management and configuration coordinated across at multiple networks must be applied. The Mars Network would rely on the network management capabilities in each participating network to conduct service management and network control functions at the space internet level. Analogous to the terrestrial Internet, the network management function for Mars Network embodies a collection of policies, rules, standard operating procedures (SOP), and network monitor and control capabilities provided by all networks using certain standard network management protocols. For each of the above, cybersecurity-related capabilities are an inherent aspect of the system.

Key network management capabilities are as follows:

- Obtain service requests from user missions, generate network-wide contact plans and the DTN contact graphs, define configuration needs for DTN nodes and the underlying links DTN uses, set up the network and monitoring it to make sure it executes user's service requests properly;
- For missions requiring services involving multiple DTN nodes, "coordinate" the service management functions conducted by the relevant networks;
- Obtain the status of communication assets monitored at each DTN node, and assess the aggregate behavior of the participating DTN nodes for service sessions;
- Identify network faults and suggest recovery actions with coordination across all networks to resolve internetwork issues;
- Coordinate configuration management at each network to ensure that across the Mars Network the network configuration is as desired. CM also includes the DTN-related items such as source/destination addressing, routing paths, and QoS assignments.
- Analyze performance of individual networks based on traffic data collected to detect performance bottlenecks, generate past/present performance summary statistics, and analyze trends.
- Ensure each DTN node meets the regulatory standards and complies with applicable laws and regulations of each relevant country;
- Coordinate cybersecurity actions and practices taken by all networks and identify security risks based on data gathered from the participating networks.

(6) Ka-band, i.e., 34 GHz bands, for high-rate forward link: The activity/traffic modeling conducted in 2017 concluded that the maximum uplink data rate for the crewed Mars Short-Stay Mission (MSSM) is about 30 Mbps. The rate would far exceed the available X-bandwidth. Therefore, the 34 GHz Ka-band has been recommended for the Earth-to-Mars high-rate link. Together with the 32 GHz Ka-band for downlink, a full-duplex, high-rate trunk link between an Earth station and a Mars relay orbiter would be realized. This is another key feature of the Mars communications architecture of this era. An important ramification of the high-rate trunk link is it can convey multiple loads of forward data destined to their respective user vehicles via Mars relay, hence alleviates the heavy demands on X-band bandwidth by deep space missions and constrains the X-band be used for infrequent TT&C purpose as much as possible.

(7) K-bands, i.e., 22 GHz and 26 GHz, for high-rate proximity link: To fulfill the needs for high-volume and high-rate transfer of data between a user vehicle and its Earth-based MOC, the high-rate end-to-end link must be provided. As the complement to the trunk link discussed above, the high-rate proximity link using the 22 GHz K-band for forward link and 26 GHz band for return link is recommended. The approach is synergistic with that for Lunar proximity link, thus allowing maximum commonality and reusability between the Moon and Mars radios, not only for that on relay orbiters but also the user vehicles.

(8) Security in Communications Architecture: As more relay orbiters, surface vehicles and Earth stations become increasingly interconnected with each other, it is crucial to provide an integrated approach to addressing both the security concerns traditionally faced by Earth networks and users' mission operations systems, and those in Mars environment. This must be

done within the context of an open architecture that allows the entire Mars exploration community to contribute to secure solutions while recognizing that vulnerabilities in the architecture will be visible to all.

In order for a Mars network communications architecture to be successful it must be capable of reliably delivering data to and from all of the elements that participate in it. It must allow access to, and provide services to, all of the qualified users, and these users must be able to protect any of their data that they consider sensitive. These protections are likely to include commands and other uplink data, and may include protection to some or all downlinked data as well.

To that end, it is important to maintain that encrypted data will be a "pass through" at the ground stations or other intermediate elements on the end-to-end data path because it removes the need to have encryption and decryption within the ground tracking sites. This is a potential operational complexity that is best avoided (and confined to the two communicating ends), especially with multiple countries working towards full interoperability. The recommendation is that all command data, and any science or personnel data that need to be secured be protected by end-to-end user applied authentication or encryption.

(9) New relay services: In addition to data delivery service, time service and in-situ tracking/navigation services would be infused as new service types. These services may be crucial to some crewed activities. The potential radiometric observables acquired over the relay-enabled proximity links must be integrated together in order to provide an estimate of a user vehicle's position and velocity state. Part of this processing requires knowledge of the relay satellite's location at the time of the observation to process the data onboard. When processing this data, errors in time between two elements will feed into errors in position and velocity estimates. As such, the position and timing are inexorably linked for absolute ranging. Even for relative navigation, any timing errors will show up as system latencies, but due to the typically lower relative velocities, these errors have a smaller effect. Similarly, performing a time transfer between two elements requires a measurement of the light travel time between them. As such, any errors in state on either asset will cause timing synchronization errors between the spacecraft. Aided by a high stability onboard oscillator, i.e., an Ultra Stable Oscillator or better yet an atomic clock, or synchronization of onboard time with Earth-based master clocks, it is feasible and practical for the relay satellites to undertake the role of ensuring timing accuracy at user vehicles. To perform time transfer within the Mars communications architecture, the relay satellite could broadcast a time message to update onboard time and use an approach like the Network Time Protocol (NTP) to synchronize time across the network and achieve an order-of-microseconds accuracy.

As to the radiometric observables acquired over the proximity links, a Joint Doppler and Ranging (JDR) scheme that would allow real-time position determination by Mars landers/rovers is considered a viable solution. It is essentially a single-satellite localization scheme that leverages on the proximity link between a vehicle and an orbiting relay to perform Doppler and range measurements, and with the altitude knowledge of the vehicle, to determine in real-time the position of the surface vehicle. The JDR scheme[47] can achieve nominal position accuracy at 19.9 m (mean) and 23.8 m (RMS) given a Lunar relay at 12-hour frozen orbit. For view periods when two relay satellites are available, the user vehicle would be able to localize with nominal position accuracy at 14.7 m (mean) and 17.6 m (RMS).

(10) Multiple access to proximity link: By multiple access, it is to mean the link access mode which allows multiple user vehicles to have shared access to a physical link at the "same time". Multiple access mode is an important attribute of the relay services. It is estimated that during the era the number of potential simultaneous relay users would be ~4 for high-rate links, and ~11 for low-rate links. Studies[43] conducted previously for Lunar and Mars relay networks have all recommended a TDMA scheme as forward link multiple access method. The recommended time-sharing granularity should correspond to the multiplexing PDUs of the link layer protocol employed. For Mars, it will be the size of the USLP transfer frames or Proximity-1 frames. For return link, the general conclusion is that FDMA is more bandwidth efficient and scalable with network growth than CDMA[43]. However, for lightly loaded relay networks, both FDMA and CDMA are suitable. For relay networks with larger population and higher capacity requirements, FDMA is recommended for its scalability and bandwidth efficiency. In the context of Moon-to-Mars initiative, this is an area where design and implementation for Mars relay should adhere to and benefit from that for the Lunar relay network.

(11) User vehicle-initiated service initiation mode: Another important attribute of the Mars relay services is the service initiation mode. Undoubtedly, the pre-scheduled mode will be applicable to some use scenarios where absolute determinism of the service provision is needed. The nominal mode of relay operations would be based on the User vehicle-Initiated Service (UIS) initiation mode. The UIS allows a user to autonomously request a service from the relay network. The UIS framework relies on the Service Acquisition Protocol (SAP). Through a signaling channel pre-provisioned by the relay orbiter for service acquisition, UIS SAP messages are conveyed between the user vehicles and the relay. User vehicles can utilize the signaling channel to request service on data channel. User vehicles with existing service on data channel can use it to send both user data and UIS SAP messages to acquire additional service. The relay orbiter responds to request by either (a) granting request as is, (b) granting request with additional input, (c) denying request allowing user time-out. For the multiple access link, the SAP is therefore a session control process that operates with the underlying data link protocol and multiple access process in an integrated fashion.

(12) Single beam sharing and arraying configurations for Earth antennas: Significant reliance on the multiple-spacecraft-per-antenna (MSPA) configuration to support up to 4 missions simultaneously by a single antenna, hence reducing the demands on Earth antennas, will continue into this era. The increase in the number of spacecraft due to elevated science and crewed mission activities would exert more pressure on the utilization efficiency of Earth stations. Given the n-MSPA configuration (where n is the number of source spacecraft), the current 4-MSPA configuration using X-band would have to be extended to 8-MSPA or perhaps more. Moreover, for supporting multiple relay orbiters over dual-trunk link and others, the MSPA configuration during this era would be applied to Ka-band as well, a capability that exists today but rarely operated. Use of CDMA could be beneficial in such scenarios.

Regarding single beam sharing on uplink, the multiple-uplink-per-antenna (MUPA) configuration would be used more heavily in conjunction with the MSPA. The MUPA replaces the “serial uplink swap” approach, a practice, along with the MSPA, taken by some Earth networks to support Mars missions for decades. It allows all the spacecraft (rather than only one at a time) in the antenna beam to operate in 2-way coherent mode, thus improving the flexibility and performance of radiometric tracking for all. Of all the approaches we assessed over the past few years, the most practical one is based on a scheme where uploads for multiple spacecraft are multiplexed onto a single uplink frequency. All spacecraft would lock onto the uplink signal and maintain two-way coherence with their respective downlink frequencies. Each would accept only the frames for its own upload data, differentiated by spacecraft ID. The spacecraft transponder would need the capability of sweeping and achieving lock (for uplink acquisition) in event of large differential Doppler shifts. For two-way coherent tracking variable turnaround ratios (as standardized by the CCSDS recently) on the spacecraft transponder are required. Clearly, MUPA is another step toward the efficient use of expensive antenna assets for deep space communications.

For achieving the persistent high-rate link (> 100 Mbps) including at Mars-Earth farthest/farther distance up to 2.67 AU, the Earth network will continue employing the antenna arraying configuration where the combined aperture of two or more antennas, either collocated or distant over large baseline, would yield the required G/T to close the downlink. Arraying is not a new capability. What is new for this era is the integrated use of arraying, MSPA, and MUPA configurations to support the maximum set of spacecraft. In this operating mode, an antenna participating in arraying to support a spacecraft doing high-rate Ka-band downlink is also actively supporting multiple spacecraft via the MSPA and MUPA configurations.

(13) Optical for direct-to-Earth links: During this era, driven by certain data types, like 16K UHD videos, in some mission scenarios, optical (in addition to Ka) communications capability would be needed for high-volume and high-rate data return. The use of optical link for deep space communications has been studied and advocated by space agencies for more than two decades. A NASA study[45]in 2017 suggested that the combined demands on DSN (measured by antenna track hours) by the 22 missions, analyzed for optical to achieve the equivalent high rate downlink data volume, is an order of magnitude less than required with Ka-band. For crewed Mars missions support the cost benefit lies in the potential reduction of three 34m BWG stations in DSN to achieve the needed high-rate downlink. Several notable challenges remain to be addressed. Chief among them are the need to build an optical ground infrastructure, i.e., an optical network consisting of stand-alone 12m ground stations (or multiple 8m RF-Optical hybrid apertures) at geographical locations similar to those of the DSN for global coverage, and the optical flight terminal, i.e., one with 50 cm aperture and 50 W laser power for high-rate links at Mars farthest distances. Both are big-ticket cost items, nevertheless by no means technology bottlenecks. To make the cost not so prohibitive, a viable solution is to share the infrastructure costs and ownerships through an international collaborative effort, which the human Mars exploration is intended to be anyway.

(14) Optical for crosslink between relay satellites: The move of optical communications into the Mars mission regime could also be realized by flying optical for the crosslink between relay satellites which is the backbone interconnect of a Mars relay network. This would be a low-hanging fruit step toward the application of optical communications in deep space. It is cost affordable since many commercially available flight optical terminals used for inter-

satellite links (ISL) in LEO regime are readily available. These optical terminals also offer some SWaP advantages. i.e., requiring low power (~2.2 to 4 W?) and small aperture size (< 10 cm?) in flight . Optical is an optimal band for the relay-to-relay crosslinks because it would alleviate the problem of local K-band congestion so that all high-rate proximity links, surface-to-orbit and orbit-to-orbit links, could be done at 22/26 GHz without potentially interfering with each other.

(15) Dual-trunk link for high-rate direct-with-Earth link: The design of Mars relay network for this era must take into account minimizing the cost of the relay systems while containing the number of deep space antennas required to support the high-rate "trunk-links" with Earth networks. Our previous studies suggested the use of cross-links to data-share the downlink burden between multiple relay satellites, so that the aggregate downlink rate for any one satellite is one half (when two satellites are in Earth view) of what it might otherwise have to be. Such crosslinks would enable load-balancing of data volume between two relay satellites, thereby creating a dual-trunk link with Earth network. During the peak aggregate data volume periods, the two relay orbiters can also maintain their respective DTE/DFE links, using the 32/34 GHz Ka-bands, with the same Earth network site, and simultaneously downlink the data sets stored on-board. They would each downlink half their data at half the maximum data rate. As a result, through the MSPA configuration the Earth station(s) would be able to acquire the total data using half of G/T that would be needed for the single-trunk link.

(16) Dynamic ModCod for extreme bandwidth-constrained links: As the achievable maximum data rates for some future Mars-to-Earth links are getting very close to the Shannon limit, to further increase efficiency adaptive modulation and coding (ModCod) schemes have been suggested. ModCod methods allow the missions to adapt the transmitted information data rate to dynamic link conditions by changing coding and modulation during a communication session in real-time or near real-time. It can significantly increase overall effective data throughput when the spacecraft radio and Earth station are configured adaptively to fully utilize link capacity. The ModCod protocol provides a mechanism to rapidly switch the channel coding and modulation used during a communications session. After a transmission using one coded modulation, another coded modulation may be used to match dynamic link conditions in near real time. Such dynamic conditions may arise, for example, because of changes in geometry, weather, interference, launch plumes, and scintillation. With judicious choice of the coded modulations over time, excess margin can be reduced and total data throughput increased. At present three ModCod protocols have been adopted or defined by the CCSDS, i.e., the SCCC, the DVB-S2, and LDPC VCM. For applications by human Mars exploration, the decision as to which protocol would be selected is probably dependent on that for the human Lunar exploration.

(17) Hot, stand-by contingency links: To ensure safety of crew members, hot, stand-by contingency links would have to be available. Unlike that for supporting the mission critical events, such as EDL and certain trajectory maneuvers of typical Mars robotic missions, the demands on contingency links may occur more frequently and last for longer period. This would pose significant impact on the loading and capacity of Earth networks. The approach taken for the crew activities in the Moon may be beneficial.

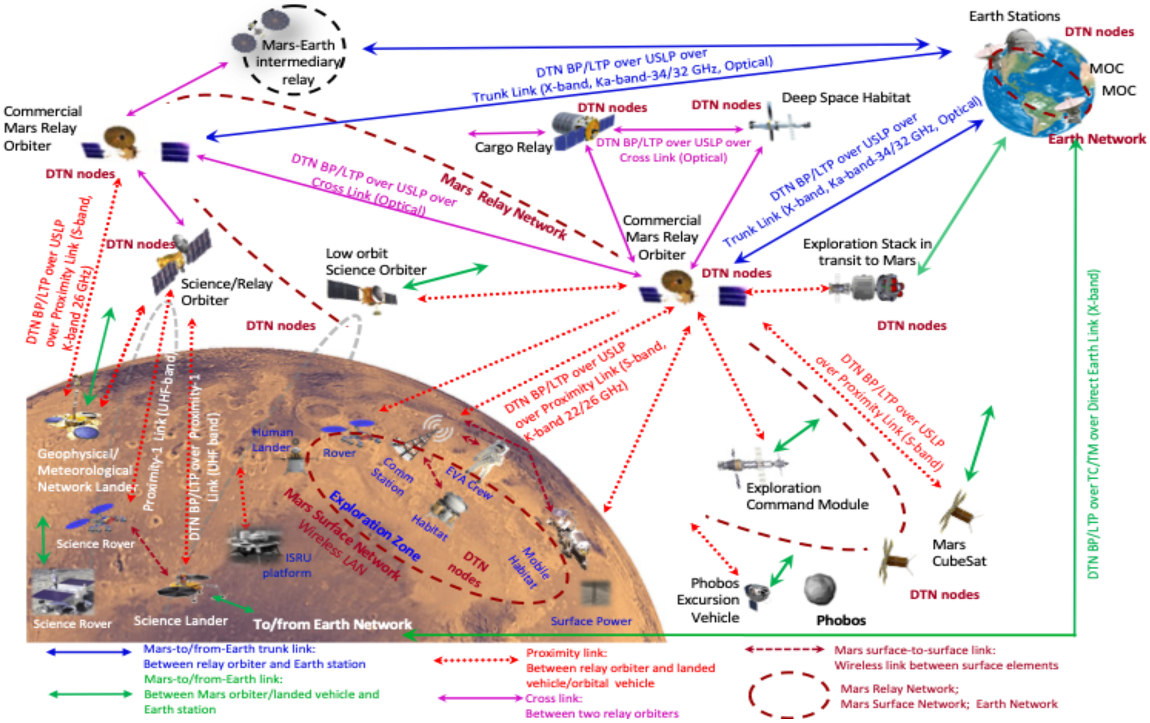


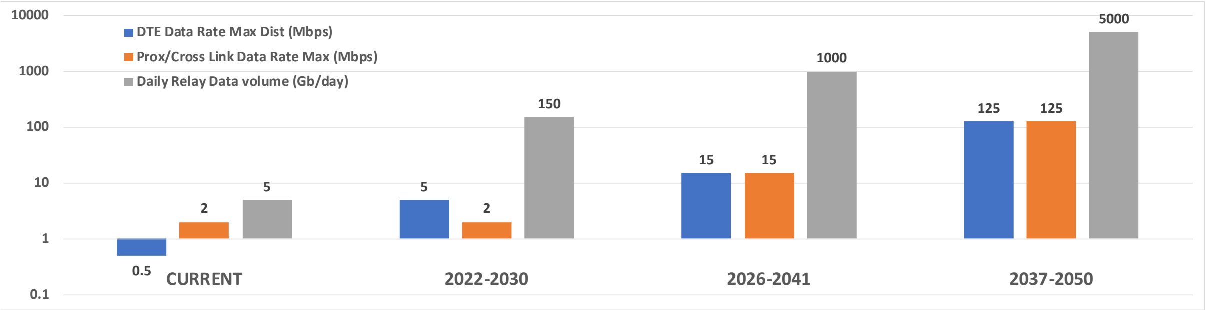
Figure 5.2-5 Mars Communications Architecture – Future Long-Term Mission Era

(18) Commercial relay services: Looking forward into this era, the crewed missions reaching the surface of Mars and teleoperating the surface activities from the deep space habitat in high Mars orbit, will require persistent connectivity and high data rates/volumes like their counterparts in Lunar exploration. Given the current advocacy and undertaking in the commercialization for Lunar communications, Mars relay architecture needs to evolve by following a similar path. It would encompass high-capacity communications satellites dedicated to providing communications services. The relay network would be built and operated by commercial provider(s). The relay services it provides would be offered on a fee-for-service basis. And in its end state, it would function very much like a commercial terrestrial network. That said, there are challenges to meet this objective. Chief among them are (a) the need for a credible business model taking into account a much limited customer base and smaller scale of economy; (b) the need for a sustainable operating plan in view of the unique nature of deep space links and Mars environment.

5.2.4 Summary of the Evolution of Mars Communications Architecture

The Mars communications architecture will evolve over the next two decades. Sections 5.2.1-5.2.3 have discussed the projected capability increments for the three mission eras. To illustrate and summarize the architecture transformation, Table 5.2-1 shows the growth of data rates/data volumes, and some new functional capabilities (albeit only a select few).

Table 5.2-1 Evolution of Mars communications architecture – data rate, data volume, mission count and networking

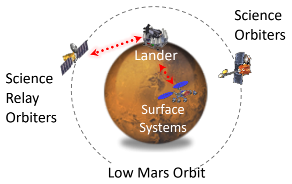


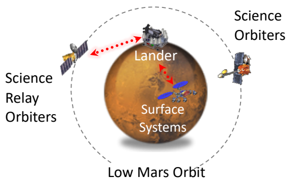
Orbiters: 8 Surface Vehicles: 5
X-band with Doppler/Range/ DDOR;
UHF proximity link
RS Coding; TC/TM/Prox-1 Protocol

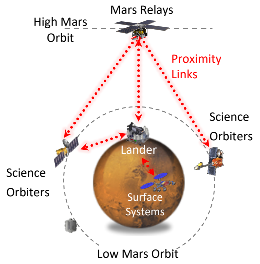
Orbiters: 12 Surface Vehicles: 8
Ka-band downlink, PN
Ranging/DDOR, LDPC;
Network scheduling; min CSSM

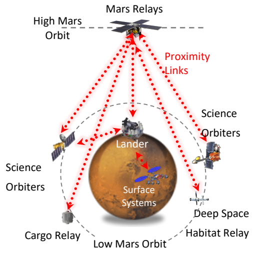
Orbiters: 15 Surface Vehicles: 10
Dedicated relay telesats, X/Ka-prox link,
USLP, DTN; full CSSM; Demand/Multiple
Access

Orbiters: 20 Surface Vehicles: 15
PNT from telesats; optical, Ka-band uplink,
surface network,
Human exploration begins









5.3 Mars Relay Networks

Within the Mars network, a Mars relay network is comprised of one or more relay orbiters, each of which provides communications and/or navigation services to user space vehicles or elements, in orbit or on the surface, over proximity links. When such relay interfaces provide network layer services, the relay orbiter(s) and the user nodes together form a relay network. The relay orbiter, in this context, can be a dedicated relay satellite or a science spacecraft acting as a network node via the relay function of the communications subsystem (see Figures 5.2-2 through 5.2-4.).

5.3.1 Current Mars relay networks

In fact, the currently flying relay satellites are all of the latter case (for lack of better terms, we called it the "hybrid" relay) although they lack the network layer functionality. Table 5.3-1 gives a summary on their respective attributes.

Table 5.3-1. A Summary on Currently Flying Relay Orbiters

	Mars Odyssey	Mars Express	MRO	MAVEN	ExoMars/ TGO	Tianwen-1
Agency	NASA	ESA	NASA	NASA	ESA/RSA	CNSA
Launch Date	2001	2003	2005	2013	2016	2020
Orbit	400 km circular 93^{o} inclination; Sun-synchronous ~4 AM LMST ascending node	298x10,100 km elliptical 86^{o} inclination; Non-sun-synchronous	255x320 km 93^{o} inclination; Sun-synchronous ~3 PM LMST ascending node	150x6,200 km 75^{o} inclination; Non-sun-synchronous	400 km 74^{o} inclination	265x12,000 km 86.9^{o} inclination
Proximity link: Freq & protocol	UHF band	UHF; CCSDS Proximity-1	UHF; CCSDS Proximity-1	UHF; CCSDS Proximity-1	UHF; CCSDS Proximity-1	UHF; CCSDS Proximity-1
Proximity link: Antenna	Quadrifilar Helix	Txmt/Rcv Patches	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	TBD
Proximity link: Return data rate	256 kbps	128 kbps	2048 kbps	2048 kbps	2048 kbps	2048 kbps
Proximity link: Transmit Power	12 W	8.5 W	5 W	5 W	5 W	TBD
DTE link	X-band 1.3 m HGA/ 15W SSPA	X-band 1.65 m HGA/ 65W TWTA	X-band 3 m HGA/ 100W TWTA	X-band 2 m HGA/ 100W TWTA	X-band 2.2 m HGA/ 65W TWTA	X-band TBD HGA/TBD TWTA; Max rate 4096 kbps

For the past two decades, the hybrid relay approach has successfully served Mars science community. And it will persist into the rest of 2020's and even 2030's. In the longer-term, there is the need for paving the road for the human Mars exploration era starting with a set of robotic precursor missions in late 2030's and ultimately to the human habitat and surface missions (both short stay and long stay) in 2040's. The ability for the astronauts/taikonauts to communicate with Earth would become a principal technical challenge. Platforms and vehicles on the surface of Mars would demand much higher communications capacity with Earth than they are today. The limited mass and power available to them would have to be optimized for mission-specific surface activities rather than communications. That also means the current Mars relay approach which can only provide sporadic support and short-duration contacts would fall short severely.

Even for the robotic precursor missions, a valid question to ask is: should the current approach by which every Mars science orbiter carries its own independent HGA system for direct-with-Earth (DWE) link be continued for them, the exploration vehicles? Shouldn't their resources on-board be better spent on exploration zone mapping, ISRU platform deployment, landing site survey, and installation of utility facility?

Appendix A lists current Mars missions and spacecraft and also provides projections for future Mars missions and spacecraft for each of the four eras of Mars Exploration. As shown in Table 5.2-1, in each roughly decade-long era (including the present-day era), 15-20 Mars vehicles/users are anticipated to arrive, each needing communication services with the Earth. The demand for relay services could in fact be higher if some users require telecom services for more than a decade.

Table 5.3-2 shows rough data rates/volumes and contact time anticipated for different classes of Mars mission users, i.e., Mars surface and orbiting users in the coming decades, of a Relay

Network. As inferred from the projections in Appendix A, it is assumed that 15-20 Mars users would arrive roughly every decade. The numbers in Table 5.3-2 suggest that a Mars telecom relay service capable of several hundred Gb/day in the late 2020s to early 2030s, and longer-term capability of 1 Tb/day, will be needed. The present-day Mars Relay Network utilizing several science orbiters as "opportunistic" relays provides about 4 Gb/day, which is a factor of 100x to 250x lower than the projected need in the coming 1-2 decades. In fact, the use of low-altitude science orbiters as relays severely constrains the throughput of the current relay network since each surface user has access to only 2-3 short (5-10 min) relay passes per day, while dedicated relay orbiters at higher (6,000-8,000 km) altitudes could provide nearly continuous relay coverage.

Table 5.3-2. Mars relay user missions - anticipated data rates/volumes and contact times in the coming decades

	Large Orbiter	**SmallSat/CubeSat Orbiter**	**Large Lander/Rover**	**Small Lander/AeroBot**
Assumed Communication Duration per Sol	16 hrs/sol	5 hrs/sol	60 min/sol	30 min/sol
Target Average Data Volume per Sol ≥	500 Gb/sol	10 Gb/sol	50 Gb/sol	0.100 Gb/sol
Target Average Instantaneous Data Rate ≥	10 Mbps	0.5 Mbps	14 Mbps	56 Kbps

Credit to Steve Lichten, Caltech/JPL

5.3.2 Future Mars relay networks

In view of this communications challenge, it is fair to conclude the future Mars communications architecture must embody the dedicated relay networks, along with the Earth-based network(s), to form the essential communications infrastructure. This infrastructure should provide reliable, near-continuous support to surface and orbital user missions, lower communication latency, and higher data rate for both proximity and Mars-to-Earth trunk links. It should result in greater ROI due to the reduced cost and risk of future robotic and human Mars missions and increased data return.

Over the past decade, several studies have been conducted to define the architecture of future Mars relay networks, all focused on the dedicated relay orbiters. The scopes range from one or more relay orbiters to support science missions of the subsequent decade to full-fledge satellite constellations capable of meeting the needs of human Mars missions. Driven by differences in the targeted user missions, the various architectures vary in relay orbit types, number of relay satellites, class of spacecraft bus, design life, capacity in proximity and DWE links (and/or crosslink), service types offered, and space internetworking capability.

Mars relay orbits

Since the orbits of relay satellites or constellations are the choice of the service providers based on their respective business cases, given the principle of open architecture, the eventual existence of a variety of orbits is quite possible. Table 5.3-3 gives a summary on four of the orbits investigated in the past. Pros and cons in terms of coverage performance are addressed (TBD).

Table 5.3-3 Potential Mars relay orbits

Orbit type	Orbit attributes	Coverage performance	Remarks
Equatorial	A constellation of three satellites at 6000-8000 km altitude; circular orbit[40].	• Coverage up to +/- 63 deg lat • Users within +/- 25 deg lat: 24/7 coverage • Users within +/- 60 deg lat: At least 5 hrs of contact per day with no gaps more than 4 hrs	
Equatorial - inclined 30 deg	A constellation of three satellites in three orbital planes, phased 120 degree, at 6000-8000 km altitude[40].	• Global overage at least 8.5 hours of contact per sol, but gaps could be ~4.85 hours long • Users within +/- 25 deg lat: At least 22+ hrs of contact per day with no gaps more than 1 hr • Users within +/- 60 deg lat: At least 14 hrs of contact per day with no gaps more than 4 hrs	
Critically-Inclined ¼-Sol Elliptical	A constellation of three satellites at 950 x 8500 km altitude; inclination 63 or 117 deg	Global coverage 5.2 hours per sol, maximum gap time 12 hours	
Areostationary	A constellation of two-three satellites at ~ 13,644 km altitude (17,040 km orbital radius); circular, equatorial.	Coverage +/- 70 degree latitude, continuous 24x7 coverage; no gap within coverage zone	

Among all the orbits assessed, the lowest altitude that can provides continuous visibility to a landed asset and allows cross-link between relay satellites and with orbital user spacecraft, applying ~10 deg local horizon mask, is about 6,000 km. The lowest altitude at which each relay orbiter is visible to Earth 90% of the time (i.e., not occulted by Mars) is 8,000 km. So, the preferred orbital altitude for the dedicated relay orbiters should be between 6,000 and 8,000 km. Since the human exploration zone(s) will most likely be located within +/- 40 degree altitudes, constellations of three satellites at 6,000-8,000 km altitude in equatorial, circular orbit for the Future Long-Term Mission era may be reasonable[41]. Figure 5.3-1 depicts the notional architecture of such Mars relay networks.

The 3-spacecraft constellation would carry a combination of radios to enable a variety of surface and orbiting Mars missions, for both exploration and science purposes, that do not exist or even possible today. Chief among them would be SmallSats/CubeSats, crewed rovers, ISRU platforms, surface/orbital habitats, communications station, geophysical stations, net-landers, mini-rovers, and helicopters. To the degree possible, backward compatibility to service certain Mars landed and orbital missions carried forward from the prior era should also be provided.

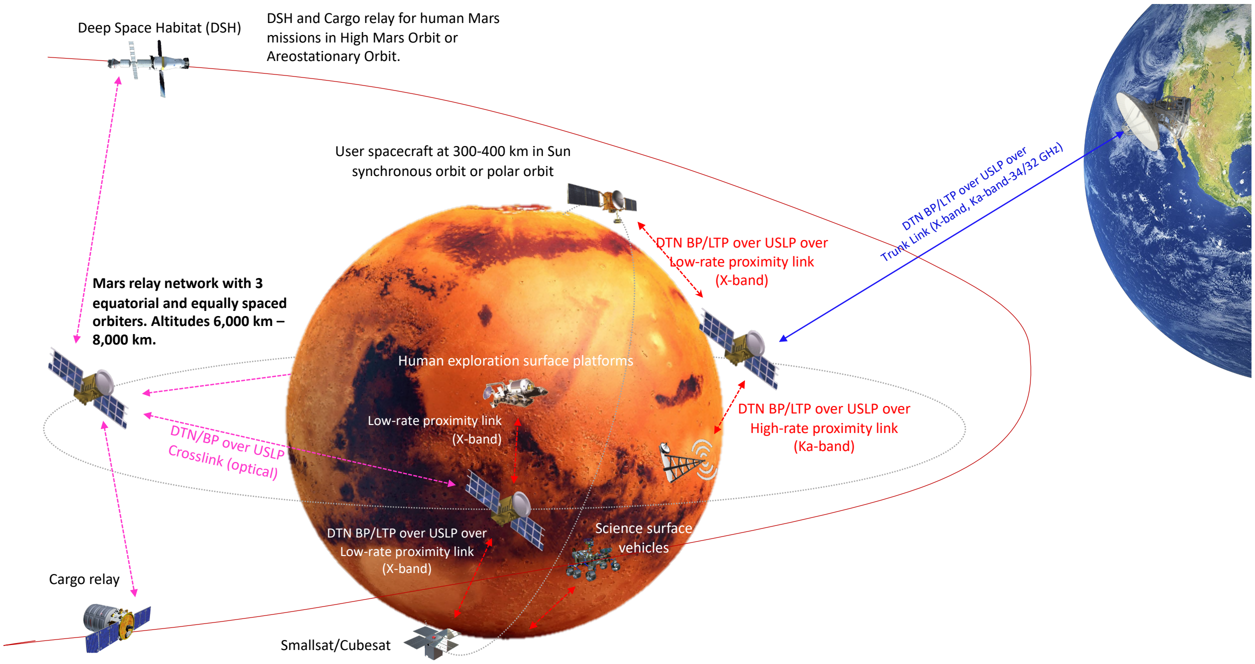


Figure 5.3-1. A notional Mars relay network architecture

Proximity links:
The future Mars Relay Network must be able to support 50 Mbps return links and 10 Mbps forward links to both in-situ landed and orbital users. Over the proximity links, not only the relay data delivery services but also radio metric services will be provided. This may suggest both near-Earth X-band (or S-band) and K-bands are the preferred frequency bands, although the use of only K-band for interfacing with human Mars vehicles is a possibility and its feasibility is yet evaluated.

Cross Links:
Cross links in this context are defined as the inter-satellite links between two relay orbiters. The relays could be dedicated relay or hybrid science orbiters. Since occultation events on the link between relay satellite to Earth can introduce increased latency in data delivery to/from the user spacecraft, cross links (RF or optical) between the relay satellites are crucial to reduce the latency. Cross links also enable load-sharing among the various relay orbiters for return of data on the trunk links with Earth. This results in a configuration called "dual-trunk link"[42]. It is suggested that optical links are the preferred solution to the provision of cross links for high-capacity Mars relay networks, i.e., between the dedicated relay satellites. For the cross link between a dedicated relay and a hybrid science orbiter, RF bands, near-Earth X-bands (or S-band) for low-rate and K-bands for high rate link, may be the practical approach.

Trunk links:
For the trunk links, i.e., the relay orbiter's direct with Earth (DWE) links, it is expected that the maximum return data rate would be around 125 Mbps and for forward link 20 Mbps, given what we know about the needs by the human Lunar exploration up to this moment. Clearly, maintaining this high-rate return link persistently into Mars farther/farthest distances (towards 2.67 AU) would

be a challenge to the relay's telecommunications subsystem. Since the orbits suggested for the Mars relay network(s) allows two relay orbiters simultaneously visible to Earth 99% of the time, leveraging the MSPA capability of the Earth station to acquire downlink signals from two relay orbiters would result in a reduction of the EIRP demand on each orbiter by almost 50%. The "dual-trunk link" configuration, therefore, is essential to a high-capacity Mars relay network.

The preferred frequency bands are deep space X-band for low-rate TT&C and Ka-bands for high-rate links.

5.3.3 Mars relay services:

The relay services are end-to-end services since they encompass interfaces across multiple physical links, i.e., proximity, direct-with-Earth, and cross links, and vertically interfaces at multiple layers, i.e., physical, data link, and network layers.

The exhibition of network layer service and multiple links across two planetary bodies, Mars and Earth, points to the need for formalizing Mars relay services. In this section, we have defined the various types of relay services, relay methods, relay access modes, and relay service initiation modes.

Relay services are likely to involve communications assets from more than one agency, multi-mission consortium, or even commercial entity. As such these arrangements will have to involve some sort of cross support agreements, adherence to agreed policies and governance, monitoring, and a shared security model.

Relay Service Types

The primary service provided by relay vehicles is the relay data service. It is an end-to-end service that offers the transfer of a single interoperable data entity over one or more assets, i.e., relay assets, between the two end points. This single interoperable data entity must be at, or at a higher level than Layer 3 on the ISO model. It shall be created at the start point and preserved during its transition through the relay asset(s) until acceptance at the end point.

For the Mars communications architecture this data entity is a DTN bundle. The end-to-end transfer of relay data across the Mars relay network and Earth network resembles the function of terrestrial internets. As such, the Mars relay data service is in fact a Space Internetworking Service.

In addition to the relay data services, the involved relay asset(s) may provide other types of services, e.g., network time service, in-situ tracking service, and in-situ navigation service. Table 5.3-4 gives a definition for each of the Mars relay services.

Table 5.3-4 Mars Relay Services - Types of Services

Service Type	Description
Space Internetworking Service	Provides routed, assured, secure delivery of mission data using DTN protocol suite. A special mode of the relay data service is the low-latency delivery of decisional data to support ground-in-the-loop planning cycles for maximizing surface operations efficiency (this is applicable to both science and exploration missions).
Network Time Service	Distributes, synchronizes, and manages time both relative to the central body and with regard to an absolute reference system.
In-situ Tracking Service	**Ranging:** Measures the time delay between the user vehicle and the relay orbiter using RF or optical transmission (convertible to distance)
	Doppler: Measures and time tags the phase of the transmitted forward carrier and/or the received return carrier at the relay orbiter
	Antenna Pointing Angle: Measures the pointing angle of the relay RF antenna or optical terminal as it tracks the user vehicle
In-situ Navigation Service	**Positioning:** Determines the location of the user vehicle, on Mars surface or in Mars orbit, based on available tracking data types
Application Layer Services enabled by relay services are:	
End-to-end file service	Transfers files bi-directionally between a user vehicle and ground system or between two user vehicles. The preferred file transfer protocol is the CCSDS File Delivery Protocol (CFDP).
End-to-end messaging service	Transfers messages bi-directionally between a user vehicle and ground system or between two user vehicles. A potential messaging protocol is the CCSDS Asynchronous Messaging Services (AMS).
End-to-end space packet service	Transfers CCSDS space packets from a user vehicle to ground system or between two user vehicles

Relay Methods

Relay methods could be bent-pipe and store-and-forward. The definitions of the two methods and respective advantages and disadvantages are summarized in Table 5.3-5.

Table 5.3-5 Mars Relay Services – Relay Methods

Relay method	Pros	Cons
Bent-pipe: This method involves only switching from frequency of received signal to that of transmit signal. No demodulation/modulation is done at the relay in the process.	1. Simplicity in relay mechanism. The relay asset is essentially a physical layer entity, like a piece of wire. 2. Minimum on-board processing is to take place. Latency is low. 3. Minimum demands on additional on-board resources, e.g., memory and data store.	1. Fragility in service provision, as the relay asset must maintain a guaranteed visible, direct path with both source and destination throughout the contact period for data transfer. 2. Difficulty in providing higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g., dynamic routing, is not feasible.

Store-and-forward: This method involves storing the acquired data units at the relay node, before they are forwarded to the next node. The intermediate node checks whether the data unit is error−free before transmitting, thus ensuring integrity of the data units.	1. Flexibility in service provision, the relay asset does not have to rely on both source and destination being in view throughout the contact period for data transfer. 2. Amenable to the provision of higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g., dynamic routing, is feasible.	1. Complexity in relay mechanism. The relay asset must provide physical, data link, and network layer capabilities for interfacing with both its source and destination vehicles. 2. Heavier demands upon on-board resources, e.g., processing power and data storage.

Unlike that for the relay environment in Earth orbits or Lunar orbits, the store-and-forward relay method is the preferred choice for Mars relay network. However, two use cases may deserve the bent-pipe method: (a) for the relay transfer of data from user vehicles in the EDL scenario to Earth; (b) for the chatty communications “locally” between two user vehicles in Mars via a Mars relay orbiter.

Relay Access Modes

For user vehicles to access the proximity link, both single access and multiple access modes should be supported by the relay orbiters. For multiple access to proximity forward link, i.e., from a relay orbiter to multiple user vehicles, given the 1-to-N topology, a “simplified” TDMA scheme, i.e., time-sharing at the granularity of Proximity-1 frames or USLP frames, is viable[43]. On the return link, either the FDMA or CDMA approach should suffice[43].These could be accompanied by a multi-beaming approach using phased array antenna on board the relay orbiter.

Relay Service Initiation Modes

For user vehicles to initiate the access to proximity link, hence relay services, it is recommended that the future Mars relay networks depart from the current pre-scheduled contact approach. The User-vehicle initiated Service (UIS) mode is preferred. Through this mode, the access to relay services would be initiated by user vehicles on demand, thus accommodating both routine and opportunistic service requests in an autonomous fashion. Included in the UIS mechanism are two processes:

- The link acquisition mechanism (or protocol) for access to the proximity link: An example of such mechanisms is the CCSDS Proximity-1 hailing control mechanism.

- The UIS service acquisition protocol for requesting relay services at application layer. The request can be specified as exactly desired or can be specified with open-range parameter of time, duration, data rates, code, etc. The request can be confirmed and accepted for service execution or queued for later execution (in a multi-user environment).

The UIS, therefore, provides some flexibility for user vehicles to get their relay needs fulfilled in multi-user environment where the simultaneous demands exceeds the multiple access capacity of the relay orbiter’s proximity links.

Moreover, except for the voice communications which is more persistent, the needs for communication sessions by some crewed activities during Mars surface missions are less deterministic or even opportunistic. The UIS, therefore, would provide more responsive support for their mode of operations. Other scenarios that might benefit from the UIS mode are:

- A small satellite could fly its mission and signal for relay services only when it has enough power to do so.
- Small landed missions could signal for relay services at a preferred time of day or burst data after it has been collected.
- A net-lander mission might signal for relay services only when it has detected relevant events.

5.4 Mars Surface Networks

As discussed in Section 5.1, no persistent surface-to-surface communications exist in the current Mars mission architecture. Up to this moment, the Perseverance mission has conducted twelve short-lived communication sessions between the Ingenuity helicopter and rover using a UHF link. Past Mars surface communications only occurred in 1997 by the Mars Pathfinder mission between its lander and Sojourner rover (and the lander served as the relay between the rover and Earth stations). For the ESA/NASA's Mars Sample Mission in 2026, although some surface communications between the Mars Sample Fetch Rover and Mars Sample Return Lander may take place, it will still be limited to a point-to-point link.

It is expected that, during the Future Long-term Missions era, crewed activities on Mars surface will rely on surface-to-surface communications at an unprecedented level. The 24-day Mars Short-Stay Mission[44] defined by Hoppy Price, et al, has given us some good understandings about the surface operations scenarios, hence the demands on surface communications. The primary goal of the Mars Short Stay Mission (MSSM) is to prepare the way for the Mars Long Stay Mission. So, key activities are aimed at the mission objective of demonstrating in-situ oxygen and water production. Major elements involved in the MSSM are a few vehicles/platforms on surface:

- Lander: it is composed of Aeroshell, Descent Stage, and Mars Ascent Vehicle
- Crew Mobility Chasis (CMC)
- Oxygen Production System (OPS)
- Water Processing System (WPS)
- Rover: it is comprised of the CMC and Pressurized Crew Module
- EVA Suits: Extra-Vehicular Activity Suits
- Portable Utility Pallet (PUP)

In addition, the participating flight elements are Orion (a.k.a., Multi-Purpose Crew Vehicle or MPCV) docked with Deep Space Habitat (DSH), MAVBS (Mars Ascent Vehicle – to – High Mars Orbit Boost Stage), and DSH Resupply Module. The surface operations scenario starts at the descent of the Lander (its descent stage) to the Martian surface and ends at the astronauts' return to the descent stage and the readiness for ascent via the Mars Ascent Vehicle (MAV). Teleoperations are conducted between the crew members in the DSH-Orion and the surface EVA crew and elements via the relay proximity link and surface-to-surface link. Crewed activities such as set up/check out the oxygen production and water processing facilities, local EVA, distant road trip, and local science would involve heavy interactions among the surface elements. An ensuing traffic analysis[45] in 2017 produced some sizing estimates in terms of data rates/volumes and latencies for the various data types (see Table 5.4-1).

Table 5.4-1. Traffic summary during surface operations for Mars Short-stay Surface Mission (MSSM)

Type	Rate (kbps)	Duty Cycle	Latency	Comment
Biomedical[m]	33	100%	seconds	Urosepsis Biomedical Emergency Analysis, "Vital Signs" (from the Urosepsis Biomedical study).
Caution and Warning[m]	10-20	0.3-1.6%	seconds	Engineering judgement. Low-rate signal. Depends on complexity of the system
Teleoperation	200	0.8-25%	seconds	From past experiments. Tactile would be higher. Excludes video.
Software Files	24,000	0.03-1.6%	minutes-hours	Depends on complexity of system, Engineering judgement.
Health and Status[m]	25-500	100%	seconds	Depends on complexity of system. Engineering judgement
Navigation Type I	2	0.07-1.6%	minutes	Navigation products based on radiometric measurements.
Navigation Type II	1	100%	seconds-minutes	Navigation and timing beacon
DTN Network Data	1000	2-17%	seconds	Depends on DTN protocol used. Mostly TBD
Public Affairs Office (PAO) Video[n]	21,000	100%	seconds-hours	1400 x 800 at 24 fps. Use ISS rate.
HD Science Video	16,000	100%	seconds-hours	Different formats for different experiments: Static experiments, 4000 x 2250 @ 2 fps. Dynamic experiments, 640 x 480 @ 60 fps
Standard Video[m]	1,500-10,000	100%	seconds	Depending on the Situation. 640 x 480 @ 6 fps for console monitor, EVA video critical
Situational Awareness Video[m]	500-2,900	100%	Seconds-minutes	640 x 480 at 2 to 12 fps, frame rates vary according to situation.
Stereo Video Pair[n]	2,500	100%	seconds	640 x 480 6 fps x 2.
Science Data	2,000-8,000	10-75%	seconds-hours	Depends on the Element
Voice[m]	128	30-100%	seconds	Depends on mode of operation. CCSDS 766.2-B-1

[m]Considered mission-critical, requires two independent paths. [n]Subject to consideration as mission-critical on occasion.

Clearly, videos are the single largest driver to the communications involving EVA crew, local mobility vehicles, science packages, public affairs cameras, in-situ sensor platforms, landers and cargo pallets. These elements could return and receive data via the relay proximity links using their respective communication terminals. That may mean they all have to be equipped with a telecommunications payload with at least a steered 30 cm, 15 watt transmit power, X-band antenna.

Given the duty cycles and the persistent data rates, the aggregate user burdens, i.e., the SWaP, due to the relay interfaces may not be desirable. A better approach is through a "local" Mars surface network. Such a Mars surface network would feature one or two communication hubs that provide the essential function of multiplexing surface traffic (destined to Earth or relay orbiters) onto the proximity links with a Mars relay network. The surface hubs also de-multiplex data (originated on Earth or relay orbiters) from the Mars relay network and distribute the data to the surface elements over the Mars surface network. The Mars surface network is a wireless network using UHF- or S-band and interface protocols in compliance with IEEE 802.11[11], 3GPP LTE[30], or 3GPP 5G[31] standards prevalently applied by terrestrial networks. It is envisioned that further into the human Mars exploration, e.g., 500-day Mars Long-stay Surface Missions, there would be multiple Mars surface networks deployed by different agencies/commercial providers at different locations. They may vary in mobile communications technology and standards.

An alternate communications path is the DWE links between the Mars surface hub and Earth stations. This will have to be limited to X-band links for engineering TT&C data.

The preferred frequency bands for the proximity links are X-band for low-rate TT&C and K-bands for high-rate links.

Figure 5.4-1 shows a cartoon-like representation of the conceptual architecture for the Mars surface network.

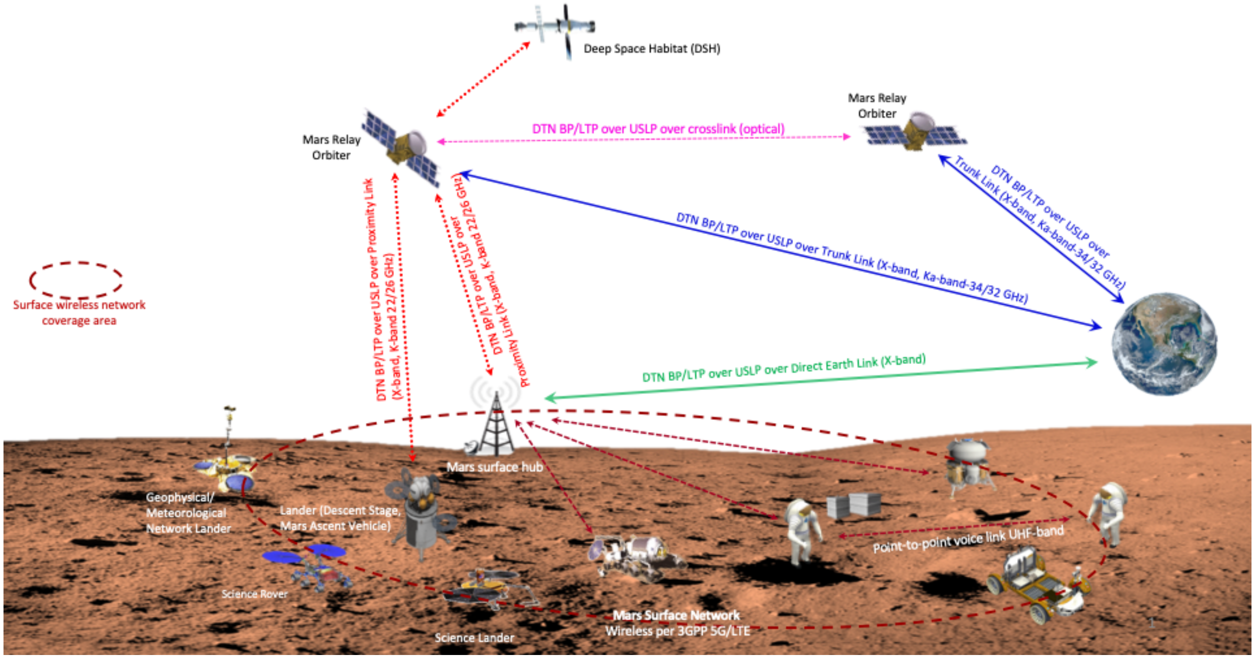


Figure 5.4-1. Conceptual architecture for the Mars surface network.

The dissimilarity in frequency bands and communication protocols between the Mars relay network and surface network suggests that Mars surface hubs must act as the gateway between the two types of networks. This exemplifies the concept of open space internetworking architecture per the DTN where only adjacent nodes (in this case a surface hub and a relay orbiter) have to be interoperable down to the physical layer in order to transfer DTN bundles over their immediate links. In other words, not all nodes need to be fully interoperable to be part of the Mars communications infrastructure. However, for end-to-end data transfers between a surface vehicle and a MOC, the DTN Bundle Protocol (BP) at network layer must be abided by all elements on the data path since it is the only means to ensure end-to-end connectivity and data integrity across the Mars surface networks, relay networks and Earth networks.

5.5 Earth Networks

Section 3 contains the descriptions for the various Earth stations that are currently in operations and/or being planned for the IOAG member agencies to support Mars missions. Joining the club of deep space communication networks are a few antennas, recently installed/upgraded or being implemented. In total, 29 stations have been deployed globally plus additional 2 to 5 stations in the plan for future readiness by some agencies. Table 5.5-1 gives a dashboard or at-a-glance view of all the Earth network assets capable of communicating over Mars distances. Antennas with aperture smaller than 30m in diameter are not included in the table due to the difficulty for them to close the space link. Information about any antenna’s S-band capability is omitted since the preferred frequency bands for Mars-to/from-Earth links are X- and Ka-bands.

Table 5.5-1. A dashboard view of Earth network assets for Mars mission support

Agency	**Antenna Aperture**	**Location**	**Uplink (EIRP)**		**Downlink (G/T)**		**Remarks**
			X-band	**Ka-band**	**X-band**	**Ka-band**	
ASI	64m	Sardinia	>112 dBW (TBC)	>112 dBW (TBC)	>56.5 dB/K*	Plan TBD	Newly upgraded
CNSA	66m	Jiamusi	>108.3 dBW (10 kW)	Plan TBD	>53.3 dB/K (10°EL)	Plan TBD	
	35m	Kashi	>104 dBW (10 kW)	Plan TBD	>49 dB/K (10°EL)	>56 dB/K (10°EL)	
	35m	Neuquen	>104 dBW (10 kW)	Plan TBD	>50.2 dB/K (10°EL)	>56 dB/K (10°EL)	
	70m	Tianjing	No plan	No plan	55 dB/K (10°EL)	No plan	New antenna
ESA	35m	New Norcia	107 dBW	Plan TBD	55.5 dB/K (90°EL)	Planned 63 dB/K (90°EL)	Two antennas at New Norcia, by end of 2025. G/T performance projected with cryo-feed. Enhancement of Malargüe Ka-band EIRP planned by 2025
	35m	Cebreros	108 dBW	Plan TBD	55.5 dB/K (90°EL)	63 dB/K (90°EL)	
	35m	Malargüe	107 dBW	Current: >94.7dBW (100W) Planned: >101.7dBW (500W)	55.5 dB/K (90°EL)	63 dB/K (90°EL)	
ISRO	32m	Bylalu	98 dBW	Plan TBD	47.0 dB/K	Plan TBD	
JAXA	54m	Misasa	>142.6 dBm (20kW)	Plan TBD	>53.3 dB/K (15°EL)	>59.3 dB/K	New antenna
	34m	Uchinoura	>138.7 dBm (20 kW)	Plan TBD	>47.7 dB/K (15°EL)	Plan TBD	
NASA	34m	Goldstone	>110 dBW (20 kW)	Planned for 2025	>54.2 dB/K (45°EL)	>61.1 dB/K (45°EL)	3x34m BWG now. 4th by 2026
	34m	Canberra	>110 dBW (20 kW)	Planned for 2026	>54.2 dB/K (45°EL)	>61.1 dB/K (45°EL)	3x34m BWG now. 4th by 2028
	34m	Madrid	>110 dBW (20 kW)	Planned for 2028	>54.2 dB/K (45°EL)	>61.1 dB/K (45°EL)	4x34 BWG now

Agency	Antenna Aperture	Location	Uplink (EIRP)		Downlink (G/T)		Remarks
			X-band	Ka-band	X-band	Ka-band	
	70m	Goldstone	>116 dBW (20 kW)	No plan	>61.5 dB/K (45^{o}EL)	No plan	
	70m	Canberra	>116 dBW (20 kW)	No plan	>61.5 dB/K (45^{o}EL)	No plan	
	70m	Madrid	>116 dBW (20 kW)	No plan	>61.5 dB/K (45^{o}EL)	No plan	
	34m HEF	Goldstone	>110 dBW (20 kW)	No plan	53.2 dB/K	No plan	
UKSA	32m	Goonhilly	>95 dBW	Plan TBD	>45 dB/K (5^{o}EL)	Plan TBD	Newly upgraded
	30m	Goonhilly	No plan	No plan	55 dB/K (TBC)	No plan	Newly upgraded
Roscosmos	70m	Yevpatoria	Data TBD	Plan TBD	Data TBD	Plan TBD	
	64m	Bear Lakes	Data TBD	Plan TBD	58.5 dB/K	Plan TBD	
	64m	Kalyazin	113.5 dBW	Plan TBD	58.2 dB/K	Plan TBD	
	64m	Ussuriisk	Data TBD	Plan TBD	Data TBD	Plan TBD	

Footnotes: "Planned" - The capability is not available now, but its development is in the Agency's plan.
"No plan" - The capability in not in the Agency's plan at all.
"Plan TBD" - Unknown state. Need Agency's input about if there is a plan for the capability or not.
"Data TBD" - Actual EIRP or G/T measurement is yet to be determined.
"TBC" – The value is based on theoretical analysis. To be confirmed by actual measurements.
* *for ASI – The value refers to the present provisional downlink configuration to be updated*

Driven by the complexions of future Mars mission sets, the evolution of Mars communications architecture described in Section 5.1 will impose some challenges to the Earth networks. These challenges and their respective ramifications to the Earth networks are addressed as follows:

(1) Network capacity: The projected number of new Mars spacecraft, i.e., 15-20 for every decades, will demand a significant increase in the capacity of Earth networks. To a Mars-faring agency, acquiring new antennas to meet the capacity shortfalls is a solution, but that may be the last resort. As we have seen so far in the gradual unfolding of commercial communication services for Lunar exploration, it is reasonable to expect the same trend to occur for the future Mars communications. The commercial Earth networks will have to be coherently integrated into the overall Mars communications architecture. Using cross support services provided by the Earth networks owned by other space agencies, a practice successfully applied for a long time, is another effective approach to mitigating the capacity shortfalls.

(2) Antenna utilization efficiency: Related to the above is the need to enhance the efficiency of antenna utilization by user missions. The MSPA and MUPA techniques as discussed in Section 5.1 allow multiple Mars spacecraft to share the same antenna beam, hence significantly reducing the demand on the number of antennas that otherwise would be needed. Likewise, the use of Ka-band for medium to high volume data transfer should lower the required antenna time by almost a factor of four (relative to that using X-band), thus help solve the network capacity problem.

(3) Link efficacy: To maximize the reliability and power efficiency of the Mars-to/from-Earth links, the Earth network along with the Mars user mission must take advantage of coding gains

offered by the LDPC codes and the adaptability of ModCod. Link efficacy can further be raised by the selective retransmission capability of the DTN/LTP for guaranteed data delivery.

(4) Spectrum efficiency: A consequence of the continued increase in the number of Mars spacecraft is more severe competition for allocations of spectrum bandwidths, especially for the deep space X-band. Applying the bandwidth-efficient modulation per GMSK by the Earth networks and Mars user missions would go a long way to lessen the pressure of spectrum congestion. For certain high-rate scenarios during the Future Long-term Missions era, bandwidth allocations for Ka-band would face similar problem. The move to optical communications may be the best solution. That means ground-based optical telescopes would have to be operationally integrated into some Earth networks. As such, new operational approach geared towards the heterogeneous network must be defined.

(5) Interoperability: Adherence to CCSDS standards will remain essential to almost all Earth networks engaged in deep space communications. For better interoperability to accommodate higher cross supportability, the various Earth networks will have to implement the full set of CCSDS cross support service management (CSSM) standards and comply with the down-selected standards as defined in Section 4.

(6) Internetworking architecture: The architecture of the Mars Network (MarsNet) suggests that each Earth network should be "networked" with the ground system elements, e.g., MOCs, of Mars user missions on one side and with the various Mars spacecraft on another side. For ensuring end-to-end connectivity and data integrity, the Earth network nodes, e.g., the Earth stations, will have to interface with the end nodes, e.g., the MOCs, via DTN BP protocol at network layer.

(7) Data rate/volume: During the Future Medium-term Missions era, the international Mars Ice Mapper mission would need 16.7 Mbps of persistent return data rate. A much bigger challenge is the needed data rates/volumes by human Mars missions. Ignoring the data rates (215 Mbps for return link and 30 Mbps forward link)[45] [42]cited in Section 5.2.3 (6) and (7) and instead assuming that stated for the current human Lunar exploration, the data rates at 150 Mbps (return) and 20 Mbps (forward) over Mars farther/farthest distances would still pose a challenge to any Earth network both in terms of G/T and EIRP. As addressed in Section 5.2.3 (15), the dual-trunk link approach enabled by the elaborate use of the antenna arraying and MSPA capabilities of the Earth networks would be the most cost effective solution. Figure 5.5-1 illustrates the dual-trunk link configuration at an Earth network. Since any of the two antennas could also simultaneously support any other Mars missions via the MSPA/MUPA beam-sharing, at any given time only two deep space stations have to be dedicated to all Mars missions. The network capacity problem due to high data rates/volumes can be significantly mitigated.

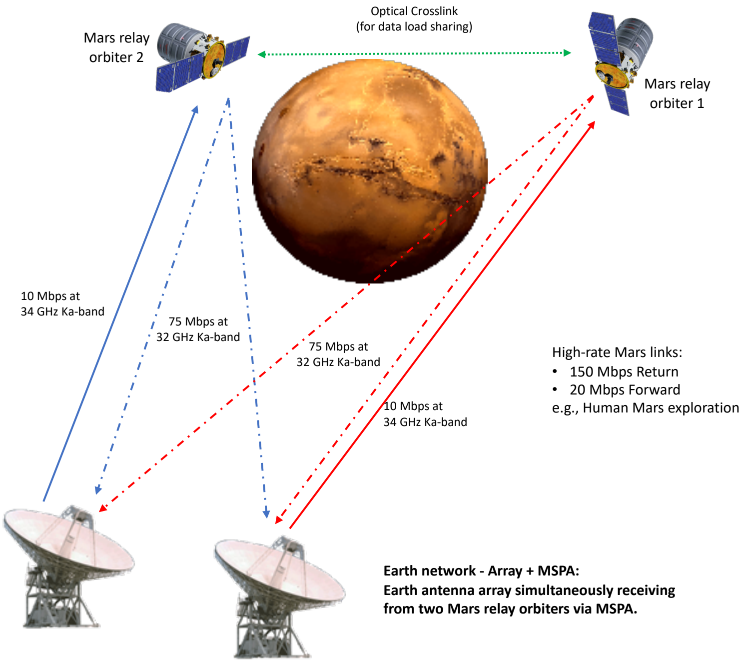


Figure 5.5-1. Earth network dual-trunk link configuration

(8) Service availability: Robotic Mars missions typically require high service availability (> 99%) for mission critical events, e.g., Mars orbit insertion and EDL. The approach taken by Earth networks to fulfilling this requirement is through the set-up of a backup station. Exacerbating the network capacity challenge (discussed in (1) above) during the human Mars exploration era will be the persistent needs for high-availability services to ensure crew safety. A viable solution is to leverage the "dual-trunk link" configuration identified in Section 5.2.3 (15) and Figure 5.5-1 of Challenge (7) above. In the event of any failure in one of the two stations, the X-band link for TT&C can be maintained by the other station without losing any "live" communications and vital data for crew safety. For high-rate data transfer, e.g., HD videos, the network would operate in a degraded mode with the single-trunk link capacity.

(9) Navigation accuracy: Delta-DOR as a tracking data type will continue to play a pivotal role in navigation for all deep space missions. The price rendered is the two antennas needed to simultaneously track the transmitting spacecraft – a burden on Earth network's capacity. As the number of Mars missions increases, the aggregate effect on the capacity of Earth networks is a serious matter to reckon with. On the other hand, through delta-DOR more benefit can be gained by improved accuracy using the Ka-band PN delta DOR capability (see Section 5.2.1 (3).) Aside from Earth-based radiometric tracking, it is expected that the Deep Space Atomic Clock (DSAC) will enable spacecraft to safely navigate independently in deep space rather than rely on the time-consuming process of waiting to receive/transmit signals from/to Earth. The DSAC, therefore, will shift the navigation architecture to a new paradigm that is more efficient and flexible. Above all, a possible ramification to an Earth network is the reduced demand on network capacity or, at a minimum, the required network time.

(10) Cross Support Services at the Space Data Link Layer

A key ingredient of the Mars network architecture described in this section is the space internetworking capability enabled by the DTN protocol suite. The cross-support to Mars missions by Earth communication assets, owned by the space agencies and commercial service providers, will be through the Bundle Protocol, with the transfer of DTN bundles between each user's Mission Operations Center (MOC) and the service-providing asset, e.g., a ground station. One may rush to conclude that the current cross-support transfer services, based on the SLE/Cross Support Transfer Services (CSTS) standards and used by almost all agencies, will become irrelevant and obsolete. However, our past experience in operating many spacecraft has shown that monitoring and controlling any spacecraft through the rudimentary level of the communication system is essential from time to time. That means a cross-supported mission must be able to conduct the following scenarios by directly "poking" into the space data link layer without or bypassing the DTN layers:

- Link performance analysis, anomaly detection and isolation, troubleshooting
- Special configuration and control: bootstrapping flight computer and hardware commanding
- Spacecraft emergency and contingency modes
- Certain mission critical events
- Space vehicles and ground systems that lack DTN functionality

Therefore, out of necessity, the provision of cross-support services at the space data link layer by Earth communication assets will persist into the DTN era, although only in some limited scenarios.

5.6 Mars Network Management Architecture

As the end-to-end Mars network evolves into an internetworked system using the DTN protocol suite to facilitate the functionality of network layer and above, it is important to remind us that DTN is actually an architecture framework which embodies capabilities more than just that provided through its communication protocols. The network management aspect of the DTN architecture must also be defined and applied to address the key issue as to how the network will be operated.

5.6.1 The challenges

Towards the era of future long-term missions, it is projected that the Mars Network would involve communication assets affiliated with multiple space agencies and commercial providers. To support the increasing number of user missions, these assets would include, in addition to the various Earth networks, likely two or more Mars relay networks and one or more Mars surface networks. The introduction of additional relay assets (in particular the ones more dedicated to relay communications) along with their respective service providers would exacerbate the N:M relationship between the user missions (as a group) and each asset type (i.e., Earth networks, relay networks, or surface networks) making the Mars network management in DTN era more complicated than that in the past (i.e., for the point-to-point link services). Therefore, a Mars network management architecture will have to be formalized to facilitate interoperability among the collaborating missions and cross support by participating communication assets.

5.6.2 The proposed network management architecture

We propose the following tenets be applied to Mars network management architecture:

(1) Network domain-based:

A Mars network domain is defined to encompass all the network assets that support those Mars missions owned by the collaborating space agencies according to pre-existing cross support service agreement(s). The various elements of Mars user missions are also part of the network domain. A Mars network management architecture is defined for network operations purpose within a given domain. Across multiple domains, some interfaces for situational awareness may have to be defined.

(2) Network management functions:

Network management in this context is comprised of two functions:

(a) Service management: It includes the processes concerning the user missions' demands of services to be provided by the Earth networks and Mars relay network -
  - Allocating communication resources in response to user missions' service requests.
  - Assigning, prescribing, and scheduling (in case of Earth stations/antennas) communication assets. Note: Scheduling for services by relay networks will be necessary at least initially during the transition of relay operations from the current pre-scheduling paradigm to the on-demand access mode.

(b) Network control: The processes conducted by the service providing systems for:
  - Configuring the communication assets in preparation for service execution, and
  - Monitoring and controlling the state/behavior of communication assets.

Three types of system elements will interact with one another for network management operations: the Mission Operations Center (MOC), one for each user mission, the Network Operations Center (NOC), one for each Earth network, and the Relay Operations Center (ROC), one for each relay network.

(3) Integrated network management:

Managing a DTN network involves not only the DTN internetworking layer services and DTN node internal states, but also the underlying layers of communications. In DTN era, as the capabilities at the network layer and above are introduced, service management and network control will leverage the CCSDS cross support standards and extend them to the layers above the link layer (vertically) and end-to-end across the Mars network domain (horizontally). As such, the coordination of planning and operations between DTN node owners is an inherent part of the network management. This implies that the current set of CCSDS cross support service management (CSSM) standards for link layer functions will have to "move" beyond the Earth network services over the space-ground links. CSSM must be augmented to address DTN services and services offered by other types of communication assets, e.g., relay satellites for relay proximity links.

(4) Executable Contact Plan:

At the networking layer, the contact graph routing (CGR) plan (in short, “contact plan”) per the CCSDS Schedule-Aware Bundle Routing standard[39] is an essential data structure in the service management process. In order to piece together a final, executable contact plan involving multiple space agencies and network service providers, an efficient scheme is needed. The format for the contact plan and mechanisms for distribution will have to be standardized by the CCSDS.

(5) A two-venue approach to service management:

The service management process features two distinct, parallel paths driven by the service requests from all Mars user missions in a given network domain:

Venue 1: Requests for Earth network services: The focal points on the service provider side are the various Earth network operations centers (NOC). A current example of the NOC is the DSN’s NOCC (See Figure 5.6-1).
Venue 2: Requests for relay network services: The focal point on the service provider side is the Mars relay operations centers (ROC) which is associated with the Mars relay network designated as the primary relay network among all the participating relay networks. Current examples of the ROC are the JPL Mars program’s MAROS (See Figure 5.6-2) or the European Relay Coordination Office (ERCO)[61].

The designation of a primary ROC (and the primary relay network) is important to simplify the N:M:X multi-variable process among the multiple user missions, Earth networks, and relay networks (Note: Interactions for service management among N number of user missions, M number of Earth networks, and X number of relay networks would demand a very complex process). It essentially serves as the agent on behalf of all Mars user missions in working with other ROCs to address relay service needs. The collaborating space agencies may take turns to designate their respective Mars relay networks as the primary network, hence the primary ROC.

Each Earth network has to take into account the service needs by Mars as well as non-Mars user missions and relay orbiters due to the secondary effect of capacity demands on proximity and DWE links.

Figures 5.6-1 through 5.6-3 depict the service management aspect of the proposed Mars network management architecture.

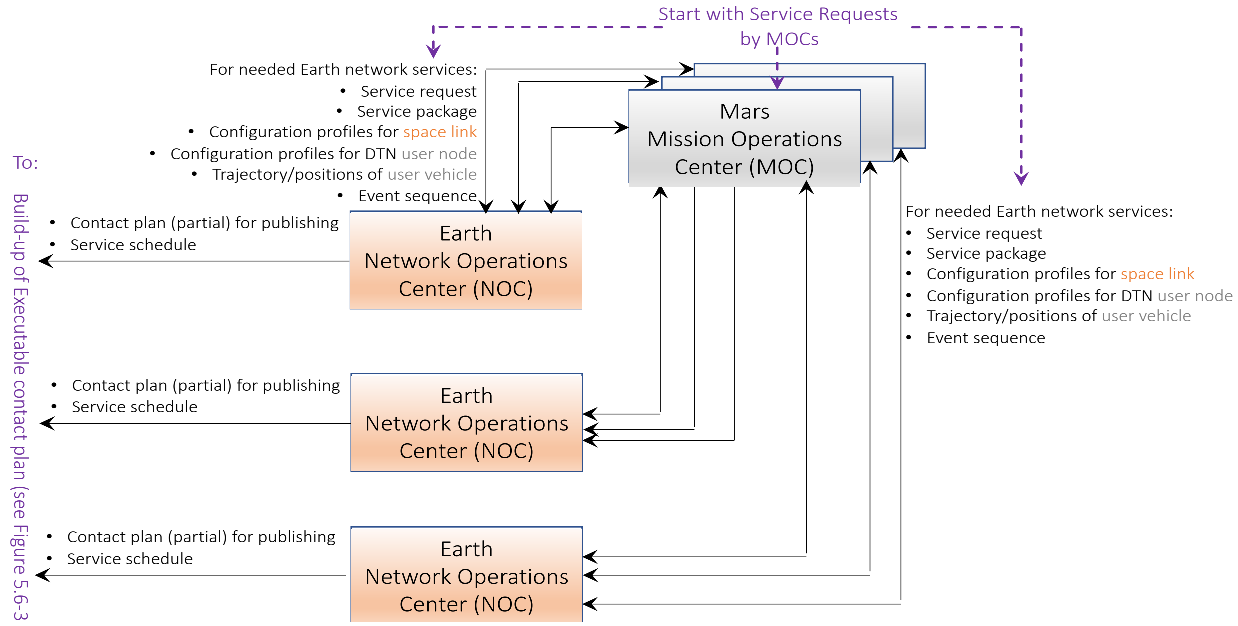


Figure 5.6-1. Venue-1 Mars service management for Earth network services - From service requests to contact plans

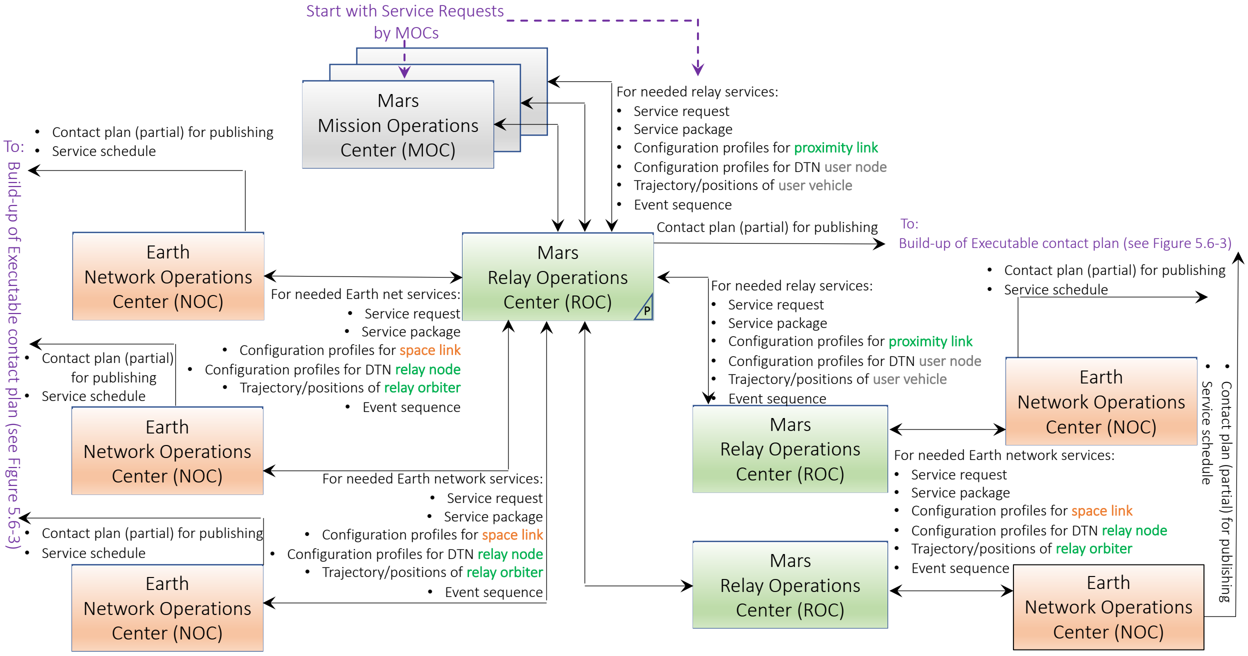


Figure 5.6-2. Venue 2 Mars service management for relay network services - From service requests to contact plans *(Note: The primary ROC is represented by the green entity denoted by a letter P on the lower right corner.)*

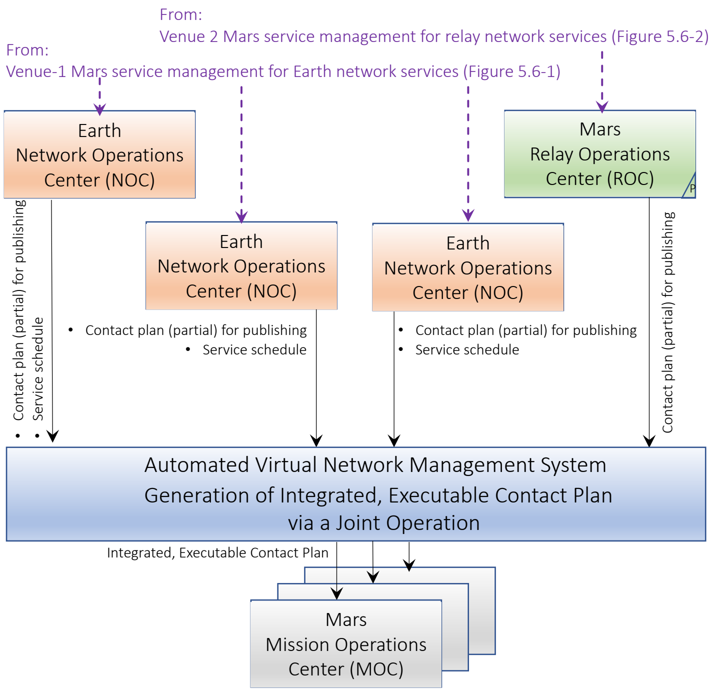


Figure 5.6-3. Mars service management for Mars network services – Build-up of executable contact plan

(6) DTN network management standards:

The recommended practices as defined in the Architecture requirements document (ARD) for Space Communications Cross Support (SCCS)[38] by the CCSDS should be observed. All specifications for the CCSDS CSSM standards, in work or planned for future work, must be extended to include service management related to DTN and relay orbiters. These include Service Request, Service Package, and Configuration Profiles. Specific to DTN network management, the Asynchronous Management Architecture (AMA), that is ready to be approved as an IETF standard, should also be followed for Mars network management. This document describes an architecture suitable for providing application-level network management services in a challenged networking environment.

In addition to the CCSDS Contact Graph Routing standard[39] mentioned above, the pending DTN Asynchronous Management Protocol (AMP), currently in the form of an Internet IETF draft, will have to be employed to support the network monitor and control function. In that regard, the monitor data parameters being defined in Functional Resource Model by the CCSDS CSSM must also be extended to standardize those associated with the various types of DTN nodes, e.g., the relay orbiters and end user elements. Since the AMP may still take additional work to completion, it is proposed that, in the interim, the Functional Resource Model be applied as a common method for internal network management by all participating agencies/providers. Of course, this would only result in agency-specific network operations. But it could serve as a viable solution for the smooth transition towards a fully interoperable phase after the DTN network management standards such as AMA and AMP are realized.

Inherent to network management is the process for managing key distribution, i.e., the Delay-Tolerant Key Administration (DTKA). This touches upon the entire subject of Mars Network Security Architecture (see Section 5.8).

Figure 5.6-4 through 5.6-6 gives a general description of the end-to-end network control architecture.

(7) Automated Virtual Network Management System:

The proposed network management architecture is more distributed and federated in nature. There is not a central body or system to direct the interfaces and generation of major data products by the various MOCs, NOCs, and ROCs. Nevertheless, a virtual system with an expert toolset deployed over the cyberspace to support the operational processes may be essential.

Key capabilities of the virtual system with automated network management capabilities are as follows:

- Generation of the integrated, executable contact plan from the partial contact plans published by the various NOCs and the primary ROC.
- Distribution of the integrated, executable contact plan to all DTN node owners
- Analysis of the overall Mars network status based on the monitor data published by the various MOCs, NOCs and the ROCs.
- Analysis of the overall performance of the Mars network based on the monitor data published by the various MOCs, NOCs and the ROCs.
- Functioning as the clearinghouse and repository of the network management data.

Figure 5.6-3 and 5.6-6 illustrates the role of this virtual system in service management and network control, respectively.

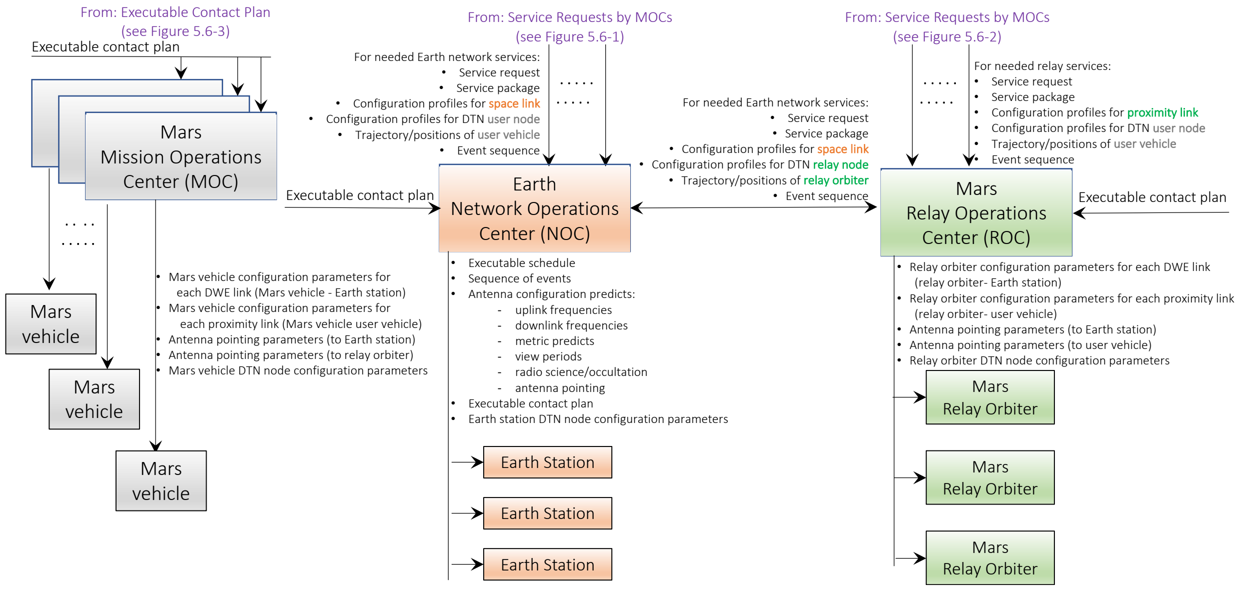


Figure 5.6-4. Mars network control – From service requests, etc. to network asset control

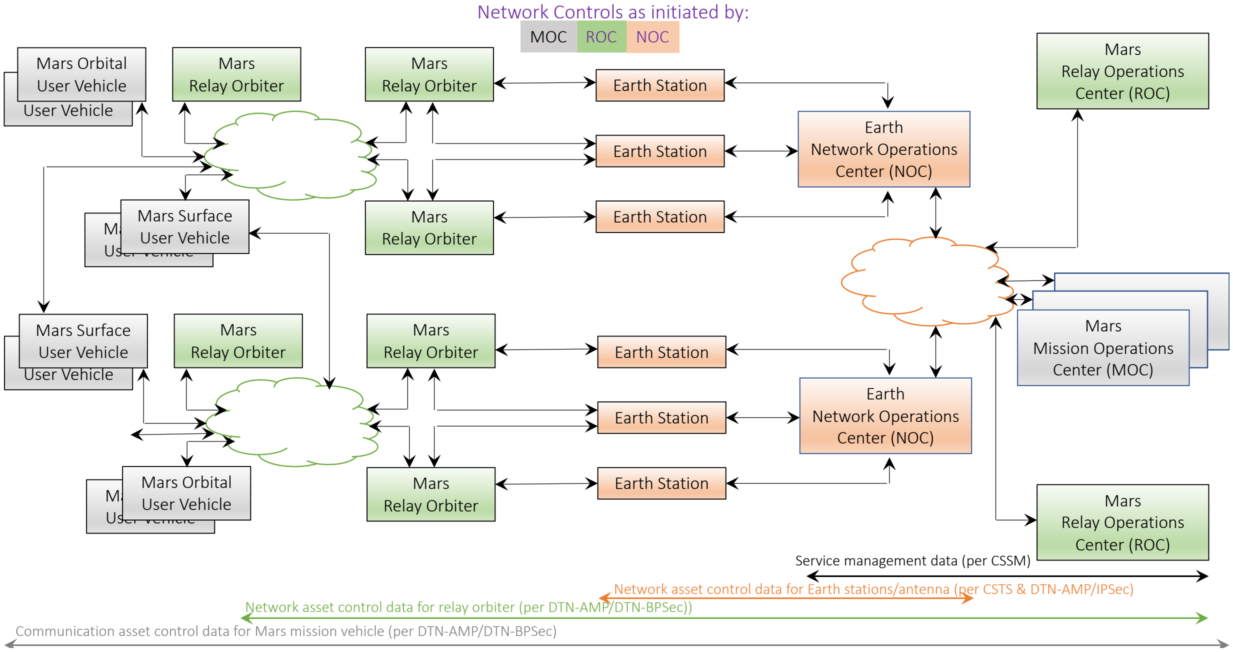


Figure 5.6-5. Mars network control – The end-to-end data path

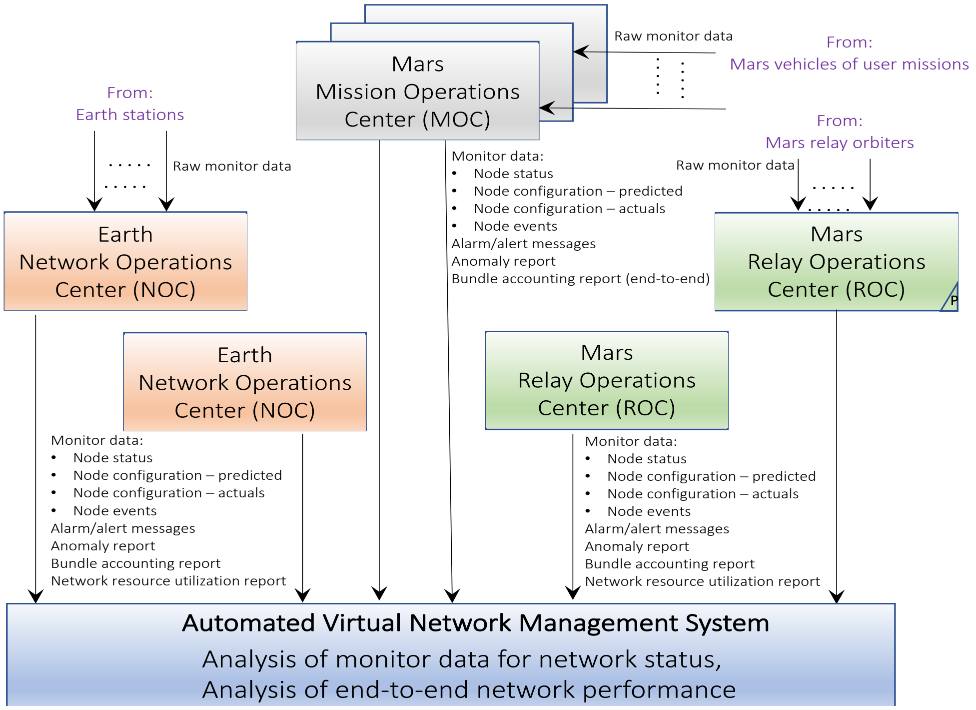


Figure 5.6-6. Mars network control – The end-to-end network monitoring

5.7 Navigation Architecture

For more than four decades, navigation for deep space missions, be it flyby to celestial bodies, orbit insertion/maintenance, rendezvous, and landings, relies on radiometric tracking capabilities performed by Earth stations. Through observable acquired over a two-way RF space link, spacecraft line-of-sight (or radial-to-Earth) position and velocity are directly measured by range and Doppler, and plane-of-sky information is provided by delta-DOR using natural radio source as timing calibration signal. These data types when combined with onboard optical data, i.e., images of nearby target bodies taken by the spacecraft camera, have generated very accurate navigation for missions. However, even with this approach the heavy dependency on ground-based navigation has an inherent shortcoming. The round-trip light-time delay and the data processing latency on ground inevitably are the primary factors contributing to the spacecraft's inability of applying the acquired navigation information for timely execution in response to the immediate event.

It is expected that the traditional ground-based tracking and navigation will continue to be a very important ingredient of the Mars communications architecture in the future. However, the emergence of the "on demand" contacts with Earth stations and the precise onboard deep space atomic clocks (DSAC) will be transformational for deep space navigation. First, with the advent of the DSAC, accurate one-way radiometric tracking will replace many currently needed two-way contacts, thus reduce the needs for tracking time of Earth antennas. The current practice of long cruise contact periods to be scheduled far in advance and intense campaigns of Earth-based tracking leading up to Mars orbit insertions and landings and critical events will ultimately be replaced with less frequent contacts which are scheduled as needed via "on demand" services. Beyond this, Earth-independent "autonomous optical navigation"[46] can provide precise tracking, navigation, and targeting onboard the vehicle, thus eliminating the hours to days delay between maneuver calculation and maneuver execution. It will become a more cost-effective alternative to the traditional radiometric approach for Mars missions because of more responsive execution of spacecraft activities and reduced demands on Earth network capacity. This approach features an autonomous optical-only navigation system on-board the spacecraft. It applies a camera mounted on the spacecraft to take line-of-sight measurements to multiple natural or artificial target bodies (that serve as beacons) in the far fields. The LOS information are then used to compute the spacecraft position and velocity on-board.

As the essential element of the Mars local infrastructure, the Mars relay network would lead Mars missions to a different paradigm of autonomous on-board navigation. The dedicated communications satellites could provide tracking and navigation services to support various human and robotic activities on the Mars surface and in orbit. These include entry/descent/landing, surface discoveries and returning to sites, construction/assembly of structures and habitats, rendezvous and docking, Mars ascent, and orbit insertion, etc.

An example is the positioning service that can be realized by a localization scheme which leverages on the proximity link between a user vehicle and a relay satellite to perform Doppler and range measurements, and with the altitude knowledge of the user vehicle, executes a real-time position determination. The Joint Doppler and Ranging (JDR) scheme can be applied to relative positioning for a Mars surface user, when there is a nearby reference station, for example, a lander operating in the vicinity. This is achieved based on (a) the two Doppler measurements, i.e., one between the relay satellite and the user vehicle, and the other between the relay satellite and the reference station, (b) the two range measurements: one between the relay satellite and the user vehicle, and the other between the relay satellite and the reference station, and (c) the user vehicle's known altitude. The JDR scheme can also support absolute positioning when no reference station is available, but with reduced performance.

The JDR scheme is particularly useful to provide real-time 3-dimension (3D) positioning services with a small number of relay nodes (as small as one) for a user on the Mars that uses only proximity link radio with ranging and Doppler measurement capability. No separate dedicated navigation radio is required. With more satellites, the known altitude assumption can be disregarded, and/or the real-time 3D positioning accuracy can be improved.

Moreover, the DSAC-based clock system resident in the Mars infrastructure would ease a great deal the time management effort at all participating mission elements and provide much higher time accuracy, as the clock can remain ultra-stable over decades, potentially up to 50 times more stable than the atomic clocks on GPS satellites.

Figure 5.7-1 illustrates the various navigation approaches in the future Mars communications architecture. The repertoire offers multiple choices for the missions to use taking into account the types of missions, specific events, performance needs, and spacecraft capability. The mix of techniques vary from the ground-based RF navigation (the current expert in-the-loop and automated operational practices) to on-board autonomous optical navigation and relay infrastructure-based tracking/navigation services.

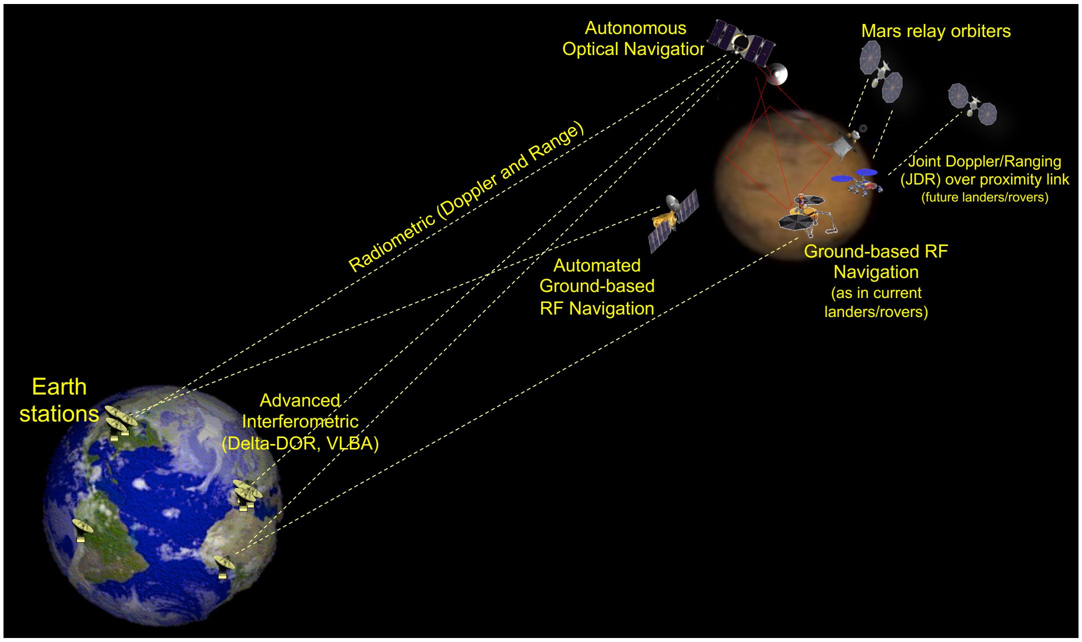


Figure 5.7-1. Future Mars navigation architecture
(Modified from the figure prepared by Joe Guinn of Caltech/JPL)

5.8 Mars Network Security Architecture

The Mars Network, in terms of its security aspect, should be thought of as being composed of four types of elements: a user, a DTN router, a DTN inter-domain gateway (DTN gateway for short), and a DTN Certificate Authority [56]. Each participating agency will provide one or more of these elements. Each agency (or a multi-mission consortium) may deploy its own user elements, each of which contains a DTN Bundle Agent, and a DTN store-and-forward router. These elements may belong to one agency, or consortium, and may operate as a closed system, transferring data only for that organization. But, in order to provide broader coverage, redundant paths, emergency services, and likely higher performance and reliability, these separate network domains may interconnect using a designated inter-domain gateway. In the limited, closed system, case it is possible to manage the security identities and associated keys using purely manual processes. This approach might use pre-stored, symmetric keys. In the more general case, an inter-regional gateway will be required, as will a trusted certificate authority that will be used as part of access management, authentication, and encryption of data using an asymmetric, public key, infrastructure.

The general case requires that trusted identities are assigned to all user elements, as well as to all service providing elements, relay spacecraft, DTN routers, inter-domain gateways, ground stations, and end-user systems. Without this it is not possible to identify the source of traffic on the network nor the identities of the elements that participate in providing and using services. Even if there is no attempt to control or block access, it is essential to monitor and understand who, and how, the network is being used. After all, communications bandwidth and data storage are always going to be constrained commodities.

5.8.1 Mars Network Security Identities

It is recognized that space internetworking services introduce the potential for network *security vulnerabilities* like those experienced in the terrestrial Internet. A fundamental method for addressing vulnerabilities, from the outset, is to ensure that all entities have an established identity that can be trusted and validated, a variant of an approach adopted in current terrestrial network security [52]. This approach is not unlike checking to see who is at your front door before you unlock it and let them inside. The management of these trusted identities is the job of the Certificate Authority. For efficiency there will need to be at least one of these located at Mars, to eliminate, to the greatest extent possible, Earth round-trip delays. These identities, and the security certificates that can be used to validate them, will become a key part of the security fabric used for access control (where it is needed), authentication of data (how you can verify who sent it), and encryption (securing/obscuring the contents of the transfers where needed).

While there has been work done within CCSDS to define an Inter Governmental Certificate Authority (IGCA) that supports secure identity creation and management across multiple organizations, the use of identities, certificates, key management [55], and secure network management within DTN [56] is not yet a settled issue. A proposed approach to providing authentication and confidentiality to all registered elements/users over the end-to-end Mars Network is depicted in Figure 5.8-1.

Before deploying and interconnecting an element to the network, each organization should ensure that the element is properly certified and accredited in accordance with national or local organizational guidelines. Certification will involve creating identities and providing trusted certificates for all entities within the distributed, and hierarchical IGCA structure. It will also involve testing and evaluating the technical and non-technical security features of the systems to determine the extent to which they meet a set of specified security requirements. Accreditation is the official approval by an authorizing official that the system may operate for a specific purpose using a defined set of safeguards at an acceptable level of risk.

Security controls will be implemented and conducted as an operational activity and as a prelude to any element joining the network. They must include verification of identities, assignment of roles, access, and service permissions (which may be waived). These identities will then be used as part of authentication, access controls, and encryption services, and will be important in supporting network governance, including intrusion detection/prevention, auditing, virus scanning, and threat identification.

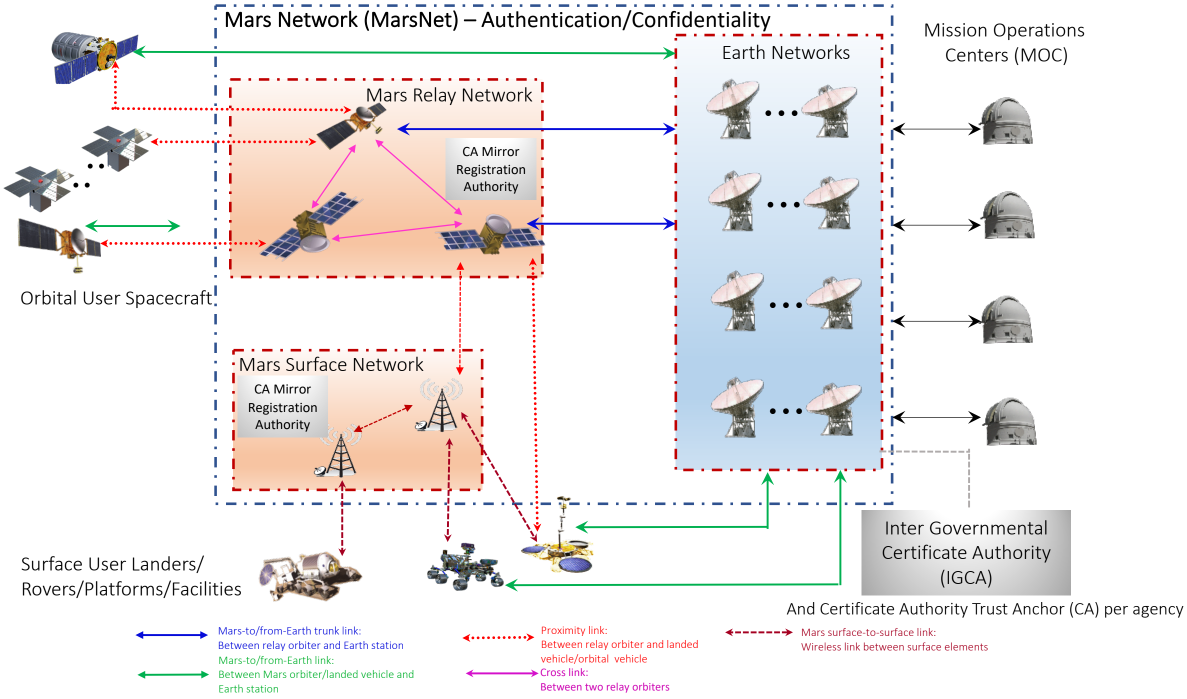


Figure 5.8-1. Mars Network Security – Authentication and Confidentiality

Credit to Chuck Sheehe, NASA/GRC, & Peter Shames, Caltech/JPL, for the IGCA/CA mirroring concept

Unimpeachable identities of all of the participating elements, user nodes, network service nodes, and management nodes must be an intrinsic part of the fabric. Consideration must be given to the “local” deployment of Control Authority “mirror” sites to support efficient access to the network and services that adopt access controls. And consideration must be given to the means to provide cross support services in the case of contingency or emergency operations.

5.8.2 Mars Network Security Layers

From the start of architecture transition into the Future Long-Term era, the security objectives of Confidentiality, Integrity, and Availability (CIA) will be applied to all data carried across the network. This will be achieved by a security architecture incorporating a layered security approach, including application data security, where it is required, bundle layer security for DTN networking, secure access control and network management so that the control of this communications “fabric” itself is secure against tampering. In a closed network deployment some of these mechanisms may not be used, but in the general case, for interoperability, secured identities, access controls, secure network management, and bundle security protocols will need to be deployed on all of the nodes.

Security mechanisms must be viewed as an inherent element of the Mars communications architecture. Authentication and access controls must be used to managed access to the network "fabric" itself.

For the data transfers themselves authentication or encryption must be applied at one of the following two layers:

- Network Layer security – is applied either within the DTN stack using Bundle Protocol Security (BPsec)[20] or within an IP stack, for Mars local communications, using Internet Protocol Security (IPsec). BPsec takes the form of bundle 'extension' blocks that can provide authentication and/or encryption of the data that the network carries, so its deployment of does not entail the insertion of additional protocol layers at any nodes. Wherever BPsec is deployed, mechanisms for distributing BPsec keys to DTN nodes must be deployed. In a fully interoperable deployment, a Mars-local inter-domain Certificate Authority will participate.
- Space Data Link Layer security – is applied to the contents of data link frames using Space Data Link Security (SDLS) protocol. The SDLS defines a security header and trailer for applying authentication and encryption. The frame headers are protected but left in the clear. Key management, symmetric or asymmetric, is also a concern for this kind of deployment.

Application layer security for providing security services in addition to any such services provided at network layer or space data link layer may also be applied to the data by endpoint user applications. This kind of security, which nominally just involves the two user endpoints, may just rely upon pre-loaded symmetric keys.

Figure 5.8-2 shows a representative set of end-to-end interface pattern based on the security protocols described above.

NOTE: Not all three layers (application, network, and data link layers) of the security mechanisms/protocol are likely to be simultaneously implemented for a given mission or mission set. The protocol stack diagram shows them all merely for the purpose of depicting a viable, inclusive security architecture.

Furthermore, regarding the "certificate" tagged to each communicating entity in the above diagram, it is important to point out that at this point the BPSec and BPv7 does not provide any mechanism for handling certificates nor using them for authentication of participating entities for access to the network. These new features have been in discussion for some time and a project to provide this is likely in the near term. Right now, authentication can be accomplished by combining BPSec services with other components, such as link layer security using SDLS. Or they could depend upon "security associations" where the "identities" of the participants are assumed and defined by pre-loaded keys and symmetric key encryption.

All of the communication layers shown in this figure can be thought of as the "data plane". In addition to these, but not shown, is a set of protocols that can be thought of as a separate "control plane". These include the routing update protocols, network management protocols, security / identity management protocols, and monitoring protocols. Some of these, like the Application

Management Protocol (AMP) and related support structures are being defined in the DTN working group of the Internet Engineering Task Force (IETF). New control plane protocols for managing identities and the distributed IGCA will also be needed, along with the means for expressing policies and governing access.

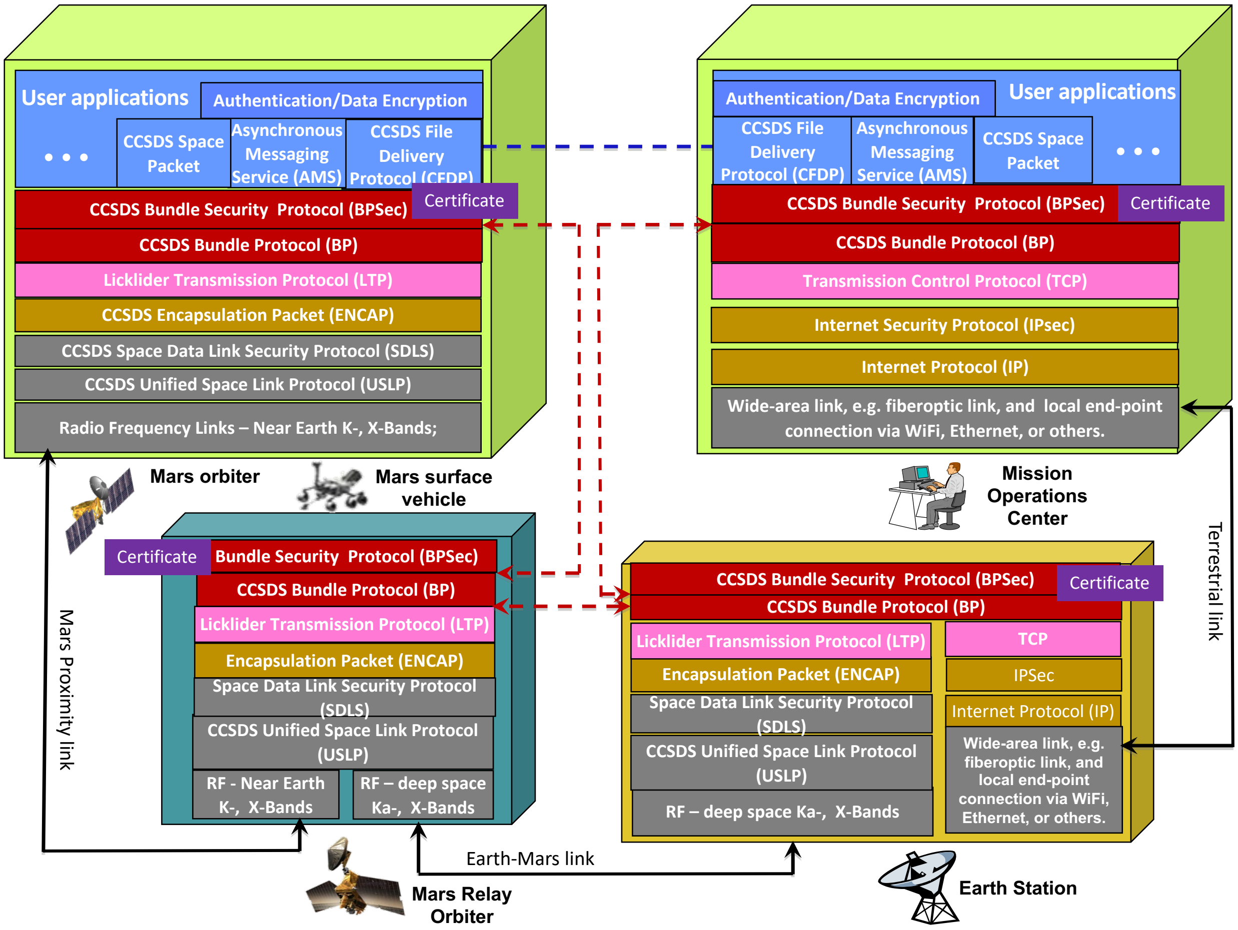


Figure 5.8-2. Mars Network Security – End-to-End Interface Pattern

5.8.3 Mars Network Security Needs

Three essentially orthogonal issues remain to be resolved by the CCSDS:

- Point-to-point/SDLS: the key has to be known at both ends of a single link (a key at the spacecraft, and a key at the origination of the uplink) and if one agency owns both ends, no problem. If the Earth network node isn't owned by spacecraft owner, then a "trust" issue for SDLS that has to be worked out and a trusted Certificate Authority may be involved.
- End-to-End data encryption/BPsec. Here, where the owner of the data and the user of the data belong to the same agency, they can share keys and no one else in the middle has to know them. The key management issue is then more of a matter of how to validate/ transfer/ confirm/ repudiate keys from multiple sources when they are not all in communication with the key manager at the same time. So, for DTN, the Delay-Tolerant Key Administration (DTKA) and the Inter-governmental Certificate Authority (IGCA) [53] being defined by the CCSDS should aid in solving these end-point to end-point key distribution issues.

- Identity Management / Access control: The DTN protocol suite, including BPSec, does not at the time of this writing have a generalized, authenticated, and unambiguous means of identifying all of the entities that participate in a system deployment, and of using these identities to control access to the network or to services attached to the network. Some sort of extension to DTN and/or BPSec is needed to provide this capability and to supports its use in multi-mission and multi-agency contexts.

It is recommended that the following general security policy be adopted by Mars missions and service-providing systems:

- All Mars missions and participating elements should have a verified identity, vetted by a trusted source, and an associated secure certificate, such as ITU-T X.509 [54], that can be used to unambiguously authenticate that identity.
- All Mars service-providing elements should use verified identity certificates to manage access to the network, to network attached services, and to network management interfaces.
- All Mars missions, regardless of robotic science, or human crewed missions, should use the BPsec or SDLS using Advanced Encryption Standard-Galois Counter Mode (AES-GCM) in authentication mode, at a minimum, for all links in all directions.
- All crewed or human exploration missions should use the AES-GCM in Encryption, or Authenticated Encryption mode with 256-bit (or larger) keys, for all links in all directions.
- All robotic science missions should use the AES-GCM in Authentication, or Authenticated Encryption mode with 256-bit keys, for all links in forward direction.
- Adopt the CCSDS SDLS Protocol – Extended Procedures as standard practice for key management.

It must be noted that at the time of this writing, IGCA, Identity Management, Identity-based access control, BPsec key management and SDLS key management have not yet been standardized – and to further complicate things, key management for servicing one agency's missions by another's services is problematic because agencies don't want to share their keys with the cross supporting network(s).

6. Conclusions and Recommendations

6.1 Study Conclusions

The working group has managed to collect the information about all the current assets and capabilities (space and ground) that are applied for Mars communications by the eight space agencies participating in this study. Through the down-selection from the repertoire of CCSDS and SFCG standards, as well as thorough the identification of their potential future extensions, consensuses have been reached on the preferred frequency bands, modulation, coding, and ranging schemes plus the space data link and network layer protocols for the future Mars communications architecture. It is believed that this should serve as the guidance for Mars-faring space agencies as well as service providers (commercial or agency-internal) to achieve high-degree of interoperability among their communication assets.

We have analyzed the current and future Mars mission sets. Towards the three future mission eras, evolutions of the Mars communications architecture have been defined. For the foreseeable future long-term mission era, the Mars Network (MarsNet), in a form of space internet, that embodies Mars relay network(s), Mars surface network(s), and Earth network(s), is defined. New capabilities, key attributes and salient behaviors of this end-to-end network during each of the mission eras have been identified.

A Mars network management architecture is recommended to tackle the extra operational complexity due to the functionality at network layer and above, the new types of networks (relay and surface networks), and multiple service providers (agencies and commercial companies) involved. Closely related to network management is network security. The Mars network security architecture we defined has addressed an identity management approach with capabilities for authentication and confidentiality. While some of the capabilities for network security are yet to be worked by the CCSDS, it is crucial for the Mars-faring agencies to influence the priorities of the development effort for the various relevant standards. To alleviate the inherent shortcomings in navigation due to the heavy dependency on ground-based measurements, it is envisioned that on-board autonomous optical navigation and localization scheme using radiometric observables acquired over the proximity link will become the new ingredients in the future Mars navigation architecture. As such, more choices will be available to Mars missions.

It will be a challenge to ensure that future missions will evolve according to the presented framework, taking into account programmatic constraints, e.g., of financial nature, as well as considering the appealing robustness of legacy solutions. Indeed, this report has to be seen as a first step in breaking the re-use/heritage cycle, in order to move forward. Ultimately, for the future international Mars exploration at a global scale, the IOAG may want to coordinate with its member agencies to gradually build up the end-to-end Mars network and communications architecture. Furthermore, on the practical side, ensuring backwards compatibility of future missions to heritage technology could help in breaking the heritage cycle, by investing on increased on-board computer power or reconfigurable avionics. For instance, subject to cost and feasibility analysis and trade-off, and relevant to a future communications architecture, new orbiters (or landers) could introduce new features as per identified roadmap, yet embarking capabilities to support legacy landers (or orbiters).

6.2 Key recommendations for down-selection in FMCRL schemes

The preferred FMCRL standards are identified in Table 4.2-1. A few salient recommendations are high-lighted in this section. Chief among them is the selected coding schemes. The working group has concluded that the communication architecture should include both LDPC and turbo codes, wherein the turbo codes can be used for power constrained links and LDPC codes be opted for bandwidth constrained links.

The working group invariably felt that, balancing the heritage of present Mars relays and the re-use of RF hardware of lunar environment, coexistence of S-, X- and K-bands for Mars proximity links for a range of data rates is essential and this report shows a major emphasis towards this end. To the degree possible, across-the-board homogenous solutions for modulation, coding, data link layer and security protocols are recommended for "all" Mars missions, all link directions (forward, return, and cross links), all data rate regimes (high, low, and medium rates), and RF/optical. It is suggested that the Unified Space Link Protocol be adopted for the future.

6.3 Key recommendations for the Future Near-term Missions Era (2022 onwards)

While there is no mission demanding high-volume data return during this era, it is important for the IOAG community to observe any initial move towards migrating to high rate links using 32 GHz Ka-band as a technology demonstration. The working group believes PN ranging should start emerging as the sole ranging technique to achieve higher degree of interoperability in providing radiometric tracking services. It is also envisioned to introduce a new Delta-DOR approach making use of Ka-band and PN ranging to improve the angular accuracy. For realizing higher coding gain for all link types, it is suggested to replace the decades-old concatenated Reed-Solomon/convolutional codes with LDPC codes. Moreover, cross support between space agencies is prophesied to go in a long way by infusing a few rudimentary Cross Support Service Management (CSSM) capabilities standardized by CCSDS.

6.4 Key recommendations for the Future Mid-term Missions Era (2026 onwards)

In this era, driven by one or two high-rate science instrument, e.g., the SAR, Ka-band capability for direct-with-Earth links will become operational. Along with this is the dedicated Mars relay satellite(s) deployed on higher orbits providing user mission with longer coverage periods with simultaneous multiple access to proximity links. Most notably is the emergence of an early form of the end-to-end Mars Network (MarsNet) that encompasses Mars relay network, Mars surface network, and the relevant Earth networks. Patterned after the DTN architecture model, the MarsNet is essentially a Mars space internet. As an adjunct to the DTN network layer capability, the Unified Space Link Protocol (USLP) at the data link layer is recommended in order to accommodate high data rates with maximum link efficiency. Optical downlink is expected to be a logical option for high-rate data return, yielding shorter contact times and potentially offering optimetric measurements for precise navigation. The use of new GMSK and Modcod methods is proposed as a preferred approach to maximizing the X-band spectrum efficiency while allowing simultaneous transmission of data and PN ranging.

6.5 Key recommendations for the Future long-term Missions Era (2037 onwards)

For supporting the human Mars exploration, the architecture for this era will feature the full-grown Mars relay network, Mars surface network and a set of more capable Earth networks. As such, the MarsNet would evolve into a more encompassing end-to-end space internet than the previous era. In addition to the data transfer at the space internetworking layer, the Mars network management capabilities, in terms of service management and network control, will be infused to operate network assets provided by the collaborating space agencies and commercial service providers. Closely coupled with the Mars network management is the network security. The network security architecture we defined features the trusted certificate authority that will be used as part of access management, authentication, and encryption of data using an asymmetric, public key, infrastructure. It requires that trusted identities are assigned to all user elements, as well as to all service providing elements, e.g., relay orbiters, DTN routers, surface communications hub, Earth stations. To cater to the increased data throughputs, the 34 GHz Ka-band (uplink) and 32 GHz Ka-band (downlink) as well as optical communications at 1030 – 1070 nm (uplink) and 1530 – 1567 nm (downlink), are applied to form the trunk links between Earth and Mars. As the complement to the trunk link, the high-rate proximity link using the 22 GHz K-band for forward link and 26 GHz band for return link is recommended.

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Appendix A. Current and Potential Future Mars Missions

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communications assets♪
Mars Odyssey	2001	NASA	1	Orbiter	ESA	DSN, ESTRACK
Mars Express	2003	ESA	1	Orbiter	NASA	ESTRACK, DSN
Mars Reconnaissance Orbiter (MRO)	2005	NASA	1	Orbiter	ESA	DSN, ESTRACK
Mars Science Laboratory (MSL): Curiosity	2011	NASA	1	Rover	ESA	DSN, ESTRACK, NASA/ESA relay orbiters
Mars Orbiter Mission-1 (MOM-1): Mangalyaan-1	2013	ISRO	1	Orbiter	NASA	IDSN, DSN
MAVEN	2013	NASA	1	Orbiter	ESA	DSN, ESTRACK
ExoMars Trace Gas Orbiter (EDM-TGO)	2016	ESA	2	Orbiter, Lander	Roscosmos	ESTRACK, DSN
InSight	2018	NASA	1	Lander	DLR, CNES, ESA	DSN, ESTRACK, NASA/ESA relay orbiters
Tianwen-1	2020	CNSA	2	Orbiter, Rover	ESA	China DSN, ESTRACK
Perseverance Rover	2020	NASA	2	Rover, Helicopter	DLR, CNES, ESA, JAXA	DSN, ESTRACK, JAXA Network
Emirates Mars Mission (EMM) - Mars Hope	2020	UAE Space	1	Orbiter	NASA	UAE DSN, DSN
ExoMars RSP	2022	ESA	2	Rover, Surface Science Platform, carrier	Roscosmos	ESTRACK, EXM- TGO, NASA Relay orbiters
Tera-hertz Explorer-1 (TEREX-1)	2022	NICT	1	Small Lander	NASA	DSN, JAXA Network
Mars Orbiter Mission-2 (MOM-2): Mangalyaan-2	2024	ISRO	1	Orbiter	NASA	IDSN, DSN
Tera-hertz Explorer-2 (TEREX-2)	2024	NICT	1	Orbiter	NASA	DSN, JAXA Network
Martian Moon eXploration (MMX)	2024	JAXA	1	Phobos/Deimos sample return	NASA, ESA, ASI, CNES, DLR	JAXA Network, DSN, ESTRACK, SDSA (Sardinia)
Mars Micro Orbiter*	2024	NASA	1	Orbiter	TBD	DSN
Phobos-Grunt 2	2024	Roscosmos	1	Sample return	ESA, others?	[TBD]
Mars Sample Fetch Rover	2026	ESA	1	Rover	NASA	DSN, ESTRACK, NASA/ESA relay orbiters
Earth Return Orbiter	2026	ESA	1	Orbiter	NASA	DSN, ESTRACK, NASA/ESA relay orbiters
Mars Sample Return Lander	2026	NASA	2	Lander, Mars Ascent Vehicle	ESA	DSN, ESTRACK, NASA/ESA relay orbiters
Mars 2026 SmallSat*	2026	NASA	1	Orbiter	ESA	DSN, ESTRACK, NASA/ESA relay orbiters

Mission	Launch Year	Agency	# of Vehicles	Mission Type	Cooperating Agencies	Supporting communications assets♪
Tianwen-2 (TBC)*	2026	CNSA	3	Sample return		
Mars SAR/ IceMapper*	2026	NASA, JAXA, CSA	2	Science Orbiter, Relay Orbiter	TBD	DSN, JAXA Network
Small Mars Science Orbiter*	2028	ESA	1	Orbiter	TBD	ESTRACK, DSN NASA/ESA relay orbiters
Mars Communication and Navigation Infrastructure Network*♪	2031	ESA	3+	Orbiter	TBD	ESTRACK, DSN
Mars Icebreaker Life*	2033	NASA	1	Lander	[TBD]	[TBD]
Mars Short-Stay Mission - SEP1*	2033	NASA	1	Cargo deployment #1		
Mars Long-Lived Weather Network Mission*	2033	ESA	4 landers 1-2 orbiters	Lander/Orbiter Network	[TBD]	DSN, ESTRACK, NASA/ESA relay orbiters
Mars Ice Access and ISRU demo Mission*	2035	ESA	1	Lander	[TBD]	NASA/ESA relay orbiters
Mars Short-Stay Mission - SEP2*	2035	NASA	1	Cargo deployment #2		
Mars Astrobiology Rover	2037	ESA	1	Rover	[TBD]	DSN, ESTRACK, NASA/ESA relay orbiters
Mars Communication and Navigation Infrastructure Network Augmentation*♪ *	2037	ESA	3+	Orbiter	[TBD]	DSN, ESTRACK,
Mars Short-Stay Mission - Lander*	2037	NASA	1	NEP Crew Lander staged for crew arrival		
Mars Areostationary Relay 1*	2037	NASA	1			
Mars Short-Stay Mission - DSH*	2039	NASA	1	1st Human Mars Mission: DSH-Orion stack	ESA	
Mars Short-Stay Mission - MAVBS*	2039	NASA	1	Mars Ascent Vehicle with Boost Stage		
Mars Short-Stay* Mission - CubeSats	2039	NASA	10			
Human surface mission support	2041	ESA	1	Lander/Rover	[TBD]	
Mars Areostationary Relay 2*	2043	NASA	1			

Footnotes: * Proposed mission or mission concept in planning.
♪ A ground station, network, or relay orbiter.

Color codes: Gray: Currently flying missions;
Green: Future near-term missions - Starting 2022 launch
Brown: Future near-term missions - Starting 2026 launch;
No color: Future long-term missions – Starting 2037 launch

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Appendix C. List of Acronyms

3GPP	3rd Generation Partnership Project
ADR	Adaptive data rate
AES-GCM	Advanced Encryption Standard-Galois Counter Mode
AMA	IETF Asynchronous Management Architecture standard
AMP	CCSDS DTN Asynchronous Management Protocol
AOS	CCSDS Advanced Orbiting Standard
ASI	Agenzio Spaziale Italiana
AU	Astronomical Unit
BCH	Bose–Chaudhuri–Hocquenghem codes
BP	CCSDS DTN Bundle Protocol
BPSec	CCSDS DTN Bundle Security Protocol
BPSK	Binary Phase Shift Keying
BWG	Beam Wave Guide
C&DH	Command & Data Handling subsystem
CCSDS	Consultative Committee for Space Data Systems
CDMA	Code Division Multiple Access
CIA	Confidentiality, Integrity, and Availability
CLTU	Communications Link Transmission Unit
CNES	Centre national d'études spatiales
CNSA	China National Space Agency
CSA	Canadian Space Agency
CSSM	Cross Support Service Management
dBm	decibel milliwatt
dBW	decibel watt
dB/K	dcibel/Kelvin
DFE	Direct-From-Earth
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DOR	Differential One-way Ranging
DSAC	Deep Space Atomic Clock
DSCC	Deep Space Communications Complexes
DSH	Deep Space Habitat
DSN	Deep Space Network
DTE	Direct-To-Earth
DTKA	Delay-Tolerant Key Administration
DTN	Delay/Disruption Tolerant Network
DVB-S2	Digital Video Broadcasting by Satellite-2 standard
DWE	Direct-with-Earth link
EDL	Entry, Descent, and Landing
EIRP	Effective Isotropic Radiated Power
ERT	Earth Receive Time
ESA	European Space Agency
ESOC	European Space Operations Center
ESTRACK	ESA's tracking station network
EVA	Extra-Vehicular Activity
FDMA	Frequency Division Multiple Access
FMCRL	Frequency, Modulation, Coding, Ranging, and Link Protocol

Gb	Giga bits
GHz	Giga hertz
GMSK	Gaussian Minimum Shift Keying
GN	JAXA's Ground Network
G/T	Gain-to-Noise-Temperature
HD	High Definition
HEF	High Efficiency type antenna
HGA	High Gain Antenna
ICSIS	International Communication System Interoperability Standards (ICSIS)
IDSN	Indian Deep Space Network
IDST	Integrate Deep Space and Radio Science Transponder
IETF	Internet Engineering Task Force
IF	Intermediate Frequency
INAF	Italian National Institute for Astrophysics
IFMS	Intermediate Frequency and Modem System
IOAG	Inter-agency Operations Advisory Group
IP	Internet Protocol
ISL	Inter Satellite Link
ISO	International Organization for Standardization
ISRU	In-Situ Resource Utilization
ISSDC	Indian Space Science Data Center
ISTRAC	ISRO Telemetry Tracking and Command Network
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JDR	Joint Doppler and Ranging
JPL	Jet Propulsion Laboratory
kbps	Kilo bits per second
km	Kilo Meter
ksps	Kilo symbols per second
LAN	Local Area Network
LCA	IOAG Lunar Communications Architecture
LCAWG	IOAG Lunar Communications Architecture working group
LCP	Left Circular Polarization
LCT	Laser Communications Terminal
LDPC	Low Density Parity Check coding
LEO	Low Earth Orbit
LGA	Low Gain Antenna
LMST	Local Mean Solar Time
LOS	Line-of-sight
LTE	Long Term Evolution
LTP	Licklider Transmission Protocol
MAC	Medium Access Control
MarCO	Mars Cube Orbiter
MaROS	Mars Relay Operations Service
MAV	Mars Ascent Vehicle
MAVBS	Mars Ascent Vehicle Booster Stage
MAVEN	Mars Atmosphere and Volatile EvolutioN mission
Mbps	Mega bits per second
MEX	Mars Express mission

MFSK	Multiple Frequency-Shift Keying
MGA	Medium Gain Antenna
MMX	Mars Moon Explorer mission
MOC	Mission Operations Center
ModCod	Adaptive Modulation and Coding
MOI	Mars Orbit Insertion
MOM	Mars Orbiter Mission
MRO	Mars Reconnaissance Orbiter
Msps	Mega symbols per second
MSSM	Mars Short-Stay Mission
MSPA	Multiple Spacecraft per Antenna
MUPA	Multiple Uplink per Antenna
nrad	Nano radiance
NRZ	Non-return-to-zero
NASA	National Aeronautics and Space Administration
NICT	National Institute of Information and Communications Technology
NOC	Network Operations Center
NOCC	Network Operations Control Center
O3K	CCSDS Optical On-Off Keying
OOK	CCSDS On-Off Keying
OQPSK	Offset Quadrature Phase Shift Keying
PAO	Public Affairs Office
PCM	Pulse Code Modulation
PDU	Protocol Data unit
PIF	Planning Information Format
PLOP-2	Physical Link Operations Procedure-2
PM	Phase Modulation
PN	Pseudo Noise
PNT	Positioning, Navigation, and Timing
PSK	Phase-Shift Keying
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAF	CCSDS Return All Frame service standard
RCF	CCSDS Return Channel Frame service standard
RCP	Right Circular Polarization
RF	Radio Frequency
RMS	Root-mean-square
ROC	Relay Operations Center
ROI	Return on investment
RTG	Radioisotope Thermoelectric Generator
Rx	Receive at X-band
SAP	Service Acquisition Protocol
SAR	Synthetic Aperture Radar
SBSP	Streamlined Bundle Security Protocol
SCCC	Serial Concatenated Convolutional Code
SCCS	Space Communications Cross Support
SCPPM	Serial Concatenated Pulse Position Modulation
SDLS	CCSDS Space Data Link Security protocol
SDR	Software Defined Radio

SDSA	Sardinia Deep Space Antenna
SDST	Small Deep Space Transponder
SEP	Sun-Earth-Probe angle
SFCG	Space Frequency Coordination Group
SLE	CCSDS Space Link Extension standards
SOP	Standard Operating Procedures
SPC	Signal Processing Center
SSF	Simple Schedule Format (SSF)
SSPA	Solid State Power Amplifier
SSR	Solid State Recorder
SWaP	Size, Weight and Power
Tb	Tera bits
TBC	To Be Confirmed
TBD	To Be Determined
TC	CCSDS Telecommand standard
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TEREX	Terahertz Explorer mission
TGO	Trace Gas Orbiter mission
TM	CCSDS Telemetry standard
TT&C	Tracking, Telemetry and Command
TTCP	Tracking and Command Processor
TWTA	Traveling-Wave Tube Amplifier
Tx	Transmit at X-band
UIS	User vehicle-Initiated Service
UHD	Ultra-High Definition
UHF	Ultra-High Frequency
USLP	CCSDS Unified Space Link Protocol
USO	Ultra-Stable Oscillator
UTC	Coordinated Universal Time standard
VCDU	Virtual Channel Data Unit
VCM	CCSDS Variable Coded Modulation standard
VLBI	Very Long Baseline Interferometry