IPN Progress Report 42-246 • August 15, 2026

Recommendation for the Next-Generation Mars Relay Orbiter

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ABSTRACT. — Today's Mars Relay Network (MRN) represents a highly successful international collaboration between NASA and the European Space Agency (ESA). As of this report's writing, the MRN consists of five heterogenous science orbiters, launched over the past few decades. In the years ahead, the current MRN topology is expected to change significantly. Robotic missions to Mars (on the surface as well as in orbit) are expected to increase in number, followed by dramatic increases in the data rates/volumes that will be needed in the era of Mars human exploration. This paper provides recommendations for a next-generation Mars relay orbiter to begin the process of replenishing the existing network, providing relay support to both surface and orbital relay service users in the future. It suggests capabilities that could be implemented in a single future orbiter, rather than representing a set of capabilities that could be supported by a constellation of orbiters. However, the idea of follow-on orbiters was considered.

I. Introduction

A. Motivation

This report provides a recommendation for a next-generation Mars relay orbiter mission to begin the process of replenishing the existing network and laying the groundwork for additional capabilities to be sent to Mars thereafter. It suggests capabilities that should be implemented in a single future orbiter, rather than representing a set of capabilities that could be supported by a constellation of orbiters. However, the idea of follow-on orbiters was kept in mind, and it is noted throughout this report when more than one orbiter could enable enhanced capability. The development of this report was funded by the Mars Exploration Program (MEP) at the Jet Propulsion Laboratory (JPL).

Today's Mars Relay Network (MRN) represents a highly successful international collaboration between NASA and the European Space Agency (ESA). As of this report's writing, the MRN consists of five heterogenous set of five science orbiters, launched over

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

the past few decades, including NASA's Mars Odyssey (ODY, 2001), Mars Reconnaissance Orbiter (MRO; 2005), and Mars Atmosphere and Volatile Evolution (MAVEN; 2016) orbiters, as well as ESA's Mars Express Orbiter (2003) and ExoMars Trace Gas Orbiter (TGO; 2016).

In the years ahead, the current MRN topology is expected to change significantly. Robotic missions to Mars (on the surface as well as in orbit, and as contributed by NASA, ESA, other nascent space agencies, and even private industry) are expected to significantly increase in number. Furthermore, on the horizon are dramatic increases in the data rates/volumes that are expected to be needed in the era of Mars human exploration.

The pace of evolution of the MRN is throttled by a variety of factors, including an ongoing need to support existing missions; the long lead time between mission formulation, design, implementation, and then launch and operations; and uncertainty in the budget environment in which new missions can be realized. Given these factors, changes to the overall architecture are expected to take a significant amount of time to take effect. Ultimately, the objective is to implement communications capabilities at Mars that are analogous to those supported by space systems at Earth; however, this will take significant time and resources to realize.

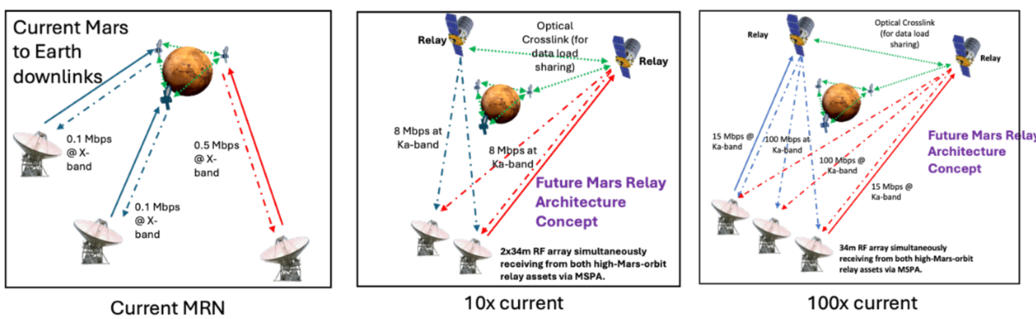


Figure 1. Typical MRN data rates are 0.1–0.5 Mbps at Mars' furthest distance (2.7 astronomical units [AUs]). In the 2030s, a pair of Ka-band dedicated relays could establish a trunk line to Earth and improve Mars science return by 10× utilizing existing Deep Space Network (DSN) capabilities and moderate spacecraft telecom subsystem advances. In the 2040s and 2050s, 100× increases could be achieved. [1]

As the existing orbiters in the MRN are well into their extended missions, their ability to continue to provide relay services into the next decade is in doubt. New orbiters are being formulated by a variety of organizations, in part to address the needed replenishment of the MRN.

Isolating the recommendation to capabilities that can be achieved by a single orbiter is intentional, given the historical difficulty of implementing any orbiter at Mars. In addition, the recommendation focuses on capabilities that are already mature as represented by existing space missions, are known to be forthcoming, or require what are thought to be minimum investments to achieve. To that end, this recommendation does not suggest a fully formed nor fully capable network, as suggested by [2], but, instead, one that is a smaller augmentation on what is already at Mars, leading toward a more capable future.

Each aspect of the recommendation is outlined briefly below, and the subsequent sections detail each of these aspects and their rationale.

B. Recommendation

Table 1 summarizes the recommendations, outlining where within this document each area of the recommendation is addressed. The recommendations are further summarized in the remainder of this section, with full detail in subsequent sections of this document.

Table 1. Summary of recommendations.

Recommendation	Note	Addressed in Section
1. If PNT is not a driver: 500–1000 km altitude orbit, inclines at whatever serves use base best **2. If good PNT is a driver: 1500–2000 km altitude, 50–60° inclined orbit**	Altitude maximizes data throughput for low-power users (including orbiting users), while inclination facilitates PNT capability.	II, IV
Proximity link frequency: UHF (omni) and K/Ka-band (directed)	UHF is for backward compatibility and for future low-capability users. K/Ka-band is for higher bandwidth, enabling higher data rates.	III
Using Ka-band on links with Earth	This moves away from X-band, which is congested.	III
PNT using radiometric measurements over proximity link	To achieve 10-m, 3-sigma position and 1-cm/s, 3-sigma velocity uncertainty. Not a beacon-oriented nav capability (i.e., not GPS).	IV
Stable atomic clock for PNT performance	HPAC currently in development provides GNSS-class signal-in-space errors near 1 m.	IV
Proximity-1 (heritage and updated) and USLP (next-gen)	This leans toward new protocols to support high data rates.	III
Support for multiple relay users at the same time	Presently, the MRN only provides access to one user at a time in a single footprint.	III
Science opportunities that augment previous investigations	MEP is a Science Mission Directorate organization, after all.	V
Expandability—future orbiters enhance capability	This recommendation highlights what could go to Mars next, as the first element of an intentional build-up.	IV
Software-defined architecture	Allows for software-defined, follow-on capabilities to be deployed post-launch.	III
Add-on Capabilities (could be implemented post-launch)	**Notes**	
DTN	This is not demanding DTN right away but instead suggests a DTN-ready implementation.	N/A
Cross-links between orbiting assets	Does not dedicate frequency bands for cross-links, but future orbiters could cross-link if using compatible frequency bands.	N/A

NOTE: PNT = positioning, navigation, and timing. UHF = ultra-high frequency. HPAC = High-Performance Atomic Clock. GNSS = global navigation satellite system. USLP = Unified Space Data Link Protocol. DTN = delay-tolerant networking.

1. Choice of Orbit

In the choice of orbit for a Mars relay orbiter, the drive for high data volume (DV) return is stacked against user access (access frequency, duration, and gaps) and requirements for providing position, navigation, and timing (PNT) services over the proximity link to relay service users. If there are no requirements to provide PNT service, then a 500–1000 km altitude orbit is recommended with an inclination that best supports the expected user base.

If PNT service over the proximity link is required in the next Mars relay orbiter, a 1500–2000 km altitude circular orbit is recommended at an inclination that supports surface users at any latitude. At an orbit altitude of 1500 km, an inclination of 53° provides pole-to-pole coverage. Additionally, at an orbit altitude of 2000 km, an inclination of 54° provides sufficient PNT performance while placing the orbiter in a possible constellation of orbiters that could support enhanced PNT capability (see Section IV for details on PNT).

The choice of orbit is further discussed in Section II.

2. Telecommunications Capability—Proximity Links

The use of ultra-high frequency (UHF) is recommended in the next Mars orbiter to maintain backward compatibility with existing Mars assets; it is also the best frequency band for future low-power users. In addition to UHF, the use of K/Ka-band is recommended to provide significantly more bandwidth compared to UHF, over 130 times more, which enables far higher data rates over the relay link.

The Consultative Committee for Space Data Systems (CCSDS) Proximity-1 protocol is still expected to be used over UHF and K/Ka-band, and the software-defined architecture of this recommended platform allows for the Unified Space Data Link Protocol (USLP) to be implemented. USLP removes the Proximity-1 constraints on frame sizes and data rates, which will increase link efficiency and utilize the greater bandwidth that K/Ka-band provides.

Additionally, the next Mars relay orbiter should have capability for providing relay services to at least two assets simultaneously. The use of a software-defined spacecraft architecture and the inclusion of K/Ka-band relay enables this with a larger available bandwidth.

Telecommunications capability on proximity links is further discussed in Section III.

3. Telecommunications Capability—Links with Earth

To support the increased DV to/from Mars from a larger number of users, it is recommended to use Ka-band for direct-to-Earth link (downlink) with the option of using either X-band or Ka-band for the direct-from-Earth (uplink). There is also an option for using optical communication, which has already been demonstrated at Earth–Mars distances, if data rates higher than those achievable at Ka-band are required. Optical communication should be used as an augmentation—not a replacement—to RF links with

Earth due to optical links being more susceptible to weather-based outages at ground stations, resulting in missed communications passes with Earth.

Telecommunications capability on Earth links is further discussed in Section III.

4. Position, Navigation, and Timing

An ideal PNT orbit solution is one that provides two-way and one-way range and Doppler tracking with the greatest geometric diversity in the shortest amount of time. For surface localization, this naturally pushes orbit selection to higher altitudes and with multi-satellite constellations that can provide multi-fold simultaneous coverage (for instance, the global positioning system [GPS] constellation provides continuous, global four-fold coverage from a 12-hour circular orbit). This contrasts with data relay prioritization, which has increased data rates for lower altitude orbits relative to higher altitude ones. In the current study, with priority being given to data relay, and PNT playing a supporting role, a single satellite orbit near 2000 km in a circular, 54° inclination orbit provides the best overall surface positioning performance across all latitudes and at the lowest altitude. Furthermore, if this single orbiter were to be the first member of a global continuous-coverage constellation, that constellation would conform to a Walker 14/7/4 configuration with 14 total satellites in 7 equally spaced orbit planes (hence, two satellites per plane). Finally, in addition to two-way tracking service (which would be primary), this orbiter can also offer high-quality, one-way radiometric tracking services to surface and orbiting users if it is manifested with a stable atomic clock (such as the High-Performance Atomic Clock [HPAC] currently in development) so that it could provide global navigation satellite system (GNSS) class signal-in-space errors near 1 m.

Position, navigation, and timing are further discussed in Section IV.

5. Science Opportunities

A spacecraft placed in either of the recommended low Mars, circular orbits (either 500–100 km or 1500–2000 km altitude) offers the opportunity to conduct a range of high-priority science investigations that address key knowledge and data gaps in our understanding of the Martian environment. These investigations, as prioritized by the Mars science community, would further help reduce entry, descent, and landing (EDL) and surface operations risks for both future robotic and human explorers at the Martian surface. While remaining relatively close to the surface, but beyond the range of low Mars orbits, a precessing orbit provides valuable time-of-day coverage of both the surface and atmosphere, providing unique views of the Martian environment. Further, altitudes in the recommended range fall within a particularly useful band for studying the upper atmosphere and how it interacts with the solar wind. A variety of high-heritage, lower cost payloads suitable for these orbits have been assessed and are available to maximize the value of a future MRN.

Possible science opportunities are further discussed in Section V.

II. Orbit

The choice of orbit for a Mars relay orbiter is a fundamental trade-off between competing mission priorities: 1) maximizing proximity data throughput, 2) optimizing access, and 3) ensuring consistent PNT services. Maximizing data throughput favors lower orbital altitudes to minimize communication range, while achieving robust, globally uniform PNT services and access continuity favor higher altitudes (but too high of an altitude, such as areostationary, diminishes the utility of a single relay and requires a multi-satellite constellation to be useful for surface positioning) with specific inclinations. The orbital parameters (altitude, inclination, and eccentricity) determine the period, surface visibility, eclipses, and occultations that ultimately dictate the line-of-sight (LOS) access duration, frequency, gaps, and, most importantly, the range to both surface and orbital users.

A. Orbit Types for Telecom

In support of this effort, over 150 potential orbits were studied to characterize multiple aspects of telecom performance. The Telecom Orbit Analysis and Simulation Tool (TOAST) [3] was used to analyze the orbital access and data return characteristics over a wide range of orbits and users, both on the surface and in orbit. Assumptions were made to characterize the telecom subsystem/sizing of the relay orbiter and the relay user, operational constraints, and elevation mask. The nature of these assumptions, along with the subjective relative importance of performance parameters (point to figure of merit [FoM] below) ultimately determine which orbits are “best.”

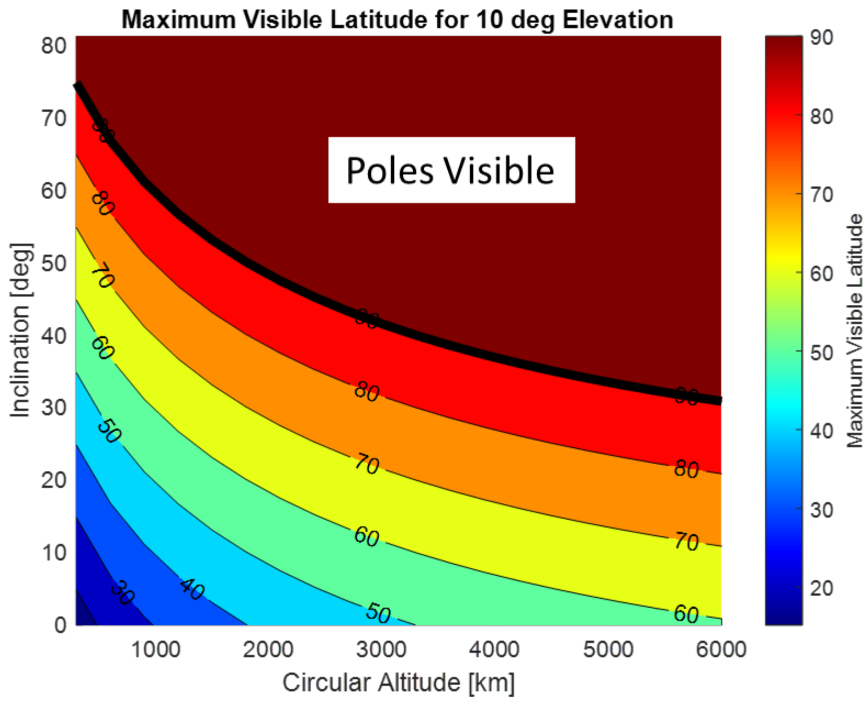
Potential orbits for telecom relay can be broken down into three main families:

1) **Circular Orbits:** Ranging from low to high altitude, and equatorial to polar inclination.

2) **Elliptical Orbits:** Incorporating varying eccentricities and orientations.

3) **Special Orbits:** Those with specific, fixed properties such as repeating ground tracks (RGT), Sun-synchronous (SS), apoapsis constant critically inclined (ACCI), and areostationary/areosynchronous (AREO).

As a rule, orbits that provide full surface access to all latitudes are preferred. Maximum latitude visibility increases with both inclination and altitude, but full polar coverage leads to an inverse trade between the two—higher altitudes can compensate for lower inclinations, and vice versa. With a 10° elevation mask applied, Figure 2 shows the maximum latitudes visible with the given inclination and altitude for circular orbits. Orbits above the black line, with inclinations ranging from 75° at 300 km all the way down to 20° at 17,000 km (not shown), provide visibility of the poles. The accompanying table in Figure 2 shows the minimum inclination needed at each altitude to ensure global visibility.



Altitude (km)	Minimum Inclination (deg)
300	75
500	70
1000	60
1500	53
2000	49
3000	42
5000	34
10,000	25
17,000	20

Figure 2. Pole visibility vs. orbiter inclination:
Top) Maximum visible surface latitude from circular orbits given altitude, inclination, and a 10° elevation mask.
Bottom) Table of the minimum inclination required at each altitude needed to see the poles.

By applying the ground rule of providing polar access, the orbits considered were reduced to the seven orbit types in Table 2. This grouping admittedly does not include all orbits, as evidenced by gaps between the orbit types, but it does provide a framework to gather the key features of each family, along with their pros and cons with respect to a telecom orbiter.

Table 2. Types of orbits considered for telecom relay—
Blue: circular orbits out to 6000 km, broken down by altitude and inclination,
Yellow: special elliptical orbits with fixed properties, and Green: areostationary/areosynchronous orbits.

Orbit Type	Altitude (km)	Incli. Range (deg)	Period (hrs)	Notes
1) Low Circular	300–800	75–94	1.9–2.2	Most common orbit for remote-sensing science missions. Provides the highest data rates but has the shortest passes.
2) Mid Circular	1000–3000	45–105	2.5–4	Less common medium-altitude orbits that represent a trade between range, PNT support, and access.
3) High Circular	4000–6000	30–90	5–8	Higher circular orbits that provide greater accessibility with longer passes but significantly lower data rates.
4) Elliptical Sun Synch	200 × 400–12,000	92–110	2–8	Range of orbits of increasing ellipticity at a Sun-synchronous inclination with low 200-km periapsis. Integer number of orbits per sol allows for repeating ground tracks.
5) Triple Synchronous	200 × 11,420	116.6	7.4	Unique orbit that is Sun-synchronous, has a repeating ground track, and a fixed apoapsis at critical inclination.
6) Apo-Constant Critically Inclined	940 × 8500	63.4	6.2	ACCI is critically inclined to have periapsis fixed over a desired latitude; this version has 4 orbits per sol.
7) Areostationary	17,031	0	24.8	Analogous to geosynchronous. Fixed over given ground point, could include some inclination (i.e., areosynchronous). Fixed view of one hemisphere. Very low data rates.

B. Discussion of the Effects of Orbital Characteristics on Relay

Circular orbits are advantageous for telecom relay because they provide consistent and repeatable coverage for both surface and orbital users. Ground tracks are uniformly spaced and can be designed to be repeatable (using combinations of specific altitudes and inclinations), which gives regularity to comm passes to ground-based users. Lower orbits (<600 km) provide the shortest ranges to the surface and are commonly desired for remote-sensing science missions. For this reason, it is likely to be synergistic to combine relay functionality in these lower orbits on missions with science instruments that require surface proximity. Historically, relay functionality has been added to science missions, most of which have been in low Mars orbit (e.g., MRO, Mars Global Surveyor [MGS]).

Orbital altitude exerts the greatest influence on telecom relay performance. The primary effect is range, which governs achievable data rates and volumes through the inverse-square dependence on distance. At lower altitudes, shorter visibility windows and longer gaps between passes limit contact opportunities, although the achievable data rate is higher due to shorter ranges. Higher altitudes provide broader surface coverage and significantly longer contact durations, but at the expense of reduced data rates and the need for extended passes to achieve equivalent DVs [4]. For relay back to Earth, lower altitude Mars orbits may experience extended occultations, up to ~40 minutes in a

2-hour orbit, depending on the orbit plane orientation relative to Earth. Higher orbits remain subject to occultation, but for a smaller fraction of the orbital period.

Inclination primarily determines the range of latitudes accessible from a relay satellite. Higher inclinations enable observations and communications over broader latitude bands and improve navigation and positioning determination by providing out-of-plane geometry. High-inclination orbits, including polar and Sun-synchronous, offer dense coverage at high latitudes but relatively sparse coverage near the equator. In contrast, mid-inclination orbits that still reach the poles provide a more balanced distribution of coverage across high, mid-, and low latitudes, providing equal access for lower latitude users.

Sun-synchronous orbits maintain a fixed beta angle (the angle between the Sun and the orbital plane) and provide communication opportunities for surface assets at consistent local solar times each orbit. This repeatable illumination and geometry simplify concept-of-operations planning and scheduling for both relay and surface activities. Elliptical Sun-synchronous orbits, particularly those with high apoapses, preserve a constant beta angle but introduce variations in local solar time of surface contacts, which can differ by several hours depending on the spacecraft's position in orbit. These orbits also exhibit greater variability in range and geometry during each pass, which must be considered in link and operations planning. As a secondary effect, changes in time-of-day coverage may be beneficial or detrimental to the orbital science conducted by the spacecraft.

Apoapsis at constant time-of-day critically inclined orbit, which occurs at an inclination of 63.4°, exploits Mars's oblateness to maintain a fixed orientation of the line of apsides, preventing the natural precession of an elliptical orbit. These retrograde orbits can be used to keep the apoapsis positioned over a specific site at a constant time of day, allowing the relay satellite to dwell longer over specific regions while maintaining regular close passes over others. This geometry can be advantageous for supporting surface assets located at known latitudes. However, data rates are reduced when the spacecraft is near apoapsis due to the increased range from the surface.

Areostationary orbits, analogous to Earth's geostationary orbit, are attractive for telecommunications because a spacecraft in this orbit remains fixed relative to the Martian surface and is visible from most of the hemisphere. Surface assets can treat the relay satellite much like a terrestrial ground station, using their direct-to-Earth (DTE) antennas. However, the large orbital radius (~17,000 km) results in long communication ranges that reduce data rates by three orders of magnitude compared to low Mars orbit and makes UHF links to the surface impractical. An areostationary satellite provides visibility up to roughly ±70° latitude. To extend coverage to the poles, an inclination of about 20° would be required, but introducing inclination (i.e., areosynchronous) causes the satellite to trace a figure-eight pattern rather than remain fixed. Achieving near-global coverage would typically require a constellation of three to four areostationary satellites.

Constellations of relay satellites can provide continuous or near-continuous coverage. Future users at Mars, including crewed missions, may require continuous comms and GNSS services only available through a global constellation. By phasing multiple satellites in complementary orbits, communication gaps can be minimized, and simultaneous support can be maintained for assets at different locations or latitudes. Global constellations may consist of satellites at a single altitude and multiple planes (e.g., Walker constellations) or combine low-altitude relays for high data rates with higher altitude elements for extended visibility, achieving a balance between link performance and coverage continuity. The potential build-up from one relay satellite to a future constellation should be considered when choosing the first orbit.

C. Orbit Analysis

Telecom Orbit Analysis and Simulation Tool: TOAST is a JPL-developed software that was used to generate line-of-sight contacts and telecom predicts between the relay orbiters and users. Simulations span a time period of 126 sols (sufficiently long to assess performance and trends) with a temporal resolution of 10 seconds and use a 10° elevation mask to assess visibility.

Relay Satellite Orientation: Our simulation assumes the apsidal line passes through the prime meridian at the equator with the argument of periapsis of zero.

Surface User to Relay Satellite: To get a unique quantitative value for a metric between a surface user and a relay orbiter, surface users are assumed to be situated along a longitude with latitudes varying from –90° to 90° at increments of 1°. The average for each metric is calculated as an area-weighted average,

$$M = \sum_{\lambda=-90^\circ}^{\lambda=90^\circ} M(\lambda)\cos(\lambda) \Bigg/ \sum_{\lambda=-90^\circ}^{\lambda=90^\circ} \cos(\lambda) \qquad \begin{matrix} \lambda \text{ is the latitude} \\ M(\lambda) \text{ is the metric average at } \lambda \end{matrix}$$

Orbital User to Relay Satellite: Orbital users are assumed to be in 400-km circular Sun-sync orbits. However, since the relay satellite's ascending node could be precessing, orbital users are assumed to be at three different rising ascending nodes (0°, 45°, and 90°) to capture the possible seasonal contact variability. Each orbital metric is averaged over the three orbits and time.

Note that other potential orbits of higher altitudes, especially elliptical, would produce a different set of results that are highly dependent on the specific attributes of any given orbit and are beyond the scope of this study. However, the access trends between relay orbiter locations and potential users are likely to be similar to the results from 400-km users.

Direct-with-Earth (DWE) Communications: These metrics assess the maximum percentage duration for which the relay satellite is out of view of Earth.

Relay Satellite Performance Metrics: The simulation generated the following contact metrics:

1. **Surface User Metrics:** Number of passes per sol, total contact time per sol, in-view range, maximum communication gap, max latitude of coverage, and number of 10-minute passes per sol.

2. **Orbital User Metrics:** Number of passes per sol, total contact time per sol, in-view range, maximum communication gap, and number of 30-minute passes per sol.

3. **DWE Metrics:** Maximum Earth occultation duration and maximum Earth occultation percentage (occultation duration / orbital period).

Figures 3 and 4 display heat maps, where each map shows a metric's performance across the relay orbiter candidates. The candidates are specifically limited to a perfectly uniform grid of circular orbits, defined by eight altitudes (500 km to 6000 km) and nine inclinations (10°, 20°, ..., 90°). Isolated, non-grid candidates were not evaluated. The performance of these metrics is color-coded, with unfavorable performance indicated by red and favorable performance by green. The heat maps reveal performance trade-offs; a region favorable for one metric may be unfavorable for another. For instance, while the number of passes per sol is maximized in the low-altitude / high-inclination region, the total contact time shows the opposite trend.

Combining Relay Satellites' Performance Metrics: Rather than assessing relay satellite performance through numerous individual metrics, we simplify the evaluation by defining a few critical FoMs. These three influential FoMs—data throughput, user access, and DWE communications—are discussed and generated below. The FoMs are normalized by their respective maximum values so that the most favorable performance is assigned a value of one. This normalized value is consistently plotted in green, mirroring the representation used for the individual metrics (Figures 3, 4, and 5). Each FoM plot also includes a dashed curve (in blue) that specifies the minimum orbital altitude and inclination angle required for the orbiter to provide relay support to surface users at the poles, assuming a 10° elevation mask.

1. **Proximity Telecom:** This FoM represents the DV between the relay satellite and its users. It is generically represented as the ratio of the total contact time to the average of the square of the in-view range. This formulation yields a standardized value equivalent to the DV but is notably independent of specific frequency band and telecommunication configuration. To ensure global telecommunication support for surface users, the overall proximity FoM also integrates the maximum latitude of coverage metric. Consequently, orbiters capable of servicing both poles are ranked more favorably. The mathematical formulation for this proximity telecommunication FoM is defined as:

$$\mathrm{FoM}_{\mathrm{Telecom}}^{\mathrm{Proximity}}\,\text{for Surface User} = \mathrm{Time}_{\mathrm{in-view}}/\mathrm{Range}_{\mathrm{in-view}}^{2} \cdot \mathrm{Coverage}_{\mathrm{Latitude}}^{\mathrm{Max}}$$

$$\mathrm{FoM}_{\mathrm{Telecom}}^{\mathrm{Proximity}}\,\text{for Orbital User} = \mathrm{Time}_{\mathrm{in-view}}/\mathrm{Range}_{\mathrm{in-view}}^{2}$$

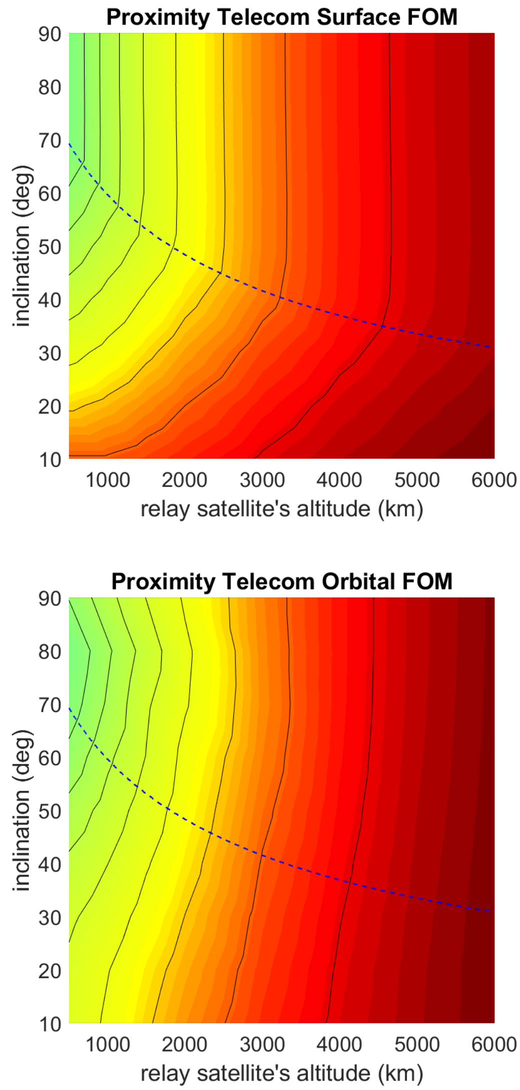


Figure 3. Proximity telecom FoM. The normalized DV metric is shown for all surface users (top) and orbital users (bottom). The dashed line represents the region above which the poles are visible with a 10° elevation mask.

2. **Relay Access:** The relay access FoM reflects the overall contact quantity between users and the relay satellite. For surface users, it is calculated as the product of the number of contacts per sol, the total contact time, the reciprocal of the communication gap, and the latitude of coverage. This design choice gives inclined orbits a higher score because they offer superior pole-to-pole accessibility. Beyond contacts, this FoM is also a strong indicator of navigation performance by rewarding more frequent, longer, and geometrically diversified contacts.

   The access FOM incorporates the number of passes per sol to prioritize orbits that offer multiple connectivity throughout the day. This metric is particularly critical for surface assets requiring high-cadence support—such as Mars Sample Return (MSR) or autonomous rovers—which rely on consistent PNT updates for safe and effective self-navigation.

For orbital users, the FoM for access is simply the average contact time per sol. Other standard metrics, such as the total number of contacts per sol and the maximum communication gap, were intentionally excluded from this specific calculation. This exclusion was primarily due to two factors: the seasonal effects of orbit precession and the limitations of the short simulation time span. Nevertheless, the average contact time per sol remains a reliable and robust metric for evaluating relay access performance for orbital assets.

$$\mathrm{FoM}_{\mathrm{Access}}^{\mathrm{Relay}} \text{ for Surface User } = \mathrm{Number}_{\mathrm{contacts}} \cdot \mathrm{Time}_{\mathrm{in-view}} / \mathrm{Gap}_{\mathrm{in-view}}^{\mathrm{max}} \cdot \mathrm{Coverage}_{\mathrm{Latitude}}^{\mathrm{Max}}$$

$$\mathrm{FoM}_{\mathrm{Access}}^{\mathrm{Relay}} \text{ for Orbital User } = \mathrm{Time}_{\mathrm{in-view}}$$

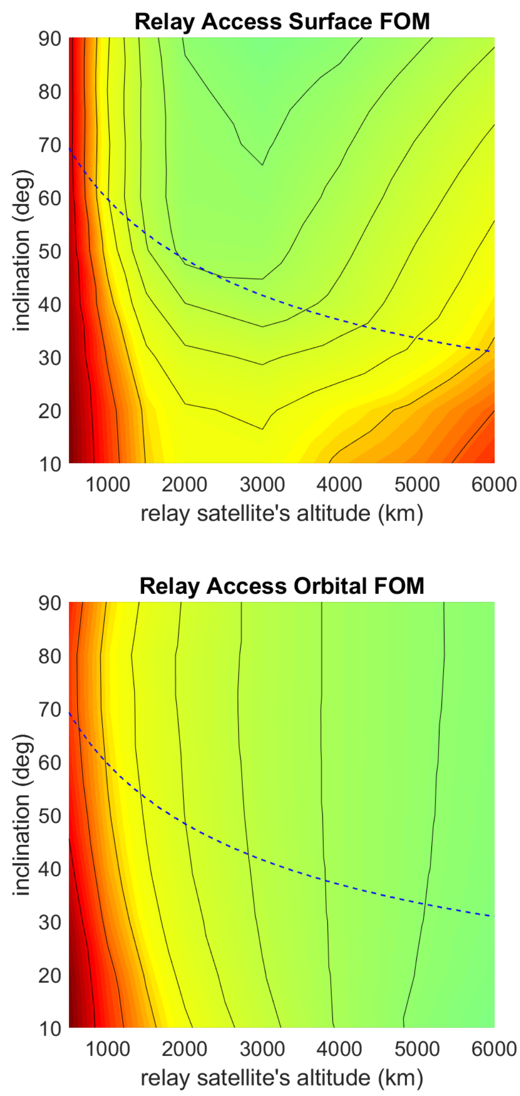


Figure 4. Relay access FoM. The normalized access metric is shown for all surface users (top) and orbital users (bottom). The dashed line represents the region above which the poles are visible with a 10° elevation mask.

3. **DWE Telecom:** A key factor for achieving excellent DWE communications is ensuring the relay satellite spends a minimal percentage of time occulted (hidden) behind Mars:

$$\mathrm{FoM}_{\mathrm{DWE}} = \mathrm{Duration}_{\mathrm{Occult}}^{\mathrm{max}} / \mathrm{Period}_{\mathrm{satellite}}^{\mathrm{relay}}$$

   Due to the constraints of our simulation—specifically, the 126-sol duration limit and the unspecified satellite orientation—we rely on the theoretical maximum occultation duration derived through a geometric model. This maximum duration represents the worst-case scenario, occurring when the satellite passes directly behind the center of Mars relative to Earth. Consequently, an eccentric satellite orbit would experience larger occultation duration because the satellite, moving at its slowest velocity near apoapsis, spends a proportionally longer time traversing the region where occultation is geometrically possible.

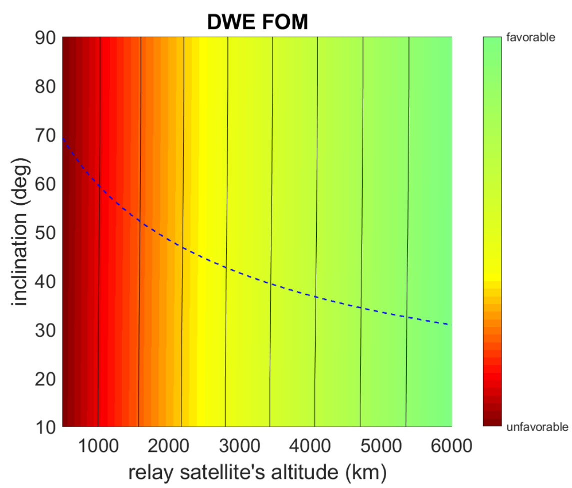


Figure 5. DWE FoM. It is directly correlated with the percentage of each orbit that could be occulted from the Earth in the worst-case orientation. Higher orbits could have longer occultations but are lower in percentage of total orbit.

A Single Representative FoM: These five crucial FoMs (for both orbital and surface users) were aggregated using a weighted formulation to generate a single representative value for decision making.

$$\mathrm{FoM}_{\mathrm{Combined}} = \sum_{i=1}^{5} W_i \, \mathrm{FoM}_i,$$

$$\mathrm{FoM}_1 = \mathrm{FOM}_{\mathrm{Telecom}}^{\mathrm{Proximity}}(\mathrm{surface}), \mathrm{FoM}_2 = \mathrm{FOM}_{\mathrm{Access}}^{\mathrm{Relay}}(\mathrm{surface}),$$

$$\mathrm{FoM}_3 = \mathrm{FOM}_{\mathrm{Telecom}}^{\mathrm{Proximity}}(\mathrm{orbiter}), \mathrm{FoM}_4 = \mathrm{FOM}_{\mathrm{Access}}^{\mathrm{Relay}}(\mathrm{orbiter}), \mathrm{FoM}_5 = \mathrm{FOM}_{\mathrm{DWE}}.$$

Detailed performance indicators are available across all domains (telecom, access, and DWE), yet the final selection of an optimal relay orbit is ultimately a trade-off. This is because the FoM for telecom favors inclined, low-altitude orbits, which conflicts with the

FoM for access and DWE, which prefer similarly inclined, but higher, altitudes. The "best" choice is thus subjective, depending on how specific mission criteria are weighed.

To pursue a more balanced FoM that satisfies both telecom and access needs for orbital and surface users, it is necessary to consider the relative weighting of the five FOMs, which themselves have been normalized over a range of parameters to indicate favorability. This weighting is subjective, based on the value attached to data rates, access, users, etc. Also, the relative ranges between what is deemed "favorable" vs. "unfavorable" across the FoMs vary and must be normalized through relative weighting as well. A combined FoM was created that equally considers the value of proximity telecom vs. access and orbital vs. landed users. DWE FoM is weighted lower due to its small dynamic range and relative importance.

Figure 6 illustrates that the highest overall FoM is attained in the orbital zone spanning 1000 to 3000 km in altitude and 55° to 80° in inclination. Although increasing the weighting on the DWE FoM moves the optimal solution to higher altitudes, this trade-off significantly reduces the telecom FoM, thereby undermining the relay's core function. Therefore, the designated optimal region remains stable, provided the telecom and access criteria are prioritized in the weighting. Furthermore, the regions above the line offer the advantage of guaranteed global coverage, which was established early in the investigation as required to cover any future user.

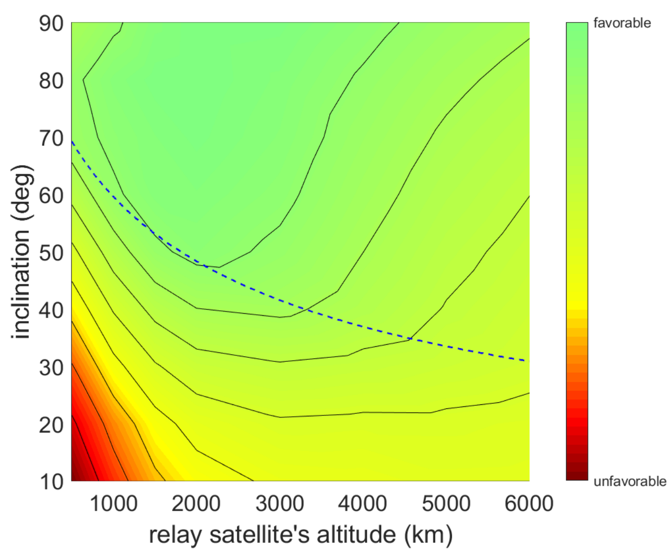


Figure 6. Combined FoM. Each of the five previous FoMs (proximity telecom for orbit and surface, relay access for orbit and surface, and DWE) are combined on a normalized scale to indicate orbital parameters that are more favorable. The dashed line represents the region above which the poles are visible with a 10° elevation mask. This formulation broadly indicates that the more favorable telecom orbits lay between 1000 and 3000 km and higher inclinations.

Orbit Evaluations and Recommendation: Even with detailed orbital and telecom performance analyses in hand, the selection of a "best" telecom orbit is ultimately subjective. So much depends on assumptions, FoM weighting, use cases, and trade-offs. Table 3 shows a color-coding scheme for the relative utility of orbits for telecom across the various FoMs. No orbit is “green” in every category, leading to trade-offs and relative weighting to select an orbit.

Table 3. Relative utility of orbit families for Mars telecom. The coloring (and number coding, with 1 being the worst and 10 being the best) is subjective based on the range of orbits in the orbit family for each of the FoMs evaluated for an averaged performance. The PNT column is included here as an important factor but is discussed in detail in Section IV.

	Orbit Family	Telecom	Access	DWE	PNT
1	**Low Circular** Altitude: 300–800 km Inclination: 70–95° (SS)	10	4	6	6
2	**Mid Circular** Altitude: 1000–3000 km Inclination: 50–90°	7	8	8	10
3	**High Circular** Altitude: 4000–6000 km Inclination: 35–90°	3	9	9	8
4	**Low Elliptical (ESS)** 200 × 800 km × 93° (apo 800-1800 km)	8	5	7	6
5	**High Elliptical (3SEO)** 200 × 11420 km × 116° (triple synchronous)	3	7	8	6
6	**ACCI** 940 × 8500 km × 63°	5	7	9	7
7	**Areostationary** 17,031 km × 0°	2	7	10	1

Best
10
9
8
7
6
5
4
3
2
1
Worst

Non-Selected Orbit Types

Low Circular and Equatorial Orbits: Low, near-equatorial circular orbits were not selected due to their limited latitude coverage and short-duration contact opportunities. While such orbits offer high data rates because of their proximity to the surface, they can only support assets within a narrow equatorial band and require a large number of satellites to achieve continuous coverage. Even with high inclination and polar access, the frequent Earth occultations and short visibility windows make them less efficient for Mars-wide relay service.

High Circular Inclined Orbits (4000–6000 km): High circular orbits were not selected despite their favorable geometry for surface access, Earth visibility, and potential support to PNT functions. At these altitudes, the relay can view a large portion of the planet and maintain long-duration passes with surface assets. However, the increased range significantly reduces achievable data rates and overall DVs, even when high-gain antennas (HGAs) and higher frequency bands are considered. This degradation in link performance outweighs the geometric advantages, making such orbits less effective for high-throughput relay operations compared to lower altitude alternatives.

Low Elliptical Sun-Synchronous (ESS) Orbits: Elliptical Sun-synchronous orbits were not selected primarily due to their performance being worse than comparable circular orbits. While they can maintain a constant beta angle, the local solar time of surface contacts does vary throughout an orbit. Their high apoapsis introduces a greater average range to surface assets, resulting in data rate reduction, which outweighs the benefit of lengthened contact times near apoapsis. Additionally, these orbits introduce significant variability in the geometry of each pass, which adds complexity to link and operations planning.

Highly Elliptical and Frozen Orbits (Triple Synchronous and ACCI): Highly elliptical orbits, such as the triple synchronous and ACCI orbits, were not selected due to their overall poor performance in the DV FoM. While the ACCI orbit can be configured to maintain a fixed line of apsides, allowing the relay satellite to dwell longer over a specific surface region at a constant time of day, this advantage is offset by the significantly reduced data rates that occur due to the increased range at apoapsis. These orbits also offer less competitive overall scores across the various FoMs for telecom and access compared to the recommended circular orbits.

Areostationary and Areosynchronous Orbits: Areostationary orbits were not selected for primary relay service due to their high altitude and resultant long ranges, which drive large power and antenna size requirements for both the relay and surface terminals. UHF links are infeasible at these distances, and while higher frequency bands could be used, link budgets remain challenging for small surface assets. A full constellation of three to four spacecraft would be required for global coverage, significantly increasing cost and operational complexity.

Selected Orbit that Fit the Most Needs

The trade space analysis resulted in two distinct orbital types that best satisfy the mission requirements, depending on the prioritization of DV versus PNT. Both options prioritize high data throughput, which remains the most important role of the relay network.

If maximizing DV is the sole priority, with PNT and access treated only as a best-effort, opportunistic service, the optimal choice is an inclined low Mars orbit between **500 and 1000 km** in altitude. The proximity link to the surface ensures the highest possible data rates. For inclination, the selection should be based on maximizing coverage for the primary user base, noting that orbits with higher inclination and/or closer to the 1000 km upper bound offer better options for achieving pole-to-pole coverage.

However, if providing robust DV while still enabling high-quality, operational PNT services is required, the best trade-off resides in **circular orbits in the 1500–2000 km altitude band**. This slightly higher altitude still achieves competitive data rates while significantly improving the geometric visibility required for PNT localization. For this regime, we recommend specific, critically optimized inclinations: a 1500-km orbit at 53° inclination, which provides the most uniform pole-to-pole coverage, or a 2000-km orbit at 54° inclination, which is ideal for a stable, global Walker constellation configuration. These orbits represent the optimal balance between communications performance and navigational support.

III. Telecommunications

The primary driver for any spacecraft providing relay service is to transfer the most amount of data to and from Earth, and this recommendation is no different. Pushing the envelope for DV transfer should be the aim for the next Mars relay orbiter to support increased presence at Mars and eventual human exploration of the planet. The following section details the recommended telecommunications platform to support both Earth and proximity links. This platform can be applied to any spacecraft, with the specific choice of telecom hardware components left to the needs of the mission and relay service users at Mars. A detailed spacecraft telecom point design is not presented; rather, the selection of frequency bands and possible hardware selection that can increase DV return to Earth and forward to Mars to support missions in the coming decades is provided.

In this section, for proximity links, the return link refers to the transfer of data from Mars assets to the relay orbiter, and the forward link refers to the transfer of data from the relay orbiter to Mars assets. The term “proximity” and “relay” can be used interchangeably. For links with Earth, or DWE links, downlink or DTE refers to the transmitting of data from the relay orbiter to Earth-based ground stations via the telecom link and uplink or direct from Earth (DFE) refers to the transmitting of data from Earth-based ground stations to the relay orbiter via the telecom link. In this way, for a relay orbiter, there are two sets of links. Links with Earth, consisting of a downlink and an uplink, and proximity links, consisting of a return link and a forward link.

A. Proximity Telecom

1. Frequency Band Selection for Proximity Link

The Space Frequency Coordination Group (SFCG) acknowledges that those designing Mars missions could choose to use a variety of frequency bands for proximity links and provide recommended frequency bands for proximity links at Mars, all within the traditional bands allocated for space telecommunications (UHF, S-band, X-band, and K/Ka-band).

The existing orbiters in the MRN all operate relay links within the UHF band, 390–405 MHz for the return link and 435–450 MHz for the forward link. This is the lowest frequency band in the recommended set of bands for space telecommunications. In any telecommunications link, distance is the biggest enemy of data throughput. A low frequency of transmission results in links with low space loss, that is, the attenuation of the radio-frequency (RF) signal traveling through space. This means that a relay service user requires less RF power, and thus direct-current (DC) power, to overcome space loss to the orbiter, enabling the return of high DVs. Omnidirectional antennas are ideal for relay with low-power relay service users that do not have the resources to point directional antennas. The ability to overcome relatively low space loss while using relatively low-power telecom components makes UHF for relay links an obvious choice for many types of relay service users.

It is recommended that the next Mars relay orbiter support relay links over UHF, just as the existing MRN does. This facilitates backward compatibility with all existing Mars assets and enables relay service on par with the performance achieved today, especially with low-power relay service users that are unable to spend large amounts of DC power on high-power amplifiers or directional antennas.

However, looking toward the future of Mars relay with a greater number of users needing more DV transfer than is currently achievable, the available bandwidth at UHF would quickly become limiting. UHF allocates a 15-MHz bandwidth for the return link and another 15 MHz for the forward link. Under the set of modulation and coding schemes that the MRN currently uses for relay, a data rate of ~2 Mbps from a single user fills up nearly this entire allocation with its transmitted signal. In the early days of the MRN, this was acceptable given the small number of relay service users anticipated and their locations on the surface of Mars. Looking forward to more users possibly needing relay service simultaneously, this quickly becomes limiting.

Since the current MRN started providing relay service, the next frequency band to be used for relay has been discussed. Making the leap to a higher frequency band is difficult when there is a strong motivation to maintain heritage systems from spacecraft to spacecraft, especially when those spacecraft are primarily science orbiters with an additional relay capability. Given the expected DV requirements of eventual Mars human exploration missions, and the large number of spacecraft that will be present at Mars to ensure the success of those missions, it is recommended that the next Mars relay orbiter have K/Ka-band proximity link capability in addition to the heritage UHF. For K/Ka-band links, the SFCG recommends 22.55–23.55 GHz (K-band) for the forward link and 25.5–27.5 GHz (Ka-band) for the return link. This results in 1-GHz and 2-GHz total bandwidth for forward and return links, respectively, meaning that the number of simultaneously operating users will not be nearly as limited or constrained in available bandwidth.

To operate at K-band (for example), one must overcome additional space loss at a higher frequency, which is 35 dB extra at 23 GHz compared to 400 MHz. A 50-cm reflector (70% efficient) at 23 GHz has ~40 dBi of directivity versus ~5 dBi for a low-gain antenna (LGA), roughly offsetting the additional space loss of 35 dB for a given slant range. A reflector antenna at both ends of the link can therefore increase range and/or throughput compared to a traditional LGA–LGA link. For example, a 30-cm reflector (70% efficient) in addition to the aforementioned 50 cm reflector would provide ~35 dBi additional link gain. This could be used to support links at extended range and/or higher data rates. Compared to a nominal relay at 400 km, a relay at 4000 km would consume 20 dB of this gain, leaving room for a 32× increase in data rates to ~66 Mbps. However, requiring a reflector antenna on the lander can come with practical challenges, such as accommodation, cost, reliability, and complexity of operations (the antenna has to track the relay orbiter). Phased array antennas may provide flexibility in terms of accommodation and operations, with the caveat that space-qualified phased arrays face issues of technical maturity and cost.

S- and X-band are not strictly required if using UHF and K/Ka-band but could be added as additional frequencies if the size, weight, and power (SWaP) resources are present on the spacecraft. S-band, while common on Earth and lunar spacecraft with commercial off-the-shelf (COTS) telecom hardware available, does not have significantly more useable bandwidth at Mars than UHF, while incurring ~5× the space loss compared to UHF, making UHF the more favorable frequency band for low-rate users. COTS telecom hardware presently available in S-band was not developed for Mars relay telecommunications, which requires specific hardware configuration and firmware/software capability to run the link protocols. Although S-band hardware is smaller with antennas that can be designed to have omnidirectional coverage for surface assets, it requires the relay orbiter to increase its relay antenna size and RF amplifier power to overcome the space loss, while not offering more bandwidth compared to UHF.

K/Ka-band was chosen over X-band as the high-rate, high-frequency band to make the leap to a much higher bandwidth allocation, providing as much futureproofing as possible. For the same size antennas on the orbiter and relay service user, K/Ka-band offers a 10× improvement in data rate over X-band. Additionally, X-band has only 1/20th the bandwidth as compared to K/Ka-band. Lastly, the SWaP is lower for K/Ka-band components than for X-band.

2. Proximity Link Capability

The following section outlines the proximity link capability (return link DV throughput) that is possible at the outlined choice of orbit and frequency band selection. A comprehensive link analysis was performed at all the different orbit types outlined in Section II to show how the choice of orbit offers high return DV throughput. This proximity link analysis used a reference telecom subsystem that a next-generation relay orbiter could readily fly.

To establish a comprehensive communication architecture, we must consider the full spectrum of user assets and relay satellites, leading to two distinct telecommunication configuration pairs. These range from a modest system, involving a small user asset and a simple relay satellite using UHF, to an advanced system, connecting a sophisticated spacecraft with a high-performance relay orbiter at K-band frequency. The underlying telecommunication assumptions for these scenarios are specified in detail in Table 4.

In the modest telecom scenario, the user asset utilizes a low-power UHF radio coupled with an omnidirectional antenna. This signal communicates with an LGA on the relay satellite. For simplicity, the gains for both the transmitting and receiving UHF antennas are assumed to be 3 dBi.

Conversely, the advanced communication link assumes that the user asset can point its 15-cm steerable medium-gain Ka-band antenna toward the relay orbiter. This 15-cm diameter is deliberately maintained to control the pointing loss, similar to the accuracy demonstrated by the Mars Perseverance rover. The diameter for the Ka-band HGA on the relay orbiter is assumed to be 1 m.

Crucially, the user's transmitting power is kept low at 5 W for both scenarios, although a higher transmitting power from a 15-W solid-state power amplifier can also be assumed for the advanced link if increased margin is required.

Based on these configurations, the communication links successfully close at a range of 2000 km. The modest link (UHF) achieves a data rate of 128 kbps with an adequate margin of 4.39 dB, which aligns with existing UHF capability. The advanced link (Ka-band) achieves a data rate of 64 Mbps with a margin of 3.30 dB. This advanced performance represents a 400× increase over the modest link, advocating itself as a capability for future high-speed communication systems.

Table 4. Reference proximity telecom link parameters for analysis.

Link Budget	Unit	Mars User—Low-Gain Antenna UHF Return	Mars User—Medium-Gain Antenna Ka-band Return
Transmitter power (W)	W	5.0	5.0
Transmitter power (dBW)	dBW	7.0	7.0
Frequency	GHz	0.4015	26.00
Transmit antenna diameter	m	0.46	0.15
Antenna efficiency	%	55.0	55.0
Transmit antenna gain	dBi	3.0	29.6
Transmit antenna 2-sided beamwidth	deg	115.0	5.4
Antenna pointing error	deg	0.00	3.00
Antenna pointing loss	dB	0.00	–3.72
Polarization	CP/LP	CP	CP
Circuit loss	dB	–2.00	–2.00
Effective isotropic radiated power (EIRP)	dBW	8.0	30.9
Range	km	2000.0	2000.0
Free space loss	dB	–150.5	–186.8
Atmospheric attenuation	dB	0.0	0.0
Multipath loss	dB	0.0	–0.2
Receive antenna diameter	meters	0.42	1.00
Antenna efficiency	%	65.0	65.0
Receive antenna gain	dB	3.0	46.8
Receive antenna 2-sided beamwidth	deg	126.03	0.81

Link Budget	Unit	Mars User—Low-Gain Antenna UHF Return	Mars User—Medium-Gain Antenna Ka-band Return
Antenna pointing error	deg	0.00	0.50
Antenna pointing loss	dB	0.0	–4.60
Receive antenna polarization	CP/LP	CP	CP
Polarization loss	dB	–0.2	0.0
Circuit loss	dB	–2.0	–2.0
Received signal power	dBW	–141.7	–115.8
Receiver noise figure	dB	4.0	4.0
Sky temperature	K	230.0	230.0
System noise temperature (K)	K	426.7	426.7
System noise temperature (dBK)	dBK	26.3	26.3
Receive gain/temperature	dB/K	–25.5	13.9
Noise power spectral density (N0)	dBw/Hz	–202.3	–202.3
Transmit power to noise power spectral density (Pt/N0)	dB-Hz	60.6	86.5
Bit rate (kbps)	kbps	128	64,000
Bit rate (dB)	dB	51.1	78.1
Available energy per bit to noise density ratio (available Eb/N0)	dB	9.5	8.4
Required energy per bit to noise density ratio (required Eb/N0)	dB	4.1	4.1
Receive system implementation loss	dB	–1.0	–1.0
LINK MARGIN	dB	4.39	3.30

The communication system's data rates are varied; they are dynamically adjusted based on the received signal power at the orbiter (adaptive data rate switching) and the telecom configurations specified in Table 4. To ensure robust data transmission, the overall DV is calculated using an adaptive data rate scheme that incorporates a 3-dB margin. Our simulations covered a period of 126 sols with the temporal resolution of 10 seconds. The speed of data transfer is subject to specific upper limits depending on the frequency band. Transmission in the UHF band is capped at 2 Mbps, while the higher frequency K-band allows for a significantly greater maximum rate of 100 Mbps. We calculate two distinct categories of DVs to satisfy different mission objectives. The first metric focuses on meeting the needs of energy-constrained users. In this case, the DV calculation is based on the system utilizing the two best communication passes per sol. These passes have strict time limits based on the user's location: Surface users are limited to a maximum pass duration of 10 minutes each, and orbital users are limited to 30 minutes each. The second type of DV is designed to establish the absolute maximum data throughput capability achievable over a single sol, serving as a performance standard for the system—this is our maximum throughput benchmark.

The simulations evaluate 72 distinct relay satellite configurations against a comprehensive set of 181 surface users. These users are distributed along the prime meridian at 1° increments, spanning latitudes from –90° to 90°. To determine the total daily DV, we calculate the area-weighted average of the throughput collected from each surface user.

In contrast, orbital users are modeled in circular, Sun-synchronous orbits at a 400-km altitude. These orbits are distributed across three ascending nodes (0°, 45°, and 90°). The daily data throughput for this group is determined by averaging the DV across the three specified orbits over time.

The resulting DVs for surface and orbital users are illustrated in Figure 7 and Figure 8. Our analysis yields the following findings:

- **Surface DVs:** Daily UHF DV typically ranges between 100 and 1000 Mb, calculated from the two best 10-minute passes. However, when accounting for all possible passes, daily volume can reach up to 1600 Mb.
- **Pass Efficiency:** For high-altitude relay orbiters, the best two 10-minute passes capture nearly 100% of the total potential daily DV. For low-altitude orbiters, these two passes still account for 68% of the total available contact volume.
- **Frequency Band Comparison:** K-band DVs for both surface and orbital users are approximately two orders of magnitude higher than corresponding UHF volumes.
- **Orbital vs. Surface Performance:** Orbital DVs are two to three times greater than surface volumes. This performance gap is driven by shorter communication ranges, longer allowable pass durations (30 minutes vs. 10 minutes), and longer average cumulative daily contact times.
- **K/Ka-band Assumptions:** The K/Ka-band DV calculations assume that both the relay satellite and the orbital user maintain sufficiently accurate mutual pointing.
- **Performance in Recommended Orbits:** Telecom performance is generally favorable within the recommended orbital design space (altitudes of 500–1000 km to 1500–2000 km and inclinations between 55° and 80°).

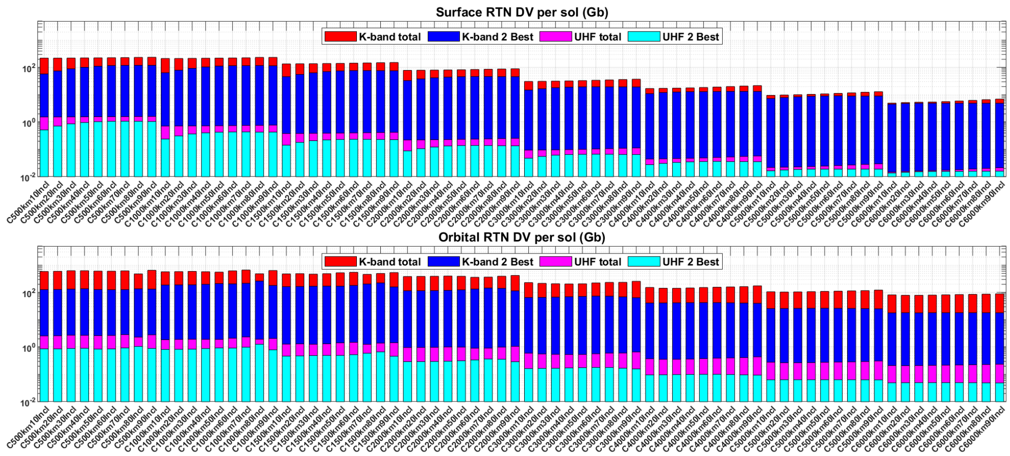


Figure 7. Return DV performance for various orbit types to a surface user (top) and orbital user (bottom) at UHF and K-band.

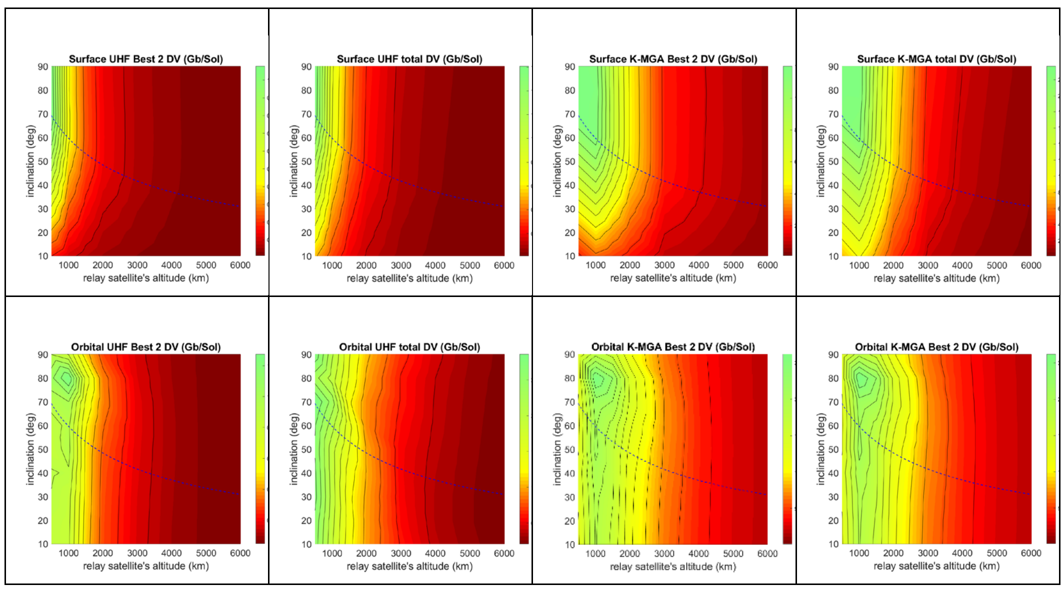


Figure 8. Daily return UHF and K-band DVs based on the total DVs and two best 10-minute (surface user; top) and 30-minute (orbital user; bottom) passes.

B. Direct-with-Earth Telecom

1. Frequency Band Selection for DWE Links

Current Mars orbiters use X-band for the trunk line back to Earth for science data generated directly by those orbiters and the science data from Mars assets to which they provide relay service. These systems are capable of downlink data rates of up to 1 Mbps to a 34-m DSN station. For the next Mars relay orbiter, it is recommended to switch from X-band to Ka-band for the primary DWE links (uplink and downlink), with an option of maintaining X-band uplink and downlink capability to mitigate weather effects present at Ka-band. The use of Ka-band for the primary downlink frequency to Earth will increase downlink data rates by one order of magnitude just by switching from X-band to Ka-band with the same HGA size and RF amplifier power, and up to two orders of magnitude if using larger HGAs and higher power RF amplifiers.

For the uplink of data from Earth, Mars relay orbiters have used X-band exclusively. Looking toward the future when even more assets at Mars have even higher uplink data rate needs, moving toward Ka-band would be necessary. At the time of writing, the only DSN station to provide Ka-band uplink capability is DSS-25 at Goldstone. However, the DSN plans to include Ka-band uplink capability for at least one station at each DSN complex in the coming years and, for human exploration support, it is anticipated that more than one Ka-uplink-capable antenna will be required at each DSN complex. Still, maintaining an X-band DWE system can mitigate risks (weather effects, station availability) of relying solely on Ka-band. Ka-band uplink can be used to transfer data from Earth for high data rate users, such as human exploration missions.

Additionally, with the successful operation of Deep Space Optical Communication (DSOC) on Psyche at Earth–Mars distances, optical communication for the Earth link can, and should, be considered to increase the data rates with Earth by an additional order of magnitude over Ka-band. DSOC demonstrated 8-Mbps downlink at 2.7 AU (farthest Mars–Earth distance) under relatively favorable conditions. Building a similar DSOC for the next Mars orbiter could achieve 5–10 Mbps downlink, with further improvements in laser output power providing even greater downlink capability.

2. DWE Link Capability

Modern software-defined radios (SDRs) are modular and can support multiple frequency bands in a single radio, including the frequency bands used in both proximity and Earth links. This has been demonstrated in the Universal Space Transponder (UST) architecture, where UHF relay and X-band have been supported simultaneously in a single radio for the Mars Sample Return project.

Current Mars orbiters employ 100-W RF-output X-band traveling-wave tube amplifiers (TWTAs). Ka-band TWTAs up to 500 W in RF output power have been designed, which would greatly increase the amount of data transferred to Earth by the relay orbiter. The same effect can be achieved with two 250-W TWTAs used together.

Parabolic dish HGAs of 2–3 m diameter are used on the current Mars relay orbiters, both with two-axis gimbals and without (i.e., body-fixed HGAs). Existing launch vehicles only allow space for up to ~4-m HGAs. Deployable HGA technology has developed and matured greatly, thanks in part especially to deployable radar antenna technology that have flown on many Earth missions. Future Mars missions should lean more heavily into the use of deployable HGAs. While increasing the size of an HGA also increases the required pointing accuracy needed, spacecraft pointing systems have been able to keep up with growing antenna sizes and the demands of higher throughput telecom subsystems.

Telecommunications systems with these components can achieve up to 50-Mbps uplink data rates and up to 500-Mbps downlink data rates, assuming up to a 12-m deployable

HGA and utilizing bandwidth efficient coding schemes such as low-density parity check (LDPC) 7/8.

C. Technology for Enhancing Proximity and DWE Telecom at Mars

JPL and MEP have developed several technologies applicable to enhancing Mars proximity and Earth link performance. These new technologies were developed specifically with the next-generation Mars relay orbiter in mind, and technologies like these and with similar capability should be considered for inclusion on the next Mars relay orbiter.

UST—for Proximity and DWE

SDRs are the backbone of modern Mars proximity communications. The SDRs flown on Mars relay orbiter missions can be reprogrammed in flight with any software or firmware used for modem processing or link protocol. This reprogrammability has been used to implement electromagnetic interference (EMI) filters on MRO and implement new coding schemes on MAVEN and TGO. Additionally, this function could be used to implement new link protocols, coding schemes, and modulation types in flight as they are needed for new mission scenarios or new relay service users. The processing power of modern field-programmable gate arrays (FPGAs) enables the incorporation of different frequency slices in a common chassis to support both proximity communications and DWE communications. These features are the key to provisioning low-SWaP communications solutions to a diverse range of future Mars missions. These SDRs can and should also be used for the link with Earth in future Mars relay missions.

The Universal Space Transponder is a Class-A/B SDR developed by JPL. The UST radio was developed originally from the Electra UHF transceivers flown on MRO, MAVEN, and TGO to extend the modular architecture, SDR to S-band, X-band, and Ka-band deep-space telecom frequencies. The UST offers significantly higher data rates, simultaneous multi-band and multi-channel operation, advanced modulation and coding techniques, support for new networking strategies such as delay tolerant networking (DTN), and cutting-edge radiometric schemes [5]. The modular architecture of the UST has common digital, power, and frequency hardware resident in each UST, with the RF frontend chosen depending on the operating frequencies required for each application. For Mars relay, that could include both relay frequencies (UHF and K/Ka-band) and Earth-link frequencies (Ka-band) capability in a single radio. This provides both mass and power savings, as well as considerable cost savings, to the Mars relay orbiter in addition to simplicity in spacecraft operations.

The software-defined nature of the UST allows for adding into firmware and software next-generation modulation and coding schemes not yet used in Mars relay, including quadrature phase-shift keying (QPSK) and Gaussian minimum-shift keying (GMSK) modulation and higher order coding schemes (greater than ½ rates used in the existing Mars relay orbiters). These capabilities can also be applied after launch, as the reprogrammability of the UST allows for patching firmware and software in flight.

UHF UST-Lite—for Proximity

UST-Lite is the next generation of Mars relay SDRs. It is designed from the ground up to be modular and to have a small form factor, making it adaptable to a wide variety of mission needs, including small, power-constrained missions. UST-Lite supports data rates of up to hundreds of megabits per second, depending on the frequency being used and modulation scheme. Based on the CCSDS standards, UST-Lite's SDR architecture ensures interoperability and allows for reprogramming post-launch, providing flexibility to accommodate new collaborators and adapt to evolving mission needs.

UST-Lite integrates cutting-edge digital processing and direct waveform sampling to enable higher data rates over multiple frequency bands simultaneously, while also provisioning precise navigational services. UST-Lite is architected to support beam steering of UHF antenna arrays, enabling relay services with a new class of low-SWaP Mars landers.

UST-Lite is being developed as a collaboration between JPL and industry partner Argotec, Inc. to deliver cost-effective, space-grade radios to NASA and non-NASA customers. UST-Lite inherits all the capabilities of legacy Electra UHF SDRs, while advancing MEP's initiatives to deploy high-performance communication systems critical for the future exploration of Mars.

The first versions of the UST-Lite to be developed were those with S-band and X-band capability for deep-space, DWE communication. A recent effort, funded by the Mars Exploration Program Office at JPL, developed the UHF RF module for the UST-Lite to bring UHF capability to this radio platform. With this development, the UST-Lite could be built and configured to serve as the next-generation relay-providing transceiver with Proximity-1 capability, with applications for future Mars missions in mind. This current effort is also developing beam-steering capability in the UST-Lite firmware itself. As opposed to active phased array antennas that build similar capability in the antenna with active electronics, beam steering in the UST-Lite allows the digital signal processing algorithms involved in electronically directing the signal to exist in the radio while using a simpler antenna array to transmit and receive the signal.

Multi-element UHF Antenna Arrays for Beam Steering—for Proximity

To capitalize on the beam-steering capability in the new UHF UST-Lite, a new UHF antenna array was also developed using Mars Exploration Program Office funding. The array, shown in Figure 9, has a footprint of 80 cm × 80 cm. One of its elements provides similar gain to the current helix antennas flying on existing Mars orbiter missions MAVEN and TGO (7-dBi max gain), while four arrayed together, as shown, provide 12-dBi gain maximum. That improvement, plus the ability to direct the signal to maintain near-boresight gain throughout an overflight pass with a Mars surface asset, increases the overall DV throughput by at least four times over current Mars orbiters. This is a much-needed boost in performance for orbiters that have used similar UHF antenna technologies for the past two decades, while not adding active electronics to the antenna assembly itself and taking advantage of the digital signal processing algorithms housed in the UST-Lite.

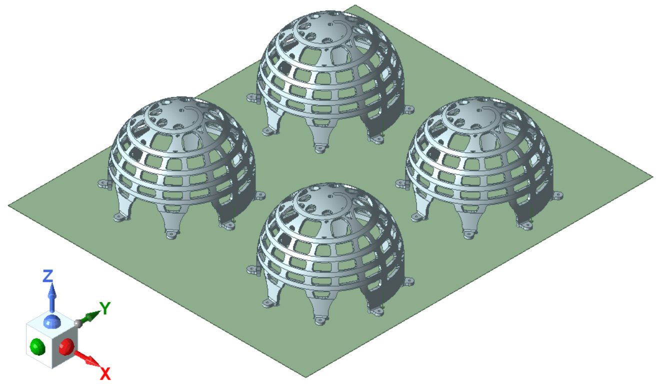


Figure 9. Model of arrayed UHF antenna.

Low SWaP UHF Transponder Arke—for Proximity

While it is likely not for use on a Mars relay orbiter itself, the Arke radio, developed at JPL, is the newest in a line of software-defined radios for deep space. Arke is a very low-SWaP transponder, designed to support a variety of flight missions ranging from Class-D to Class-A/B and, because of the low SWaP (it's roughly the same footprint as a credit card), is well suited for SmallSats, CubeSats, helicopters, and compact land/rover applications. The Arke transponder has both UHF and S-band designs and operates in half duplex mode only where either transmit or receive functionality is being utilized, rather than the simultaneously bidirectional full duplex links commonly operated at Mars. With a mass of < 300 grams, power consumption of < 10 W DC and 2 W RF output power without an external amplifier, and volume of 50 x 100 x 45 mm, this new low SWaP transponder represents the future of transponders for low-resource CubeSat and SmallSats.

Deployable Ka-band HGA—for Proximity and DWE

In addition to the recent technical developments outlined above, another effort has also been funded and carried out to develop a deployable HGA at X- and Ka-band, specifically for use by future Mars assets. This was an industry partnership with Tendeg, with whom JPL has worked with on technical development efforts and flight missions in the past. Antennas that are deployable can provide similar performance to the rigid, parabolic dishes generally flown on orbiter missions. This is shown in the table below, comparing the Tendeg 3-m deployable antenna to those flown on recent Mars orbiter missions. The benefit of using deployable HGAs is that the host spacecraft does not need as much launch vehicle fairing space as that required by a rigid parabolic dish antenna. This is especially important for SmallSat and CubeSat missions that might be delivered via rideshare to their destination. A deployable HGA allows these smaller missions to have the same antenna performance as larger missions that can have large parabolic dish antennas. Deployable HGA technology has been developed further and has become more reliable in the past ~10–20 years such that deployable antennas should be considered in future spacecraft. These antennas could be used on either the proximity links or links with Earth.

Table 5. Comparison of HGAs on Mars orbiter missions.

	Antenna Diameter	Antenna Mass	Frequency	Gain (dBic)
ODY	1.3 m	3.15 kg (full antenna)	X-band	UL: 36.6 DL: 38.3
MRO	3 m	19.1 kg (reflector only)	X-band	UL: 45.2, DL: 46.7
		22.6 kg (full antenna)	Ka-band	DL: 56.4
MAVEN	2 m	—	X-band	—
Tendeg Deployable Antenna	3 m	16 kg (reflector only)	X-band	UL: 45.5, DL: 47.0
			Ka-band	DL: 56.5

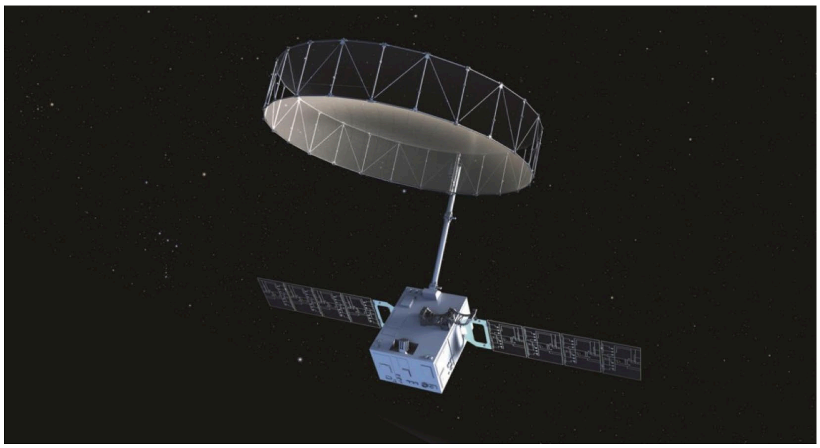


Figure 10. Deployable HGA on CubeSat.

IV. Position, Navigation, and Timing

A next-generation Mars Network (MN) configuration that is optimized for both communications and PNT performance for surface users will yield a different solution than one optimized only for communications or only for PNT. In the current study, the primary weight has been given to optimizing the data services that can be provided by a next-generation MN; however, PNT services are still a significant factor and have been considered with orbit selection. Indeed, unlike data relay where orbit altitude is a primary factor governing data rate, effective PNT services are affected by having diverse tracking geometry. For instance, [1] suggests a 6000-km altitude, three-satellite equatorial constellation to be optimal for communications to Mars surface users located in the latitude range from 60°S to 60°N; however, the use of equatorial orbits is not suitable for surface positioning because the north-south geometry is degenerate. In the present study, because data relay services to surface users (with potential lower power) carry a higher priority over PNT, lower altitudes will prevail, but if the relay orbit is too low, its ability to support orbiting users becomes much more difficult and requires pointing the relay spacecraft to the orbiting user. Another key support that the MN orbiter will provide is PNT services to low-cost orbiters with no DTE capability; indeed, sufficient PNT services to this class of orbiter is enabling for those users.

Seven key factors have been considered in evaluating the orbits to optimize PNT services of the next-generation Mars relay orbiter:

1. The MN relay PNT services provide two-way and one-way Doppler and range tracking to users in orbit to support their orbit determination (OD) and on the surface of Mars to support their global localization. Note that the relay orbiter must carry a stable reference clock for one-way radiometric tracking to be effective. This will be further discussed in a subsequent section. However, for this first orbiter, preference has been given to PNT performance using two-way data in the FoM weightings.

2. The MN relay PNT services also provide a timing service (via one-way ranging and Proximity-1 time synchronization services) that also require a stable reference clock.

3. The Mars relay PNT services are to be provided by each relay orbiter to all latitudes within any given orbit of the relay. Additionally, given that a single orbiter can only cover a limited longitudinal area during an orbit, repeating ground tracks are not desirable because they would yield regions with poor geometric coverage (or even none). For instance, an extreme case is an areostationary satellite that supports only a fixed latitude and longitude with little to no geometric variation. This class of orbit cannot yield viable global localization from a single orbiter.

4. Even though only a single orbiter is being selected in this study, it should be selected with the potential for it to be a participant in a future constellation that would provide global (or near global) coverage. For circular orbits, Walker constellations provide the most efficient global coverage properties (vs. other design approaches such as streets-of-coverage or flower constellations that require repeating ground tracks) and have been used as a guide for selecting this first orbit.

5. For both global localization of surface users and orbit determination for orbiting users, the time to achieve a desired level of position accuracy (for surface users) or orbit accuracy (for orbiting users) is a key metric. Since a single orbiter cannot provide instantaneous position or orbit solutions like GPS at Earth, the goal in the orbit selection process is to minimize the time to achieve the desired accuracy. In the current study, the accuracy after the first, second, and third pass have been used to determine a minimal time. Accuracy statistics based on the number of passes have been selected over actual wall clock time because time average results are easily skewed based on the selected initial geometry and epoch for any given simulation. Statistics based on the ordinal number of passes yield a better average with fewer statistical variations.

6. For both orbiting and surface users, the relay orbiter is assumed to have nadir-oriented omnidirectional antennas. For surface users, the geometric visibility with a 10° elevation mask has been assumed. For orbiting users, the user is assumed to

have an omnidirectional, zenith-oriented antenna that obtains visibility of the relay's nadir-oriented antenna when both hemispherical regions are in view of each other. No range limitation has been assumed.

7. As is the case for equatorial orbiters yielding degenerate localization capability for near equatorial surface users, the differential geometry between the MN satellite and orbiting satellite is critical for the user orbit determination performance to be sufficient. The implication is that the MN satellite should not be co-planar with the user and not at the same altitude as the user. In the following PNT analyses, we will present results for the global localization of users at any latitude and the orbit determination of a canonical lower altitude orbiter, which for this analysis assumed MRO's orbit (near polar, Sun-synchronous with 250 km × 315 km altitude orbit).

A. User Surface Global Localization and Orbit Determination Results

Our PNT analyses focus on a Mars relay satellite in circular orbits at various inclinations and altitudes in the range of 1000 km to 6000 km. For the lower altitude satellites, inclinations that prevent polar coverage have been excluded in the aggregated FoM.

Details of Mars relay orbiter simulation and surface user positioning filter scenario can be found in [6]. In summary, a high-fidelity PNT analysis has been developed using the Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE), JPL's operational navigation software that enables accurate assessment of the user PNT outcomes for a range of tracking and timing architectures [7]. The analysis includes high-fidelity modeling of dynamic and measurement errors affecting the PNT constellation ephemeris and timing accuracy and perform Monte Carlo simulations of selected scenarios. We collect sample statistics from Monte Carlo simulation of surface users located across Mars and assess their solution accuracy and compare them to their filter's formal a posteriori uncertainty. This capability allows us to assess the value of a given constellation design/architecture for surface users in selected regions, globally, and for orbiting users of the MN. By parametrically varying tracking data types and constellation orbit parameters, we can determine constellations that provide the best PNT outcomes for users.

We can investigate two tracking scenarios for the surface users, one using two-way range and Doppler for determining the user's position and the other using one-way range and Doppler for the position estimation. One-way tracking utilizes code-division multiple access (CDMA) modulation so that a user may track multiple satellites in-view simultaneously, while two-way tracking uses time-division multiple access (TDMA) modulation that permits duty cycling between a fixed number of in-view satellites (currently switching every 5 minutes between two satellites). The tracking network satellite-broadcast orbit and time ephemeris is utilized by the surface user to obtain the MN spacecraft location and time with the residual error in the ephemerides still present in the data. To compensate for the residual error in the orbit ephemeris, the user's positioning filter state is augmented by estimating for the orbiter's offset position errors with respect to its broadcast ephemeris using a white noise model. The user resolves their position and, if using one-way range and Doppler, also their clock using a 2-D stochastic model developed by Zucca and Tavella [8].

In the current study, orbit selection is focused on PNT outcomes using only two-way tracking. We will discuss the implications of providing a one-way tracking service when discussing clock selection in a later section.

We begin by considering the surface PNT localization from a MN orbiter at a 2036-km altitude circular orbit in various inclinations from 10˚ to 90˚. Also included is a 54˚ inclination case, which would place this orbiter as the first element of a global coverage constellation in a Walker 14/7/4 constellation configuration [9], where 14 is the number of satellites, 7 is the number of orbit planes, and 4 is the spacecraft phase factor. The 54˚ value is the specific inclination that results by applying the Walker coverage algorithm for this altitude, elevation mask, and 14/7/4 constellation configuration.

In this first result, Figure 11 shows the positioning of surface users at latitudes in the range +/-60˚ after 24 hours of tracking for either two-way tracking or one-way tracking (assuming the user has a miniature atomic clock [MAC] and the MN relay uses a HPAC for broadcasting the one-way range and Doppler signal). The orbiters are in different inclinations ranging from 10˚ to 90˚ with the 54˚ case shown by the black curve.

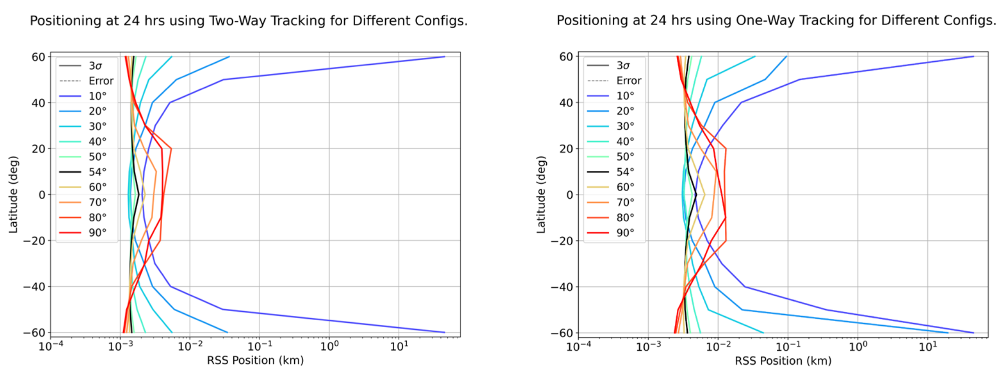


Figure 11. Global localization 3-sigma uncertainties of surface users in a ±60˚ latitude range after 24 hours (actual tracking time is much less) from a 2000-km altitude circular MN orbiter at the inclinations shown in the legend. The left plot is for a user collecting two-way range and Doppler, and the right plot is for a user collecting one-way range and Doppler where the user clock is a MAC and the MN relay clock is a HPAC. Note: Ignore the "Error" entry in the legend—these curves were excluded in the plot to enhance readability. Only the 3σ uncertainties are shown.

Note that the low-inclination orbiters yield poor positioning performance at high latitudes. This is because they begin to lose coverage at these latitudes. Also note that high-inclination orbiters yield worse performance near the equator. Indeed, the 54˚ inclination results provide the most uniform performance across all latitudes (< 2 m [3σ] for two-way, and < 5 m [3σ] for one-way). It turns out this is a consistent observation across all the orbiters inclinations studied—that the mid-inclination orbits provide the most uniform global localization performance across all user latitudes. These results represent the absolute best performance after a full day of potential tracking.

Another informative metric is how good global localization is after one, two, three, or more passes. This is captured for the two-way tracking case for a 60˚ inclination orbiter at 2000-km altitude and shown in Figure 12. The positioning results after the first pass have the most variation across latitude and range from mostly 10 m to 80 m (3σ). However, by the third pass, there is a near uniform position uncertainty of < 3 m (3σ). Also, note that for the three-pass metric, the total tracking time needed to achieve this positioning performance is ~2 hours. For mobile users, the radio tracking could be fused with its native dead reckoning (typically combining visual odometry, wheel odometry, and inertial measurements) so that absolute navigation accuracy can be maintained.

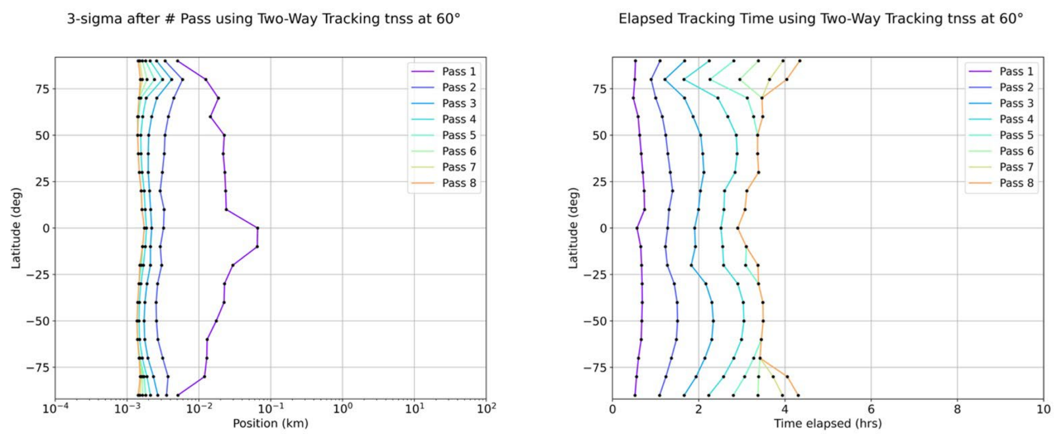


Figure 12. Global localization 3-sigma uncertainties of surface users in a ±90˚ latitude range (i.e., pole to pole) after 1 to 8 passes (left plot) from a 2000-km altitude circular MN orbiter at 60˚ inclination. The right plot shows the elapsed two-way tracking time (exclusive of periods when the MN orbiter is not in view) needed to achieve the positioning results shown in the left plot. Note: TNSS is short for tracking network system satellite.

Associated with the actual PNT performance as a function of time, it is informative to determine the average coverage statistics associated with a single orbiter globally as expressed by the average pass length and the average length of a gap in coverage. These are shown in Figure 13 with the following observations:

- Average pass ranges from 15 min to 1 hour with most being ½ to ¾ hour,
- Average gap ranges from 2 to 6 hours with most being 4 to 5 hours, and
- Shortest passes near the poles have the shortest gap.

Note that these average statistics do not accurately reflect the variances of where most passes are clumped into several and then none as Mars rotates underneath the orbit.

Now we consider the OD performance of an orbiting user (in the lower altitude, near polar MRO Sun-synchronous orbit) that is getting two-way range and Doppler tracking from a single MN orbiter at 2036-km altitude circular orbit and at 54˚ inclination. Representative position and velocity solution uncertainties (and errors from five different user realizations) are shown in Figure 14. Note that, in this case, the transient uncertainties occur in the first few hours and that after the third pass (about 3 hours into the simulation) the OD uncertainty has settled into a near steady state bounded by 10 m (3σ).

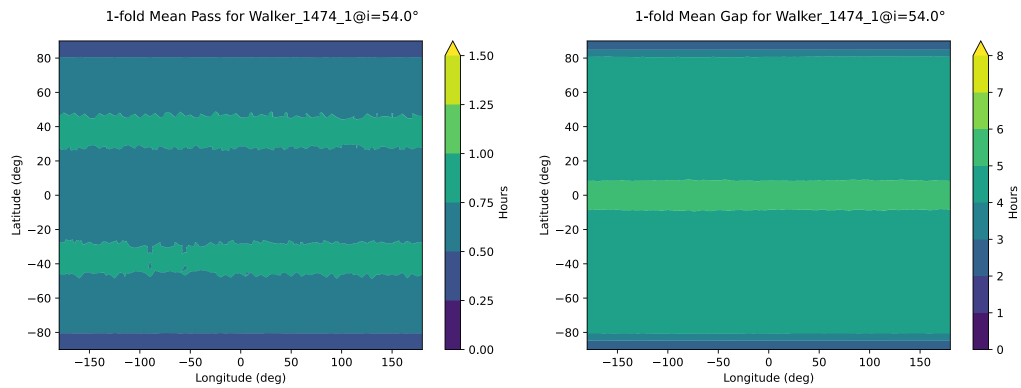


Figure 13. Mean pass length (left) and mean gap between passes (right) from a single MN satellite in a 2036-km altitude, 54° inclination circular orbit for a user as a function of its latitude and longitude.

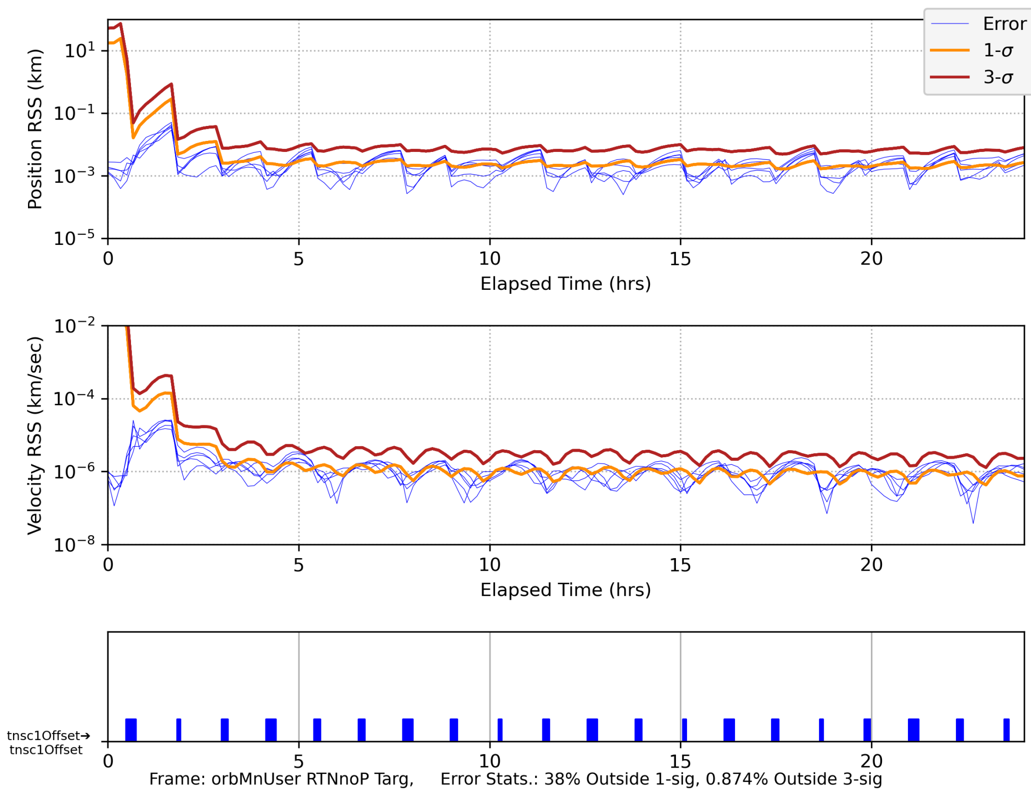


Figure 14. Position and velocity uncertainties and Monte Carlo errors of a user in an MRO-class orbit (five realizations shown for users with different random initial condition errors—each realization shown in blue) from two-way tracking to a MN relay in a 2036-km altitude, 54° inclination, circular orbit. The bottom plot illustrates the periods of two-way tracking between the relay orbiter and the user orbiter.

Because of its overall positive results, the 2036-km altitude, 54° inclination orbiter is the lowest altitude orbiter that yields the most uniform, best performing PNT outcomes and is the recommended orbit that yields the best compromise between data relay and PNT performance. Another orbit at 1500-km altitude at a 53° inclination also yields similar performance; however, the constellation size that would provide global coverage associated with this altitude is anticipated to be more than 20 satellites. The optimized solution is left for a future study. The surface and orbiting PNT results for these two orbits are summarized in Table 6.

Table 6. Summary surface position uncertainties and low orbiting user position and velocity uncertainties that can be obtained from either an MN relay orbiter at ~1500-km altitude or at ~2000-km altitude.

	~1500-km Circular Inclined					~2000-km Circular Inclined					
	Note: The 53° inclination is the lowest inclination supporting pole-to-pole coverage. Furthermore, the associated global coverage constellation would likely have > 20 satellites.					Note: The 54° case is at 2036 km, conforming to an element of a Walker 14/7/4.					
Orbit Inclination	53°	60°	70°	80°	90°	50°	54°	60°	70°	80°	90°
PNT w/ Surface User: Root sum squared 3σ position uncertainty (m) average for users (–90°, 90°) latitude											
After 1st pass	20.7	20.7	21.3	23.5	31.9	23.7	22.7	22.7	26.5	31.4	39.2
After 2nd pass	3.7	3.7	3.4	3.1	3	4.4	3.3	3.3	3.1	3.2	3
After 3rd pass	2.5	2.5	2.3	2.3	2.2	2.9	2.2	2.2	2.2	2.2	2.2
PNT w/ Low Orbiting User: Root sum squared 3σ position and velocity uncertainty (m, cm/s)											
After 1st pass	157, 65						76, 17				
After 2nd pass	22, 3						16, 2				
After 3rd pass	11, 0.5						8, 0.4				
Approximate upper bound steady state 3σ position uncertainty (m)	15						10				

If minimizing constellation size is a consideration, and the altitude constraint for data relay can be relaxed, the one-fold continuous global coverage using a Walker 55.7°: 7/7/5 constellation at a 6512-km altitude yields good surface localization performance in minimal time (< 10 m [3σ] two-way tracking, and < 30 m [3σ] after 2 hours) at all surface locations. Results for two-way and one-way surface positioning are shown in Figure 15.

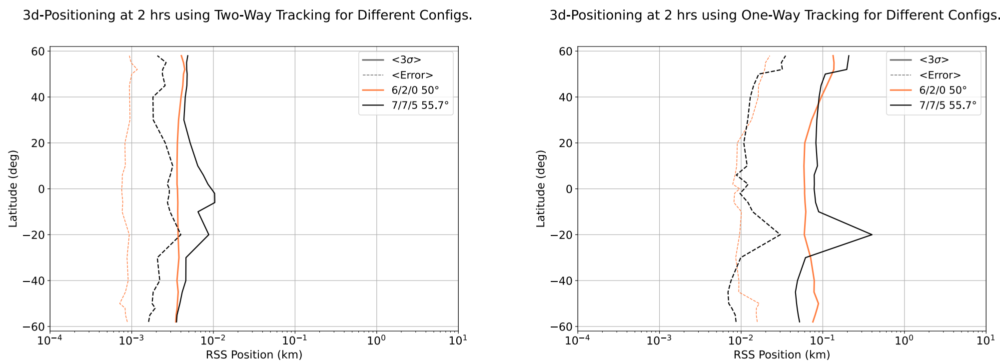


Figure 15. Positioning performance at 2 hrs for the continuous global coverage Walker 55.7°: 7/7/5 vs. Walker 50°: 6/2/0 using two-way tracking (left) and one-way tracking (right).

B. Mars Network Clock Considerations

As with GPS, accurate PNT services will require stable, precision clocks and, given the distance between Mars and Earth, clocks with minimal drift will be important for minimizing the Earth-based support needed to maintain accurate PNT services at Mars. Given this consideration, future MN relays should host atomic clocks that are equivalent or better than the standards used on GPS today. Today's GPS satellites host rubidium atomic frequency standard (RAFS) clocks; however, these clocks have a relatively high drift that requires twice-a-day updates to maintain accurate broadcast clock models to users. Mercury ion clock technology has the potential to improve RAFS stability by two orders of magnitude. This was demonstrated by the Deep Space Atomic Clock (DSAC) in 2021 [10]. The next-generation mercury ion clock technology is the HPAC, which should perform ~2× better than DSAC and require about ½ its size, weight, and power. Indeed, an Exploration Systems Development Mission Directorate (ESDMD) Mars Campaign Office–supported development of an advanced prototype HPAC is currently in development, starting fiscal year 2026. A flight unit development is being planned but not committed to by NASA as of this writing, but, if funded, could yield a commercially available HPAC flight unit by the late 2020s.

When comparing the GPS-standard RAFS clock to HPAC, it is important to consider that a GPS RAFS clock (and other space clocks such as a passive hydrogen maser [PHM] on Galileo) has high drift that would make it more complex to manage at Mars distances, while an HPAC could free run and support users with much more infrequent clock model updates. A more stable clock ensures that PNT services can continue to be provided with minimal impact. For instance, after 30 days, an ultra-stable oscillator would drift about 3 milliseconds and yield a range signal with a 900-km error, while HPAC would have drifted by about a nanosecond and yield a 1-m range error. It is recommended that, as soon as a flight HPAC becomes available, it be deployed on next-generation MN relays.

V. Science Opportunities

A range of science opportunities are available to supplement the capabilities of a next-gen relay orbiter, but optimizing science is highly dependent on the chosen orbit of the spacecraft. The benefit of augmenting an orbiter payload with one or more science-focused instruments depends on the relative capability of a payload compared to existing (or prior) instruments present at Mars. This includes both limitations in payload size, weight, power, etc., on what is primarily a telecom orbiter, as well as differences driven by, for example, relative orbital altitudes (a higher altitude may be better or worse for a specific instrument), advances in technology (generally making more recent designs an improvement on prior ones), and available DV (increased capability is of no value if the data cannot be returned). Additionally, the choice of investigation may be driven both by information need (i.e., priority data gaps) and spacecraft capability. The highest priority investigations may not be amenable to a particular orbit or a particular spacecraft design (including those prioritized above). Many trades are required to establish the correct payload for a future orbiter. Here, we largely set aside the details of these considerations and present only representative investigations that demonstrate the utility and value of science in support of future exploration activities.

There are two different orbits that have been discussed—the science that is optimally performed at each is somewhat different, so these will be discussed both in turn.

A. Altitude: 500–1000 km, Circular

A spacecraft in a circular orbit within the 500–1000 km range can be Sun-synchronous, like many current spacecraft in lower orbits (e.g., MRO, ODY), but also can employ one of several other useful orbits that are beneficial for a range of scientific investigations. The ExoMars TGO operates in a high-inclination (74°) circular orbit at ~400 km, the closest current spacecraft to this proposed altitude range, and takes advantage of its precessing orbit to conduct investigations that "walk" over the course of the Martian sol. Science return from TGO exhibits full time-of-day coverage over periods of days to weeks, depending on latitude, which offers the ability to observe changes in the atmosphere unobservable by Sun-synchronous assets, and to view the surface over a full range of illumination angles. At the higher altitudes of this orbit type, most of these advantages remain, with some degradation in spatial resolution. Examples of investigations that can be conducted in this orbit follows:

1. Atmospheric Profiling

In low Mars orbit (500–1000 km), atmospheric profiling observations can continue the decades-long record of infrared measurements of atmospheric temperature and aerosol abundance, continuously made since the beginning of MGS operations. By measuring radiance at specific wavelengths near the strong 15-µm CO_2 absorption band, it is possible to assemble a vertically resolved profile of atmospheric temperature from the surface to ~80 km with a resolution of ~1/2 scale height, which is sufficient to resolve the boundary layer and capture most of the atmosphere's dynamical activity. Judicious choice of spectral filters in the mid-IR would also allow dust, water ice, and CO_2 ice clouds to be observed and their abundances vertically resolved. Such measurements are essential to filling key data gaps driven by the current design for the Mars segment of the Moon-to-Mars architecture. Better characterization of localized Mars surface weather at, and above, prospective landing sites would, for example, provide improved landing accuracy through better knowledge of the atmospheric density profile, and reduce risk during surface operations by enabling more effective forecasting of atmospheric conditions, including dust loading.

Complementing these regular profiles, a series of occultation measurements, taken by the spacecraft as it passes behind the Martian limb from the perspective of Earth, can provide even higher resolution information about atmospheric pressure and temperature at discrete locations. The Doppler shift imposed on a spacecraft's carrier signal as it passes through the Martian atmosphere is a function of temperature. With knowledge of the geometry of the orbit, and spacecraft/Mars/Earth orientation, a profile at the point tangent to the surface can be obtained. A high-inclination orbit provides many more opportunities for widespread occultation coverage. Similarly, spacecraft-to-spacecraft occultations can be conducted in a similar fashion, with the more rapidly evolving positioning between two linked spacecraft offering an even greater range of latitude and local time measurements.

2. Winds

Winds have never been widely measured at Mars. Limited information at altitude has been obtained from descending spacecraft and from cloud tracking. Most wind measurements, however, are obtained at the surface, at the specific locations of robotic rovers and landers. Two different approaches for measuring winds orbitally have been proposed for Mars—lidar and submillimeter sounding—and both are useful for different regions of the atmosphere. Lidar constitutes pulsing a near-infrared (NIR) beam through the atmosphere and measuring the returned signal. Lidar operates by reflecting off atmospheric aerosols (e.g., dust) that move with the prevailing wind. Small variations in wavelength, due to Doppler shifting of the signal off the moving aerosol, can be converted to line-of-sight, one-axis wind velocity. By using multiple look directions, or a scanning platform, a 2-D (or 3-D) wind field can be obtained (although vertical winds are generally negligible compared to the horizontal wind field). For Mars, this is particularly useful in the lower atmosphere, which has a substantially greater aerosol content than higher altitudes.

Conversely, at higher altitudes, a submillimeter approach may be more beneficial, where motion of radiatively active atmospheric molecules is directly detected by a suitable antenna. Departure from the known emission frequency can be mapped to Doppler shift caused by molecular translational motion and, as before, a line-of-sight wind velocity can be extracted. Operating two orthogonal antennas can obtain the full horizontal wind field.

Like above, tracking of the wind field is an investigation that addresses a key data gap in the Moon-to-Mars architecture, aiding in landing accuracy and therefore overall EDL success.

3. Trace Gas Mapping

Payloads that can observe and map trace gas abundances in the atmosphere (including H_2O, CH_4, O_3, and others) have been active for several years and have shown both repeat, seasonal cycling of many of these species, as well as interannual variability. TGO continues to observe Mars in both nadir and limb orientations in its high-inclination 74° orbit. While a slightly higher altitude would degrade spatial resolution compared to TGO nadir viewing, the additional use of solar occultation techniques would still provide exquisite sensitivity that would permit continued measurement of trace gas distribution in a demonstrated way.

4. Surface Imaging

While a higher orbit will reduce spatial resolution of imaging assets compared to instruments at a lower, Sun-synchronous orbit, such an offset in resolution would be countered by an increase in swath width, permitting a larger observable surface area per image. A High-Resolution Imaging Science Experiment (HiRISE) like camera at 1000 km—approximately three times farther from the Martian surface than MRO—would suffer a 3× reduction in resolution (to about 1 m/px) but gain a 3× increase in swath width, or about 20 km per image. While potentially ineffective at resolving smaller, lander-sized rocks, it would still provide useful local coverage of notional landing sites more rapidly. A distinct advantage of a non-Sun-synchronous orbit is that its "walking" nature permits observations over the full day. This affords the ability, over time, to image the same location over a range of illumination angles, offering valuable information about surface composition and texture. Early afternoon observations (e.g., 3 am/pm as with MRO) tend to have smaller shadows, making detection of surface rocks/boulders (a useful application for landing site selection) more challenging. Early morning observations (e.g., 6 am/pm as with ODY) offer a more raking light and longer shadows; however, the visible resolution of ODY's Thermal Emission Imaging System (THEMIS) imager is insufficient to identify lander-scale surface features of greatest concern to landing. A visible, HiRISE-like camera at 1000 km would offer benefits both in spatial and time-of-day coverage. As these features generally remain static over time, information about their true size and distribution can be built up over time, augmenting the information available from other past/present imaging assets. Areas of greatest surface change—typically the polar latitudes—would not be observable by a spacecraft in a high-inclination (but not polar) orbit, but these are unlikely to be locations for future human landings.

B. Altitude: 1500–2000 km

A circular orbit in the 1500–2000 km range is still comparatively close to the Martian surface relative to spacecraft (like MAVEN, Mars Orbiter Mission [MOM], and Emirates Mars Mission [EMM]) in highly elliptical orbits with apoapses at 10,000s km. Many of the same types of measurements made at lower altitude, therefore, could be accomplished at a higher altitude, although with additional reduction in resolution or increase in surface footprint. From a higher vantage point, it additionally becomes opportune to observe the upper Martian atmosphere and its relationship with the local space weather environment.

1. Aeronomy and Space Weather

An orbit of 1500–2000 km provides a unique position to observe the Martian magnetic field and its interaction with the solar wind, somewhere between spacecraft (like MGS) in low, circular orbits and those in more elliptical orbits (like MAVEN) that travel out to great distances at apoapsis. (The upcoming Escape and Plasma Acceleration and Dynamics Explorers [ESCAPADE] mission will assume orbits even farther out than this.) Having a circular orbit at 1500–2000 km provides information in this intermediate region close to the daytime bow shock where the solar wind diverts around Mars.

A mass spectrometer flown at this altitude would be useful for looking at the energetic neutral atom (ENA) population and the composition of the Martian corona. Charge exchange between fast-moving particles in the solar wind and neutral atoms in the Martian corona (predominantly hydrogen, but also other light species) leads to production of ENAs as the once charged solar wind particles transfer their charge to atoms in the corona. They become a useful tool for characterizing the composition of the tenuous reaches of the Martian upper atmosphere and solar wind.

While Mars lacks a global magnetic field like Earth, the localized remanent magnetic field on Mars does interact with the solar wind; auroras are generated from this interaction, which have been observed in the ultraviolet (UV) by both the MAVEN Imaging Ultraviolet Spectrometer (IUVS) and the Mars Express Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM). Continuing to observe the formation of auroras across Mars further refines our understanding of the temporal and spatial variability of the solar wind's interaction with the Martian atmosphere and provides valuable information about the radiation environment on and around Mars for future explorers under different solar wind conditions.

Elsewhere, any of a variety of electrostatic analyzers could be used to measure both atmospheric escape from Mars as well as charged particle input into the Martian system. Electrostatic analyzers can provide information about the energy, direction, and species of charged particles in and around the solar wind and upper atmosphere. Given a putative orbital altitude of 1500–2000 km, it may be possible to identify these conditions both within and outside of the Martian magnetosheath, depending on solar wind conditions.

The example instruments, and their corresponding investigations on the above list, were curated to illustrate their scientific value for future exploration, and the retirement of priority knowledge or data gaps in the Martian system. Full characterization of the Martian atmosphere, both lower and upper, is essential both for safe EDL and for longer term survival of a future human crew. A better understanding of surface safety—rock abundance, slope, and composition, which can be addressed through continued visible imaging—would further retire risks for future human-class missions. The instruments presented also take full advantage of the precessing orbit, which carries the spacecraft through the full diurnal cycle, allowing measurements to be made at all times of day, rather than two times of day as with Sun-synchronous orbiters. By maintaining a continuous record of the Martian surface and atmospheric environment, we gain confidence in our understanding of the scale, duration, and frequency of extreme events that present risk that can be retired. Leveraging an existing telecom orbiter to conduct priority exploration science investigations takes advantage of an existing platform with minimal to no interference to the primary spacecraft mission.

VI. Conclusion

The recommendation outlined in this document defines a comprehensive and forward-looking approach to the development of a next-generation Mars relay orbiter capable of supporting future Mars Exploration Program needs. By examining orbit selection, telecommunications architectures, PNT services, and potential science opportunities, the study addresses both current mission needs and anticipated future requirements.

Lower altitude orbits prioritize high DV return and frequent user access, while also offering sufficient PNT performance. By identifying specific altitude (500–1000 km and 1500–2000 km) and inclination combinations suited to different mission priorities, the recommendation allows for tailoring the orbit to the specific mission needs. The choice of orbit leaves open the potential transition from a single relay spacecraft to a constellation of additional spacecraft capable of continuous global PNT coverage in the future.

Of course, telecommunications capability is central to a future, high-performance Mars relay orbiter. On the proximity link, the continued use of UHF ensures compatibility with existing Mars assets and supports low-power users, while the addition of K/Ka-band proximity links dramatically increases available bandwidth and enables simultaneous support of multiple users. The continued use of reprogrammable, SDRs and modern data link protocols further enhances efficiency and adaptability, allowing the relay network to accommodate higher data rates and future protocols. On the DWE link, the recommended primary use of Ka-band for DTE links and either X- or Ka-band for the DFE link, with optional augmentation via optical communication, provides a scalable solution for meeting what is expected to be a large jump in data transfer needs between Mars and Earth.

The purposeful integration of PNT services in this next relay orbiter means that it could provide critical support to low-power surface and orbital relay service users without sufficient DWE links. The recommended orbit and supporting technologies offer meaningful improvements in surface and orbital navigation performance and reduce dependence on Earth-based tracking. The potential inclusion of a HPAC positions the system to deliver GNSS-class performance, supporting both immediate and future mission needs.

Finally, the opportunity to include high-value science investigations in this orbiter ensures that the mission could act not only as a replenishment to the MRN but also as a valuable science orbiter. Orbits within the recommended altitude ranges enable important observations of the Martian surface, atmosphere, and space environment, addressing key knowledge gaps while directly contributing to the reduction of risks associated with EDL at Mars.

Taken together, these recommendations offer a robust next Mars orbiter platform for advancing Mars relay capabilities.

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