Constellation Design for Mars Navigation using Small Satellites

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With continued interest in Mars exploration, and even colonization, comes a need for more accurate and reliable navigation solutions. Currently, ground-based assets rely on a combination of image processing and data relayed through the Deep Space Network for navigational needs. This is a costly and time consuming process. To improve upon the timeliness and reliability of navigation updates, we outline a navigation architecture to provide global, continuous coverage of the Martian surface. The resulting constellation is deemed the Constellation for Mars Position Acquisition using Small Satellites or COMPASS. The proposed design will consist of 15 small satellites, providing enhanced situational awareness at Mars.

I. Introduction

To date, Mars exploration efforts have produced a number of Mars orbiting satellites as well as successful landings of semi-autonomous rovers. From these missions, we have been able to significantly bolster our understanding of Mars and our solar system, with many of the advancements coming within the last three decades. A major challenge in the design and execution of these missions is that of remotely navigating in the Martian environment. The challenge is made drastically more difficult without the resources available for Earth-based missions. For example, the Mars Exploration Rovers (MER) rovers rely extensively on image processing for navigation and path planning.[1] More accurate updates to the rovers' position estimates are available infrequently, depending upon access windows to the Deep Space Network (DSN), Mars Reconnaissance Orbiter (MRO), or Mars Odyssey. In order to help facilitate and encourage more ambitious Mars mission concepts, a more robust navigation solution is required.

Many obstacles must be overcome to navigate the Martian environment. For starters, Mars is located no closer than 54.6 million kilometers from the Earth. Transferring any amount of material between the two planets requires high delta-V, helping to explain why Mars missions are some of the most expensive to date. Additionally, with respect to the Earth, Mars' core is relatively inactive, lending to Mars' much smaller magnetosphere. The resulting electromagnetic field is too weak to establish a global north or south, rendering compasses infeasible for Mars navigation. Furthermore, satellites operating even at low-Mars orbit are susceptible to the effects of solar weather, requiring robust satellite architectures made resistant to long-term radiation effects. Ultimately, any proposed navigation network for Mars must be sophisticated, environmentally robust, and minimalistic in order to address these challenges. Fortunately, CubeSats may provide a solution.

CubeSats are compact and lightweight by design. Recently, CubeSats have been designed for deep-space applications, demonstrating their potential capabilities as full-service satellites for complicated science missions. MarCO will be the first CubeSat mission to operate at Mars and will demonstrate long range communications on a CubeSat using X-Band radio waves.[2] INSPIRE, NEAScout, and Lunar Flashlight are other examples of deep space CubeSat missions.[3–5] Using these satellites as promising examples of capable CubeSat designs, we propose a constellation of CubeSats to provide global, continuous coverage of Mars.

Mars constellation concepts exist, but none are designed to provide continuous uniform coverage of the entire planet's surface. The design from Nann et al. includes no more than 8 satellites, and is designed

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to characterize the Martian atmosphere and climate cycle with spatio-temporal precision.[6] Jet Propulsion Laboratory (JPL) has created a Mars constellation design which provides navigation and communication support for a variety of future Mars missions, but restricts the satellite population to 6 member satellites, providing primarily equatorial coverage of Mars.[7] Here we introduce the constellation for Mars Position Acquisition using Small Satellites, or COMPASS, with the following design goals

1. Provide continuous global coverage of Mars.
2. Minimize satellite population of constellation.
3. Provide navigational support for Mars assets.
4. Serve as a communications relay for Mars assets.
5. Serve as a communications relay between Earth and Mars.

This design is unique in terms of scale, specifically in providing continuous global coverage of Mars. COMPASS will provide navigational support by continuously transmitting time-stamped ephemeris and identifier signals to users on Mars. This information will be used to determine real-time position estimates for rovers, lower orbiting satellites, or potentially future colonies on Mars. Additionally, COMPASS can serve as a communications network to relay information across the planet. In the following sections, we present the details of the constellation design, addressing specifically, points 1 and 2 in the list above, as they pertain to the broader purpose of the COMPASS mission.

II. Navigation Model

The navigation architecture of the COMPASS constellation is similar to that of the GPS constellation on Earth, consisting of space, user, and control segments. The space segment will consist of 15 member satellites in the constellation. These satellites will provide continuous global coverage of the planet's surface with no less than four satellites overlapping a common surface segment. The user segment will comprise primarily of rovers on Mars' surface or lower orbiting satellites. A user will be equipped with a receiver to intercept carrier signals transmitted from the space segment. This signal will provide time stamped identifier and ephemeris data from the signal source to aid the user in obtaining navigation updates. The third and final segment is the control segment. The control segment is tasked with constellation monitoring and maintenance, providing clock updates and satellite course corrections as needed. Ground stations will be established on the planet's surface, or potentially on Mars' moons, and will assist in satellite control and systems operations. Additionally, the ground stations will act as the primary point of contact with Earth via the Deep Space Network (DSN) and will allow for direct communication with the entire navigation network.

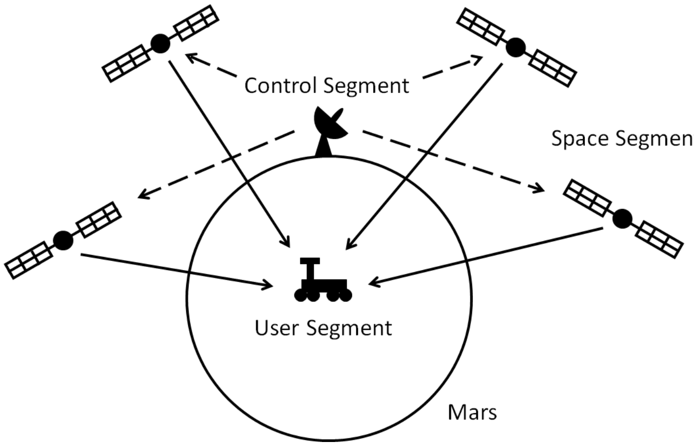


Figure 1. Navigation structure for COMPASS constellation

III. Constellation

Many organized constellation designs fall broadly into three categories: Walker, Ballard Rosette (Walker-delta), and Flower constellations.[8–10] Walker constellations are characterized by a number of evenly-spaced circular orbits rotated about a common node. Ballard-Rosette constellations are characterized by a number of circular, inclined satellite orbits, with evenly-spaced separation about an equatorial belt, i.e., evenly-spaced right ascensions of the ascending nodes between each of the orbits. Flower constellations are less intuitive in their design, and are determined numerically with the purpose of forming repeated ground tracks on a planet's surface. For the purposes of global coverage, our constellation will fall under the category of Ballard-Rosette. The current design is fully defined by the properties in Table 1 and is illustrated in Fig. 4, located in the Appendix.

Table 1. COMPASS Constellation Parameters

Number of Satellites	15
Number of Planes	5
Satellites per Plane	3
Uniformity Phase Angle	24°
Orbit Inclination	45°
Orbit Altitude	20,427 km

For uniform coverage of Mars, the orbital planes are evenly spaced about the Martian equator, resulting in a nodal phase difference of 72° for the 5 plane design. The uniformity phase angle is the relative phase difference of satellites in adjacent planes. In other words, the uniformity phase angle is the angle, measured in the direction of positive angular momentum, between the ascending node and the nearest satellite at the instance in time when a satellite in the westerly adjacent plane is at its respective ascending node. For the 15 satellite design, the uniformity phase angle is obtained using $360°/15$, ensuring that all member satellites are uniformly spaced throughout the constellation space.

Orbital inclinations are set to 45 degrees to allow sufficient coverage of the polar regions, which are typically the least accessible regions in Ballard-Rosette designs. An areosynchronous orbital (ASO) altitude, the Martian analogue to Earth's geosynchronous orbital (GSO) altitude, is selected to cycle orbits once daily. Orbits at this altitude and inclination provide overlapping coverage of the planet's surface, as well as predictable, repeating groundtracks for simplified satellite acquisition from the surface.

A. Determination of Satellite Population

The total number of satellites per plane should be kept to a minimum to reduce the total population of the COMPASS constellation and, by extension, the total operations costs associated with establishing and maintaining the network. To provide complete circumferential coverage of the planet, each orbital plane requires a minimum of three satellites. A single satellite, placed infinitely far from Mars, will have access to half of the Martian surface. The addition of a second satellite will account for the remaining, inaccessible hemisphere, but this will only be true for satellites placed at infinity. Ultimately, practicality requires three satellites to achieve full circumferential coverage of Mars. Figure 5, located in the Appendix, illustrates surface coverage capabilities for 2 and 3 satellite planar configurations at ASO.

The Martian reference sphere, defined as the sphere with radius equal to Mars' mean equatorial radius, will be used to determine coverage analysis of the proposed constellation. By design, a user anywhere on the surface of the reference sphere must have continuous access to at least 4 network satellites to obtain accurate three-dimensional position estimates in time. For any orbital plane in the constellation, a user is guaranteed access to at least one satellite. For this reason, at least 4 orbital planes are required to allow a user access to a sufficient number of satellites at any given time. However, as illustrated in Fig. 5, each plane creates two coverage gap triangles located 180° apart on the Martian reference sphere. An additional plane is required to accommodate for these coverage gaps and guarantee continuous access to at least 4 satellites anywhere on the reference sphere. Requiring a minimum of 5 planes, with a population of 3 satellites per plane, the COMPASS constellation is ultimately made up of 15 satellites.

B. Coverage Analysis

The altitude and inclination of the COMPASS orbits influence planetary coverage efficiency. Greater altitudes provide greater surface coverage while increased inclinations allow access to higher latitudes. Additionally, the size and location of regional coverage gaps are effected by altitude and inclination respectively. These parameters must be selected to manage the dimensions of the regional coverage gaps, as well as ensure no overlap occurs between neighboring gap regions. Geometry will dictate how to manage these concerns.

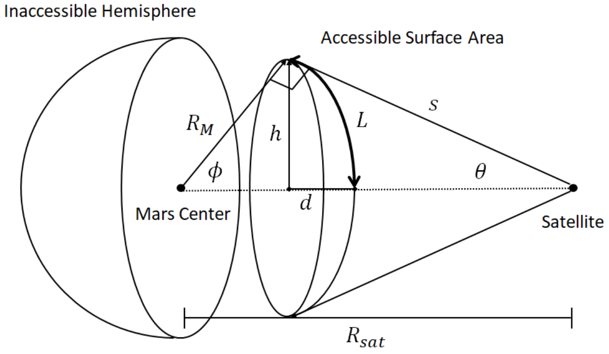


Figure 2. Geometry of planetary surface coverage area

Table 2. Single Satellite Efficiency

Mars Mean Equatorial Radius, R_{Mars}	3.3962×10^3km
Satellite Radius from Mars, R_{sat}	2.0427×10^4 km
Maximum Coverage, $A_{\max}$	7.1469×10^7 km^2
Tangent Distance, s	2.014×10^4 km
Maximum Coverage Radius, h	3.3486×10^3 km
Coverage Depth, d	2.8316×10^3 km
Half-arc Length, L	4.7675×10^3 km
Half-cone Angle, ϕ	80.43°
Half-arc Angle, θ	9.57°

Figure 2 provides an exaggerated illustration of the accessible surface area, for a single satellite, with respect to half of the Martian reference sphere. The half-cone angle, θ, is the angle between the tangent distance, s, between the satellite and the surface of the reference sphere, and is obtained from

$$\sin\theta = \frac{R_{\text{M}}}{R_{\text{sat}}} \tag{1}$$

where R_{M} is the mean equatorial radius of Mars and R_{sat} is the radius of the satellite from Mars' center. Using the half-cone angle, the half arc-angle, ϕ, can now be determined as

$$\phi = \frac{\pi}{2} - \theta \tag{2}$$

resulting in half arclength

$$L = R_{\text{M}} \cdot \phi \tag{3}$$

The maximum surface area accessible by a single COMPASS satellite, $A_{\max}$ is

$$A_{\max} = \pi(R_{\text{M}}^2 - d^2) + 2\pi R_{\text{M}} \cdot d \tag{4}$$

where coverage depth, d, is defined as

$$d = R_{\text{M}}(1 - \sin\theta) \tag{5}$$

For the COMPASS constellation, each individual satellite provides $\approx 7.15 \times 10^7$ km^2 of coverage, or 49.3% coverage of the entire planet. Table 2 contains the parameter values for a single COMPASS satellite.

Within a gap triangle, users are unable to obtain access to any of the three satellites in a particular orbital plane. To analyze this region, Figure 3 illustrates the gap triangle, with parameter values listed in Table 3.

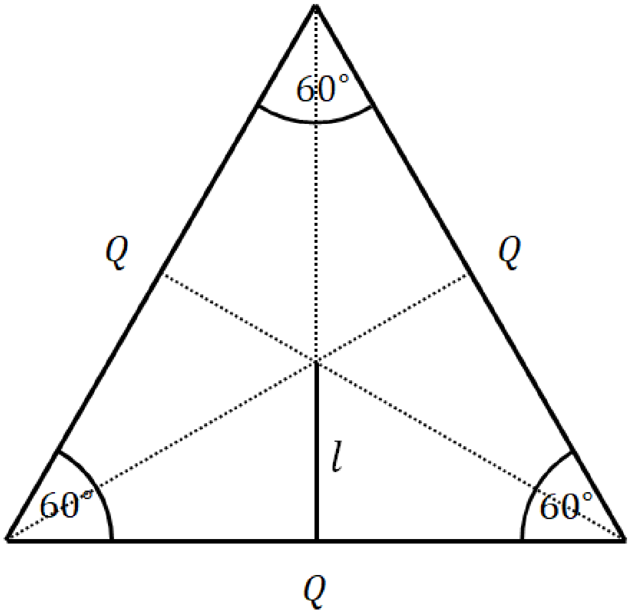


Figure 3. Dimensions of coverage gap triangle.

Table 3. Coverage gap parameters

Gap Triangle Area	1.6721×10^6 km^2
Gap Triangle Depth, l	7.1469×10^7 km^2
Gap Triangle Base Length, Q	2.014×10^4 km

To determine desired inclination and altitude values for the constellation, the gap triangles must be characterized using the half arclength L computed in Eq. (2). First, assuming uniform spacing in the orbital plane, the interior angles of the gap region are known to be 60°. With this angle, the gap depth, l, defined as the shortest distance between the center of the gap triangle to the gap perimeter, can be obtained. From geometry, the gap depth is the difference between the half arclength and half the circumference of the reference sphere

$$l = \frac{\pi}{2} R_{\mathrm{M}} - L \tag{6}$$

The gap triangle base length, Q, can now be obtained as

$$Q = 2\sqrt{3} l \tag{7}$$

For p number of orbital planes, a worst-case, limiting gap circumference, C_{lim}, must be compared with the circumference of the true latitude where the gap triangles reside, C_{gap}. The limiting circumference is the distance created by summing the maximum triangle gap length for each of the p orbits, resulting in

$$C_{\mathrm{lim}} = pQ \tag{8}$$

To ensure no overlap exists between any two neighboring triangle gap regions, C_{lim} must be less than C_{gap}, defined as

$$C_{\mathrm{gap}} = 2\pi (R_{\mathrm{M}} \cdot i - l) \tag{9}$$

where i is the inclination of the constellation orbits. The requirement, $C_{\text{lim}} < C_{\text{gap}}$ is met for the COMPASS constellation with $C_{\text{lim}} = 9.83 \times 10^3$ km and $C_{\text{gap}} = 1.32 \times 10^4$ km.

The total serviced area of the COMPASS constellation is over 7 times that of the total Martian surface area. These coverage redundancies ensure sufficient user access to the constellation, while mitigating potential losses for users within the triangle gap regions. For the COMPASS constellation, the area of a single triangle gap region can be computed, using Q, as 1.67×10^6 km^2. From simulation, users within a gap region experience access to no less than 4, and no more than 7, satellites at a time. A summary of the coverage performance data is listed in Table 4.

Table 4. COMPASS Constellation Surface Coverage Summary

	Surface Area (km^2)	**% of Total Area**
Mars Reference Sphere	1.4494×10^8	-
Serviced Surface Area (Single Satellite)	7.1469×10^7	49.31
(Orbital Plane)	1.4160×10^8	97.69
(Constellation)	1.0720×10^9	739.63
Coverage Redundancy (Adjacent Plane)	2.4270×10^7	16.74
(Constellation)	9.2710×10^8	639.63
Coverage Gap Triangle	1.6721×10^6	1.15
Total Area of Gap Regions	1.6721×10^7	11.54

IV. Control Station Placement

The control segment will monitor and regulate the COMPASS satellite, serving as the central command hub to send orbital corrections or clock updates to each satellite. These segments can also serve as relay stations between Earth and the COMPASS constellation. In this manner, all deep-space communications can be centralized to only a few command stations, as opposed to creating Eart-to-Mars relay capabilities for each satellite. Candidate locations for the control segment are available on Mars, Phobos, and Deimos. The orbits of all three bodies are well documented and would provide a more stable command environment for the COMPASS constellation, especially with regards to ephemeris updates and orbit tracking for each satellite. Here we present a brief access analysis for command stations placed on either Mars or its natural satellites.

Equatorial locations are more suitable for potential human habitation and provide the best option for setup of the command segment. Two ground stations, located 180 degrees apart within Mars' tropic region, will provide access to all satellites in the constellation. The requirement of two stations alleviates the data processing requirements for each station, and additionally introduces command redundancy for data relay within Mars and with Earth.

Due to the 45° inclination orbits at ASO altitudes, the poles of Mars provide a common access point to every satellite, once daily, for approximately 6 hours each. To minimize the number of ground stations needed to maintain the constellation, a single command station can be placed on either of Mars' poles. However, polar placement would introduce harsh environmental stresses on the command station, which may threaten reliability and accessibility of the command segment.

A command station on either Phobos or Deimos will also provide access to the entire constellation. Phobos, located within the constellation, is more susceptible to occultation from the planet, but has an orbital period which allows for multiple access windows per day for each of the 15 satellites. Deimos, orbiting beyond the constellation, exhibits nearly continuous access to each satellite for days at a time. Brief occultation events occur infrequently for durations of less than 3 hours. Command stations on the moons would require additional long-term, exo-atmospheric safeguarding to ensure reliability and robustness to the space environment.

Free-orbiting command solutions are less stable, less predictable, and operationally more complicated. Additionally, maintaining a constellation relative to an orbiting command module will introduce greater uncertainty in the clock and ephemeris updates for each satellite, as the orbiting module itself will be susceptible to orbital perturbations and clock uncertainties. Ultimately, the best solutions for the command segment involve establishing ground stations on Mars or either one of Mars' natural satellites. Figures 6-9, located in the Appendix, illustrate the expected access profiles for these configurations.

V. Conclusion

As the number of Mars missions continues to grow, so too does the demand for a more robust and reliable navigation system for the red planet. Using a Ballard-Rosette constellation design, global, continuous coverage of Mars can be achieved. The proposed constellation, named the Constellation for Mars Position Acquisition for Small Satellites, or COMPASS, is supported using a geometric constraint analysis to validate our selection of satellite population, number of orbital planes, inclination, and altitude. The solution consists of 15 small satellites, continuously transmitting time-stamped ephemeris and identifier signals across 5 evenly spaced planes. Potential ground control stations can be established on either Mars, Phobos, or Deimos, taking advantage of their orbital predictability and access to the entire constellation. Future work will investigate the stability of the constellation orbits, particularly in terms of long-term responses to gravitational perturbations and anticipated station-keeping practices. Using this navigation architecture, future Mars missions can enjoy enhanced operation with improved navigation capabilities, networked communication, and increased situational awareness.

Appendix

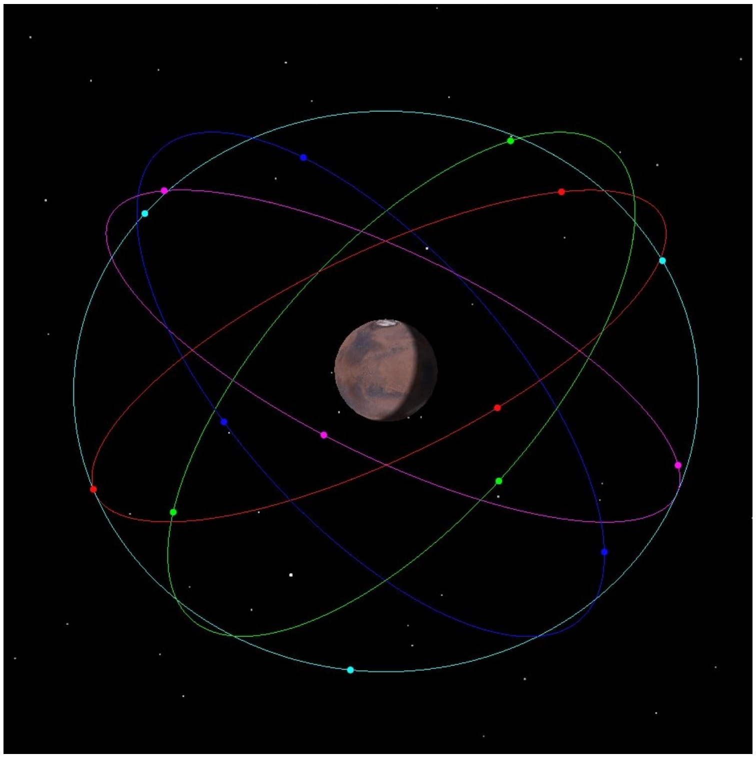
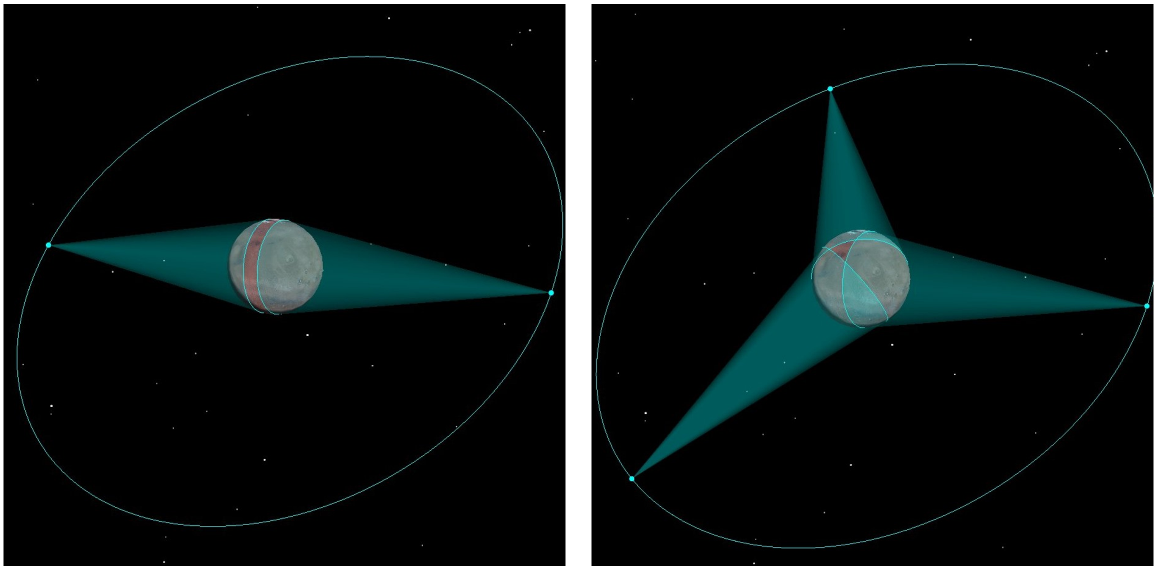


Figure 4. Illustration of proposed Mars navigation constellation.



(a) 2 Satellite Planar Configuration

(b) 3 Satellite Planar Configuration

Figure 5. Planetary surface coverage visualization of 2 and 3 satellite planar configurations.

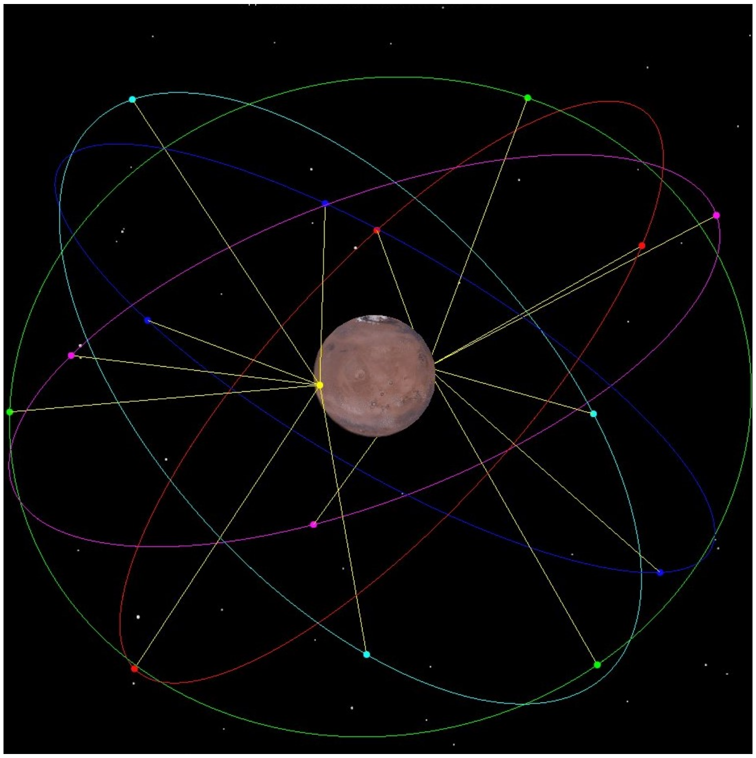


Figure 6. Access profiles for Mars equatorial command stations.

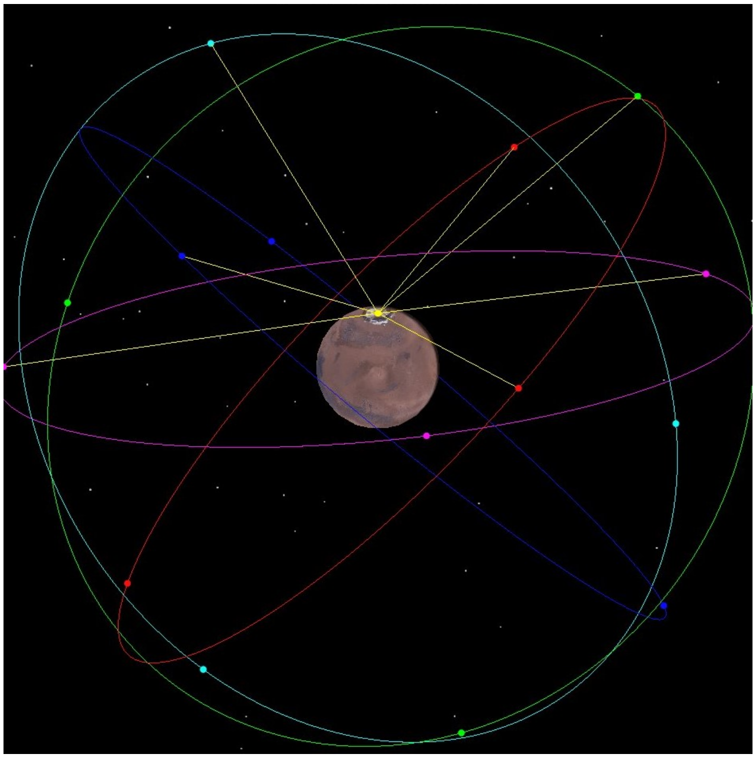


Figure 7. Access profile for Mars polar command station.

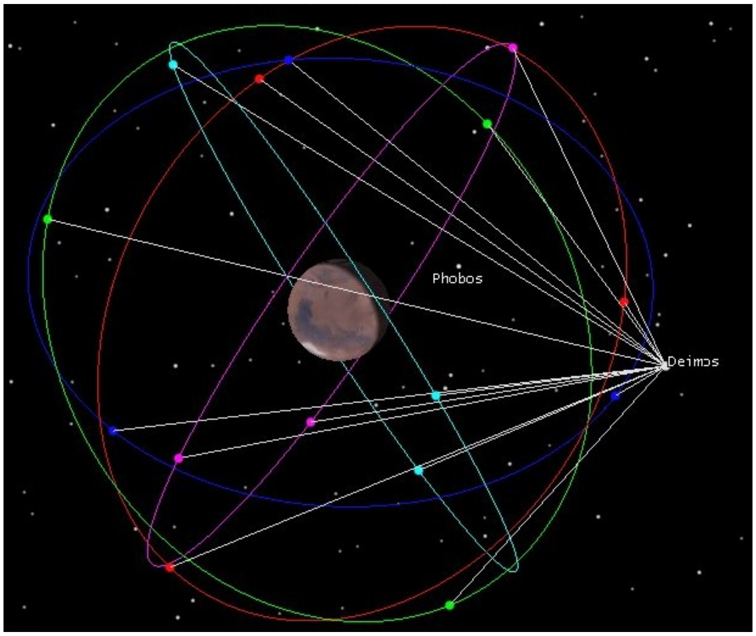


Figure 8. Access profile for Deimos command station.

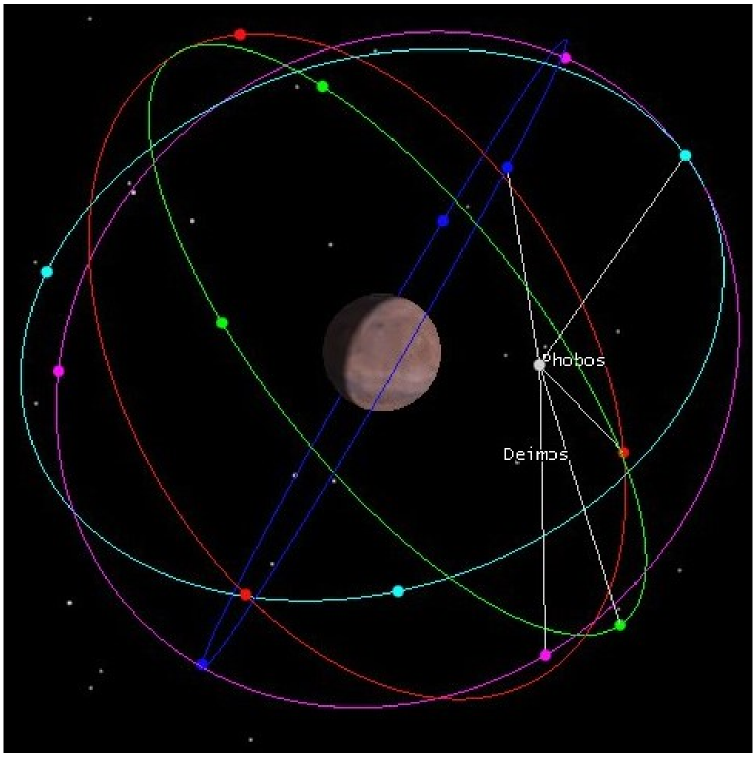


Figure 9. Access profile for Phobos command station.

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