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Geometric Visibility of Ground Sites for Beacon/Relays on the Martian Moons

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Introduction

FUTURE exploration of the surface of Mars will likely require a navigation/communications infrastructure to be built in the vicinity of the planet. Enhancing the accuracy of information about the trajectories of spacecraft approaching the orbital regime and the surface of the planet could significantly improve the probability of mission success. This Note presents a study of one principal aspect (geometric visibility) of an interplanetary navigation beacon/communication relay system for Martian exploration. Using this system would allow mission controllers to develop supplemental or alternative navigation solutions to those obtained via the Deep Space Network alone.

One potential location for these beacons/relays is on the surface of one or both of the Martian moons, Phobos and Deimos. Placing beacons/relays on the moons (rather than on Mars's surface) would avoid problems associated with dust storms and provide science assets (e.g., signal source for accurate determination of the moons' spin-axis precession rates). Other trades, such as the reduced frequency of eclipsing on the moons vs better diversity in Doppler data from orbital beacons, go beyond the scope of this study.

Before proposing such a system, it is important to know how often during the synodic period of Earth and Mars this system can be used. This is accomplished with a geometric analysis of the visibility characteristics between the beacon and Mars, Earth, and the sun. Likewise, should such a system also be used as a communications relay, the geometric relationships must be understood to provide for proper placement of the communications equipment.

This study analyzes line-of-sight visibilities between each Martian moon and Earth, including two possible ground site locations on each of the moons. The visibility was tested from 1 January 2000 to 28 February 2002 (an interval 12 days longer than the 778-day synodic period of the Earth and Mars system[1]). Each of these locations was examined for unobstructed visibility (a 180-deg field of view) and an obstructed viewing case with a 10-deg reduction in viewing all around (160-deg field of view). The line-of-sight results for each moon were then combined to determine the overall line-of-sight visibility of the system, assuming that beacons are placed on both moons.

Background

This is not the first proposed use of the moons of Mars; it is, however, their first proposed use as the location of navigation beacons. Studies by Singer[2] have proposed sending a human mission to Phobos or Deimos. In the first option, a direct approach is suggested, in which all cargo and crew would be carried to one of the Martian moons in one spacecraft. The second option advocates a "split-sprint" strategy, in which cargo and crew travel to the Mars vicinity separately and at separate rates. Once at Phobos or Deimos, a period of exploration is suggested.

Others have examined the need for a Martian navigation infrastructure. For example, Brand and Shepperd[3] have proposed that a local navigation infrastructure (LNI) on Mars will likely be necessary in the near future. Infrastructure purposes include the elimination of delays associated with Deep Space Network tracking and the ability to provide the accuracy necessary for critical mission phases such as aerocapture and precision landing. Physical and mission constraints involving the Martian surface and orbital factors are analyzed to determine the relative performance of various versions of the LNI. All versions presented consist of some combination of surface and orbiting navigation beacons, but do not propose utilization of the moons. Results conclude that a radio-based infrastructure is superior to that of an optical one (because of dust storms), although an optical infrastructure might be necessary during the survey stage of the mission. Hastrup et al.[4] describe a network of low-altitude and aerosynchronous satellites that could provide navigation and communications relay capability for approaching spacecraft and surface rovers.

Regarding use of the Martian moons for communication relays, Stevenson[5] speculates on the probable communications requirements for Mars exploration and discusses several possible systems, including the use of Phobos and Deimos as communication relay bases. However, because the moons alone cannot provide full coverage of the polar regions of Mars as a result of their equatorial orbits, the author dismisses this approach as a lasting solution unless a series of polar satellites is used in conjunction with the Martian moons. Later, suggested long-term communication systems include a Mars Global Positioning System and a Trojan satellite relay system, consisting of relay satellites placed at the Earth–sun libration points. This latter system possesses the added benefit of bypassing the periodic occultation by the sun.

Beacons for Martian navigation are not entirely new either, although previous studies have not focused on moon placement of these beacons. Tuckness[6,7] offers a comparison of an orbiting navigation facility and a single-surface beacon navigation facility. Analysis indicates that surface beacon navigation is the more accurate of these options. Thurman and Estefan[8] and Vijayaraghavan et al.[9] analyze and compare combined Doppler- and range-data-based navigation systems. They conclude that although both systems are capable of relatively good accuracy radial position as determined from Doppler data is fundamentally limited by the nature of the combined solar and Martian gravity fields near Mars. Radial position determined from Doppler data depends strongly on the partial derivative

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Table 1 Mean orbital elements (J2000)[10,a]

	Mean values[b]					
Epoch	a, km	e	i, deg	Ω, deg	$\tilde{\omega}$, deg	l, deg
2000 January 1.5 Earth relative to sun	149,597,816	0.0167	0.0001	−11.2606	102.9472	100.4644
2000 January 1.5 Mars relative to sun	227,936,530	0.0934	1.8506	49.5785	336.0408	355.4533
1990 January 1 Phobos relative to Mars[c]	9,389.821	0.0164	1.0872	319.922	270.658	190.575
1990 January 1.5 Deimos relative to Mars[c]	23,484.831	0.0012	1.7858	148.030	123.335	109.694

[a]Data available online at http://ssd.jpl.nasa.gov/elem_planets.html [cited 29 April 2003].
[b]a = semimajor axis, e = eccentricity, i = inclination, Ω = right ascension of the ascending node, $\tilde{\omega}$ = longitude of periapsis, l = mean longitude.
[c]Elements are with respect to a Mars inertial frame, compatible with IAU 2000 Working Group Report.[11]

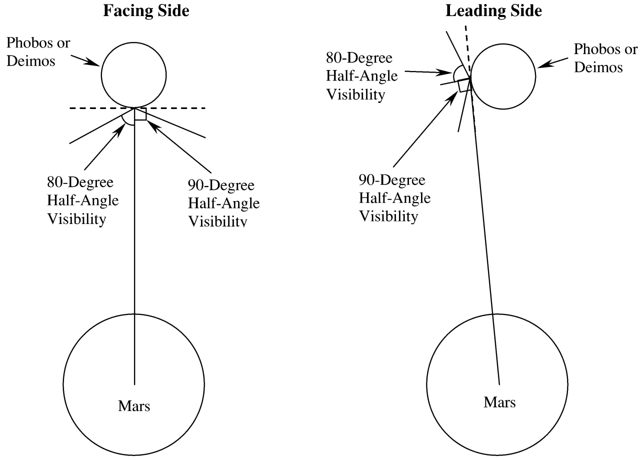

Fig. 1 Depiction of facing- and leading-side beacons.

Table 2 Orbital elements of Martian moons accounting for Mars oblateness perturbations (mean values epoch = 2000 January 1)[a]

Moon	Ω, deg	ω, deg[b]	M, deg[b]
Phobos	−297.97	105.66	140.54
Deimos	−335.45	265.24	230.6

[a]Data available online at http://ssd.jpl.nasa.gov/elem_planets.html [cited 29 April 2003].
[b]ω = argument of periapse, M = mean anomaly.

Table 3 Visibility summary, % of synodic period

	Cone half-angle			
	90 deg		80 deg	
Visibility link	Facing side, %	Leading side, %	Facing side, %	Leading side, %
Phobos–Earth	38.9	44.7	33.4	41.9
Deimos–Earth	45.7	47.8	40.1	44.6
Combined	66.8	71.1	60.1	67.9
Visibility increase for Deimos relative to Phobos	6.7	3.2	6.7	2.7

of acceleration with respect to position. This changes rapidly near Mars, and so for high-speed approaches (and therefore short tracking intervals) the radial position accuracy is low.

Line-of-Sight Analysis

A geometric line-of-sight analysis was conducted to determine visibility of the sun and Earth from two possible ground sites on each of the Martian moons. Figure 1 shows the locations examined and the assumed symmetric conical geometries of the visibility windows. Each ground-site beacon is assumed to radiate a signal within a conical beam, and the site's power generation, using photovoltaic cells, is assumed to be functional if the sun lies within a similar cone whose axis is normal to the moon's surface. In each case, a cone half-angle of 90 deg (field-of-view angle of 180 deg) and a cone half-angle of 80 deg (field of view of 160 deg) were examined. Propagated ephemerides for Earth, Mars, and its moons employed simple models of solar gravity only and J_2 effects of Mars on the moons' orbits [Tables 1 (Refs. 10 and 11) and 2].

Tables 3–5 summarize the key results. The maximum visibilities of the system are 66.82% of the synodic period for the facing side and 71.13% for the leading side. Overall, Deimos has the greatest line-of-sight visibilities to the sun and Earth. Deimos also has the longest access intervals, allowing for a longer duration of navigation data to be transmitted. When comparing the leading side and facing side, the leading side always has the greatest line-of-sight visibility and longest access periods. From these two facts, the argument can be made that the best location for a moon-based navigational beacon would be the on the surface of Deimos, on the side of the moon that is leading its orbital path.

The placement of a single communications relay is slightly more complicated if Mars-relay and relay-Earth link times are to be maximized. To make a recommendation, a few facts can be examined.

Deimos has the greatest line-of-sight visibility and longest access intervals for the relay of data from the surface of Mars to the relay site and then to Earth. The leading side case always provides better line-of-sight visibility between the surface of the moon and Earth. The facing side allows for the longest access intervals between the surface of the Mars and the moons because of the sight always facing the center of the planet. The leading-side location only has a periphery view of the Martian surface, therefore less of a surface swath. Therefore, the leading-edge locations provide less uplink and downlink time from the relay and the surface of Mars.

Communications with Deimos from the surface of Mars would require more power or higher antenna gain (an additional 10 dB) to uplink to the relay. With this in consideration, Phobos would potentially be a better site for large volumes of data.

Based on the examination of the leading side and facing sides only, the best location for a communications relay would be the Mars-facing side of Deimos. Link budget considerations might favor the closer moon Phobos, but this option sacrifices between 3–7% of line-of-sight visibility and up to 10 h in mean access interval length per synodic period.

Multiple transmission sites would give superior performance because of eclipsing concern. There are several possible configurations that would provide almost total coverage with the best being dual sites on Deimos.

With the leading-edge site of Deimos having visibility about 47% of the period, this site would be one of the two beacon locations. Based on the procedure and results obtained, it appears that a trailing-edge site would have similar results. With both sides having visibility close to 47% and with most of this visibility not being redundant because of system geometry, having two sites on opposing sides appears to be the best arrangement for guidance beacons. The only period in which the system would

Table 4 Access intervals for the facing sides

	Phobos, facing side				Deimos, facing side			
	Cone half-angle							
	90 deg		80 deg		90 deg		80 deg	
Access interval	Earth	Sun	Earth	Sun	Earth	Sun	Earth	Sun
Min duration, h	1.4	1.4	1.2	1.2	6.9	6.9	6.0	6.0
Max duration, h	3.9	3.9	3.5	3.5	15.2	15.2	13.5	13.5
Mean duration, h	2.0	2.1	1.8	1.8	11.1	12.7	9.7	11.2
Total duration during one synodic period, h	8250.7	8459.1	7148.0	7350.0	9244.0	9362.6	8134.6	8245.6

Table 5 Access intervals for the leading sides

	Phobos, leading side				Deimos, leading side			
	Cone half-angle							
	90 deg		80 deg		90 deg		80 deg	
Access interval	Earth	Sun	Earth	Sun	Earth	Sun	Earth	Sun
Min duration, h	3.2	2.2	3.0	2.2	0.0	13.1	13.4	12.3
Max duration, h	3.9	3.9	3.5	3.5	15.2	15.2	13.5	13.5
Mean duration, h	3.6	3.6	3.3	3.3	14.9	15.1	13.5	13.4
Total duration during one synodic period, h	8862.0	8984.1	8086.3	8190.9	9366.5	9422.7	8405.5	8401.2

not have visibility would be when the moon is totally eclipsed by Mars.

Even greater visibilities can be obtained using more than two locations. The more locations for beacons, the greater the visibility and redundancy will be. These locations can be stations on the surface of moons or spacecraft orbiting Mars.

Conclusions

This preliminary analysis into the feasibility of utilizing the Martian moons Phobos and Deimos as locations for communication relays and navigational beacons show that the utilization of the moons is a viable option. Additional locations such as sites between the leading and facing edges should be examined as well as instances for double relays. For the optimum placement of navigation beacons, various families of typical orbital transfer trajectories between Earth and Mars can be analyzed further for line-of-sight visibilities conditions.

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