Paper AAS 99-300

American Astronautical Society

Architectural Design for a Mars Communications & Navigation Orbital Infrastructure

R. J. Cesarone*, R. C. Hastrup*, D. J. Bell*, D. T. Lyons* and K. G. Nelson**

* Jet Propulsion Laboratory, California Institute of Technology

** Stanford Telecommunications, Inc.

AAS/AIAA Astrodynamics Specialist Conference

Girdwood, Alaska 16-19 August 1999

AAS Publications Office, P.O. Box 28130, San Diego, CA 92129

AAS 99-300

ARCHITECTURAL DESIGN FOR A MARS COMMUNICATIONS & NAVIGATION ORBITAL INFRASTRUCTURE

R. J. Cesarone, R. C. Hastrup, D. J. Bell, D. T. Lyons
Jet Propulsion Laboratory, California Institute of Technology

K. G. Nelson
Stanford Telecommunications, Inc.

ABSTRACT

Mars has become the focus of an unprecedented series of missions spanning many years, involving numerous nations and evolving from robotics to humans. Operations of this exploratory fleet will require implementation of a new communications and navigation architecture, satisfying the needs of robotic landers, rovers, ascent vehicles, sample canisters, balloons and airplanes, as well as eventual human explorers. NASA's Jet Propulsion Laboratory has begun development of this architecture, comprising Mars orbiting communications and navigation satellites, along with linkage to traditional Earth-based assets, such as the Deep Space Network. The total system will effectively extend Earth-based nodes to Mars, initiating an interplanetary Internet that will bring planetary exploration right into our homes. Focus is on the orbital infrastructure. The baseline architectural system design is presented, as derived from evolving mission and program requirements. Communications and navigation performance characteristics are provided. Launch, near-Earth, interplanetary and Mars orbit insertion phases are briefly treated.

INTRODUCTION

By the summer of 1998, Mars Pathfinder had successfully completed its mission, the Mars Global Surveyor had arrived at the planet, the Mars Climate Orbiter and Mars Polar Lander were rapidly approaching launch, and design of the Mars '01 mission was nearing finalization. With these events as a backdrop, NASA felt that it was time to reassess the overall program of Mars exploration and set an updated course for the future.[1] Thus, JPL was tasked to lead the definition and development of this revised program architecture.

The first step was to incorporate the expertise of a wide group of stakeholders, which included not only the NASA/JPL Space Science Enterprise robotics community, but also representatives from the Human Exploration and Development of Space Enterprise (HEDS), as well as significant participation by representatives from the European, French, and Italian space agencies. The second step was to create a number of technical working groups to conceptualize the various program elements and begin the detailed engineering that would turn these into reality.

One such working group was chartered to investigate a so-called "Mars Infrastructure," which would have the purpose of significantly improving the ability to communicate with, and provide navigation for, assets at Mars, while simultaneously bringing the space exploration experience directly to the public. Recommendations of this working group led to funded Phase A definition studies during FY99 and are expected to proceed into program approval and implementation beginning in FY00.[1]

This paper presents a high-level overview of the envisioned Mars communications and navigation infrastructure, tracing its architecture to requirements emanating from robotic missions, eventual human exploration, and public involvement. Because the architecture relies heavily on assets operational in Mars orbit, the paper will present the results of orbit design trades that affect the resulting communications and navigation capabilities. A roadmap of how this infrastructure is initiated and evolves over time will be shown. Finally, highlights of other orbit and trajectory aspects, including launch, near-Earth operations, interplanetary transit, and Mars orbit insertion will be briefly treated.

A companion paper, entitled "Mars Network Constellation Design Drivers and Strategies,"[2] provides a detailed description of the communications and navigation analyses carried out in the orbital design of the satellite constellation.

ARCHITECTURAL OVERVIEW

The Mars communications and navigation infrastructure, depicted in Figure 1, comprises four main elements. The first of these is a set of Mars-orbiting, relatively low-altitude micro-satellites (MicroSats). Extensive analyses and numerous studies over the last few years have consistently demonstrated the benefits of low-altitude Mars relay satellites for support of landed elements.[3, 4, 5, 6] The currently envisioned MicroSats are to be launched as piggyback payloads on the Ariane 5 launch vehicle.

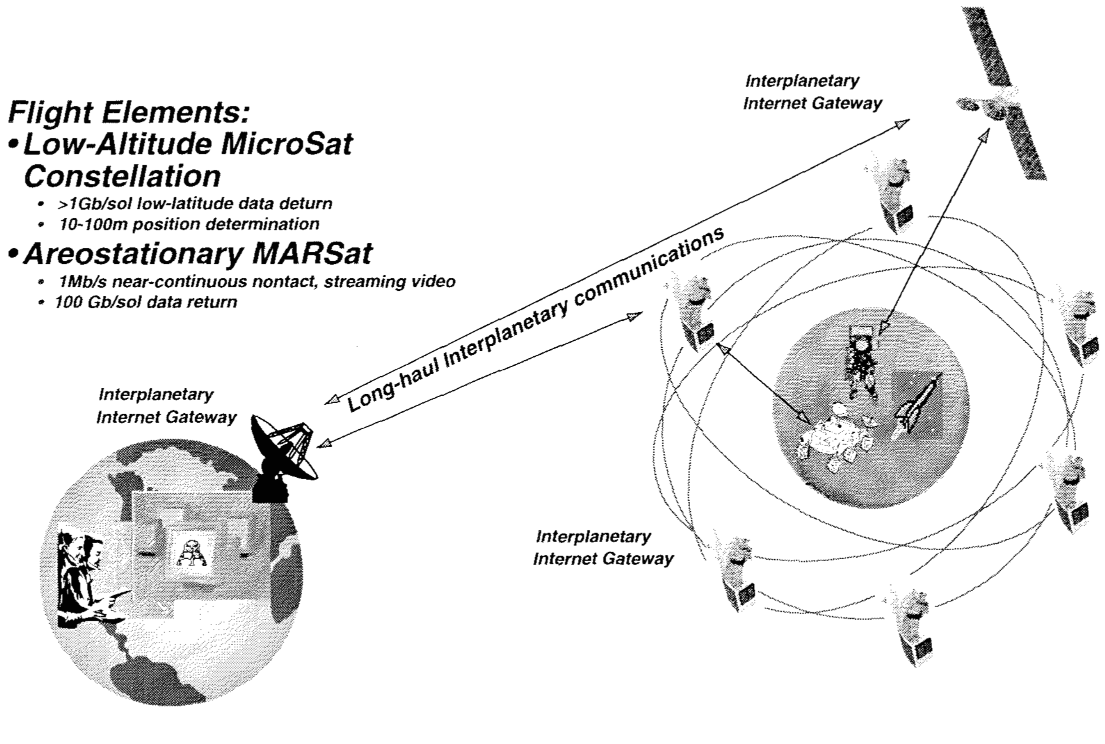

Figure 1 Mars Network Overview

The technique enabling this low-cost approach was first proposed by Blamont[7] and subsequently extended by others.[8, 9, 10] After spending time in a near-Earth phasing orbit, MicroSats will depart for Mars, be inserted into a high elliptical capture orbit, and aerobraked into a final low altitude circular orbit. Wet mass is on the order of 220 kg at launch, of which 140 kg is propellant, necessary to accomplish all ΔVs to arrive at the operational Mars orbit. The actual communications and navigation payload is limited to 6 kg.[11] Despite the modest size of these assets, they are able to provide noticeable improvements in connectivity and end-to-end data rates, as well as the ability to enable position determination in a manner analogous to that of the GPS satellite system at Earth.

A first MicroSat is expected to depart for Mars in the 2003 opportunity, to eventually take up residence in an 800 km, near equatorial orbit. At each succeeding Earth-to-Mars opportunity (~ 26 months), two more such spacecraft will be dispatched to Mars, targeted for near-equatorial and high inclination orbits as needed. Equatorial orbiters provide excellent connectivity to low-latitude landed-elements, which are expected to include most sample return operations. Highly inclined orbiters round out the constellation by providing global coverage for the benefit of high-latitude surface elements. Six satellites are nominally planned for the steady-state constellation. More would be desirable, especially for real-time positioning, but budget constraints will likely preclude this.

The second element consists of a small number of Mars-orbiting areostationary satellites (MARSats). Because of the ΔV requirements to attain this high-altitude orbit, these must be heavier, more expensive, prime launch vehicle payloads and hence limited in number. Nevertheless, they will provide dramatic increases in end-to-end data rates, with nearly continuous coverage over most of the martian hemisphere under their stationary longitudes. The first of these assets will launch at the 2007 Earth-to-Mars opportunity at the earliest. They will eventually provide the high-capacity link that will be required as the near-term robotics program transitions to robotic outposts and then to the set of missions culminating in humans on Mars. The necessary equatorial orbit and lack of orbital dynamics will minimize the utility of the areostationary satellites for global positioning.

A third element of the overall architecture is the set of large deep space tracking antennas located on Earth. These will primarily comprise the antennas of NASA's Deep Space Network, located in the California desert, Spain and Australia. However, tracking assets of other nations are expected to interoperate with the DSN so as to expand capacity and support the overall effort.

The fourth element is the set of systems and software that tie the whole architecture together, and provide a front-end through which the public can participate in the martian adventure. Indeed, the total system can be thought of as an extension of DSN nodes and services to the Mars *in-situ* region. The concept has been likened to the beginnings of an interplanetary Internet that will bring the exploration of Mars right into our living rooms.

MISSION NEEDS

Several planned near-term Mars missions are designed to utilize *in-situ* UHF relay support. However, the baseline requirements and designs of these missions were necessarily established without assuming the potential benefit of Mars Network MicroSats. For the 2003 opportunity, the following missions are in planning or development:

- Micromission Aircraft—Short 15–30 minute flight mission using remote sensing instruments on 17 Dec 2003 (100th anniversary of Wright Brother's flight) with simultaneous UHF relay transmission via the Micromission Carrier, which is targeted to over-fly the aircraft during closest approach of its Mars flyby. Maximum total data return desired (> 1 Gb). Backup relay support by the Mars Surveyor (MS) '01 Orbiter or an '03 MicroSat.

- Mars Sample Return (MSR) Lander—Three month mission in equatorial zone culminating in launch of Mars Ascent Vehicle containing Mars surface and air samples. An S-band link provides 2-way communications between the MSR Lander and Rover. A 2-way direct-to-Earth link is used for commands and return of 70 Mb/sol. UHF capability is also available to supplement and back up the direct link. Desired Doppler surface location determination < 1 km.

- MSR Rover—Delivered by MSR Lander for three-month sample gathering primary mission with possible 3-month extension. Two-way communications via S-band link with MSR Lander or via UHF link with an orbiter. Desired Doppler surface location determination < 1 km.

- MSR Canister—Rides on the Mars Ascent Vehicle and injects into 600 km altitude, 45 deg inclined parking orbit for later retrieval by '05 MSR Orbiter/Earth Return Vehicle. Has low power UHF transponder, which provides a continuous Doppler signal while in sunlight, which is to be received (probably open loop) by the MS'01 Orbiter, Mars Express, or possibly, an '03 MicroSat for orbit determination. Note that Mars Express is a joint Project of the European Space Agency (ESA) and Agenzia Spaziale Italiana (ASI), comprising a remote sensing orbiter and lander to be launched in the 2003 opportunity.

- Beagle 2—Search for life landed element of the Mars Express Project, delivered to Mars for a 180-day mission at a site within 0 to 10 deg latitude. Average relay data return via Mars Express is 15 Mb/sol with contacts every 4 or 5 days. Greater number of contacts and data return desired.

For the 2005 opportunity, the following missions are in planning or development:

- MSR Lander, Rover, and Canister—Repeat of '03 missions at another equatorial zone site.

- Netlanders—Four stations, doing seismic, climate and other network investigations, delivered by the MSR'05 Orbiter for one year of surface operation at sites within ± 35 deg latitude. Average relay data return via Mars Express is 10 Mb/sol with contacts every 4 or 5 days for each netlander. Augmented support desired.

- Micromission probe(s)—are under consideration for the 2005 opportunity.

Although the above near-term Mars missions are not being designed based on required support from Mars Network MicroSats, MicroSats launched in '03 and '05 should be capable of providing enhanced and/or backup communications support for all of these missions. Since most of these missions will be operating in Mars' equatorial zone, the '03 MicroSat will require a low inclination orbit.

The above near-term missions illustrate the very active interest in Mars exploration. The mission requirements and designs for future opportunities are, of course, less well defined; however, international interest and enthusiasm in future Mars exploration appears to be strong.

For the 2007 and following launch opportunities, NASA is considering the options of additional sample return missions and the initiation of robotic outposts. Small-scale probe missions, such as those that can be delivered by Micromission carriers, are also of high interest. The science and public interest in these missions is expected to continue increasing the requirements for higher data volume and connectivity as well as global positioning capability.

Although the MS'01 Orbiter and Mars Express are expected to provide relay support for missions launched in '03 and '05, no known additional science orbiters are planned which would provide future relay capability. Therefore, implementation of an evolving Mars Network should provide the needed future relay capability. For the large missions, implementation of the Network MicroSats should lead to an aggregate capability to return up to a few Gb/sol with very frequent contacts. For smaller scale missions, the global capability of the MicroSats should be an important enabling capability.

For substantially higher data volume and more continuous connectivity, as would be expected to be required for robotic and human outpost missions, the Network areostationary MARSats would be deployed.

ORBIT DESIGN TRADES FOR MICROSAT CONSTELLATION

Five performance goals influence the design of the Mars orbital infrastructure:

1. Provide high capacity coverage of the equatorial regions, even in the event of the loss of any single spacecraft in the constellation. Many robotic missions focus on regions within the ± 15 deg latitude band. Additionally, the first crewed missions are planning near equatorial landing sites. The practical result is to deploy two spacecraft in near equatorial orbits.

2. Provide global coverage, even in the event of the loss of any single spacecraft in the constellation. Some mission types, such as seismic or meteorological networks, require global low capacity coverage. The practical result is to deploy two spacecraft in near-polar orbits.

3. Maximize coverage/performance across all latitudes and longitudes.

4. Minimize coverage/performance variations across all latitudes and longitudes

5. Minimize orbital maintenance and coverage variability due to precession effects.

Goals 3 and 4 can be achieved by "tuning" the inclination and altitude of the satellites making up the constellation.

The communications and navigation performance of many candidate constellations was investigated. Common among the best constellations was a pair of near equatorial orbiters to provide regular communications opportunities for low latitude surface elements. Adding a number of higher inclination orbiters completes the desired planet-wide coverage. Gap times for higher latitudes depend upon the number of inclined orbiters, their orbit spacings and altitudes. A set of variously inclined orbits, with specified relative in-orbit positions was shown to provide optimum coverage over the surface of Mars at any given epoch of time. However, differential perturbations of the elements of these orbits, primarily due to the martian gravity field, result in deterioration of the optimized coverage over time. Ultimately, a baseline constellation having its four near-polar satellites in the same inclination, and at the same altitude, was selected. With elements of these orbits precessing together, the constellation is able to provide long-term consistent coverage. Finally, choice of orbital altitude was influenced by tradeoffs between strength of the radio link and gap time between contacts. Low altitude constellations are characterized by strong links, but longer gap times. Higher altitude constellations have a weaker link, albeit with shorter gap times between contacts. Reduced gap times aid in quick position location of surface elements.

The present conclusion is to baseline a constellation known as the "4Retro111." The complete constellation consists of 2 retrograde, near equatorial (172 deg) satellites and 4 retrograde, highly inclined (111deg) satellites, all in 800 km, circular orbits. This constellation's key features include:

- Best long-term telecommunications/navigation combined performance
- Locked ascending nodes result in consistent/minimum gap times
- Equatorial satellites provide a pass on every orbit to all longitudes within:
  - 14 deg of the equator (assuming 15 deg minimum elevation angle)
  - 18 deg of the equator (assuming 10 deg minimum elevation angle)
- Redundant coverage of all regions and high performance redundancy in the near equatorial region
- Reasonable prospects for constellation evolution
- Retrograde orbits provide improved pass statistics

However:

- 1100 km equatorial satellites would provide wider latitude coverage of equatorial regions and better navigation performance.
- 400 km polar satellites would provide 4 times the communications performance, for energy-limited links, than that of the 800 km satellites

MARS NET EVOLUTION

Figure 2 provides an overview of the evolution of a proposed network at Mars. Both current missions and missions in development are shown as currently planned. The constellation of small satellites is shown as extending beyond 2012. Additional areostationary satellites, for support of high data rates and potential manned missions are depicted as overlapping the small satellites, starting in 2007.

Table 1 provides the planned implementation of the 4Retro111 constellation. Shown is a single prototype MicroSat launched in 2003, followed by two additional satellites at each subsequent launch opportunity. Figure 3 displays the results of investigating the evolutionary performance of the "4Retro111" as spacecraft are added to the constellation.

Note how the first near equatorial spacecraft only provides coverage out to ± 35 deg latitude and gap times start to deteriorate rapidly outside 10 deg latitude. Elements within 10 deg of the equator receive a pass every orbit whereas elements above 10 deg begin to miss passes and thus gap times deteriorate.

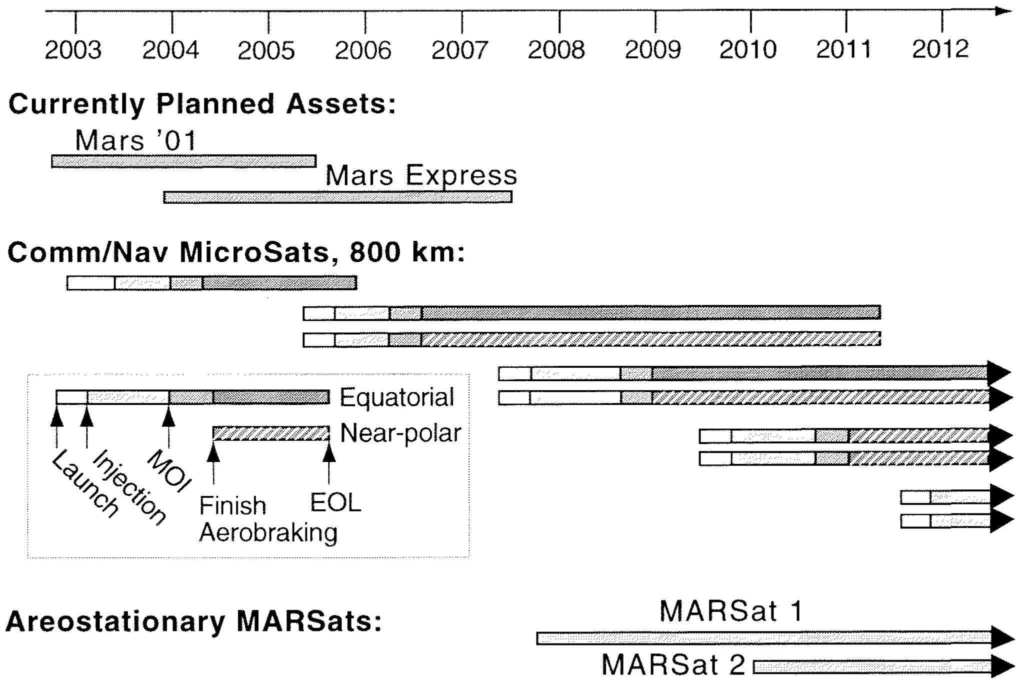

Figure 2 Strategy for an Evolving Infrastructure

Table 1
4Retro111 Constellation Parameters

Injection into Trans-Mars Trajectory	**May '03**	**Sept '05**	**Sept '07**	**Oct '09**
Mars Orbit Insertion	**Dec '03**	**March '06**	**August '08**	**Sept '10**
Finish Aerobraking	**April '04**	**July '06**	**Dec '08**	**Jan '11**
MicroSat 0*	172°, 800 km	------------------		
MicroSat 1		172°, 800 km	------------------	------------------
MicroSat 2		111°, 800 km	------------------	------------------
MicroSat 3			172°, 800 km	------------------
MicroSat 4			111°, 800 km	------------------
MicroSat 5				111°, 800 km
MicroSat 6				111°, 800 km

* prototype, not part of final constellation

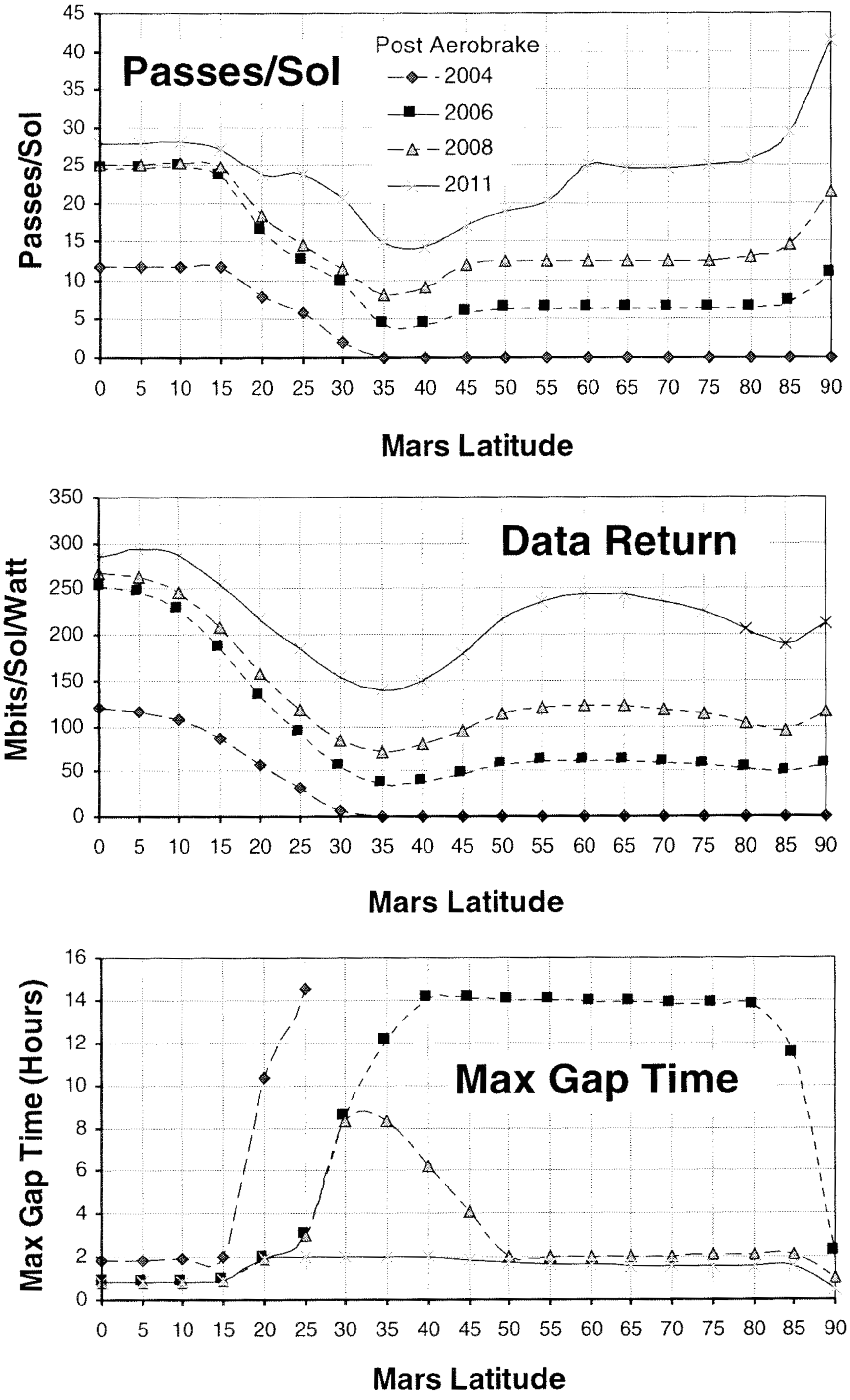

Figure 3 4Retro111 Constellation Performance Summary

On the second launch opportunity, two additional comm/nav orbiters are planned. One of these, inserted into a high-inclination orbit, ensures that all locations on Mars get service. The max gap statistic shows a worst case revisit time of 13–14 hours for the higher latitudes. The implication is that users in these regions are now guaranteed a minimum of roughly two passes per sol. The average is 5 passes per sol. The other orbiter is deployed to the equatorial region. It is assumed, somewhat ideally, that this orbiter is phased 180 deg from the first equatorial orbiter in ascending node. This evenly distributes coverage over the north/south near-equatorial latitudes and provides revisit times of less than 1 hour out to ± 10 deg from the equator and revisit times of less than 2 hours out to ± 20 deg from the equator. Real constellations may or may not have such ideal nodal orientations. Although such orientations are always achievable by waiting in the large elliptical capture orbit until the desired geometry is available, the time required, which may be lengthy, must be deducted from the spacecraft's expected life. Additionally, spacecraft may eventually insert directly into the operational Mars orbit, e.g., using ballute technology, in which case the nodal orientation will not be a targetable parameter.

The third deployment opportunity sees one more equatorial and one more inclined orbiter deployed. The first equatorial orbiter is assumed to be dead by this time, thus the constellation now consists of two equatorial and two inclined orbiters. The second inclined orbiter dramatically reduces max gap times above 50 deg latitude.

Finally, on the fourth deployment opportunity, the constellation is completed by adding two more inclined orbiters. At this point the revisit time to any location on Mars is less than 4 hours and each location is visited on average 15 or more times per sol.

Note that in all cases, the data return numbers are listed as Mbits/Sol/Watt. If a surface element has 10 W Effective Isotropic Radiated Power (EIRP), then the data return numbers scale up by a factor of 10.

A very similar constellation, known as the "4Incl69" had also been temporarily considered. As a "mirror-image" of the "4Retro111" constellation, its only difference was that its orbiters would be inserted into posigrade orbits (i.e., 8 deg and 69 deg) rather than retrograde orbits. Though otherwise acceptable, a posigrade orbit for the 2003 MicroSat suffers from long eclipse durations during orbital insertion phase operations. Conversely, the retrograde orbit for the first MicroSat has short duration eclipses while in the initial elliptical orbit. The differences in performance between the 4Incl69 and the 4Retro111 are subtle. First and most important is the increase in number of passes per sol and reduction in max gap time for elements supported by the near equatorial MicroSats. The equatorial posigrade MicroSat completes 11 orbits per sol and produces 10 passes per sol to any near equatorial surface site. The equatorial retrograde MicroSat completes 11 orbits per sol and produces 12 passes per sol to any near equatorial surface site. The impact is a 20% increase in number of passes and a 17% reduction on maximum gap time. These are the two most important statistics to mission planners. Hence the retrograde equatorial orbits have a slight advantage over the posigrade orbits.

Data return per sol values are essentially unaffected by the switch to retrograde orbits. Whereas the retrograde orbits provide more passes per sol, each pass is of shorter duration because the ground site and the orbiter are moving in opposite directions. There may be some minor advantages to combining posigrade inclined spacecraft with retrograde equatorial spacecraft. This has not yet been investigated.

As the "4Retro111" constellation is emplaced it is also characterized by evolving, indeed improving, navigation performance. Figure 4 depicts position location capability for Mars fixed surface assets (i.e., landers), orbiting satellites (e.g., sample return canisters), and approaching spacecraft. For comparison, capability provided by sole reliance on the Deep Space Network (DSN) is also provided. Gravity field uncertainties derived from Mars Global Surveyor are assumed. All methods provide improved accuracy given longer time periods.

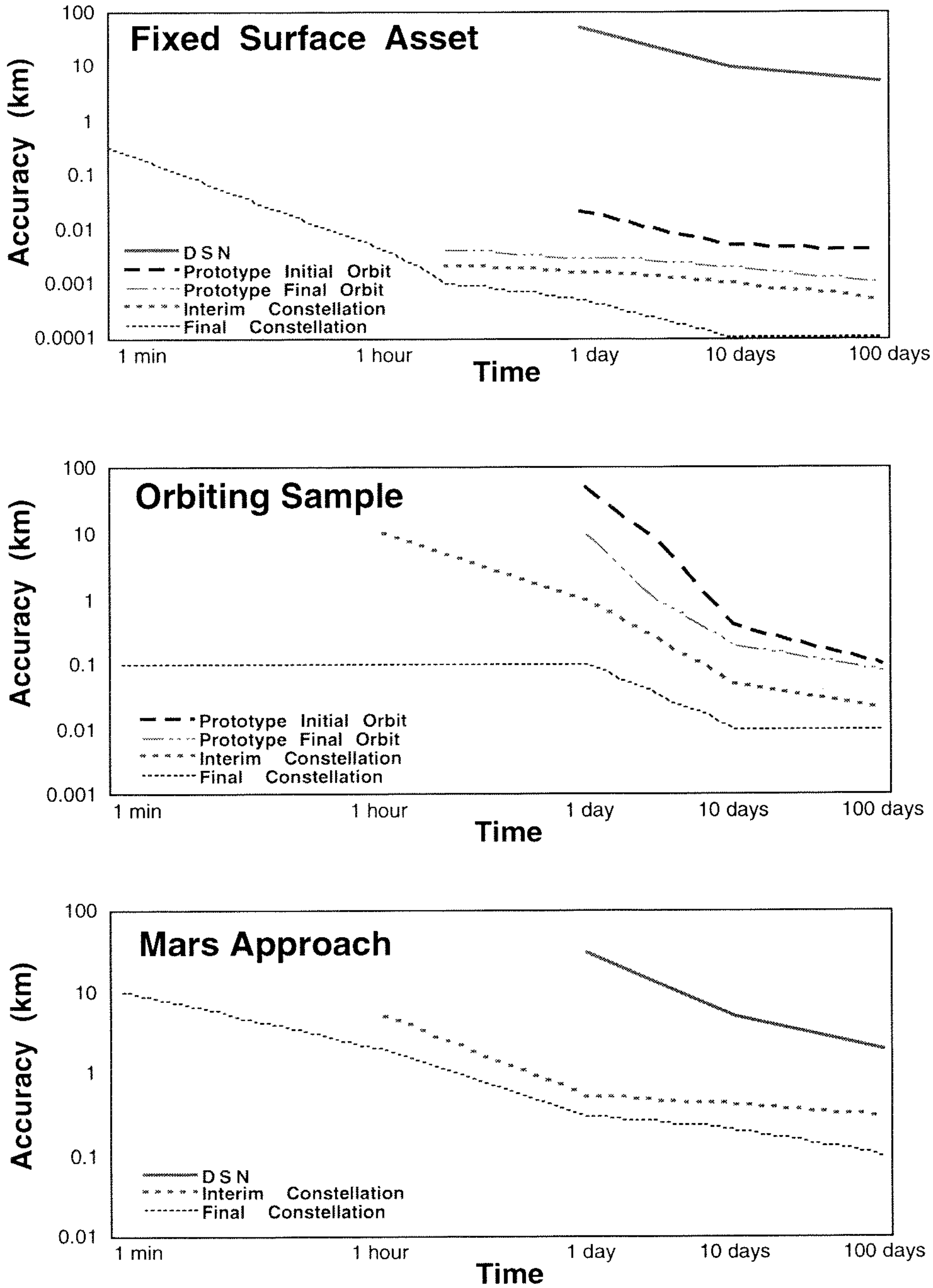

Figure 4 Navigation Performance for Fixed Surface Asset, Orbiting Sample, and Mars Approaching Spacecraft

The 2003 prototype spacecraft, inserted into its near-equatorial orbit, will provide the following *in-situ* navigation capabilities:

- 1-Way UHF-band Doppler to landers, rovers, and orbiting sample canisters at ranges exceeding 1000 km, at an accuracy of 0.5 mm/s (1min samples).
- 2-Way UHF-band Doppler to the Mars airplane, rovers, and orbiting sample canisters at ranges ≤ 1000 km, at an accuracy of 0.5 mm/s (1 min samples).
- 2-Way UHF-band Doppler to a fixed lander at ranges ≤ 5000 km, at an accuracy of 0.5 mm/s (1 min samples).

As Figure 4 shows, the prototype spacecraft, in its final, operational orbit, will be able to locate a fixed lander to within ~ 5 m, using just the small number of tracking passes spaced over a few hours. Gradual improvement in position knowledge is then available as the tracking period lengthens. Although positioning capability is available while the spacecraft is in its initial 3 sol orbit, it is not quite as refined, amounting to ~ 20 m after a 1 day tracking period. For comparison, Earth-based, i.e., DSN, tracking is much coarser, on the order of ~ 70 km after 1 day, again with only gradual improvement over a lengthy tracking period. The prototype spacecraft also supports positioning for the orbiting sample canister. Position knowledge, after 1 day, is ~ 10 km from the final orbit and ~ 60 km from the initial orbit. Note that Earth-based, i.e., DSN, navigation is not available for the orbiting sample because of the sample beacon's very low EIRP. The prototype spacecraft does not support navigation for Mars approaching spacecraft.

For its own navigation, the prototype spacecraft will rely on 2-Way X-band Doppler to the DSN at an accuracy of 0.05 mm/s (10 min samples).

By the time an interim constellation, comprising 2–5 spacecraft, in 111 and 172 deg orbits is emplaced, it will be capable of providing:

- All of the prototype spacecraft's capability, plus
- Radio direction finding for low power users

Figure 4 shows that the interim constellation will provide ~ 2 m positioning for a fixed lander, with a few hours of tracking. This represents a nominal improvement over the capability provided by the prototype spacecraft. The interim constellation provides more significant improvement in positioning for an orbiting sample canister, amounting to ~ 10 km after only 1 hour, and ~ 1 km after 1 day, of tracking. As a new capability, the interim constellation can provide positioning for Mars approaching spacecraft to the level of ~ 5 km after 1 hour, and 0.5 km after 1 day, of tracking.

Two possibilities exist for DSN based navigation of interim constellation satellites. One option makes use of the previous 2-Way X-band Doppler capability used for navigation of the prototype spacecraft. Alternatively, interim constellation satellites can autonomously determine their own orbits using 1-Way X-band Doppler from the DSN. The latter capability is made possible by inclusion of an Ultra Stable Oscillator (USO) in the MicroSats, having a performance of 10^{-14} s/s over 60 s.

Finally, when the final constellation, comprising six or more spacecraft, in 111 and 172 deg orbits is emplaced, it will be capable of providing:

- All of the interim constellation's capability, plus
- 1-Way or 2-Way UHF-band range for precision landing and autonomous operations
- High precision radio direction finding

For the final constellation, Figure 4 shows improvements not just in navigation performance, but more importantly, in the time required to obtain such performance. One meter level position accuracy is available for a fixed lander with a few hours of tracking. However, near real-time positioning, to the ~ 200 m level, is also available. For an orbiting sample canister, the improvement is even more significant, with ~ 100 m positioning being available in near real-time. Finally, near-instantaneous navigation accuracy for a Mars approaching spacecraft can be obtained to the 10 km level, with gradual improvement evident as the tracking period is extended.

Finally, by this point, no 2-Way X-band Doppler will be required for navigation of constellation satellites. Rather, reliance on fully autonomous constellation navigation is anticipated. This will be enabled by UHF cross-links among MicroSats and X-band cross-links between MicroSats and areostationary MARSats.

LAUNCH, NEAR-EARTH, INTERPLANETARY, AND ORBIT INSERTION PHASES

MicroSats are designed to be launched as piggyback payloads, nominally on the Ariane 5. Consequently their launch dates are driven by the timing requirements of the prime payload, typically a commercial communications satellite, and can be as much as 6 months prior to the date of injection to Mars. However, the date of final injection into the Earth-Mars transfer trajectory is fixed, specifically May 31, 2003 for the first MicroSat. Following deployment of the prime Ariane 5 payload, the MicroSat will be deployed into a geosynchronous transfer orbit. Shortly thereafter, the MicroSat will enter a phasing orbit in the Earth-Moon system that will allow it to "kill time" until the injection day arrives. Single or multiple lunar flybys are possible, coupled with 3, 5, or 7 burn maneuver strategies. Mechanics of this trajectory phase have been analyzed by Blamont[7] and Penzo and others[8, 9, 10] and are not further discussed herein.

The interplanetary phase is characterized by a standard Earth-Mars transfer trajectory. For the 2003 and 2005 missions, this will be a Type 1 transfer, and the 2007 will likely utilize a Type 2 transfer.

The nominal, minimum ΔV, Mars orbit insertion date for the 2003 MicroSat is December 26, 2003, at which point it is propulsively captured into a 3 sol orbit with a periapsis altitude of 250 km, inclined 172 deg to the Mars Equator. Aerobraking will be used to shrink the orbit to 800 by 100 km, followed by a periapse raise maneuver. The aerobraking phase will take less than 4 months and 300 orbits. Average dynamic pressure at periapsis, assuming a 2.5 m^2 projected frontal area, would be about 0.45 N/m^2 and the average free stream aerodynamic heating rate at periapsis would be about 0.20 W/cm^2.

Before aerobraking begins, the MicroSat could spend several weeks or months in the 3 sol orbit, so that it could provide a relay link for other assets at Mars. Various assets on the surface could use the MicroSat as a relay during this pre-aerobraking phase. However, timing the initial orbit to arrive several orbits before the Mars airplane, to enable overflight of, and relay for, the airplane during its short flight, is considered likely. This option results in a Mars arrival date of December 11, 2003. Advancing the arrival time by 15 days results in a ΔV increase of 47 m/s at Mars orbit insertion plus an additional 2 m/s at Earth perigee burn which places the MicroSat on the interplanetary trajectory. As discussed earlier, the retrograde inclination is selected to minimize the duration of eclipses while in the elliptical orbit. Another ramification of providing a relay link to the aircraft is to enter a 168 deg rather than 172 deg inclination orbit. Although this is slightly less equatorial, the effect on coverage statistics is not too severe. Future MicroSats, which will replace and augment the 2003 spacecraft, will nominally rely on the 172 deg inclination described earlier.

Once aerobraking begins, it is not possible to predict the ground track accurately due to uncertainties in atmospheric density. Aerobraking will begin with a "walk-in" phase, where periapsis is propulsively lowered into the atmosphere in several steps until the desired atmospheric density is found. Drag from the atmosphere will shrink the orbit by slowing the speed at periapsis. Propulsive maneuvers at apoapsis are required occasionally to adjust the altitude of periapsis in order to maintain the desired drag. The atmospheric density at periapsis changes because periapsis altitude drifts up and down due to gravitational perturbations. The density also changes with the seasons on Mars and dust levels in the atmosphere, as well as with the changing latitude of periapsis. Near the end of aerobraking, the desired drag is reduced to allow enough time to recover from any spacecraft problems. When the apoapsis altitude reaches the desired final value, periapsis is raised with a large, 160 m/s propulsive maneuver. This puts the MicroSat into its final 800 x 800 km orbit.

Several options are being studied to reduce the time required for aerobraking and thus achieve the operational orbit earlier. Since deployable "flaps" have to be added to achieve aerodynamic stability, one option is to increase the area of the flaps to double or possibly triple the surface area exposed to the flow. This would reduce, by one-half to two-thirds, the time required for aerobraking, currently specified as 4 months. Flying at higher dynamic pressures would further reduce the time, but would require a more careful thermal design and more stressful flight operations. Using any unallocated propellant to reduce the orbit period before starting aerobraking would also help significantly. For example, a propulsive strategy to achieve a 1 sol orbit, which will cost an additional ΔV of 116 m/s, may be possible, pending sufficient propellant reserves. These options could potentially reduce the aerobraking duration to several weeks. A possibility under investigation is to capture into orbit using a large, inflatable ballute that is deployed just prior to Mars Orbit Insertion. The ballute would be towed through the upper atmosphere by a tether that would be cut when the velocity had been reduced to the desired value. Because ballute technology is still unproven, it will not be used on the first orbiter mission.

SUMMARY

Planning and implementing a communications and navigation satellite constellation in the manner described provides a long-term, renewable infrastructure at Mars. Orbiting relay satellites will allow small, low-power, surface elements to communicate with Earth, without the mass and complexity that direct-to-Earth links require. Consolidation of in-situ data on these satellites reduces the DSN time required to communicate with assets at Mars. The combined bandwidth capabilities of such a constellation will allow for the increasing amounts of data anticipated and provide new avenues for interaction with Mars-located science instruments. The choice of orbit inclinations will provide coverage to the entire planet, making all latitudes of Mars increasingly accessible from Earth. Frequent, and sometimes simultaneous, contacts with surface elements allow these to be located more accurately and in shorter time frames. The addition of areostationary satellites would allow for even higher data rates, and provide continuous coverage where needed on the planet, to enable high-bandwidth, continuous communications.

ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the efforts of D. S. Abraham, C. D. Edwards, T. A. Ely, J. R. Guinn, E. Levene, S. N. Rosell, T. Svitek, and S. A. Townes in the preparation of this manuscript.

REFERENCES

1. J. F. Jordan and S. L. Miller, "The Mars Surveyor Program Architecture," IEEE 1999 Aerospace Conference Paper 2.201, Snowmass at Aspen, Colorado, March 6–13, 1999.

2. T. A. Ely, R. L. Anderson, Y. E, Bar-Sever, D. J. Bell, J. R. Guinn, M. K. Jah, P. H. Kallemeyn, E. D. Levene, L. J. Romans, and S-C. Wu, "Mars Network Constellation Design Drivers and Strategies," AAS/AIAA Astrodynamics Specialist Conference Paper AAS 99-301, Girdwood, Alaska, August 16–18, 1999.

3. R. Hastrup, R. Cesarone, R. Cook, P. Knocke, and R. McOmber, "Mars Relay Satellite Orbit Design Considerations for Global Support of Robotic Surface Missions," AAS/AIAA Astrodynamics Specialist Conference Paper AAS 93-564, Victoria, British Columbia, Canada, August 16–19, 1993.

4. R. Hastrup, R. Cesarone, A. Miller, and R. McOmber, "Mars Relay Satellite: Key to Enabling & Enhancing Low Cost Exploration Missions," Proceedings of the IAA International Conference on Low-Cost Planetary Missions, Laurel, Maryland, April 12–15, 1994, *Acta Astronautica* Vol. 35, Suppl., pp. 367–376, 1995.

5. T. Svitek, J. King, J. Neuman, R. Fulton, R. McOmber, R. Hastrup, and A. Miller, "Mars Relay Spacecraft: A Low-Cost Approach," 9th Annual AIAA/USU Conference on Small Satellites Paper, Logan, Utah, September 18–21, 1995.

6. W. Horne, R. Hastrup, and R. Cesarone, "Telecommunications for Mars Rovers and Robotic Missions," *Space Technology*, Vol. 17, No. 3/4, pp. 205–213, 1997.

7. J. Blamont, "Using Large Launchers for Small Satellites," JPL Publication 96-26, Introductory Lecture to the 10th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 16, 1996.

8. R. Gershman, P. Penzo, and A. Wiercigroch, "From GTO to the Planets," 3rd IAA International Conference on Low-Cost Planetary Missions Paper IAA-198-0903, Pasadena, California, April 27–May 1, 1998.

9. P. Penzo, "Planetary Missions from GTO Using Earth and Moon Gravity Assists," AIAA/AAS Astrodynamics Specialist Conference Paper AIAA 98-4393, Boston, Massachusetts, August 10–12, 1998.

10. P. Penzo, "Mission Design for Mars Missions Using the Ariane ASAP Launch Capability," AAS/AIAA Space Flight Mechanics Meeting Paper AAS 99-106, Breckenridge, Colorado, February 7–10, 1999.

11. R. C. Hastrup, R. J. Cesarone, D. D. Morabito, and J. M. Srinivasan, "Mars Comm/Nav MicroSat Network," 13th Annual AIAA/USU Conference on Small Satellites Paper SSC 99-VII-5, Logan, Utah, August 23–26, 1999.