Constellation Design of the Mars Network
A System for Communication and Navigation at Mars

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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. JPL has begun development of the MarsNet architecture, comprising Mars orbiting communications and navigation satellites, along with linkage to traditional earth-based assets, such as the Deep Space Network. The baseline architectural system design is presented, as derived from evolving mission and program requirements. Focus is on the orbital infrastructure, considering effects of orbit design trades on telecommunications and navigation performance.
1st MarsNet Spacecraft and Constellation Development Phases

- Design of the MarsNet telecom and navigation constellation has focused on two important and related phases

- The presentation follows this natural division

![Diagram showing initial elliptical orbit, circularized orbit, and evolving constellation.

Constellation Design of the Mars Network]
Part I: The 1st MarsNet Comm Orbiter (MMCO)

- Performance Goals and Metrics
- First MMCO Orbit Selection
- MSR Data Return and Nav Results
- Support of the ‘03 MAV and Orbiting Sample
- X-band Link to Earth
Performance Goals and Metrics

• Coverage
  • Coverage of the Equatorial Region
    • 15 degrees North/South latitude on every orbit
    • 30 degrees North/South latitude at least one pass per sol
  • Coverage of MAV launch and Orbiting Sample

• Telecom
  • 1 Pass per orbit of important surface sites, e.g. MSR, achieving 50Mbits per pass or more from all orbits
  • Repeatable/predictable daylight coverage of MSR especially from initial elliptical orbit

• NAV
  • 100 m positioning accuracy in 3-days from initial elliptical orbit
  • 10 m positioning accuracy in 3-hours from circular orbit

• Evolution
  • MMC0 #1 as a logical 1st component of the evolving MarsNet constellation
MMCO #1 Orbit Selection

- A near Equatorial orbit provides maximum coverage of 2003 & 2005 equatorial surface sites
- Stay away from Altitudes that produce an orbit period synchronous with 1 Sol.
- Lower Inclination satellites provide *CONSISTENT* telecom coverage to the widest latitude band.
- Inclination angles below 5 degrees result in weaker navigation geometry
- Regions NOT seen on every orbit may be subject to daytime/nighttime coverage asymmetries that evolve over time

**RESULT** - Inclination of 5-10 degrees, (or 170-175) is most desirable for equatorial ASAPs
- MMCO #1 Orbit: 172° Inclination, 800km Altitude
Initial Orbit: 1-Sol vs. 2-Sol vs. 3-Sol

- December 2003 arrival geometry results in potential prograde and retrograde orbits as shown below.
- Without aerobraking, the prograde 1-sol orbit evolves into a geometry with solar eclipses of 3-7 hrs. The evolution of the retrograde orbit results in eclipse durations of less than 2 hrs. This consideration makes selection of the retrograde orbit obvious.
- The 1-sol, 2-sol and 3-sol orbits are important options because they provide regular and predictable coverage of surface sites with identical pass geometry on every pass.

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Apoapsis Alt.</th>
<th>Added ΔV Rel. to 3-Sol Orbit</th>
<th>Propellant Rel. to 3-Sol Orbit</th>
<th>Data Rtn. Rel. to 3-Sol Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Sol</td>
<td>32,000 km</td>
<td>107 m/sec</td>
<td>+3.0 kg</td>
<td>x3</td>
</tr>
<tr>
<td>2-Sol</td>
<td>58,000 km</td>
<td>22 m/sec</td>
<td>+0.6 kg</td>
<td>x1.5</td>
</tr>
<tr>
<td>3-Sol</td>
<td>78,000 km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MSR Data Return per pass is Identical for 1-, 2- & 3-Sol

Assumptions
- MSR at 5° North Latitude
- A 2-way link is required
- Command link is uncoded PSK, 10e-5 BER Error rate.
- Available data rates are only 8, 32, 128 and 256 kbps; Choose single rate that maximizes data return
- Monopole to 10 dBi Link.
- Steered ASAP Antenna
- 10 watts RF
- 10 degree minimum elev.

<table>
<thead>
<tr>
<th>Longitude Relative to Periapsis</th>
<th>Data Return per Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-Sol</td>
</tr>
<tr>
<td>30 West</td>
<td>196 Mbits</td>
</tr>
<tr>
<td></td>
<td>12.8min @ 256k</td>
</tr>
<tr>
<td>60 West</td>
<td>151 Mbits</td>
</tr>
<tr>
<td></td>
<td>19.7min @ 128k</td>
</tr>
<tr>
<td>90 West</td>
<td>87 Mbits</td>
</tr>
<tr>
<td></td>
<td>5.7min @ 256k</td>
</tr>
</tbody>
</table>

|                                 | 2-Sol                |
|                                 | 197 Mbits            |
|                                 | 12.8min @ 256k       |
| 60 West                         | 146 Mbits            |
|                                 | 29.8min @ 256k       |
| 90 West                         | 84 Mbits             |
|                                 | 5.0min @ 256k        |

|                                 | 3-Sol                |
|                                 | 197 Mbits            |
|                                 | 12.8min @ 256k       |
| 60 West                         | 142 Mbits            |
|                                 | 18.5min @ 256k       |
| 90 West                         | 84 Mbits             |
|                                 | 5.5min @ 32k         |

* Overflight of deep null in monopole antenna pattern causes reduction in data return.

Antenna Patterns

Constellation Design of the Mars Network

Data rates scaled from reference 32kbps @ 1000km range achievable with 1 watt RF omni-to-omni, rate 1/2 coded return data link.
MSR Data Return Using “Real” Antenna Patterns and Various Antenna Pointing Strategies

Assumptions
- MSR at 15° South Latitude, 60 West of Periapsis
- 1-way link
- 2 (Mars ’98) Helix antennas, 1 Fore, 1 Aft,
- Available data rates are only 8, 32, 128 and 256 kbps;
  Choose single rate that maximizes data return
- Monopole pattern includes polarization loss
- 10 watts RF
- 10 degree minimum elev.

Data Return per Pass, (1 Pass per Sol)

<table>
<thead>
<tr>
<th>ASAP Antenna and Pointing</th>
<th>MSR Antenna Monopole</th>
<th>Patch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Point 03 Helix (+ Anti Earth)</td>
<td>32 Mbits</td>
<td>36 Mbits</td>
</tr>
<tr>
<td></td>
<td>4.2 min @ 128k</td>
<td>4.6 min @ 128k</td>
</tr>
<tr>
<td>Earth Point 98 Helix (+ Anti Earth)</td>
<td>50 Mbits</td>
<td>62 Mbits</td>
</tr>
<tr>
<td></td>
<td>6.4 min @ 128k</td>
<td>6.1 min @ 128k</td>
</tr>
<tr>
<td>Nadir Point Helix</td>
<td>68 Mbits</td>
<td>82 Mbits</td>
</tr>
<tr>
<td></td>
<td>8.9 min @ 128k</td>
<td>10.7 min @ 128k</td>
</tr>
<tr>
<td>Steered Helix</td>
<td>79 Mbits</td>
<td>95 Mbits</td>
</tr>
<tr>
<td></td>
<td>10.3 min @ 128k</td>
<td>12.4 min @ 128k</td>
</tr>
<tr>
<td>Steered 10 dBi</td>
<td>237 Mbits</td>
<td>225 Mbits</td>
</tr>
<tr>
<td></td>
<td>15.4 min @ 256k</td>
<td>14.7 min @ 256k</td>
</tr>
</tbody>
</table>

Data rates scaled from reference
32kbps @ 1000km range achievable
with 1 watt RF omni - to - omni, rate
1/2 coded return data link

Constellation Design of the Mars Network
Positioning Performance of Surface Elements with 1st MMCO

- UHF 2 Way Doppler to Element (.5 mm/s @ 60 sec) at Equator & X-Band 2 Way Doppler to DSN (.05 mm/s @ 600 sec)
- Initial operations ⇒ 3-Sol orbit with MGS75B gravity error and 10% SRP error considered
- Pre aerobrake operations ⇒ 3-Sol orbit with gravity field and SRP estimated
- Final operations ⇒ Final orbit with gravity and SRP considered (data above uses MGS75B and 10% SRP, actual will have new field data)
Telecom Support of ‘03 MAV Launch

- Assumes
  - Morning MAV Launch from equatorial location and other spacecraft geometries as shown to the right
  - Open-Loop sampling and digital recording of the received signal and reconstruction on Earth in a 40 Hz BW loop receiver

<table>
<thead>
<tr>
<th>Mars Net 1</th>
<th>MAV Launch</th>
<th>2 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 dBi steered antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max range = 35,000 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars ‘01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Omni&quot; antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10,000 max range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rover</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Range = 6000 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>omni antenna 0° min elev</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars Express</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Omni antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max range = 20000 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any 1 sees MAV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any 2 sees MAV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Orbiting Sample Visibility from Orbiting Platforms: 5-Sols

<table>
<thead>
<tr>
<th>Platform</th>
<th>Contact Information</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Express; 7 hr 0 dBi</td>
<td>0 contacts - 0.0 min</td>
<td>1000 km</td>
</tr>
<tr>
<td>Mars Net-1; 1 sol 0 dBi</td>
<td>1 contact - Avg. 4.0 min</td>
<td>5000 km</td>
</tr>
<tr>
<td>Mars Net-1; 1 sol 10 dBi</td>
<td>5 contacts - Avg. 10.9 min</td>
<td>5000 km</td>
</tr>
<tr>
<td>Mars Net-1; 800 km 0 dBi</td>
<td>16 contacts - Avg. 3.6 min</td>
<td>5000 km</td>
</tr>
<tr>
<td>Mars Net 2005</td>
<td>37 contacts - Avg. 4.0 min</td>
<td>5000 km</td>
</tr>
</tbody>
</table>

- Contacts indicated below include the requirement that the canister be sunlit
- Pass durations not to scale on the chart

Time (Sols): 0, 1, 2, 3, 4, 5

<table>
<thead>
<tr>
<th>Platform</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars '01</td>
<td>93° 400 km</td>
</tr>
<tr>
<td>Mars Express</td>
<td>86.5° 250 km x 11583 km</td>
</tr>
<tr>
<td>Mars Net-1</td>
<td>172° 1 sol orbit</td>
</tr>
<tr>
<td>Mars Net-1</td>
<td>172° 1 sol orbit</td>
</tr>
<tr>
<td>Mars Net-1</td>
<td>172° 800 km circular</td>
</tr>
<tr>
<td>Mars Net 2005</td>
<td>1 - 172° 800 km</td>
</tr>
</tbody>
</table>

Pre-Aerobrake

Post-Aerobrake

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Positioning Performance of Orbiting Sample with 1st MMCO

- **Initial ops**
  - 3-Sol orbit with MGS75B gravity error and 10% SRP error considered
  - Open Loop 1 Way Doppler to OS (5000 km max range)
  - < 1 km performance achieved with a single 16 min pass
  - Velocity uncertainties yield predicted error of 10 - 100 km level
- **Final ops**
  - Final orbit with gravity and SRP considered (data above uses MGS75B and 10% SRP, actual will have new field data)
  - Closed Loop 2 Way Doppler to OS (1000 km max range)
  - < 100 m performance achieved with ~ 1 day worth of passes
X-band Return Link to Earth

X-band, 8.45 GHz
8 hours/day to 3 DSN Sites,
(Minus Occultations)
Return: 5.5 kbps at 2.6 AU Range
150 kbps at 0.5 AU Range

Options for Increasing Data Return to Earth

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Factor</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>20w ---&gt; 40w</td>
<td>x2</td>
<td>More Solar Panel, go to TWTA, mass</td>
</tr>
<tr>
<td>0.8m ---&gt; 1.2m</td>
<td>x2.25</td>
<td>Mass, Need to fit folded between tanks</td>
</tr>
<tr>
<td>34m ---&gt; 70m</td>
<td>x4</td>
<td>DSN time on bigger antenna</td>
</tr>
</tbody>
</table>

- One 30-60 minute Occultation per day while in the 1-sol orbit
- 1/3 of Earth link time lost to Occultations when in the final circular orbit
Part II: The Entire Constellation

- Performance Goals
- Coverage Considerations
- Candidate Constellations
- Metrics
- Preliminary design leading to the 4retro111 constellation
- Buildup of the 4retro111 Constellation
- Open Issues/Continuing Effort
Mars Network Constellation Performance Goals

- Global coverage over a selected time span (not continuous)
- Higher volume comm support of the equatorial regions
- Maximize comm & nav performance across all latitudes and longitudes
- Minimize comm & nav performance variations across latitude and longitude (except focused support near equator)
- Maximize utility during buildup of the constellation
- Redundant coverage in the event of the loss of any single spacecraft
- Minimize coverage variability due to long-term orbit perturbations
Coverage Considerations

- Small constellation with maximum of 6 satellites
  - Low altitudes 400 ~ 1200 km
    - Support low-power comm users
    - Continuous global coverage not possible
  - Inclined planes ⇒ cover poles & global support over time
  - Nonsynchronous altitude ⇒ avoids significant longitudinal biases
  - Nonequatorial ⇒ avoids navigation position fix sensitivity at equator
  - Multiple inclinations ⇒ spreads latitudinal support & focus at equator
Coverage Considerations - Multiple Inclinations

- Relative drift of orbit planes ⇒ degenerate plane spacing possible

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Multi-Inclined Orbit Planes
- $i = 10^\circ, 35^\circ, 55^\circ, 65^\circ, 75^\circ, 85^\circ$
- Initial equal spacing between nodes
- Relative nodal drift yields degenerate geometries

4retro111 Orbit Planes
- $i = 2 @ 172^\circ & 4 @ 111^\circ$
- No relative nodal drift between planes within each subconstellation

⇒ Use Hybrid of 2 Subconstellations
## Candidate Constellations

<table>
<thead>
<tr>
<th>Constellation</th>
<th>$4inc65$</th>
<th>$4retro111$</th>
<th>$4inc80$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat 1</td>
<td>$10^\circ, 1100$ km</td>
<td>$172^\circ, 800$ km</td>
<td>$10^\circ, 1100$ km</td>
</tr>
<tr>
<td>Sat 2</td>
<td>$10^\circ, 1100$ km</td>
<td>$172^\circ, 800$ km</td>
<td>$10^\circ, 1100$ km</td>
</tr>
<tr>
<td>Sat 3</td>
<td>$65^\circ, 1100$ km</td>
<td>$111^\circ, 800$ km</td>
<td>$80^\circ, 400$ km</td>
</tr>
<tr>
<td>Sat 4</td>
<td>$65^\circ, 1100$ km</td>
<td>$111^\circ, 800$ km</td>
<td>$80^\circ, 400$ km</td>
</tr>
<tr>
<td>Sat 5</td>
<td>$65^\circ, 1100$ km</td>
<td>$111^\circ, 800$ km</td>
<td>$80^\circ, 400$ km</td>
</tr>
<tr>
<td>Sat 6</td>
<td>$65^\circ, 1100$ km</td>
<td>$111^\circ, 800$ km</td>
<td>$80^\circ, 400$ km</td>
</tr>
</tbody>
</table>

- Single satellite per plane
- $4inc65$ & $4retro111$: ascending node between planes within subconstellations spaced uniformly
- $4inc80$: nodes spaced equally between $(10^\circ, 80^\circ, 80^\circ, 10^\circ, 80^\circ, 80^\circ)$
Communication Metric

- Mean Data Volume/Sol/Watt – Data quantity metric for a power limited mission.
  - Altitudes ~ 400-1200 km yield highest total data return per sol, range-squared energy dispersion dominate at higher altitudes.

- Assumptions
  - Omni- directional antenna on the landed element & spacecraft
  - 500 Kelvin receive system noise temperature
  - 400 MHz communication frequency
  - 3 dB of polarization and feed losses
  - 2.8 dB of receiver losses
  - Threshold \( \text{Eb/ No} = 3.2 \text{ dB} \), \( (K=7, R=1/2 \text{ with } (255, 223) \text{ R- S Code}) \). Corresponds to BER of \( 1 \times 10^{-6} \) for non- interleaved codes
  - Minimum elevation angle of 15°
Navigation Metric

- Mean Response Time (MRT) – Average time to collect sufficient measurement observations to compute a users position to a prescribed accuracy (10 m accuracy in subsequent plots).
  - Minimizing time to collect observations key to enabling autonomous rover operations.

- Assumptions
  - 2-Way Doppler (.5 mm/sec @ 60 sec) - shown. Other data types analyzed include 2-Way Range (1 m) & 1-Way Range (1 m) (1σ). Results available on request.
  - User clock fractional frequency stability of 10 E –11 for 60 sec. When estimating positions using 1-Way range it is assumed that the clock errors are estimated simultaneously. The satellite clock is considered to be perfect for analysis purposes (a current specification for this clock is 10 E –13 for 60 secs).
  - Orbit errors are considered at a level of 2m radial (1σ), 7 m along track (1σ), 7 m cross track (1σ). (These error levels are consistent with the new martian gravity field MGS75B developed from data collected by the Mars Global Surveyor satellite.)
  - Atmospheric error and other error sources are neglected
**Constellation Comparisons**

- **Focus at equator**
- **Minimal overlap at poles**
- **Lower altitude than 4inc65**
- **Retrograde avoids long eclipses**
- **Redundancy**
- **All users get 140 Mbits/Sol/Watt and 10 m positioning within 1.5 hrs**

*JPL*  
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4retro111 Buildup Performance

Build Up Plan

2004
172° 111° proto

2006
172° 111° proto + 1 1

2008
172° 111° 2 2

2011
172° 111° 2 4

Constellation Design of the Mars Network
Continuing Effort & Open Areas

- Antenna types, pointing, thrusters, fuel and momentum wheels
- Minimum elevation angle, propagation effects
- Comm & nav architecture and operating scenarios
  - Multiple data rates per pass
  - Simulation of end-to-end data performance including protocols
  - Refine strategies for providing comm and nav user services
    - Scheduled vs. Random access to MarsNet services
    - User & Network Navigation services
  - Crosslink architecture
  - Autonomous self-nav with 1-way Doppler from DSN with $10^{-13}$ oscillator and/or crosslinks
  - Determine constellation maintenance requirements/strategies - analyze long term constellation behavior
  - Integration of Aerostationary MarsNet spacecraft
Continuing Effort & Open Areas (cont)

- Precision landing and real time navigation performance - utilization of radio direction finding
- Time management architecture
- Optimize hybrid constellation parameters - next iteration constellation design