Constellation Design of the Mars Network

A System for Communication and Navigation at Mars

Presenters: Dave Bell & Todd A. Ely

Comm/Nav Constellation Design Team Members:

R. Anderson, Y. Bar-Sever, D. Bell, T. Ely, J. Guinn, M. Hart, P. Kallemeyn,
E. Levene, M. Jah, L. Romans, S. Wu

1999 International Symposium on Space Communications and
Navigation Technologies,
Pasadena, CA
September 21-23, 1999

ACKNOWLEDGEMENTS

The work described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

JPL

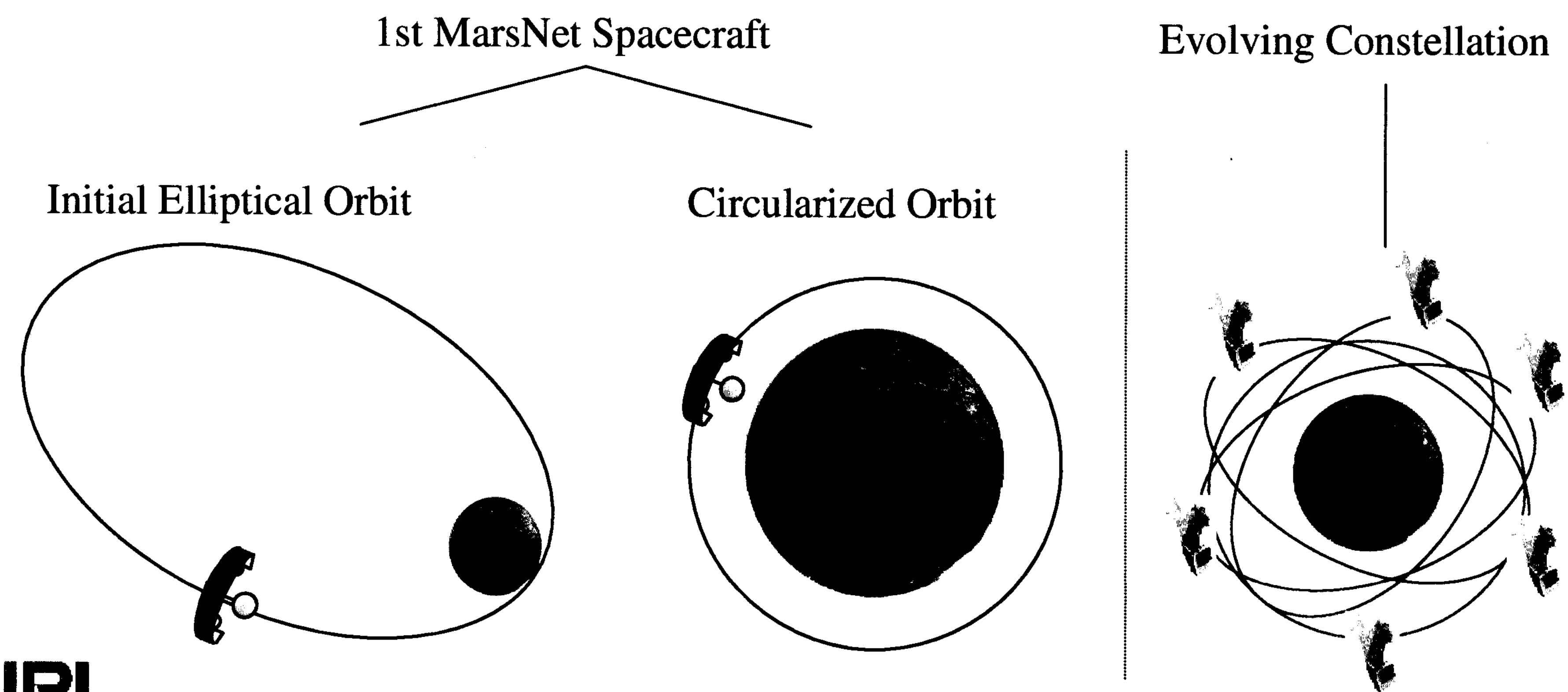
Abstract

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



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

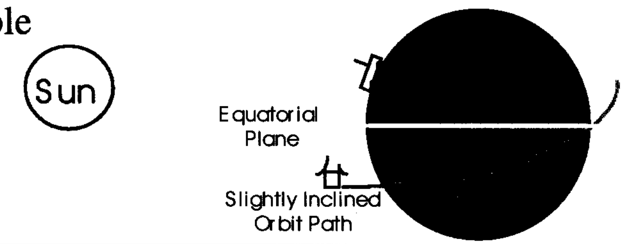
- Telecom
  - 1 Pass per orbit of important surface sites, e.g. MSR, achieving 50Mbits per pass or more from all orbits
  - Repeatable/predictable daylight coverage of MSR especially from initial elliptical orbit

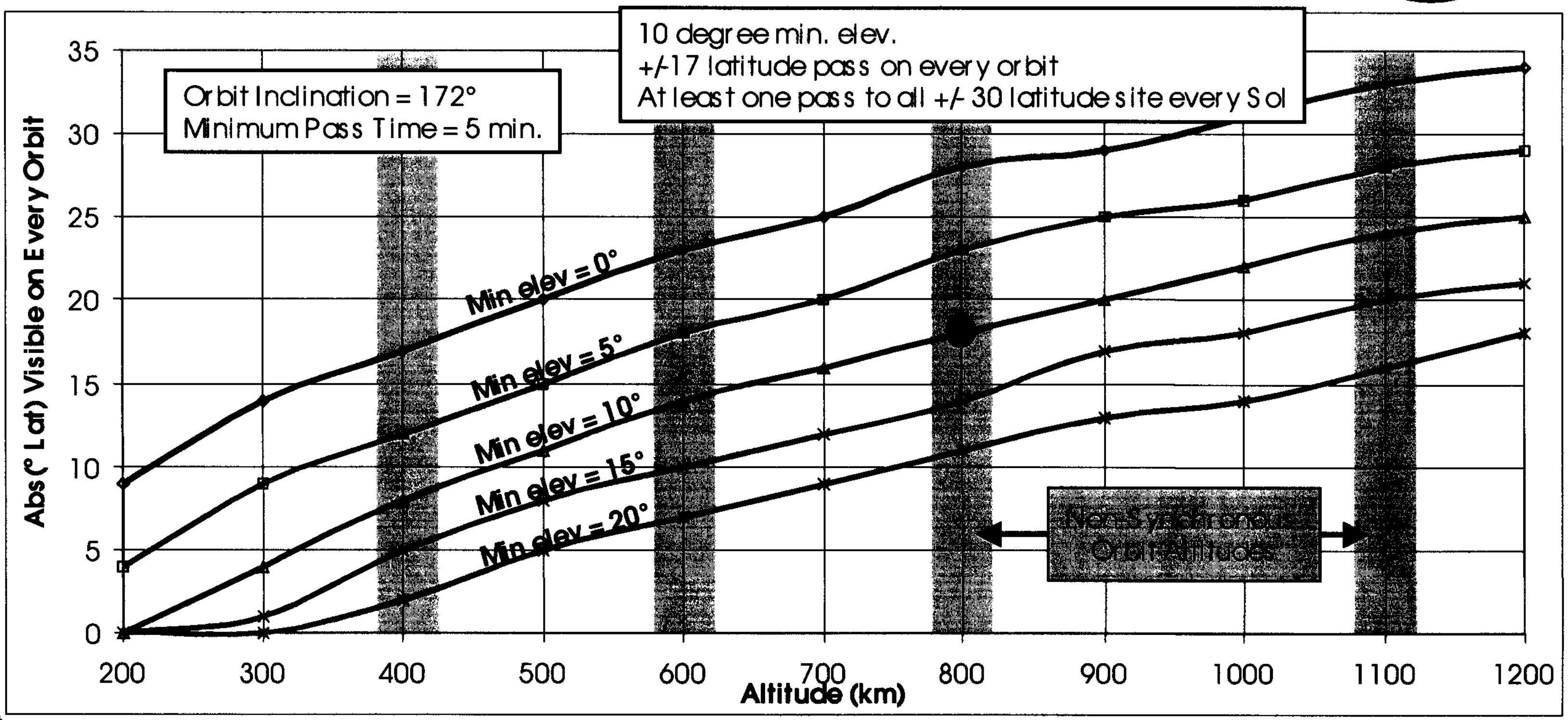
- NAV
  - 100 m positioning accuracy in 3-days from initial elliptical orbit
  - 10 m positioning accuracy in 3-hours from circular orbit

- Evolution
  - MMCO #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



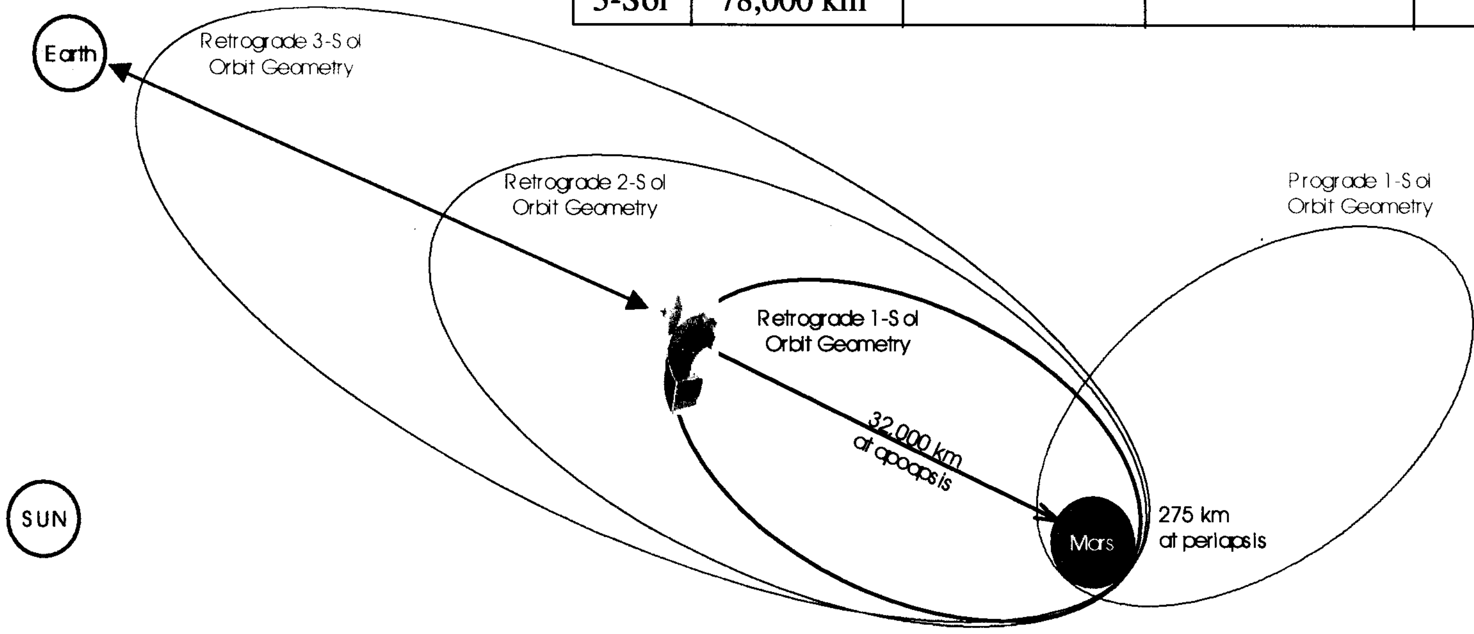


JPL

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.

Orbit	Apoapsis Alt.	Added ΔV Rel. to 3-Sol Orbit	Propellant Rel. to 3-Sol Orbit	Data Rtrn. Rel. to 3-Sol Orbit
1-Sol	32,000 km	107m/sec	+3.0 kg	x3
2-Sol	58,000 km	22m/sec	+0.6 kg	x1.5
3-Sol	78,000 km			



View from above Martian North Pole Jan. 1, 2004

JPL

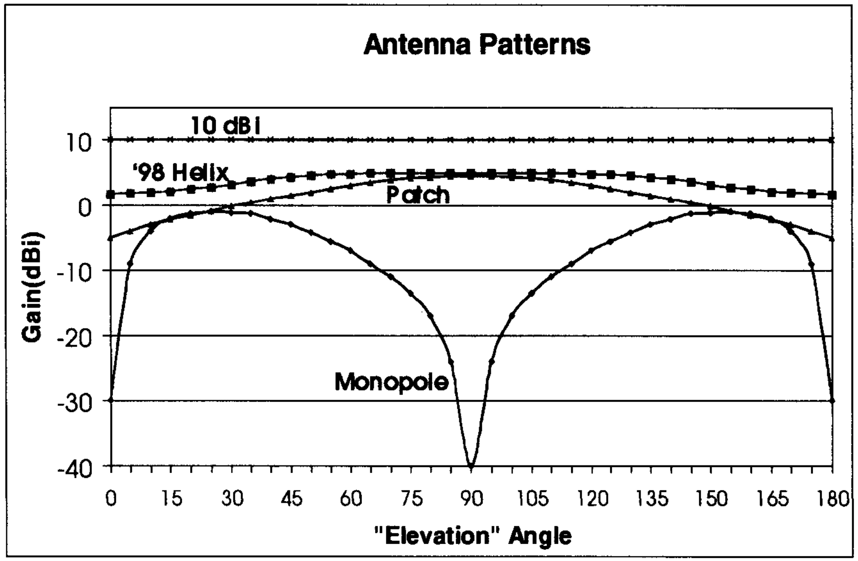
MSR Data Return per pass is Identical for 1-, 2- & 3-Sol

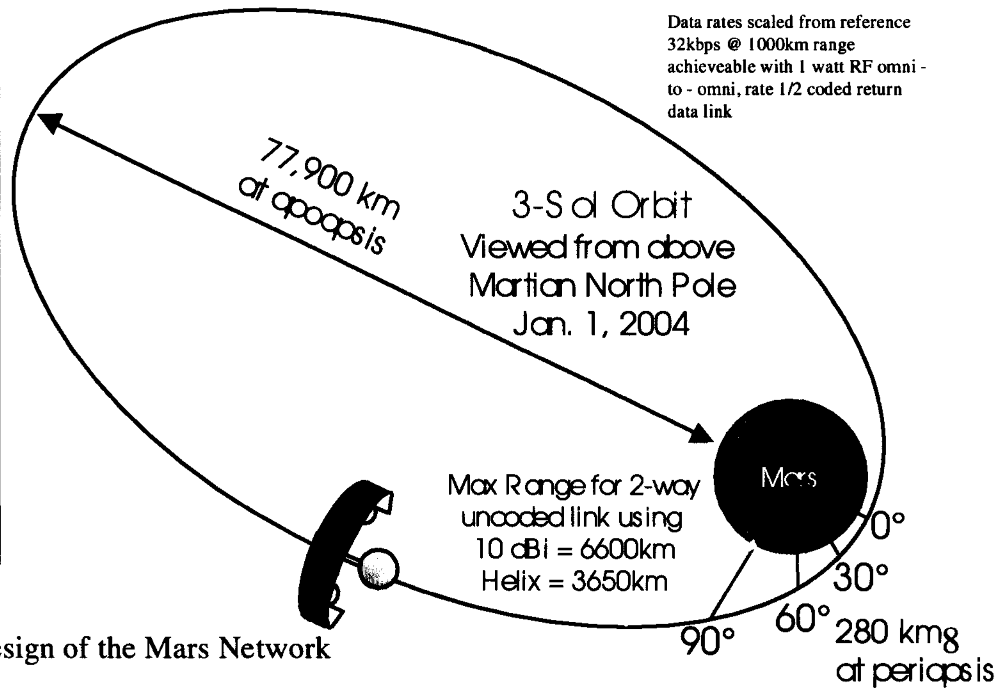
Assumptions
- **MSR at 5° North Latitude**
- **A 2-way link is required**
- **Command link is uncoded PSK 10e-5 BER Error rate.**
- **Available data rates are only 8, 32, 128 and 256 kbps; Choose single rate that maximizes data return**
- **Monopole to 10 dBi Link.**
- **Steered ASAP Antenna**
- **10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

Data Return per Pass

Longitude Relative to Periapsis		1-Sol	2-Sol	3-Sol
30 West		196 Mbits 12.8min @ 256k	197 Mbits 12.8min @ 256k	197 Mbits 12.8min @ 256k
60 West		151 Mbits * 19.7min @ 128k	146 Mbits 29.0min @ 256k	142 Mbits * 18.5min @ 256k
90 West		87 Mbits * 5.7min @ 256k	84 Mbits 5.0min @ 256k	84 Mbits * 5.5min @ 32k

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



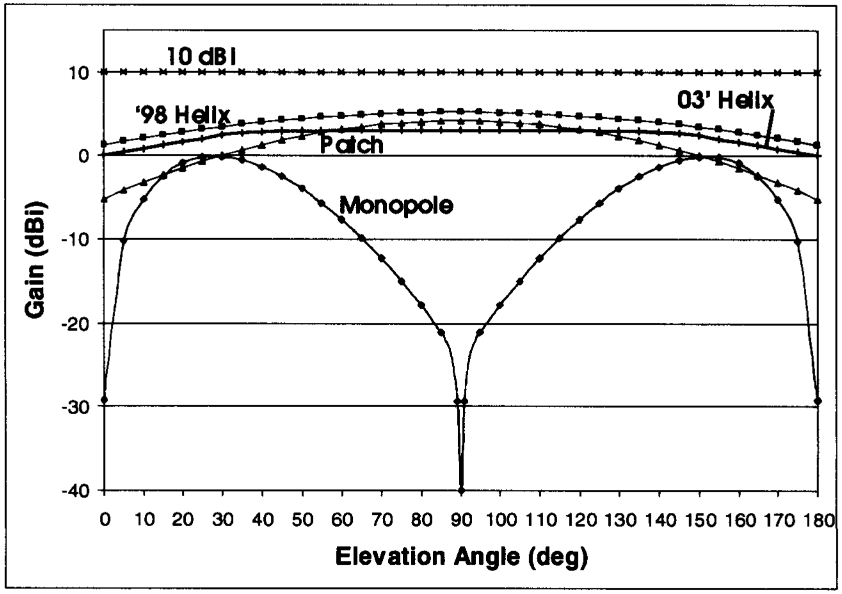


15° South, MSR Data Return Using "Real" Antenna Patterns and Various Antenna Pointing Strategies

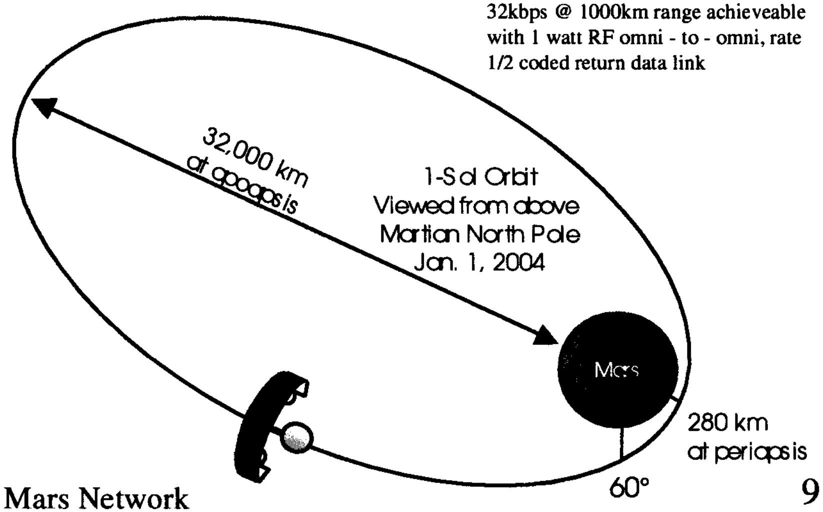
Assumptions
- **MSR at 15° South Latitude, 60 West of Periapsis**
- **1-way link**
- **2 (Mars '98) Helix antennas, 1 Fore, 1 Aft,**
- **Available data rates are only 8, 32, 128 and 256 kbps; Choose single rate that maximizes data return**
- **Monopole pattern includes polarization loss**
- **10 watts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

Data Return per Pass, (1 Pass per Sol)

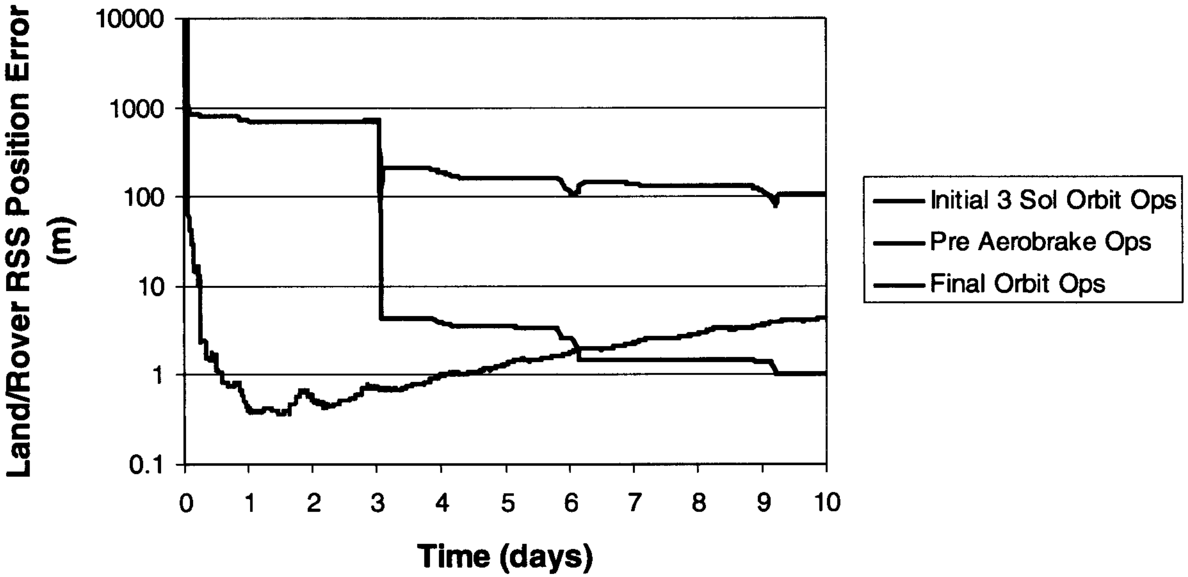
ASAP Antenna and Pointing	MSR Antenna Monopole	MSR Antenna Patch
Earth Point 03 Helix (+ Anti Earth)	32 Mbits 4.2 min @ 128k	36 Mbits 4.6 min @ 128k
Earth Point 98 Helix (+ Anti Earth)	50 Mbits 6.4 min @ 128k	62 Mbits 8.1 min @ 128k
Nadir Point Helix	68 Mbits 8.9 min @ 128k	82 Mbits 10.7 min @ 128k
Steered Helix	79 Mbits 10.3 min @ 128k	95 Mbits 12.4 min @ 128k
Steered 10 dBi	237 Mbits 15.4 min @ 256k	225 Mbits 14.7 min @ 256k



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



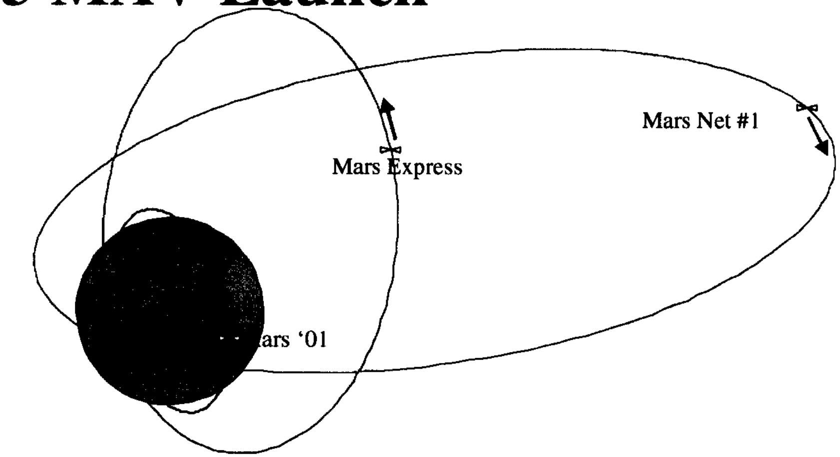
Positioning Performance of Surface Elements with 1st MMCO

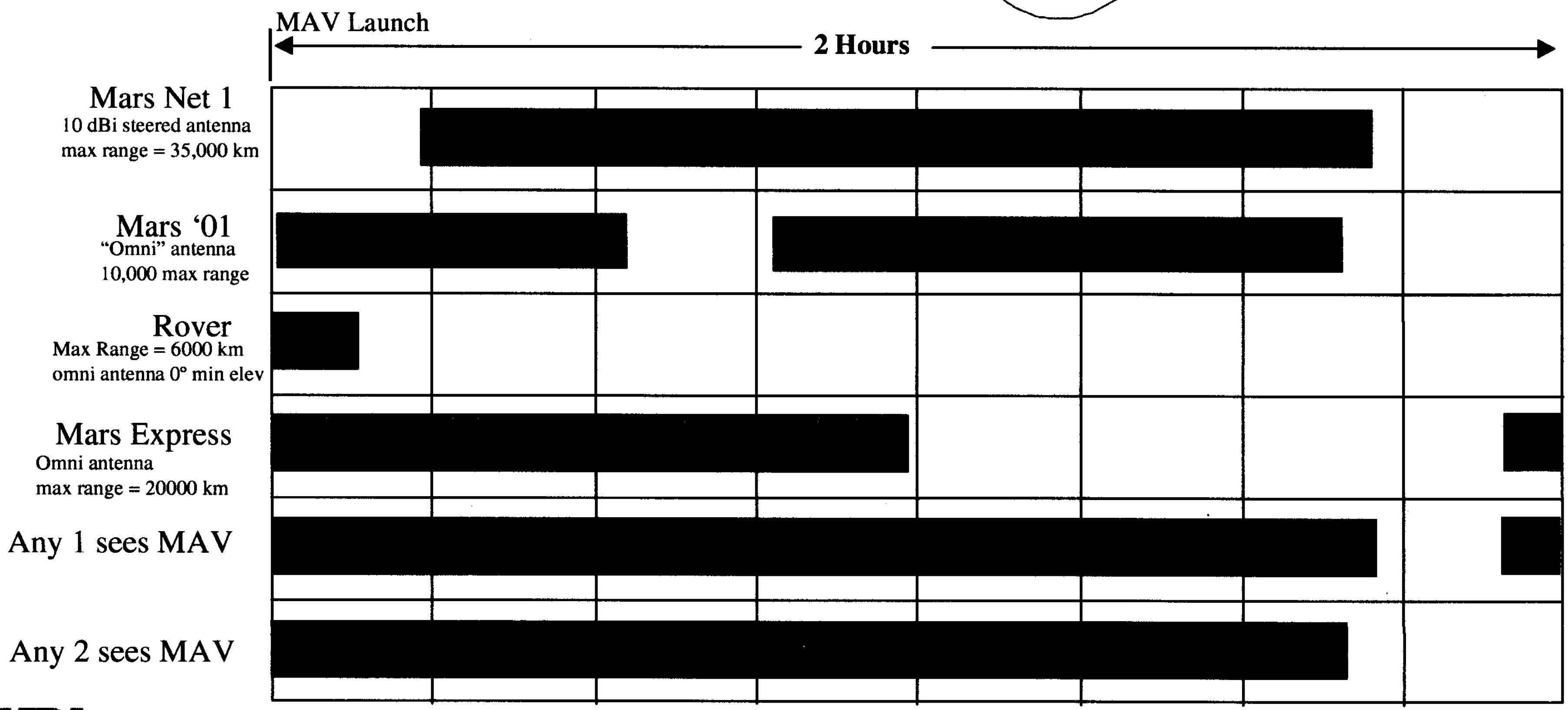


- UHF 2 Way Doppler to Element (.5 mm/s @ 60 sec) at Equator & X-Band 2 Way Doppler to DSN (.05 mm/s @ 600 sec)
- Initial operations ⇒3-Sol orbit with MGS75B gravity error and 10% SRP error considered
- Pre aerobrake operations ⇒ 3-Sol orbit with gravity field and SRP estimated
- Final operations ⇒ Final 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

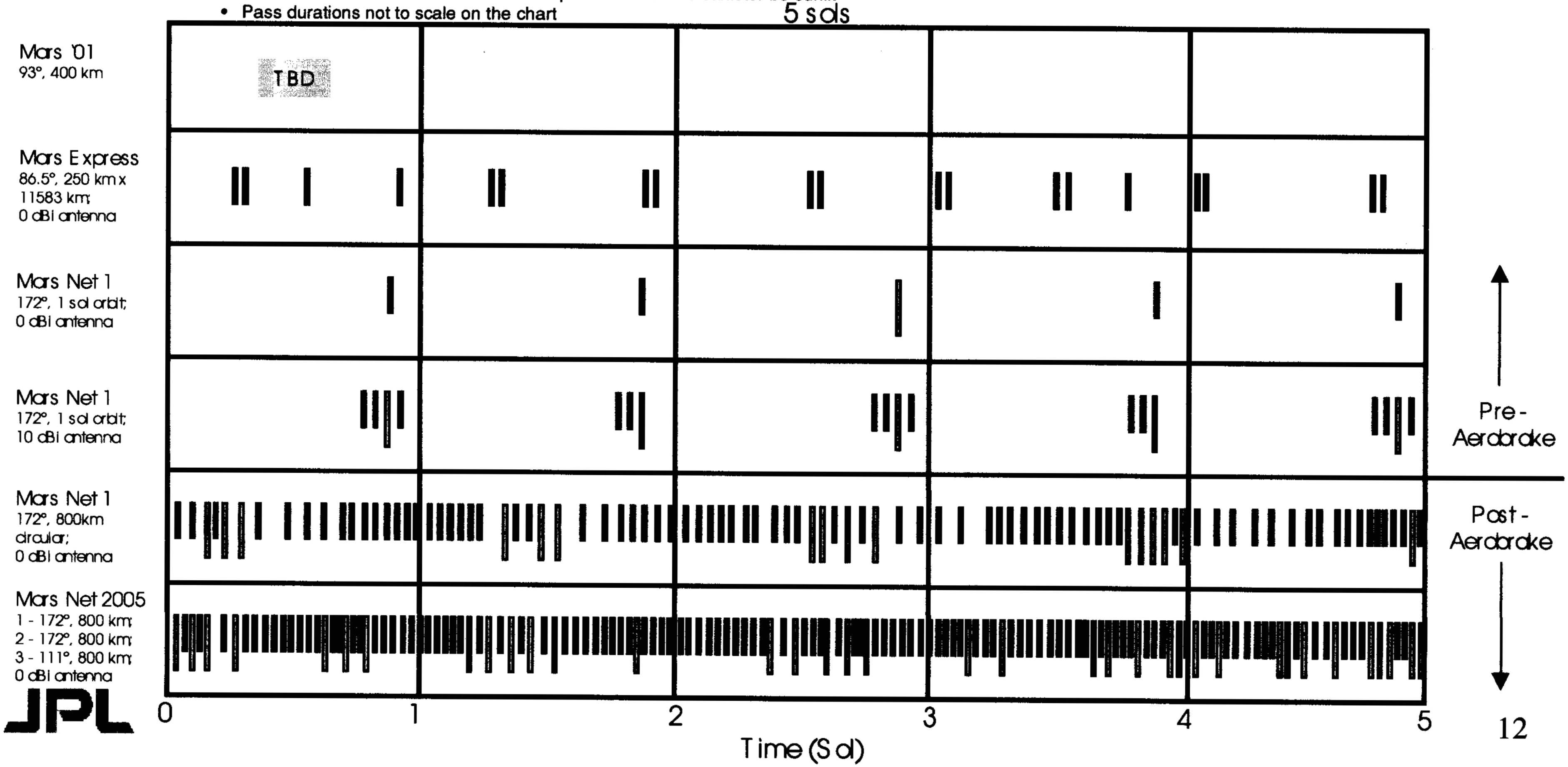




Orbiting Sample Visibility from Orbiting Platforms: 5-Sols

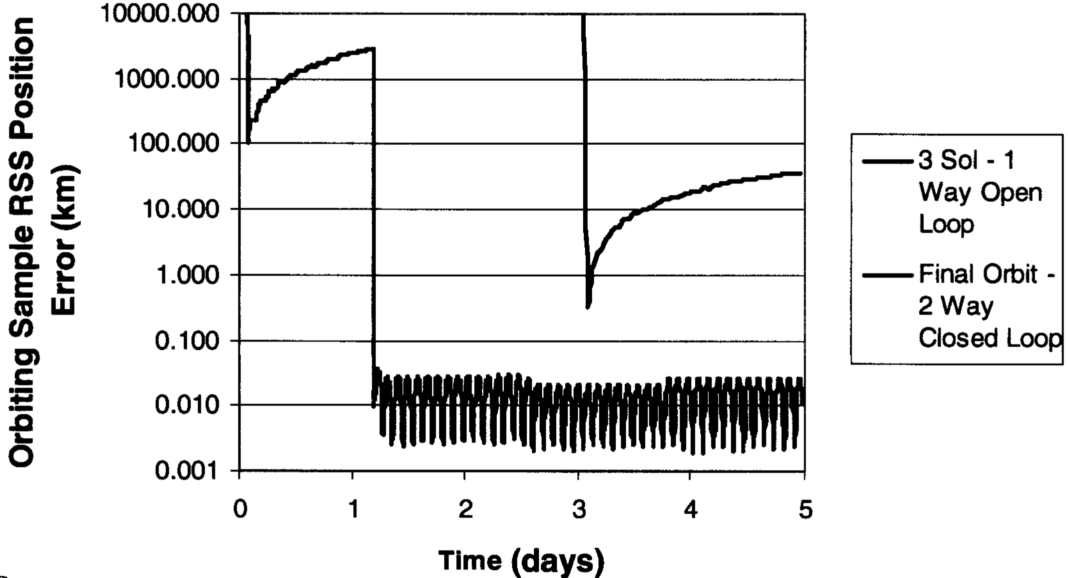
	▯ = 2 way Doppler 1000 km	▮ = 1 way Doppler 5000 km
Mars Express; 7 hr 0 dBi	0 contacts - 0.0 min	19 contacts - Avg. 18.0 min
Mars Net-1; 1 sol 0 dBi	1 contact - Avg. 4.0 min	5 contacts - Avg. 18.0 min
Mars Net-1; 1 sol 10 dBi	5 contacts - Avg. 10.9 min (3162 km for 10 dBi Ant.)	18 contacts - Avg. 25.7 min (15,811 km for 10 dBi Ant.)
Mars Net-1; 800 km 0 dBi	16 contacts - Avg. 3.6 min	97 contacts - Avg. 18.4 min
Mars Net 2005	37 contacts - Avg. 4.0 min	188 contacts - Avg. 22.9 min

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



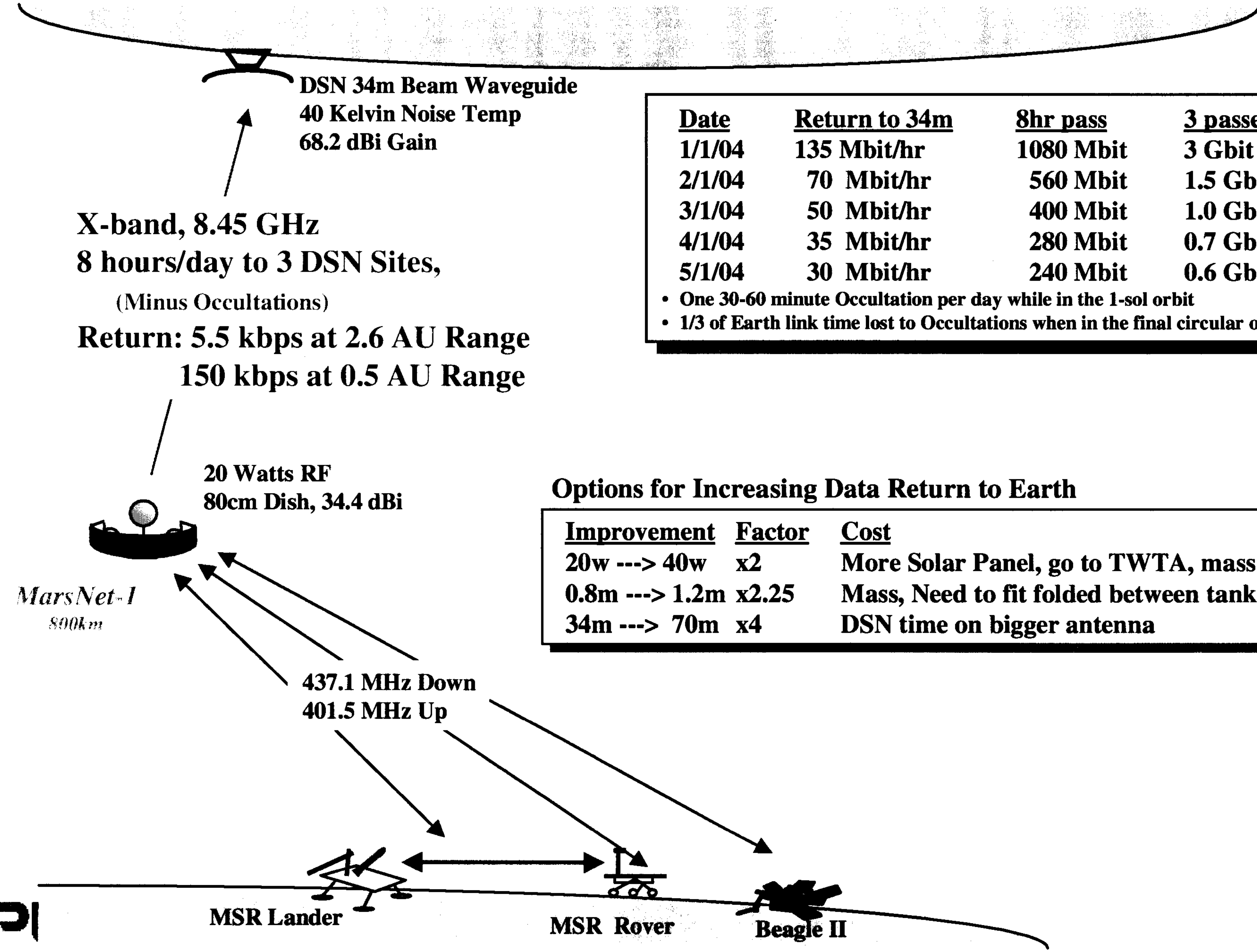
JPL

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



Date	Return to 34m	8hr pass	3 passes
1/1/04	135 Mbit/hr	1080 Mbit	3 Gbit
2/1/04	70 Mbit/hr	560 Mbit	1.5 Gbit
3/1/04	50 Mbit/hr	400 Mbit	1.0 Gbit
4/1/04	35 Mbit/hr	280 Mbit	0.7 Gbit
5/1/04	30 Mbit/hr	240 Mbit	0.6 Gbit

- 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

Options for Increasing Data Return to Earth

Improvement	Factor	Cost
20w ---> 40w	x2	More Solar Panel, go to TWTA, mass
0.8m ---> 1.2m	x2.25	Mass, Need to fit folded between tanks
34m ---> 70m	x4	DSN time on bigger antenna

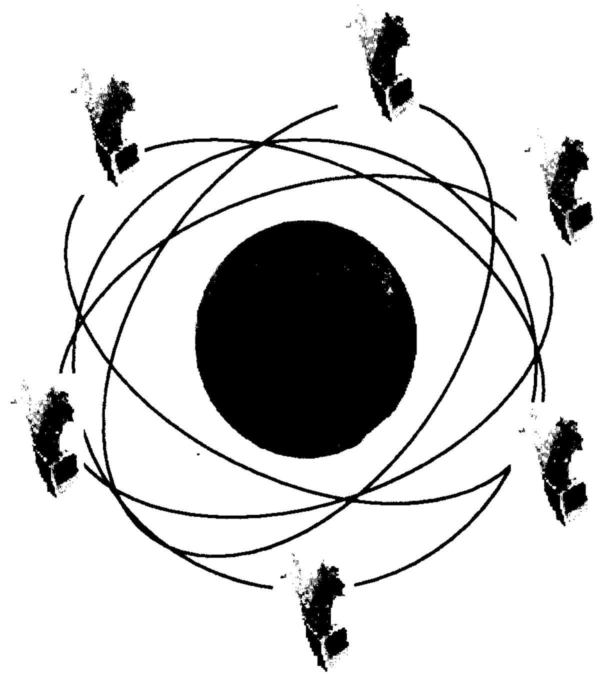
JPL

Part II: The Entire Constellation

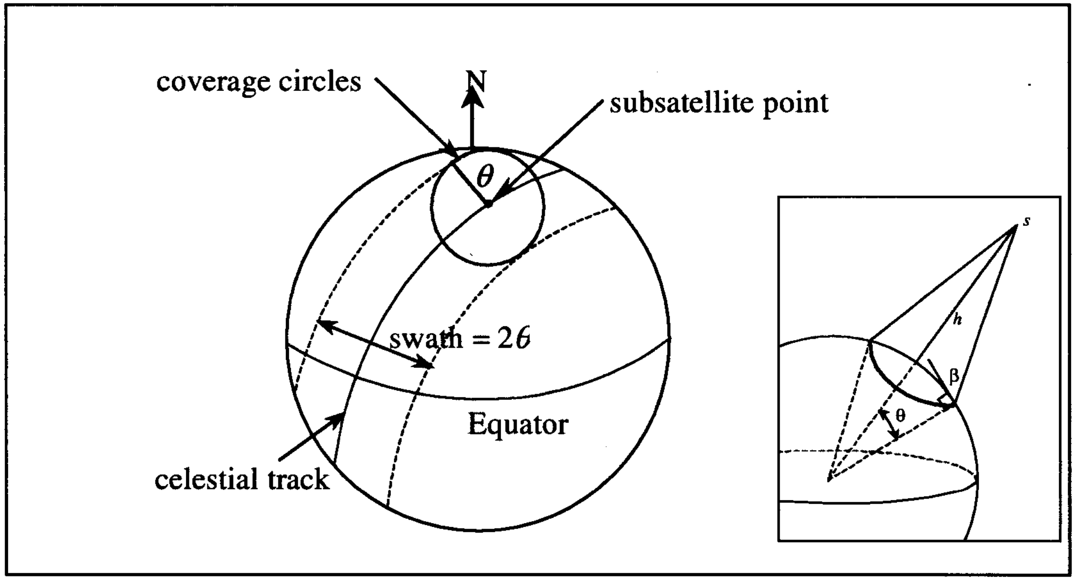
- Performance Goals
- Coverage Considerations
- Candidate Constellations
- Metrics
- Preliminary design leading to the 4retro111 constellation
- Buildup of the 4retro111 Constellation
- Open Issues/Continuing Effort

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



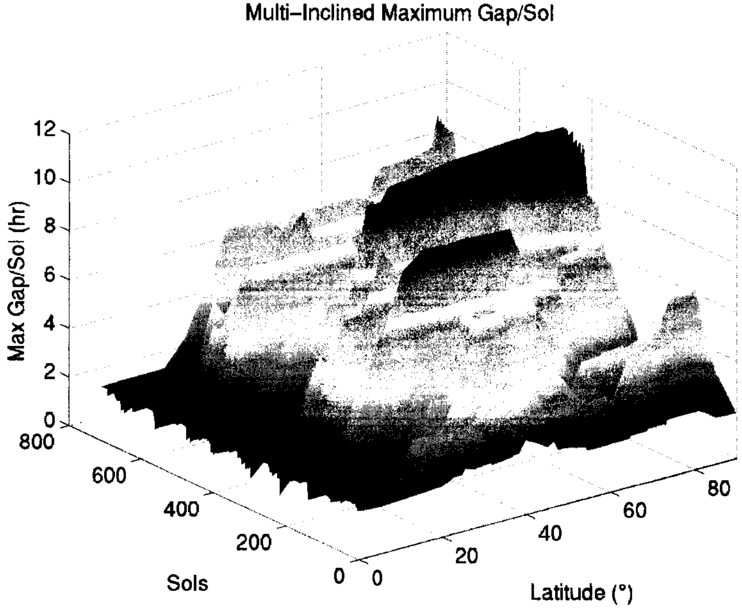
Coverage Considerations

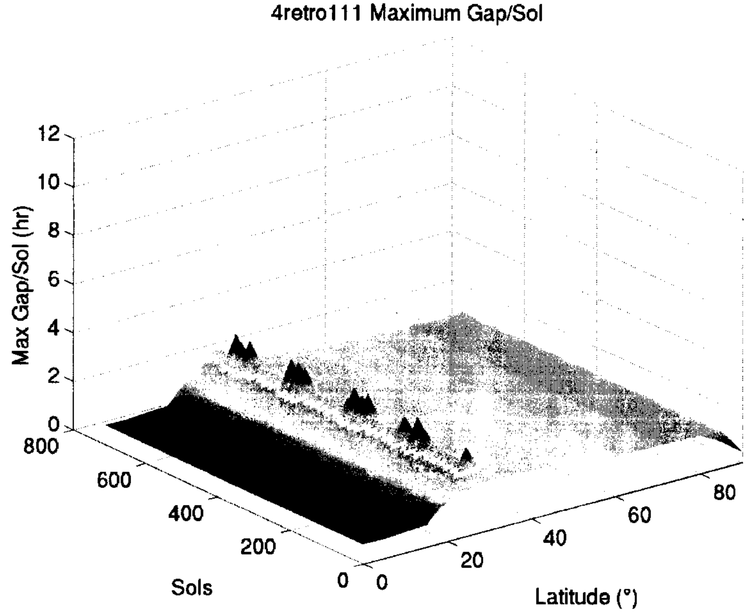


- Small constellation with maximum of 6 satellites
  - Low altitudes 400 ~ 1200 km
    - Support low-power comm users
    - Continuous global coverage not possible
  - Inclined planes ⇒ cover poles & global support over time
  - Nonsynchronous altitude ⇒ avoids significant longitudinal biases
  - Nonequatorial ⇒ 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





Multi-Inclined Orbit Planes

- i = 10°, 35°, 55°, 65°, 75°, 85°
- Initial equal spacing between nodes
- Relative nodal drift yields degenerate geometries

4retro111 Orbit Planes

- i = 2 @ 172° & 4 @ 111°
- No relative nodal drift between planes within each subconstellation

⇒ Use Hybrid of 2 Subconstellations

Candidate Constellations

Constellation	4inc65	4retro111	4inc80	
Sat 1	10°, 1100 km	172°, 800 km	10°, 1100 km	Lower Sub.
Sat 2	10°, 1100 km	172°, 800 km	10°, 1100 km	
Sat 3	65°, 1100 km	111°, 800 km	80°, 400 km	Upper Sub.
Sat 4	65°, 1100 km	111°, 800 km	80°, 400 km	
Sat 5	65°, 1100 km	111°, 800 km	80°, 400 km	
Sat 6	65°, 1100 km	111°, 800 km	80°, 400 km	

- Single satellite per plane
- 4inc65 & 4retro111: ascending node between planes within subconstellations spaced uniformly
- 4inc80: nodes spaced equally between (10°, 80°, 80°, 10°, 80°, 80°)

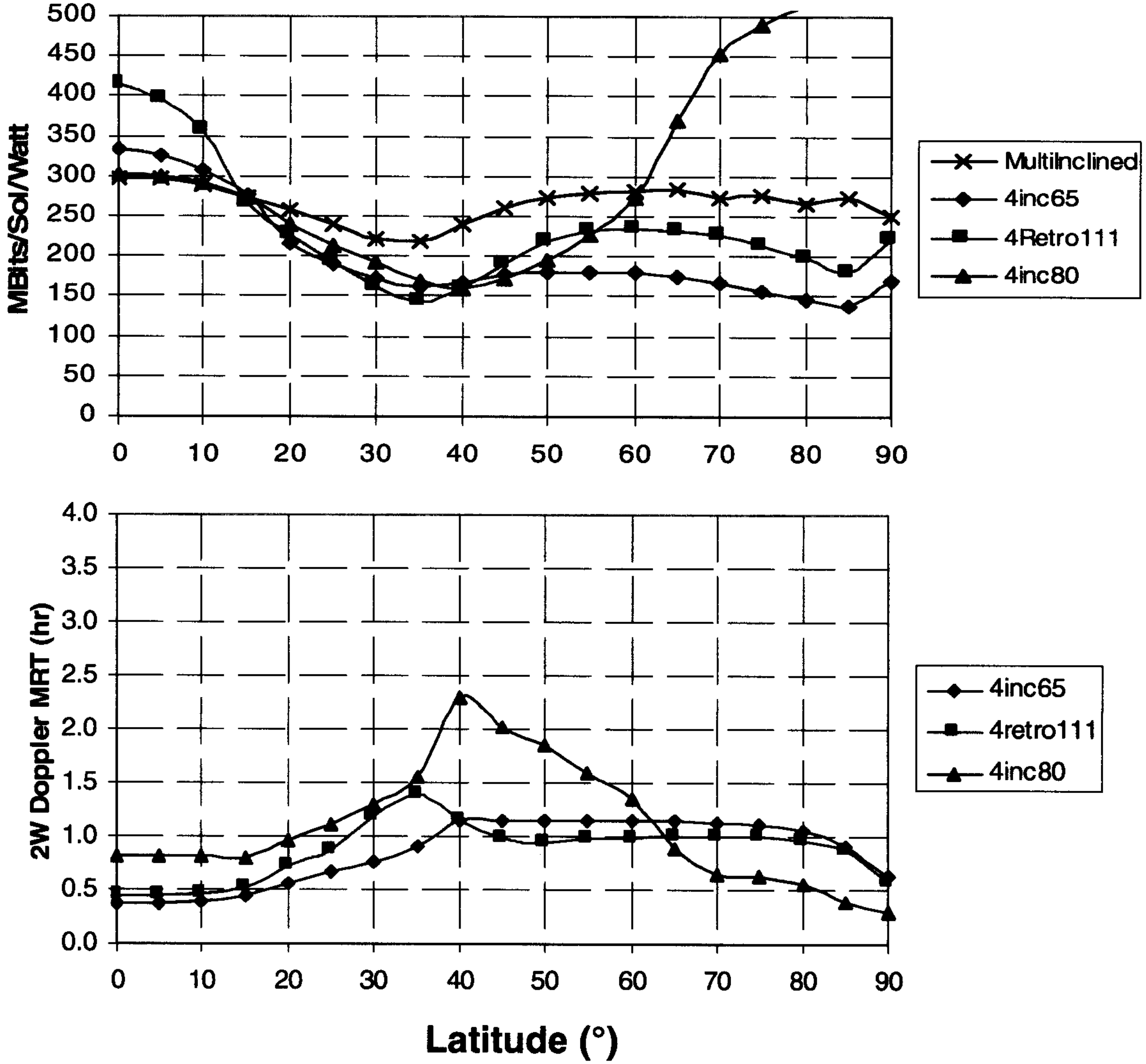
Communication Metric

- 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 Eb/ No = 3.2 dB, (K= 7, R= 1/ 2 with (255, 223) R- S Code). Corresponds to BER of 1 x 10e- 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

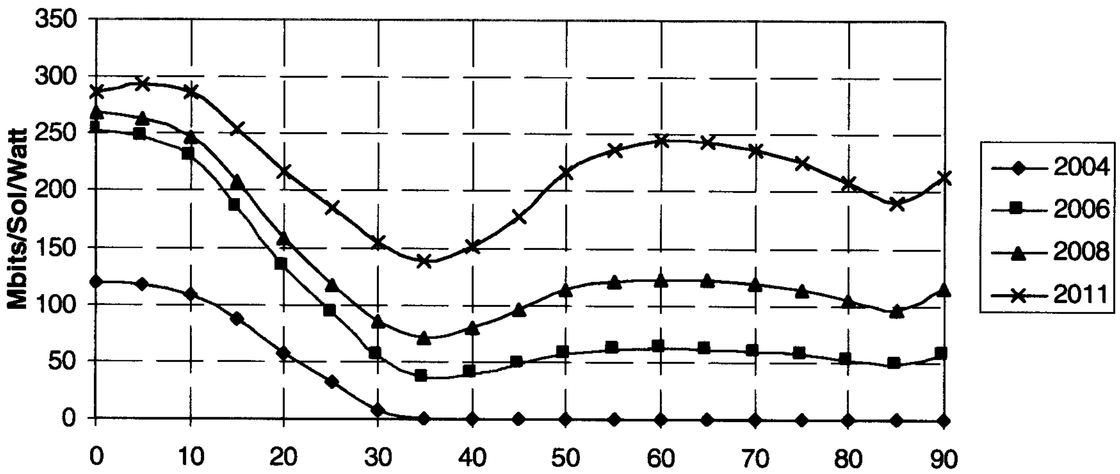
Constellation Comparisons

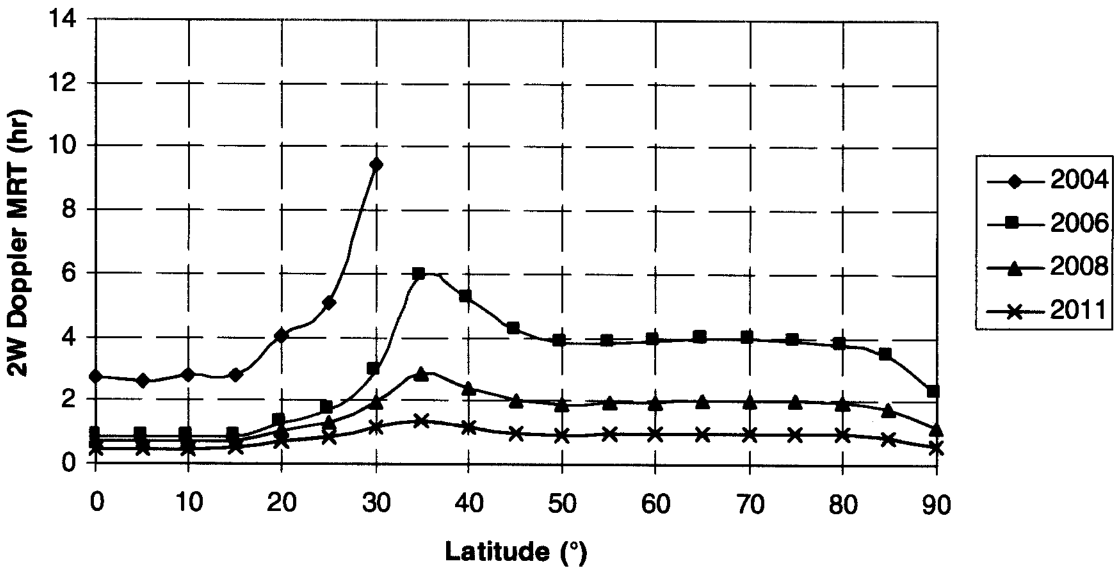


4retro111

- 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

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

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