Telecommunications and Navigation Strategies in NASA's Mars Exploration Program

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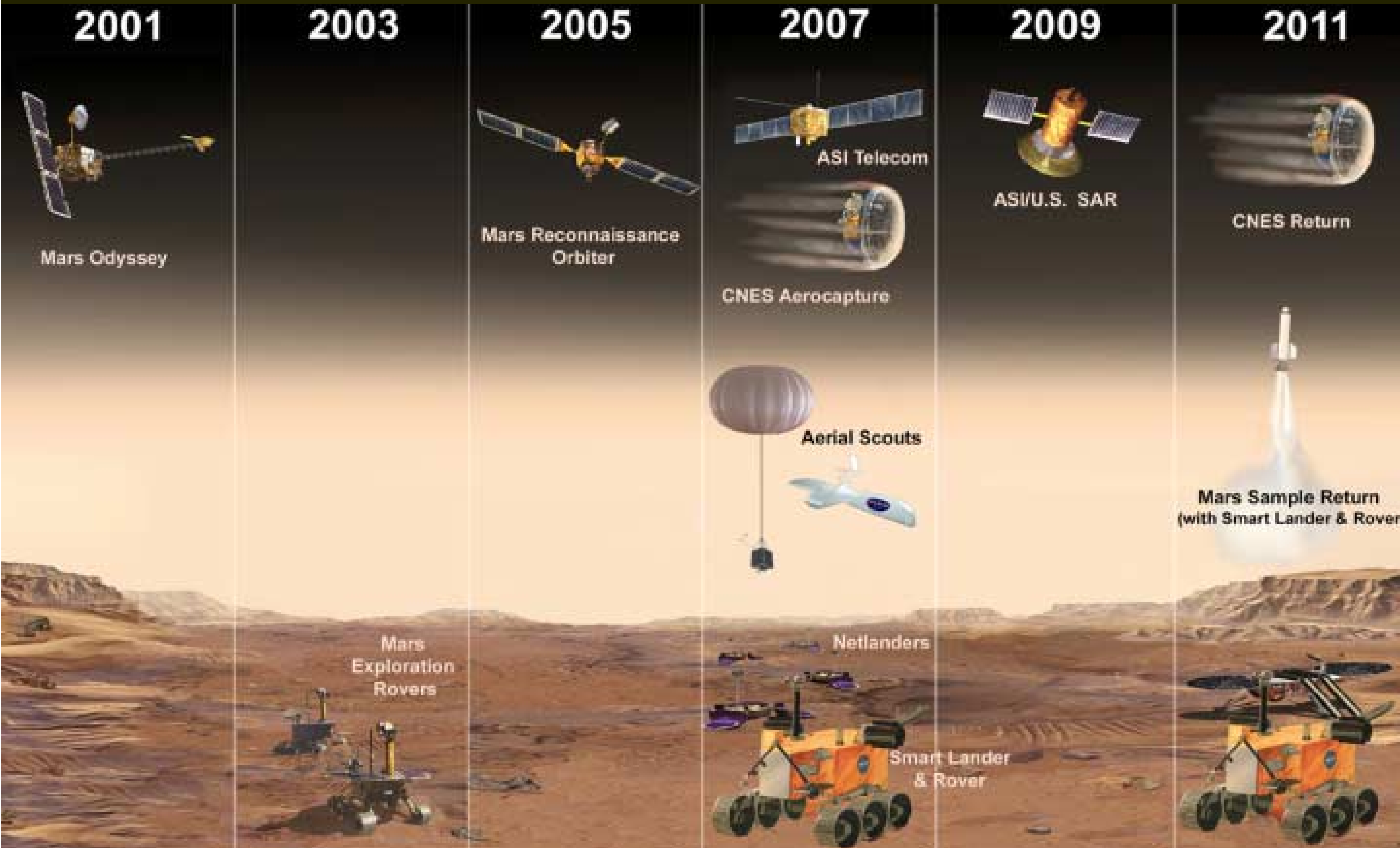
Outline

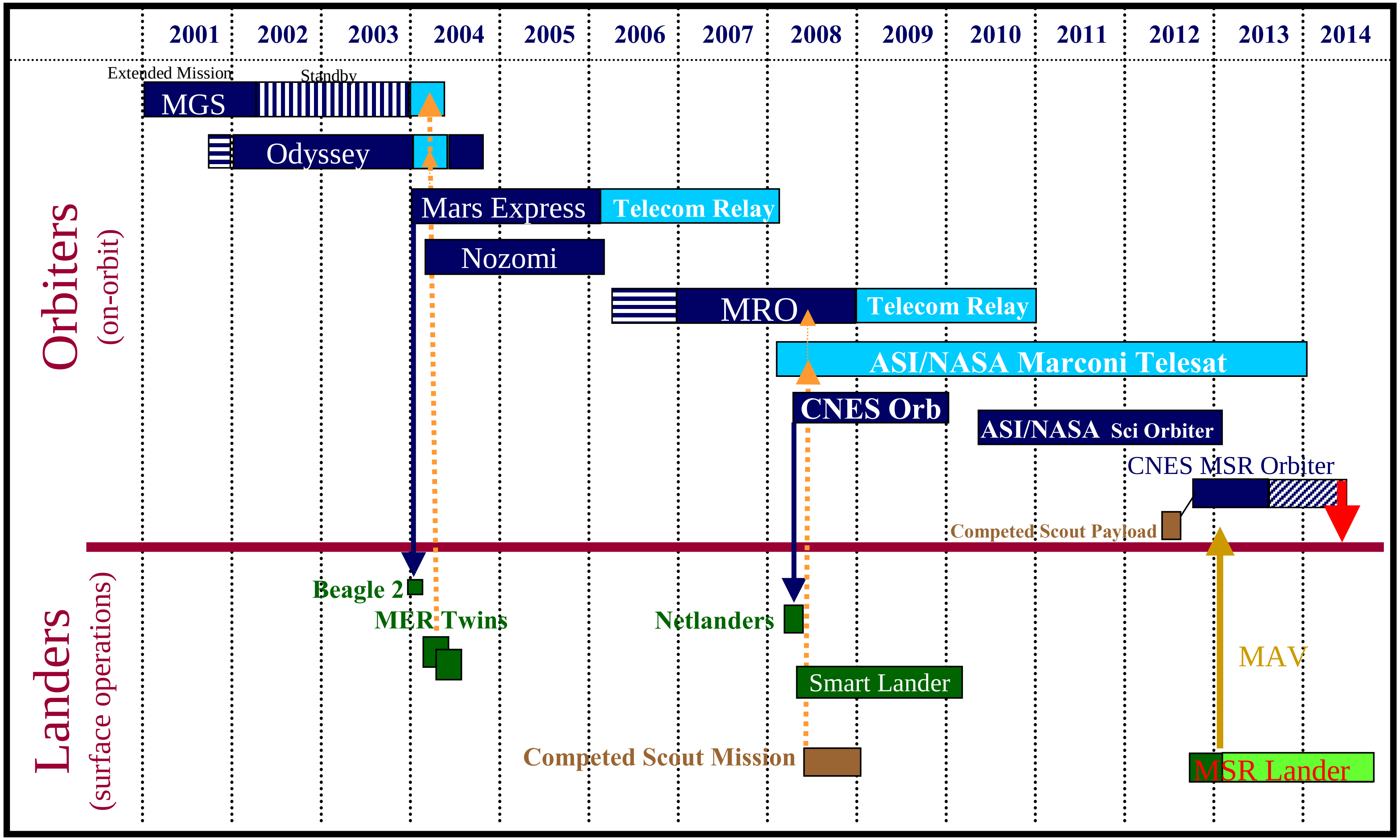
- **Introduction & Acknowledgments**
- **Program Overview**
- **Capability Trades**
  - Telecommunications
  - Navigation
- **Electra - A Standardized Proximity Link Comm/Nav Payload**
- **Communications Protocols**
- **Key Technologies**
- **Summary**

Acknowledgments

- **Many people & organizations have contributed over the past several years to the concepts presented here, including the Mars Network team as well as the current MGS, Odyssey, and MER project teams**
- **Key contributors include:**
  - Dave Bell, Todd Ely, Tom Jedrey, Shel Rosell, Steve Townes, Jeff Srinivasan, Jon Adams, Joe Guinn, Rolf Hastrup, Bob Cesarone, Stan Butman, Yoaz Bar-Sever, Steve Lichten, Polly Estabrook, Adrian Hooke, Loren Clare, Greg Kazz, Ed Greenberg, Tony Barrett, *and many more...*


2001
2003
2005
2007
2009
2011
Mars Odyssey
Mars Reconnaissance Orbiter
ASI Telecom
CNES Aerocapture
ASI/U.S. SAR
CNES Return
Aerial Scouts
Mars Sample Return (with Smart Lander & Rover
Mars Exploration Rovers
Netlanders
Smart Lander & Rover

Mars Exploration Timeline



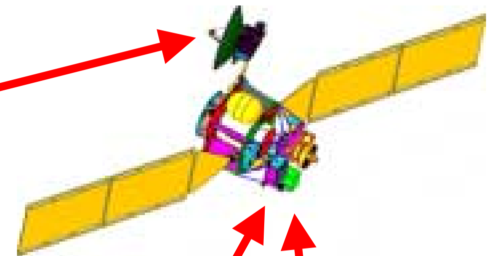
Program Drivers on Comm/Nav Infrastructure

- Increased science data return (e.g., for multi-spectral surface pancam imagery)
- Complexity of MSR surface operations, with the resulting need for frequent command cycles and rapid, low-latency engineering data return to support operations planning
- Robust, high-accuracy radio-based approach navigation (e.g., ~<1 km entry knowledge for aerocapture or precision landing)
- Capture of real time engineering telemetry during critical events such as EDL, aeromaneuvering, MAV launch, etc., for feed-forward fault diagnosis in the event of anomaly
- Energy-efficient relay telecommunications for energy- and mass-constrained scout-class missions
- Radio tracking of orbiting sample canister to support in-orbit sample rendezvous
- Surface position determination to support long-range rover navigation

Mars Telecommunications: Representative Capabilities

Orbiter Direct-to-Earth Link

- **10 kbps - 1 Mbps to 34m @ 2.7 AU**
- **Example: MGS**
  - 25 kbps
  - 1.5 m HGA
  - 25 W TWTA

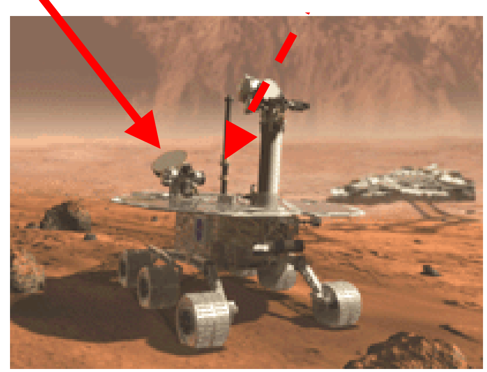


Lander Relay Link

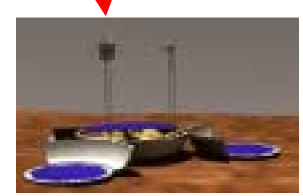
- **100 kbps - 1 Mbps**
- **Example: MER**
  - 128 kbps
  - Omni UHF antenna
  - 10 W SSPA

Large Lander Direct-to-Earth Link

- **1 kbps - 10 kbps to 70m @ 2.7 AU**
- **Example: MER**
  - 2 kbps
  - 28 cm HGA
  - 15 W SSPA

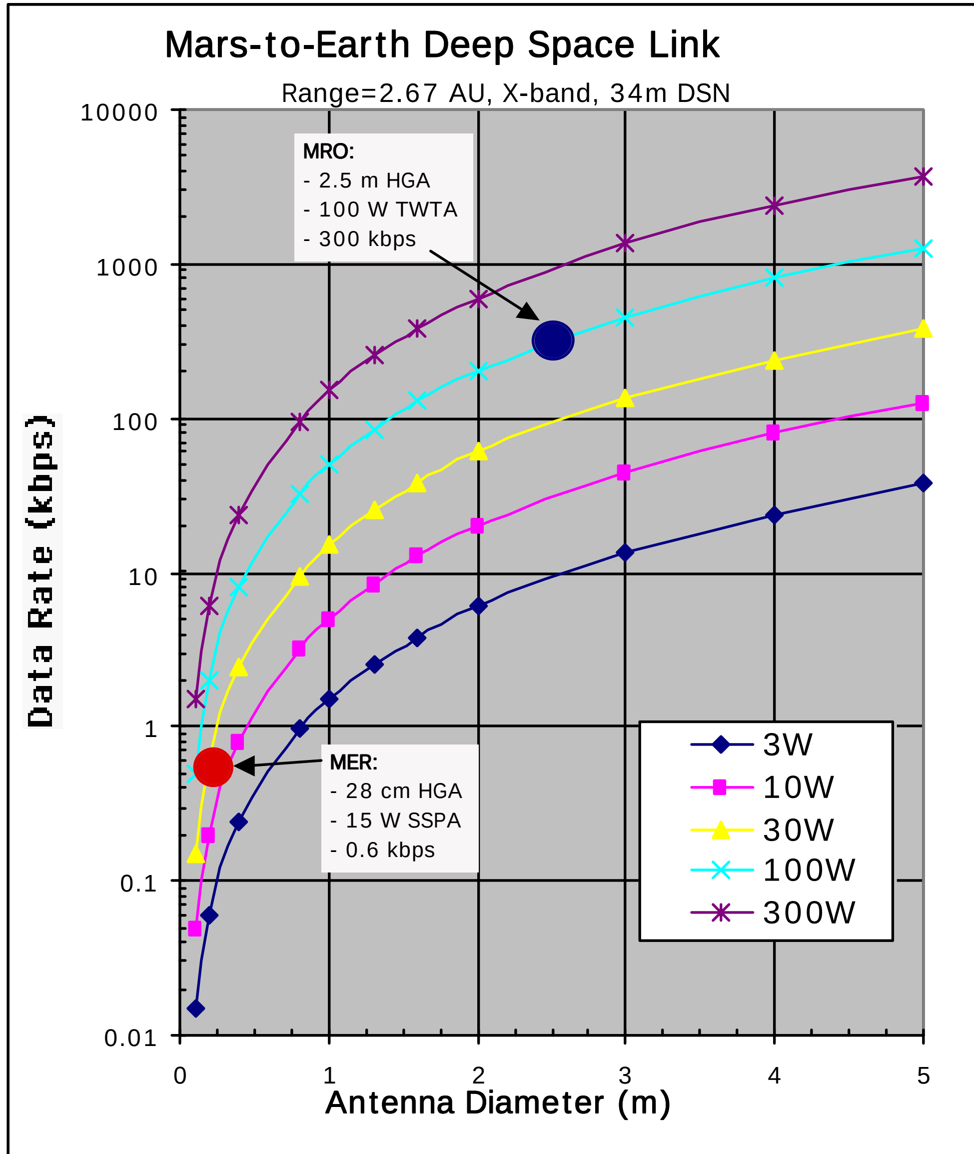


No DTE capab ility for Scout-class landers

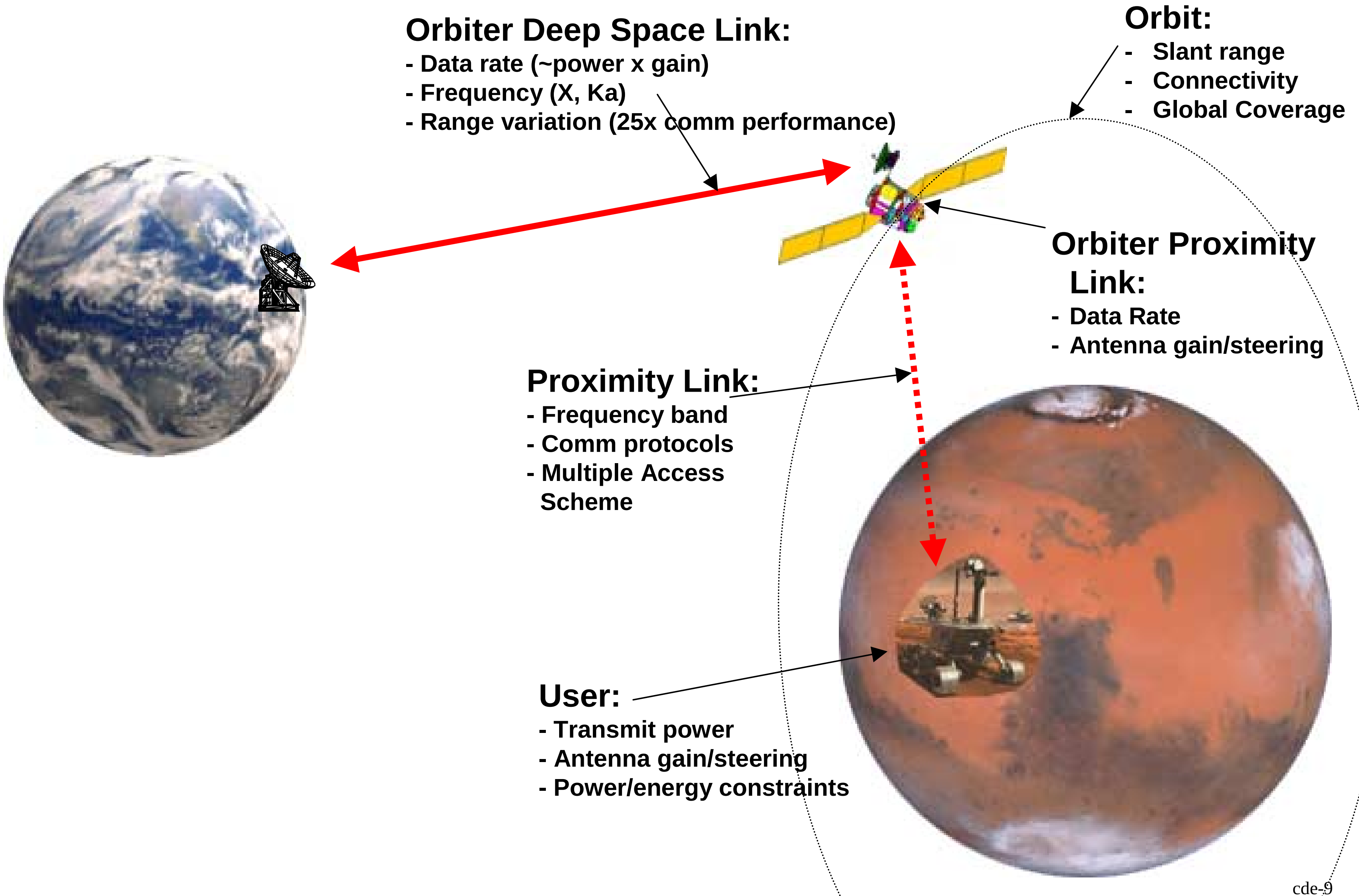


Direct-to-Earth Communications

- **Keys to increased DTE link capability:**
  - Transmit power
  - Transmit aperture
  - Frequency (Ka-band offers ~4x improvement over X-band
  - Earth receive aperture (70m offers ~4x improvement over 34m)
- ***Mass, power constraints imply landed DTE capability will always fall well below orbital DTE capability***



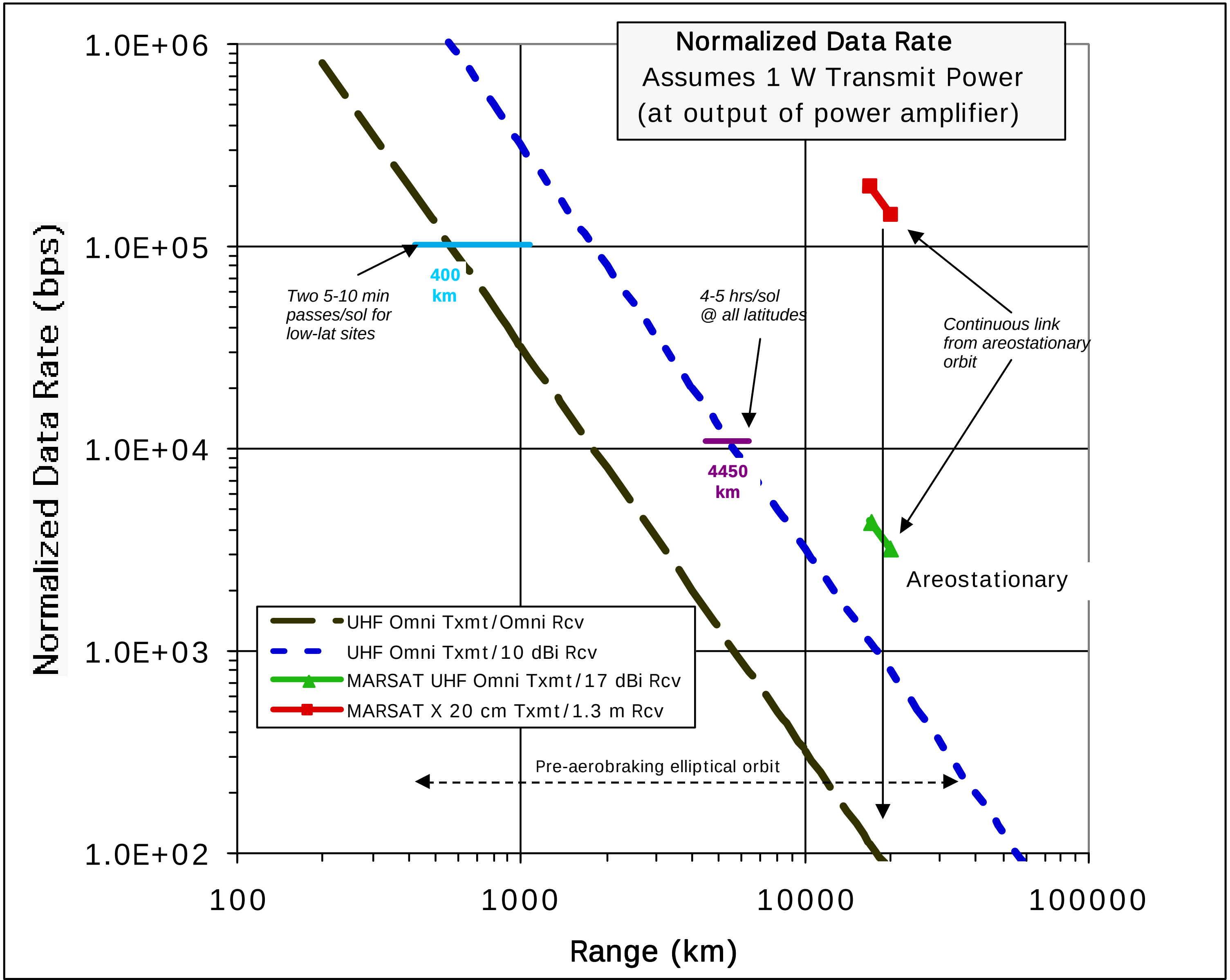
Key Aspects of Relay Communications



Proximity Link Characterisitics

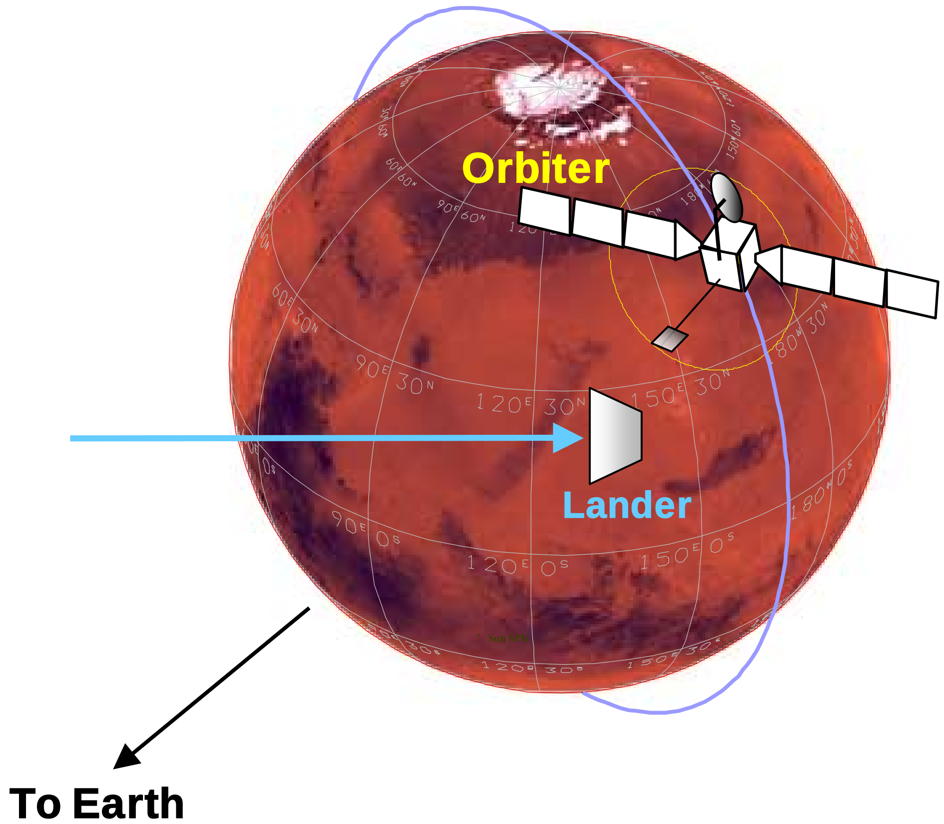
- **Omni-to-omni links**
  - Simple ops for lander and orbiter
  - Link performance scales as $1/freq^2$
  - Current ~400 MHz UHF band represents balance between link performance and RF component size
- **Omni-to-directional links**
  - Increased orbiter antenna gain can significantly improve link performance
  - To first order, for fixed orbiter aperture size, link performance is frequency-independent
  - However, orbiter antenna pointing requirements scale with frequency
- **Directional-to-directional links**
  - Opens possibility for very high link performance, event over long slant-range links
  - Requires antenna pointing at both ends of link
  - Link performance scales as $freq^2$

Proximity Link Communications



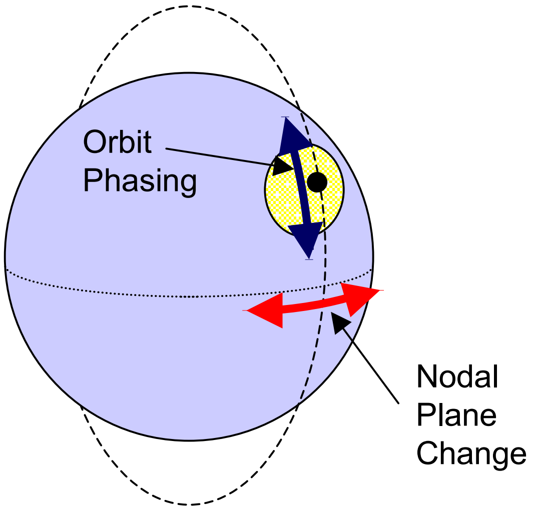
Critical Event Communications

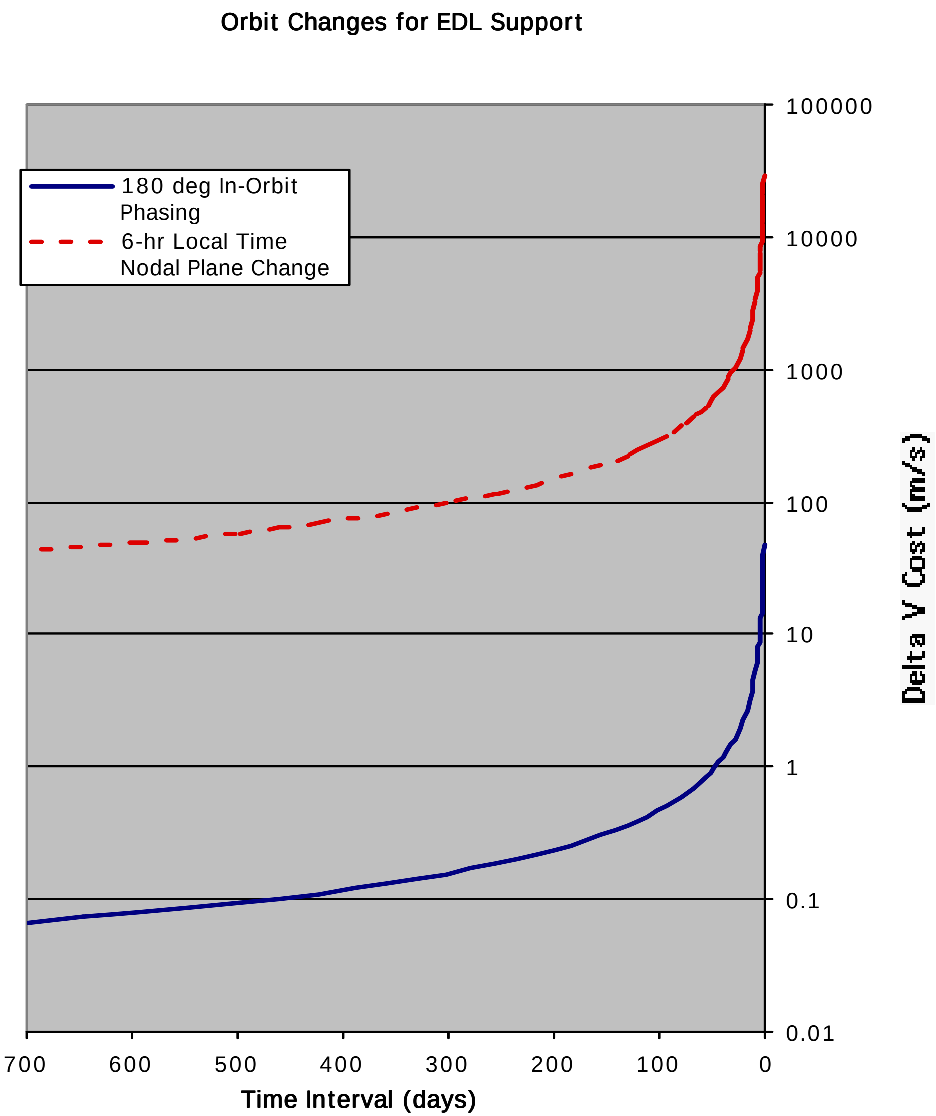
- **Program policy is to ensure realtime communications for critical mission events**
  - Entry, Descent, and Landing
  - Mars Ascent Vehicle Launch
  - Aerocapture MOI
- **Options:**
  - DTE "semaphores" can provide ~ 1 bps capability
  - High-rate prox link (will be required to characterize more complex 2nd-gen systems)
    - Infrastructure orbiters
    - Converted cruise stage
    - Black box



Orbital Changes to Support EDL Communications

- **Use of low-altitude science orbiter for EDL comm relay requires orbit adjustment to ensure EDL visibility**
- **Preliminary analysis of ΔV partial derivatives**
  - In-plane orbit phasing: ~0.26 m/s per deg/day
  - Nodal plane change: ~326 m/s per deg/day





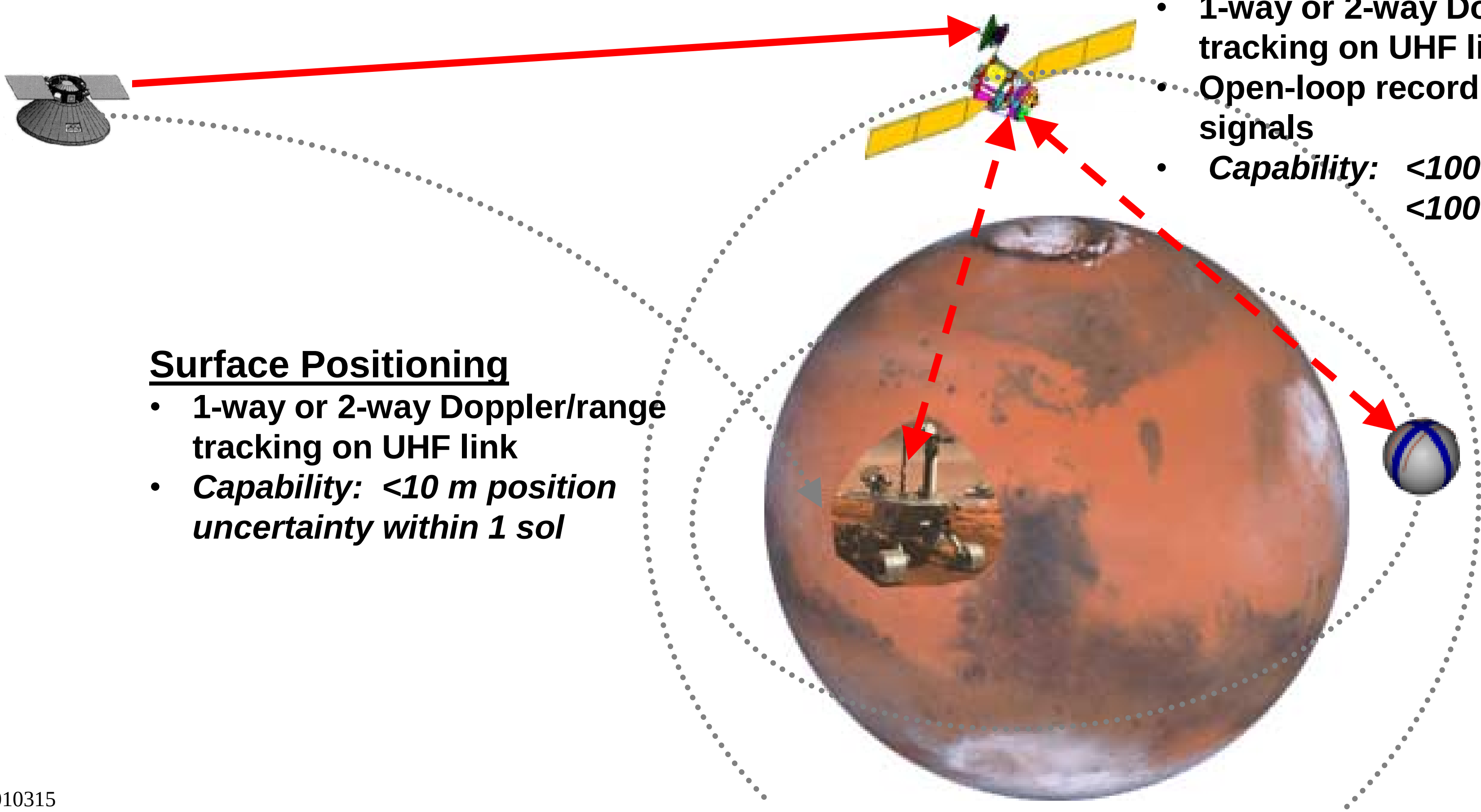
Key Aspects of Relay Navigation

Precision Approach Navigation

- **X-band Doppler on HGA link between approach s/c and orbiter**
- ***Capability: <0.5 km B-plane error @ E-1 day***

Orbiting Sample Canister Tracking

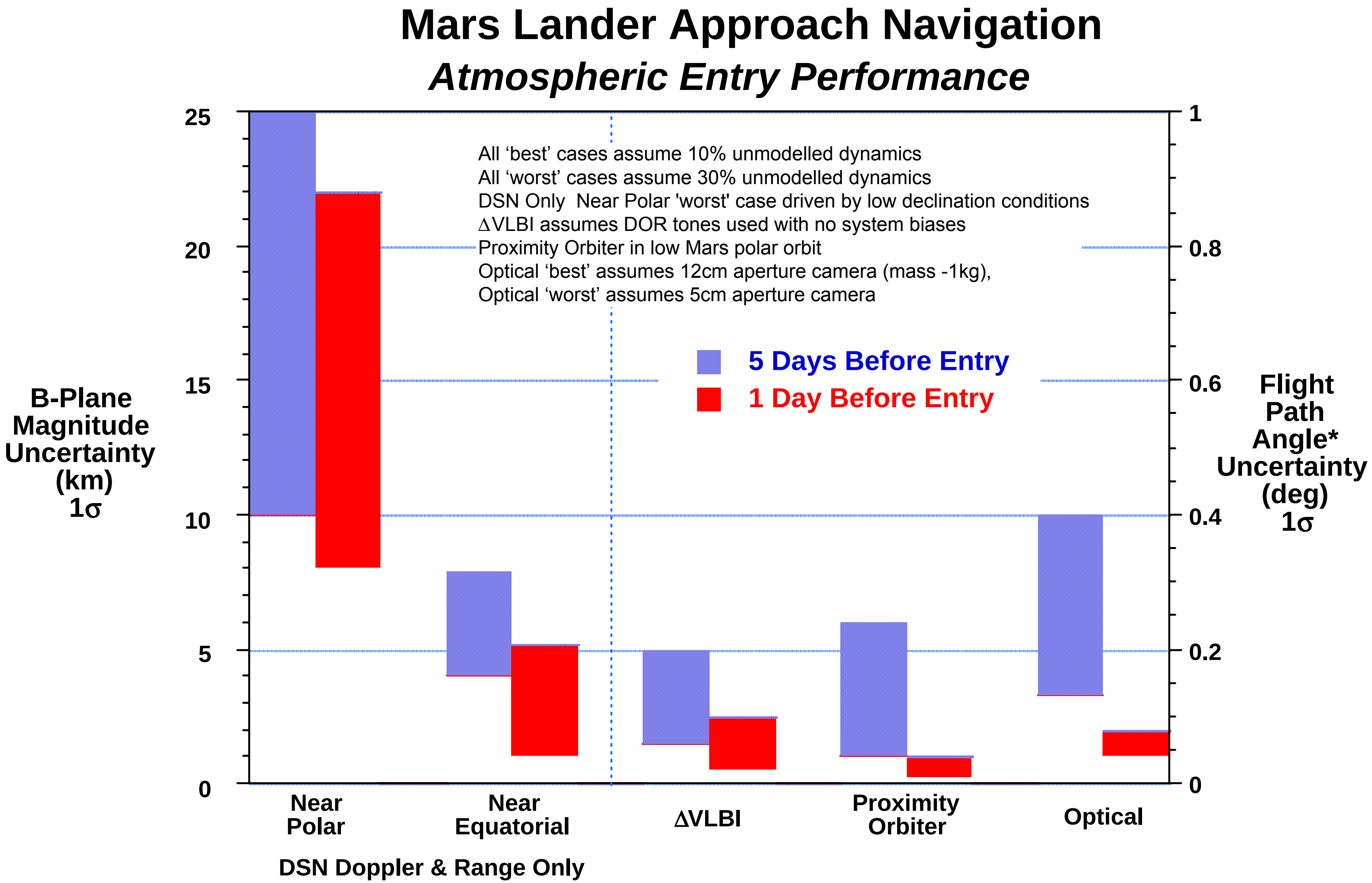
- **1-way or 2-way Doppler tracking on UHF link**
- **Open-loop recording for weak signals**
- ***Capability: <100 km 1-way***
  <100 m 2-way



Surface Positioning

- **1-way or 2-way Doppler/range tracking on UHF link**
- ***Capability: <10 m position uncertainty within 1 sol***

Mars Approach Navigation



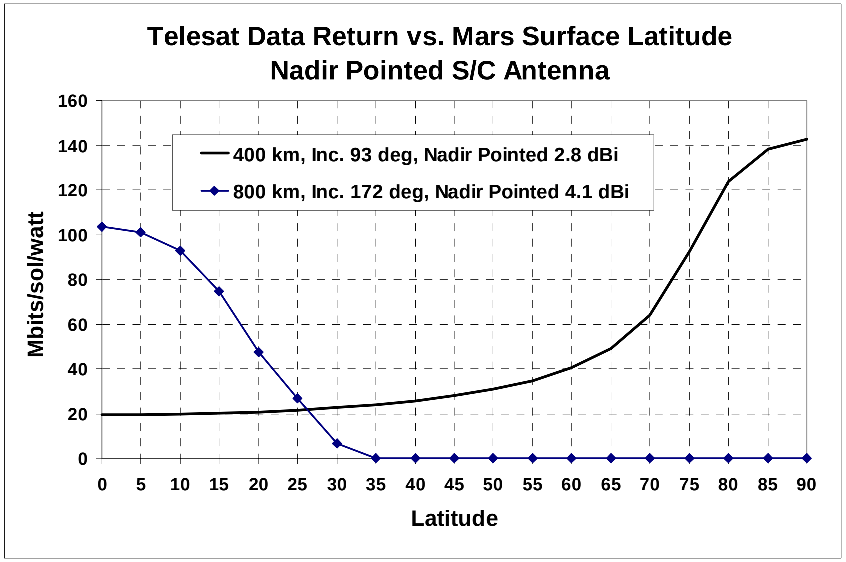
Mapping between Flight Path Angle and B-Plane Magnitude Uncertainties depends on entry conditions.
All cases assume equavalent mapping for -15 deg Flight Path Angle and -5345km B-Plane Magnitude

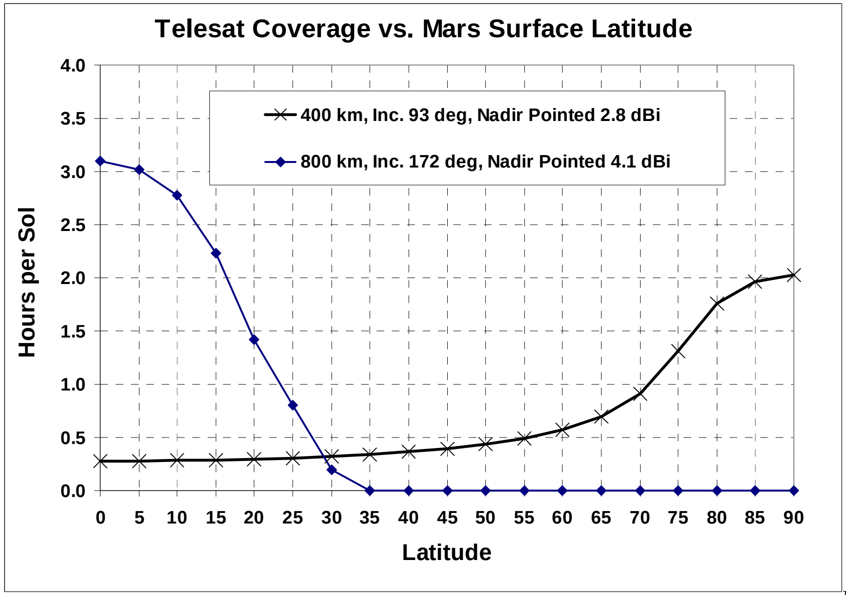
Trade Space: Relay Orbits

Orbit	Pros	Cons
Low-altitude polar	Global coverage; low slant-range for energy-efficient relay comm, even with simple omni antennas	Very limited connectivity, particularly in equatorial band
Low-altitude equatorial	Frequent contact to equatorial region (can complement polar orbiters); low slant range	No coverage to mid-lat and polar regions
Mid-altitude (e.g., alt = 4450 km, incl = 130 deg)	Global coverage with uniform connectivity from pole to pole; longer and more frequent pass durations	Larger slant range (can be compensated to some extent by increasing orbiter antenna gain)
Areostationary (alt = 17,000 km)	Continuous contact to one region of planet	Large slant range; hi-rate links will require directivity from surface user; no global coverage
ÒHigh-NoonÓelliptical orbits	Several orbits exist with precession such that apoapse is fixed near local noon, resulting in long daytime passes	Large slant range at apoapse; hi-rate links will require directivity from surface user; variable slant range over orbit increases ops complexity

Low-Altitude Relay Orbiters

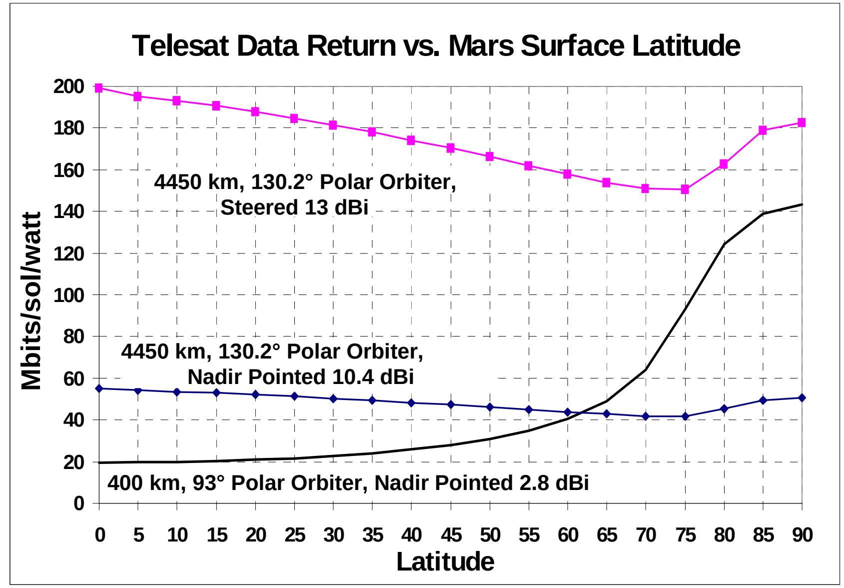
- Polar orbit provides global coverage but limited coverage of low-latitude sites
- Equatorial orbit provides frequent contact, increased data return for low-latitude sites, but no coverage beyond +- 30 deg

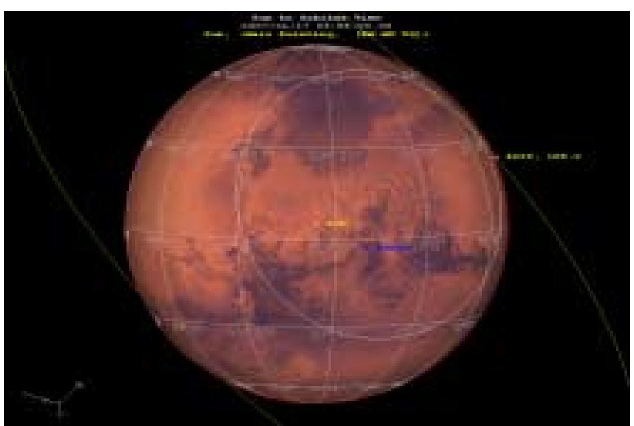


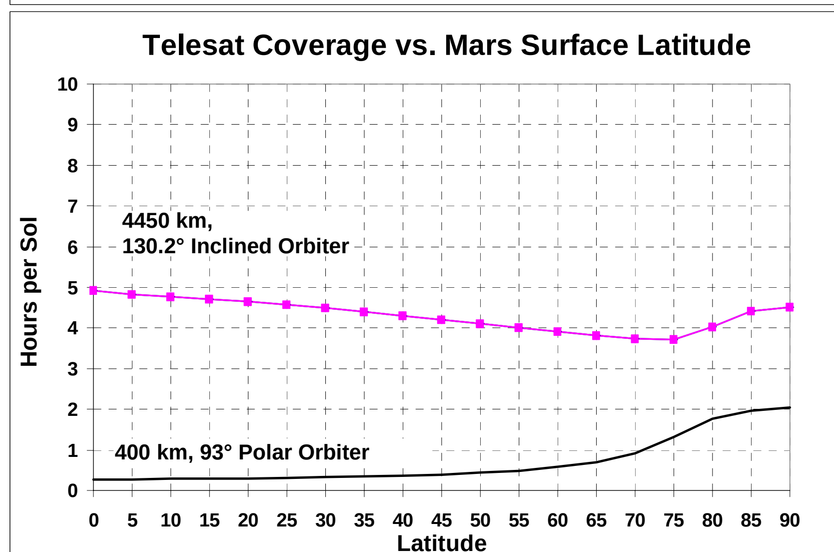


Mid-Altitude Orbiters

- **4450 km altitude provides increased coverage**
  - Large ground track
  - 4-5 hrs contact per sol, nearly uniform in latitude
  - Multi-Gb/sol with steered orbiter antenna





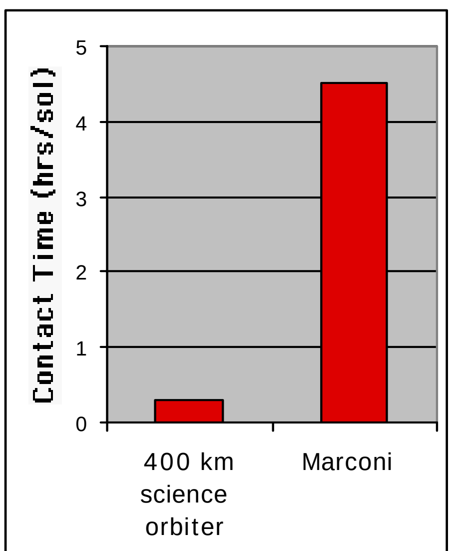


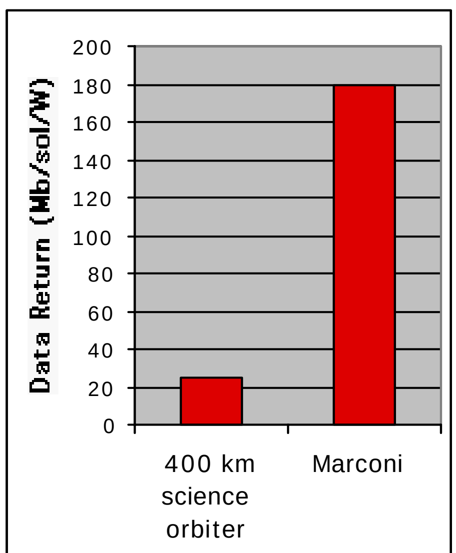
Areostationary and Highly Elliptical Orbiters

- **Areostationary**
  - 17,000 km altitude
  - Continuous view of one region of planet (~25% of planet centered about sub-satellite point; no view of polar regions)
  - High-rate (~1 Mbps) continuous relay to Earth with directional surface antenna (satellite at fixed point on sky w.r.t. surface user)
  - Lower-rate (~10 kbps) continuous relay to Earth with simple omni surface antenna
- **HEO**
  - Several “sun-sync” orbits exist with apoapse at a fixed local time (e.g., local noon); long daytime passes
  - Large slant range at apoapse -> similar link considerations as for areo: directional surface antenna req’d for high rate (but now satellite moves on sky w.r.t. surface user)

2007 Marconi Comm/Nav Orbiter

- **First dedicated Mars telecommunications and navigation orbiter**
  - Mid-altitude orbit optimized for comm/nav role, improving performance relative to low-altitude science orbiters
  - Will provide comm (EDL and surface relay) and nav (approach nav, surface position, orbital rendezvous) services to other elements of Mars program





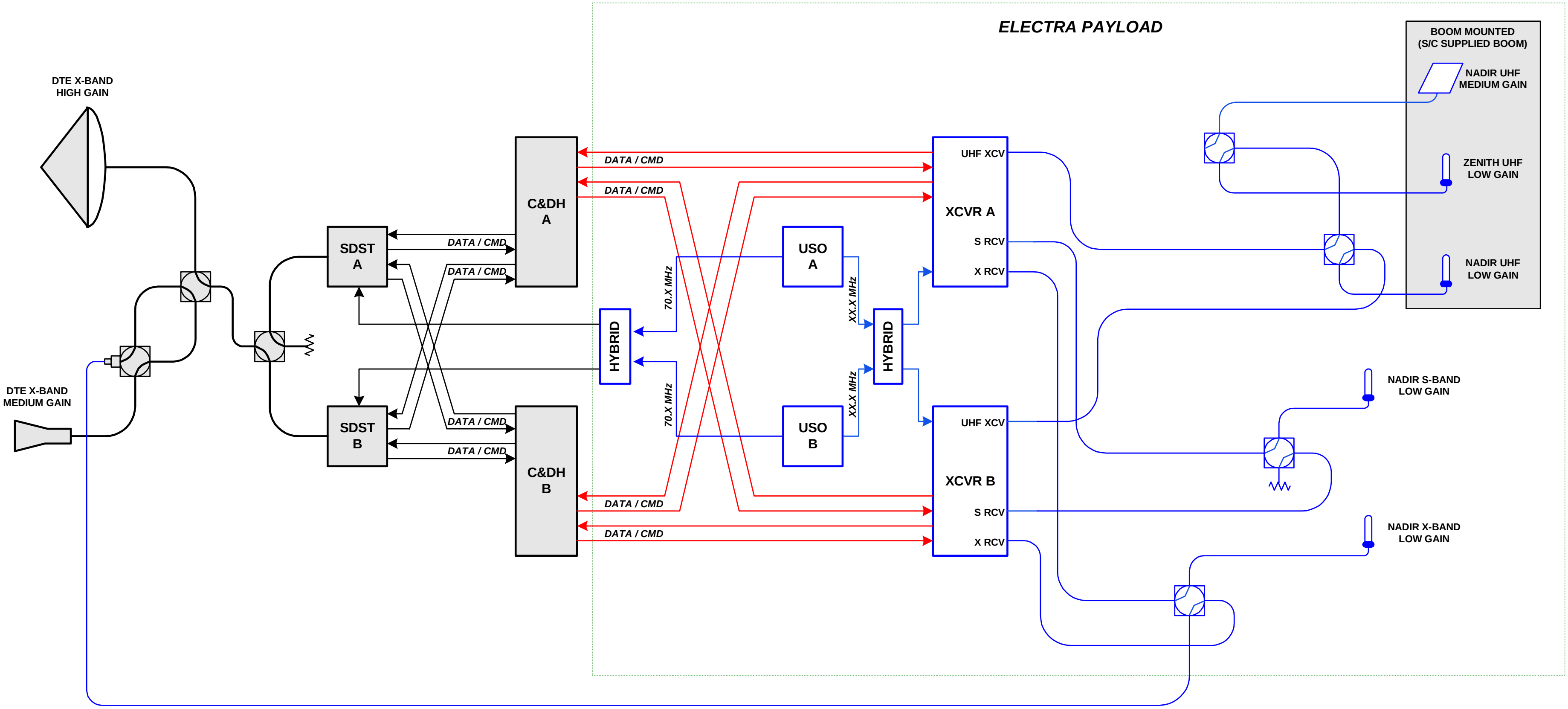
(results for +-30 deg latitude band)

- **Joint ASI/NASA mission**
  - ASI provides:
    - Spacecraft
    - ATLO
    - S/C flight engineering
  - NASA provides:
    - Launch vehicle
    - Prox link comm/nav payload
    - Deep space-specific engineering support
    - Mission ops

Electra Proximity Link Payload

- **Effort is underway to develop a next-generation standardized Mars proximity link payload**
  - To be flown on all Mars orbiters, starting with MRO'05 - provides *de facto* interoperability and enables gradual implementation of Mars orbital comm/nav infrastructure at low incremental cost
  - Flight reconfigurable/reprogrammable over long mission lifetime
  - Greater flexibility (wider range of supported data rates; swappable txmt/rcv bands, multi-channel operation)
  - Addition of X-band (8.4 Ghz) proximity comm/nav capability
  - Improved navigation/timing performance
  - Improved performance (coding, low-loss half-duplex mode, reduced NF, increased PA efficiency, …)
  - Modularity to allow scaling for low-mass lander/scout applications
  - Portability to facilitate integration with variety of orbiters
  - Self-contained relay functionality (including relay data management) for improved testability

Electra Physical Configuration



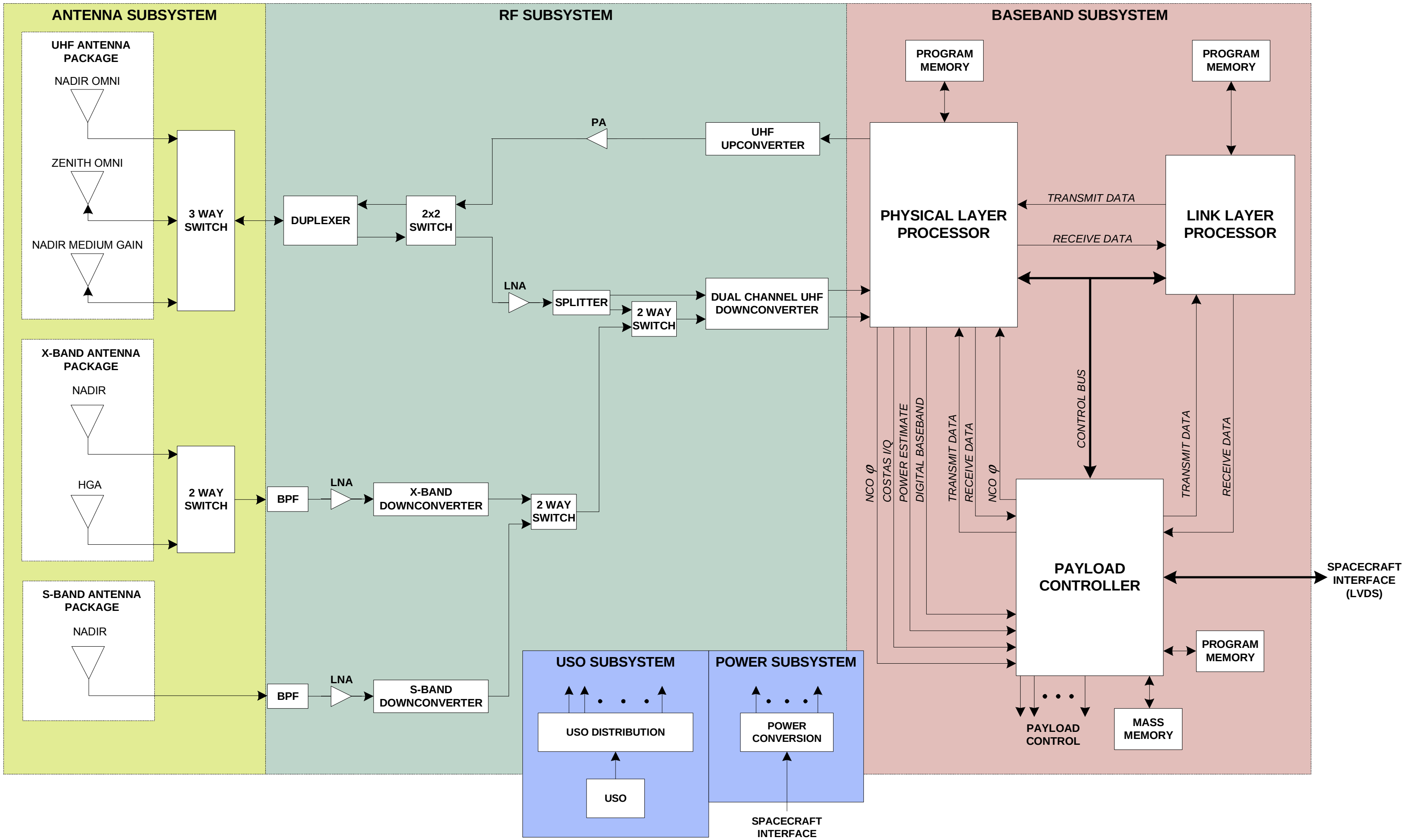
LEGEND

Spacecraft Supplied

Electra Supplied

Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91109
Project: Mars Technology Program Design: **Electra Payload** Page Description: **Redundant Payload/SC Integration**
Designed By: **T. Jedrey** Updated By: — Rev 1.0
Size — Date 01/29/01 — Document Number — Sheet 1 of 1

Electra Functional Block Diagram



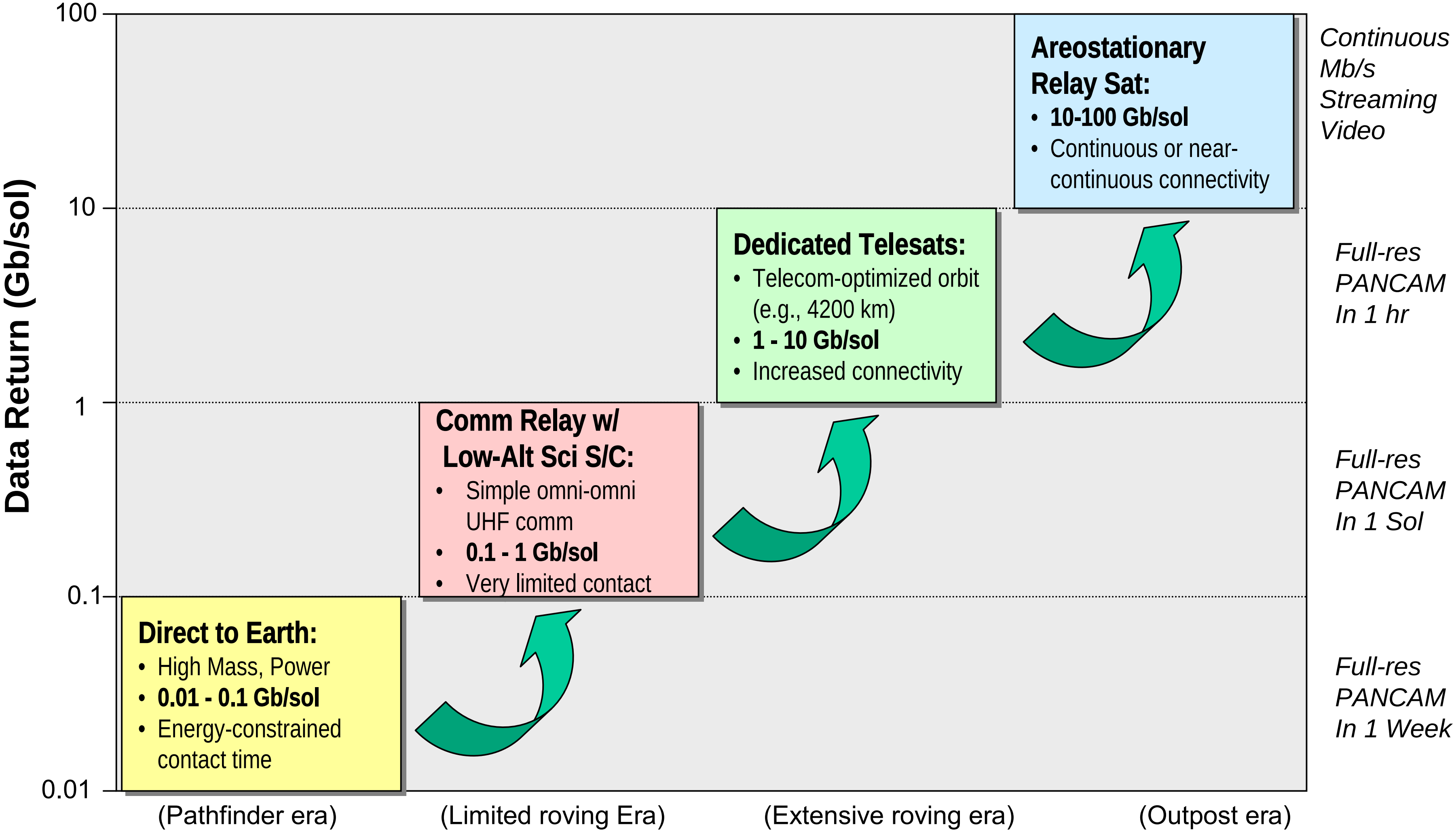
Protocols

- **CCSDS Proximity-1 Space Link Protocol**
  - Provides standards for the physical and data link layers for Mars proximity communications
  - First implementation on Mars Odyssey
  - Will be key for achieving interoperability among MER A/B, Beagle 2, Mars Exp, Odyssey
- **CCSDS File Delivery Protocol**
  - Provides reliable end-to-end file delivery
  - Addresses unique aspects of deep space communications
    - Long RTLT
    - Intermittent connectivity
    - High BER links
    - Multi-hop store-and-forward relays
    - Custody transfer to minimize onboard storage rqmts

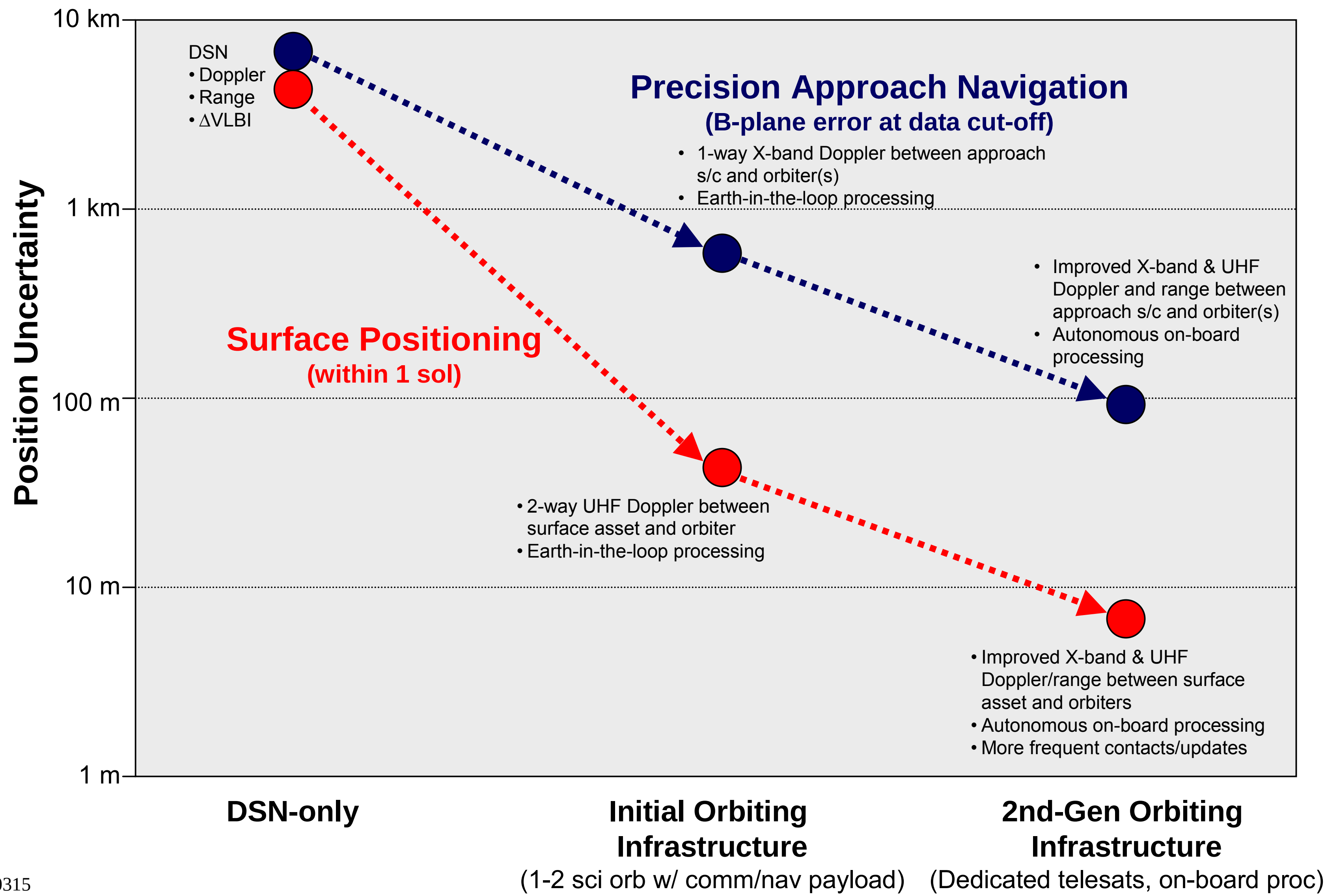
Key Technologies

- **The Mars Technology Program is funding a number of important comm/nav technology task:**
  - Deep Space Communications
    - High-EIRP RF Technologies (B. Lovick)
    - Optical Comm Flight Demo (K. Wilson)
  - Mars Proximity Communications
    - Electra Advanced Development (T. Jedrey)
    - UHF Antennas (K. Kelly)
  - Radio-Based Navigation
    - ST5 Flight Demo (W. Bertiger)
    - In Situ Navigation (J. Guinn)
  - Communications Protocols and Coding
    - Proximity Link Protocols (L. Clare)

Evolution of Mars Telecommunications Capability



Evolution of Mars Radio-Based Navigation Capability

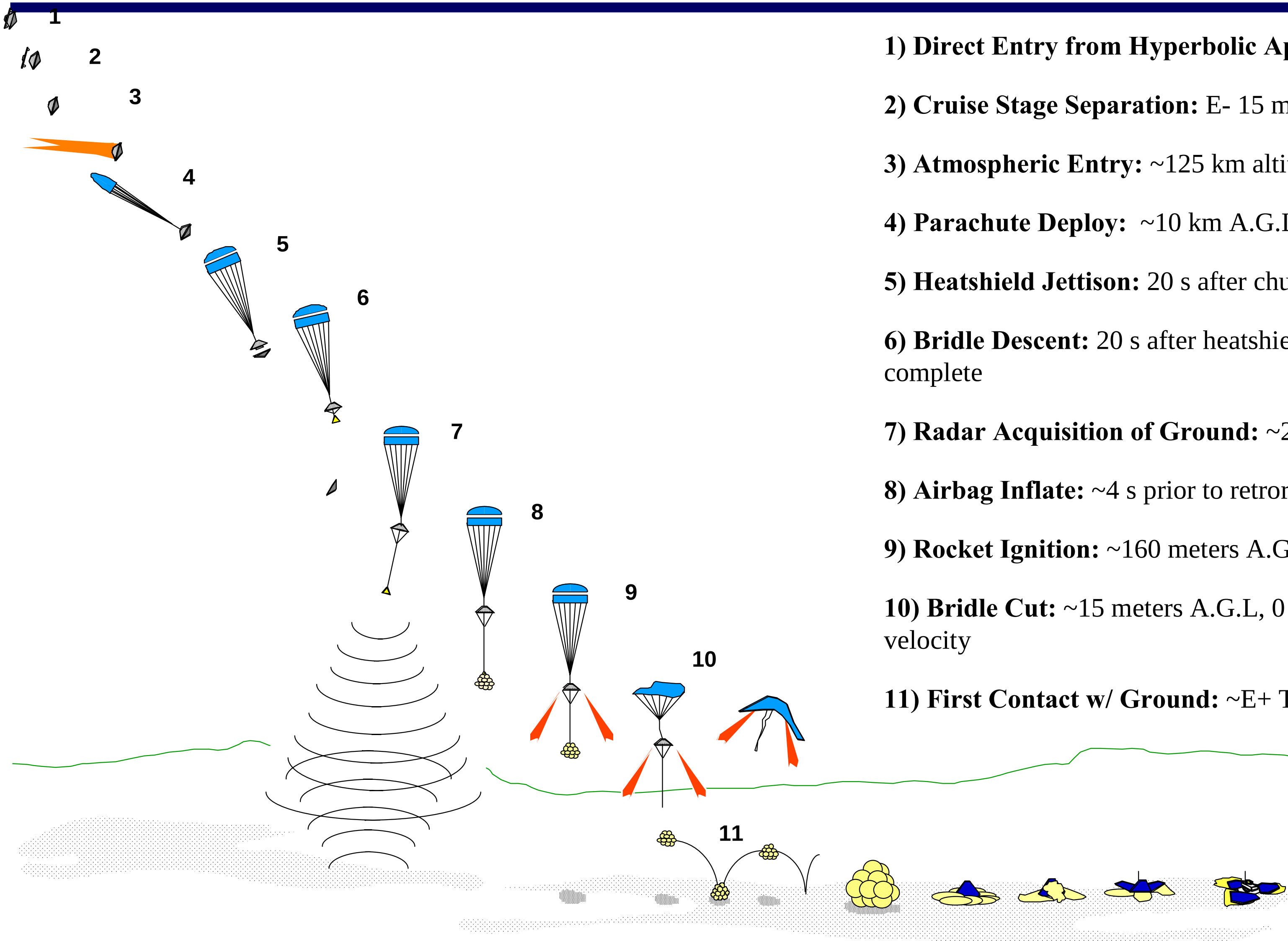


Some Parting Questions...

- **How do we manage and operate a heterogenous collection of orbital relay spacecraft as an integrated Mars comm/nav infrastructure?**
- **What is the science value of increased bandwidth and connectivity?**
  - How would a continuous high-rate areostationary relay change our surface operations concepts?
- **When is it cost-effective to transition to:**
  - Demand access proximity service concept?
  - On-board radiometric data processing?
  - Higher-frequency directional lander links?
- **How should our proximity link standards evolve?**
  - Physical layer
  - Modulation and coding
  - Higher layers of data management
  - Ultimate interface with IPN vision

A Real-World Example:
MER EDL Communications

EDL Sequence of Events Overview



1) Direct Entry from Hyperbolic Approach

2) Cruise Stage Separation: E- 15 minutes

3) Atmospheric Entry: ~125 km altitude

4) Parachute Deploy: ~10 km A.G.L., ~E+ TBD s

5) Heatshield Jettison: 20 s after chute deploy

6) Bridle Descent: 20 s after heatshield jett., 10 s to complete

7) Radar Acquisition of Ground: ~2.4 km A.G.L

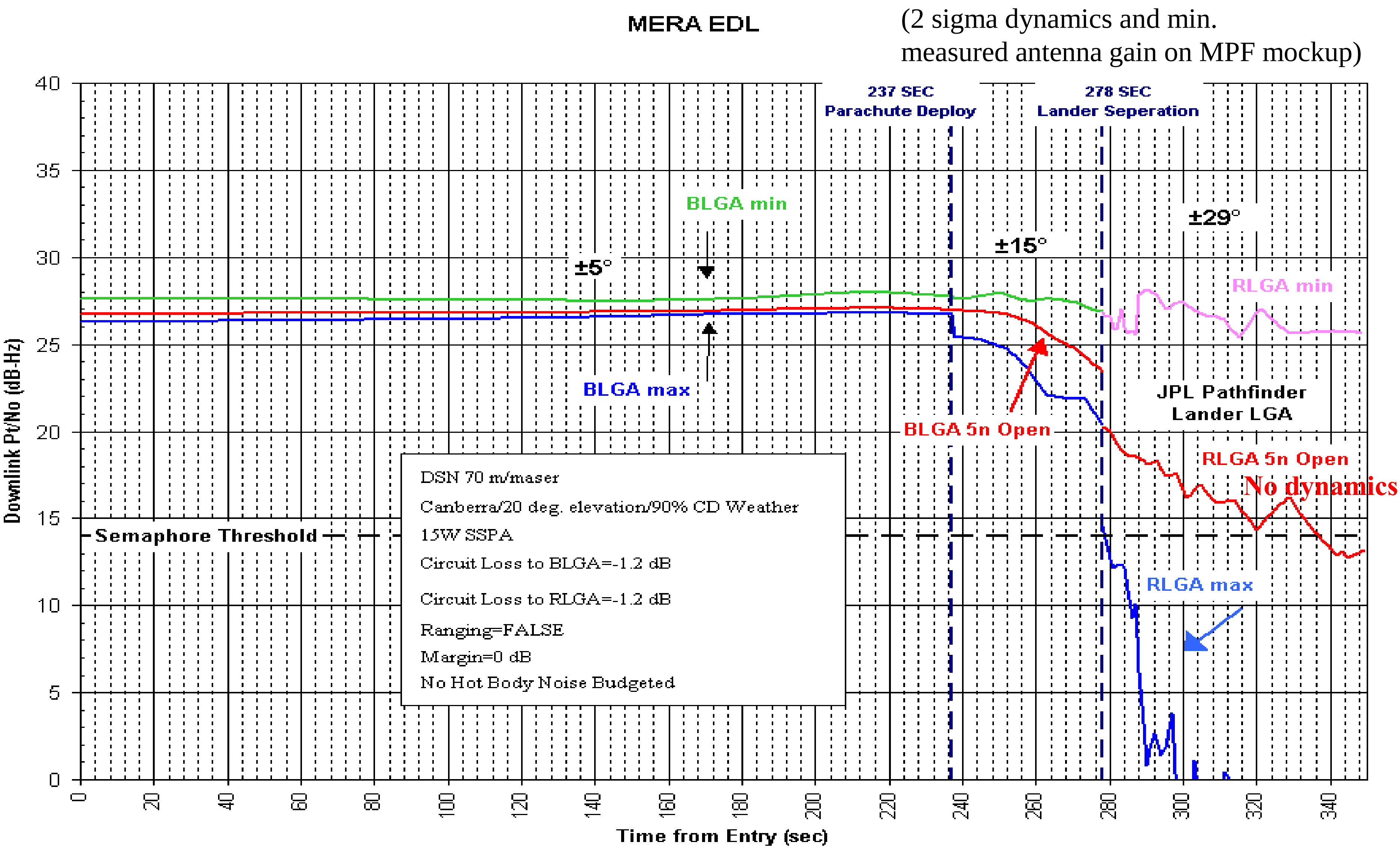
8) Airbag Inflate: ~4 s prior to retrorocket ignition

9) Rocket Ignition: ~160 meters A.G.L

10) Bridle Cut: ~15 meters A.G.L, 0 m/s vertical velocity

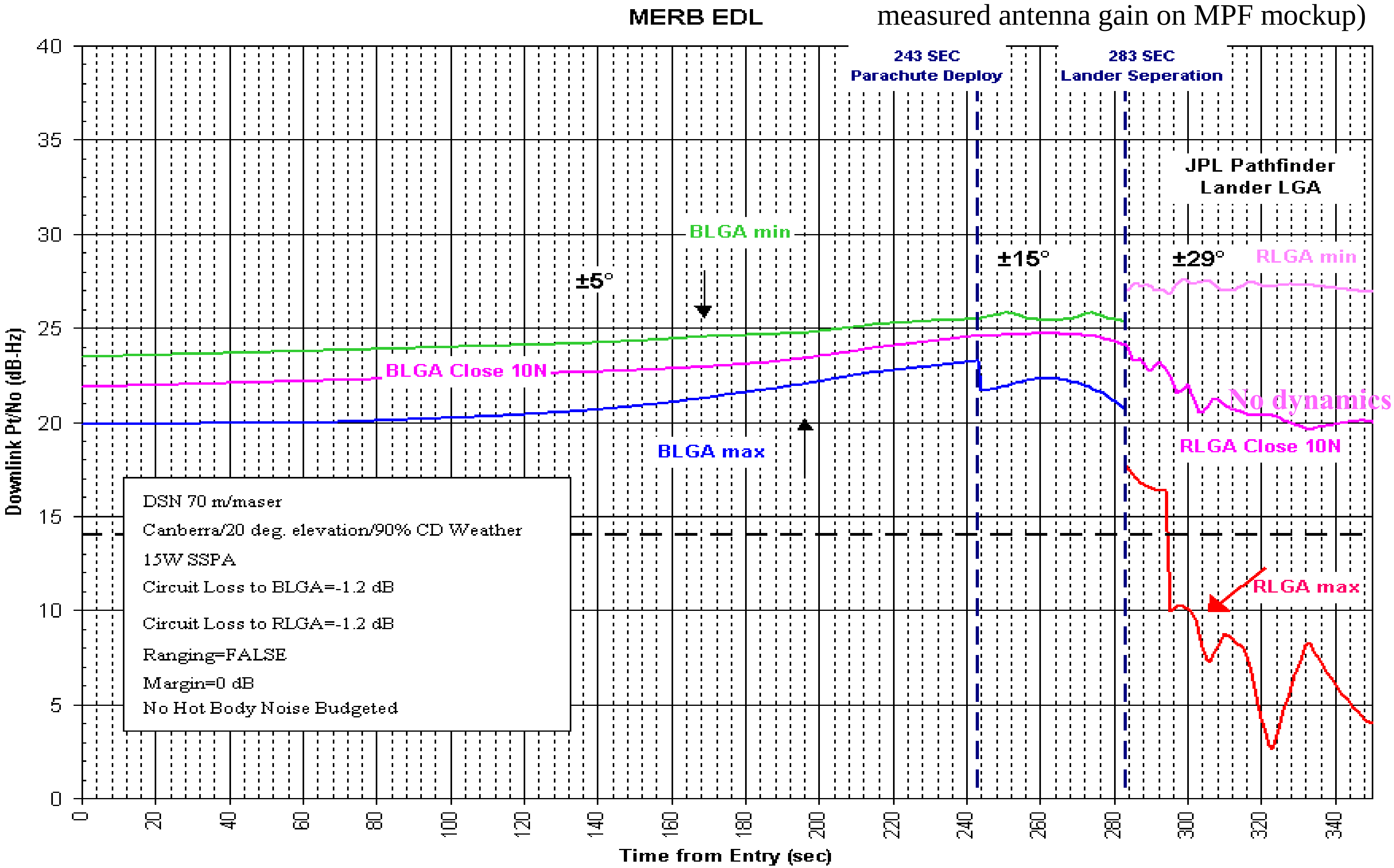
11) First Contact w/ Ground: ~E+ TBD s

MERA EDL: Pt/No for Backshell LGA and Rover LGA

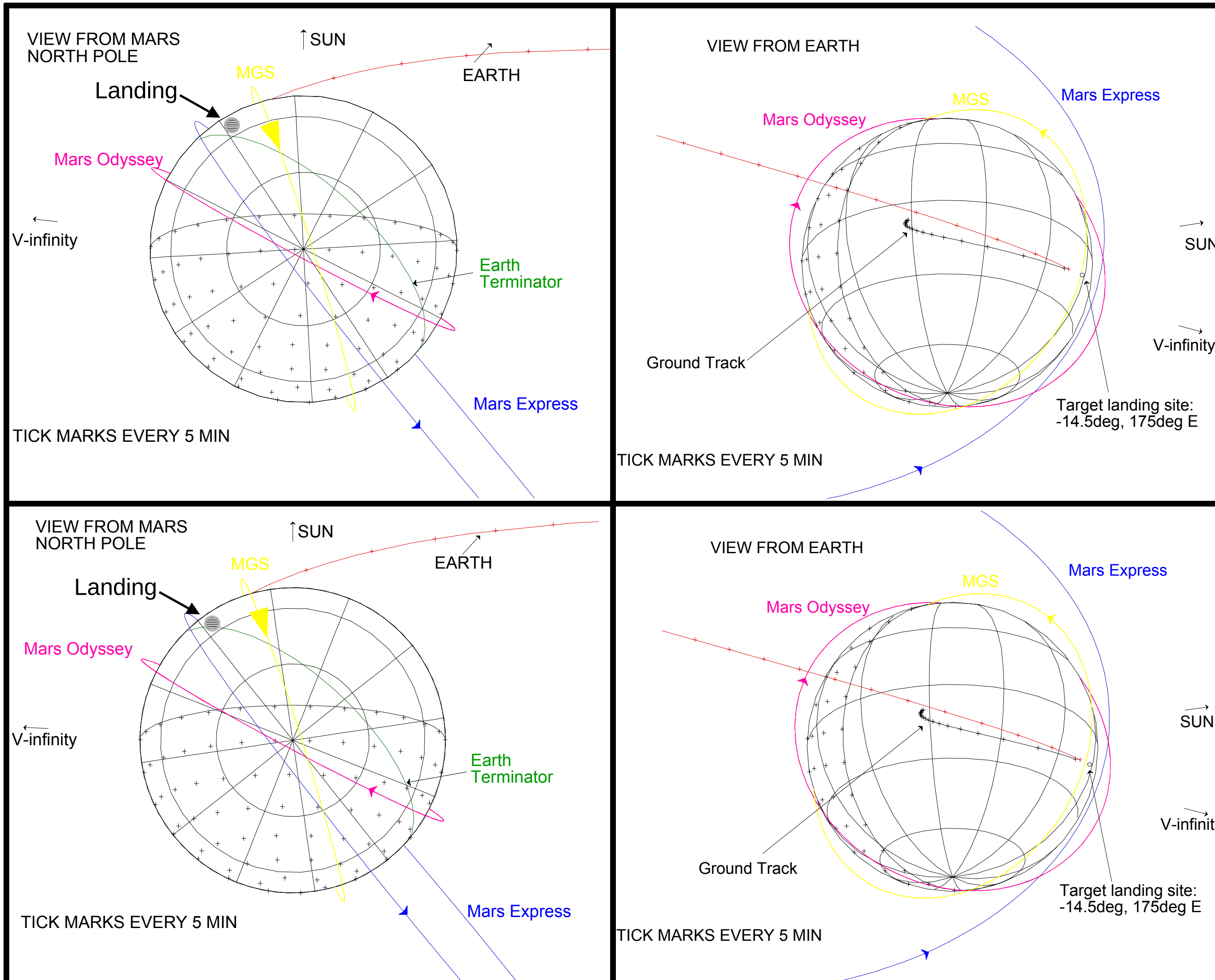


MERB EDL: Pt/No for Backshell LGA and Rover LGA

(2 sigma dynamics and min. measured antenna gain on MPF mockup)



MER-A Approach Geometry



MER-A Open

Launch 5/30/03
Arrival 1/4/04

MER-A Open

Launch 5/30/03
Arrival 1/4/04

Approach Trajectory
- V_∞ = 2.77 km/s
- Declination of V_∞ = 2.04 deg (MME)

MER-A Close

Launch 6/16/03
Arrival 1/4/04

MER-A Close

Launch 6/16/03
Arrival 1/4/04

Approach Trajectory
- V_∞ = 2.70 km/s
- Declination of V_∞ = 4.38 deg (MME)

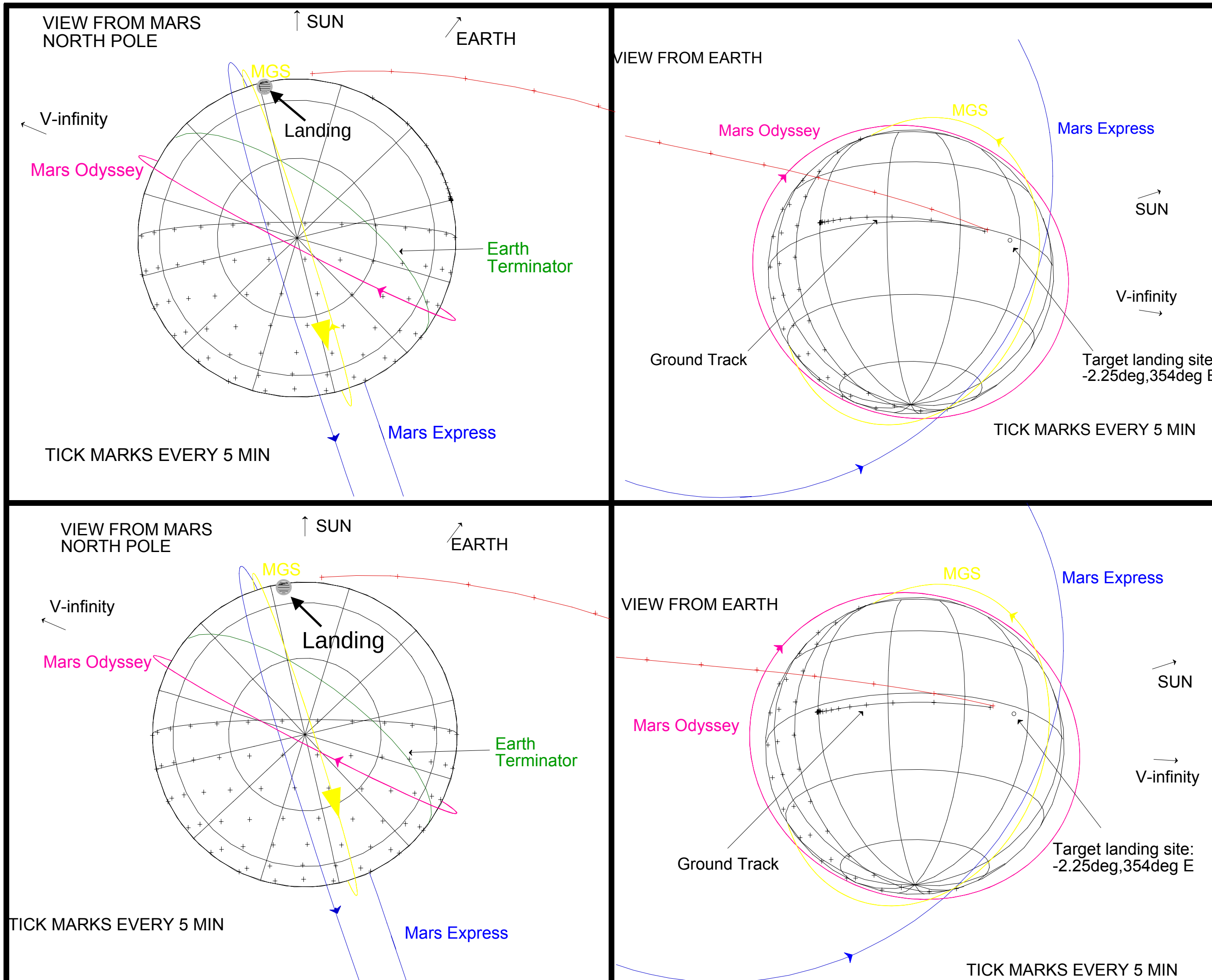
MER-B Approach Geometry

MER-B Open

Launch 6/27/03
Arrival 2/8/04

MER-B Close

Launch 7/14/03
Arrival 2/8/04



MER-B Open

Launch 6/27/03
Arrival 2/8/04

Approach Trajectory
- V_∞ = 3.02 km/s
- Declination of V_∞ = -4.69 deg (MME)

MER-B Close

Launch 7/14/03
Arrival 2/8/04

Approach Trajectory
- V_∞ = 3.50 km/s
- Declination of V_∞ = 1.45 deg (MME)

Mars Program Assessment of Available Assets to Support MER EDL

Mars Program Selection → (Mars Global Surveyor (MGS))

Potential EDL Communications Assets	Pros	Cons
Odyssey Mars 2001 Orbiter	• Odyssey aerobraking will be complete • UHF radio compatibility is well understood (same UHF radios on both vehicles)	• Requires change in orbit which significantly reduces the science return of the GRS instrument
Mars Global Surveyor (MGS)	**• Currently at Mars and operational** **• Prime science mission will be completed** **• Orbit provides good geometry for both MER EDL events**	**• Extended lifetime will require careful propellant management and ops strategy**
Mars Express ESA Orbiter	• Planned to be at Mars during MER landings	• Arrives only 10 days prior to MER-A EDL • The potential large ranges due to orbit geometry may prevent MER EDL support • More complex inter-agency interface