Navigation and EDL for the Mars Exploration Rovers

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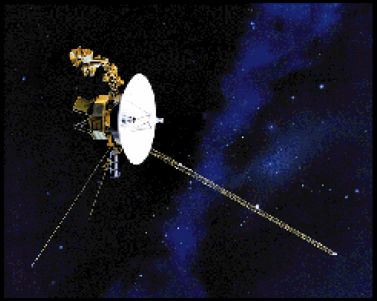
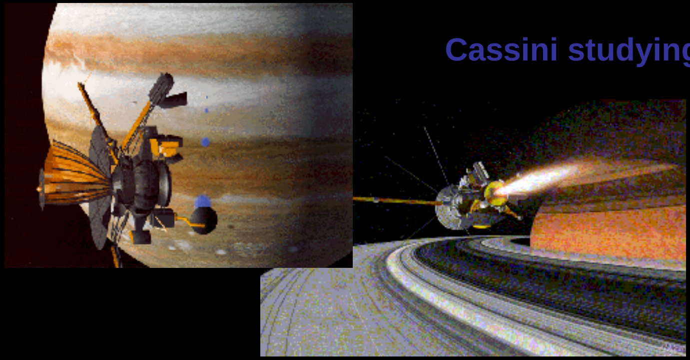
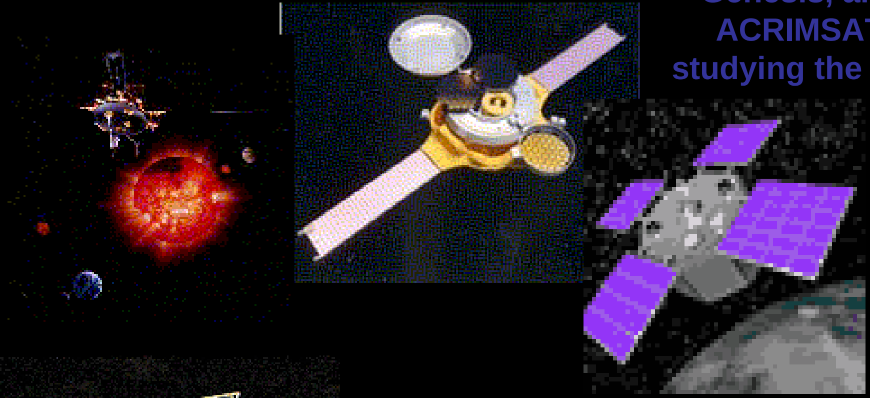
JPL spacecraft operating across the solar system



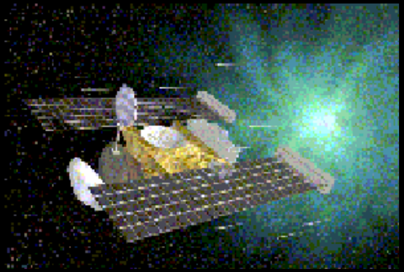
Two Voyagers on an interstellar mission



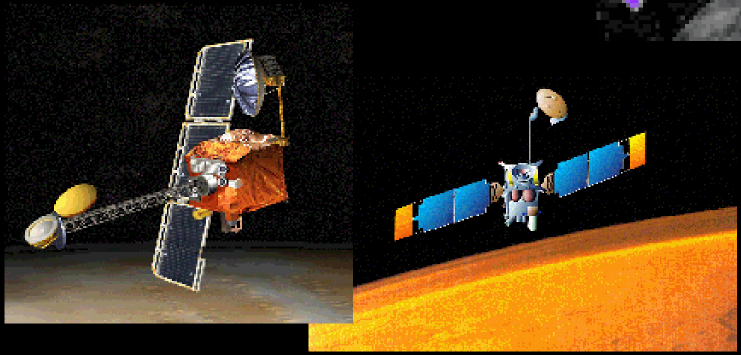
Cassini studying Saturn



Ulysses, Genesis, and ACRIMSAT studying the sun



Stardust returning comet dust



Mars Global Surveyor and Mars Odyssey in orbit around Mars

Topex/Poseidon, Quickscat, Jason 1, and GRACE monitoring Earth

2003 - 2004: The Busiest Period in JPL's History

April 2003	Galaxy Evolution Explorer (GALEX) launch
June 6, 2003	Space Infrared Telescope Facility (SIRTF) launch
June 25, 2003	Mars Exploration Rover – 1 (MER-1) launch
August 25, 2003	Mars Exploration Rover – 2 (MER-2) launch
December 25, 2003	Mars Express arrival
January 2, 2004	Stardust Encounter with Comet Wild-2
January 4, 2004	Mars Exploration Rover – 1 (MER-1) landing
January 25, 2004	Mars Exploration Rover – 2 (MER-2) landing
June 20, 2004	Microwave Limb Sounder (MLS) and Tropospheric Emission Spectrometer (TES) launch on EOS-AURA
July 1, 2004	Cassini Saturn orbit insertion
September 8, 2004	Genesis solar wind sample return (first samples from beyond lunar orbit)
October 26, 2004	First Cassini images of Titan surface
December 24, 2004	Huygens probe release
January 14, 2005	Huygens probe Titan atmospheric entry

Deep Space Navigation Will Enable Many of the New NASA Missions

- New growth area is low thrust (particularly nuclear electric propulsion)
  - Extremely complex trajectory optimization
  - Algorithms for rendezvous/operation in gravity well poorly understood

- Many new missions involve asking the s/c to do things faster and with *much* less a priori knowledge about its target than in the past

  - Small body encounters/landings/sample return
    - Asteroid or comet of unknown shape, mass, rotational state, brightness, surface roughness, etc
    - Need new classes of dynamic modeling, new sensors, autonomy

  - Titan/Venus landers
    - Cloud covered
    - Extreme conditions

  - Europa Subsurface navigation
    - Drill through 10 km of ice
    - Who knows the conditions?

What Exactly is Navigation vs. GNC for Deep Space?

- Classic Definition of "Mission Design and Navigation" refers to the "translational" (trajectory) of the s/c and not to Attitude Control.
- Have traditionally been handled quite separately at JPL because
  - Time constant of translational system much longer than the rotational system
  - Attitude control is an intimate part of the Fault Protection/Automated Response of the s/c
    - Point antenna at Earth and solar panels at Sun
- Now seeing many Deep Space applications where time constants are same and which require the system to make real time decisions:
  - Entry/Descent/Landing
  - Spacecraft rendezvous/sample capture etc
- Future Trends
  - Greater autonomy
  - Integrated Guidance, Navigation and Control - JPL GNC reorganization

Cruise and Approach: Why is Deep Space Nav So Difficult?

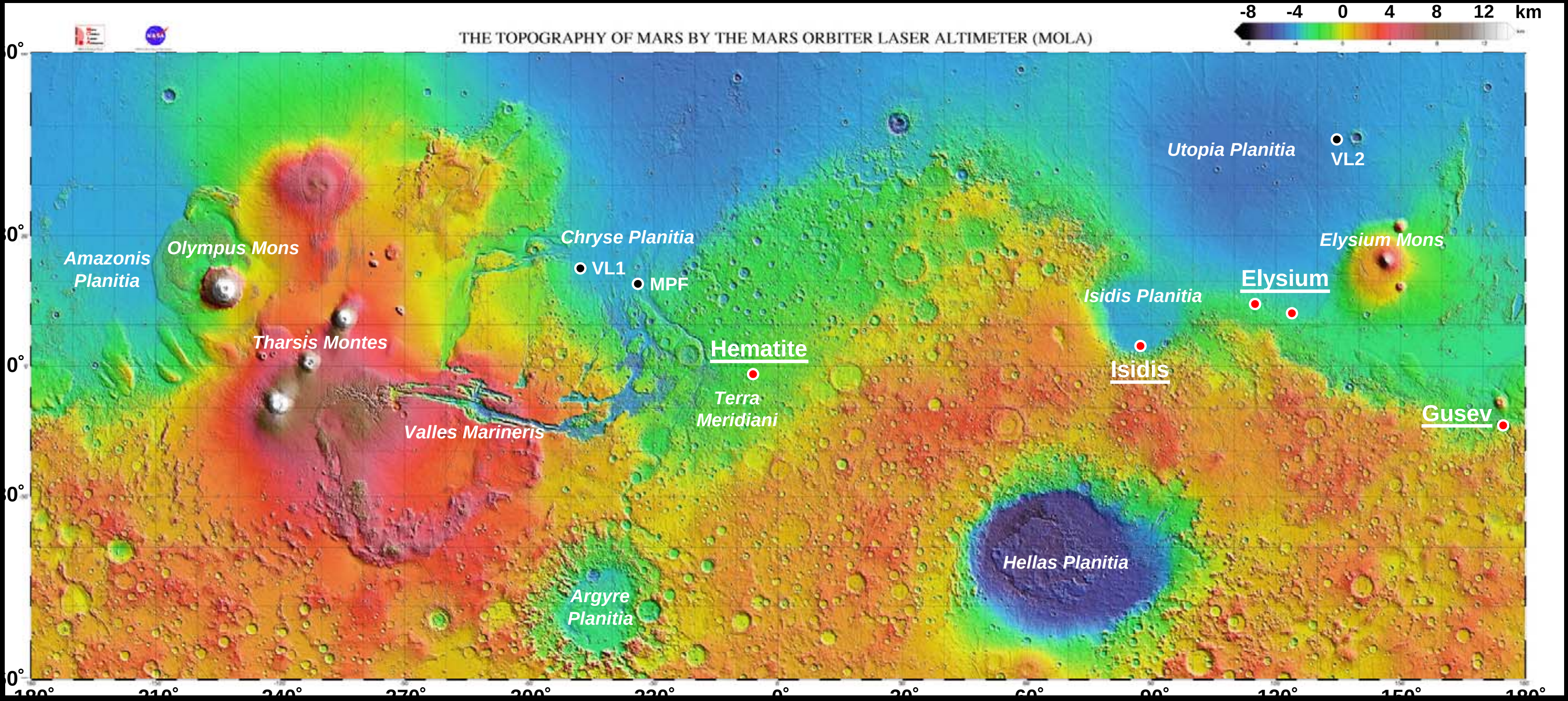
- *Tiny* nongravitational forces add up over time and are extremely difficult to solve for and even harder to predict into the future for targeting
  - 10 nanometer/s/s error => 3.7 km drift over 10 days
  - Can only know if you're getting it right by consistency of solutions over time

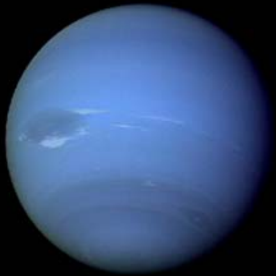
- Tracking Data traditionally only supplies line of sight (1 component) position and velocity.
  - Other components inferred from dynamics + time
  - Exceptions: DDOR (VLBI) and target relative optical navigation

- Celestial mechanics doesn't help much
  - Generally small central angle travel (180 degree transfer over months or years)
  - No out of orbit plane dynamic constraint

Project Importance of GNC: Landing Site Selection

- Nav can target accurately enough to land inside it
- Safe for landing
  - slopes, rocks, wind
- High science value





Planetary Communications and Tracking

Neptune

- One-way signal time is over 4 hrs.
- Communicating bits is 10 billion times harder than from a GEO comsat
- The received energy from Voyager at Neptune, if integrated for 300 million years, would be just enough to set off a small photographic flashbulb!

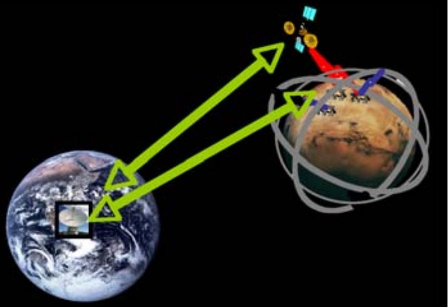
Spain

California

Australia

Advanced RF Communications

Pioneer Optical Comm

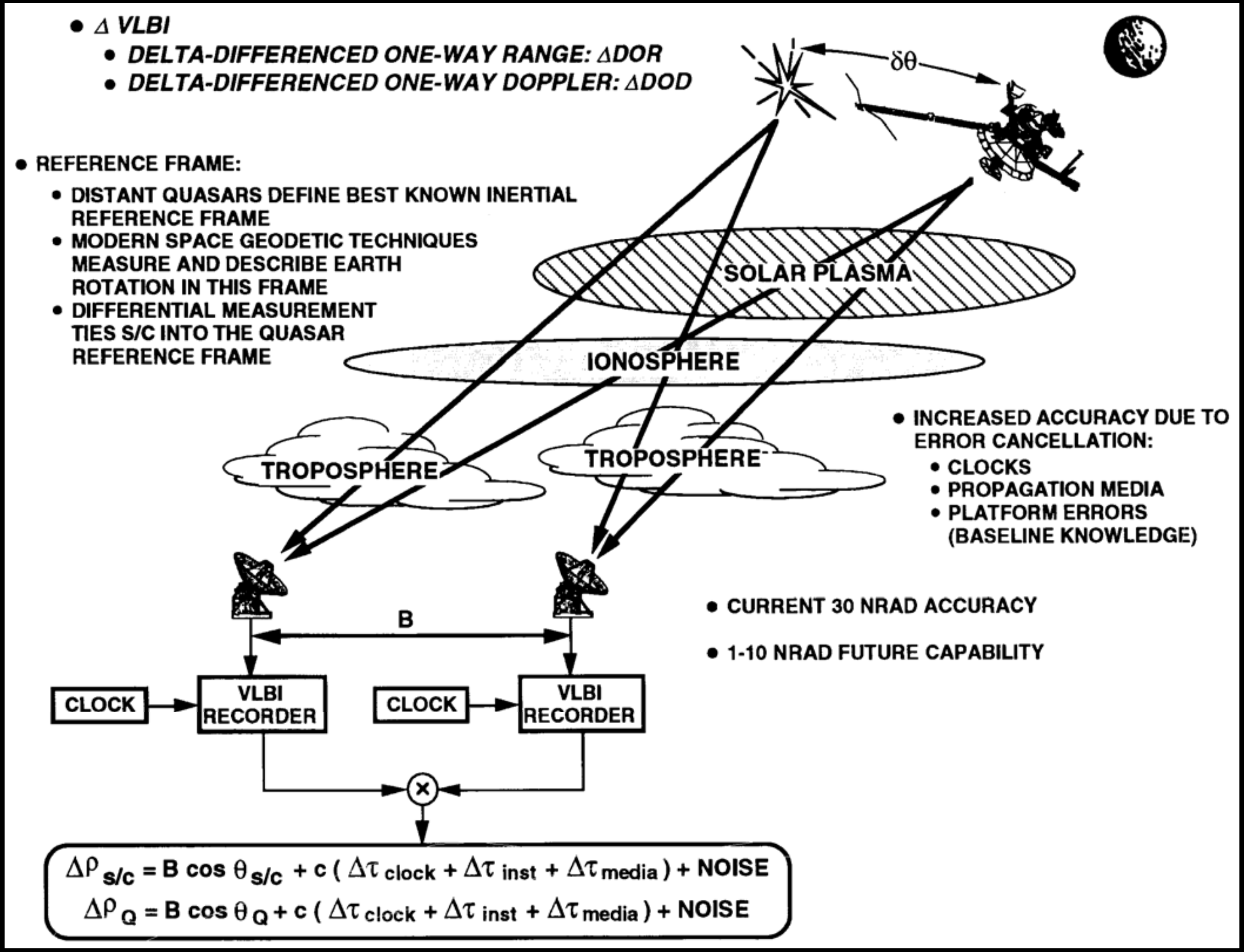


Network the Space Comm Assets

Tracking Data Types

- 2-Way Coherent X-Band Doppler (7.2 GHz up/8.4 GHz down)
  - Measures line-of-sight velocity of S/C via frequency shift in radio signal
  - Noise: 0.02 – 0.2 mm/s
  - Nominally weighted at 0.1 mm/s (60 sec count time)
- Range
  - Directly measures the relative Earth-S/C distance via the round-trip timing of coded signal modulated on the signal
  - Noise < 1 meter
  - Nominally weighted at 3 meters
  - Stochastic pass dependent range biases estimated at 5 meters
- ΔDOR
  - Measures angular position in Earth plane of sky
  - Noise < 4.5 nrad or 0.12 nsec in geometric delay for two stations separated by 8000 km
  - Weighted at 0.12 nsec
  - Position accuracies of 90 – 680 meters for Earth-S/C distances of 20 Mkm (Jun 01) – 152 Mkm (Odyssey MOI, Oct 23)

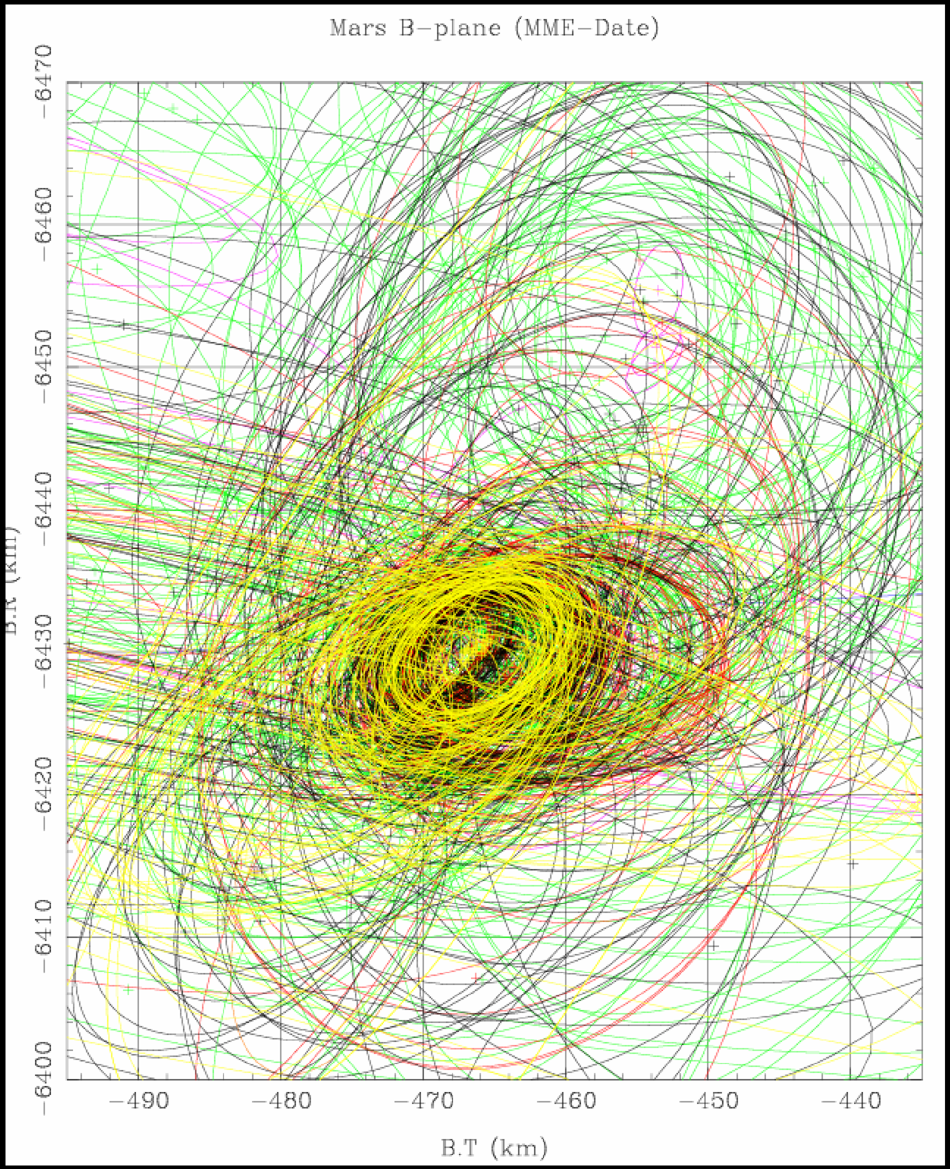
Delta Differential One-Way Range (ΔDOR)



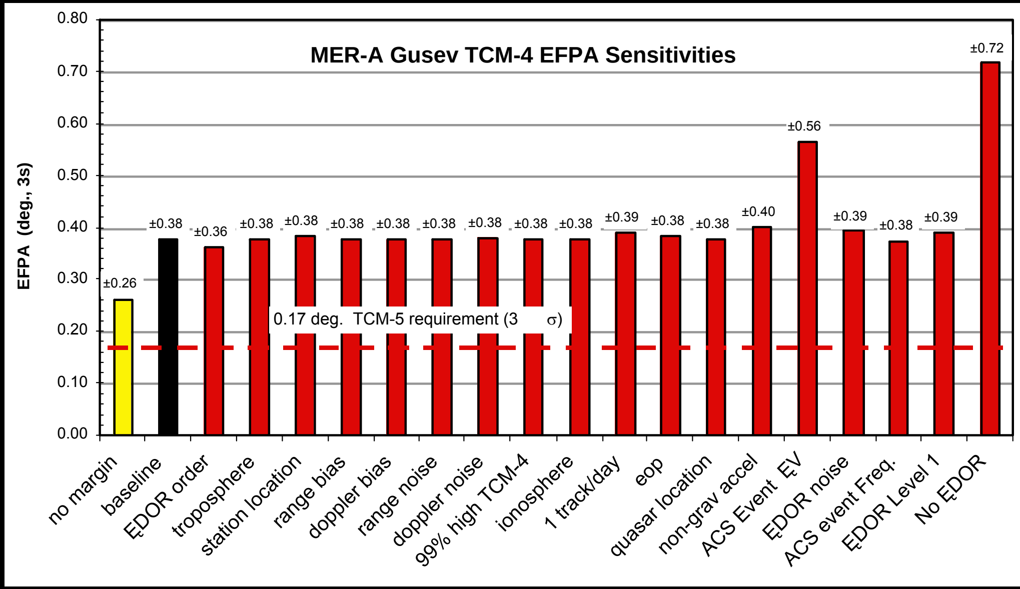
MER OD Filter Configuration

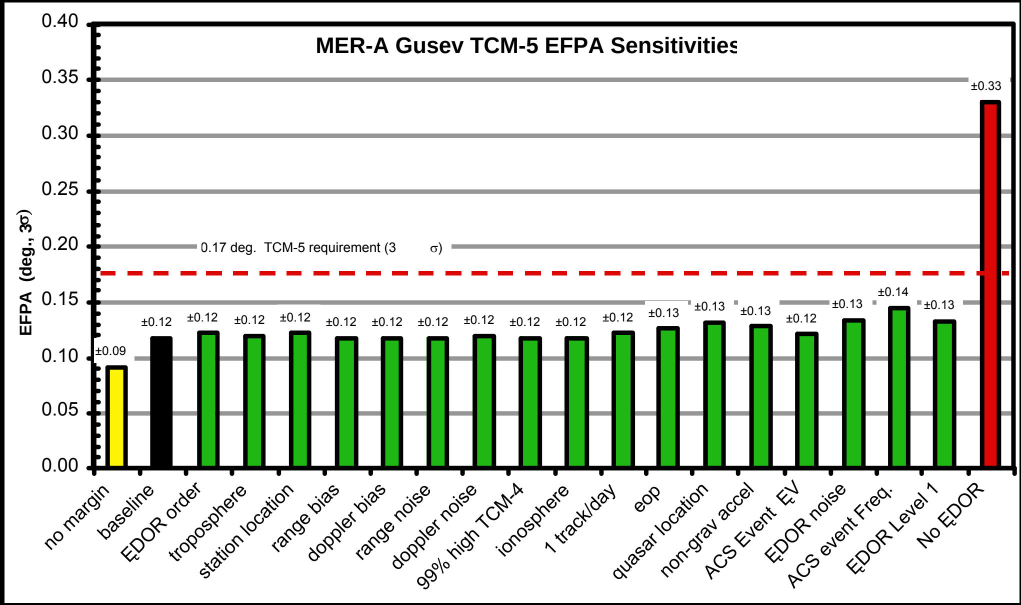
Error Source	Estimated?	No Margin A Priori Uncertainty (1σ)	Baseline A Priori Uncertainty (1σ)	Degraded A Priori Uncertainty (1σ)	Correlation Time	Update Time	Verified by Analysis	Observed In-Flight	Comments/References
2-way Doppler (mm/s)	Š	0.05	0.075	0.1	Š	Š	Martin-Mur/Estabrook	<0.05	~3 mHz (Ref. 1)
Range (m)	Š	4	4	8	Š	Š	Martin-Mur/Estabrook	< 4m	29 range units (Ref. 2)
ĘDOR (nrad)	Š	4.5	4.5	9	Š	Š	Border	<2.0	0.12 ns (Ref. 3)
ĘDOR Schedule		DSN request	DSN request	Level 1 (~50%)			N/A	N/A	DSN request.
ĘDOR Latency (days)		1	2	2					Commitment for 24-hr turnaround.
Epoch State									
Position (km)	√	1000	1000	1000	Š	Š	N/A	N/A	
Velocity (km/s)	√	1	1	1	Š	Š	N/A	N/A	
Range Bias (m)	√	1	2	4	0	Per pass	Martin-Mur/Estabrook	<2	Estimated per pass.
Doppler Bias (mm/s)	√	0.005	0.005	0.01	0	Per pass	Martin-Mur	<0.005	Estimated per pass. (Represents upper limit.)
Mars & Earth Ephemerides		DE405+	DE405+	DE405+	Š	Š	Standish	MGS/Odyssey DDOR	New Delivery + Ref. 4
Station Locations (cm)		3	3	10	Š	Š	Folkner/Watkins	Geodetic VLBI	New Delivery + Ref. 5
Pole X, Y (cm)	√	1 → 10	2 → 10	20	0	6 hrs	Ratcliff/Watkins	<1 → <5	
UT1 (ms)	√	1 → 10	2 → 10	20	0	6 hrs	Ratcliff/Watkins	<2 → <10	Ref Ratcliff
Quasar Locations (nrad)		2	2	4	Š	Š	Border	2	VLBI + Ref. 7
Ionosphere Š day (cm)	√	55	55	75	0	6 hrs	Wilson	N/A	S-band values. (Ref. 8)
Ionosphere Š night (cm)	√	15	15	15	0	6 hrs	Wilson	N/A	
Troposphere Š wet (cm)	√	1	1	2	0	6 hrs	GPS	N/A	Ref. 6
Troposphere Š dry (cm)	√	1	1	2	0	6 hrs	GPS	N/A	
Solar Pressure									Sunlit area of spacecraft.
Area (%)	√	5	5	5	Š	Š	McElrath/Goguen	?	New Model for improved area calculation
ACS Event ĘV (mm/s)		Every 12 days	Every 8 days	Every 4 days	Š	Š	N/A	N/A	Will be less frequent than 8 days
Line-of-Sight Comp.	√	1	3	6	Š	Š	N/A	<0.5 MER-A <1 MER-B	
Lateral Comp.	√	1	3	6	Š	Š	N/A	<0.5 MER-A <1 MER-B	Actual Test + Ref. 12
Normal Comp.	√	1	3	6	Š	Š	N/A	<0.5 MER-A <1 MER-B	
TCMs									Spherical uncertainty (mm/s).
TCM-1	√	422	422		Š	Š	N/A	<baseline	MER-A Open
TCM-2	√	17	17		Š	Š	N/A	<baseline	TCM-4 at E - 8 days
TCM-3	√	3	3		Š	Š	N/A	unknown	TCM-5 at E - 2 days
TCM-4	√	3	3	5	Š	Š	N/A	unknown	TCM-6 at E - 6 hrs
TCM-5	√	3	3	3	Š	Š	N/A	unknown	5% (3s) prop. error (per axis)
TCM-6	√	4	4		Š	Š	N/A	unknown	6 mm/s (3s) fixed error (per axis)
Non-gravitational Accelerations (km/s^2)	√	1.7×10^{-12}	2.0×10^{-12}	4.0×10^{-12}	10 days	1 day	Bhaskaran	$<4\times10^{-12}$	Spherical covariance. Estimated daily (1 day batches).

All solutions leading up to TCM-4 design



Entry Flight Path Sensitivities





MER Navigation Results

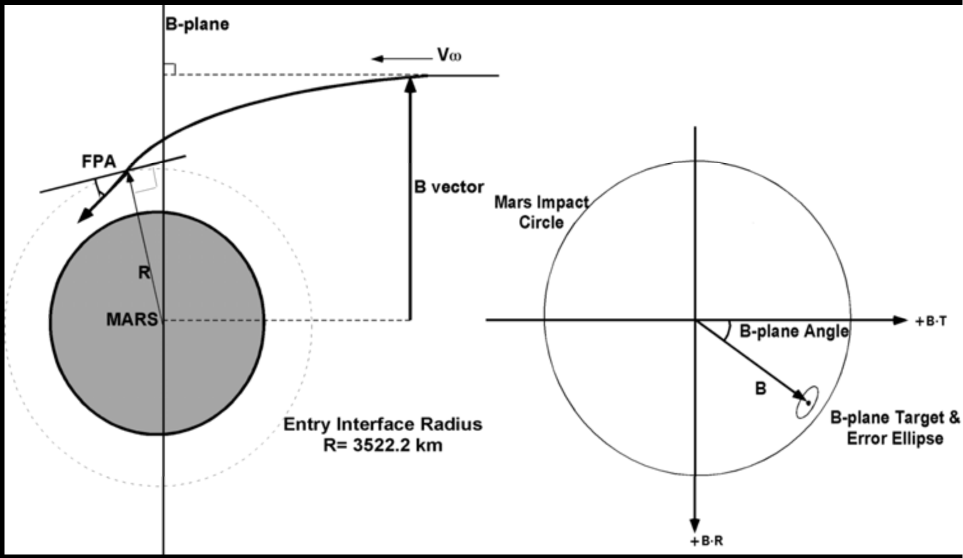
- Required atmospheric entry FPA delivery accuracies at TCM-5 (E–2 days) were ±0.12° (3σ) for Spirit and ±0.14° (3σ) for Opportunity
- Actual entry FPA errors (based on the final pre-entry OD solutions) were estimated to be –0.007° ± 0.010° (3σ) for Spirit and +0.030° ± 0.021° (3σ) for Opportunity
  - Equivalent to B-plane errors of only **~180 m** for Spirit and **~750 m** for Opportunity
  - FPA error for Opportunity would have been smaller if TCM-5 had not been canceled
- TCMs 5 (E–2 days) and 6 (E–4 hours) were canceled for Spirit
- TCMs 3 (E–65 days), 5 (E–2 days) and 6 (E–4 hours) were canceled for Opportunity
- Miss distance on surface (relative to 70–80 km downtrack dimension of landing ellipse):

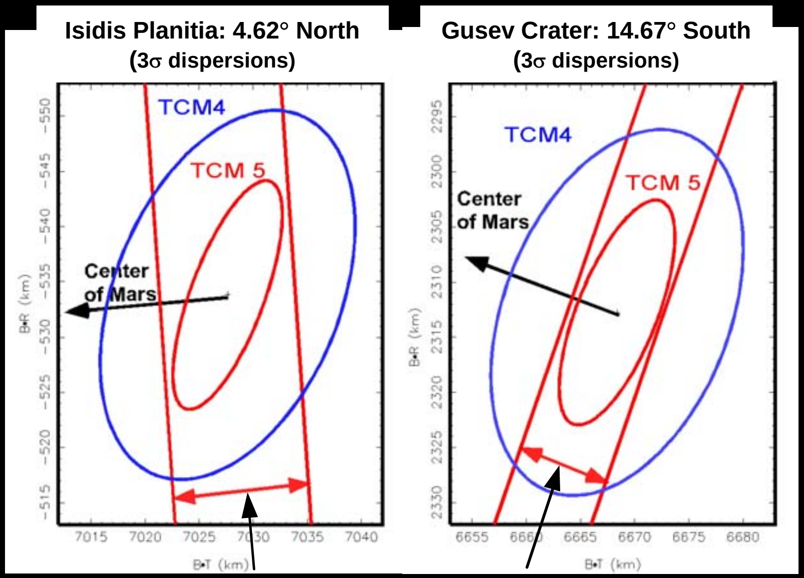
	Spirit	Opportunity
Navigation-only error	3.3 km (uptrack)	9.7 km (downtrack)
Total miss distance*	10.1 km (~downtrack)	24.6 km (downtrack)

*Including atmosphere and spacecraft aerodynamics uncertainties

Atmospheric Entry Targeting and Delivery

– Entry Flight Path Angle (FPA) uncertainty creates the dominant error source in the downtrack component of the landing ellipse.
– The desire to make the landing ellipse as small as possible to enable scientifically interesting and safe landing sites.
– The landing ellipse size (end-to-end downtrack error) ranges from 108 km to 140 km (3σ) corresponding to FPA uncertainty requirements ranging from 0.17 deg to 0.25 deg (3σ), depending on the latitude of the landing site, for the sites considered in this analysis.





Landing Ellipse Orientation

Illustrative Landing Ellipses - Based on Pre-Nav Peer Review Dispersions

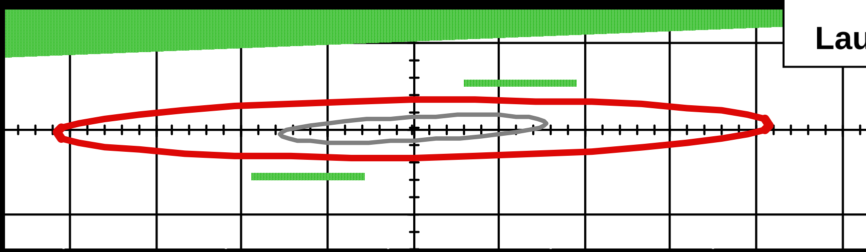
TCM-4 (E-10d, L1 ΔDOR) ΔDOR)

Site Ellipses

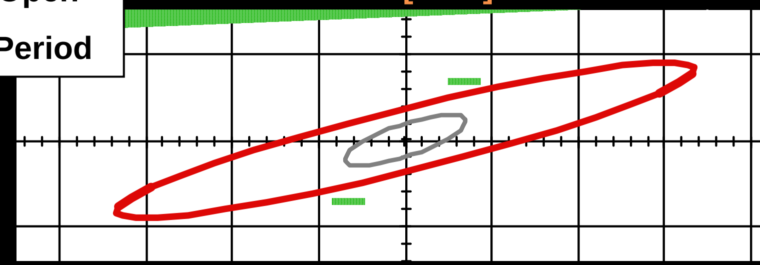
TCM-5 (E-12hr, L1

MER-A Open Launch Period

Isidis [4.7°N]

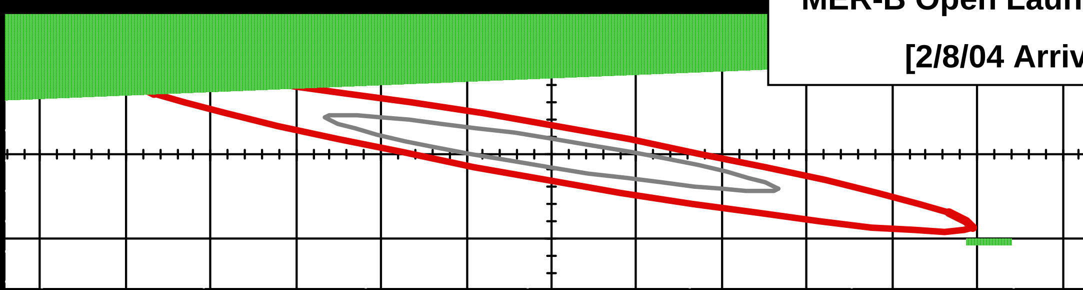


Gusev [15°S]

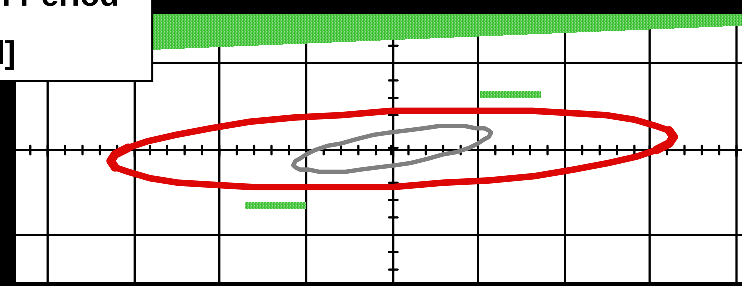


MER-B Open Launch Period [2/8/04 Arrival]

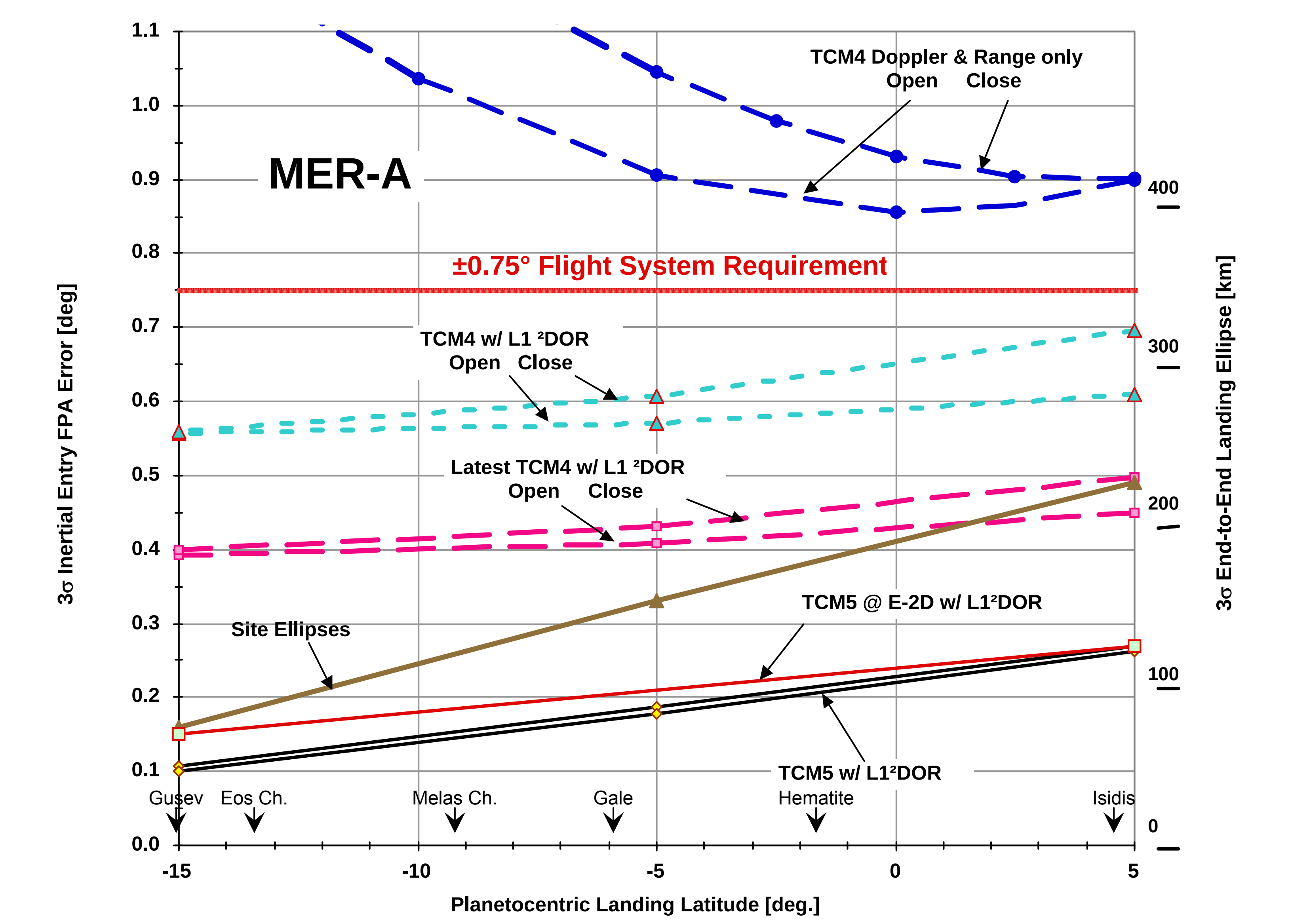
10°N



Melas [9°S]



MER landing site trade example



Saturday January 3, 2004 – 8:14 p.m. PST
15 minutes before entry

Spirit Cruise Stage Separation

Entry, Descent and Landing: Entry Guidance or What Things Do We NOT do for MER landings (but we will later…)

- Spacecraft - Spacecraft tracking
  - UHF or X-band tracking between orbiter and incoming lander could potentially give 100m accuracy
    - May demo on Phoenix (probably not) and MSL

- Guided Entry
  - We use ballistic entry, and pay a price by having slightly larger landing footprints
    - More pressure on Navigation to be perfect
    - Phoenix (probably) and MSL will use hypersonic guidance
  - Interesting point
    - Knowledge AND control both needed for ballistic
    - For guided entry:
      - Knowledge is the more driving requirement
      - Control just has to be "in the box" (~0.3 deg FPA)

Entering Martian Space

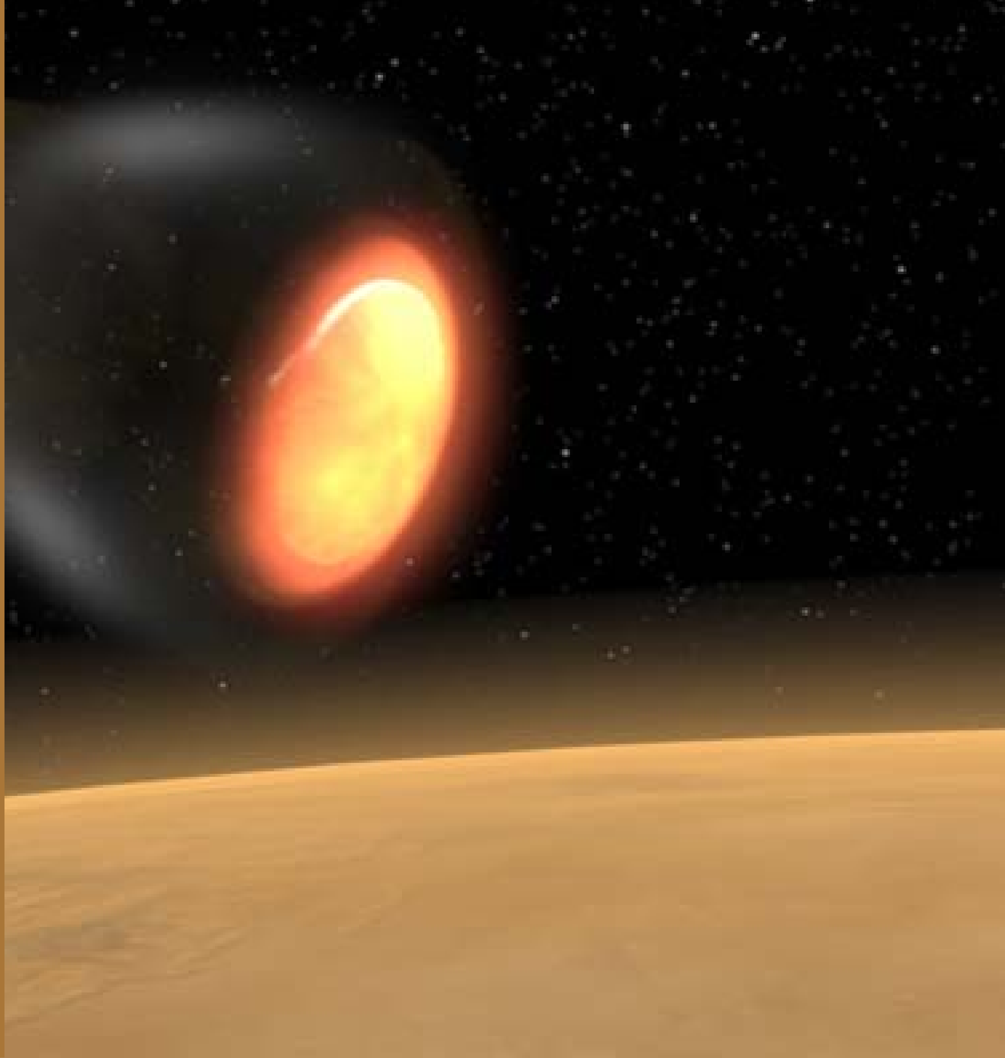
8:29 p.m. PST (ERT)

24 hours before entry, the spacecraft was traveling at speed of 6,000 mph relative to Mars.

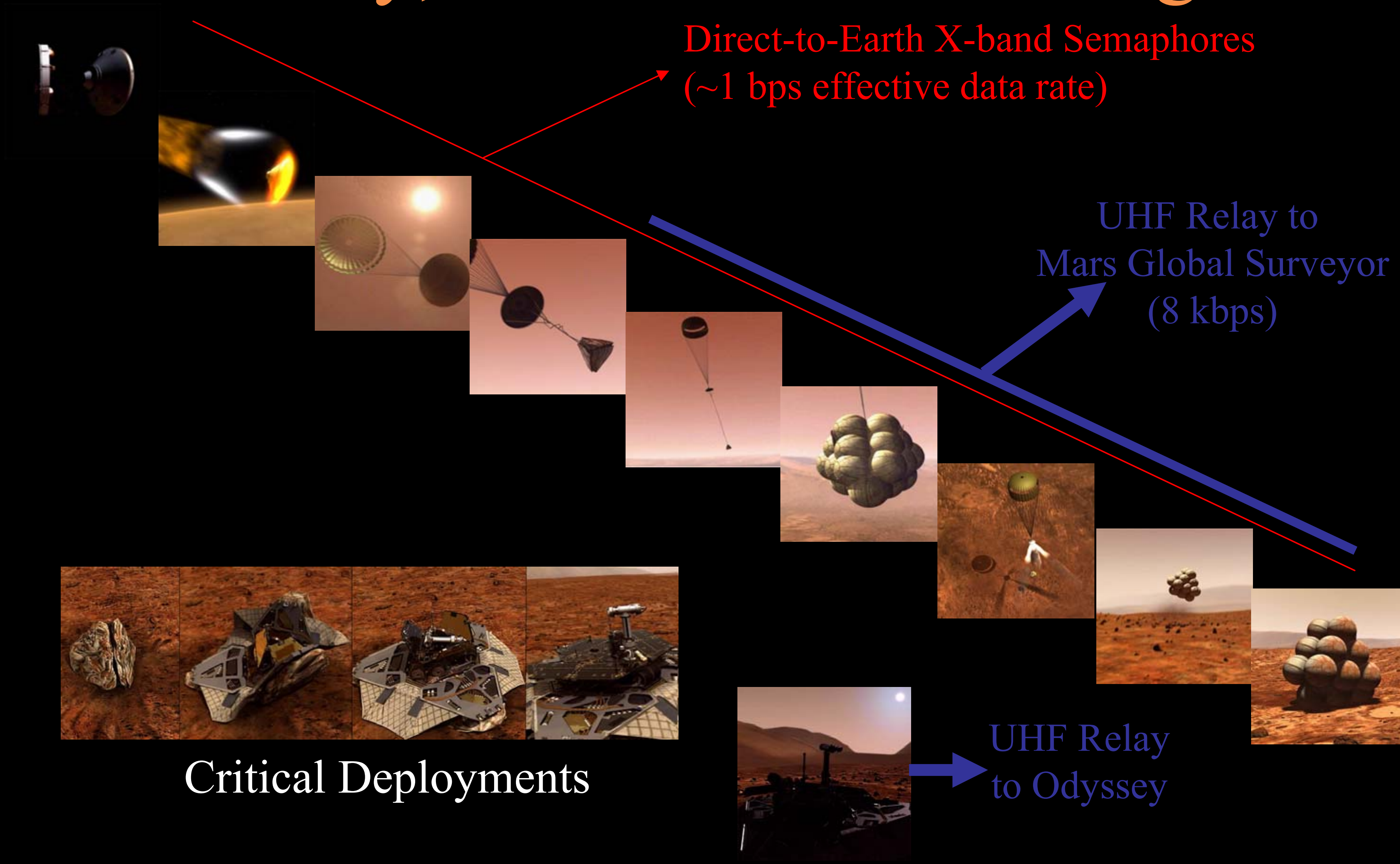
During the course of the day, its speed steadily increased to 7,000 mph.

But in the last two hours, firmly in the grasp of Mars gravity, the spacecraft accelerated to 12,000 mph at entry point 80 miles above the surface.

It is less than 6 minutes before landing.



Entry, Descent and Landing



Entry, Descent and Landing: Terminal Guidance

- Terrain sensing for landmark navigation
  - Not done for MER: Since we are unguided, we do not use cameras to identify landmarks for navigating to target
  - Probably NOT done for either Phoenix or MSL (possible demo)
- Hazard Detection/aviodance
  - Airbag lander, no terminal guidance or control
    - Except to null horizontal velocity (DIMES/TIRS)
    - Also NOT done for Phoenix or MSL!
      - Risk and cost are high, odds of landing on a rock are lower…

The Challenge

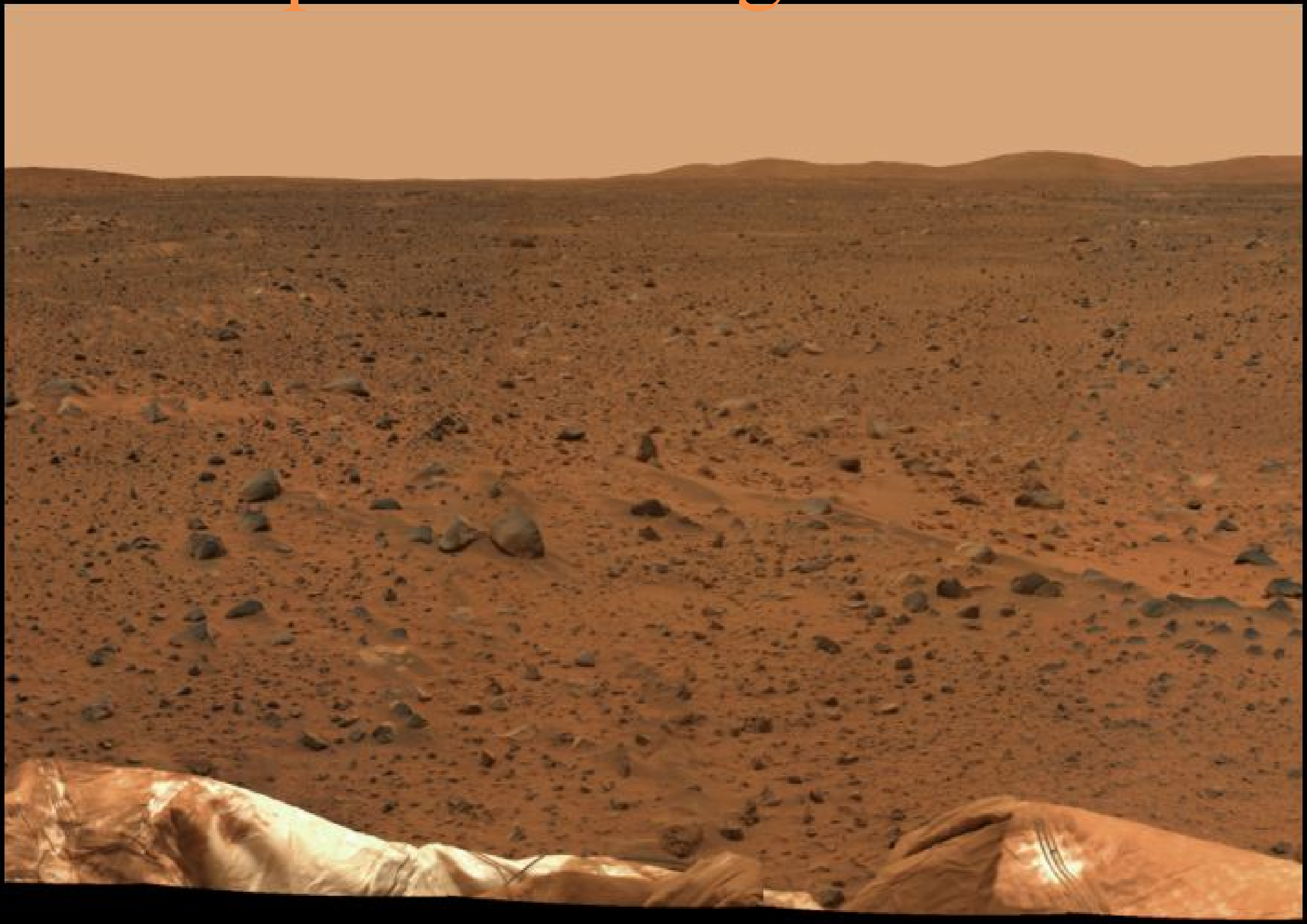
Going from 12,000 mph to Zero in Less Than Six Minutes

The Ultimate Brake System

Spirit Has Landed

After ~30 bounces and a roll of
1/4 of a mile, Spirit comes to rest.

Spirit Landing Location



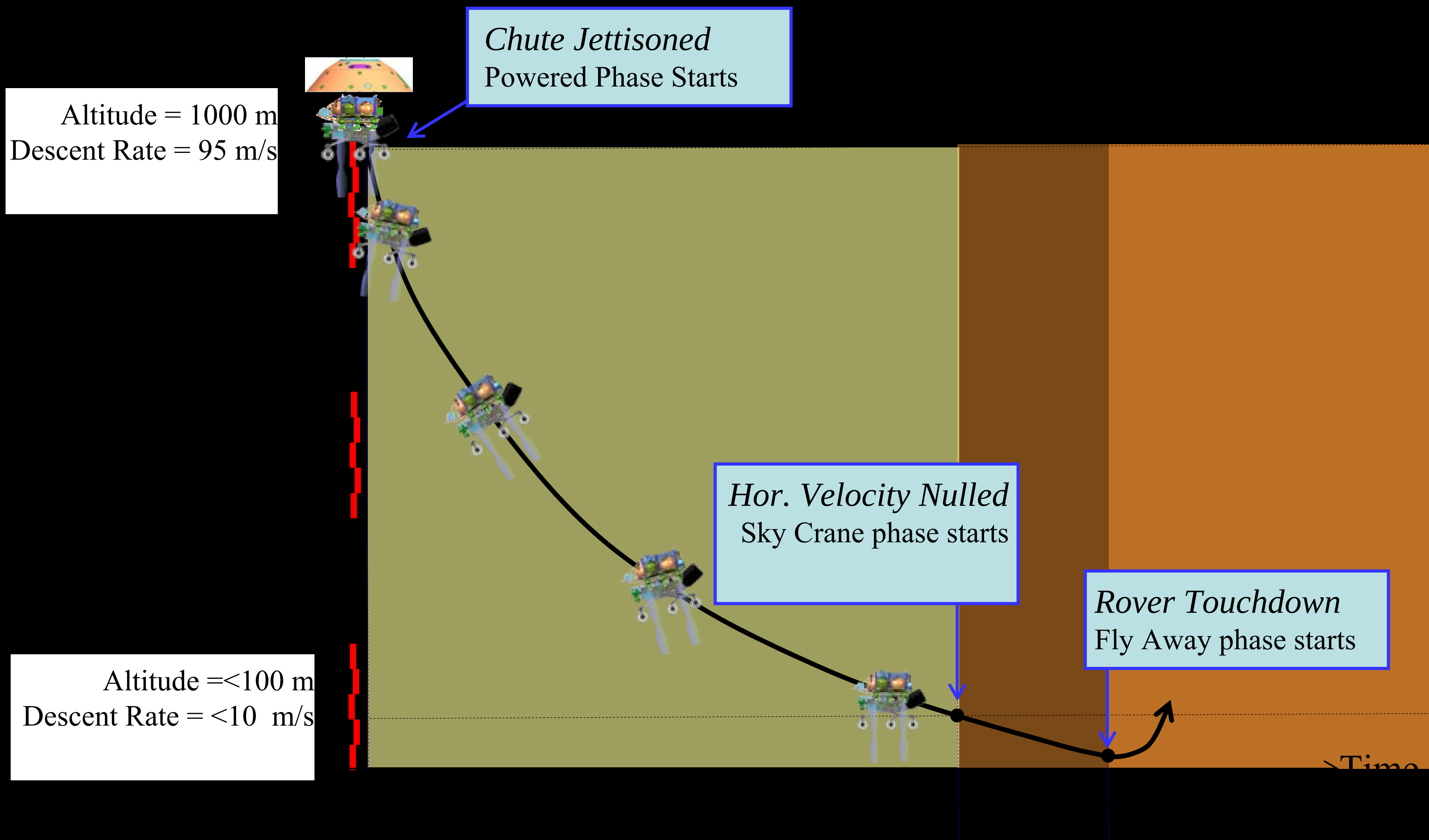
Parameter	Target (deg)	Navigation Solution Value (deg)	Uncertainty (1σ) deg	Uncertainty (1σ) meters	Error (deg)	Miss Distance (km)
Latitude*	-14.59	-14.57189	1.14E-04	6.5	0.01811	10.1
Longitude*	175.30	175.4785	2.58E-06	0.2	0.17848	

*IAU/IAG 2000 coordinate system (areocentric).

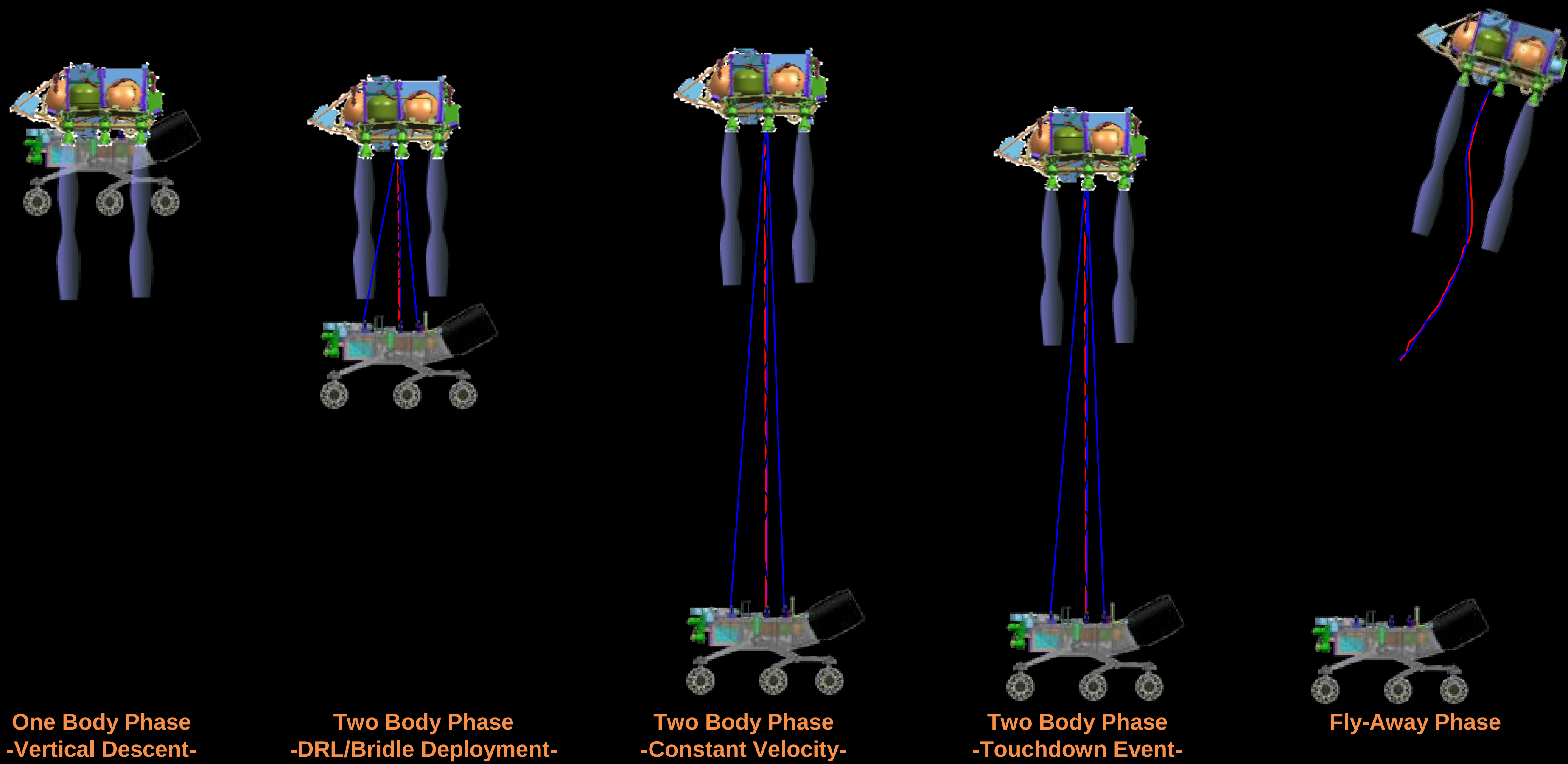
Entry, Descent and Landing: The Future

- Airbags are not a mass-efficient method for landing when the landed mass exceeds a few hundred kg.
  - Phoenix will use the Mars Polar Lander legged lander with powered descent
    - Phoenix is a fixed lander (a la Viking)
  - MSL will use the powered descent with sky crane
    - Sky crane is useful for landing rovers

Powered Descent Time-Line



Updated Sky Crane Maneuver Description



Summary

- *GNC is taking the lead in future EDL systems as we move away from “mechanically” driven systems to GNC-driven systems like sky crane*
- *“Planetary” GNC will have to include a significant aero component in EDL and aero-braking/aerocapture*
- *Great Challenges and Technologies are on the way*