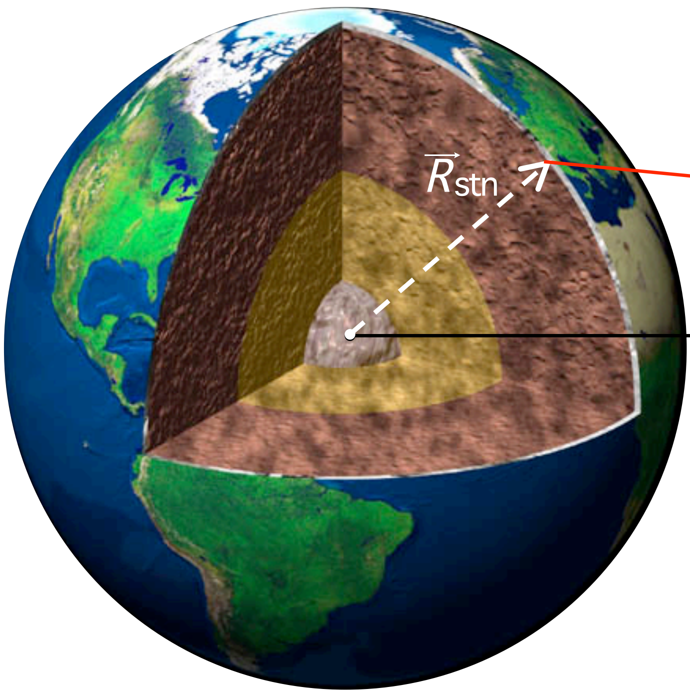
Mars Laser Ranging

Preliminary Results from an Advanced Mission Concept Study



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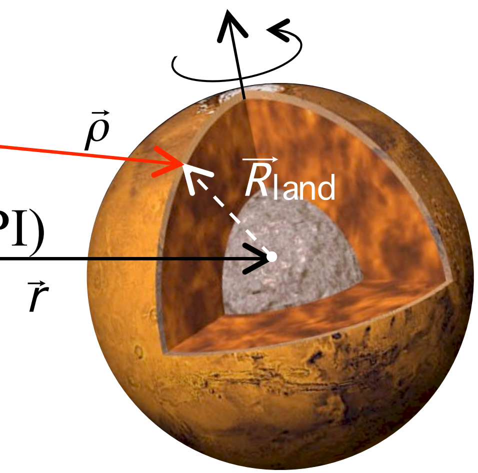
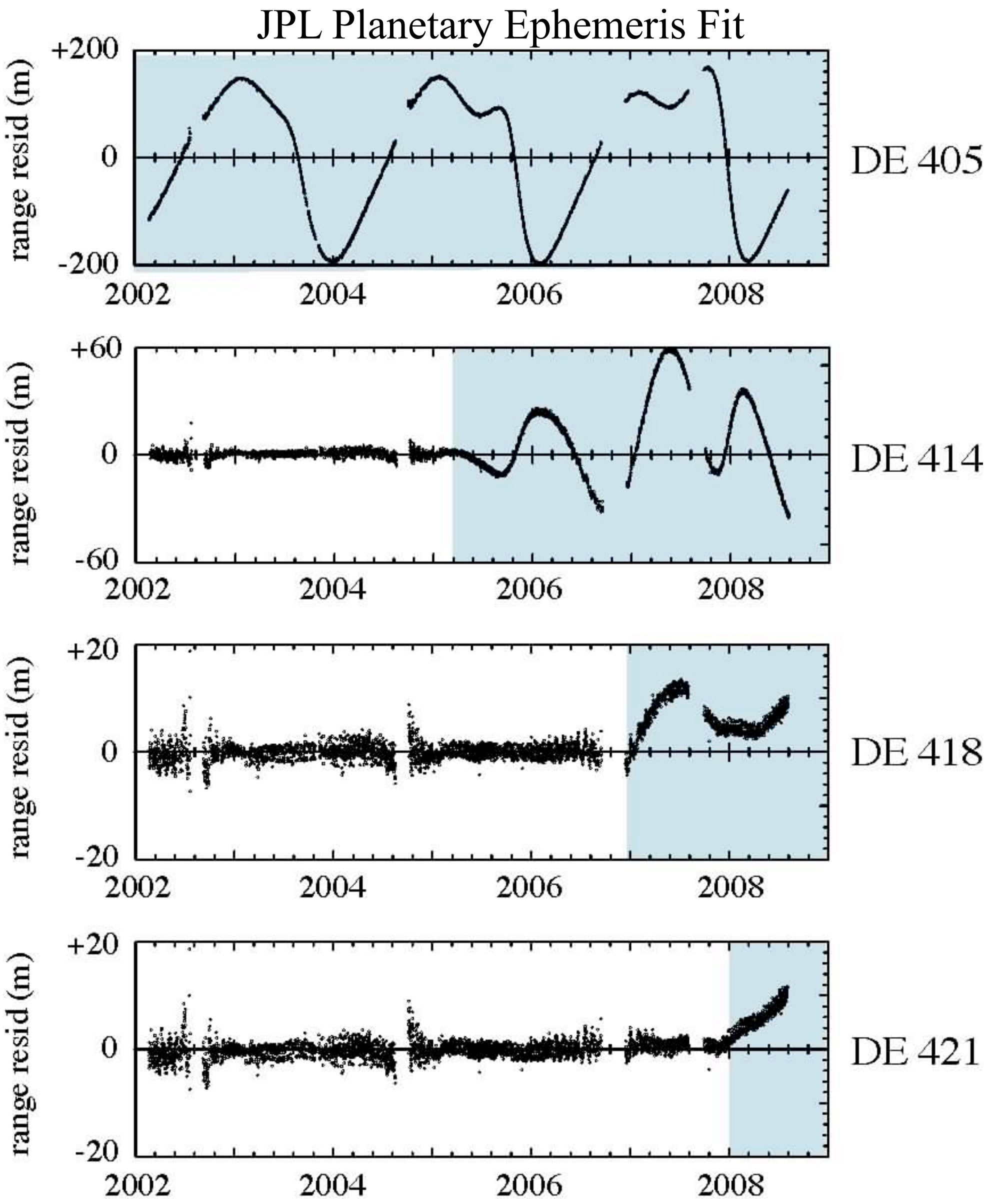


Science Goals

- Gravity—as we know it—is described by General Relativity (GR)
  - but GR is fundamentally incompatible with Quantum Mechanics
  - gravity is the least well-tested of the fundamental forces
  - the interpretation of dark energy, dark matter pre-suppose that GR is right
- 1 mm laser ranging to Mars (current level: 2 m) enables:
  - testing curvature of space via Shapiro time delay measurements at solar conjunctions: measure γ to 1.4×10^{-7} (currently 2.3×10^{-5})
  - measuring time-rate-of-change of gravitational constant, G to 3×10^{-15} per year (currently 8×10^{-13})
  - separating G-dot from M-dot of sun for the first time
  - most precise test of the inverse square law at ~1 A.U. scales
  - test of the Strong Equivalence Principle via polarization of Earth/Mars orbits toward Jupiter: measure η to 5×10^{-4} (comparable to today)
- Demonstrate millimeter-level interplanetary laser ranging capability as prelude to more solar system tests of gravity

Why Mars?

- Mars has 20-year history of range measurements
  - Helps in estimation of long-term/secular effects
- Rich history of technology for Mars landers
  - Many landers & orbiters operated for long times (e.g. Viking)
- Mars distance from Sun compatible with normal electronics & solar power
- On down-side, Mars is more perturbed by asteroids
  - But Earth is also perturbed, so sets lower limit when looking at any solar system body



Simulated Gravity Parameter Determination

- Simulated Mars laser ranging over 1-6 years of operation based on daily 1 mm range points
- Currently with 67 asteroid GM estimated (sensitivity shown on next slide)
- Mars orientation variation currently not modeled, being added in October.
- Other effects being considered; annual variation of surface relative to c.g.
- Estimated parameters include orbital elements, up to 67 individual asteroid GM, 230 other asteroids in 3 classes with densities estimated

Parameter	Current Best	1 year mission (1 conj.)	3 year mission (2 conj)	6 year mission (3 conj.)
γ	2.3×10^{-5}	3.1×10^{-7}	1.4×10^{-7}	7.8×10^{-8}
β	1×10^{-4}	4.3×10^{-4}	1.7×10^{-4}	8.6×10^{-5}
J_2 of sun	2×10^{-7}	6.9×10^{-8}	3.2×10^{-8}	2.1×10^{-8}
M-dot of sun	—	4.7×10^{-14} yr^{-1}	1.8×10^{-14} yr^{-1}	9.4×10^{-15} yr^{-1}
G-dot	6×10^{-13} yr^{-1}	1.7×10^{-14} yr^{-1}	2.8×10^{-15} yr^{-1}	1.0×10^{-15} yr^{-1}
η (SEP)	4.3×10^{-4}	1.5×10^{-3}	5.5×10^{-4}	1.5×10^{-4}

2×10^{-7}

7×10^{-14} yr^{-1}

actual magnitude

Sensitivity to Number of Asteroids

- Only 67 most significant asteroid GM modeled individually
- May need to add more at later date

- Look for saturation of parameter as more asteroids added: means no longer absorbing asteroids into parameter, making parameter estimate seem better than it is

Parameter	11 asteroid GMs	36 asteroid GMs	67 asteroid GMs
γ	7.8×10^{-8}	1.1×10^{-7}	1.4×10^{-7}
β	6.9×10^{-5}	9.7×10^{-5}	1.7×10^{-4}
J_2 of sun	1.6×10^{-8}	2.5×10^{-8}	3.2×10^{-8}
M-dot of sun	4.1×10^{-15} yr^{-1}	9.9×10^{-15} yr^{-1}	1.8×10^{-14} yr^{-1}
G-dot	2.6×10^{-15} yr^{-1}	2.6×10^{-15} yr^{-1}	2.8×10^{-15} yr^{-1}
η (SEP)	7.5×10^{-5}	1.6×10^{-4}	5.5×10^{-4}

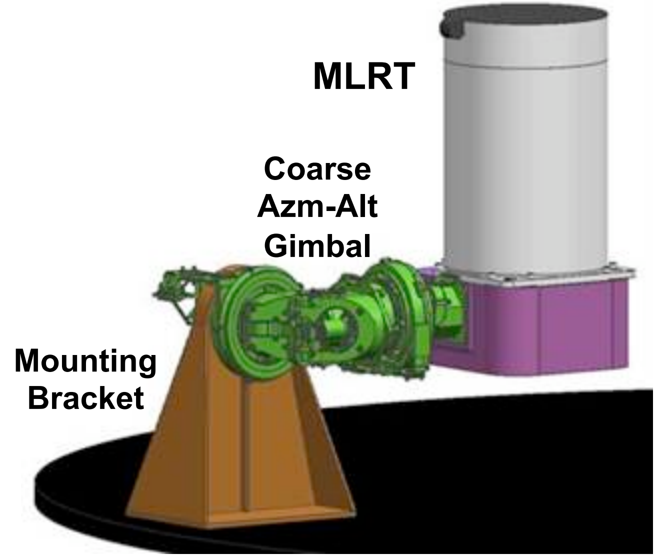
Alternative Mission Scenarios

- Phobos (moon of Mars)
  - Landing is not complicated by atmospheric entry, but landing consequently needs more ΔV
  - No dusty atmosphere to scatter light and settle on lander
  - Phobos orbit and physical librations add dynamical complexity to range model, but instead of Mars UT1, polar motion, nutations, and geocenter motion
  - Daily temperature variations larger
  - 4 hr night, 1/3 of Mars, requires less stored power
- Mercury
  - gain in measurement of β and J_2 by roughly 10×, but no appreciable gain in γ, G-dot, or η_{SEP}
  - hardships of flight (long), and thermal mitigation on surface
- Inner solar-system asteroid
  - Virtually identical science results as to Mars, but with fewer close conjunctions (so γ not as good)

Instrument Requirements

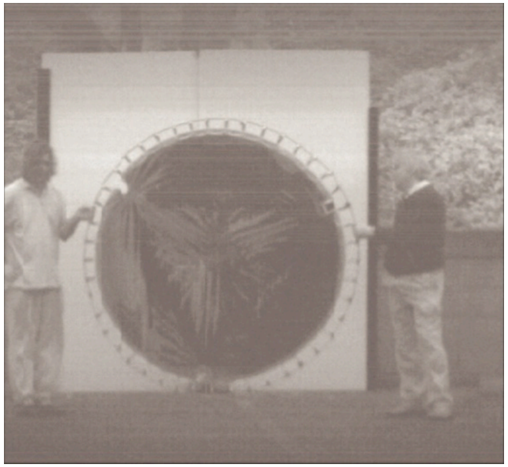
- **MLRT instrument requirements drivers include:**
  - operation within 2° of sun
    - Megaphoton/sec background rates, even with narrowband filter
  - Multi-pixel photon counter to cover full Earth FOV with per-pixel precision timing
    - 230 μrad FOV at Mars closest range
  - Earth tracking
    - Coarse gimbal pointing and wide FOV Earth image acquisition
  - Point-ahead angle
    - Up to 328 μrad with 0.35 nrad/sec maximum slew rate
  - Mars surface environment
    - Wind, dust, day/night temperature cycling
- **And of course low mass and power**

Aperture	12 cm
Transmit Beam Divergence	160 μrad
Timing Receiver FOV	230 μrad
Acquisition FOV	4 mrad
MLRT Laser Transmitter Power	250 mW
Ranging duration per Sol	1 hour
Lifetime	> 3 years

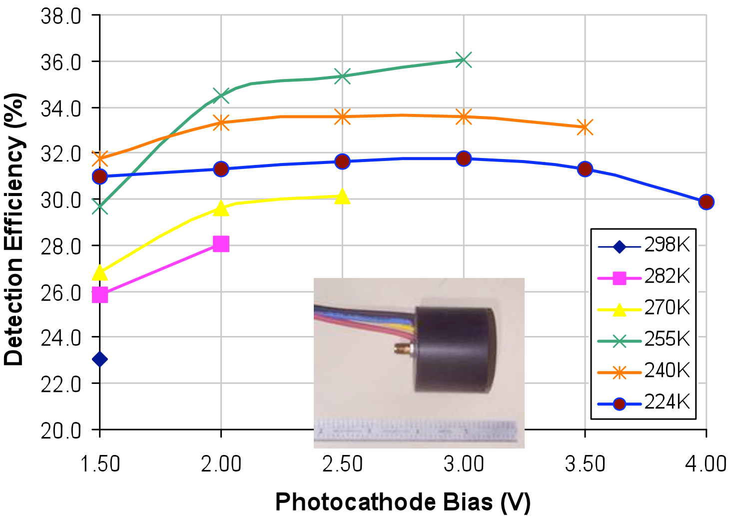


MLR Ranging Components

- **Earth side**
  - 1 m telescopes, subset of the SLR network
    - Transmits 1 KHz / 3 mJ / 12 ps pulses at 532 nm
    - 25 μrad transmit beam divergence
    - Photon counting detection of received 1064 nm signal from Mars using InGaAsP intensified photodiode (35% SPDE)
    - Solar rejection filter across telescope aperture for operations to 3° of sun
- **Mars side**
  - Landed asset: Mars Laser Ranging Transceiver
    - Transmits 1 KHz / 0.25 mJ / 12 ps pulses at 1064 nm
    - 160 μrad transmit beam divergence
    - Photon counting detection of received 532 nm signal from Earth using Si GM-APD (50% SPDE)
    - Solar rejection filter for operations to 2° of sun

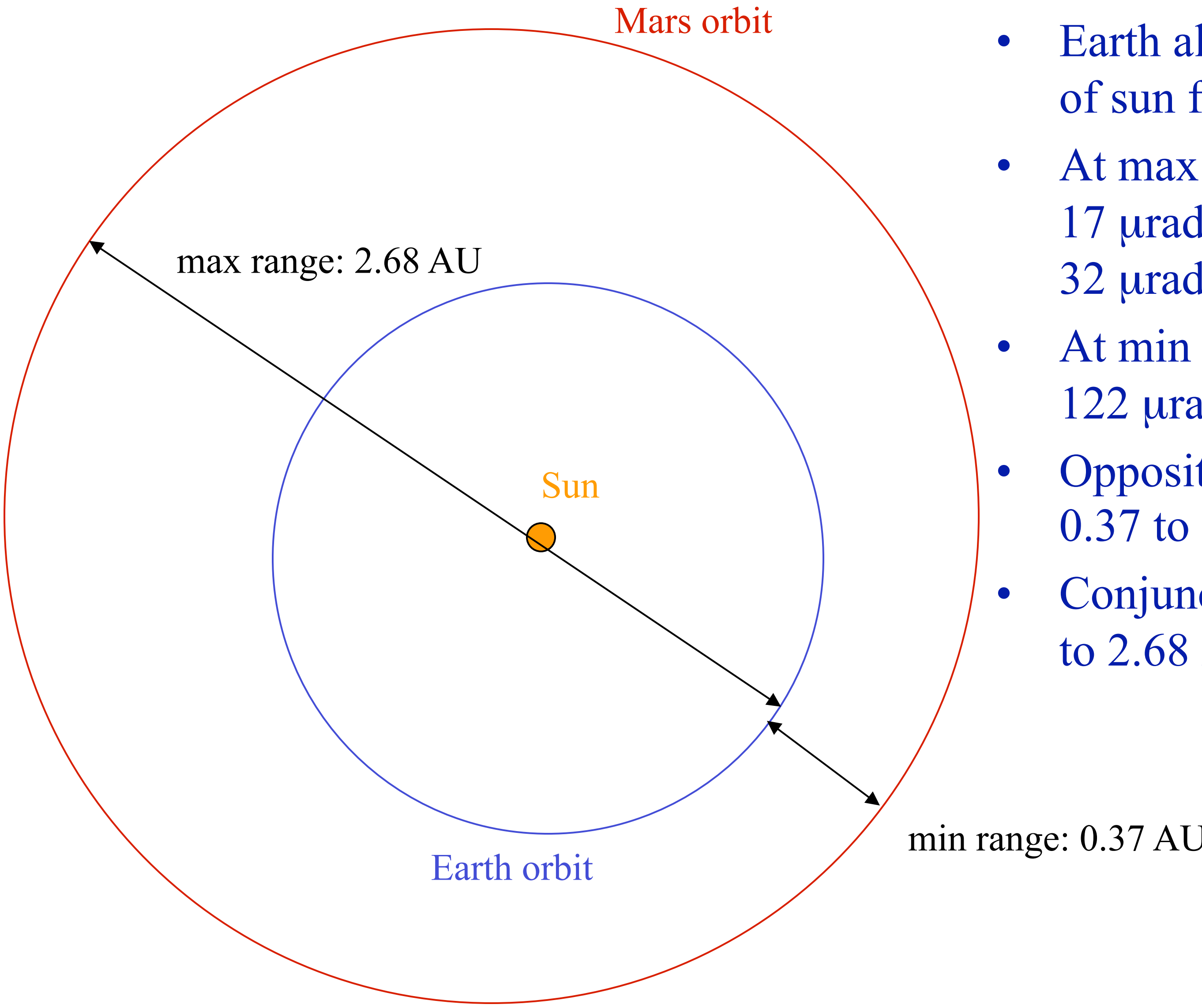


Prototype 1.5 m diameter solar protection filter



Intensified Photodiode SPDE at 1064 nm

Ranging Parameters/Geometry



- Earth always within 47° of sun from Mars
- At max distance: Mars 17 μrad diameter, Earth 32 μrad
- At min distance: Mars 122 μrad, Earth 229 μrad
- Opposition can be from 0.37 to 0.68 AU
- Conjunction can be 2.37 to 2.68 AU

MLR Link Description

- **Worst case link conditions coincide with some of the best science data acquisition**
  - Operations at solar conjunctions to 2° of sun

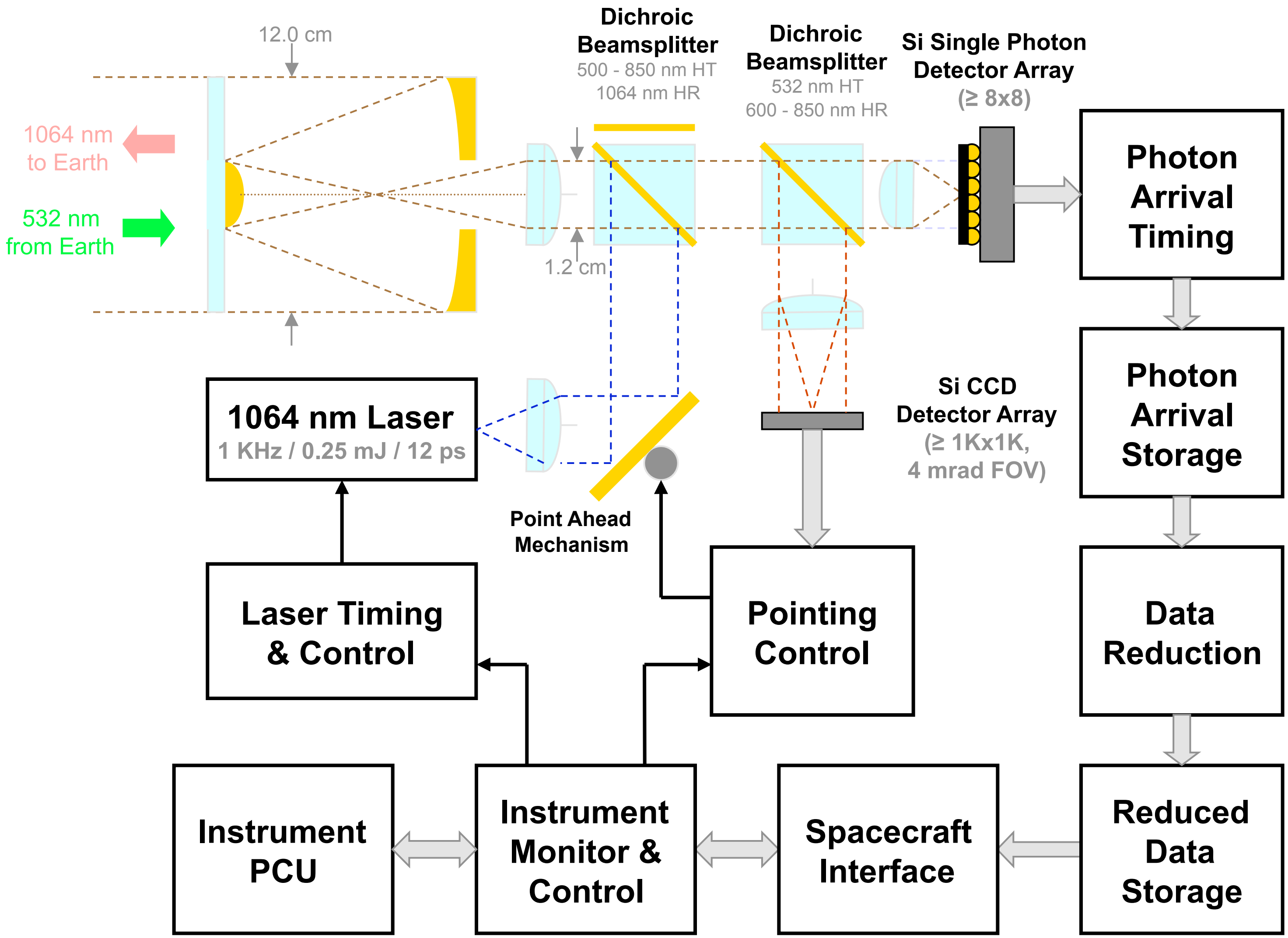
Earth to Mars

Input Parameters	worst case	nominal case	units
wavelength	532	532	nm
transmit power	3	3	W
tx throughput	0.5	0.5	
tx beam divergence	25	25	urad
tx pointing loss	-2	-2	dB
tx atmospheric loss	-3	-2	dB
tx PRF	1	1	KHz
rx atmospheric loss	-4.3	-3	dB
rx diameter	0.12	0.12	m
rx throughput	0.3	0.3	
rx detector FOV	230	230	urad
rx detector SPDE	0.4	0.4	
Earth background	32	24	W m-2 sr-1 um-1
Mars sky radiance	1100	95	W m-2 sr-1 um-1
bandpass (FWHM)	0.2	0.2	nm
range	2.6	1	AU
Derived Parameters			
photon energy	3.73E-19	3.73E-19	J
space loss	-164.2	-155.9	dB
rx signal power	1.34E-17	1.54E-16	W
Earth angular dia.	32.8	85.2	urad
Earth background	7.78E-14	3.94E-13	W
Mars sky radiance	1.32E-10	1.14E-11	W
Summary Results			
incident signal	4.03E-18	4.62E-17	W
incident noise	3.95E-11	3.53E-12	W
SNR	-69.9	-48.8	dB
detected signal	4.313	49.515	Hz
detected noise	42.329	3.780	MHz

Mars to Earth

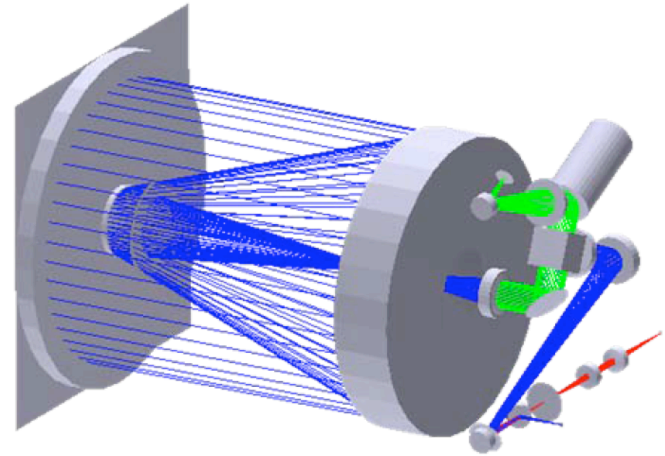
Input Parameters	worst case	nominal case	units
wavelength	1064	1064	nm
transmit power	0.25	0.25	W
tx throughput	0.5	0.5	
tx beam divergence	160	160	urad
tx pointing loss	-2	-2	dB
tx atmospheric loss	-3	-2	dB
tx PRF	1	1	KHz
rx atmospheric loss	-1.5	-0.6	dB
rx diameter	1	1	m
rx throughput	0.3	0.3	
rx detector FOV	20	20	urad
rx detector SPDE	0.35	0.35	
Mars background	20	20	W m-2 sr-1 um-1
Earth sky radiance	1200	60	W m-2 sr-1 um-1
bandpass (FWHM)	0.2	0.2	nm
range	2.6	1	AU
Derived Parameters			
photon energy	1.87E-19	1.87E-19	J
space loss	-161.9	-153.6	dB
rx signal power	3.61E-18	3.78E-17	W
Mars angular dia.	17.5	45.5	urad
Mars background	1.26E-12	1.26E-12	W
Earth sky radiance	7.54E-11	3.77E-12	W
Summary Results			
incident signal	1.08E-18	1.13E-17	W
incident noise	2.30E-11	1.51E-12	W
SNR	-73.3	-51.2	dB
detected signal	2.032	21.275	Hz
detected noise	43.115	2.827	MHz

MLRT Architecture

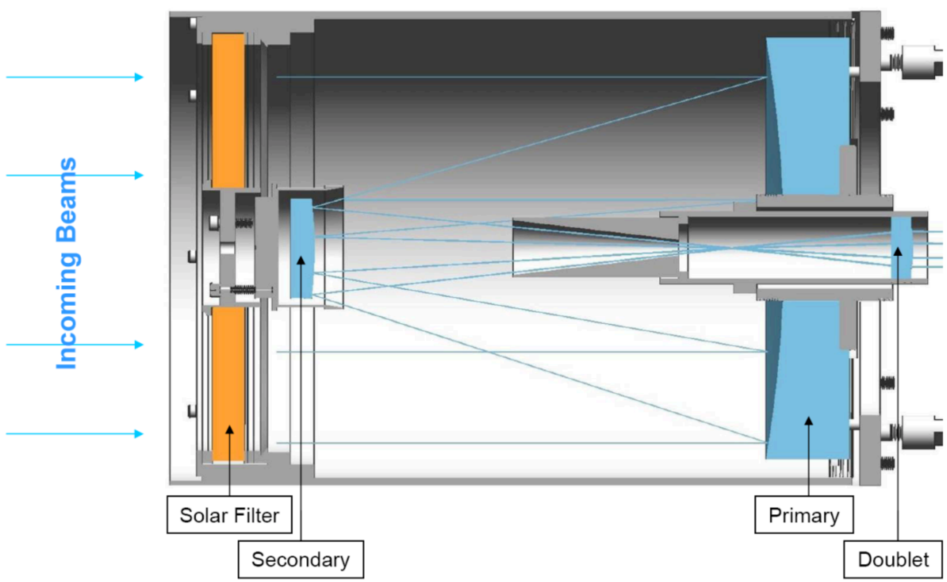


MLRT Instrument

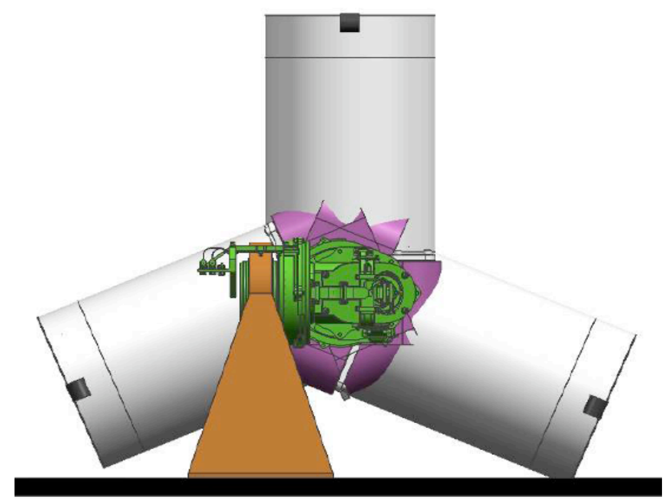
- **The MLRT instrument comprises a gimbaled optical head and a body-mounted opto-electronics box**
  - 12 cm receive aperture
  - 8 mm sub-aperture transmit beam



MLRT Optical Channels



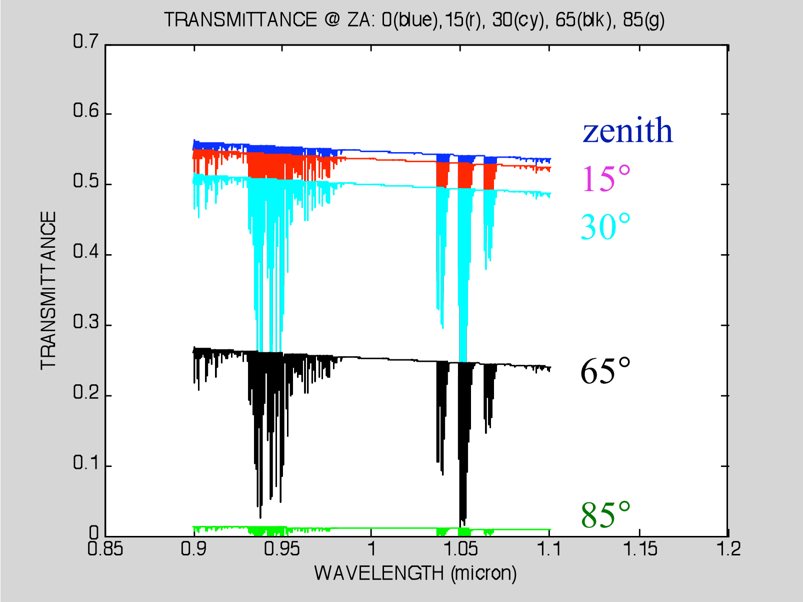
MLRT Telescope Cross-Section



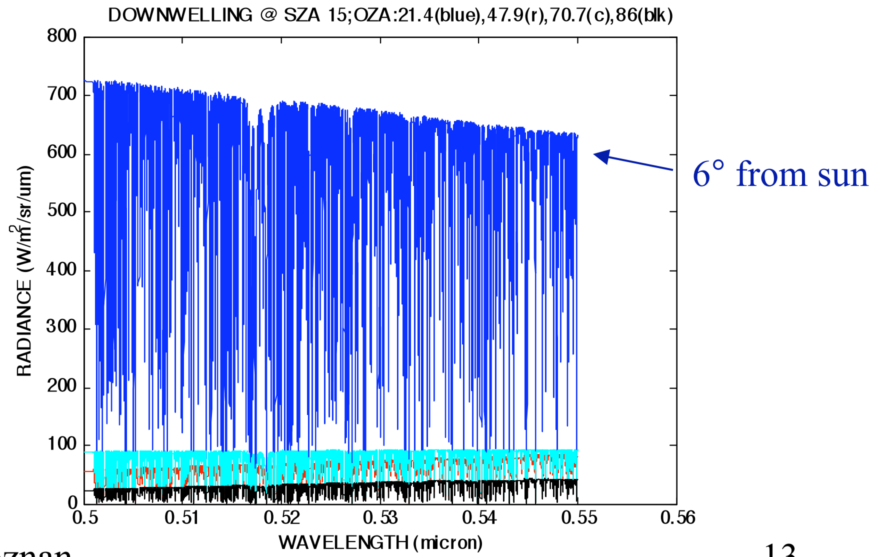
MLRT Gimbaled Optical Head

Mars Environment Challenges

- **Dust is the major concern for Mars surface operations**
  - Will contaminate entrance window and solar panels
    - Telescope is shuttered closed between ranging sessions
    - Dust accumulation limits mission lifetime
  - Creates large sky radiance and signal attenuation



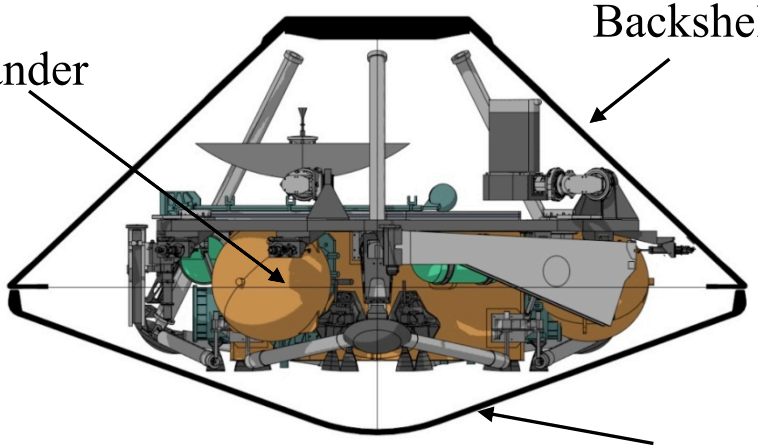
Condition	Zenith Attenuation	OD	Estimated Occurrence
Mars Clear Sky	-0.85 dB	0.2	**20% of time**
Mars Nominal Sky	-3.0 dB	0.69	**50% (Median)**
Moderately High Attenuation	-4.3 dB	0.99	**~30% of time**

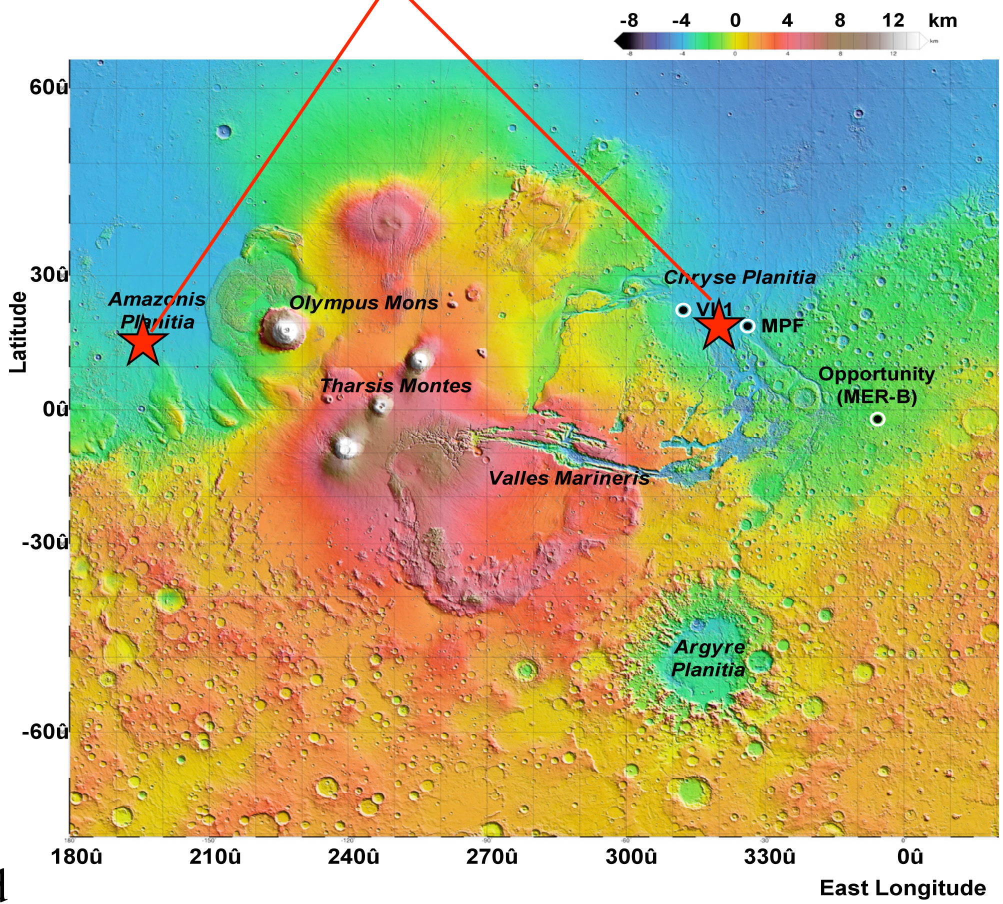


Mission Profile

- Two landers launched on single Atlas V 511
  - Shared cruise stage
- Launch May 2018, arrive December 2018
  - Type I trajectory
- Phoenix-style lander
  - Propulsive final descent, soft touchdown
  - Solar powered
  - Three year nominal mission

Suitable landing sites at 15N, 195E, and 20N, 320E





Summary

- Laser Ranging to Mars offers significant potential for improving tests of gravity
- 1 mm ranging should be possible, with photon link rates spanning a few Hz to kHz
- A baseline instrument exists, complete with mass, power, and price estimates
- We are continuing to refine studies of the instrument and science case, with a final report to be produced in early 2009