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Advanced Laser Ranging

for high-precision navigation and science investigations in Fundamental Physics

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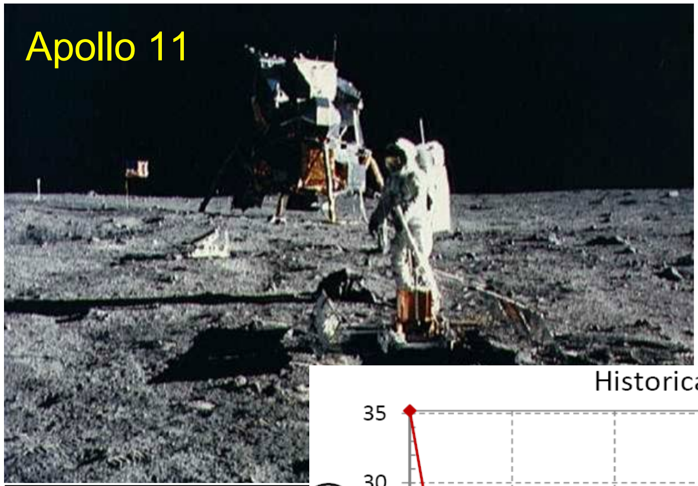
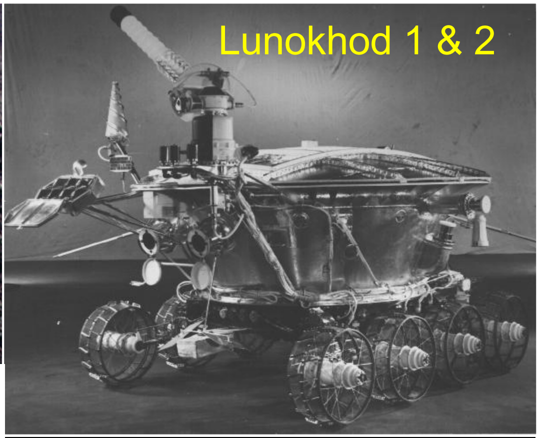
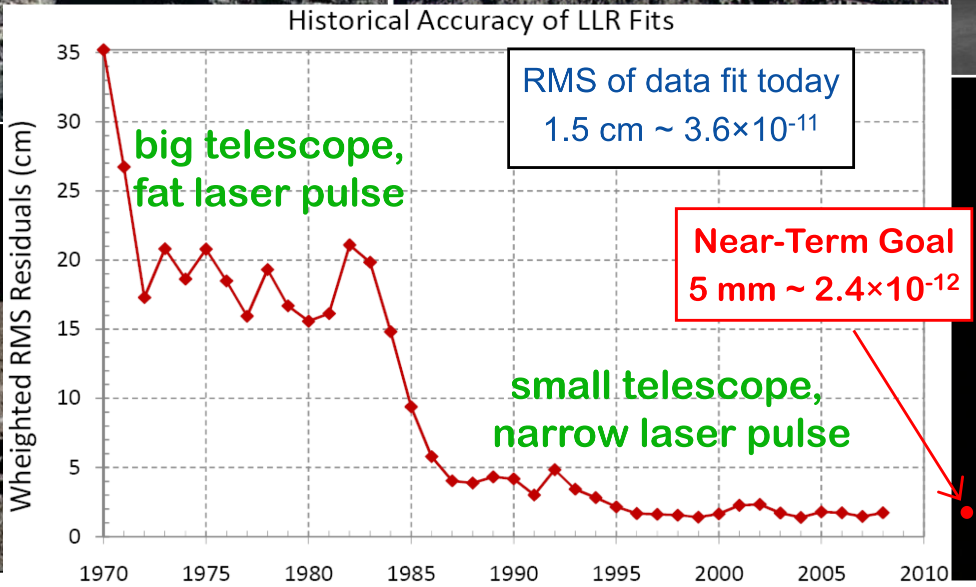
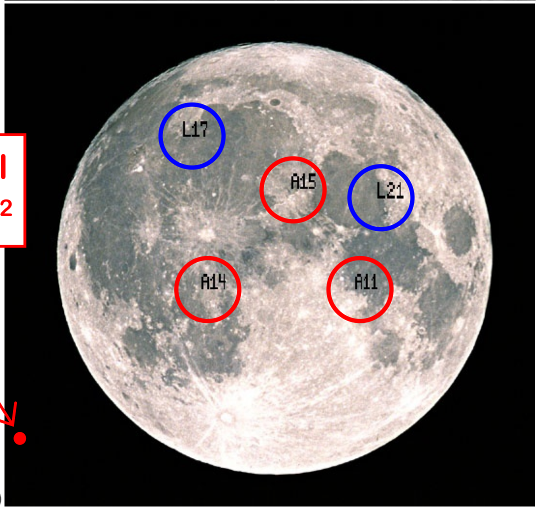
LLR is a Legacy of the Apollo Program

Apollo 11 array in 1969 initiated a shift from analyzing lunar position angles to ranges. The present day range accuracy is 8 mm, limited by Earth's atmosphere.







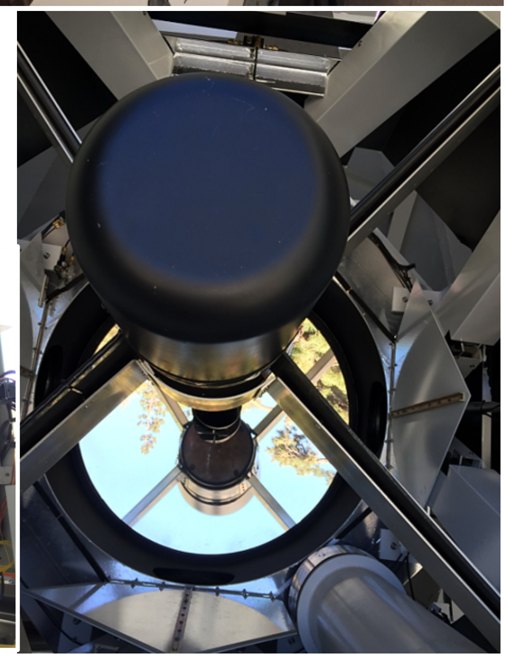


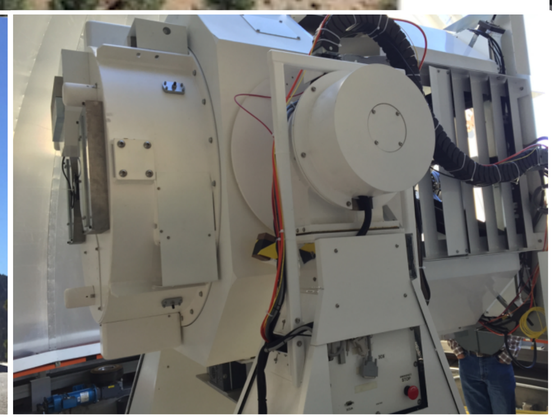
New Table Mountain LLR facility will allow a reverse shift: from lunar ranges to position angles with precision of 30 μm, a factor of 200X better than is currently available (8 mm).

Advanced Lunar Laser Ranging (AdLLR)

- New LLR facility at Table Mountain Observatory, CA:
  - 1-m telescope of JPL's Optical Communication Testbed Laboratory (OCTL);
  - High-power laser (a CW laser with 2kW average power) to range the moon;
    - This power level is 1,000 higher than is currently used by the best LLR facility at the Apache Point Observatory (APOLLO effort, which uses pulsed laser with 2W average power and 3.5-m telescope);
    - With the transmitted power at this level, for the first time, we will be able to conduct differenced LLR with a precision <30 micron (limited only by Earth¹s atmosphere) – a factor of 200 better than is currently possible.
- Towards new science investigations of the moon:
  - AdLLR would dramatically enhance our knowledge of the deep lunar interior, beyond the contributions from the GRAIL mission & current LLR efforts
    - Would provide key new insights into origin and evolution of Moon;
    - Core shape, rotation, dissipation, and stimulation of free libration modes;
    - Interior tidal rigidity and dissipation, and possible regions of partial melt.
- Potential improvement in LLR configuration:
  - Significant flux is available: AdLLR can range the moon even with a small corner-cube retroreflectors (CCR) Apollo-type (dia 3.8 cm): a CubeSat deployment?

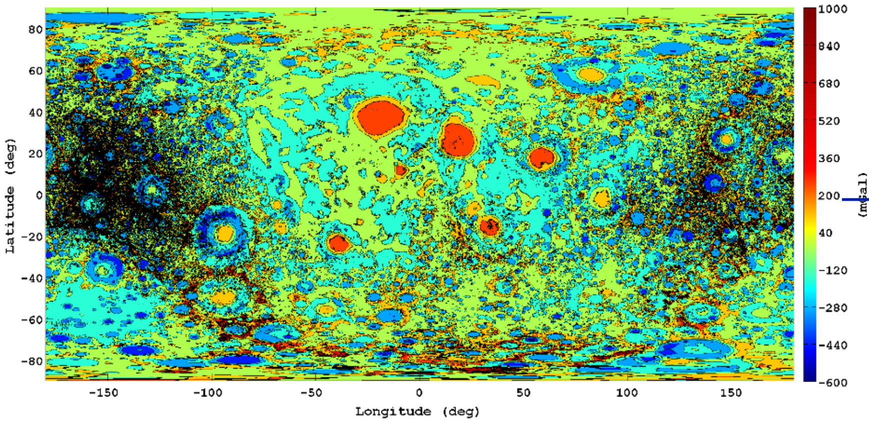
OCTL at the Table Mountain Observatory

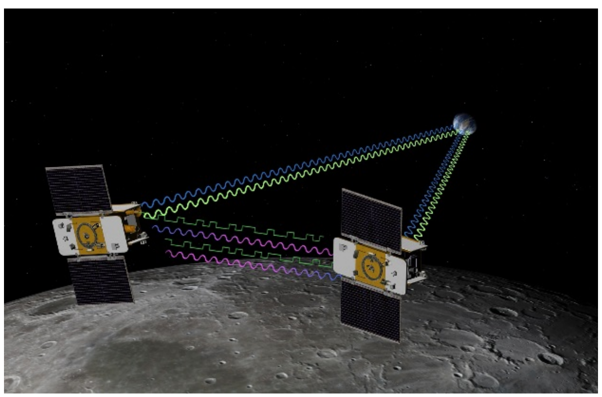




Differenced Lunar Laser Ranging (dLLR)

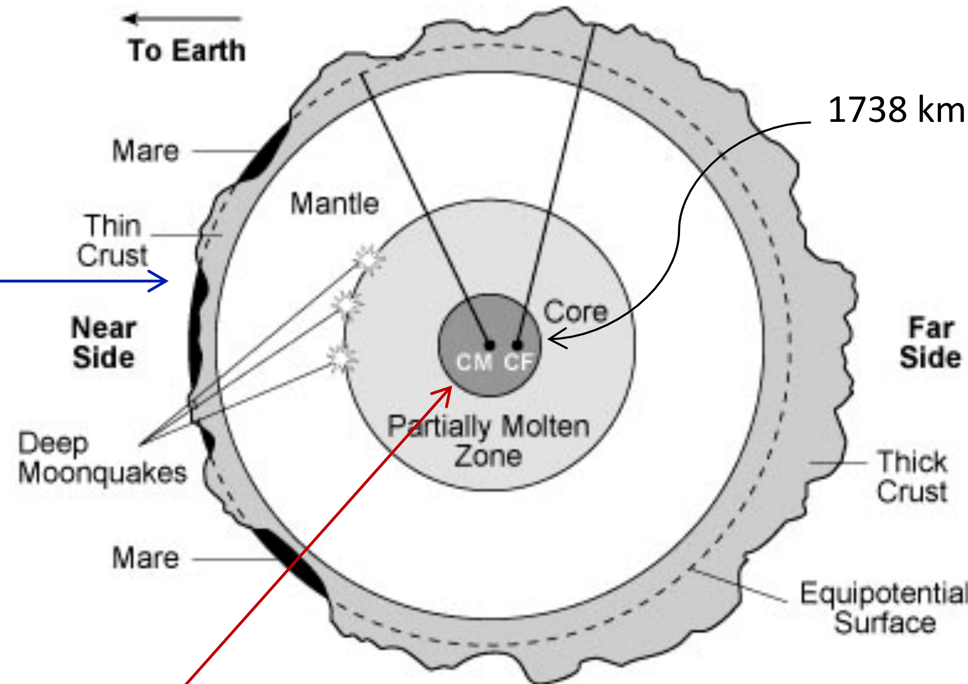
GRAIL determined lunar **gravity field** with surface resolution of few kilometers





Properties of deep lunar interior are still uncertain

Revealing Deep Lunar Interior



Major impact on lunar science:

- @LLR: lunar **orientation** to <0.1 mas
- 200X the accuracy in measuring lunar **rotation** vs current results from LLR and GRAIL combined;
- Focus on deep lunar interior: core & properties of interior down to the last ~380 km – lunar evolution.

Differenced LLR: Measurement Concept

- **Measurement concept**
  - *The baseline concept* is to amplitude-modulate a CW laser with a linear frequency chirp with bandwidth of ~2GHz with range resolution of 7 cm;
  - Pulse compression techniques give higher SNR at lower peak power (similar to RF radar that uses an optical carrier).

- **Differential Lunar Laser Ranging**
  - 1kW CW lasers modulated at GHz;
  - Photon counting detectors;
  - Existing corner-cube arrays already on the Moon.

Lunar librations hold the key to deep lunar interior

Major progress in lunar science:

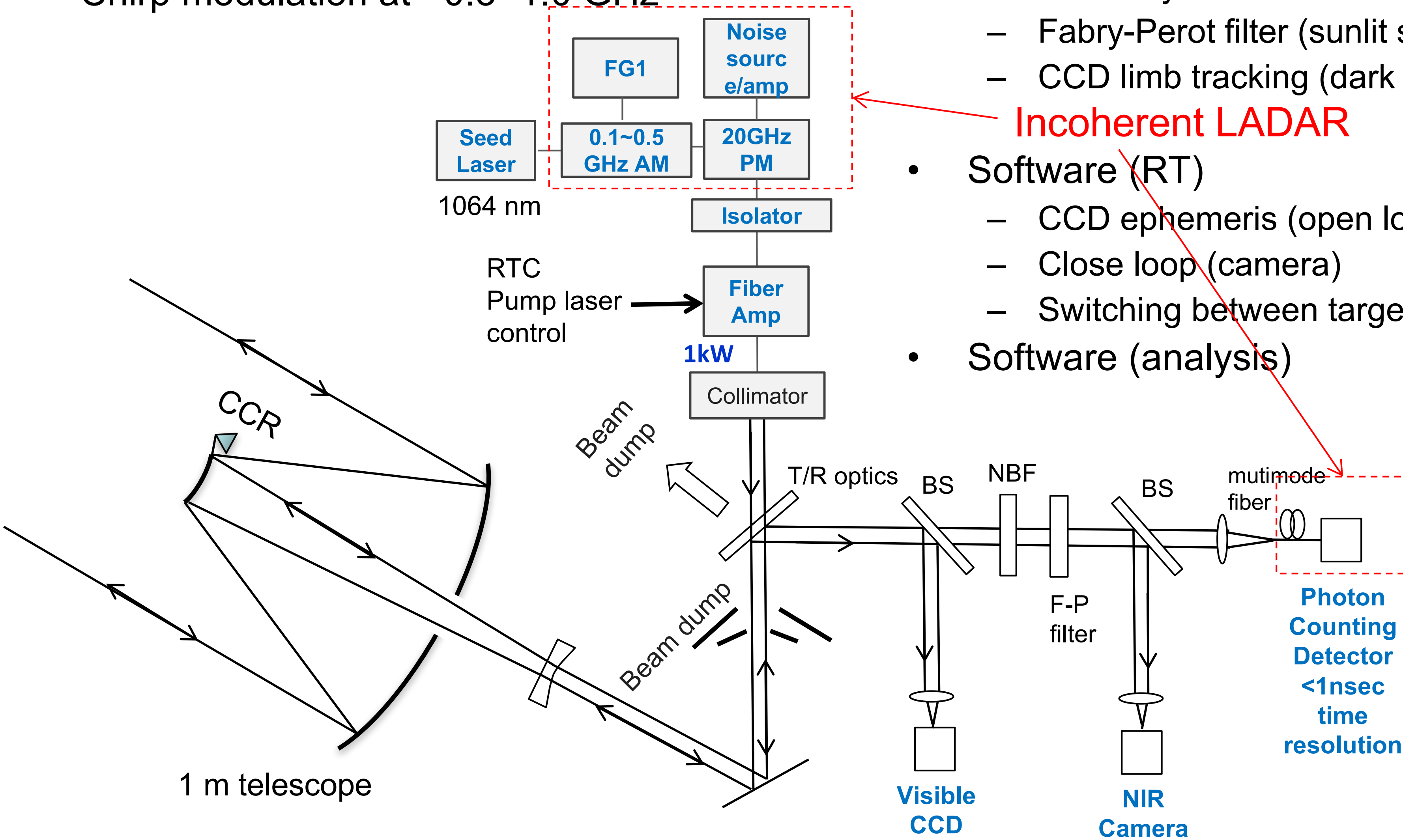
- 30 μm differential range precision, limited by Earth's atmosphere;
- Focus on lunar core & deep interior: 200X accuracy gain from rotation.

System Elements for Ranging with @LLR

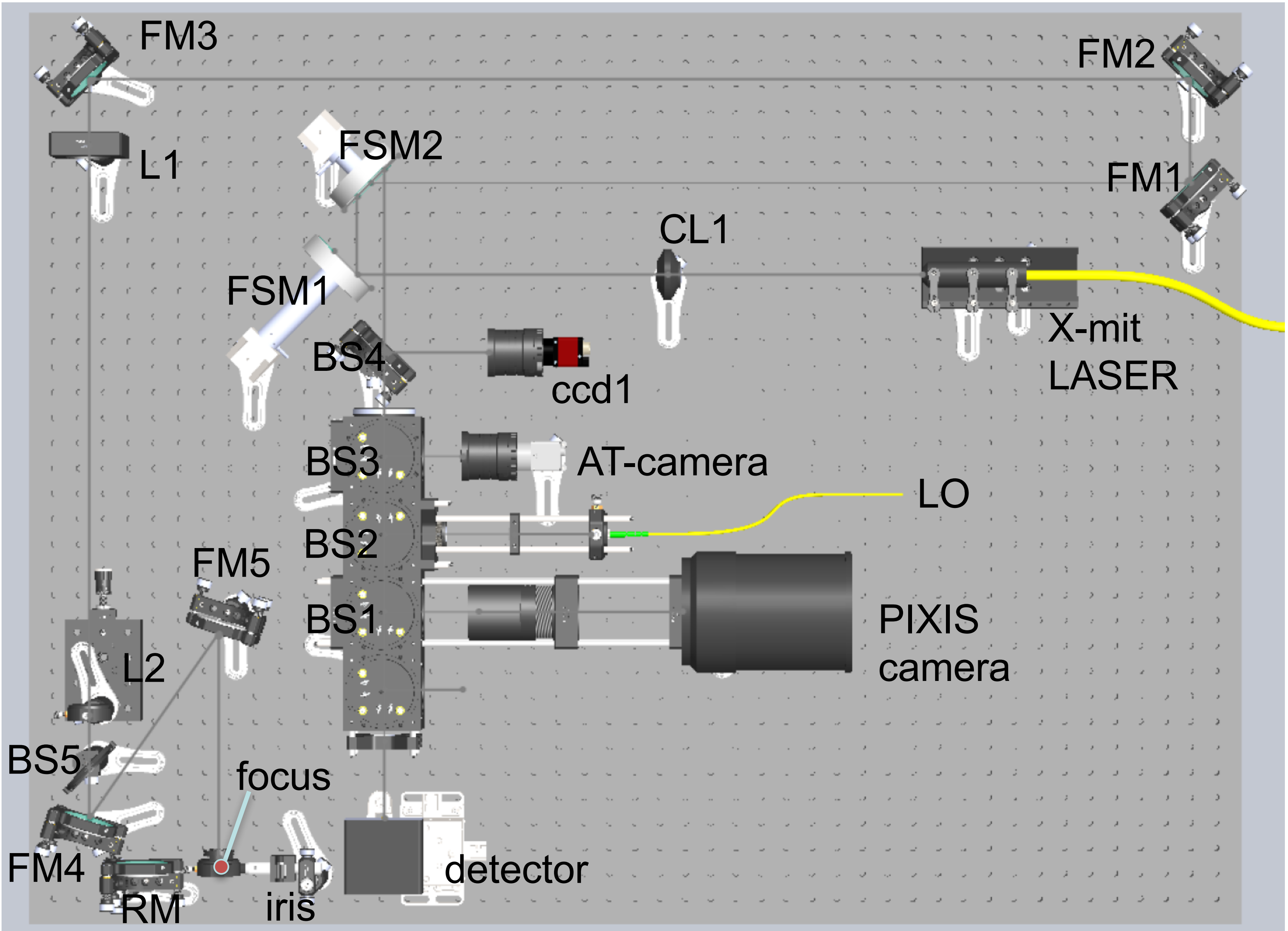
The @LLR system uses:

- High-power (~1kW) CW laser amplitude-modulated at RF frequencies;
- Chirp modulation at ~0.5−1.0 GHz

- Laser transmitter
- High-speed receiver
- Imaging camera (for target acq)
  - With very low read noise
  - Fabry-Perot filter (sunlit side)
  - CCD limb tracking (dark side)
- Software (RT)
  - CCD ephemeris (open loop)
  - Close loop (camera)
  - Switching between targets
- Software (analysis)



AdvLLR Optical Table Layout



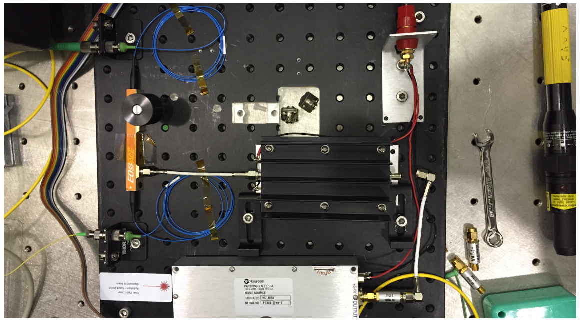
Photon Flux SNR Budget for AdLLR at TMO

Laser budget			Background flux		
Xmit			Moon	-13.6	
lambda	1.06	um	Dia	1800	arcsec
power	1,000	W	seeing	2	arcsec
	5.34E+21	phot/s	Frac	1.23E-06	
beam	10	urad			
distance	400,000	km	BW	1	picometer
spot @moon	4	km	atten	1.00E-05	
CC dia	0.038	m			
#cubes	100		Tel Area	0.707	m^2
Frac hit cube	9.03E-09				
			Full moon	8.33E+15	phot/um
Return			per eq pix	1.03E+05	
spread	27.89	urad			
@Earth	11.16	km	Optics loss	0.179	Incl QE
Rec Dia	1	m	detected	1.84E+04	
fraction	8.03E-09				
Other Losses:					
atmospheric	0.8		SNR in 1 sec	139.31	
xmit optics	0.5				
rec optics	0.5		SNR=1 range	0.15	m
det QE	0.4	incl fiber	1 sec range	1.077	mm
Total losses	0.08		1000 sec	0.034	mm
Flux received:	3.09E+04	phot/s			

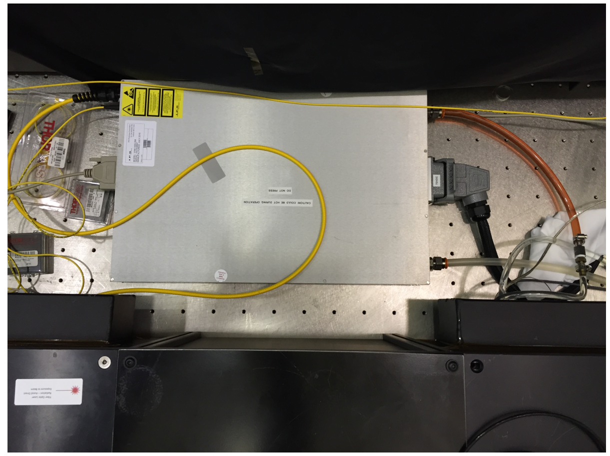
- Absolute LLR range:
  - Potentially a sub-mm range precision, but limited by Earth's atmosphere to ~5 mm
- Differenced AdLLR:
  - Was not possible before due to a poor return flux;
  - Now we can switch between the targets on the moon and take nearly-simultaneous range data;
  - If two ranges are taken within 15 min from each other, the atmospheric limit is as low as ~30 μm;
  - AdLLR will provide strong gains for lunar science, especially to the studies of the deep lunar interior.

We can range the moon even with a single small CCR Apollo-type: a CubeSat deployment?

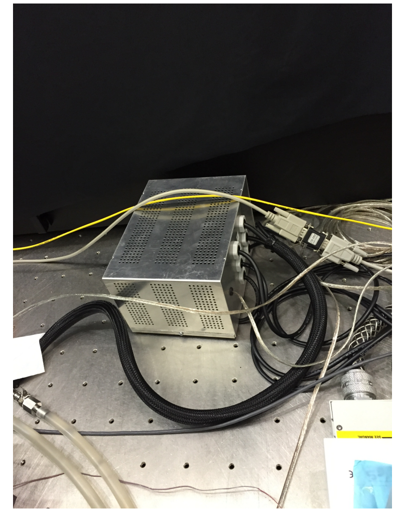
Fiber Amp System



20GHz Seed broadening
(Noise source + EOM)



Fiber amp



SS switch

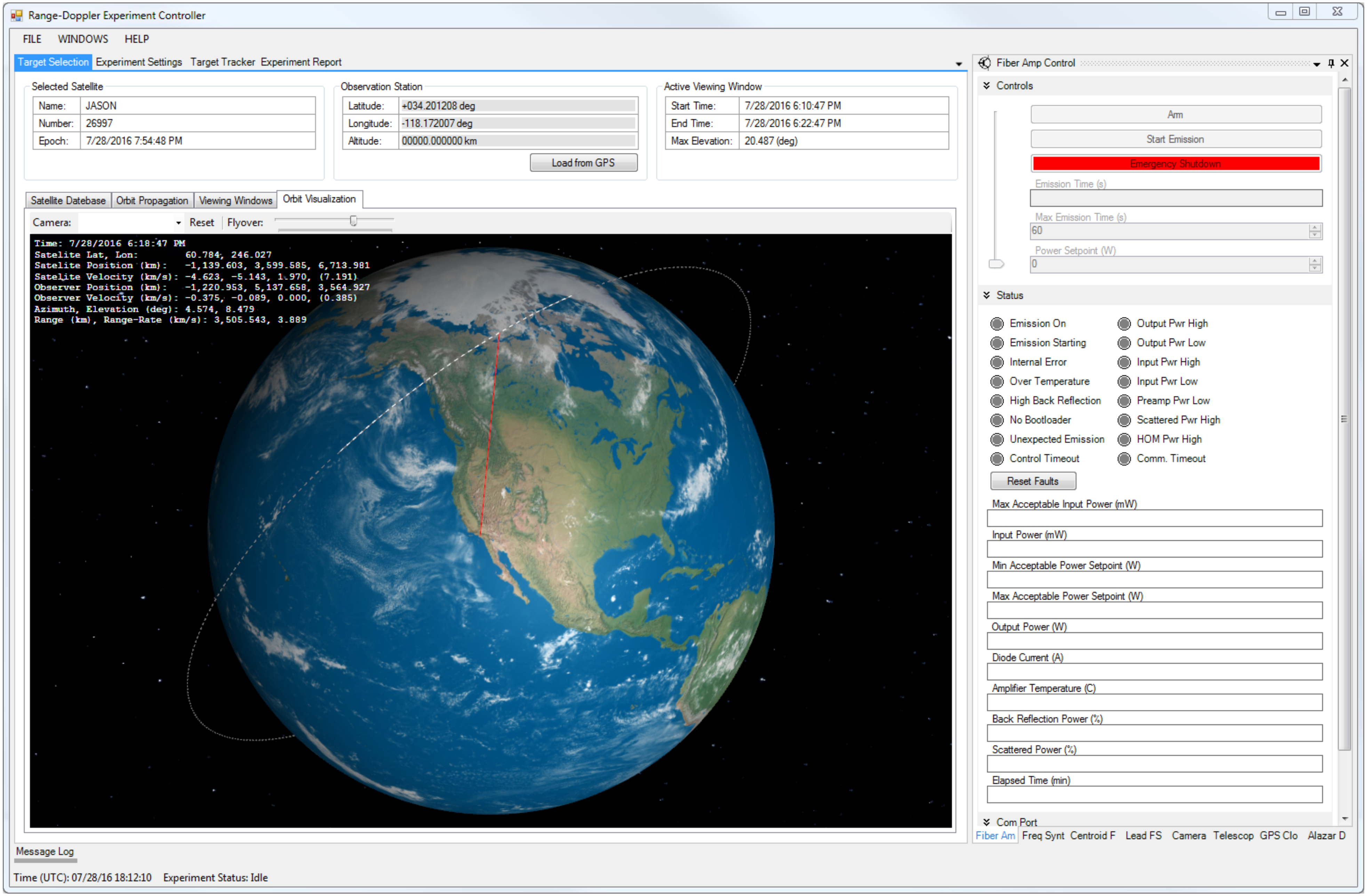
Chilled water cooler

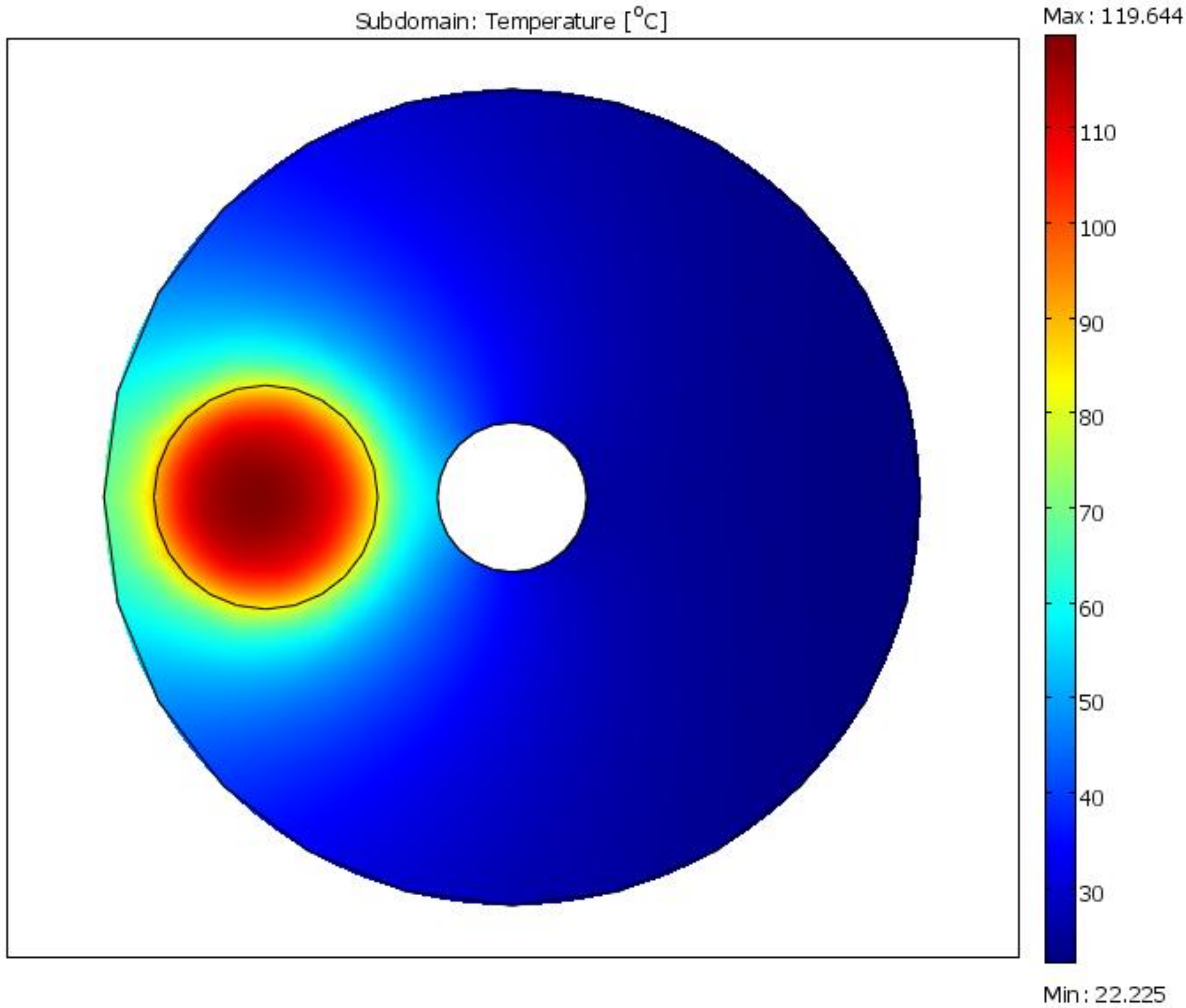
Power supply

Watchdog electronics

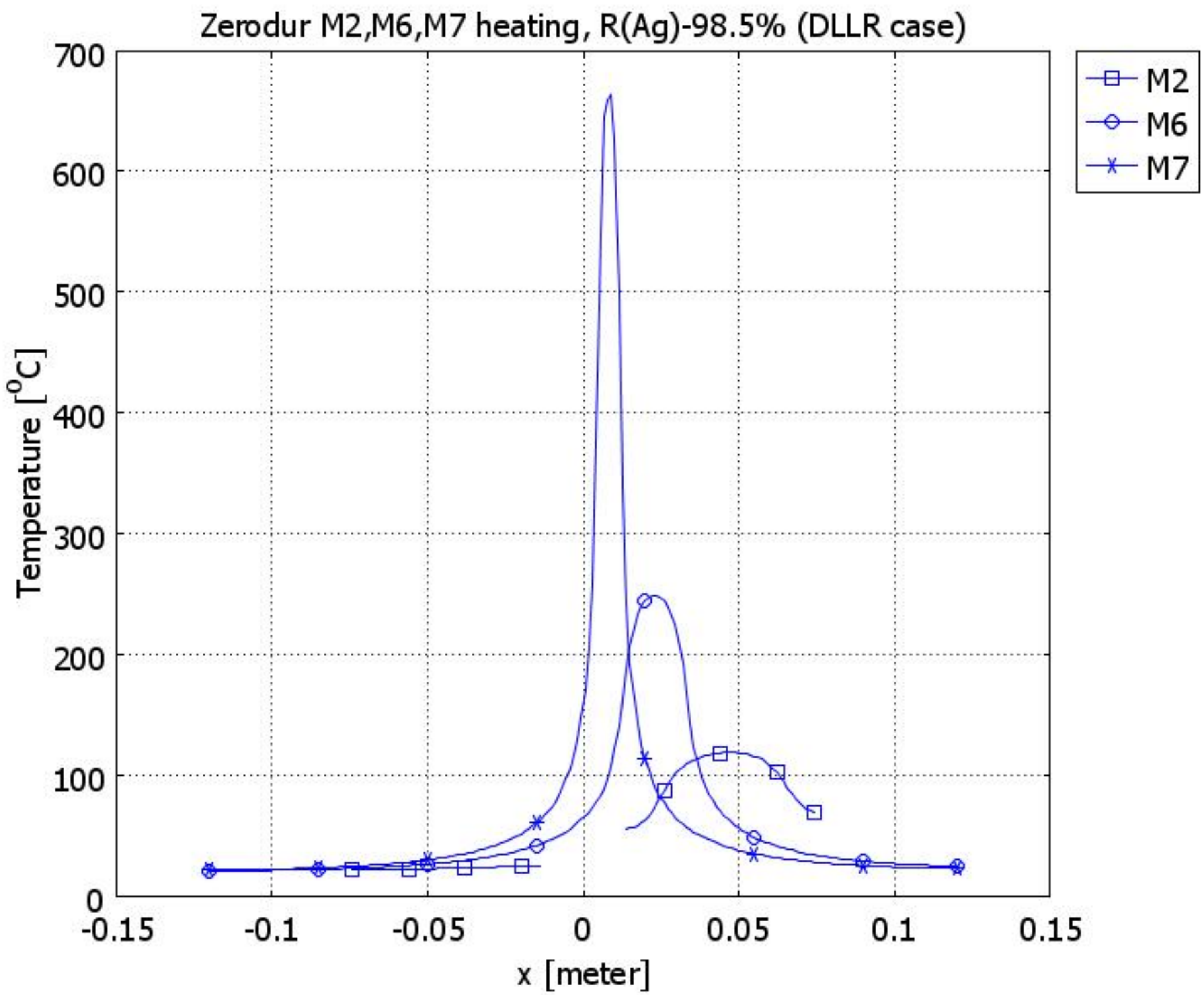
HIGH-PRECISION NAVIGATION AND SCIENCE

Control Software

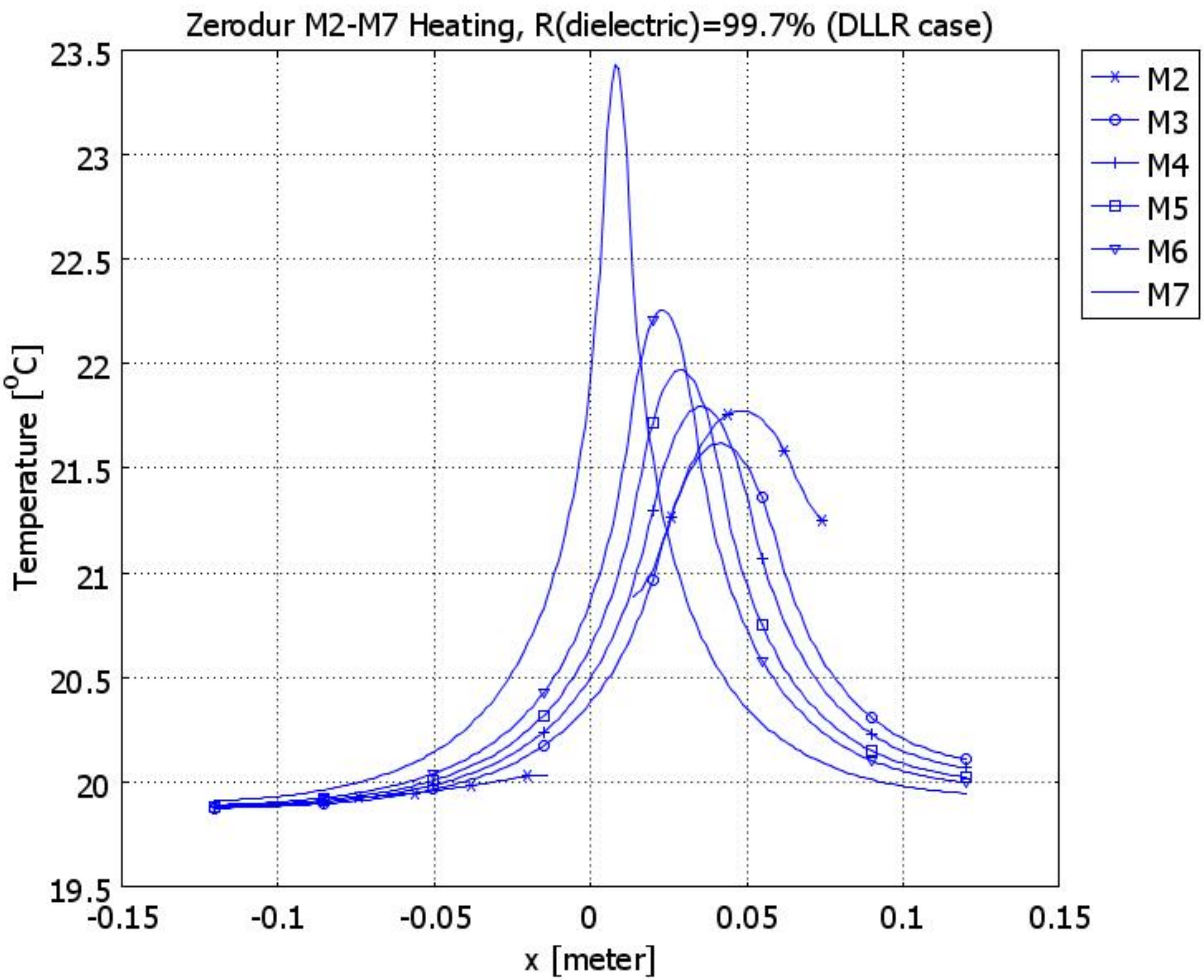



Subdomain: Temperature [°C]
Max: 119.644
110
100
90
80
70
60
50
40
30
Min: 22.225

DLLR: dielectric + Ag: reflectivity 98.5%



DLLR: dielectric only - reflectivity 99.7%



Advanced LLR: anticipated results

Tests of GR

Science	Current (cm)	1 mm
Weak Equivalence Principle	$\|\Delta a/a\|<1.3\times10^{-13}$	1×10^{-14}
Strong Equivalence Principle	$\|\eta\|<4.3\times10^{-4}$	1×10^{-5}
PPN parameter β	$\|\beta-1\|<1.1\times10^{-4}$	10^{-5}
Time variation of G	5.7×10^{-13} yr^{-1}	3×10^{-14}
Inverse Square Law	$\|\alpha\|<3\times10^{-11}$	3×10^{-13}

Lunar science

Effect	Current	Future Goals
Positions on Moon	yes	More locations
Low-degree gravity field	yes	Distinguish mantle from inner core for gravity and moments
3 free libration mantle modes	yes	Seek stimulating events
Solid-body tides	yes	Improve Love number accuracies
Tidal dissipation	yes	Improve tidal Q vs frequency
Core/mantle boundary dissipation	yes	Improve uncertainty, used to limit fluid core size
Core/mantle boundary flattening	yes	Improve uncertainty
Fluid core moment of inertia	no	Detect and determine
Fluid core free precession mode	no	Detect mode, determine amplitude & period
Inner solid core	no	Detect inner core, determine gravity
3 inner core free libration modes	no	Detect modes, determine amplitudes & periods
Inner core boundary dissipation	no	Limit inner core size

Precision Attitude & OD for an Earth orbiter

- Even with a lower power (~20 W, eye-safe), the same facility
  - Could range an EO s/c with ~5 mm precision and obtain range-rate to 5 μm/s;
  - Note that this could be done even without a single corner-cube on its surface (the signal reflected off the spacecraft will be extremely bright)!
- For high precision, we need a reference point on the spacecraft:
  - Small pieces of reflective tape in several places of the exterior surface of the spacecraft, will allow for a sub-mm-class range precision (atm-limited).
  - Reflective elements enable differential laser ranging accurate to 0.3 μm (atm-limited), which could translate in attitude precision of < 0.1 urad, 0.1 urad/s.
- Choice for a retro-reflective element:
  - An adhesive retro-reflective tape (used by US Coast Guard or bicyclists at night);
  - Commercially available from 3M, Inc. using spherical beads with 200 nm dia;
  - Costs virtually nothing (~$10), while adding less than 100g;
  - Good for orbit/attitude determination of Earth's orbiting s/c (i.e., ACES/uScope).
- Other topics :
  - Navigation, modeling, calibration, telemetry and data analysis, etc.
  - Need to introduce a new SLR data format.

Example: 3M USCGFP-30

3M

USCGFP Reflective Sheeting for U.S. Coast Guard Devices

Series USCGFP

Product Bulletin USCGFP **December 2011**

Description

Approved for use by the United States Coast Guard.

3M™ USCGFP Reflective Sheetings are designed for approved Coast Guard devices, dayboards and buoys for which enhanced visibility is needed. This highly retroreflective marking consists of prismatic lenses that are formed in a transparent, synthetic resin, sealed and backed with an aggressive pressure sensitive adhesive and paper liner.

USCGFP markings have excellent angularity that allows them to be seen at angles up to and beyond 45° from perpendicular.

Markings are available in size rolls of 1 inch up to 48 inch widths by 50 yards. Also available in letters and numbers.

Properties

Color:	White	USCGFP30
	Yellow	USCGFP31
	Red	USCGFP32
	Orange	USCGFP34
	Green	USCGFP37

Adhesive:	Pressure Sensitive
Minimum Application Temperature:	50°F (10°C) (sheeting and substrate)
Maximum Application Temperature:	100°F (38°C) (sheeting and substrate)

Coefficient of Retroreflection

The minimum coefficient of retroreflection values of these sheetings when new are given in Table A in terms of candelas per lux per square meter. Measurements are made in accordance with ASTM E-810 "Standard Test Method for Coefficient of Retroreflective Sheeting" and represent an average of values at 0° and 90° orientations. Sheeting should be applied to aluminum panels and conditioned at room temperature for 24 hours prior to measurement.

Table A. Minimum Coefficient of Retroreflection (R_A) for New Markings (cd/lux/m²)

Observation Angle[1]	Entrance Angle[2]	White	Yellow	Red	Orange	Blue	Green
0.2°	-4°	360	270	65	145	30	50
0.2°	30°	170	135	30	68	14	25
0.5°	-4°	150	110	27	60	13	21
0.5°	30°	72	54	13	28	6	10

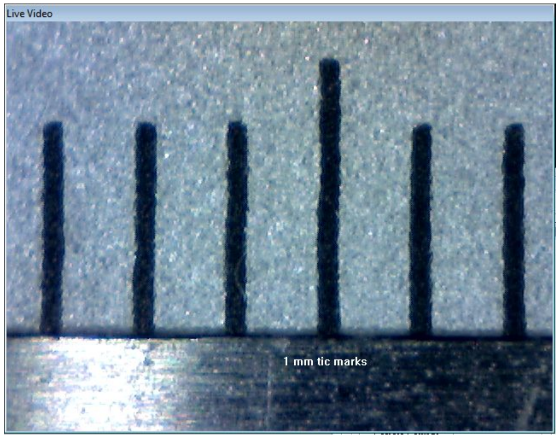
[1]Observation Angle – the angle formed by the light beam striking the reflective surface and the light beam returning to the observer.

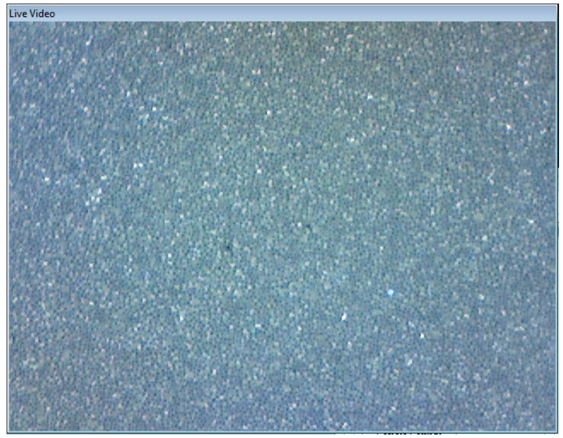
[2]Entrance Angle – the angle formed by a light beam striking a surface at a point and a line perpendicular to the surface at the same point.

Entrance Angularity Performance in Regard to Orientation

3M™ USCGFP material are designed to be effective wide angle reflective markings regardless of the orientation on the substrate. However, because the efficiency of light return from cube corner reflectors is not equal at all application angles, especially with increasing entrance angles, it is possible to get the widest entrance angle light return when the sheeting is oriented in a particular manner which takes advantage of increased performance at high entrance angles (>50°). When high entrance angle performance is a requirement for your markings you can obtain this performance easily by specifying the application angle of your markings so that the sheeting positioned at the 0° application angle (downweb direction perpendicular to the ground, ie, vertical). When the "primary groove line" (or, flat side of the diamond shape) is vertical, sheeting is said to be at a 0° application angle. When the "primary groove line" (or, flat side of the diamond shape) is horizontal, the sheeting is said to be at a 90° application angle. Unless the location and/or position of the marking requires extra wide entrance angularity performance, markings can be fabricated and installed using the application angle that most efficiently utilizes the reflective sheeting.

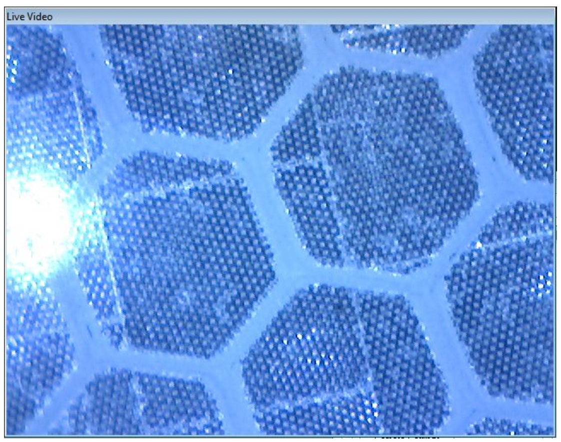
Testing Retro-Reflective Tapes

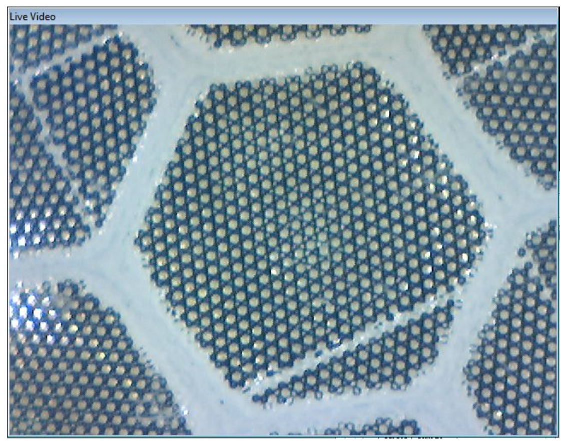


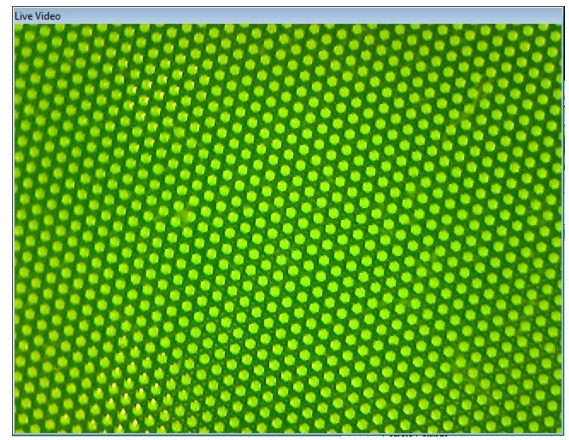


Commercially available reflective tapes (3M.com):

- Used by joggers, bicyclists, US Coast Guard, placed on license plates, etc.
- Typically 200 nm spheres or imprinted cubes;
- Uses strong adhesive.







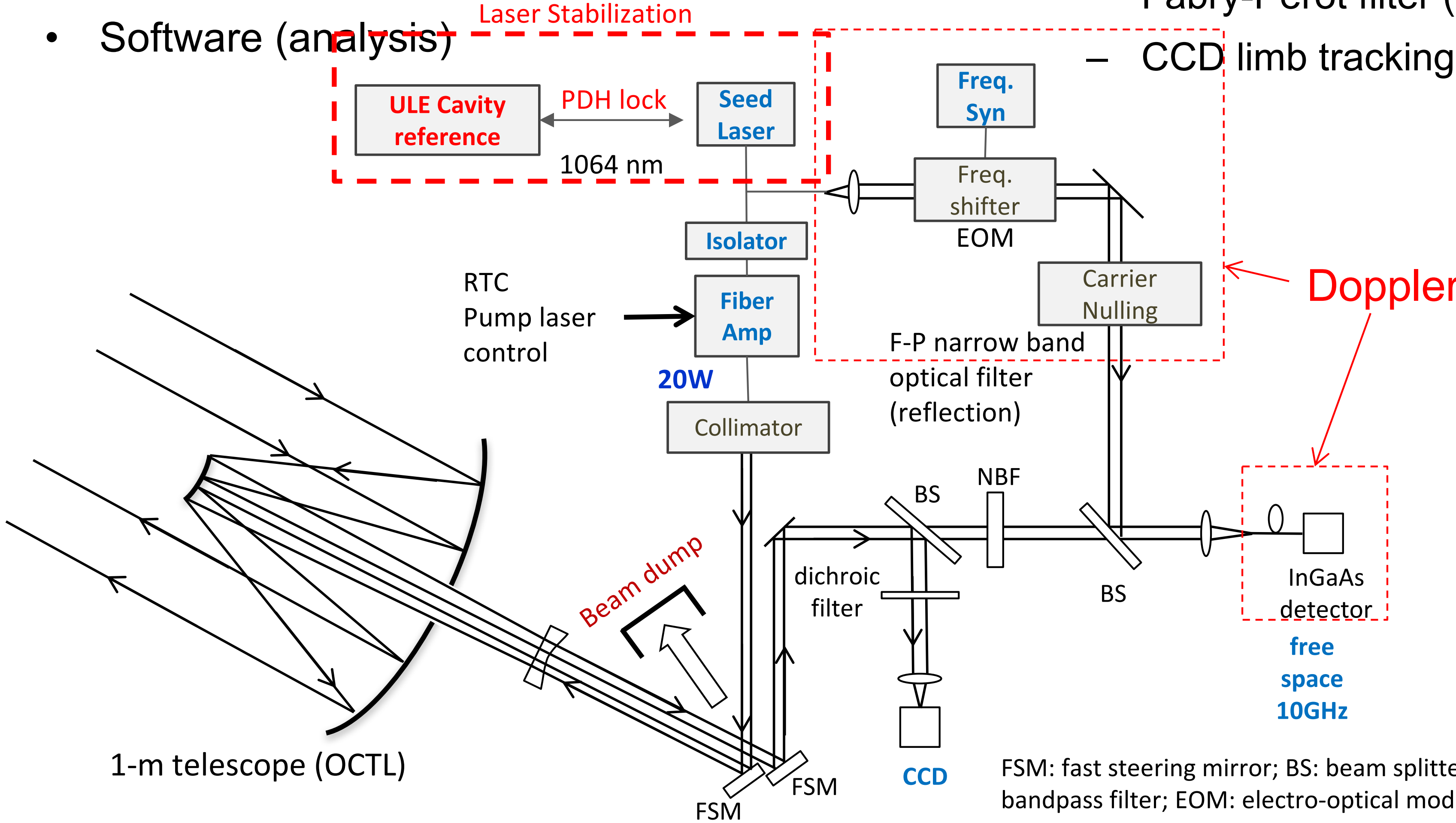
- When looked at the microscope, retro-reflective tape seem to reflect only from about 1/5 of the area, which is consistent with microbeads (i.e., 200 nm diameter spheres).
- If the diffraction from the beads is ~0.5–1°, it magnifies the return by 10,000 to 2,500. Taking 2,500/5 ~500 – the value confirmed by our laboratory measurements.

System Elements for Coherent Optical Doppler @LLR

The coherent @LLR system uses:

- High-power (~20W) CW laser amplitude-modulated at RF frequencies;
- Local oscillator (LO) for coherent operations
- Software: CCD ephemeris (open loop)
- Software (analysis)

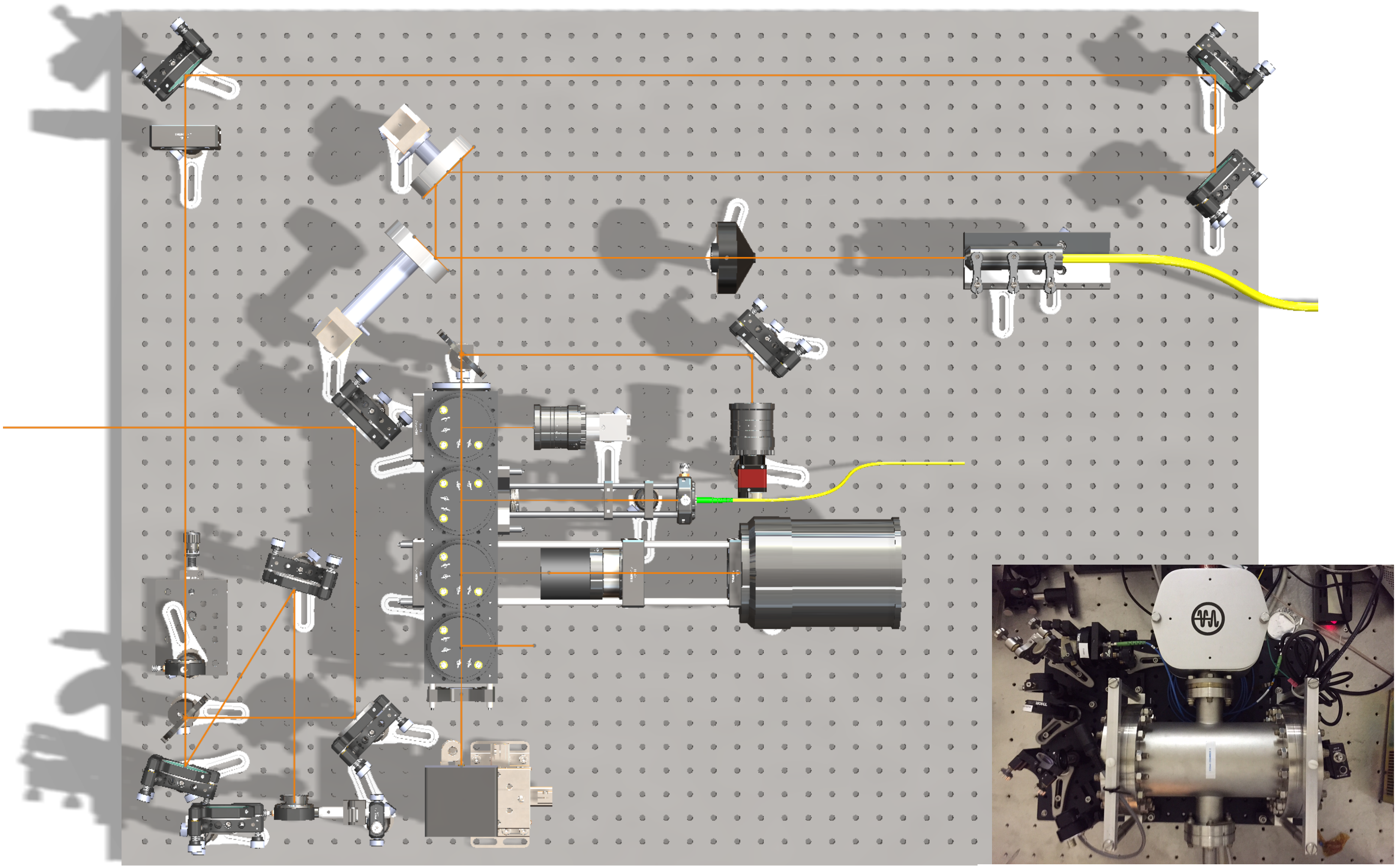
- Laser transmitter
- High-speed receiver
  - Smaller aperture (15 cm)
  - Local oscillator (seed laser)
  - Fabry-Perot filter (sunlit side)
  - CCD limb tracking (dark side)



FSM: fast steering mirror; BS: beam splitter; NBF: narrow bandpass filter; EOM: electro-optical modulator

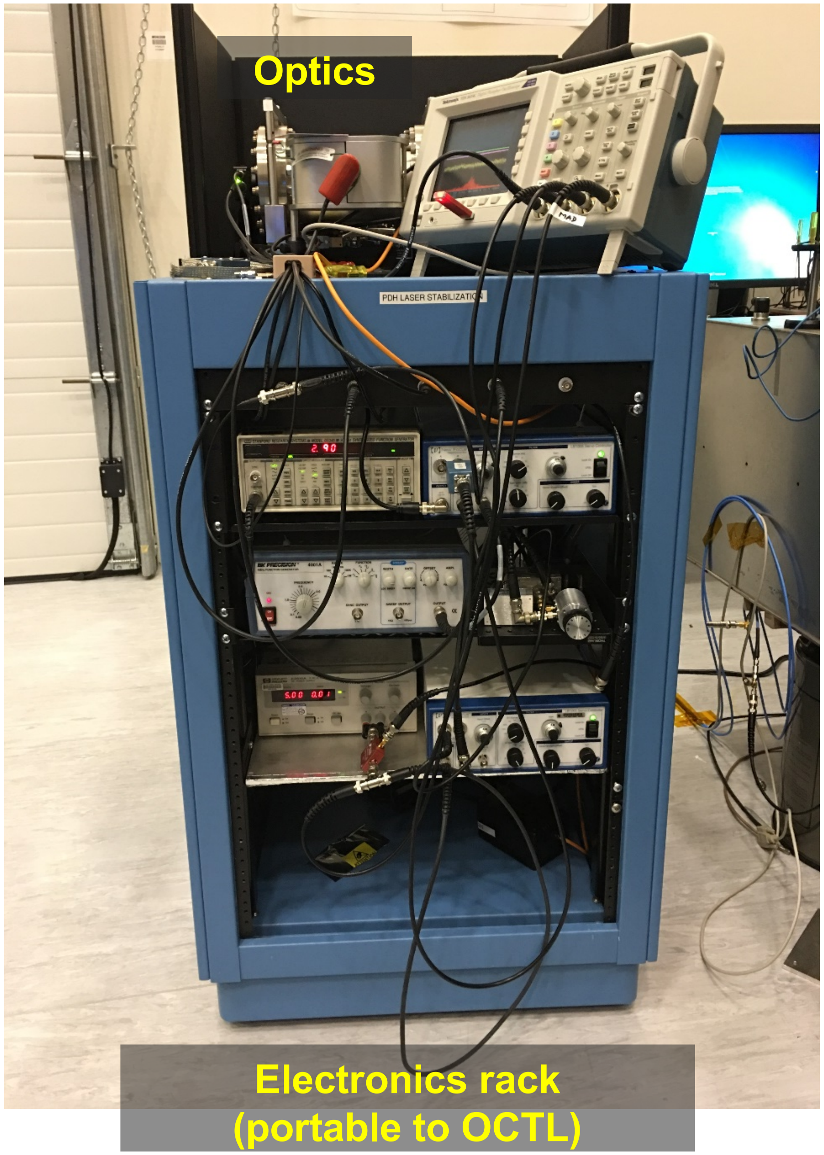
HIGH-PRECISION NAVIGATION AND SCIENCE

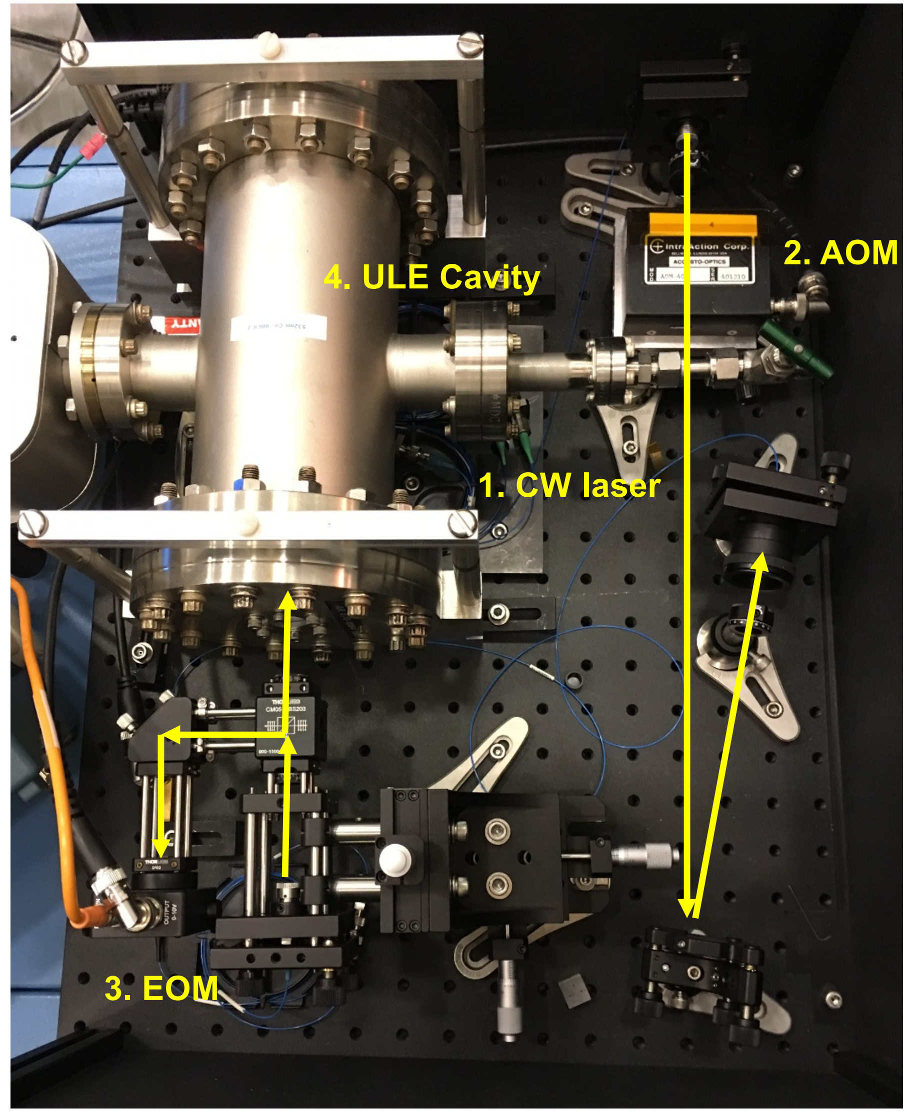
Optical Doppler – system design



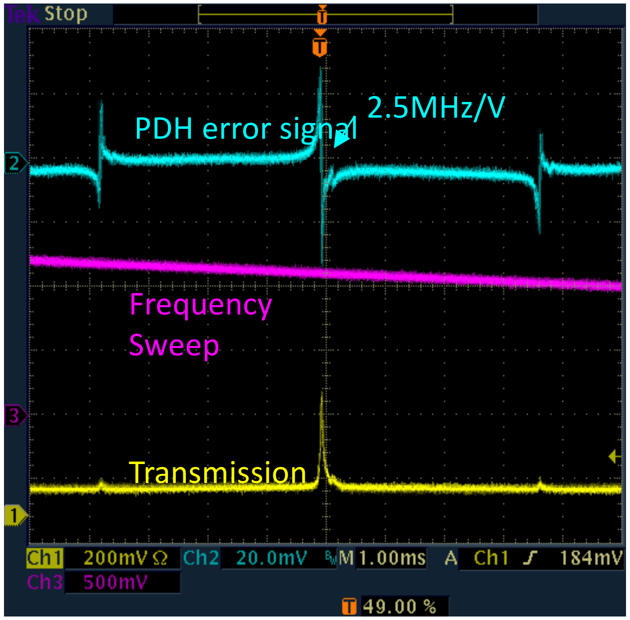
GRACE-FO GSE Cavity

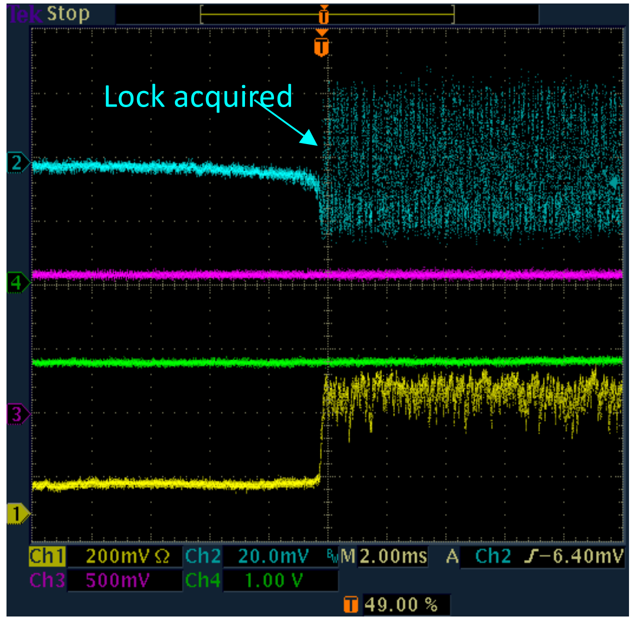
PDH Laser Stabilization Set-up

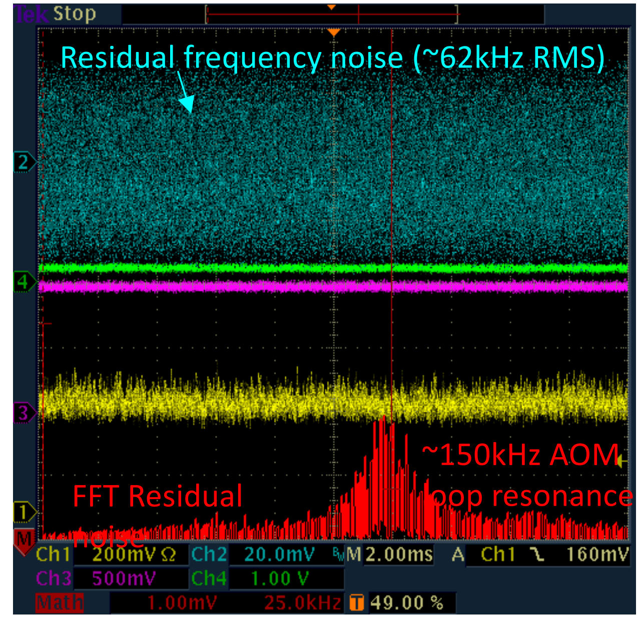




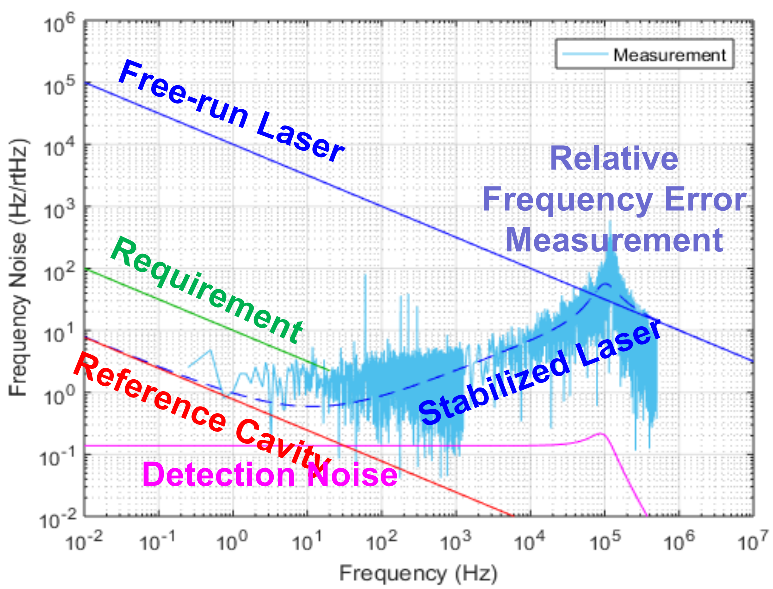
PDH Error Signal. Simulation vs Measurement

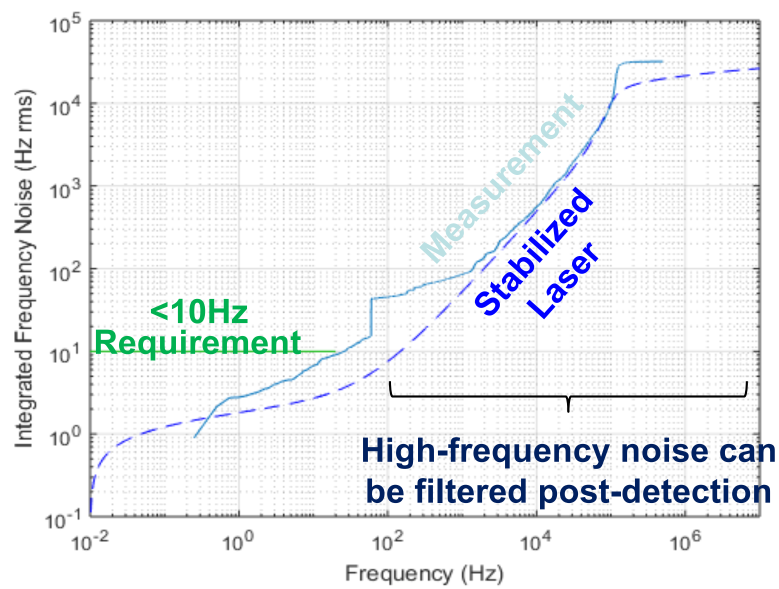






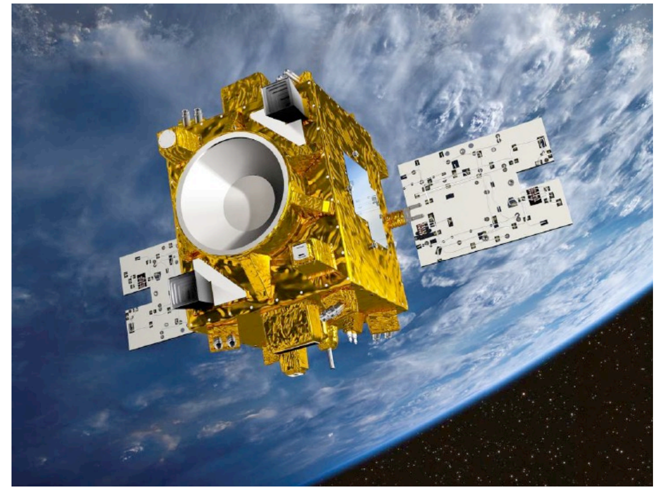
Achieved over 18 hour continuous operation



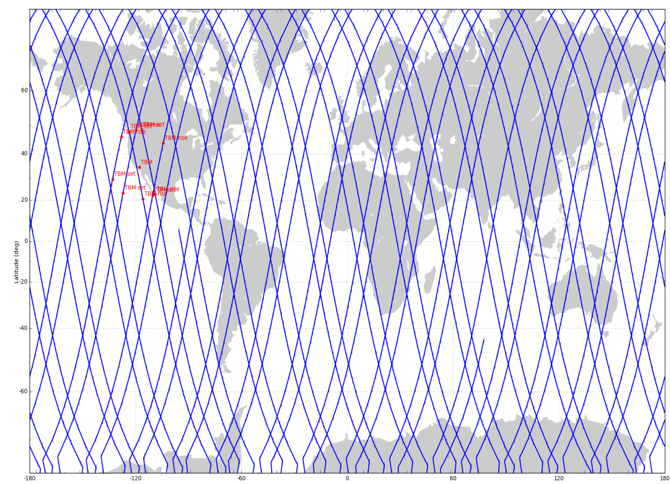


Microscope Mission – JPL Participation

- **Microscope is a mission led by CNES/ESA**
  - Developed by a consortium of CNES, ESA, ONERA, DLR, INSU, GEOAZUR, ZARM, and PTD;
  - After 20+ years in development, launched April 15, 2016 for an 18 months mission;
  - The Microscope Science Team and CNES have agreed to a proposal from NASA/JPL to participate in the mission
- **Science objectives and the orbit:**
  - To test Einstein’s Equivalence Principle to 1 part in 10^{15}.
  - To conduct various tests in relativistic geodesy;
  - Altitude 700 km with eccentricity < 5×10^{-3}
  - Test masses of two accelerometers are monitored with capacitive sensing, so that their orbits are the same to < 10pm;
  - Orbit determination: 7m; pointing: μrad
- **NASA portion of science:**
  - High-precision orbit determination using new high-power laser ranging facility at the JPL’s Table Mountain Observatory, CA
  - Independent data analysis for Microscope data at JPL.



MICROSCOPE concept artist’s drawing



MICROSCOPE orbit example

Photon Flux SNR Budget for Coherent Operations

AdLLR for coherent range and Doppler

Laser Budget			**Target**		
Tel Dia	1	m	size m	0.05	m
lambda	1.06	um	albedo	250	
lambda/D	1.06E-06	rad	flux	1.88E-19	J/phot
Range	1.00E+06	m			
xmit beam spread	1.00E-05	rad	cross section	0.49	m^2/sr
spot size dia	10.00	m			
spot area	7.85E+01	m^2			
fraction	6.25E-03	cross/spot-area			
laser power	20	W			
hit target	0.125		**Detector**		
receiver aperture	0.15	m	detector dark	100	phot/s
return solid angle	8.84E-15	sr			
watt return	1.10E-15	W	Integ time	1.00	hr
	5.88E+03	phot/s	Flux 1 hr	1.88E+06	phot/s
Atmos extinction	0.8		SNR 1 hr	1.26E+03	
Xmit losses	0.37				
Rec Losses	0.30		range 1 sec	0.05	um, ph limit
Flux received	522	phot/s	**range 1 sec**	5	mm, atm lim
SNR in 1 sec	20.9		**diff range 1 sec**	10	um, atm lim

High-precision range, Doppler, and attitude of the Microscope spacecraft may be very useful:

- To check OD & attitude obtained by other means;
- Various geophysical investigations proposed for the mission (gravity field of high degree/order)

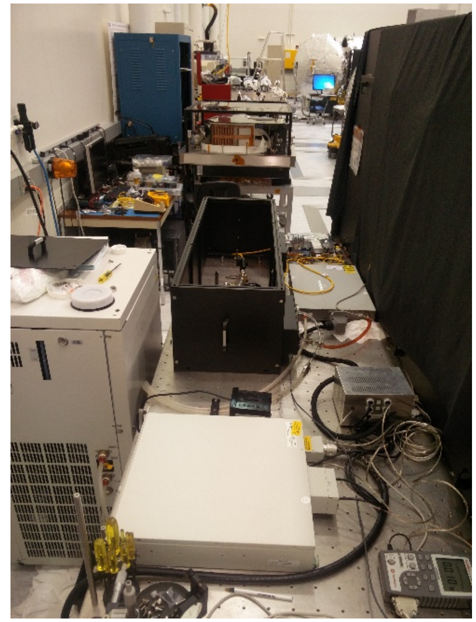
- Absolute to Microscope:
  - Range: potentially a sub-mm resolution, but limited by Earth's atmosphere to ~5 mm;
  - Range-rate: ~5−10 μm/s, limited by Earth's atmosphere.
- Differenced range AdLLR:
  - We can switch between the patches of RR-tape on the spacecraft and take nearly-simultaneous range data;
  - If two ranges are taken within 5 min apart, the atmospheric limit is as low as ~10 μm;
  - In 100 sec, this translates to attitude determination at the level ~10 μas/s (or 50 prad/s);
  - Potentially very useful as independent data for EP test.

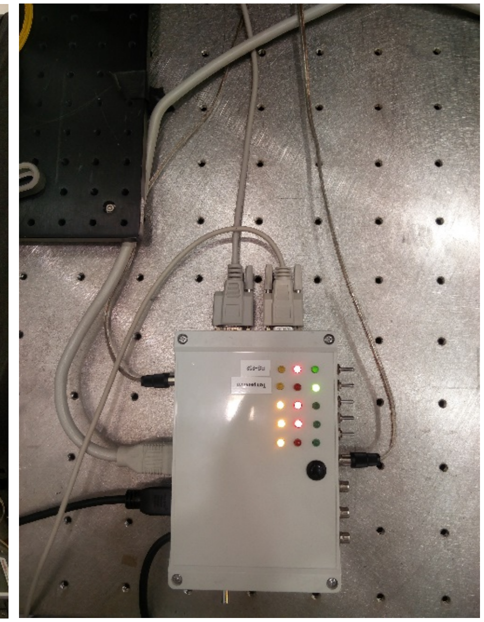
This technique enables new nav observable: OD and attitude of an Earth orbiter

Current Status

- Full power test of laser amplifier (1KW) finished in a lab at JPL
- Major components have been delivered and tested for both coherent (Doppler) & incoherent ranging
- Current activities at JPL/TMO:
  - Frequency shifter for LO for Doppler measurements (in the lab)
  - Data acquisition system for both Doppler and range LADAR
  - FAA, LCH clearances, safety, etc.

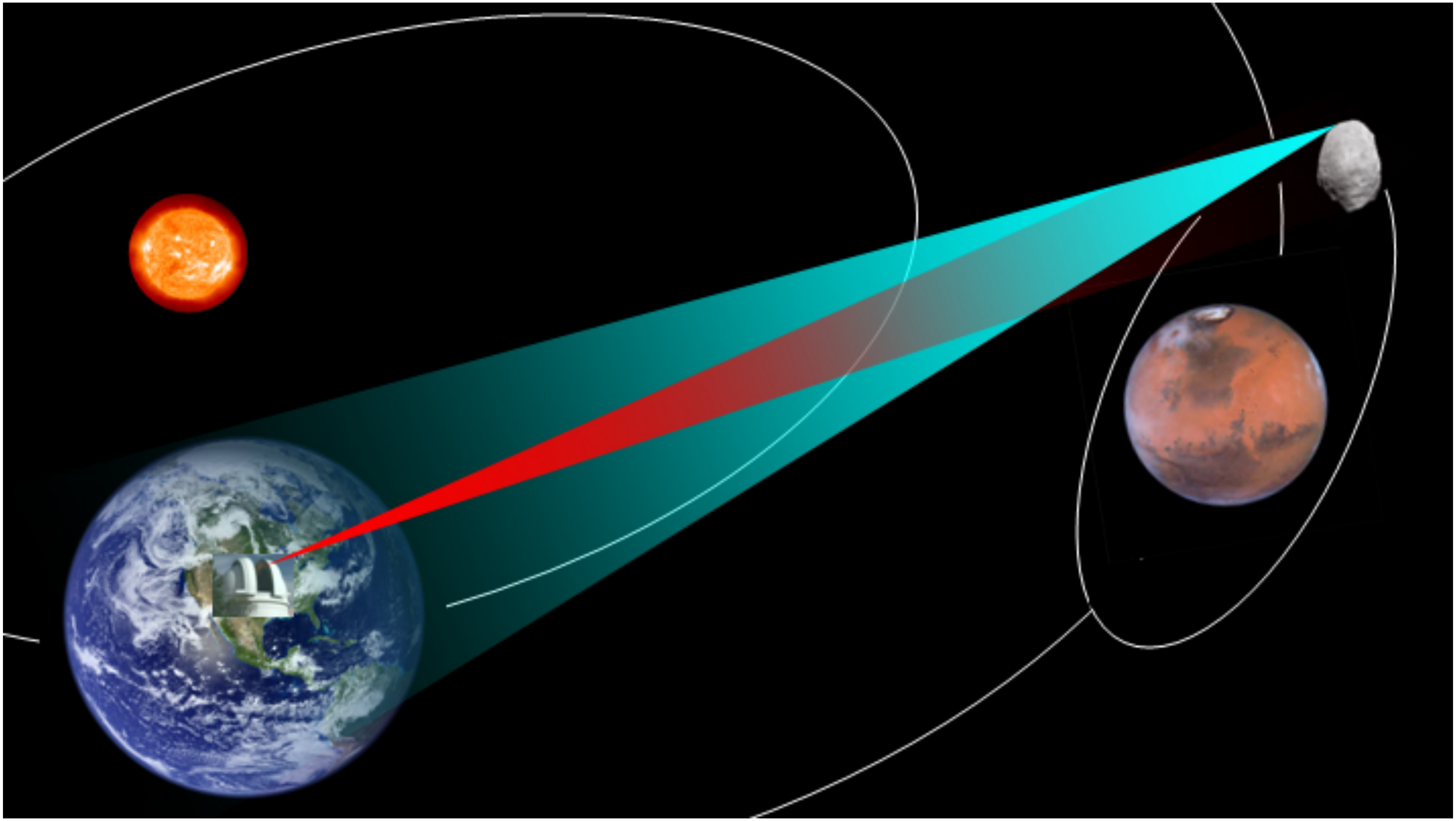
- Sep-Oct 2017: LAGEOS, LARES;
- Nov 2017: Microscope
  - Awaiting for CNES permission
- 2017-18: ready for ACES, ISS, etc.





Amplitude modulation system for dLLR.

Phobos Laser Ranging Architecture



Next Step – Interplanetary Laser Ranging

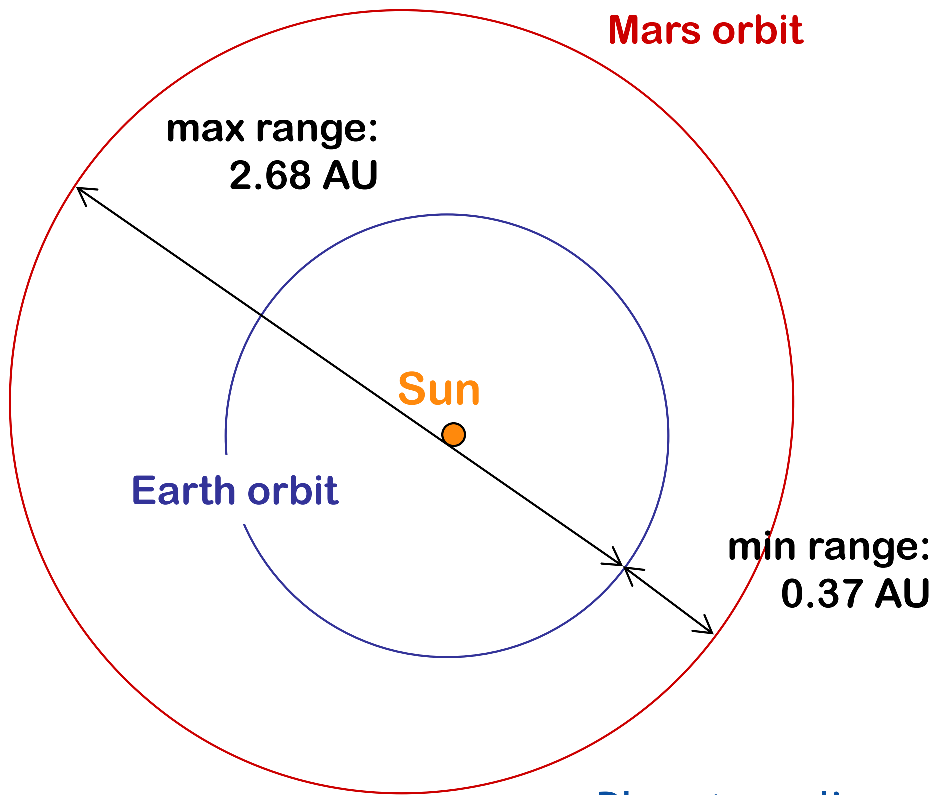
Interplanetary Laser Ranging Trade Space

- **Mercury**
  - Surface
    - ***Dark crater*** — *Expensive, conjunction communication problem*
    - ***Plains*** — *Expensive, thermal difficulties*
  - Orbit — *Expensive, orbital & thermal difficulties*
- **Mars**
  - Surface — ***Promising****, but problems with dust & atmosphere*
  - Orbit
    - ***Free orbit*** — *Orbit precision a challenge*
    - ***Phobos*** — ***Promising***
    - ***Deimos*** — *Precession too long*
- **Asteroid** — *No suitable candidate with enough conjunctions*
- **Free-flyer** — *Expensive, as a single spacecraft architecture would need a drag-free platform; Insufficient science with a time-of-flight transponder (need for coherent detection).*

Simulated: laser ranging over 1-6 years of operation based on daily 1 mm range points.

Estimated parameters (total up to 230) include orbital elements (60), up to 67 individual asteroid GMs, asteroid class densities (3), spacecraft biases (8), solar corona corrections (8), planetary features (Mars, Mercury, Phobos, etc.) and others.

Ranging Parameters & Link Budget



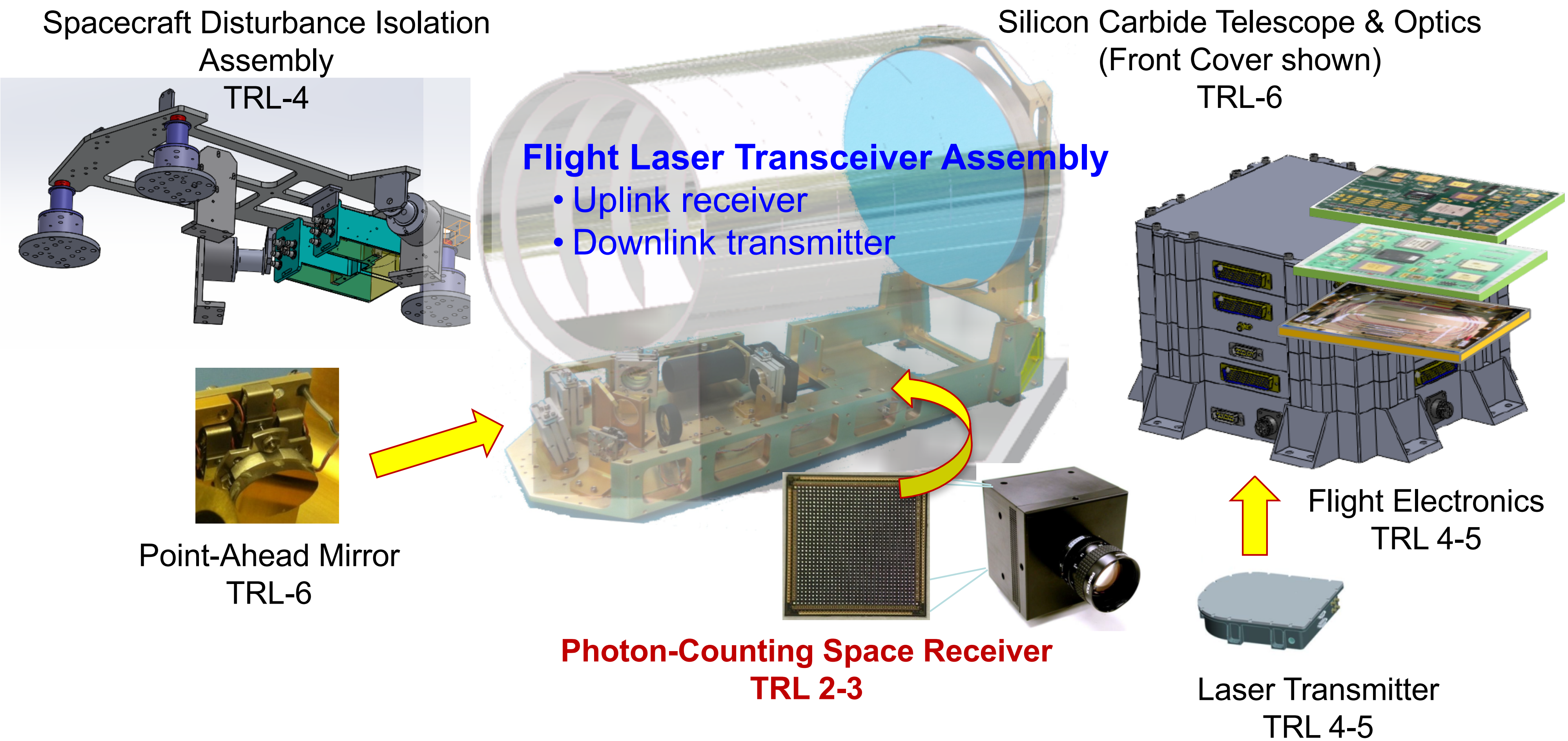
- Opposition can be from 0.37 to 0.68 AU
- Conjunction can be from 2.37 to 2.68 AU

Planetary diameters:

- @max distance:
  Mars 17 μrad,
  Earth 32 μrad
- @min distance:
  Mars 122 μrad,
  Earth 229 μrad

Input Parameters	Earth to Phobos	Phobos to Earth
wavelength (nm)	532	1064
transmit power (w)	3	0.25
tx efficiency	0.5	0.5
tx beam divergence (µrad)	25	160
tx pointing loss (dB)	-2	-2
tx atmospheric loss	-3	-3
tx pulse frequency (kHz)	1	1
rx atmospheric loss (dB)	-4.3	-4.3
rx diameter (m)	0.1	1
rx efficiency	0.3	0.3
rx field of view (µrad)	240	20
rx detector efficiency	0.4	0.4
background (W/m/m/sr/µm)	32	32
scattered light radiance (W/m/m/sr,	100	100
Earth sky radiance (W/m/m/sr/µm)	0	1000
bandpass FWHM (nm)	0.2	0.2
range(AU)	2.6	2.6
Derived Parameters		
photon energy (aJ)	0.37	0.18
space loss (dB)	-166	-162
rx signal power (aW)	9.3	1.9
planet background power (pW)	0.05	2
scattered light power (W)	0.15	6.9
sky radiance power (pW)	0	69
timing window (µs)	1024	27
Summary Results		
incident signal power (aW)	2.8	5.70E-01
incident noise power (pW)	2.7	21.3
SNR (dB)	-60	-76
detected signal rate (Hz)	3	1.2
detected noise rate (MHz)	3	46
timing window (ns)	10	10
data volume (MB/day)	100	1570

Implementation Approach



Replace the Photon Counting Space Receiver with two new detectors (COTS):

- Single pixel detector and on-board timing for comm and range;
- 2Kx2K sCMOS for pointing, link acquisition and astrometry.

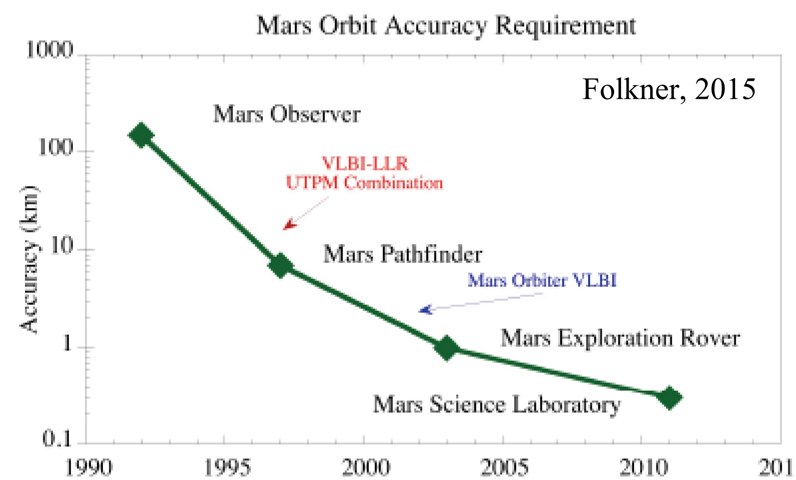
Navigation & Science Data Accuracy Goals

Tracking Error Source (1σ Accuracy)	units	Current X-band capability		Current Ka-band capability	Near-term DOT[a] capability	
		value	Int.time		value	Int.time
Range	m	2	$10–10^3$ s	0.1	5 mm	$10–10^2$ s
Doppler (range-rate)	μm/s	30	$10–10^3$ s	10[b]	10[e]	$10–10^2$ s
Astrometry from space[c]	mas	500	1-10 s		1-10	3-300 s

[a] Assumed: 0.2m aperture at 2AU distance, non-coherent detection;
[b] Demonstrated on BeppiColombo; [c] Hubble camera;
[d] Range-rate (computed as Range/Int.time = non-coherent Doppler).

Towards navigational capabilities with DOTs:

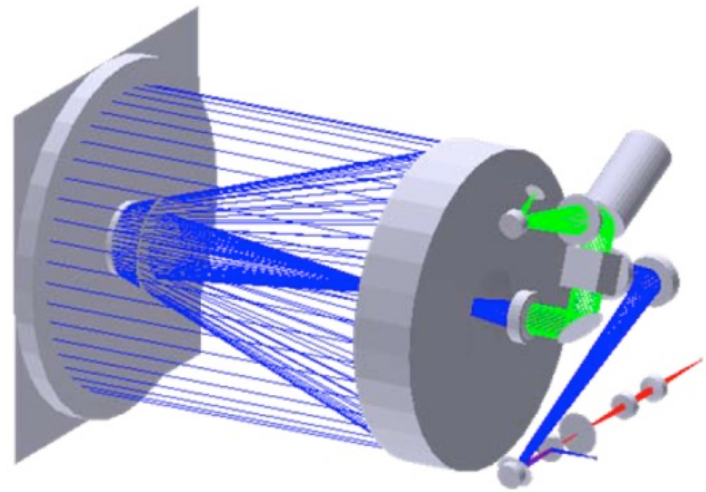
- X-band capabilities are the current state-of-the-art for deep space navigation;
- At present, there are no missions requiring nav accuracy beyond that of the X-band;
- Thus, capabilities beyond those of X-band driven by science, but available to navigation.



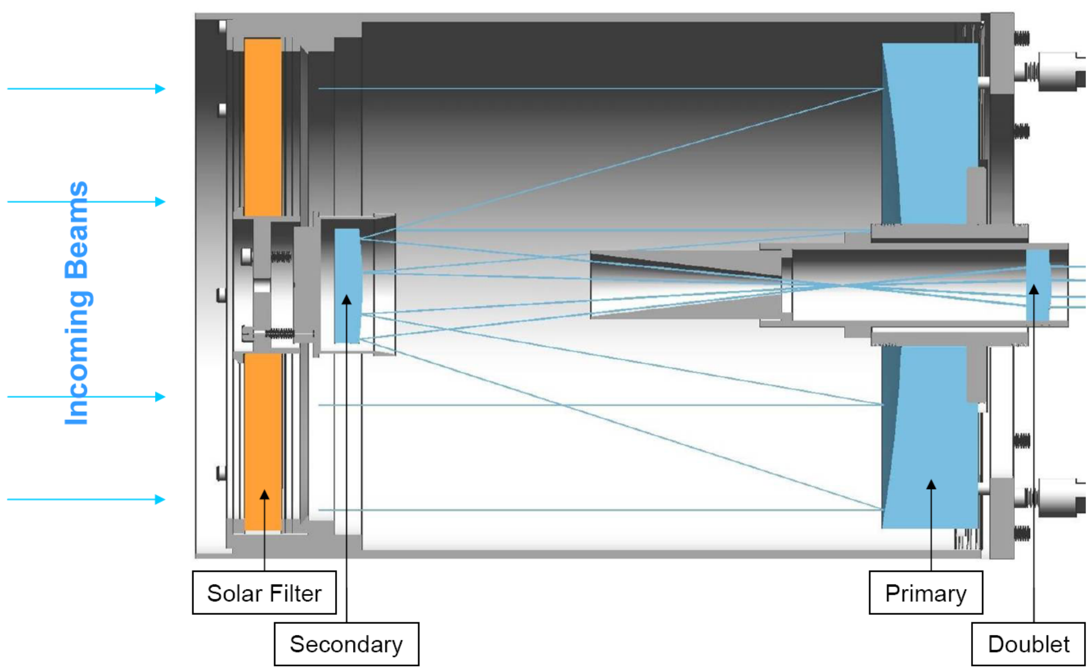
New DOT may have navigational and science capabilities beyond those of X-band

Interplanetary Laser Ranging Instrument

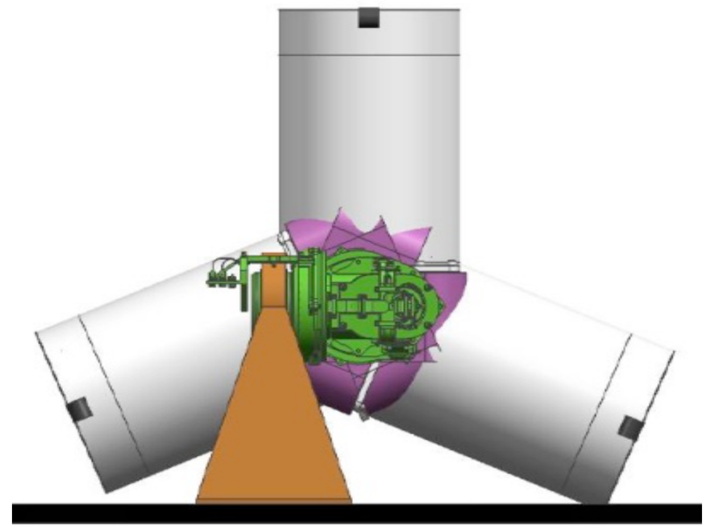
- The ILRT instrument comprises gimbaled optical head and a body mounted opto-electronics box
  - 10 cm transmit/receive aperture



ILRT Optical Channels



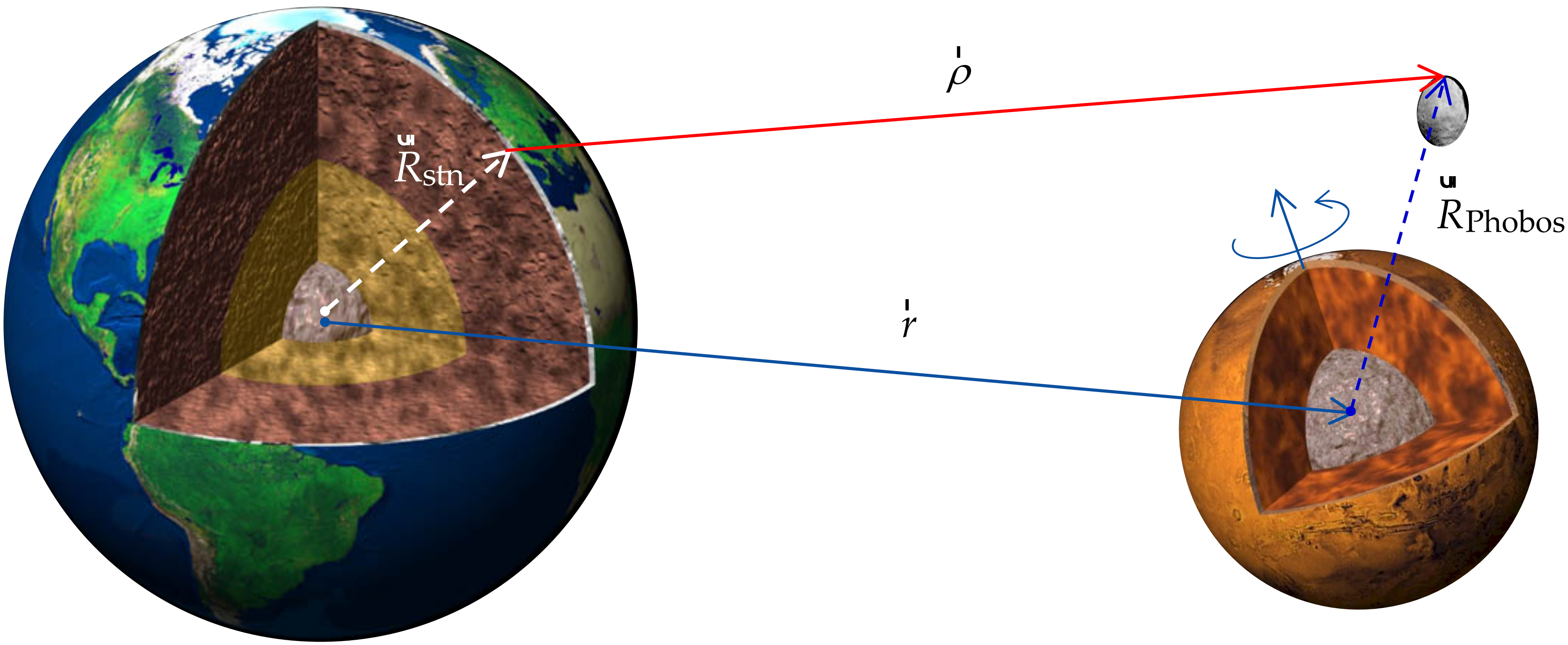
ILRT Telescope Cross-Section



ILRT Gimbaled Optical Head

Phobos Laser Ranging: Principle

1 mm range accuracy with PLR is possible



Impact on:

- Test of general relativity
- The science of Phobos, especially its interior

Gravity Tests with PLR vs Experiment Duration

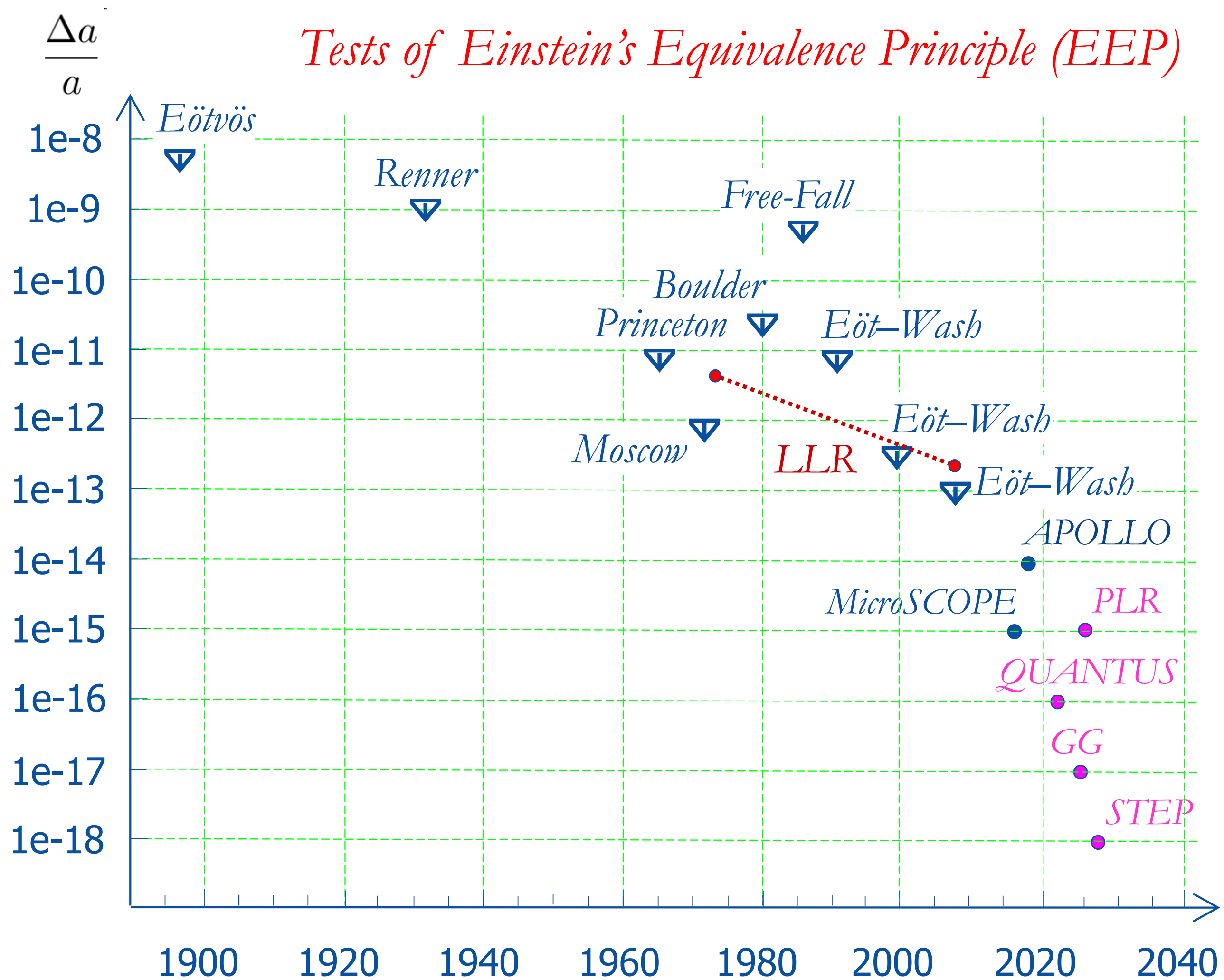
Relativistic Effect	Current best	Mission duration / N of conjunctions		
		1 yr / 1 cnj	3 yr / 2 cnj	6 yr / 3 cnj
PPN parameter γ	2.3×10^{-5}	3.1×10^{-7}	1.4×10^{-7}	7.9×10^{-8}
PPN parameter β	1.1×10^{-4}	4.3×10^{-4}	1.6×10^{-4}	9.4×10^{-5}
Equivalence Principle, η	1.9×10^{-13}	7×10^{-14}	1.2×10^{-14}	2.3×10^{-15}
Strong Equiv. Principle, η	4.3×10^{-4}	1.5×10^{-4}	2.8×10^{-5}	8.8×10^{-6}
Solar oblateness, J_2	2.0×10^{-7}	6.9×10^{-8}	3.2×10^{-8}	2.3×10^{-8}
Search for time variation in the grav. constant G, $dG/dt/G$, yr^{-1}	7×10^{-13}	1.7×10^{-14}	2.8×10^{-15}	1.0×10^{-15}
Gravitational inverse square law	2×10^{-9} @ 1.5 AU	4×10^{-11} @ 1.5 AU	2×10^{-11} @ 1.5 AU	1×10^{-11} @ 1.5 AU

Estimated uncertainties for parameters of interest as a function of Phobos lander mission duration, with 1 mm laser ranging once per day with 2 deg SEP cut-off and 67 asteroid mass parameters estimated.

Simulations by W.M. Folkner, JPL

Empirical Foundations of General Relativity:

Confrontation Between the Theory and Experiment



- • funded projects
- • proposed projects
- *LLR*, *APOLLO*, and *PLR* are testing the Strong Equivalence Principle (SEP)

$$\left[\frac{m_G}{m_I}\right]_{\mathrm{SEP}} = 1 + \eta\left(\frac{\Omega}{mc^2}\right)$$

Uniqueness of the Free Fall
(⇒ Weak Equivalence Principle):

$$\vec{F} = m_I\vec{a} = m_G\vec{g}$$
$$\Rightarrow m_I = m_G$$

All bodies fall with the same acceleration

Define the test parameter that signifies a violation of the **WEP**

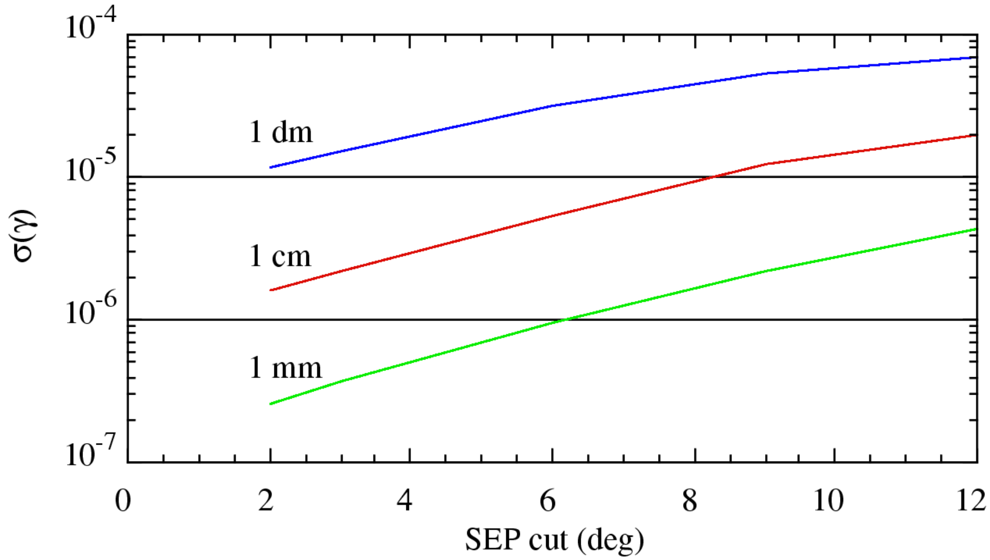
$$\frac{\Delta a}{a} = \frac{(a_1 - a_2)}{\frac{1}{2}(a_1 + a_2)} = \left[\frac{m_G}{m_I}\right]_1 - \left[\frac{m_G}{m_I}\right]_2$$

Let Ω is the gravitational binding energy of a test body, then the test parameter that signifies a violation of the **SEP** is

$$\frac{\Delta a}{a} = (4\beta - \gamma - 3)\left\{\left[\frac{\Omega}{mc^2}\right]_1 - \left[\frac{\Omega}{mc^2}\right]_2\right\}$$

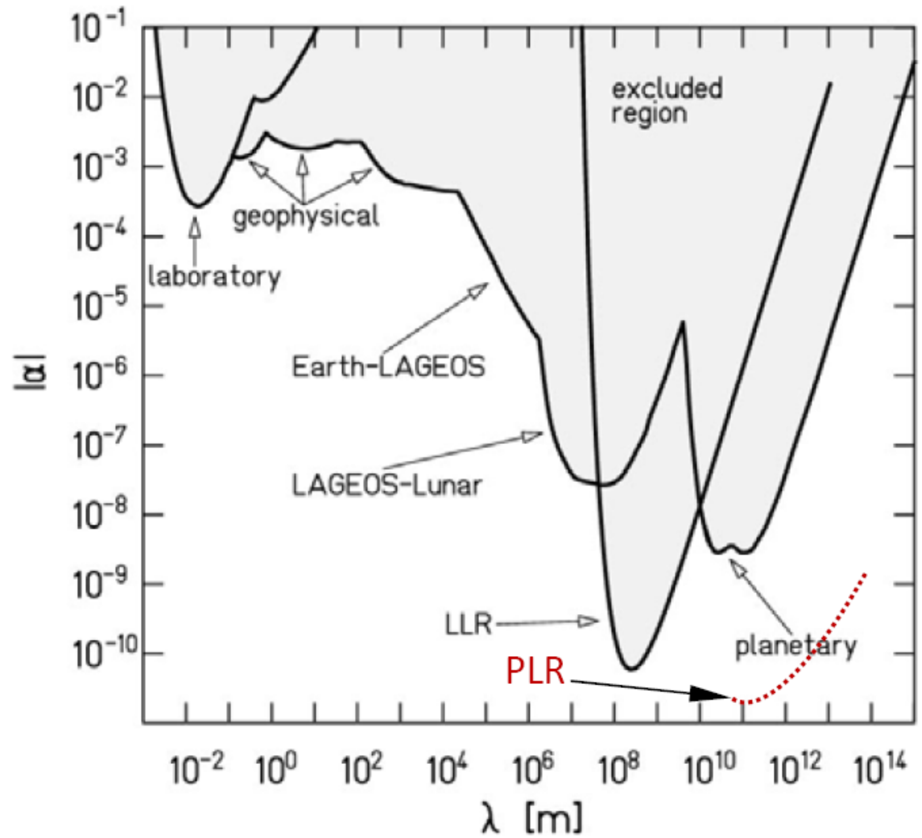
Gravity Tests with PLR: PPN γ and the ISL

Estimated uncertainty in PPN γ



Estimated uncertainty in PPN γ as a function of data accuracy and data cut-off with angular separation from the Sun as viewed from Earth.

Limits on the ISL violations



Simulations by W.M. Folkner;
background graphics from (Adelberger et al., 2003)

Major improvement in the test of ISL

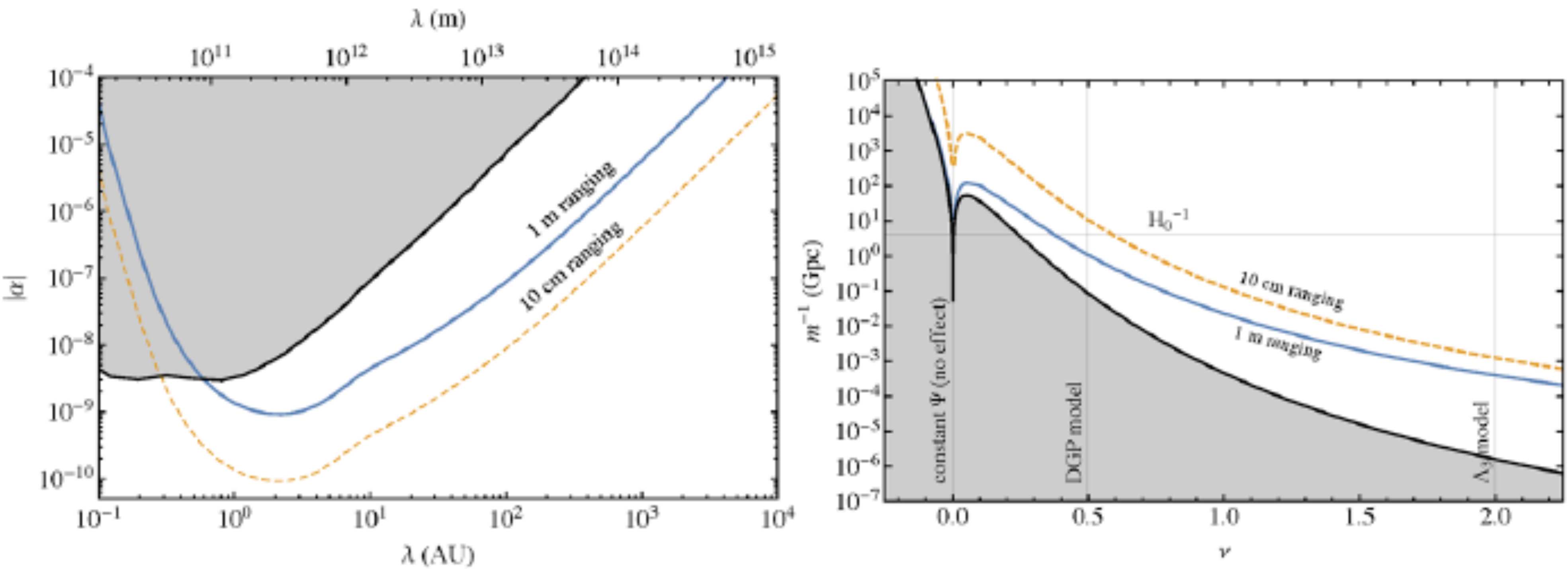


Fig 1: Forecast sensitivity of a drag-free test mass measurement concept. **Left panel**: Expected 2-σ exclusion limit on the strength α of a new Yukawa-type force with range λ. The shaded region is excluded by planetary tests of Kepler's third law. Right panel: Expected 2-σ lower limit on the graviton Compton wavelength m^{-2} of a new Vainshtein-type power-law contribution to the gravitational potential. For a particular theory with index ν, the experiment will be sensitive to the region below the curve. The vertical lines at ν= 1/2 and ν = 2 correspond to DGP gravity and ghost-free Λ_3 massive gravity respectively, and the horizontal line indicates the present-day Hubble scale which is the scale of interest for models that attempt to address the cosmological constant problem. The shaded area is excluded by lunar laser ranging. In both cases, the solid curve is for a very conservative 1m ranging precision, while the dashed curve assumes a 10cm ranging uncertainty. Better ranging precision would further improve the sensitivity to new physics. Figure taken from Buscaino et al. 2015.

Conclusion

- Recent technological progress:
  - Resulted in new instruments (COTS) with unique performance;
  - Opportunities for major improvements in the tests of relativistic gravity
  - Already led to a number of recently proposed gravitational experiments.
    - PLR is a promising concept, also synergistic with space exploration
- High-precision Orbit and Attitude Determination from TMO:
  - LEO/GEO spacecraft (Microscope, ACES, etc):
    - Doppler measurements accurate to 10 μm/s;
    - ranging measurements accurate to 5 mm;
    - range-Doppler imaging (i.e., astrometry) accurate to sub-nrad/s.
  - A very accurate orbit/attitude reconstruction – a unique SLR experiment
- Space operations and navigation with corner-reflective tape:
  - Collaboration with Prof. Harry Atwater (Caltech)
  - Patches on the ISS to monitor vibrations (needs EVA);
  - CubeSat navigation in LEO/GTO/HEO, even to sis-lunar;
  - To monitor any deployment in space.