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Advanced Laser Ranging for high-precision science investigations

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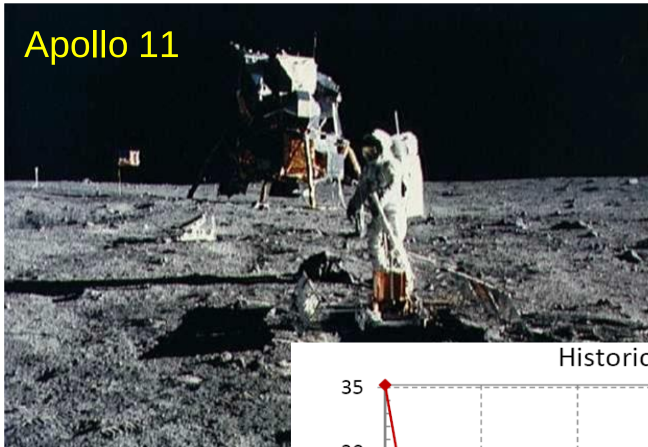
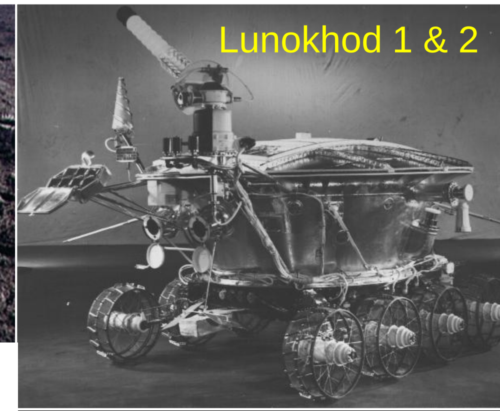
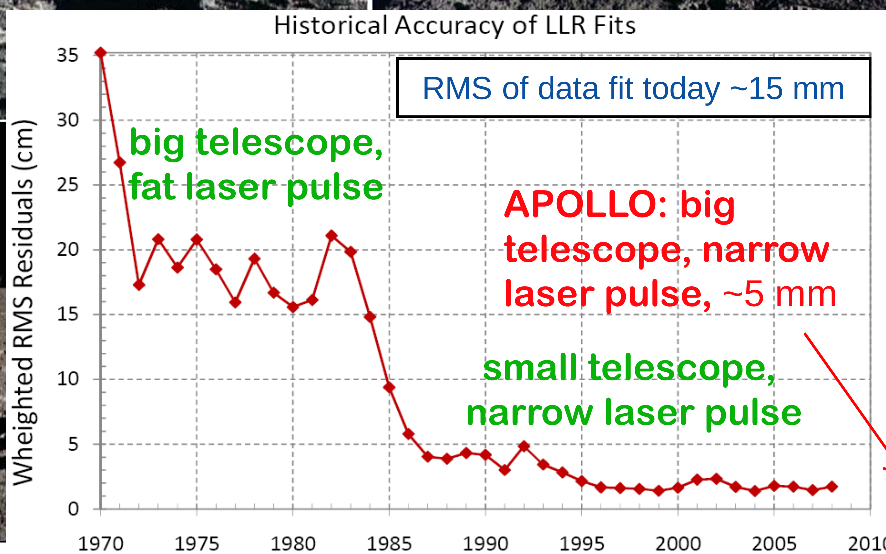
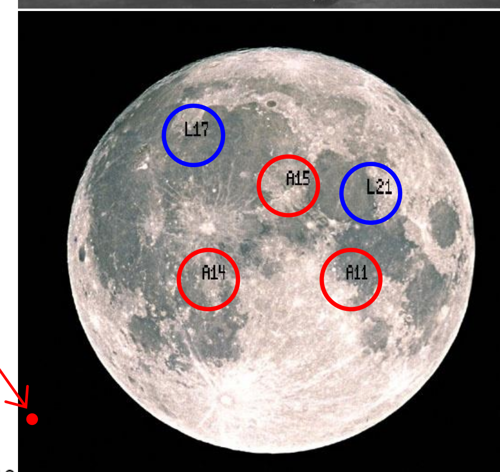
LLR is a Legacy of the Apollo Program

Apollo 11 array in 1969 initiated a shift from analyzing lunar position angles to ranges. The present day range accuracy is ~5 mm, limited by Earth's atmosphere.



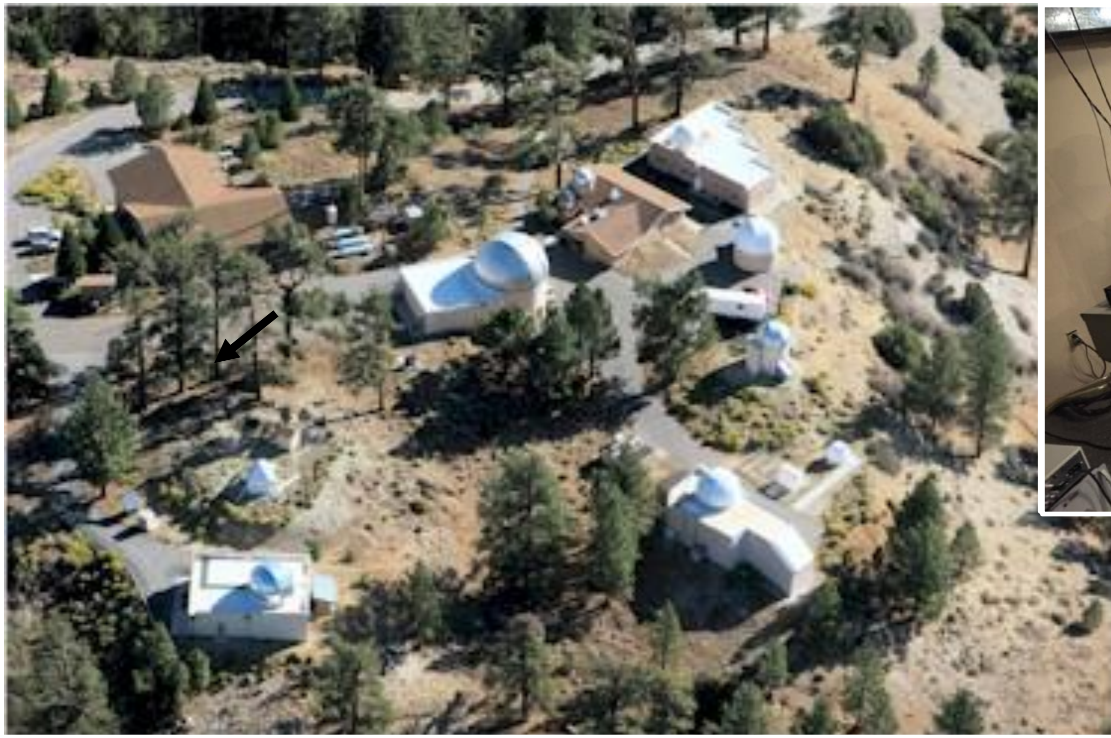


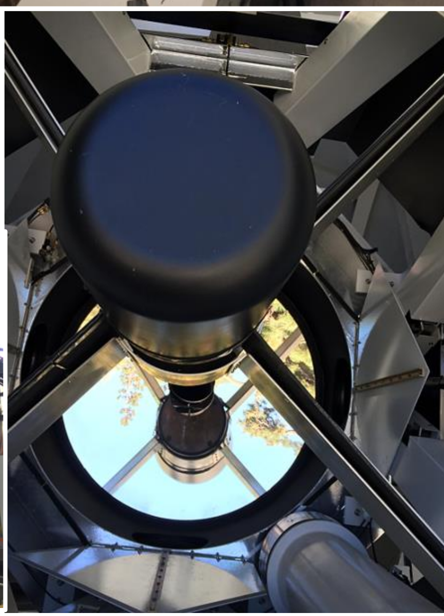


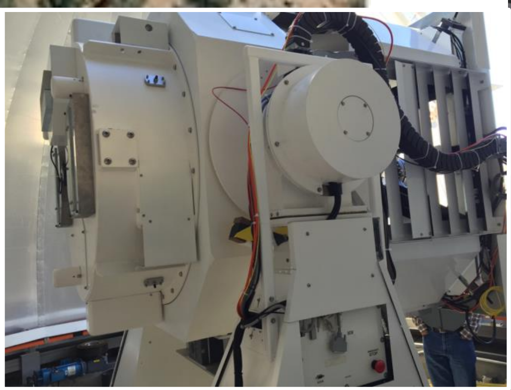


New Table Mountain LLR facility will allow a reverse shift: from lunar ranges to position angles with precision of 30 μm, a factor of 200X better than is currently available ~5 mm).

OCTL at the Table Mountain Observatory





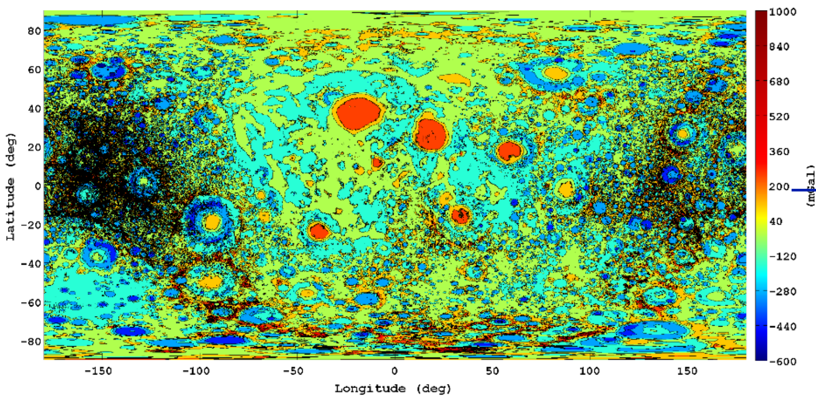


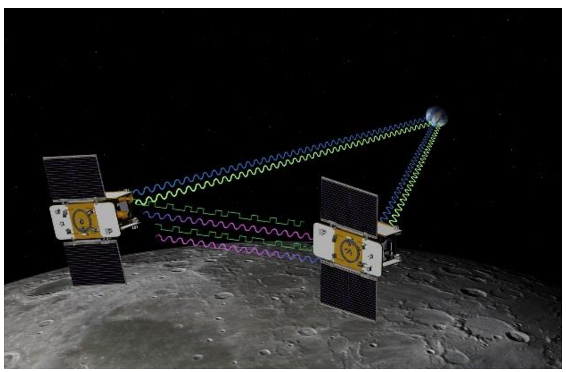
Advanced Lunar Laser Ranging (AdLLR)

- 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 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?

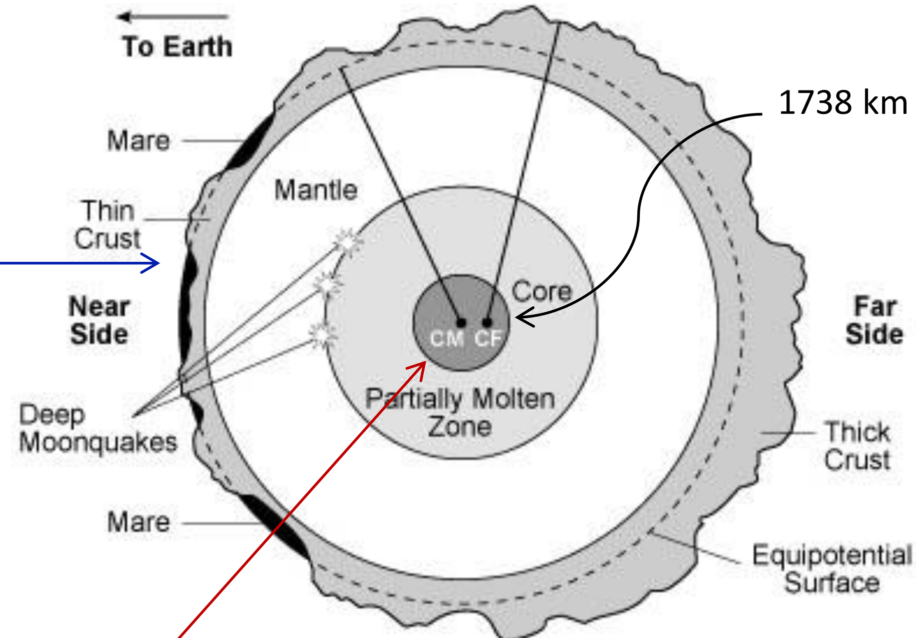
Differenced Lunar Laser Ranging

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





Revealing Deep Lunar Interior



Properties of deep lunar interior are still uncertain

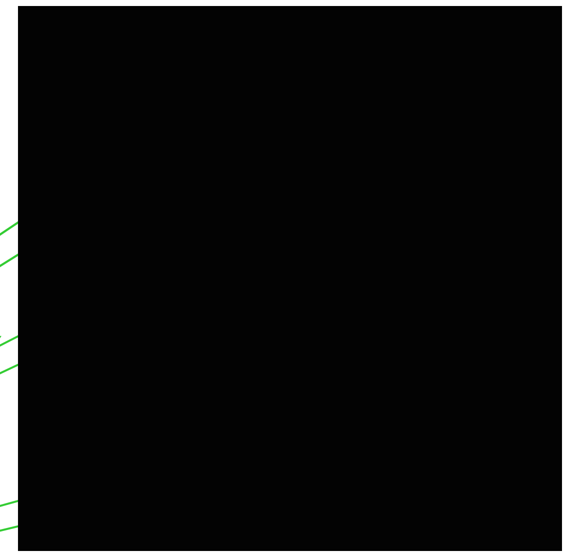
Major impact on lunar science:

- @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**
  - Amplitude-modulation of 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 (works as a microwave radar with optical carrier).

- **Differential Lunar Laser Ranging**
  - 1kW CW lasers modulated at GHz;
  - Photon counting detectors;
  - Using corner-cube retroreflector (CCR) arrays already on the Moon & new lunar CCRs, soon to be emplaced.



Lunar librations hold the key to deep lunar interior

Major progress in lunar science:

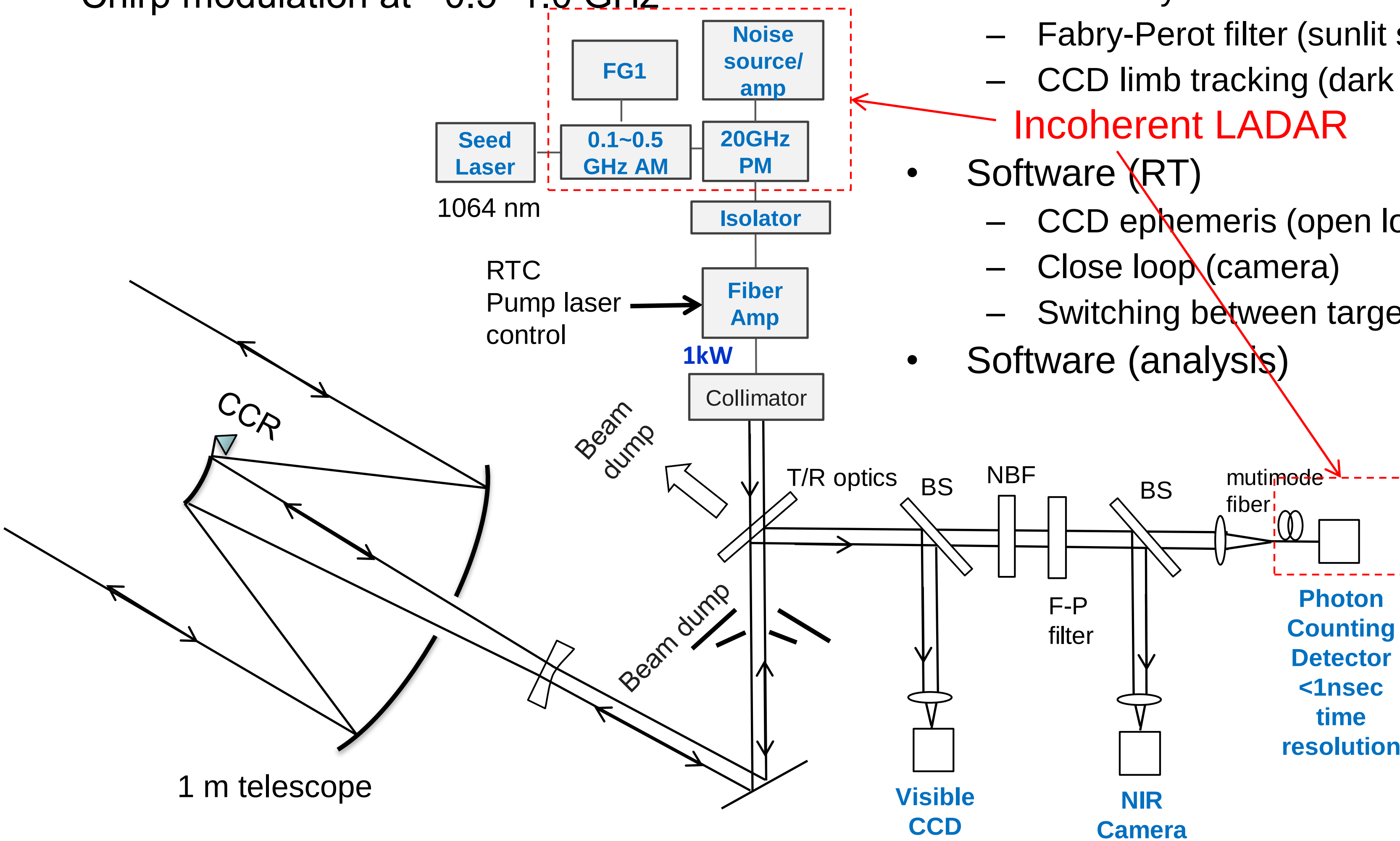
- 30 µm differential range precision, limited by Earth's atmosphere;
- Focus on lunar core & deep interior: 200X accuracy gain from rotation.

System Elements for Ranging with AdLLR

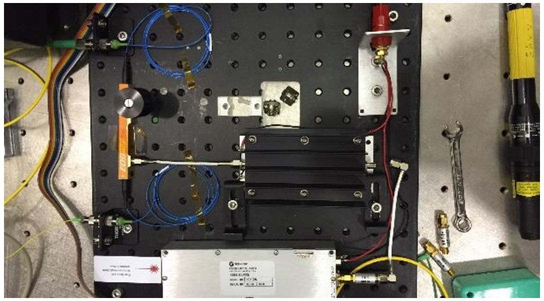
The AdLLR system uses:

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

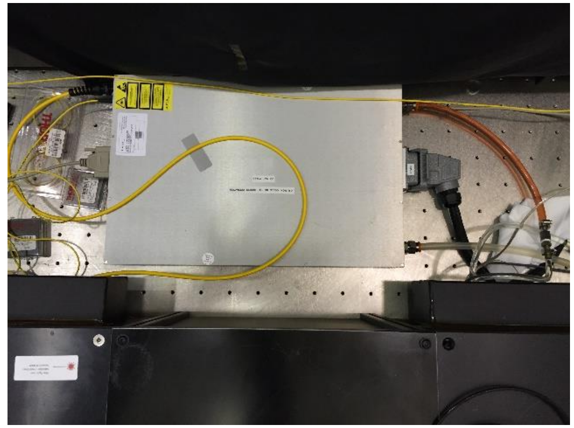
- Laser transmitter
- High-speed receiver
- Imaging camera (for target acq)
  - With very low read noise
  - Fabry-Perot filter (sunlit side)
  - CCD limb tracking (dark side)
- Software (RT)
  - CCD ephemeris (open loop)
  - Close loop (camera)
  - Switching between targets
- Software (analysis)



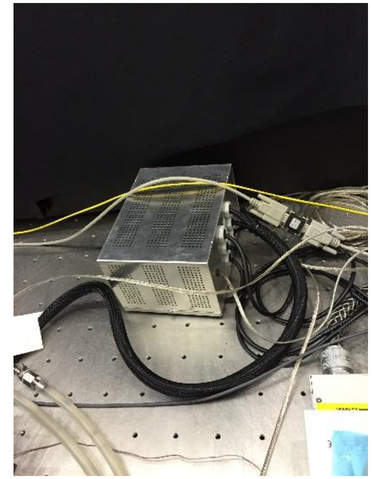
Fiber Amplifier System



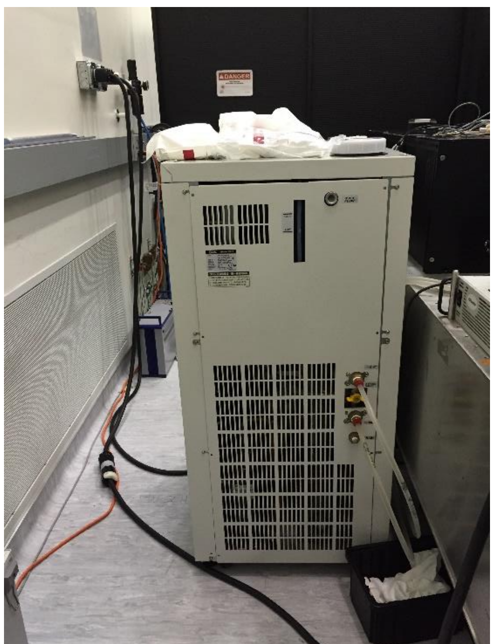
20 GHz seed broadening (Noise source + EOM)



Fiber amplifier



SS switch



Chilled water cooler

Power supply

Control electronics

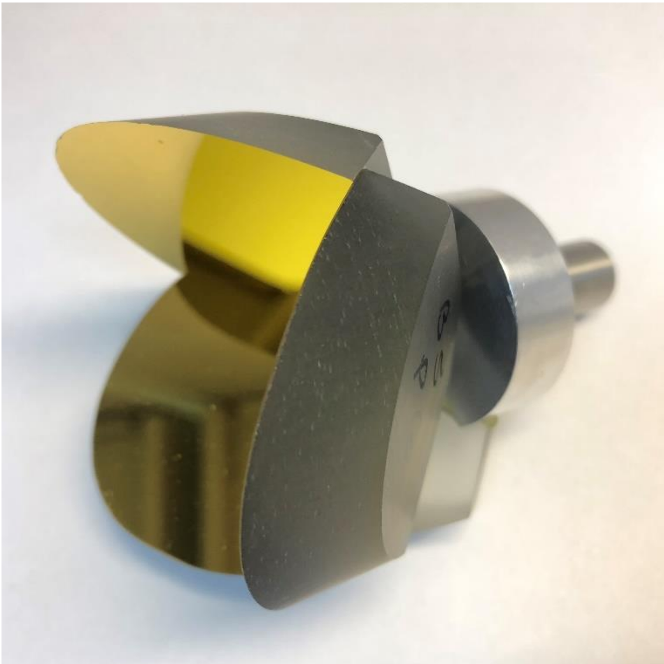
Photon Flux SNR Budget for AdLLR at TMO

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 LLR data:
  - Was not really possible previously due to 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.

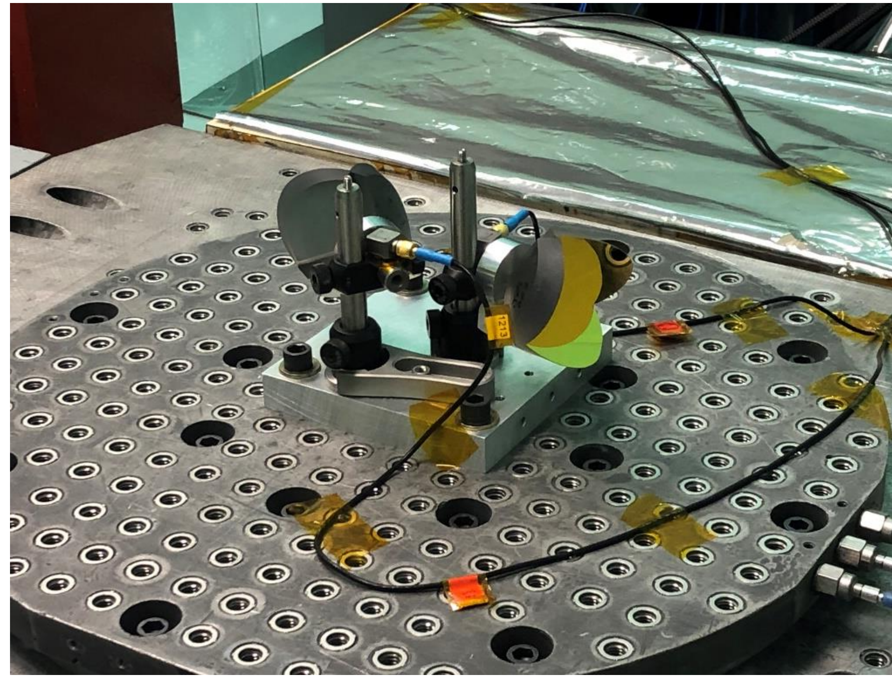
We can range the moon even with a single Apollo-type CCR: a CubeSat deployment?

AdLLR allows for small lunar CCRs



Small CCR for the Moon:

- circular aperture with diameter of 76.2 mm (3”);
- mass of 250 g;
- wavefront error of $<\lambda/4$;
- stable for the lunar environment;
- Earth-Moon range precision of <0.1 mm (single photon).



Two CCRs during vibrational test:

- The cubes survived 8.7-g (random) acceleration load (October 25, 2018)

Small single lightweight CCRs may be placed on the Moon by lunar landers in the near future.

Advanced LLR: anticipated results

Tests of GR

Science	Current (cm)	1 mm
Weak Equivalence Principle	$\lvert\Delta a/a\rvert < 1.3\times10^{-13}$	1×10^{-14}
Strong Equivalence Principle	$\lvert\eta\rvert < 4.3\times10^{-4}$	1×10^{-5}
PPN parameter β	$\lvert\beta-1\rvert < 1.1\times10^{-4}$	10^{-5}
Time variation of G	5.7×10^{-13} yr^{-1}	3×10^{-14}
Inverse Square Law	$\lvert\alpha\rvert < 3\times10^{-11}$	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 a Earth orbiting s/c with ~5 mm precision and range-rate to 5 μm/s;
  - Could be done even without CCRs on its surface as the signal reflected off the s/c will be extremely bright.

- For high precision, a reference point on the s/c is needed:
  - 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 (0.2 arcsec).

- 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., cubesats, ACES).

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.

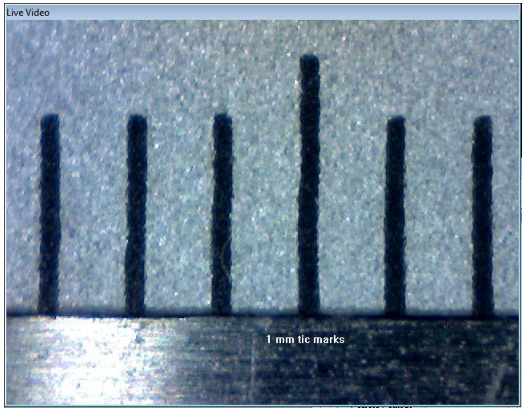
[2]Entrance Angle – the angle formed by a light beam striking a surface at a point and a line perpendicular to the surface at the same point.

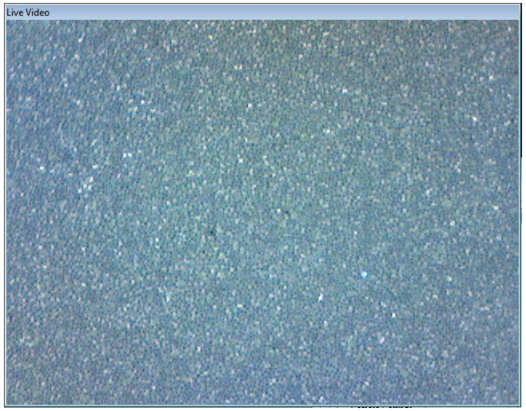
Entrance Angularity

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.

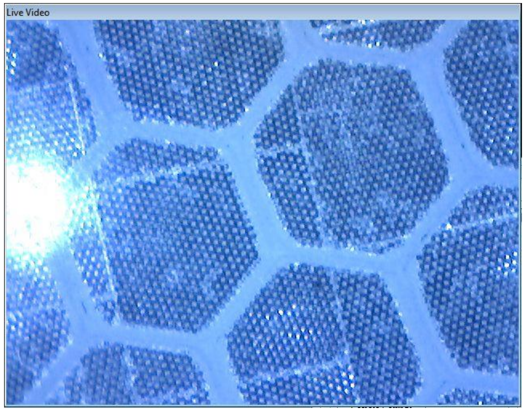
Testing Retro-Reflective Tapes

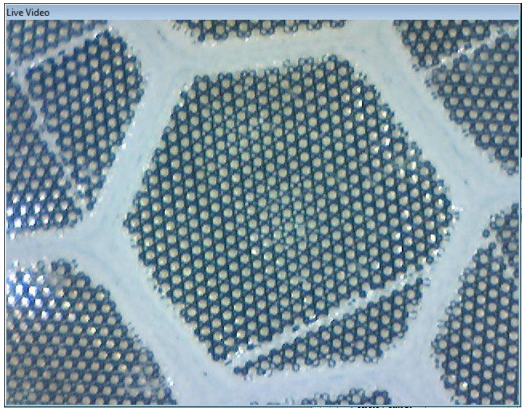


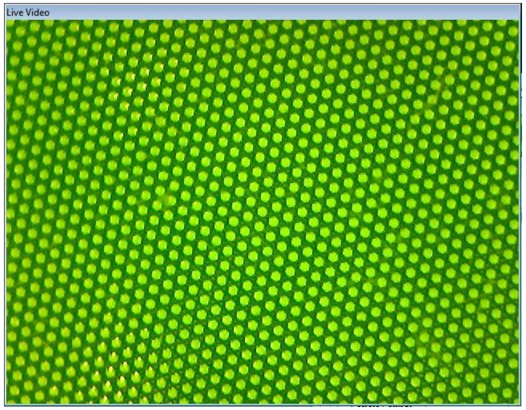


Commercially available reflective tapes (3M.com):

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







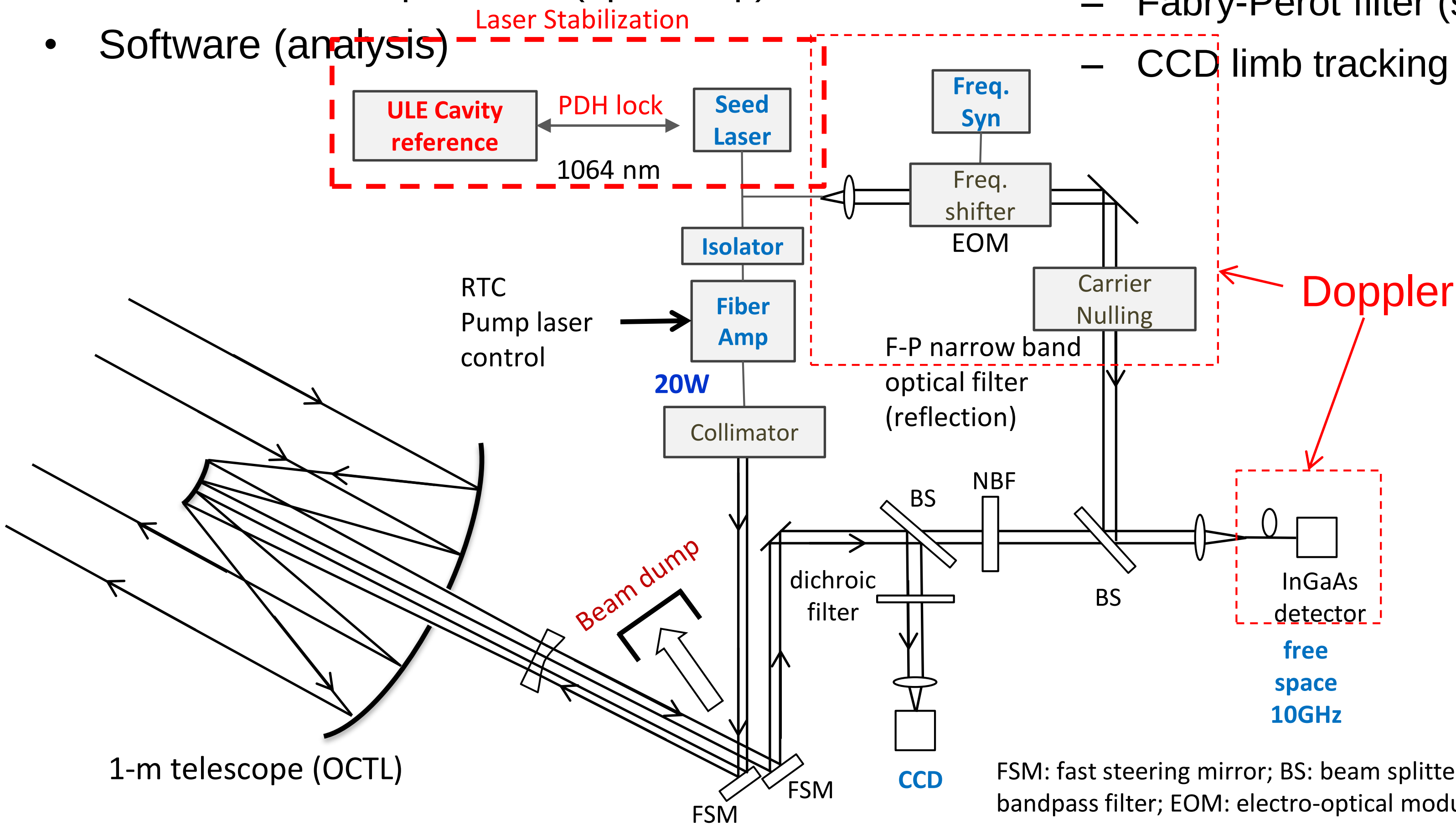
- When looked at the microscope, retro-reflective tape seem to reflect only from about 1/5 of the area, which is consistent with microbeads (i.e., 200 nm diameter spheres).
- If the diffraction from the beads is ~0.5–1°, it magnifies the return by 10,000 to 2,500. Taking 2,500/5 ~500 – the value confirmed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

System Elements for Coherent Optical Doppler AdLLR

The coherent @LLR system uses:

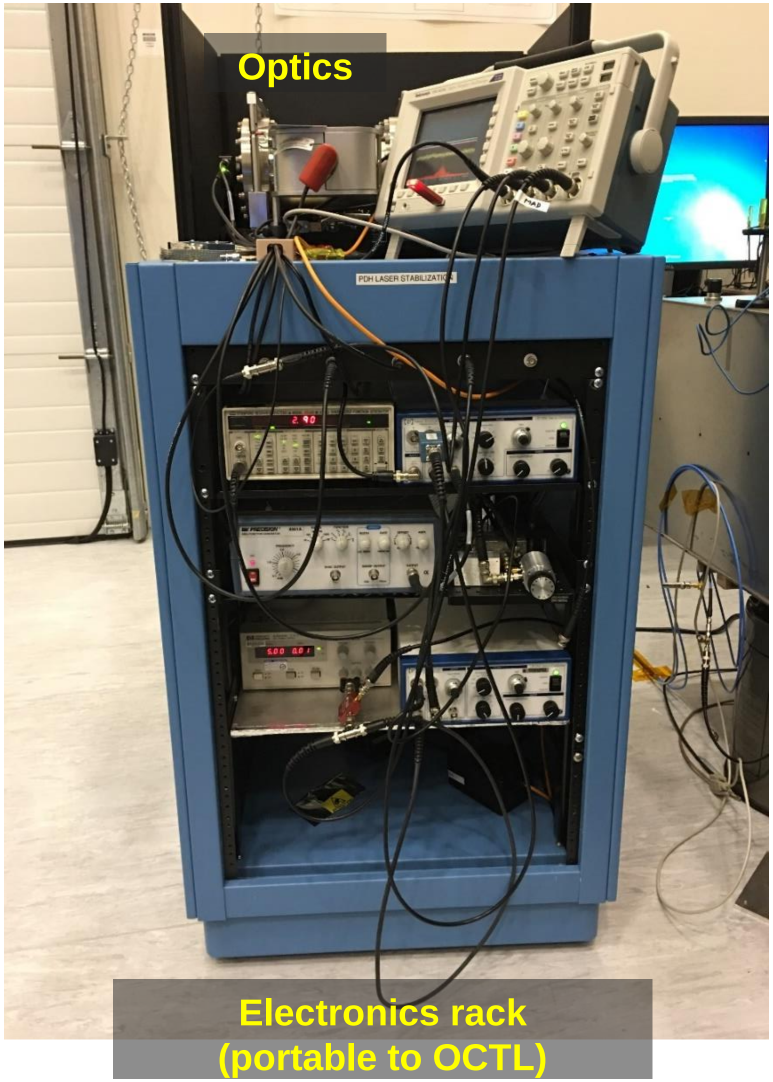
- High-power (~20W) CW laser amplitude-modulated at RF frequencies;
- Local oscillator (LO) for coherent operations
- Software: CCD ephemeris (open loop)
- Software (analysis)

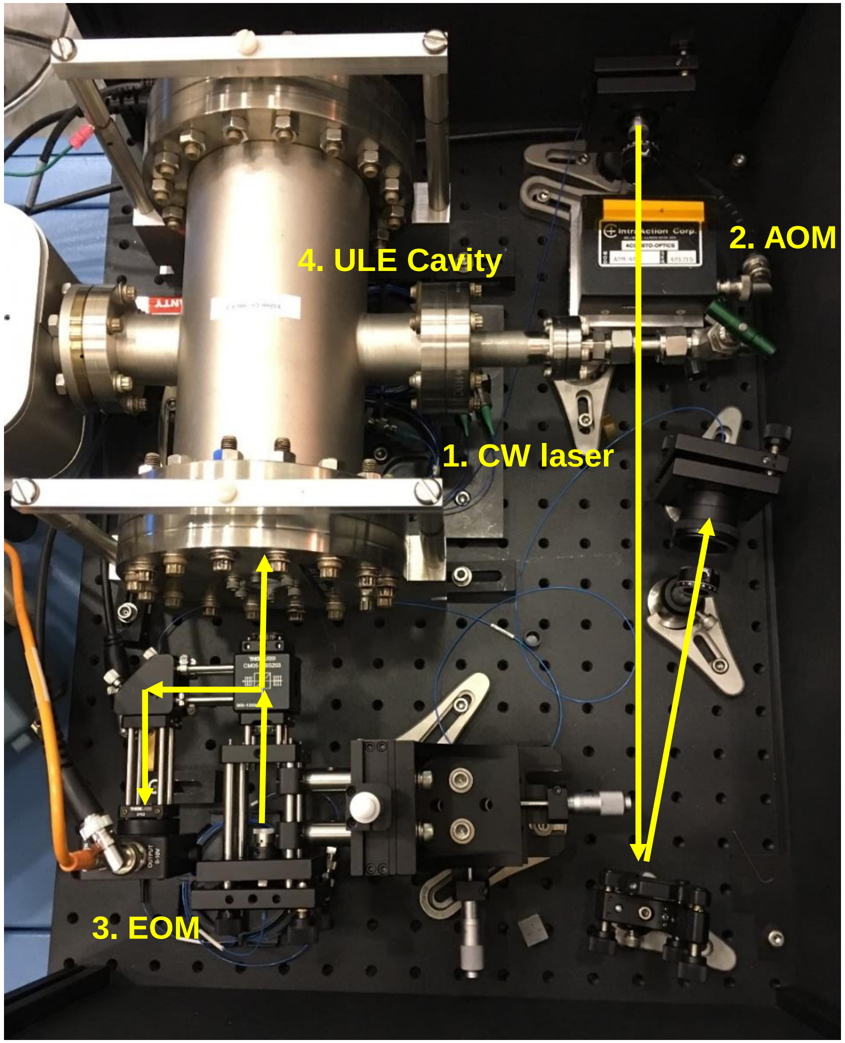
- Laser transmitter
- High-speed receiver
  - Smaller aperture (15 cm)
  - Local oscillator (seed laser)
  - Fabry-Perot filter (sunlit side)
  - CCD limb tracking (dark side)



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

PDH Laser Stabilization Set-up





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 LEO spacecraft may be very useful:

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

- Absolute to LEO/HEO s/c:
  - 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 <1 nrad/s.

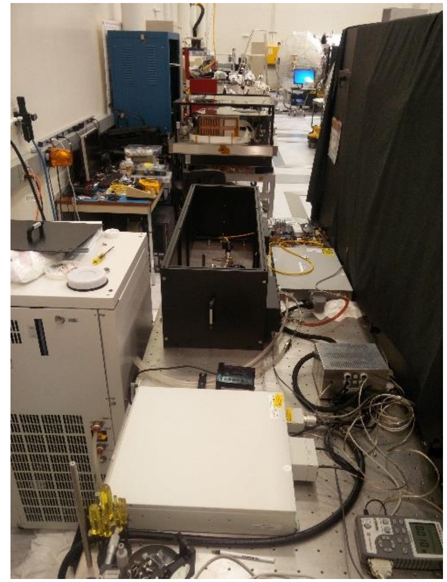
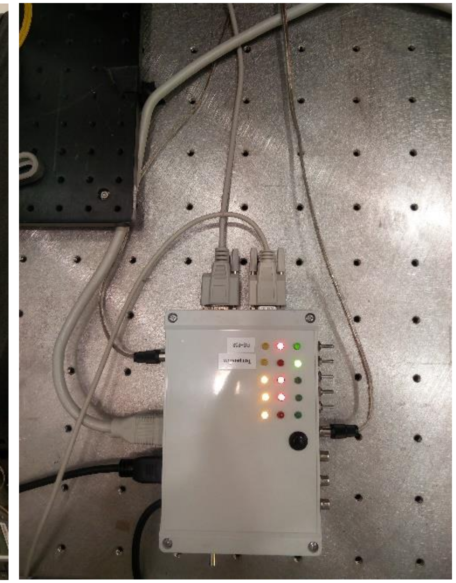
This technique enables new nav observable: OD and attitude of an Earth orbiter

Current Status

- Full power test of laser amplifier (1KW) finished in a lab at JPL
- All components have been delivered and tested for both coherent (Doppler) and incoherent ranging

- Current activities at JPL/TMO:
  - Data acquisition system for both Doppler and range LADAR
  - Safety systems for high-power and relevant approvals.

- Nov 2018: LAGEOS, LARES;
- 2019: cubesats, ACES, ISS, etc.

Amplitude modulation system for @LLR

Conclusion

- Recent technological progress:
  - Resulted in new instruments (COTS) with unique performance;
  - New opportunities for interesting science applications;
  - Many navigation and science applications are possible.
- High-precision Orbit and Attitude Determination from TMO:
  - LEO/GEO spacecraft:
    - Doppler measurements accurate to $<10\ \mu$m/s;
    - ranging measurements accurate to <5 mm;
    - range-Doppler imaging (i.e., astrometry) accurate to sub-nrad/s.
  - A very accurate orbit/attitude reconstruction via novel SLR observables
- Space operations and navigation with corner-reflective tape:
  - Developing new corner-reflective tape (CRT) at Caltech
  - Patches on the ISS to monitor vibrations (i.e., ACES);
  - CubeSat navigation in LEO/GTO/HEO, even to sis-lunar;
  - To monitor any deployment in space.