Advanced Laser Ranging
for high-precision science investigations

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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).
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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 Earth’s 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?
High-precision science investigations

Differenced Lunar Laser Ranging

GRAIL determined lunar gravity field with surface resolution of few kilometers

Properties of deep lunar interior are still uncertain

Revealing Deep Lunar Interior

1738 km

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.
**Measurements 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.

**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.
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)

Incoherent LADAR

- Software (RT)
  - CCD ephemeris (open loop)
  - Close loop (camera)
  - Switching between targets

- Software (analysis)

![Diagram of AdLLR system elements](image)
20 GHz seed broadening (Noise source + EOM)

Fiber amplifier

Chilled water cooler

Power supply

SS switch

Control electronics
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Photon Flux SNR Budget for AdLLR at TMO

### Laser budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xmit lambda</td>
<td>1.06 μm</td>
</tr>
<tr>
<td>Power</td>
<td>1,000 W</td>
</tr>
<tr>
<td>Beam distance</td>
<td>400,000 km</td>
</tr>
<tr>
<td>Spot @moon</td>
<td>4 km</td>
</tr>
<tr>
<td>CC dia</td>
<td>0.038 m</td>
</tr>
<tr>
<td>#cubes</td>
<td>100</td>
</tr>
<tr>
<td>Frac hit cube</td>
<td>9.03E-09</td>
</tr>
</tbody>
</table>

### Background flux

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xmit Moon</td>
<td>-13.6</td>
</tr>
<tr>
<td>Dia</td>
<td>1800 arcsec</td>
</tr>
<tr>
<td>Seeing</td>
<td>2 arcsec</td>
</tr>
<tr>
<td>Frac</td>
<td>1.23E-06</td>
</tr>
<tr>
<td>Tel Area</td>
<td>0.707 m^2</td>
</tr>
<tr>
<td>Full moon</td>
<td>8.33E+15 phot/um</td>
</tr>
<tr>
<td>Optics loss</td>
<td>0.179</td>
</tr>
<tr>
<td>Rec Dia</td>
<td>1 m</td>
</tr>
<tr>
<td>fraction</td>
<td>8.03E-09</td>
</tr>
<tr>
<td>SNR in 1 sec</td>
<td>139.31</td>
</tr>
<tr>
<td>SNR=1 range</td>
<td>0.15 m</td>
</tr>
<tr>
<td>1 sec range</td>
<td>1.077 mm</td>
</tr>
<tr>
<td>1000 sec</td>
<td>0.034 mm</td>
</tr>
</tbody>
</table>

### Flux received

- 3.09E+04 phot/s

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

- **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.
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.
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Advanced LLR: anticipated results

<table>
<thead>
<tr>
<th>Science</th>
<th>Current (cm)</th>
<th>1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Equivalence Principle</td>
<td>$</td>
<td>\Delta a/a</td>
</tr>
<tr>
<td>Strong Equivalence Principle</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>PPN parameter $\beta$</td>
<td>$</td>
<td>\beta - 1</td>
</tr>
<tr>
<td>Time variation of $G$</td>
<td>$5.7 \times 10^{-13}$ yr$^{-1}$</td>
<td>$3 \times 10^{-14}$</td>
</tr>
<tr>
<td>Inverse Square Law</td>
<td>$</td>
<td>\alpha</td>
</tr>
</tbody>
</table>

Tests of GR

Lunar science

<table>
<thead>
<tr>
<th>Effect</th>
<th>Current</th>
<th>Future Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positions on Moon</td>
<td>yes</td>
<td>More locations</td>
</tr>
<tr>
<td>Low-degree gravity field</td>
<td>yes</td>
<td>Distinguish mantle from inner core for gravity and moments</td>
</tr>
<tr>
<td>3 free libration mantle modes</td>
<td>yes</td>
<td>Seek stimulating events</td>
</tr>
<tr>
<td>Solid-body tides</td>
<td>yes</td>
<td>Improve Love number accuracies</td>
</tr>
<tr>
<td>Tidal dissipation</td>
<td>yes</td>
<td>Improve tidal Q vs frequency</td>
</tr>
<tr>
<td>Core/mantle boundary dissipation</td>
<td>yes</td>
<td>Improve uncertainty, used to limit fluid core size</td>
</tr>
<tr>
<td>Core/mantle boundary flattening</td>
<td>yes</td>
<td>Improve uncertainty</td>
</tr>
<tr>
<td>Fluid core moment of inertia</td>
<td>no</td>
<td>Detect and determine</td>
</tr>
<tr>
<td>Fluid core free precession mode</td>
<td>no</td>
<td>Detect mode, determine amplitude &amp; period</td>
</tr>
<tr>
<td>Inner solid core</td>
<td>no</td>
<td>Detect inner core, determine gravity</td>
</tr>
<tr>
<td>3 inner core free libration modes</td>
<td>no</td>
<td>Detect modes, determine amplitudes &amp; periods</td>
</tr>
<tr>
<td>Inner core boundary dissipation</td>
<td>no</td>
<td>Limit inner core size</td>
</tr>
</tbody>
</table>
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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).
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Example: 3M USCGFP-30

3M
USCGFP Reflective Sheeting for U.S. Coast Guard Devices
Series USCGFP

Product Bulletin USCGFP

Description
Approved for use by the United States Coast Guard. 3M™ USCGFP Reflective Sheeting is 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: (sheeting and substrate) 50°F (10°C)

Maximum Application Temperature: (sheeting and substrate) 100°F (38°C)

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<sub>L</sub>) for New Markings (cd/ux/m²)

<table>
<thead>
<tr>
<th>Observation Angle</th>
<th>Entrance Angle</th>
<th>White</th>
<th>Yellow</th>
<th>Red</th>
<th>Orange</th>
<th>Blue</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2°</td>
<td>-4°</td>
<td>360</td>
<td>270</td>
<td>65</td>
<td>145</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>0.2°</td>
<td>30°</td>
<td>170</td>
<td>135</td>
<td>30</td>
<td>68</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td>0.5°</td>
<td>-4°</td>
<td>150</td>
<td>110</td>
<td>27</td>
<td>60</td>
<td>13</td>
<td>21</td>
</tr>
<tr>
<td>0.5°</td>
<td>30°</td>
<td>72</td>
<td>54</td>
<td>13</td>
<td>28</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

*Observation Angle - the angle formed by the light beam striking the reflective surface and the light beam returning to the observer.
*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 (downwall direction perpendicular to the ground, i.e., 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 $\sim 0.5\text{–}1^\circ$, it magnifies the return by 10,000 to 2,500. Taking 2,500/5 $\sim 500$ – the value confirmed by our laboratory measurements.
The coherent AdLLR 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
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PDH Laser Stabilization Set-up

1. CW laser
2. AOM
3. EOM
4. ULE Cavity

Electronics rack (portable to OCTL)

Optics
AdLLR for coherent range and Doppler

### Laser Budget

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

### Target

- **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.

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)

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 \( \mu \text{m/s} \);
    - 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.