Lunar Laser Ranging Project

Douglas Currie

with

Tom Murphy

Stephen Merkowitz

Jan McGerry

Tom Zagwodzki
University of California – San Diego
Professor Tom Murphy
Year 1

• Assess of Theoretical tools, i.e. the status and Capability of PEP and GEODYN

• Refine Science Case for LLR with Sub-Millimeter capability

• Review Transponder Design Architectures
  – From Previous Studies for Mars Laser Ranging & GSFC Laser Transponder
University of California – San Diego
Loss of Signal for Apollo Arrays

• A surprising result of the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) is that the reflector arrays show a clear signature of degradation that is exacerbated at full moon--likely due to enhanced thermal gradients imposed by dust or abrasion. The full-moon signal reduction is roughly a factor of ten, on top of a suspected factor-of-ten reduction at all lunar phases. This discovery comes at a crucial time in the design phase of next-generation corner cubes. Doug Currie (LUNAR Col) is trying to replicate the observation in an attempt to better understand the source of the problem and ultimately a mitigation strategy. A publication is currently under review.
University of California – San Diego

LRO Observations

• The upcoming attempts to obtain two-way ranges to LRO relate to both the degradation issue and the transponder work. The strength of return from a pristine and well-characterized corner cube array compared to an adjacent measurement of the Apollo reflector return (same observing conditions) will be an interesting check on the overall degradation of the Apollo reflectors. The work is related to transponders in that several groups around the world are performing one-way laser ranging to a receiver on board the LRO spacecraft, which provides range information when compared against the on-board clock. This technique is very similar to the asynchronous transponder technique (representing half of it). By comparing the clock-independent two-way ranges from APOLLO, we will validate the one-way technique and assess its precision. This work involves a strengthened interaction between LUNAR teams at UCSD (Murphy) and at GSFC.
Finally, in collaboration with the PEP team at Harvard, we have determined that lunar orientation is the tallest pole in the PEP code at present. Attempts to improve the gravity field model and the model of the interior structure are underway. This effort still seeks funding, and is unable to go as fast as we would like at present.
• Select LLR Model Analysis Software and Begin Using
  – Port Analysis Software to Modern Computer, if Necessary
  – Run Analysis Software on Current LLR Datasets and Verify Operation
• Continue to Refine Science Case
• Select Transponder Design Elements Pertinent to LLR
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The following are slides from a recent lecture by Professor Murphy
Gravity Cries for Help

• General Relativity (GR) and Quantum Mechanics are fundamentally incompatible
  – gravity relatively poorly tested
• New physics of the dark sector could be misunderstanding of large-scale gravity
  – GR used as metric backdrop for cosmic expansion
• Scalar fields introduced by string-inspired and other modifications to GR produce potentially measurable effects
  – violation of the equivalence principle
  – time variation of fund. “constants”
The Full Parameterized Post Newtonian (PPN) Metric

- Generalized metric abandoning many fundamental assumptions
  - GR is a special case
  - Allows violations of conservations, Lorentz invariance, etc.

\[
g_{00} = -1 + 2U - 2\beta U^2 - 2\xi \phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\phi_1 \\
+ 2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\phi_2 + 2(1 + \zeta_3)\phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\phi_4 \\
- (\zeta_1 - 2\xi)A - (\alpha_1 - \alpha_2 - \alpha_3)w^2U - \alpha_2 w^i w^j U_{ij} + (2\alpha_3 - \alpha_1)w^i V_i + \mathcal{O}(\epsilon^3)
\]

\[
g_{0i} = -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)V_i - \frac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i \\
- \frac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} + \mathcal{O}(\epsilon^{5/2})
\]

\[
g_{ij} = (1 + 2\gamma U + \mathcal{O}(\epsilon^2))\delta_{ij}
\]
Simplified (Conservative) PPN Equations of Motion

\[
\ddot{r}_i = \sum_{j \neq i} \frac{\mu_j (r_j - r_i)}{r_{ij}^3} \left\{ 1 - \frac{2(\beta + \gamma)}{c^2} \sum_{k \neq i} \frac{\mu_k}{r_{ik}} ight. \\
- \frac{2\beta - 1}{c^2} \sum_{k \neq j} \frac{\mu_k}{r_{jk}} + \gamma \left( \frac{v_i}{c} \right)^2 + (1 + \gamma) \left( \frac{v_j}{c} \right)^2 \\
- \frac{2(1 + \gamma)}{c^2} \dot{r}_i \cdot \dot{r}_j - \frac{3}{2c^2} \left[ \frac{(r_i - r_j) \cdot \dot{r}_j}{r_{ij}} \right]^2 \\
+ \frac{1}{2c^2} (r_j - r_i) \cdot \ddot{r}_j \right\} + \frac{1}{c^2} \sum_{j \neq i} \frac{\mu_j}{r_{ij}^3} \\
\times \left\{ (2 + 2\gamma) \dot{r}_i - (1 + 2\gamma) \dot{r}_j \right\} (\ddot{r}_i - \ddot{r}_j) \\
+ \frac{3 + 4\gamma}{2c^2} \sum_{j \neq i} \frac{\mu_j \ddot{r}_j}{r_{ij}}
\]
Relativistic Observables in the Lunar Range

- Lunar Laser Ranging provides a comprehensive probe of gravity, currently boasting the best tests of:
  - Equivalence Principle (mainly strong version, but check on weak)
    - $\Delta a/a \approx 10^{-13}$; SEP to $4 \times 10^{-4}$
  - time-rate-of-change of $G$
    - fractional change $< 10^{-12}$ per year
  - geodetic precession
    - to $\approx 0.5$
  - $1/r^2$ force law
    - to $10^{-10}$ times the strength of gravity at $10^8$ m scales
  - gravitomagnetism (origin of frame-dragging)
    - to 0.1% (from motions of point masses—not systemic rotation)
- APOLLO effort will improve by $10 \times$; access new physics
Equivalence Principle Signal

- If the Equivalence Principle (EP) is *violated*:
  - In effect, gravitational mass and inertial mass are not equal
  - Earth and Moon would fall at different rates toward the sun
  - Would appear as a *polarization* of the lunar orbit
  - Range signal has form of \( \cos D \) (\( D \) is lunar phase angle: \( 0^\circ = \text{new}; 180^\circ = \text{full} \))
- If, for example, Earth has greater inertial mass than gravitational mass (while the moon does not):
  - Earth is sluggish to move
  - Alternatively, pulled weakly by gravity
  - Takes orbit of larger radius (than does Moon)
  - Appears that Moon’s orbit is *shifted* toward sun: \( \cos D \) signal
EP Signal, Illustrated

What could be found in the orbits

If the equivalence principle is true, the sun's gravity pulls equally on the Earth and the moon. Therefore Earth's orbit and the moon's average orbit follow the same path.

The moon orbits the Earth, but it also orbits the sun, giving its actual path this wavy shape.

This would disprove the equivalence principle, and scientists would have to go back to the drawing board.

Graphic excerpt from San Diego Union Tribune
Relativistic Observables

- **Weak EP**
  - Composition difference: e.g., iron in earth vs. silicates in moon
  - Probes all interactions but gravity itself
    - Currently tested by LLR to $\Delta a/a < 10^{-13}$
    - Comparable to best lab tests by Eöt-Wash group

- **Strong EP**
  - Applies to gravitational “energy” itself
    - Earth self-energy has equivalent mass ($E = mc^2$)
    - Amounts to $4.6 \times 10^{-10}$ of earth’s total mass-energy
    - Does this mass have $M_G/M_I = 1.00000$?
  - Another way to look at it: gravity pulls on gravity
    - This gets at *nonlinear* aspect of gravity (PPN $\beta$)
  - LLR provides the best way to test the SEP
    - pulsar timing is closest competitor
The Strong Equivalence Principle

- Earth’s energy of assembly amounts to \(4.6 \times 10^{-10}\) of its total mass-energy

\[
M_{S.E.} = \frac{G}{c^2} \int \int \frac{\rho(r_1)\rho(r_2)}{|r_1 - r_2|} d^3r_1 d^3r_2 \approx \frac{GM^2}{Rc^2}
\]

The ratio of gravitational to inertial mass for this self energy is

\[
\frac{M_G}{M_I} = 1 - (4\beta - 3 - \gamma) \frac{M_{S.E.}}{M} \equiv 1 - \eta \frac{M_{S.E.}}{M}
\]

The resulting range signal is then

\[
\Delta r = 13.1\eta \cos D \text{ meters}
\]

Currently \(\eta\) is limited by LLR to be \(\leq 4.5 \times 10^{-4}\)
Relativistic Observables, continued

• Time-rate-of-change of Newton’s $G$
  – If $G$ changes with time, Kepler’s law is broken
  – Range signal (semi-major axis) and period (phase) no longer run in lock-step
  – The *rate* of phase slippage grows linearly in time
  – The phase offset grows *quadratically* in time
  – LLR sensitivity now limits change to $\leq 10^{-12}$/yr variation
  – Less than 1% change over age of Universe

• Best test of $1/r^2$ force law at any length scale

• Geodetic precession currently tested to 0.6%
  – Precession of inertial frame in curved spacetime of sun

• Gravitomagnetism (frame-dragging) is also seen to be true to 0.1% precision via current lunar ranging
  – Same as “frame-dragging” effect sought by GPB (to $\sim$5% ?)
New Motivation for chasing G-dot

- Recent paper by Steinhardt & Wesley points out that dark energy constraints on $w$ (eqn. of state parameter) and G-dot can rule out a broad class of theories invoking extra spatial dimensions
  - basically: changing scale of extra dimensions as universe expands changes $w$ and $G$
- Modest improvements in both can have a big impact
Gravitomagnetism

• A moving mass produces a gravitomagnetic field, which then couples to other masses through a Lorentz-like force
  \[ F = m v \times B \]

• The gravitomagnetic field is:
  \[ B_j = \frac{2(1 + \gamma + \alpha_1/4)}{c^2} v_j \times g_{ij} \]
  - where \( B_j \) is the field from particle \( j \) moving at velocity \( v_j \) as seen by particle \( i \), which experiences gravito-electric acceleration to particle \( j \) of \( g_{ij} \)

• Like any magnetic field, gravitomagnetism carries with it a strong frame dependence
  - as in electromagnetism, the magnetic field can be seen as a necessary complement to the electric field to satisfy frame invariance
  - one might go so far to say that this is all gravitomagnetism really is: a piece of physics whose role in the equations of motion is to satisfy frame invariance of the gravitational interaction
Impact on Lunar Orbit

• The earth moving in the Solar System Barycenter (SSB) frame produces a gravitomagnetic field through which the moon moves
  – resulting in deflections of the lunar orbit
  – this field could be killed by shifting to the geocenter frame, but this is a poor choice of frame for analysis (not asymptotically flat)
    • then other velocity terms in the EOM would then be involved range measurements
• But magnetic fields from arbitrary mass currents cannot be transformed away by a frame change
  – a rotating collecJon of "charges" is a simple example
  – the inability to "kill" the resulting magnetic fields does not make these magnetic fields any more "real" than transformable varieties
  – the single particle case is the trivial case in that one can "kill" its gravitomagnetic field, but this does not mean that the gravitomagnetic field from a single particle represents different physics from gravitomagnetic fields arising from more complex mass currents
    • no such thing as “intrinsic” vs. gauge-dependent gravitomagnetism

WARNING: NOT ROTATION
WARNING: NOT LENSE-THIRRING
WARNING: NOT GEODETIC PRECESSION
Gravitomagnetic Effect

• The gravitomagnetic Lorentz acceleration term in the equation of motion looks like:

\[
a_i = -\frac{\mu_j (2 + 2\gamma)}{c^2 r_{ij}^3} v_i \times (v_j \times r_{ij})
\]

• If earth has velocity \( V \), and moon is \( V + u \), two terms of consequence emerge:
  – One proportional to \( V^2 \) with 6.5 meter \( \cos 2D \) signal
  – One proportional to \( Vu \) with 6.1 meter \( \cos D \) signal

• LLR determines \( \cos D \) to 4 mm precision and \( \cos 2D \) to < 8 mm
  – Constitutes a \( \approx 0.1\% \) confirmation of effect

• The same exact \( v \times v \times g \) term can be used to derive the precession of a gyroscope in the presence of a rotating mass current
  – Recovers the full effect sought by GP-B: this is not different physics
The GP-B Connection

- Starting with the same $\mathbf{v}_i \times (\mathbf{v}_j \times g_{ij})$ term, one can integrate the acceleration on each mass element in a gyroscope (particle $i$) due to each mass element in the rotating earth (particle $j$) across the volumes of both bodies.

- The net result is a torque on the gyroscope, leading to precession.
- Evaluating for GP-B orbit gives 42 mas/yr precession.
- Same physics also produces precession of LAGEOS/LARES orbits.
But isn’t this just transformation fluff?

• Since LLR is “performed” in the geocenter frame, where the gravitomagnetic field of the moving earth is nulled, can LLR really measure this physics?

• Actual process:
  – measure proper times in earth frame of photon transmit and receive
  – transform these to SSB times using $dt/d\tau = 1 + \frac{1}{2}v^2 - \Delta\phi$
  – perform least-squares fit of data to equation of motion

• In other words, we don’t apply phenomenological distortions to the orbit in moving to the SSB and then “magically” find we need them to fit our data (this would indeed be vacuous)
  – it is far more subtle: the simple time transformation is the only action
  – there are small cos$D$ effects in the $v^2$ term, but at the few-mm level

• LLR needs the physics of gravitomagnetism to work correctly
  – if another experiment found an anomaly in gravitomagnetism at the 0.1% level, LLR would stand in conflict and require resolution
  – a conflict would indicate we don’t even understand time transformation sufficiently
Gravitomagnetism “done” to < 1%

To summarize:

• The root physics that results in “frame dragging” also impacts the lunar orbit
  – see Murphy, Nordtvedt, & Turyshhev, 2007, PRL 98, 071102 (calculation)
• LLR Modeling efforts confirm no freedom to “wiggle” strength of gravitomagnetism more than ≈0.2%
  – see Soffel et al. 2008; PRD 78, 024033 (covariant analysis)
• If another experiment claims even 1% deviation of gravitomagnetic effects from GR prediction, LLR stands in conflict; we’ve got a real problem
  – e.g., we don’t understand time transformation
  – see Murphy 2009; Space Sci Rev, 148, 217 (context)
Previously
200 meters

LLR through the decades

![Graph showing the trend of LLR over the decades. The x-axis represents the years from 1970 to 2010, and the y-axis represents the range precision in millimeters. The graph includes two lines: one for modeled post-fit residuals and another for APOLLO median uncertainty.]
Summary & Next Steps

- **APOLLO** is a millimeter-capable lunar ranging station with unprecedented performance
- Given the order-of-magnitude gains in range precision, we expect order-of-magnitude gains in a variety of tests of fundamental gravity
- Our steady-state campaign is now > 3 years old
  - began October 2006, one year after first light
- Now grappling with analysis in the face of vastly better data
  - much new stuff to learn, with concomitant refinements to data reduction and to the analytical model
  - plans to develop open source LLR/planetary analysis code
- Modest improvements in gravity seen already with APOLLO data; more to follow in the upcoming months and years
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S. Merkowitz, J. McGarry, T. Zagwodzki

Year 1

• Refine the Science Case for New Laser Ranging Capability
  – Including Planetary, Relativity, and Navigation Applications
• Develop Numerical Simulations and Data Analysis Techniques for Distributed Retroreflector Arrays
• Explore PEP and GEODYN Model Suitability for Analysis of Existing and Future LLR Data
• Complete Testing of 1.5² Hollow Cubes
• Investigate Design Options for Active Ranging Instruments. Perform Basic Architecture Trade Study
• Investigate Lunar Applications of the Existing SLR Network of Ground Stations
  – Using New Lunar Laser Transponders and Retroreflectors
  – Emphasis on Reuse of Existing Infrastructure
  – Examine Issues of Adapting NGSLR Instrumentation for LLR
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Testing of the 1.5” Hollow Corner Cubes

- Setup of the Far Field Diffraction Laboratory for testing cubes.

- Preliminary testing of 1.5” hollow cubes (pyrex & zerdur) and spare LAGEOS cube.

PLX zerdur cube

FFDP of the cube
FFDP image resolution not yet sufficient for cube performance analysis.

- Improvements need to be made to this test setup to provide better resolved images:

  - Reduce air turbulence
  - Increase image magnification
  - Increase number of bits camera software records
  - Add improved air baffling
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Talks, Presentations, Papers and Posters

- “Opportunities for Probing Fundamental Gravity with Solar System Experiments” (Turyshev and Murphy, et. al.)
- “Next Generation Lunar Laser Ranging” (Merkowitz, et al.)
- “Science from the Moon: The NASA/NLSI Lunar University Network for Astrophysics Research (LUNAR)” (Burns, et. al.)
- “The Moon as a Test Body for General Relativity” (Merkowitz et. al).
- “Lunar Science and Lunar Laser Ranging” (Williams et.al)
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Clean Room Facility

• In calendar year 2009 the laser clean room at the 1.2m Telescope Tracking Facility at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt Maryland was converted to support the capture and analysis of cube corner far field diffraction patterns (FFDP). This laboratory with remote access to the telescope Coude” room originally housed high power short pulse lasers for satellite laser ranging (SLR) operations. Although the laboratory is not operated as an ultra clean facility its HEPA filters with laminar airflow and positive pressure help keep optical surfaces dust free. FFDP instrumentation including laser, collimator, test cube, reference flat, and readout device is mounted on a 2” by 5” NRC optical breadboard.
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Year 2

• Much of work originally scheduled for Year 1 has been moved into Year 2.
• Refine the Science Case for New Laser Ranging Capability
  – Including Planetary, Relativity, & Navigation Applications
• Continue Development of Numerical Simulations & Data Analysis Techniques for Distributed RR Arrays.
• Begin Development of Analysis Tools for Existing and Future LLR Data
• Development of Numerical Simulations & Data Analysis Techniques for Distributed RR Arrays.
• Complete setup of lab for testing 1.5” cubes and complete testing.
  – Add capability to lab for testing larger LLR cubes.
• Investigation of Lunar Applications of the Existing SLR Network of Ground Stations:
  – Emphasis on Reuse of Existing Infrastructure
  – Examine Issues of Adapting NGSLR Instrumentation for LLR.
• Begin design of Large Hollow Cube.
  – Size to be determined from simulations and ground network capability (items “b” and “i”).
• Develop Mechanical and Thermal Design of Hollow Cube Support Structure
• Complete Trade Study between Solid and Hollow Cubes
• Study Dust Mitigation Techniques
• Investigate Design Options Associated with Active Ranging Instruments, Including
UMCP Work Plan for of LLRRA-21
Professor Douglas Currie
Year 1

• Evaluation of Multiple Shields to Control Pocket Radiation
  – Simulation, SCF Thermal Vacuum Testing & Comparison of Modeling vs. Test Results

• Definition of Velocity Aberration Correction
  – Simulate Effects of Single Face and Two Face Angle Offsets and Select Optimal Configuration

• Mitigation of Lunar Day/Night Thermal Variation on Optical Performance
  – Simulation and Optimization of Using Figuring of Front Face of CCR
  – Effect of Tolerancing Combined Simulation with Velocity Aberration Correction

• Further Computer Simulation - esp. of SCF Tests
  – i) Detailed Simulation of Thermal Vacuum Chamber Tests
    • Warm and Hot Front Entrance Window with Control off Window Temperature
    • Effect of Relatively Warm (LN2) Chamber Walls w.r.t. Cold Space
    • Results of Absorption of Simulator Lens and Front Window
    • Impact on Comparison of Simulation and Testing

• Define Drilling Requirements and
• Contact Heat Probe Experiment Groups to Define Common Procedures
University of Maryland
Talks, Presentations, Papers and Posters

• **NLSI Lunar Science Forum 2009, July 21–23, 2009, at the NASA Ames Research Center**
  – A Lunar Laser Retroreflector Array for the 21st Century”, D. G. Currie

• **Advanced Maui Optical and Space Surveillance Technologies Conf., 14-17 September 2009**

• **60th International Astronautics Conference 2009 International Astronautical Federation, 12 October 2009**

• **41st Lunar and Planetary Science Conference, Lunar and Planetary Institute, 1-5 March 2010**

• The current degree of success of this project is the result of the support of many individuals and organizations, in particular:
  
• **LSSO Team**
  
• This was the initial group that addressed the LLRRA-21 concept with Professor Currie. This collaborative research effort was supported by the Lunar Science Sortie Opportunities program at NASA headquarters.

• **MoonLight Team**

• This was the initial group that addressed the LLRRA-21 concept with Professor Currie. The collaborative research effort was then supported by the INFN-LNF
University of Maryland, College Park
Lunar Laser Ranging Array for the 21st Century
Nominal Package
University of Maryland
Multiple Thermal Shields

- **Evaluation of Multiple Shields to Control Pocket Radiation**
  - *Simulation, SCF Thermal Vacuum Testing and Comparison of Modeling vs. Test Results*

- The following slide illustrates the complete model used in these simulations. The model addresses an extended region of regolith that extends beyond the thermal blanket and down to 3 meters, to cover the 1 meter support rod.

- In order to simulate the overall performance of the LLRRA-21, the thermal properties of the lunar regolith, the housing of the CCR and the CCR have been modeled. This has been done using data on the regolith from the Apollo missions and the properties of the elements of the housing and the fused silica of the CCR. These parameters have been incorporated into Thermal Desktop, a thermal modeling program created by C&R Technologies.

- The most important figure of merit in the current simulations is the temperature difference between the tip of the CCR and the front face of the CCR. The following slide illustrates the results of modeling the regolith, housing and CCR for one instant in the simulation of the thermal behavior through a lunar cycle (after running the model for 1,000 lunations to reach equilibrium).

- The following slide also illustrates the temperature distribution in the CCR for one instant. Finally, it illustrates the tip to face temperature distribution during a lunar cycle. This distribution is satisfactory for maintaining the quality of the return laser beam and providing a proper signal strength for the lunar laser ranging. This provides a return that is about 50% of the return from the Apollo 11 array.s.

- **Results of Simulation – Display at a typical point in the lunar cycle**
  - 0 Shields – 0.30 K
  - 1 Shields – 0.10 K
  - 2 Shields – 0.06 K
FULL Thermal Simulation

Regolith from Apollo HFE, Thermal Blanket, Current Design Housing

Temperature Distribution in CCR and Tip to Face Temperature Difference

1st Lunar Laser Ranging Workshop
February 2010
Velocity Aberration Mitigation

• **Definition of Velocity Aberration Correction**

  – *Simulate Effects of Single Face and 2 Face Angle Offsets and Select Optimal Configuration*

• Due to the velocity aberration, the optimal return occurs when one or more of the angles between the back faces of the CCR have a value different than the nominal 90 degrees. In order to investigate this effect and determine the optimal angle, we simulate the return (or more technically, the “radar cross-section”) of the retroreflector for various “offset” angles. In the table below, we see the variety of offset angles that are simulated. On the right, we see the relative return (as a percentage of the ideal return to be expected from the Apollo 11 array). One sees that the angular combinations in bold type give the highest returns. The “top” and “bottom” refer to the orientation of the CCR with respect to the relative velocity between the CCR and the ground station. Thus for 0, -0.2 and -0.2, we have excellent return, each proposed 100 mm CCR provides ~60% of the return of the Apollo 11 array.
# Velocity Aberration Mitigation

**% of Peak Intensity of A11**

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<th>E</th>
<th>W</th>
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<td>-0.2</td>
<td>53</td>
<td>55</td>
</tr>
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</table>

**MoonLIGHT CCR Intensity on the central vertical line (0 -0.2 -0.2)**

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1st Lunar Laser Ranging Workshop
February 2010
Mitigation of Effect of Lunar Day/Night Thermal Variation on Optical Performance

- Simulation and Optimization of Figuring the Front Face of CCR

  The effects of figuring the front face of the CCR have been investigated by a simulation using Code 5. In particular, the Far Field Diffraction Patterns (FFDP) for a spherical curvature of the front face have been explored for a range of spherical curvatures.

  In particular, the magnitude of the wave front curvature is defined by the difference in phase between the phase at the center and the phase at the edge.

  These values range from plus one wavelength to minus one wavelength. The primary effect of this simulated figuring is to produce a spherical wave front which in turn produces a focusing of the return beam. This is the same optical distortion as the first order effect of the thermal distortion caused by the absorption of the solar radiation within the CCR. Thus this figuring will be used to optimize the signal return between the day and night.

- Effect of Tolerancing Combined Simulation with Velocity Aberration Correction

  This item has not yet been address within the first year. It was felt that certain other items (addressed below) were more important to understand at this time. These items were:

  - Evaluation of multiple IR shields to control pocket radiation. We have purchased the IR shields and will test them in April 2010. Therefore, we needed to develop the simulations to define the parameters of the thermal vacuum test. These simulations will also be used to compare to the results of the test.

  - Create and Implement a Plan for Test Concepts for Drilling into Regolith with a simulated housing of the CCR. This was an items in the SoW for year 2. Initial tests have been performed at the laboratory of Honeywell and at the NASA/CSA/DRL 2010 Mauna Kea Lunar Analog Test Program.

  - Address the mitigation of the dust on the CCR due to electrostatically lifted dust.
SIGNAL STRENGTH

• 252/243% Return Compared to than Current Apollo 11 signal level
• 84/ 81% Return Compared to than Current Apollo 15 signal level
• 292/259 Million Square Meters in Cross Section – Still TBO
• If Apollo Signal Degradation is due to Dust from LEM Launch –
  – LLRRA-21 will use a Dust Cover during Landing
• If Apollo Signal Degradation is due to Continual Dust Levitation
  – Good Signal Level for at Least a Decade
  – But This is also Conservative due to the Expected Deployment of
    • Sun Shade
    • Dust Mitigator
• APOLLO gets thousands of returns in 5 minutes on Apollo 15
  – Almost Every Night
  – On a 3.6 meter therefore smaller telescopes can work
  – On the basis of 1,000 returns on 3.6 meter,
    • 69 Single Photo-electrons per Normal Point on a 1.0 meter Telescope
    • 25 Single Photo-electrons per Normal Point on a 0.6 meter Telescope
  – During My Early McDonald Days, Ranging to Apollo 11
    • I would shut down after the successful reception of 3 – 5 returns
University of Maryland

Computer Simulation - esp. of SCF Tests

• Further Computer Simulation - esp. of SCF Tests

• Detailed Simulation of Thermal Vacuum Chamber Tests

• The “ideal” configuration of the thermal vacuum test in the SCF at INFN-LNF in Frascati, Italy that was conducted during April 2009 has been simulated using Thermal Desktop. This simulation addresses the expected performance of the CCR in the presence of the LN2 walls of the chamber, the warm entrance window for the solar simulator and the limited accuracy of the solar simulation.

  • Warm and Hot Front Entrance Window with Control of Window Temperature

  To address issues of the front entrance window, the window has been equipped with thermocouples to determine the temperature of the window and a coil for circulating water to control the temperature. Thus one can keep the window at a known fixed temperature.

  • Effect of Relatively Warm (LN2) Chamber Walls w.r.t. Cold Space

    This effect has been addressed and is negligible for our current series of tests.

• Results of Absorption of Simulator Lens and Front Window

  The window on the solar simulator and the optics of the solar simulator absorbs most of the infrared radiation. Although the former is fabricated of a variety of fused silica that transmits extended infrared radiation, it still cuts off before the solar radiation becomes negligible. Thus the accuracy of the solar simulation is not as good as we might wish. On the other hand, the infrared radiation is absorbed on the front surface of the CCR and does not penetrate to the interior of the CCR. This heat is radiated out to space and thus does not, to first order, contribute to the temperature gradient in the CCR and thus to the optical distortion.

• Impact on Comparison of Simulation and Testing

  Due to technical difficulties, the April 2009 test was not conducted in a manner to achieve an equilibrium thermal state in a manner that matched an achievable simulation. Thus only a rough comparison has been made between the simulation and the test observations. It is expected that the March 2010 tests will allow a better comparison.
SOLAR ABSORPTION ANALYSIS

Component Temperatures

Tip to Face Temperature Difference

- FACE
- TIP
- MID TAB
- EDGE TAB
- HOUSING
FULL Thermal Simulation

Regolith from Apollo HFE, Thermal Blanket, Current Design Housing

Temperature Distribution in CCR and Tip to Face Temperature Difference

1st Lunar Laser Ranging Workshop 16 February 2010
Define Drilling Requirements

• *e) Define Drilling Requirements*

• In order to address the drilling requirements, the regolith has been simulated and the effect of the thermal blanket on the temperatures of the regolith below the CCR and around the support rod has been simulated in Thermal Desktop. Using this, the temperature changes of the INVAR support rod have been computed and the resultant vertical motion of the CCR during a lunation has been determined. When combined with the design of a compensation procedure within the CCR housing, the resultant motion of the CCR through a lunation is about ten microns. This is based upon a meter drill depth.
Evaluation of Multiple IR shields to Control Pocket Radiation

With the proper design of the housing, one of the main contributors to the thermal gradients that distorts the optical performance of the CCR is the volumetric absorption of the solar radiation within the CCR. This radiation than transfers thermal energy between the CCR and the thermal shields that protect the CCR. In this section, we address the advantages of the thermal shields. Such an evaluation must include:

– CCR Volumetric absorption
– Conductive heat flow from the mechanical interfaces (KEL-F rings)
– IR Radiation from the housing/IR shields

Experience from the Apollo era demonstrated that to maximize performances of reflectors, the heat flow from the hardware must be limited as much as possible because, in principle, at steady state it must be radiated toward space from CCR entrance face, generating an axial thermal gradient.

For the above reason the design of the LLRRA-21 experiment at this stage allows the mounting of up to two IR shields, to prevent the infrared radiation from the sun and the regolith to pass between the CCR and the pocket, that is, the thermal shields lining the pocket.

Figure UMCP 5

To evaluate effectiveness of using more than one shield a simple model has been prepared. In the model the CCR is made with a cone and the infrared radiation on the CCR has been “simulated” by directly applying a heat load on one half of the external housing. This is to check for some radial induced thermal gradient in the set up that would occur during sunrise or sunset. This is the time when the nominal sun radiation on the housing is maximum. No volumetric absorption load is considered in this model. Results are shown in the following tables, where the case of having no infrared shield has been added to check the performance of the model.
Plan for Drilling and Deploying CCR

- **Create Plan for Test Concepts for Drilling into Regolith and Deploying CCR and Housing**

- The above is one of the tasks for the second year is to address the drilling problem with tests.

- We have had the opportunity to address this task during the first year. If the CCR were placed directly on the lunar regolith, as was the case of the Apollo arrays, there would be a very significant error in the range due to the heating and cooling of the regolith during a lunation. This causes a mechanical expansion and contraction of the regolith. In order to remove this source of ranging error one must provide a mechanical anchor to the layer of the regolith which has no significant temperature variation through a lunation or through a year. This requires drilling to 0.7 to 1.0 meters and anchoring the support rod at this depth. Although similar drilling was accomplished during the Apollo landings, this was not an easy task. However, the discovery of a new drilling technology makes it appear feasible not only to effectively deploy the LLRRA-21 during a manned landing but also to deploy it from a lander or on a rover mission. On the initial review, the technology of pneumatic drilling appears to be feasible for the deployment. In order to address this further, a test was conducted at the Honeybee laboratories in a compacted lunar stimulant and a CCR housing. This test was entirely successful. Based upon these results, tests were scheduled for the NASA/CSA/DLR 2010 Mauna Kea Lunar Analog Tests in Hawaii, conducted the first week in February 2010. These tests consisted of using the CCR support rod as the pneumatic drilling mechanism with the CCR housing and the CCR mounted in the appropriate configuration. These tests again were entirely successful. Without the gas flowing, an average force of 80 pounds with peaks as large as 100 pounds were required to force the support rod to a depth of one meter. With the gas flowing, the weight of the CCR and housing was enough to cause the support rod to descend into the dry volcanic regolith with no addition force. Thus the use of pneumatic drilling, at the current stage, appears to provide a quite feasible procedure for the deployment of the LLRRA-21.

- In the next video clip of Jack Schmitt and Gene Cernan illustrates the difficulties during the drilling operations on the Apollo missions

- The next video clip illustrates the operation of the Honeybee pneumatic drilling procedure in a lunar stimulant with a CCR housing mounted on a support rod of the type to be used for the lunar emplacement.
Pneumatic Proboscis System

Components

- Pneumatic System
- Proboscis Housing
- Tape Deployment System
- Control Electronics & Temp Display
- Nozzle
- Bi-Convex Tape
- RTD & Heater Tip
- Heat Flow Sensor

Deployment

1st Lunar Laser Ranging Workshop
February 2010
University of Maryland + Dust Mitigation

- Measurements by the APOLLO ground station in New Mexico strongly suggest that the Apollo arrays have received a layer of dust that reduces the signal by a factor of almost ten.
- This is addressed in more detail in the above discussion by Tom Murphy.
- The analysis of the LLRRA-21 signal strength has also included such a loss so that the signal magnitude will still be appropriate.
- That is, even assuming the deposition of a similar dust layer, the LLRRA-21 signal level will be over half of the signal from Apollo 11 array.
- The latter has provided suitable return for 90-95% of the time that it is targeted by the APOLLO station. However, if we can prevent or reduce the dust accumulation, we may expect a much stronger signal. To this end, we have reviewed some of the current suggestions for the mitigating of dust deposits. All of these require power and/or mechanisms in some form, which means that a lifetime that has been achieved with the Apollo arrays (40 years) cannot be expected.
- To this end, we are investigating a technique that will require neither power nor moving mechanisms. Parts have been ordered and received to build a prototype for a very preliminary test. Initially, this will be tested with a stimulant of the lunar dust. Following these tests, the prototype will be evaluated in a test conducted in collaboration with Professor Larry Taylor of the University of Tennessee using real lunar dust (as opposed to a stimulant).
Mitigation of Signal Loss for Apollo Arrays at Local Noon

- The APOLLO ranging has also detected another anomaly in the magnitude of the return signal for the Apollo arrays.
  - When the sun is directly overhead, the signal is reduced further.
  - This is addressed in more detail in the above discussion by Tom Murphy.
  - As with the dust, if we can mitigate this effect, we would obtain stronger signals so that the lunar ranging could be accomplished by lunar laser ranging stations using a much smaller telescope.
  - To address this, we have accomplished some of the preliminary thermal simulations of the current candidate for the effect. We also expect to conduct thermal vacuum tests that will also address this issue.
UMCP Work Plan for LLRRA-21

Year 2

- Continue Modeling Effort and Thermal Vacuum Testing
  - Focus on Design for:
    - CCR Support,
    - Housing Properties and
    - Gold and Silver Coatings for Thermal Shields

- Define Optimal Velocity Aberration Correction
  - Offset Angles of CCR
  - Thermal Figuring of CCR
  - Compare with Simulations and Thermal Vacuum Testing

- Procure Second CCR with:
  - Optimal Offset Angles and
  - Thermal Figuring

- Create Plan and Tests for:
  - Drilling into Regolith and
  - Emplanting Housing

- Develop Design for Housing Away from Sub-Earth Point

- Develop Coating for Enhancement of Silver Inners Shield Coating
MISSION OPPORTUNITES

&

Acknowledgements

• Possible Roles for 100 mm Solid CCR Array
  – NASA - LSSO
    • First Manned Landing
      – Effort Supported by the LSSO / NASA Program
    • International Lunar Network (ILN) Anchor Nodes
      – Effort Supported by LSSO and LUNAR / NLSI / NASA
  – Lunette - A Discovery Mission Proposal - a backup - 2016
  – Astrobotics – A Google-X Proposal - 2012
  – Italian Space Agency & INFN
    • MAGIA
      – Proposed ASI Lunar Orbiter to Carry a 100 mm Solid CCR
        » Effort Supported by ASI and INFN
    • Italian ILN Retroreflector Instrument
      – MoonLIGHT-ILN INFN Experiment – Just Approved
        » Effort Supported by INFN