The Birth and Future of Lunar Laser Ranging
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Outline

• Overview of Why We Want to do Lunar Laser Ranging
• Pre-History of Professor Bob Dicke’s Group at Princeton
• Preparation for Science on Apollo 11 by NASA
• Preparation and Development of Retroreflector Array for Apollo 11
• Development of Lunar Laser Ranging Observatories
• Science Results from Our LLR Observations
• Current Limitations to the Ranging Accuracy
• Advantages and Design of NGLR formerly LLRRA-21
• Fabrication, Deployments and Flights for NGLR
• Science for NGLR
First Why

Should We Embark Such A Complicated and Risky Journey
History of Cosmology

• Twenty Years Ago
  – We Knew All About the Contents of the Universe

• Vera Rubin
  – Stars do not Rotate “Properly” about the Galactic Center
  – Do Not Know Why, but We Call the Phenomena “Dark Matter”

• Perlmutter, Schmidt & Riess
  – Distant Galaxies Were Moving Away from Us Too Fast
  – Do Not Know Why, But We Call that Phenomena “Dark Energy”

• Something Strange Seems to be Going on With Gravity
• Cannot Fit General Relativity into Quantum Mechanics
General Relativity vs. Quantum Mechanics
Theories of Gravitation

- Newton 1686  Poincaré 1890  Einstein 1912  Nordstrøm 1912  Nordstrøm 1913
- Einstein & Fokker 1914  Einstein 1915  Whitehead 1922  Cartan 1923  Kaluza & Klein 1932
- Some authors proposed more than one theory, e.g. Einstein, Ni, Lee, Nordtvedt, Yilmaz,
- Some theories are just variations of others
- Some theories were proposed in the 1910s/20s; many theories in the 1960s/70s
- Overlooked: this is not a complete list! Essentially, this ends before Dark Matter and Dark Energy

Theory must be:
- Complete: not a law, but a theory. Derive experimental results from first principles
- Self-consistent: get same results no matter which mathematics or models are used
- Relativistic: Non-gravitational laws are those of Special Relativity
- Newtonian: Reduces to Newton’s equation in the limit of low gravity and low velocities
Early Aspects & Motivation

- Historically, the Orbit of the Moon and Its Distance
  - Has Been Studied for Millennia
    - Navigation
    - Eclipse Prediction
    - Tidal Tables
- During the Last Millennium
  - GR Tests have Become an Important Part of Physics
  - Fundamental Incompatibility of QM and GR
- Later, Issues of the Internal Structure of the Moon
  - Again as It Relates to the Lunar Formation Question
  - Hints for the Physics of Planetary Formation
Pre-History Lunar Distance

• Astronomical Determination
  – Early Greek – 270 BC
    • About 386,243 km – 5%
• Radar Ranging
  – 1959 USNO 150 m
• Optical Ranging
  – 1962 - MIT – 1 ms – Few Kilometers
• Lunar Orbiting Space Craft
• Problem:
  – Not Accurate Enough for General Relativity Test
  – Not Accurate Enough to Quantify the Structure of the Lunar Interior
Early General Relativity Tests

• Initial Experimental Predictions by Einstein
  – Precession of the Perihelion of Mercury
  – Bending of Light about Massive Bodies - 1919
  – Gravitational Redshift - 1959

• Loránd Eötvös – Laboratory Experiments
  – Weak Equivalence Principle (WEP)

• Joe Weber at the University of Maryland
  – Conceptualization of Gravity Wave Measurements
  – Early GW Observations with Bar Antennae
Pre-History of Dicke Group

• Professor Robert Dicke of Princeton University
  – Early Interest in Tests of General Relativity
    • Measured the Gravitational Red Shift
    • Investigated the Precession of Mercury
    • Scalar-Tensor – Brans-Dicke – Alternative to General Relativity

• Considered Ranging to the Surface with Spotlight
  – Insufficient Accuracy – Ranging from the Surface
  – Insufficient Signal – Outgoing Beam was too Broad

• In the 1960’s – Two Great Leaps Forward
  – Ted Maiman Invented and Demonstrated the Laser
  – John Kennedy said “We are Going to put a Man on the Moon”

• Finally, Measurements of Sufficient Accuracy
  – Could Finally, In Principle, be Accomplished!!!
Laser Ranging & Retroreflectors

- Illuminate Moon with a Short Coherent, Narrow Laser Pulses
- “Normal” Diffuse Reflection from Lunar Surface
  - Radiation Goes into 2 Pi Steradians
  - Great Loss of Signal
- Need a “Directed” Return Back to the Observatory
- Could Use a Flat Mirror
  - Needs to be Actively Very Precisely Pointed
  - To Only One LLR Observatory at One Time
  - Mechanical/Electrical Components
    - Cannot Last 50 years
- Retroreflector
  - Solid “Cube Corner” of Glass
Preparation for Apollo 11 Science

• ALSEP – Major NASA Science Project for the Manned Landing
  – Starting About Two Years Before Launch
  – Major Suite of Scientific Instruments
  – Defined For All Apollo Missions Through Apollo 16

• Astronauts Began To Practice for Apollo 11 EVA
  – Using the ALSEP 11 Scientific Suite of Experiments
  – Only Short Time on the Surface
  – Not Enough Time to Deploy All Experiments
  – Surface Conditions Unknown
    • Tommy Gold Had Said That We Would Sink 30’ in the Lunar Dust

• NASA Looks for Replacement Suite of Experiments
ALSEP to ELSEP

• NASA Requests Experiments for ELSEP
  – Early Apollo Scientific Experiments Payload
  – Easy to Deploy
  – Light or No Power Requirements
  – Light or No Communication Requirements

• Initial Feasibility Calculations for Lunar Laser Ranging
  – Performed by Bob Dicke’s Group at Princeton
  – Had Been Considering Possibilities for Some Time

• Proposal for Apollo 11 LLR in the ELSEP Submitted to NASA
  – 9 Months before Launch

• NASA Accepted Our Proposal for Retroreflector Arrays for Apollo 11
Proposal and LURE Group

- Robert H. Dicke – Princeton University
  - GR Tests, Microwave Technology, Cosmic Microwave Background Radiation (CMBR)
- Carroll O. Alley – University of Maryland, College Park
  - Principal Investigator, Atomic Physics, General Relativity Tests
- Peter L Bender – JILA - University of Colorado Boulder
  - Detection of Gravity Waves in Space - LISA
- David T. Wilkinson - Physics - Princeton University
  - The Leader in the Cosmic Microwave Background Radiation (CMBR)
- James E. Faller – Physics - Wesleyan University
  - Cube Corner Retroreflectors, Absolute Gravimeters
Proposal and LURE Group

- William M. Kaula - IGPP - University of California, Los Angeles
  - Space-Based Geodesy using Satellite Orbits
- Gordon J. F. MacDonald – MIT, UCLA, UCSB, Dartmouth and UCSD
  - Geophysicist, Environmental Scientist, Continental Drift
- Henry H. Plotkin – GSFC – UMBC
  - Started the Field of Satellite Laser Ranging
- James G. Williams – JPL
  - Expert on Processing Ephemeris Data and Extracting The Science
- J. Derral Mulholland – JPL
  - Lunar Ephemeris
- Douglas G. Currie – Physics – University of Maryland, College Park
  - Lunar Laser Ranging, Hubble Space Telescope, Stellar Interferometry
Science Objectives

• Many Science Objectives
  – Too Many for My Allocated Time

• Galileo’s Apocryphal Experiment
  – Weak Equivalence Principle (WEP)
  – Rate that the Earth and Moon Fall to the Sun

• Structure of the Lunar Interior
  – Crustal Response to Tide
  – Internal Structure from the Crust to Core

• Testing of General Relativity
  – Brans-Dicke Theory
Preparation for Apollo 11

• Carroll Alley at the University of Maryland Takes the Lead
  – We at UMCP were Close to NASA Hdqrs and GSFC
  – Very Short Time for Development, Evaluation, Fabrication and Blessing
• Selected an Array of 38 mm Solid Cube Corner Reflectors
  – To Survive the Solar Heat Load Effects We Chose Uncoated (TIR) CCRs
  – With Ren-Fang Chang, We Made the First Analysis of a CCR Using TIR
• Carroll, Harry Krielmeyer, Jim Faller and Myself
  – Were Called Down to the Cape
  – To Give “Deployment Instructions” to Buzz Aldrin,
  – Of Course, He Had a Book an Inch Thick on How to Do It
Final Proposal to NASA for Apollo 11 Retroreflector Array

Proposal Delivered ~ 9 months Before Launch

Very Short Time for Preparation

Proposal Reviews

Cannot Perform Single Photoelectron Detection
  - We Had Been Doing It for Years So This Was Not an Issue

Cannot Point a Laser to the Required 1 arc-second Accuracy
  - We Had Laser Pointing Experience – Henry Plotkin was Already Laser Ranging to Satellites
  - But Plotkin Used Much Wider Laser Beams
  - To Range to LEO Satellites Which Are Far Closer Than the Moon

Coincidently I Had Been Calculating Whether the Astronauts Could See Our Laser
  - No – Due to Anomalies of the Way the Human Eye Detects Faint Point Pulses of Light
  - But Surveyor 7 Was About to be Launched to the Moon
  - This Would Be a Camera on the Lunar Surface
  - Perhaps It Could See a Laser Transmitted from Earth
Surveyor 7 Experiment

- Surveyor 7 Was to be Launched in Just Few Days
  - This was to be the Last Surveyor
- Revision of My Calculation Indicated Surveyor Could See a Laser
  - Using a CW Argon Laser Instead of the Pulsed Ruby Laser
- COA and I Went to the Surveyor Science Team
  - To Get Permission to Point a Laser at the Surveyor Camera
  - They Were Assembled for Meeting at the Cape for the Launch
  - After Our Presentation, They Oked the Experiment
- Assembled Collaborators to Project the Lasers
  - McMath Telescope at Kitt Peak – Jim Brault
  - Wesleyan University – Jim Faller
  - Table Mountain Observatory of JPL – Mike Shumate
  - Another Group in New England
McMath Telescope Operation

- Surveyor 7 is launched while we are at the Cape
- Jim Brault and I met at Kitt Peak
  - We crawled over the McMath Telescope
  - To determine what hardware would be required
- Flying back to UMCP
  - We built the hardware in 36 hours
  - Shipped the hardware to McMath
  - Installed hardware in the telescope
  - Ready on arrival of Surveyor 7 at the Moon
- McMath personnel for operations
  - Jim Brault – responsible for McMath
  - Sherman Poultney – UMCP
  - Eric Silverberg – UMCP

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• The Surveyor 7 Camera Was Operated from JPL
  – We Pointed the Camera Toward Earth
  – Image of Earth Showing Day and Night Portions
  – Four Stations Pointed Lasers Toward Surveyor
  – Laser Detections of McMath and Table Mountain
  – Eastern Stations Were in Twilight
• Life Magazine Covered with a Nice Article
• Demonstrated that Sufficiently Accurate Pointing
  – Could Be Achieved
  – Useful Definition of Good Approaches for McDonald
Contractors for Apollo 11 Retroreflectors

- Arthur D. Little – Peter Glaser - PDR
  - Analysis of Expected Returns
    - Confirming LURE Analysis for Optical Behavior
  - Thermal Modeling of Signal Return
    - Impact of 250K Temperature Swings Over the Lunar Cycle
  - Preliminary Detailed Hardware Designs

- Perkin Elmer – Paul Forman - Zygo
  - Fabrication of Cube Corner Retroreflector

- Bendix - CDR
  - Responsible for Fabrication of Flight Hardware
  - Responsible for the Interfaces with NASA

- Apollo 11 Movie

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The Preparation of the Lunar Package Is On the Way

But We Need Ground Stations To Perform the Ranging
• **We Need Lunar Laser Ranging Observatories**
  
  – Carroll and I Made Visits to Several Candidate Observatories
  
  • 60-inch Telescope at AMOS on Maui, Hawaii – Scheduling Problems
  
  • 120-inch Telescope at Lick Observatory on Hamilton Mountain, California - Backup
  
  • 107-inch Telescope at McDonald Observatory at Fort Davis, Texas - Primary

• **Developing & Deploying Hardware for LLR Observatory**
  
  – Goddard Space Flight Center Provided the Laser
  
  • Henry Plotkin

  – University of Maryland, College Park
  
  • Carroll Alley, Doug Currie, Sherman Poultney etc.

• **Installation at Observatory and Initial Operation**

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• McDonald Observatory
  – Mt. Locke, Fort Davis Texas
• Regular Operation
  – Configured for the Next Decades
• Other Stations
  – Lick Observatory, Mt. Hamilton, CA – Initial Acquisition
  – Crimea, Soviet Union – Initial
  – French MeO at Côte d'Azur, France – Long Term
  – APOLLO at Apache Point, NM
  – MLRO Station in Matera, Italy
  – Wettzell SLR Station in Bad Koetzting, Germany
Operating Personnel

• University of Maryland
  – Doug Currie
  – Eric Silverberg
  – Sherman Poulteny
  – Charlie Steggerda
  – John Mullendore
  – John Raynor

• University of Texas
  – Brian Warner
  – Wayne van Citters
  – Bernie Bopp
  – Don Wells
  – Mike McCants

• GSFC
  – Windell Williams
  – Robert Gonzales
So Much for Getting LLR Started

Has There Been Anything to Show for All This Effort?
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalence principle parameter ( \eta )</td>
<td>((6 \pm 7) \cdot 10^{-4})</td>
</tr>
<tr>
<td>Metric parameter ( \gamma - 1 )</td>
<td>((4 \pm 5) \cdot 10^{-3})</td>
</tr>
<tr>
<td>Metric parameter ( \beta - 1 ): direct measurement</td>
<td>((-2 \pm 4) \cdot 10^{-3})</td>
</tr>
<tr>
<td>Time-varying gravitational constant ( \dot{G}/G ) (year^-1)</td>
<td>((6 \pm 8) \cdot 10^{-13})</td>
</tr>
<tr>
<td>Differential geodetic precession ( \Omega_{GP} - \Omega_{deSit} ) (per century)</td>
<td>((6 \pm 10) \cdot 10^{-3})</td>
</tr>
<tr>
<td>Yukawa coupling constant ( \alpha ) (for ( \lambda = 4 \cdot 105 \text{ km} ))</td>
<td>((3 \pm 2) \cdot 10^{-11})</td>
</tr>
<tr>
<td>“Preferred-frame” parameter ( \alpha_1 )</td>
<td>((-7 \pm 9) \cdot 10^{-5})</td>
</tr>
<tr>
<td>“Preferred-frame” parameter ( \alpha_2 )</td>
<td>((1.8 \pm 2.5) \cdot 10^{-5})</td>
</tr>
<tr>
<td>Special relativistic parameters ( \zeta_1 - \zeta_0 - 1 )</td>
<td>((-5 \pm 12) \cdot 10^{-5})</td>
</tr>
<tr>
<td>Influence of dark matter ( \delta_{\text{galactic}} ) (cm s^-2)</td>
<td>((4 \pm 4) \cdot 10^{-14})</td>
</tr>
</tbody>
</table>

from Juergen Mueller and Franz Hofmann
• LLR Currently Provides our Best Tests of:
  – The Strong Equivalence Principle (SEP)
  – Time Rate-of-Change of G
  – Inverse Square Law, Deviation of 1/r
  – Gravito-Magnetism
  – Weak Equivalence Principle (WEP)
Science Objectives

• Galileo’s Apocryphal Experiment
  – With the Leaning Tower of Pisa
  – Rate that the Earth and Moon Fall to the Sun

• Structure of the Lunar Interior
  – Crustal Response to Tide
  – Interior Structure from Crust to Core

• Testing of General Relativity
  – Brans-Dicke Theory

• Earth Science
  – Continental Drift
  – Length of the Day
Improvements in WEP Measurements

- Experimental Verification of the WEP
  - Eötvös/Dicke Measurements
  - Compared the Acceleration of Different Materials
  - All Laboratory Experiments

- Lunar Laser Ranging Measurements
  - Massive Astronomical Bodies – Earth and Moon

- LLR Measures Inertial Properties
  - Of Gravitational Energy
  - Unique
Why Deploy New Retroreflectors?
LIBRATION PROBLEM

- Why is There a Problem with the Apollo Arrays
  - Lunar Librations in Tilt Both Axis by 8/10
  - Apollo Arrays are Tilted by the Lunar Librations
  - Corner CCRs can have Different Ranges
    - As large as 200 mm for the Apollo 15 array
Current Status of Our NGLR

- NASA Has Selected the UMCP to Create 3 NGLRs
- To Be Deployed On the Lunar Surface in 2021
  - By Un-Mannered Commercial Carriers
- NGLR Eliminates Libration Problem
- Supports Improved Ranging Accuracy
  - By Up to a Factor of 100 for Each Shot
  - Depends Upon the LLR Observatory Hardware
  - Better Understanding of the Earth’s Atmosphere
Flight by Commercial Carrier

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Future Progress

What is Needed

To Achieve the Greater Accuracy
Improved Ground Stations

• Need Advanced Hardware to Reach 1 mm per Shot
  – And Beyond If We Can Conquer the Atmospheric Wedge Problem

• Ideally a LLR Observatory Might Have
  – 20 ps laser
  – Electronic and Timing System with 10 ps jitter
  – Meteorological and Geophysical Stations for Calibrations
  – Better Local Range Predictions to Set Range Gate
  – Tight Range Gate – To Control of Full Moon and Day Sky Noise

• For Example – At the Wettzell SLR Station
  – Currently ~150 mm Single Shot Offsets at High Libration Angles
  – 10 ps Laser and Appropriate Electronics Implies <1 mm/shot
  – Single Shot Precision Improved by a Factor of ~100 for High Libration Angles
  – Even Better Normal Point Accuracy if the Atmospheric Wedge Angle is Known
Wedges in Atmosphere are the Current Ultimate Limit

- Currently We Measure Pressure, Temperature and Humidity Locally
- Acceptable Spherical Correction if Moon is Directly Overhead
- Never Happens
- At 40 degrees, We Are Sensitive to Changes Over ~7 kilometers
- Errors of a mm or so
  - E. Pavlis and G. Hulley
  - Typical Observations at 40 degrees Due to Latitude of LLR Observatories
- Possible Use Local Met Data to Model the Wedge
  - Various Studies of This Are in Progress
- Possible Direct Instrumental Measurements of Zenith Wedge
  - Two Color Refractometer at UMCP
- Better Knowledge of the Wedge is Even More Important
  - For Low Elevation SLR Observations
• What Explains the “Dark Matter” Observations?
  – Modification of the Gravitational Theory
    • MOND Theories
  – As Yet Unknown Particles

• Internal Lunar Structure
  – Support of Our Proposed Lunar Geophysical Network Program
  – We Have Just Received the Award of a Study Contract

• Further Tests of General Relativity
  – Conflict of Quantum Mechanics and GR
Thank You!

any Questions?
or
Comments?

with
Special Acknowledgements
to
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Italian Space Agency
INFN-LNF, Frascati
LSSO Team
LUNAR Team
&
NGLR Team

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