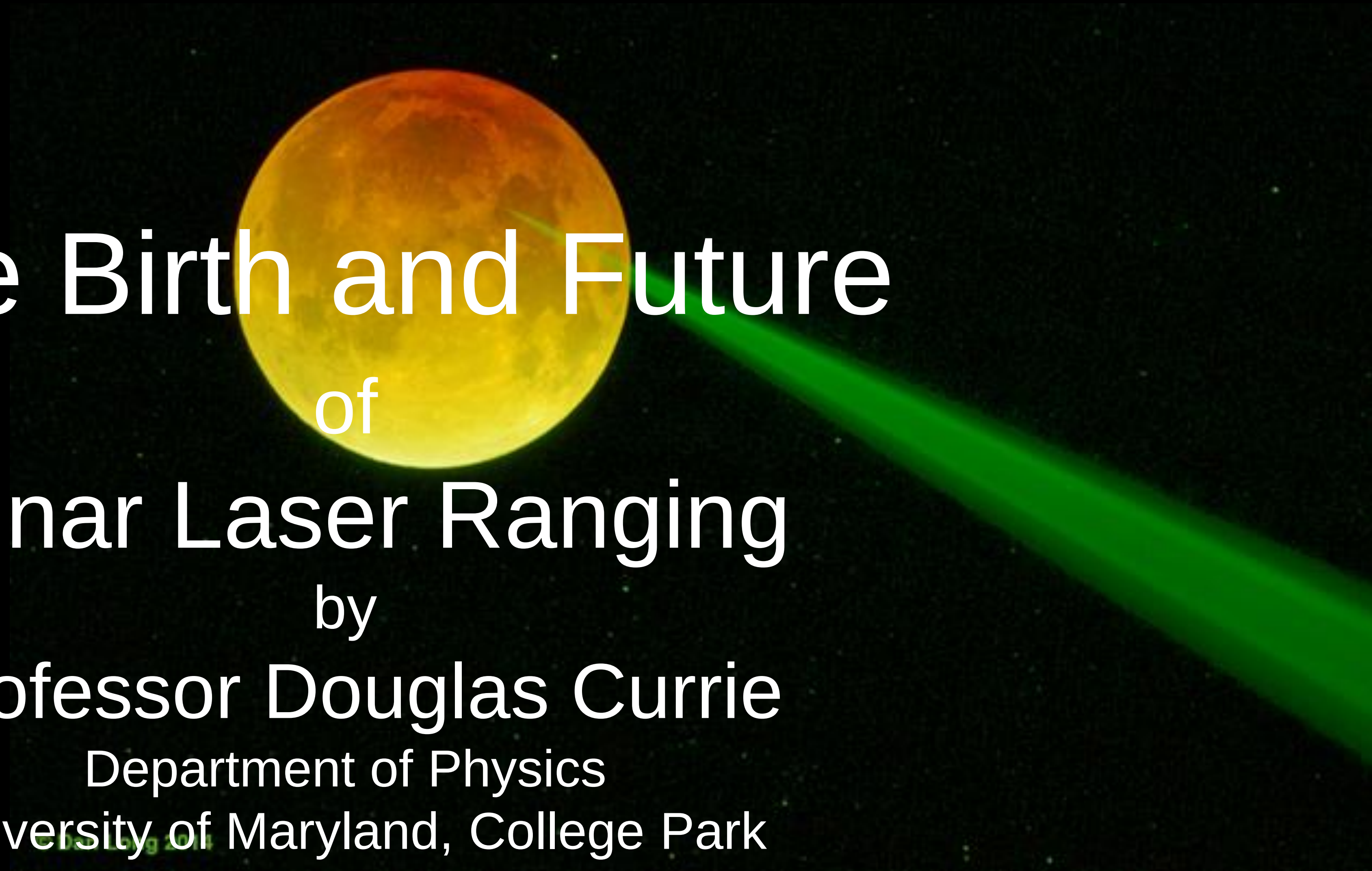
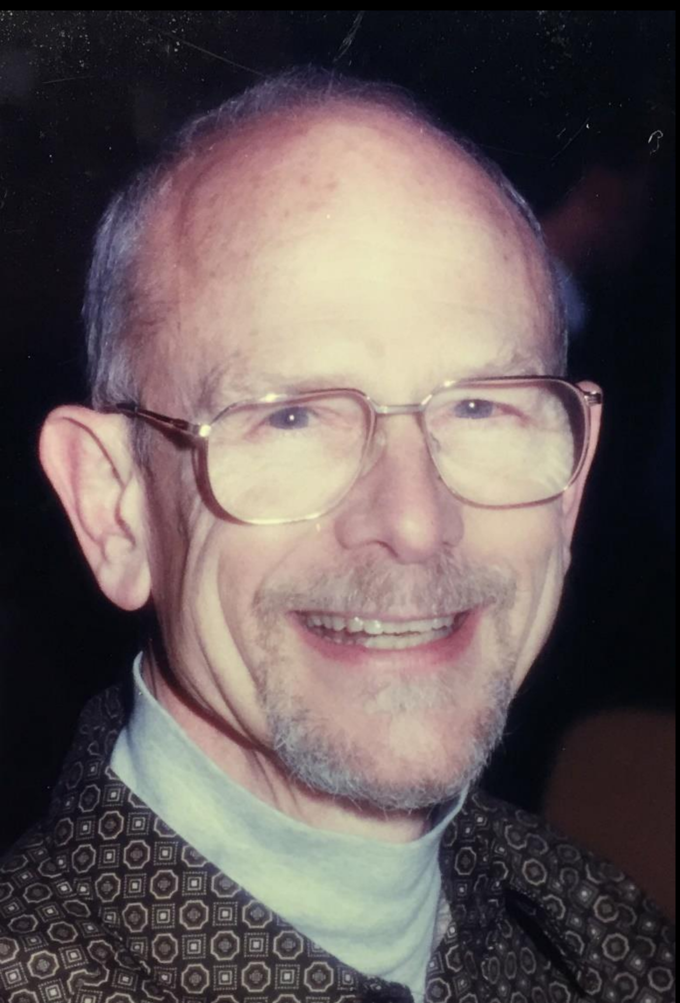


the Birth and Future of Lunar Laser Ranging

by

Professor Douglas Currie
Department of Physics
University of Maryland, College Park
with the NGLR Team
Professor Drew Baden, UMD
Dr. Dennis Wellnitz, UMD
Dr. Giovanni Delle Monache, INFN-LNF
Dr. Bradford Behr, UMD
Dr. Simone Dell'Agnello, INFN-LNF
Dr. Chensheng Wu, UMD
William Kleyman, UMD



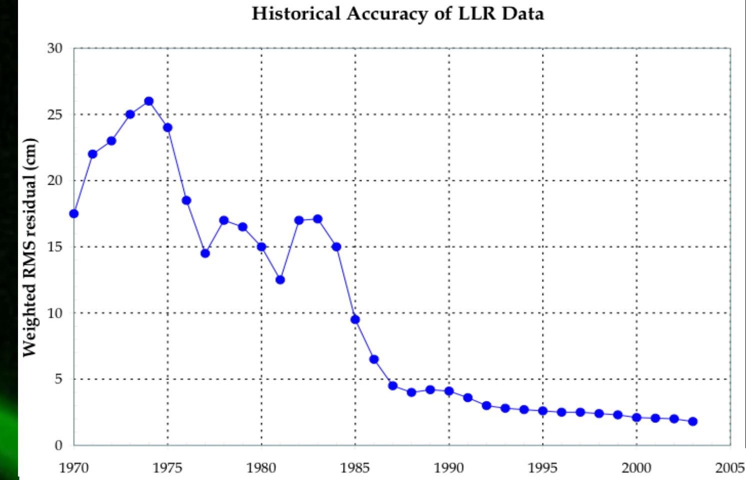
International Workshop on Laser Ranging

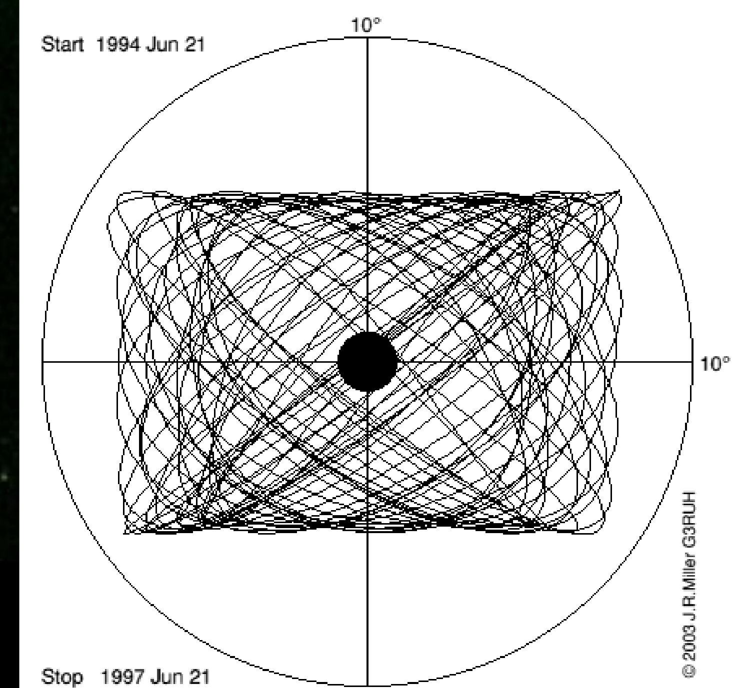
Next Generation Lunar Retroreflector

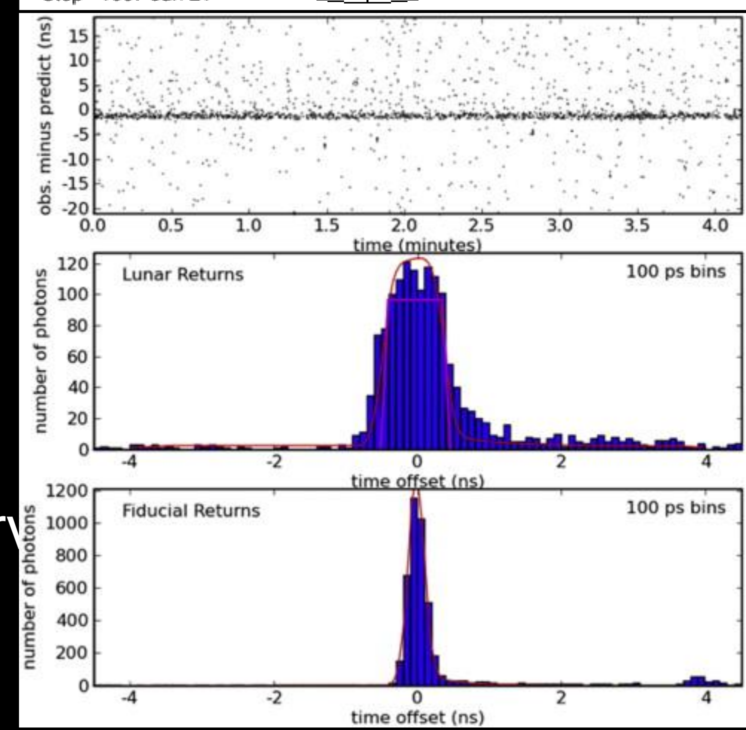
- Our Next Generation Lunar Retroreflector (NGLR)
  - Is a Follow-On, Advancing Our Deployment of a Retroreflector Array During the Apollo 11 Mission
  - With the Current Objective to Achieve Much More Accurate Scientific Results
- Our NGLR Project Was Started in 2004
  - When NASA Announced that It Plans to Return to the Moon
- New LLRO Operational Procedures for Ranging to NGLR-1 will Be Discussed Later
- In Summary, Ranging to Apollo and Lunokhod Retroreflectors
  - Has been Continuous for the Past 53 Years
  - Unique Scientific Results Have Achieved in Many Different Fields
  - LLR Ranging Results have Produced a Much Better Lunar Ephemeris
    - Current Agreement Between Ephemeris and Individual Normal Point
    - As Determined by Jim Williams at JPL
    - Currently at the 8 mm level

Why Need a New Retroreflector

- Accuracy of LLR Lunar Ephemeris Has Stabilized
- Lunar Librations
  - Moon Appears to Rotate Over One Month
- Apollo 11 Retroreflector Array of 100 Small CCRs
  - the Apollo 11 Array is 0.825 × 0.686 meters
  - Tilted by up to 10 Degrees By the Lunar Librations
- the Laser Photons Could be Reflected
  - From Far Corner or Near Corner of the Array
  - ~ 75 mm Spread in Measured Ranges (r.m.s.)
- In 2004, NASA Announced a Return to the Moon
- Our Objective is to Eliminate This Error Source
  - This Is Now Feasible
  - This Will Allow Additional Lunar Laser Retroreflector Observ

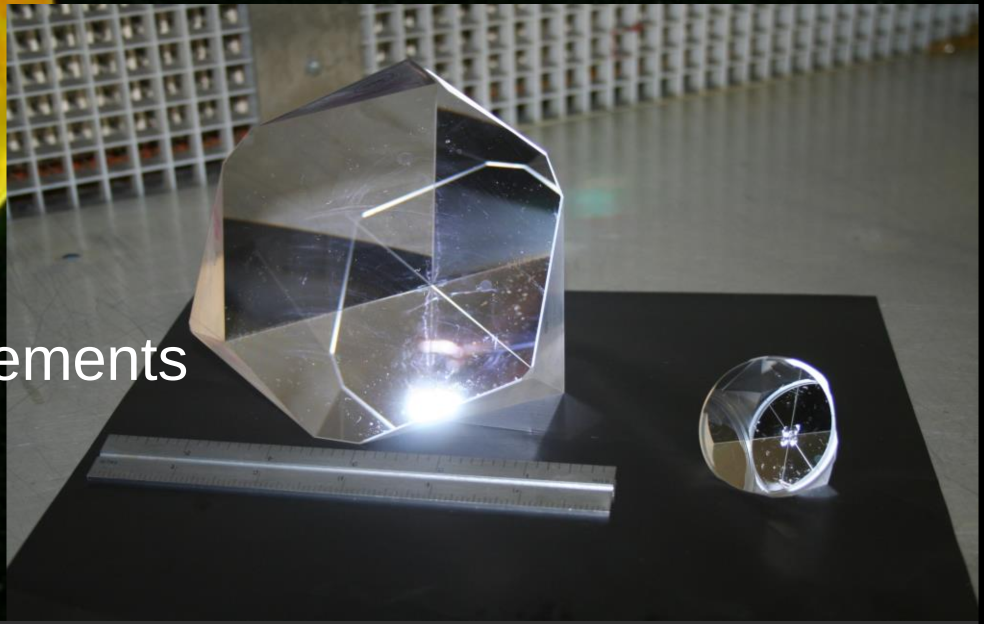


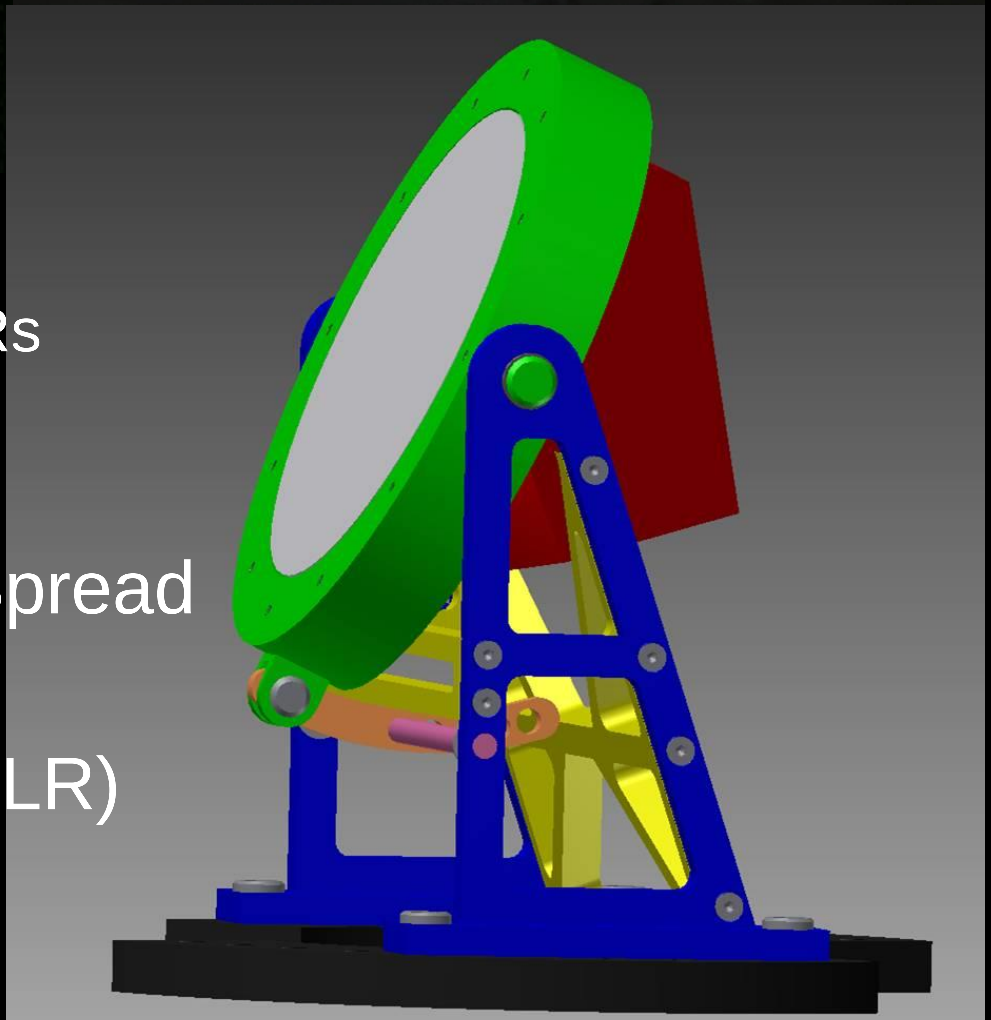




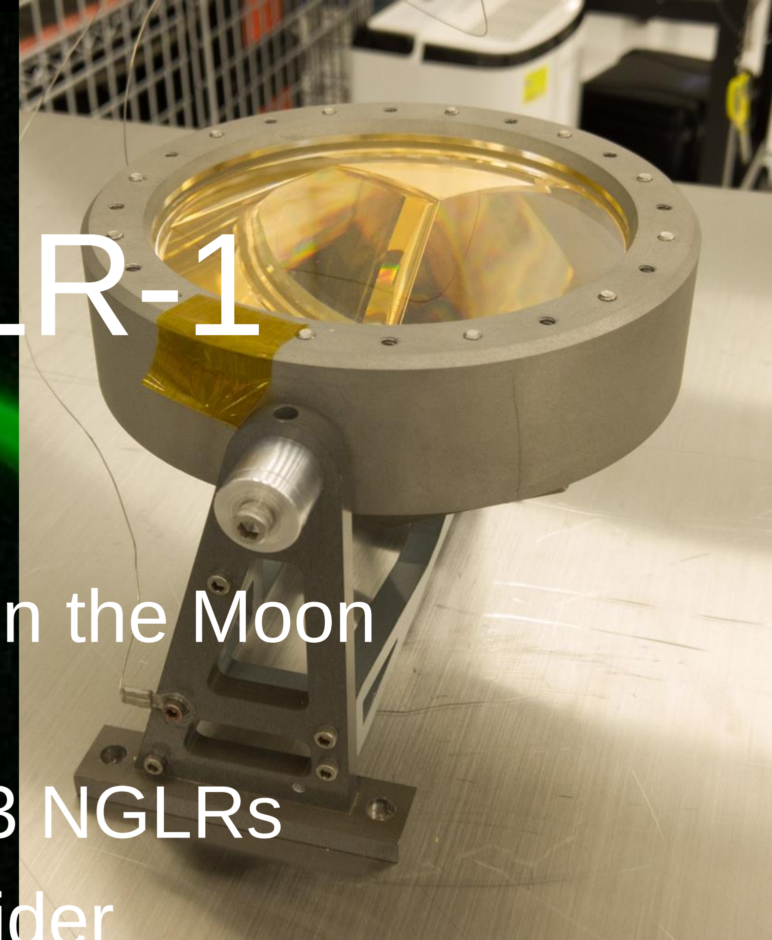
Next Generation Lunar Retroreflector

- We Need to Use Only a Single CCR
  - To Prevent Spread of Individual Range Measurements
- CCR Must Be Much Larger
  - To Provide Sufficient Signal for Measurements
- Size is Limited to ~100 mm
  - by Homogeneity of Fused Silica
- thermal Issues Are Critical
  - Temperature Gradients in the Glass of the CCRs
  - Produces Gradients in the Index of Refraction
    - Distorts Optical Qualities of the Fused Silica CCR
- Return Beam of Laser Pulses Would Be Spread
  - Over Many Kilometers Upon Return to Earth
- Next Generation Lunar Retroreflector (NGLR)



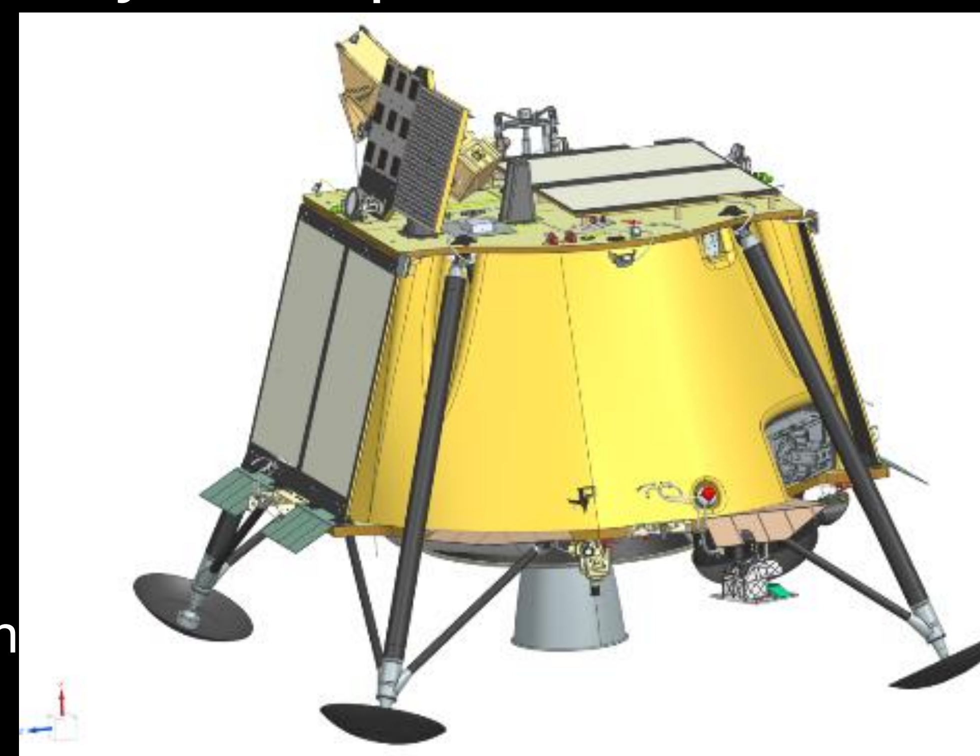


Flight Status of NGLR-1

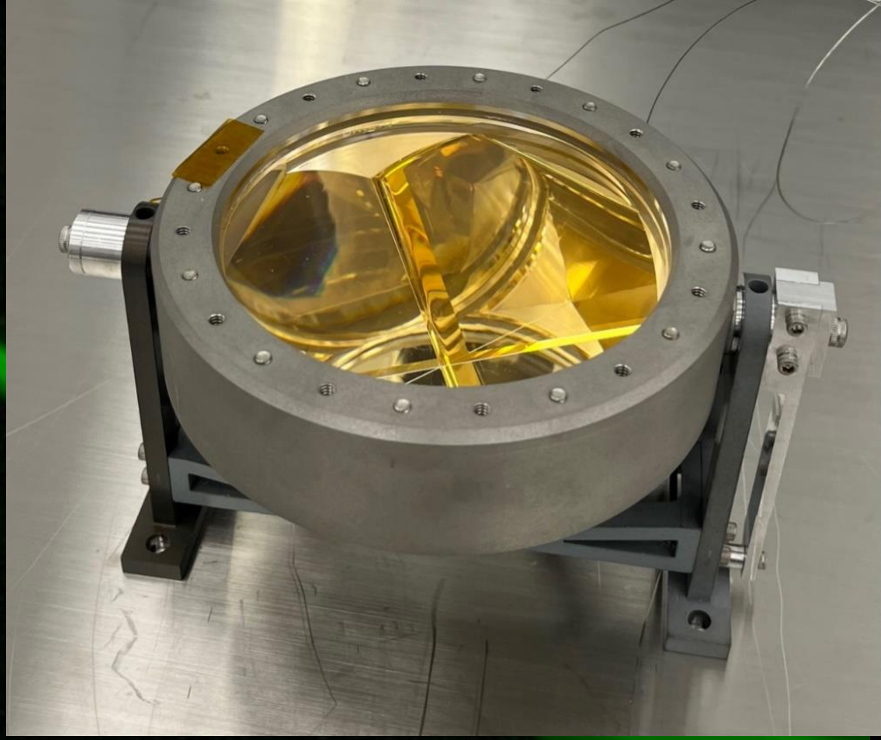


- We Prepared Proposal to NASA to Deploy NGLRs on the Moon
  - In Response to a NASA Solicitation
- In 2019, NASA Selected Our Proposal to Fabricate 3 NGLRs
- To Be Carried to the Moon By a Robotic CLPS Provider
  - Commercial Lunar Payload Services
- NGLR-1 Is To Be Deployed on the Moon by Firefly Aerospace
  - During the Summer/Fall of 2024
  - In Mare Crisium,
    - a Crater in the North-East Quadrant of the Moon
- NGLR-2 to Planned to be Deployed
  - Near the South Pole

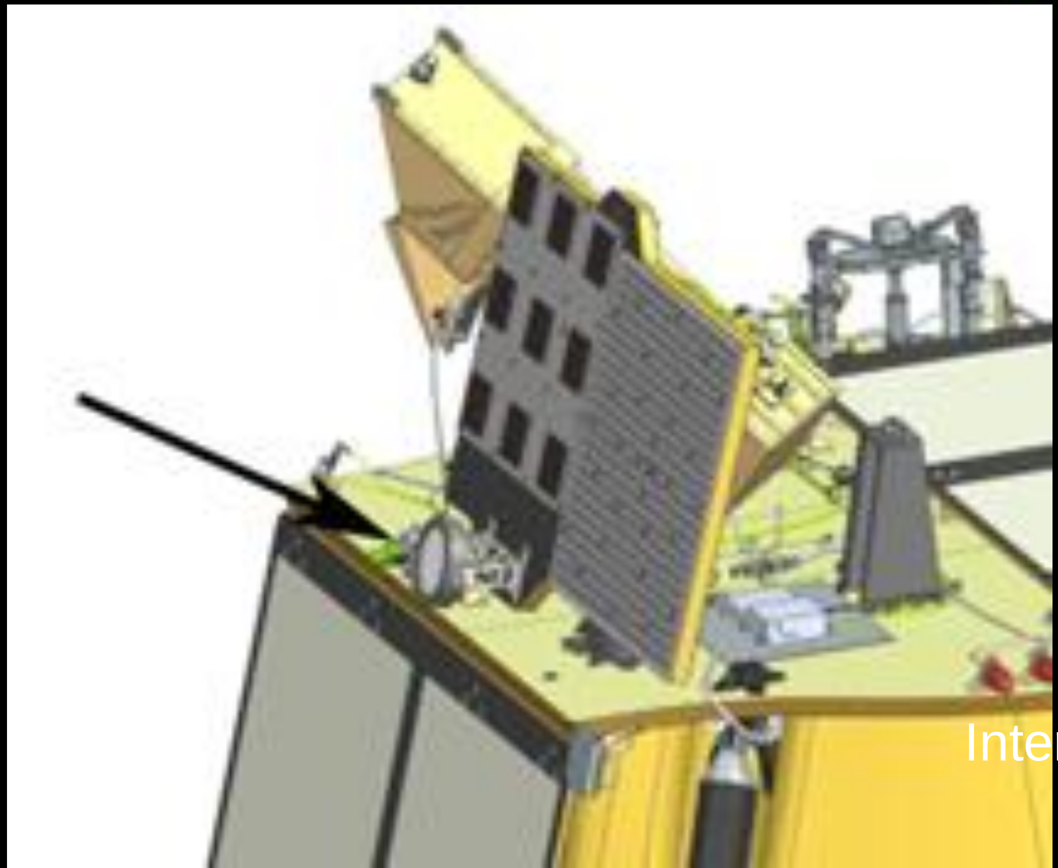
© Dan Long 2014

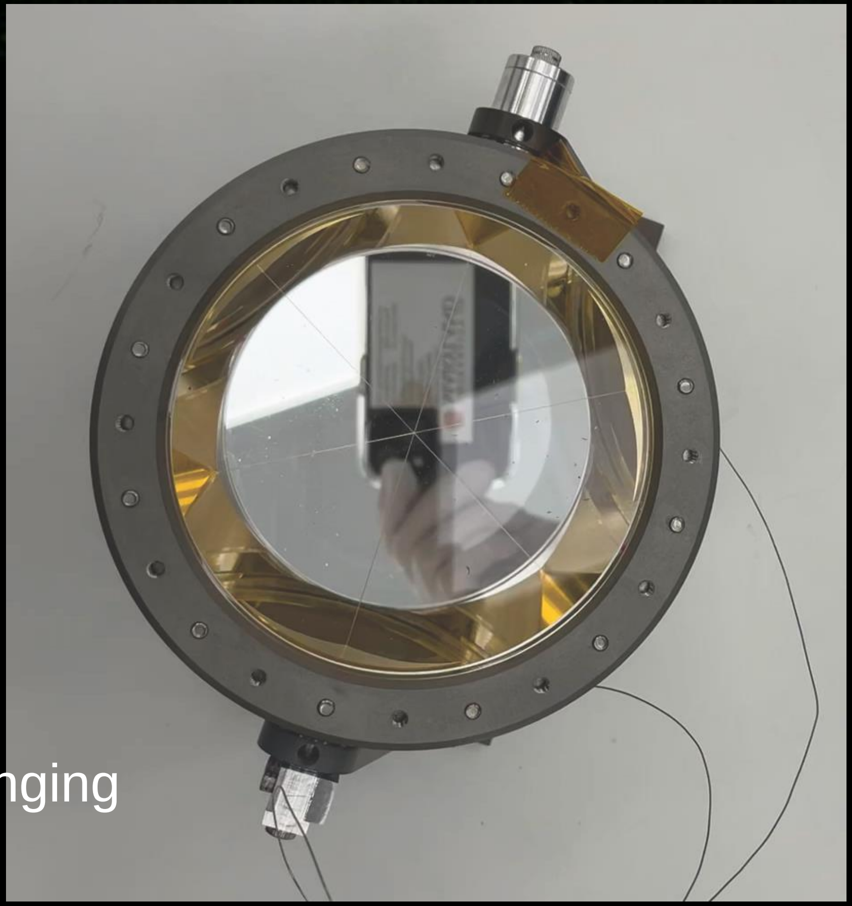


NGLR-1



- NGLR-1 As Delivered to Firefly Aerospace
- NGLR-1 Mounted on Antennae Support Panel (ASP)
  - ASP Also Carries High Gain Antenna
  - ASP Also Carries LuGRe GPS Experiment





What Science May We Expect Ranging to NGLRs

- A Simulation to Evaluate the Improvement on the Scientific Results
  - That Are Possible Within the LLR/NGLR Program
  - Has Been Conducted With James Williams at JPL
  - Using the Analysis Software Normally Used to Process LLR Data
- 6 Year Mission was Assumed
  - Investigated Many Different Parameters In Addressing for LLRO Accracy
- Sample for Two NGLR Configurations and Different LLRO Accuracies
  - Improvement over Current Accuracies Obtained with Apollo and Lunokhod RAs

Case	Beta	Gam	*h*_2	*l*_2	cos *D*	<*a*>	Tau S 815 d
SPL	92% 13x	74% 3.9x	87% 7.9x	70% 3.3x	98% 56x	98% 50x	7% 40x
CRS WST SW SPL	99% 111x	99.8% 420x	99.5% 212x	99.8% 570x	99.4% 162x	99.3% 147x	99.7% 330x

Table 2 Factors and percentages of improvement with the Artemis III mission and the assumption that ranging by the LLROs is performed at the ultimate levels of accuracy supported by the basic SBR package.

the Role of LLROs

- Lunar Laser Ranging Observatories (LLROs)
  - Absolutely Critical for Improved Scientific Results
  - Need to Be Able to Take Advantage of NGLR Capabilities
- Our Four LLROs Have Ranged to Apollo Arrays for Decades
  - APOLLO, MeO, MLRO and, Most Recently, Wettzell
- LLROs Need Upgraded Capabilities for Effective Utilization of NGLRs
  - Shorter Laser Pulses – 10/15 picoseconds
  - Accurate Local Prediction Ephemerides
  - Improved Geophysical and Atmospheric Corrections
- More LLROs are Needed for Effective Detection of Systematic Biases
  - Satellite Laser Ranging (SLR) Stations are Prime Candidates
  - NGLRs Are Effective in Combating Background Noise Rates
  - Lack of Temporal Spread Compensates for Smaller Apertures
  - Wettzell SLR Has Been Able to Range to the Apollo RAs for Several Years

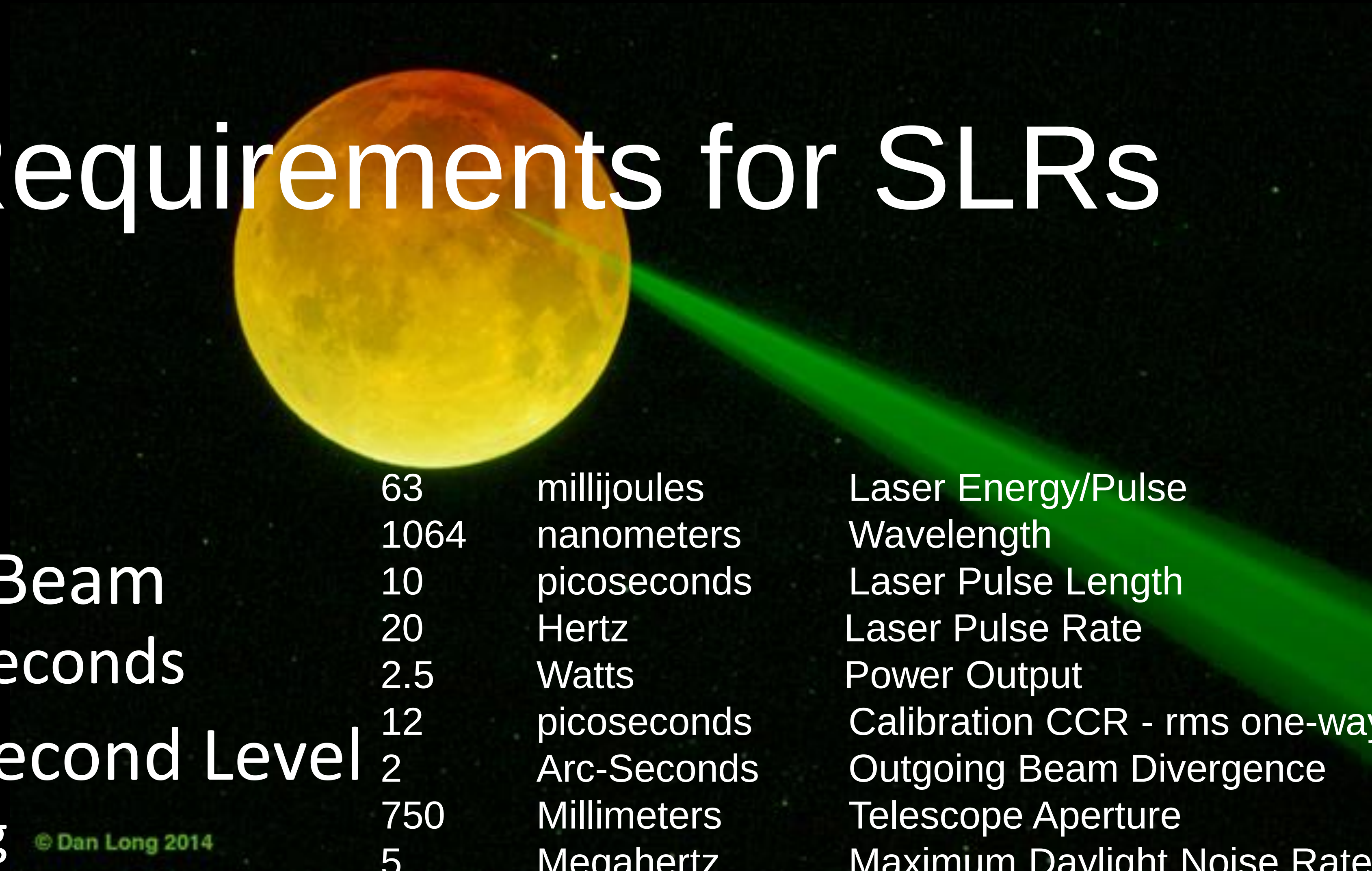
Possible Contribution of SLR Stations in LLR

- Objectives For Next Generation Lunar Laser Ranging
- Provide Millimeter Level Individual Range Measurements
  - Provide Millimeter or Sub-Millimeter Normal Point (NP) Accuracy
  - Provide Better Ability to Detect and Ameliorate Systematic Biases
- Procedure to Accomplish these Objectives
  - Removal of Target Signature of Current Apollo Retroreflector Arrays
  - NGLRs on Lunar Surface Will Support these Objectives
  - LLROs Need to Support Millimeter Level Range Measurement Precision within a NP
- Current Capabilities of Classical LLROs
  - That is, the APOLLO, Grasse, and Matera LLROs
  - Currently Long Laser Pulse Length lasers (100, 120, and 50 picoseconds)
  - Cannot Provide Millimeter Level Precision of Individual Range Measurements
  - Precision at the 50 ps or 8 mm Level
- Example of Current SLR Participation in LLR
  - Wettzell Has Been Ranging to Apollo15 and Lunokhod
  - After Optaining the First Lunar Ranges 30 years AGO
  - For the Past 4 years they Have About a 2 Millimeter Precision
  - Participation of Some SLR Stations is Clearly Feasible

Current Issues for SLR Ranging to Apollo

- Typical Precision of Classical LLROs
  - Ranging to Apollo Retroreflector Arrays
  - Of the order of 50 – 100 ps
  - Small But Significant Improvement with NGLRs
- Typical Target Signature of Apollo Arrays
  - 400 picosecond Spread of Induvial Returns
- Wettzell SLR Station
  - Calibration CCR - 12 ps r.m.s. (~ 2 mm r.m.s.)
  - Possible Improvement 400/12 ~Factor of 33 w.r.t. Apollo
  - Especially at Extremes – Data with a High Weight
  - Possible Advantage of SLR Station Capabilities with NGLRs
- Negligible Target Signature Allows Operating at Higher Noise Rates
  - Reduces Noise Blanking
  - Allows Consideration of SLR Systems with Higher Laser Pulse Rates

LLR Requirements for SLRs



63	millijoules	Laser Energy/Pulse
1064	nanometers	Wavelength
10	picoseconds	Laser Pulse Length
20	Hertz	Laser Pulse Rate
2.5	Watts	Power Output
12	picoseconds	Calibration CCR - rms one-way
2	Arc-Seconds	Outgoing Beam Divergence
750	Millimeters	Telescope Aperture
5	Megahertz	Maximum Daylight Noise Rate
0.3	Megahertz	Dark Noise Rate
Y/N		1 Arc-Second Pointing Ability

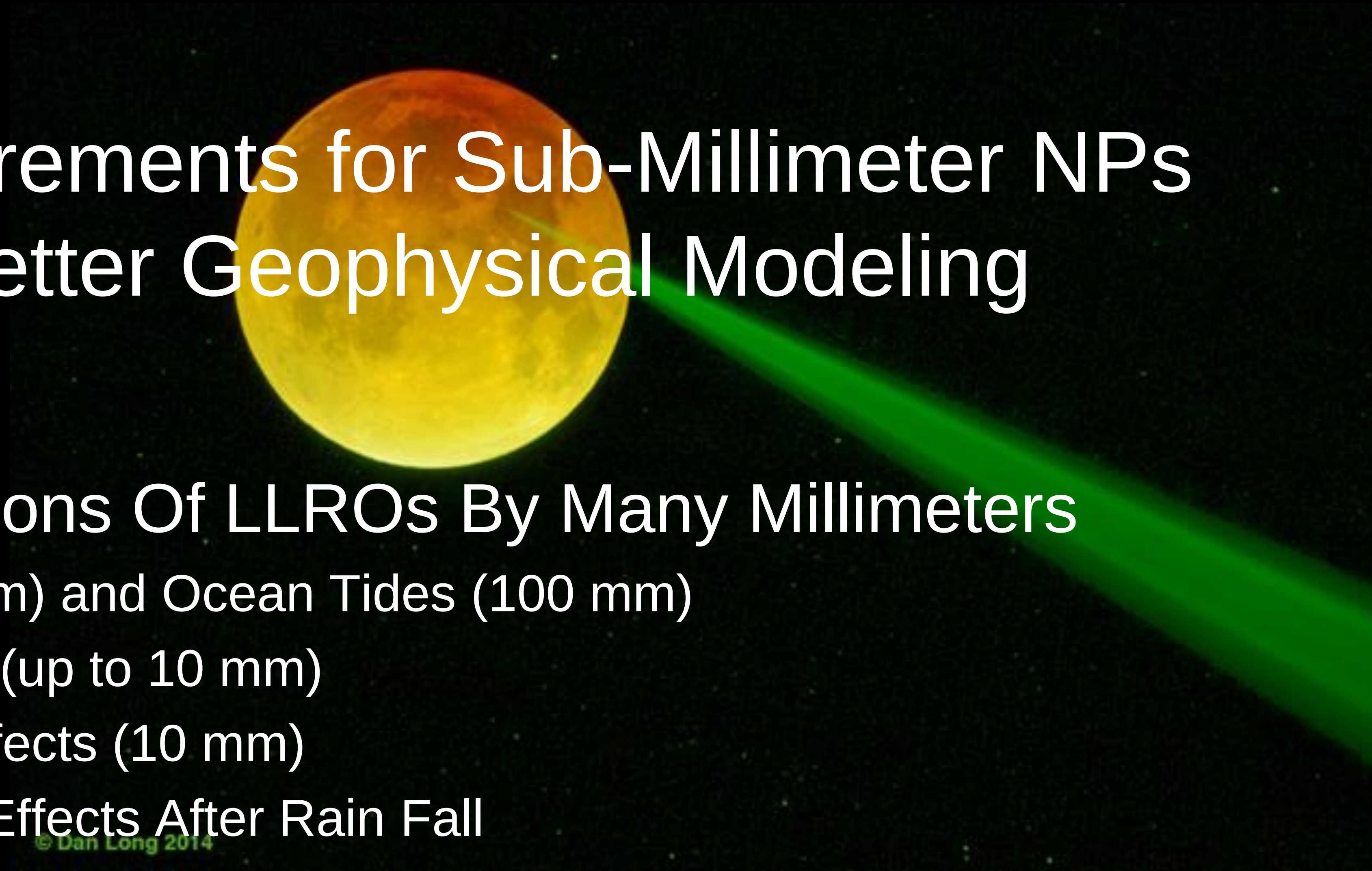
- Divergence of the Beam
  - Nominally 2 Arc-seconds
- Pointing at 1 Arc-Second Level
  - Absolute Pointing
  - Offset from Crater
  - Offset from Star
- Your SLR Station Parameters Can Address the Feasibility
  - the Possibilities and the Constraints Can Be Estimated
  - Contact Us For Parameters in Spreadsheet Format

G. C. Hulley
Erricos C. Pavlis

Requirements for Sub-Millimeter NPs
Better Atmospheric Modeling

- Horizontal Density Gradients In Earth's Atmosphere
  - Currently We Measure Local Pressure, Temperature and Humidity
  - Acceptable Atmospheric Delay Correction If Moon Is Directly Overhead
  - However, This Never Happens – Normally At Approximately 40^{o} Elevation
  - Thus, We Are Sensitive to Density Variations Over ~7 Kilometers
  - This Results In Range Measurement Offsets of 1 Or 2 Millimeters
    - Evaluated Using Satellite Observations By E. Pavlis And G. Hulley
    - Typical Observations At 40^{o} Due to Latitude Of LLR Observatories
  - Possible Use Global Weather Maps And Local Met Data to Model
    - 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

G. C. Hulley
Erricos C. Pavlis



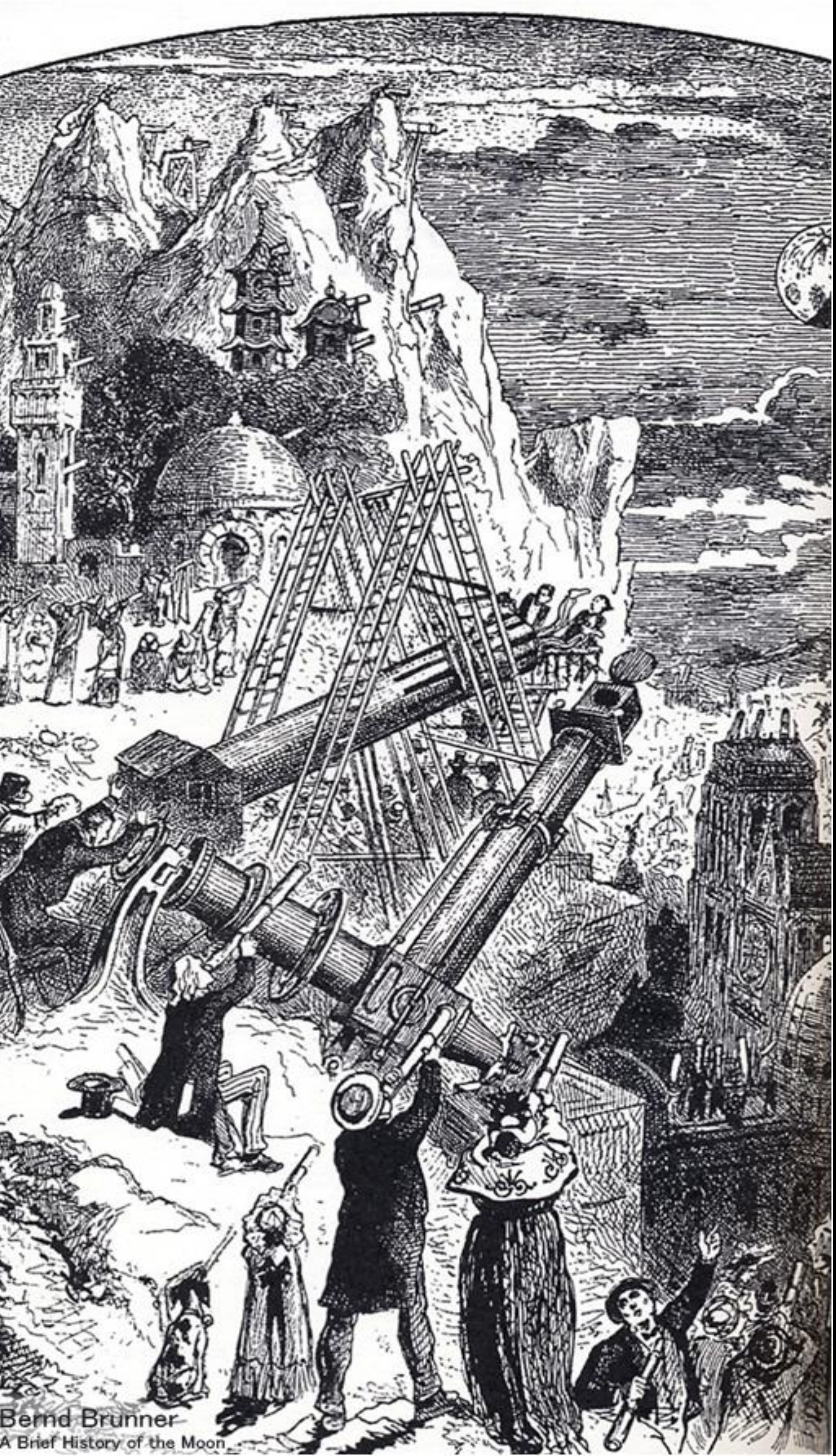
Requirements for Sub-Millimeter NPs Better Geophysical Modeling

- Geophysical Motions Of LLROs By Many Millimeters
  - Solid Earth (300 mm) and Ocean Tides (100 mm)
  - Atmospheric Tides (up to 10 mm)
  - Seasonal Water Effects (10 mm)
  - Short Term Water Effects After Rain Fall
- Currently Addressed In ILRS SLR Community at the mm Level
  - Modeling Of Solid Earth and Ocean Tides
  - Gravimeters Located at the LLROs
  - Satellite Measurenmts to Surface Retroreflectors
- Need More Analysis
  - To Reliably Achieve Range Accuracies at Sub-Millimeter Level

G. C. Hulley
Erricos C. Pavlis

Conclusions

- Results of Our Lunar Laser Ranging Program to Date
  - Demonstrated the Highly Successful LLR Technology
  - Obtained Many Of the Most Accurate Scientific Values In the Fields of:
    - Tests of General Relativity (Determined the Accuracy of WEP, etc.)
    - Cosmology (Demonstrated the Constancy of Big G in Time and Space, etc.)
    - Understanding the Physics of the Moon (Discovered the Liquid Core, Evaluated the Love Numbers, etc.)
    - Established Fundamental Lunar Reference Systems (For Cislunar Navigation and For Lunar Mapping)
- Next Generation Lunar Retroreflectors (NGLRs) Project
  - Completed Successful Fabrication of NGLR-1
  - First NGLR Has Been Delivered to Firefly Aerospace
  - Deployment on the Moon Expected in the Fall of 2024
- Expected NGLR Science Return Looks Extremely Interesting
  - Orders of Magnitude Improvement In the Accuracy Of Our Scientific Results
    - Beyond the Current Accuracy Obtained By Ranging to Apollo Retroreflector Arrays
    - Many Of Which Are Already the Most Accuracy Currently Available
- NGLRs Will Allow Some SLR Stations to Join Our LLRO Network
  - To Better Detect Systematic Biases



Thank You!
any
Questions?
or
Comments?

with
Special Acknowledgements
to
NASA Lunar Science Sorties Opportunities
NASA Lunar Science Institute
Italian Space Agency
INFN-LNF, Frascati
LSSO Team
LUNAR Team
&
NGLR Team
.

Doug Currie
currie@umd.edu
301 412 2033