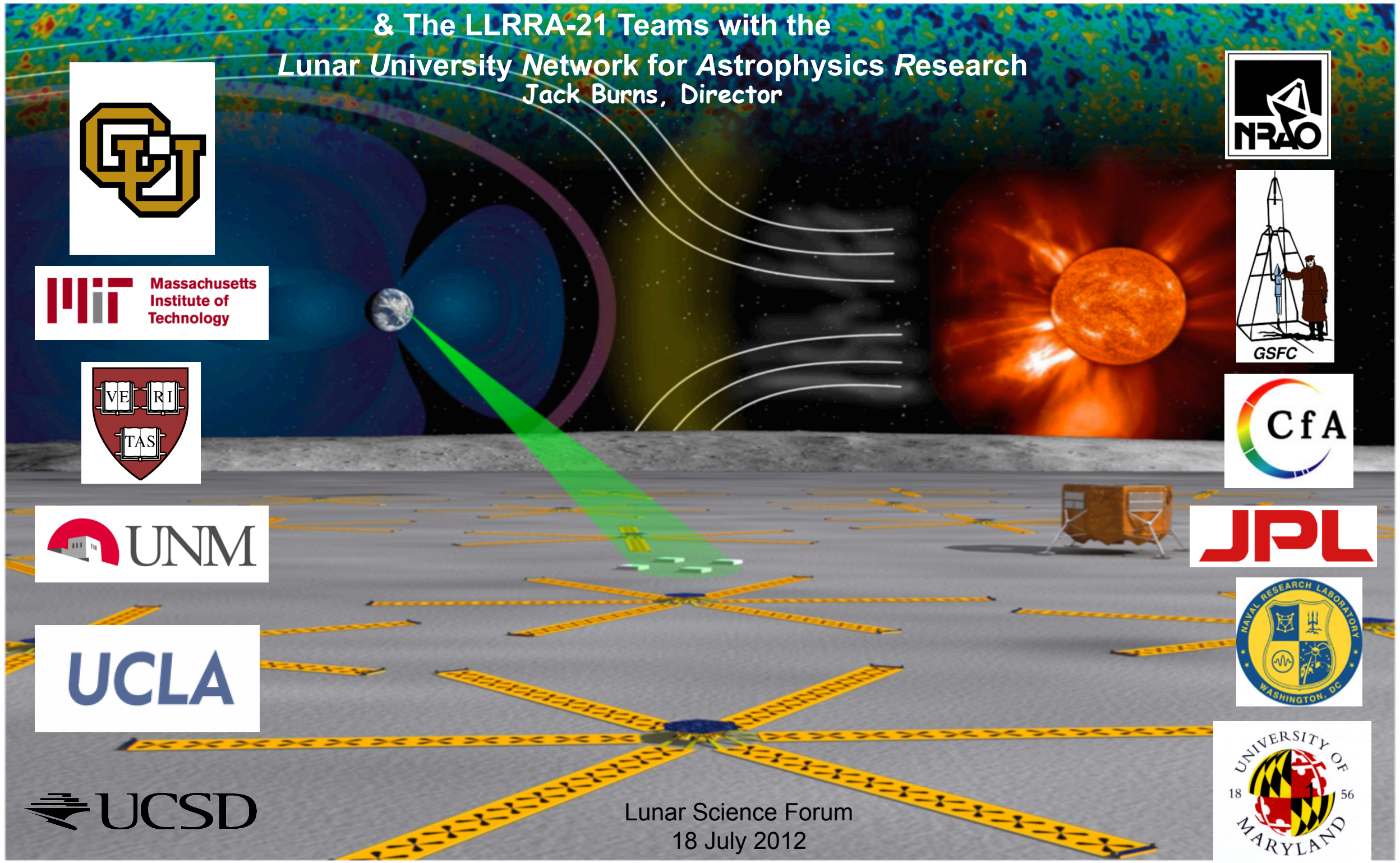
A LUNAR LASER RANGING RETRO-REFLECTOR ARRAY
for the 21st CENTURY

Professor Douglas Currie
University of Maryland, College Park, MD, USA
NASA Lunar Science Institute, Moffett Field, CA
INFN – LNF, Laboratori Nazionali di Frascati, Italy



Lunar Science Forum
18 July 2012

LLR LUNAR SCIENCE

- Inner Liquid Core
  - $Cf/C = (12\pm4)\times10^{-4}$
  - 390±30 km
  - Oblateness of the Liquid Core
    - $f=(Cf–Af)/Cf=(2.0\pm2.3)\times10^{-4}$
    - Re - Rp = 80 meters
  - Dissipation at Liquid-Core/Solid-Mantle Interface
- Physical Librations in Longitude
  - 1 yr (annual mean anomaly)
  - 206 d, and 1095 d
- Lunar Moment of Inertia
- Free Librations – in Crustal Frame
  - 3.3”x8.2” (28 m x 69 m).
  - Damping Time is about 106 yr
- Love Numbers of the Crust
  - $k2 = 0.0199\pm0.0025$ and $h2 = 0.042\pm0.008$.

CHALLENGES for SOLID CCR

- Fabrication of the CCR to Required Tolerances
- Sufficient Return for Reasonable Operation
  - Ideal Case for Link Equation
- Thermal Distortion of Optical Performance
  - Absorption of Solar Radiation within the CCR
  - Mount Conductance - Between Housing and CCR Tab
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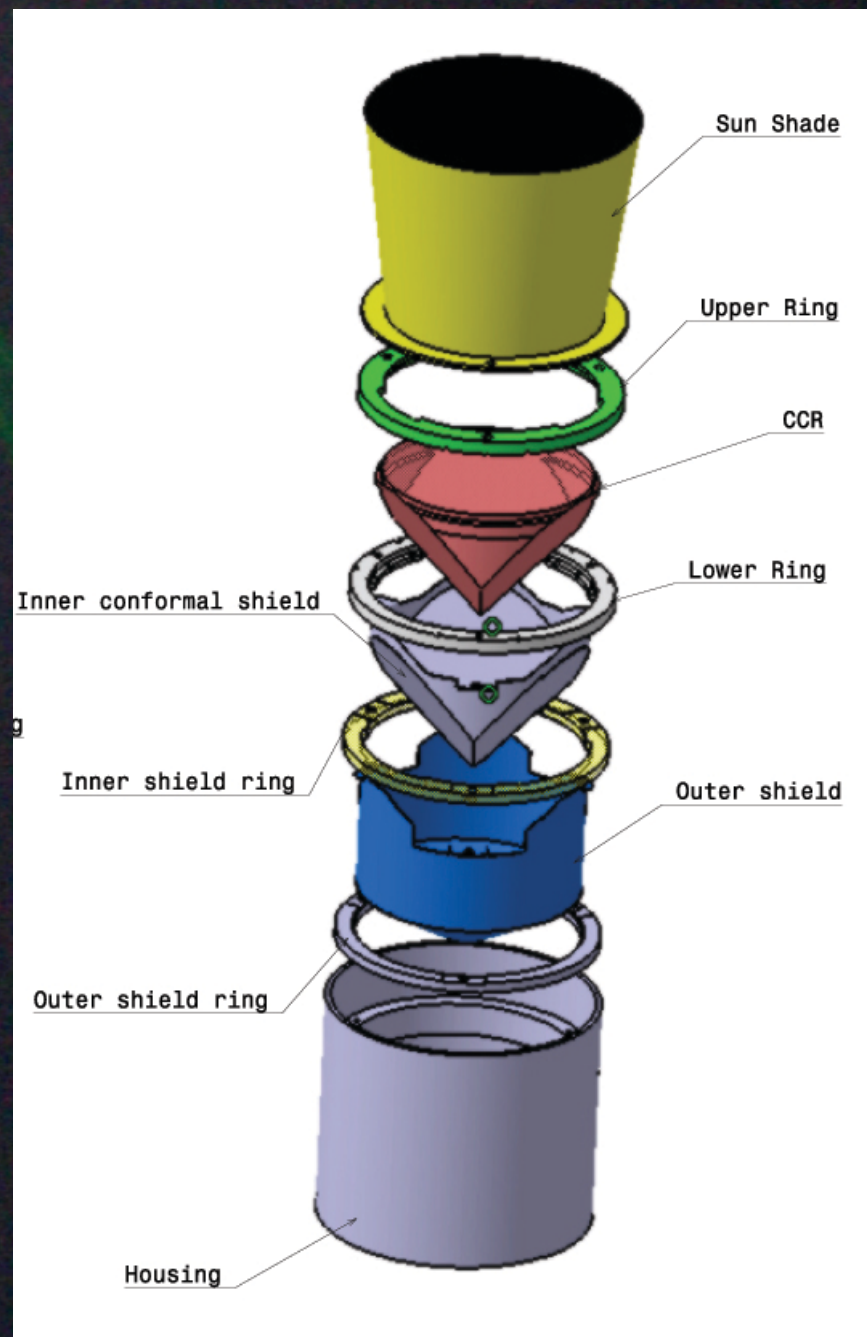
  - Problem of Regolith Heating and Expansion
  - Drilling to Stable Layer for CCR Support
  - Thermal Blanket to Isolate Support
  - Housing Design to Minimize Thermal Expansion

Simulation Procedure

- Digital Model of the Total Package
  - CCR, Housing, Internal and External Support and Regolith
- Ray Tracing for 4-D Heat Deposition in CCR
  - Through a Lunation, 1 Nanometer Wavelength Bands,
  - 30 Thousand Nodes, Reflection Effects of SunShade
- Thermal Desktop
  - Computes Temperature at Each Node
- PhaseMap – UMd IDL Program
  - Converts 3D Temperatures to 2D PhaseMap at Each of 400 Sun Angles
- Code V Optical Analysis Program
  - Adds Optical Errors (Reflection Phases, Offset Angles to Thermal Errors
- Analysis Program – UMd IDL Program
  - Evaluates Laser Return Intensity - Addressing
    - Velocity Aberrations and Station Latitude
    - Polarization Effects

Mechanical Model Drawing

- Mechanical Model of LLRRA-21
- All Compoinents
  - Cube Corner Reflector
  - Sun Shade
  - Housing
  - Thermal Shileds
- IDL – for UMD Program
- AutoCAD – Thermal Desktop



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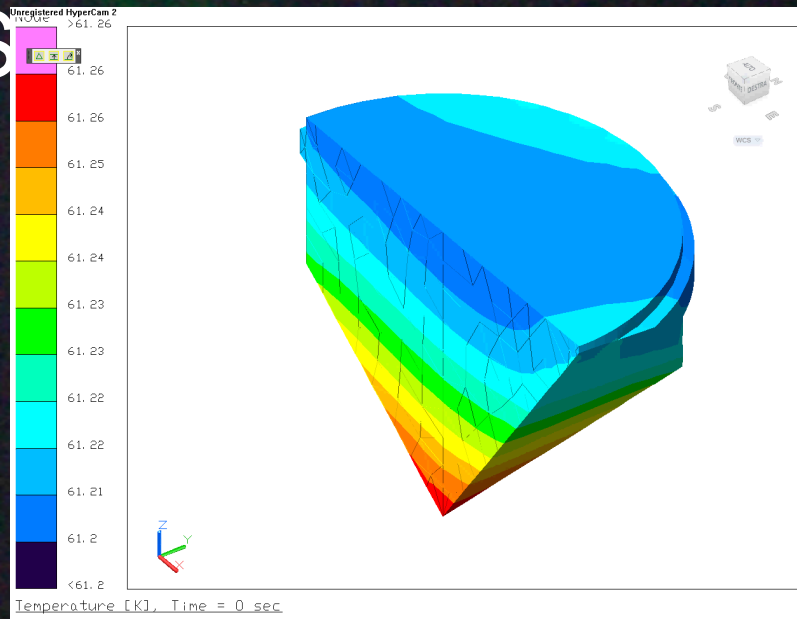
Solar Power Deposition

- IDL Program Traces 1000 Rays
  - Solar Spectrum Divided into 1 nanometer Bands
  - Entering Sun Shade and CCR
  - Within the Cube Corner Reflector
    - Divided into 30,000 2 mm by 2 mm Cells
    - Spectral Power Absorbed by Fused Silica
    - Remaining Spectral Power Transmitted
  - Total Internal Reflection at Back Faces
  - For Each Sun Angle in Lunation
- 4D Distribution of Solar Power

Thermal Desktop

- Commercial Program by C&R Technologies
- Inputs to Program:
  - Heat Deposition in CCR
  - Heat Deposition on Interior of Sun Shade
  - Solar Heating of Exterior during Lunation
  - Thermal Radiation from Regolith
  - Radiation of All Components to S
- Output:
  - 4D distribution of Temp. in CCR



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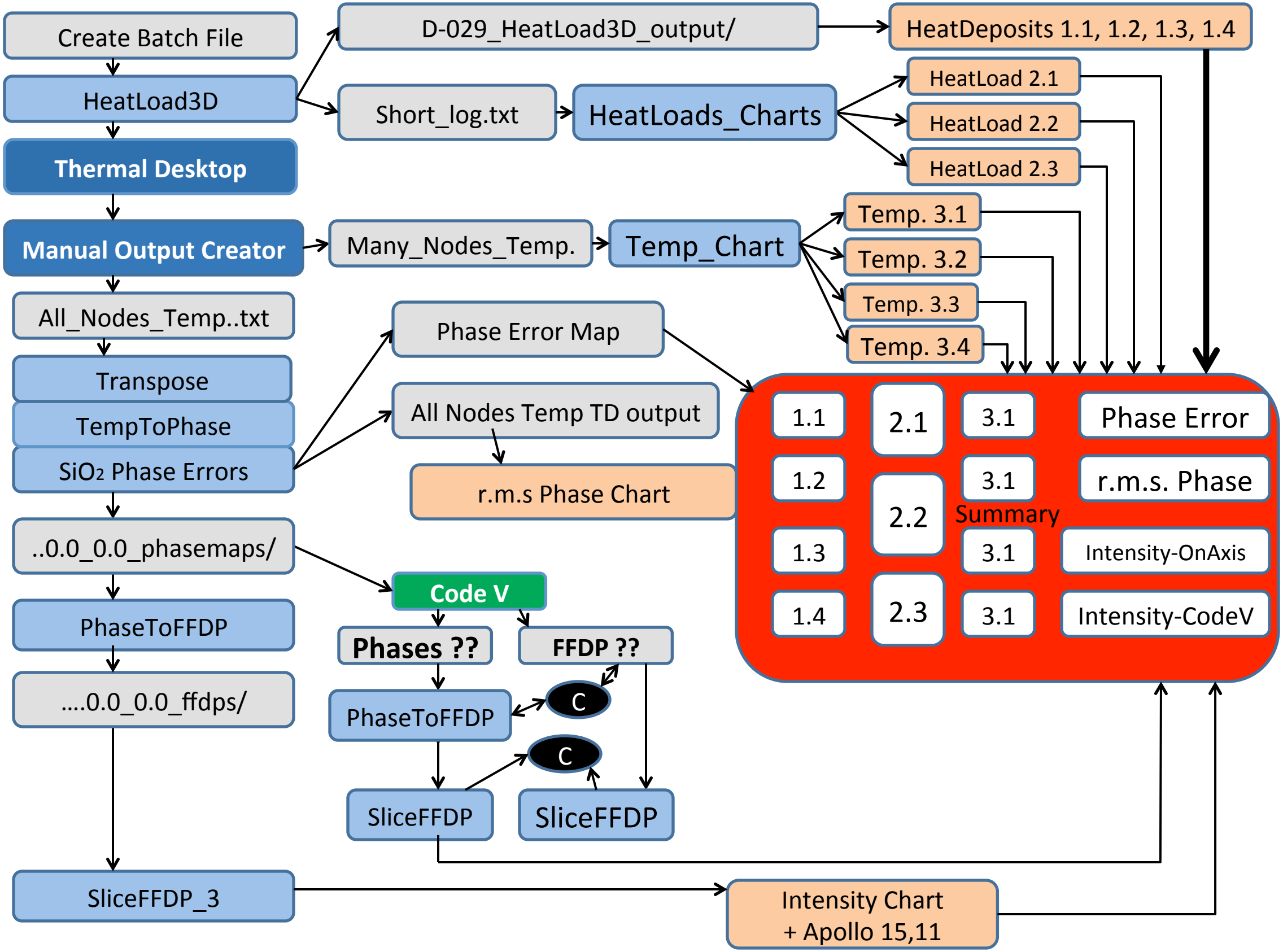
LLRRA-21 Thermal/Optical Simulation



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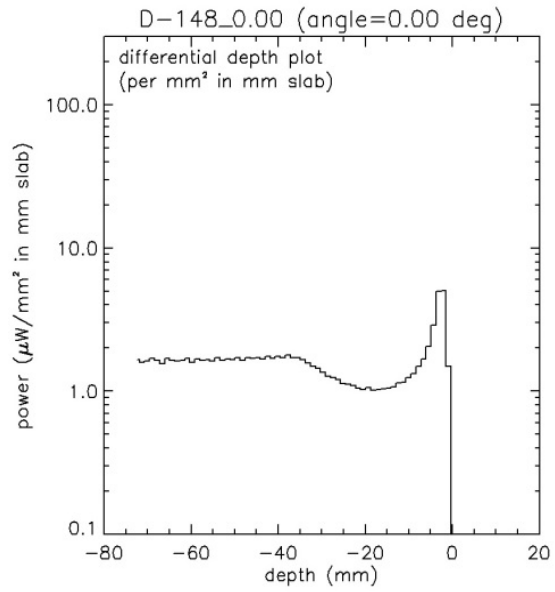

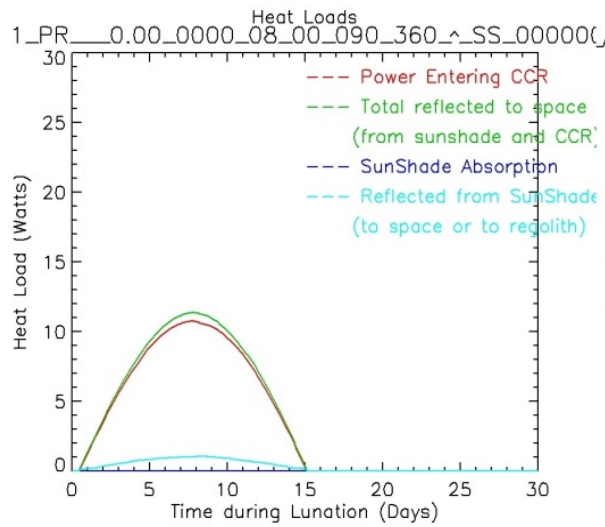

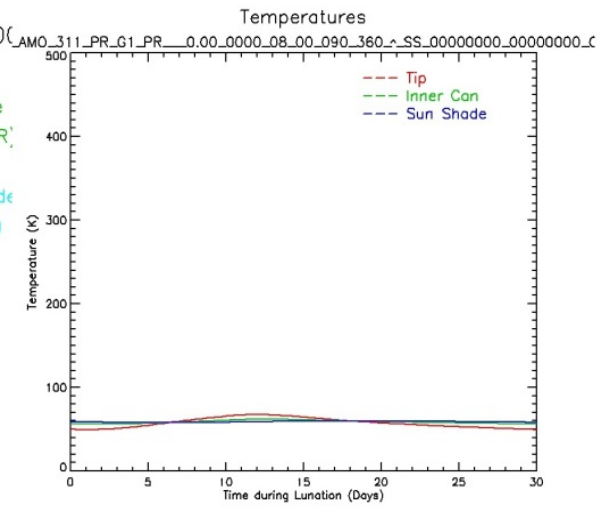

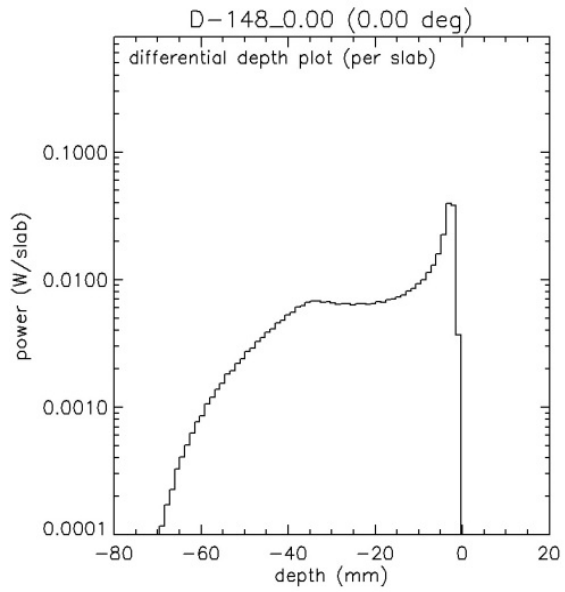

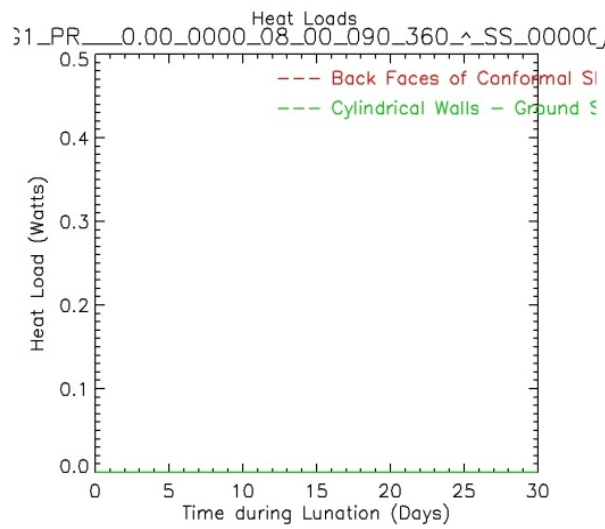

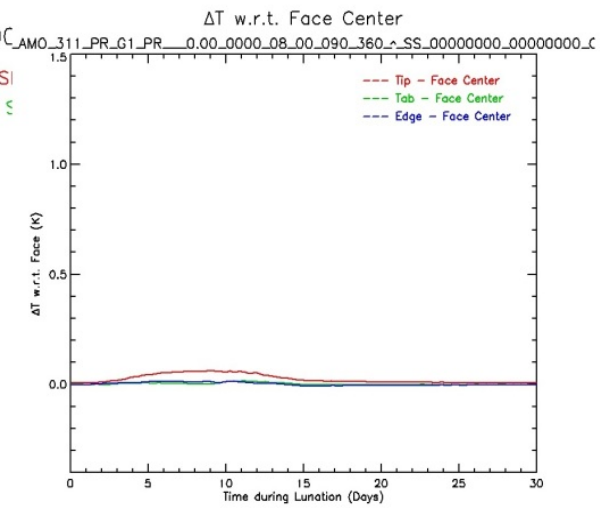

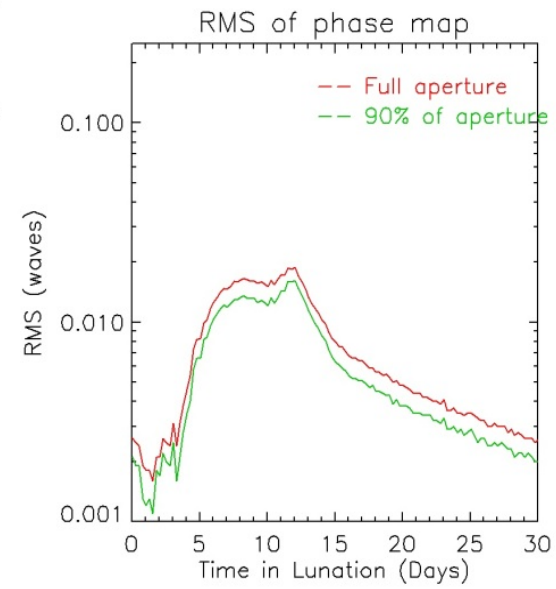

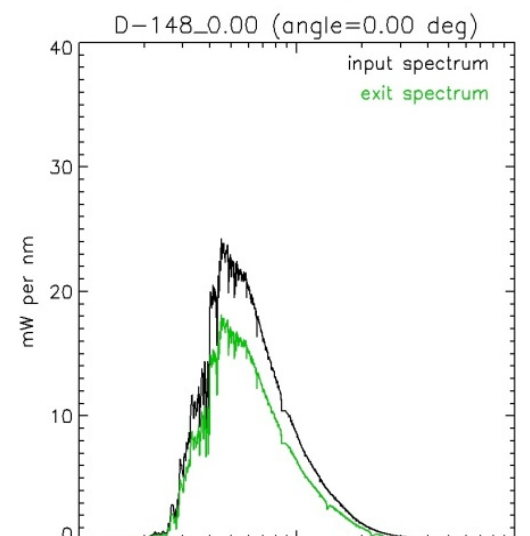

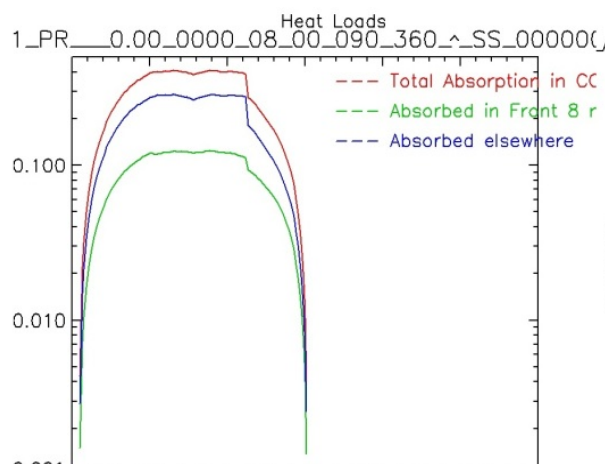

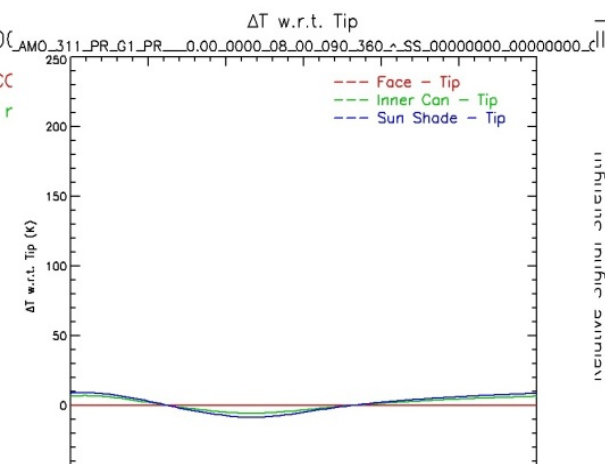

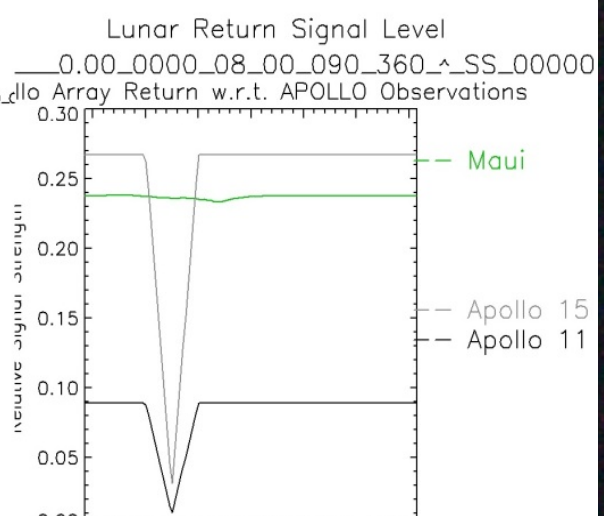

- AutoCad
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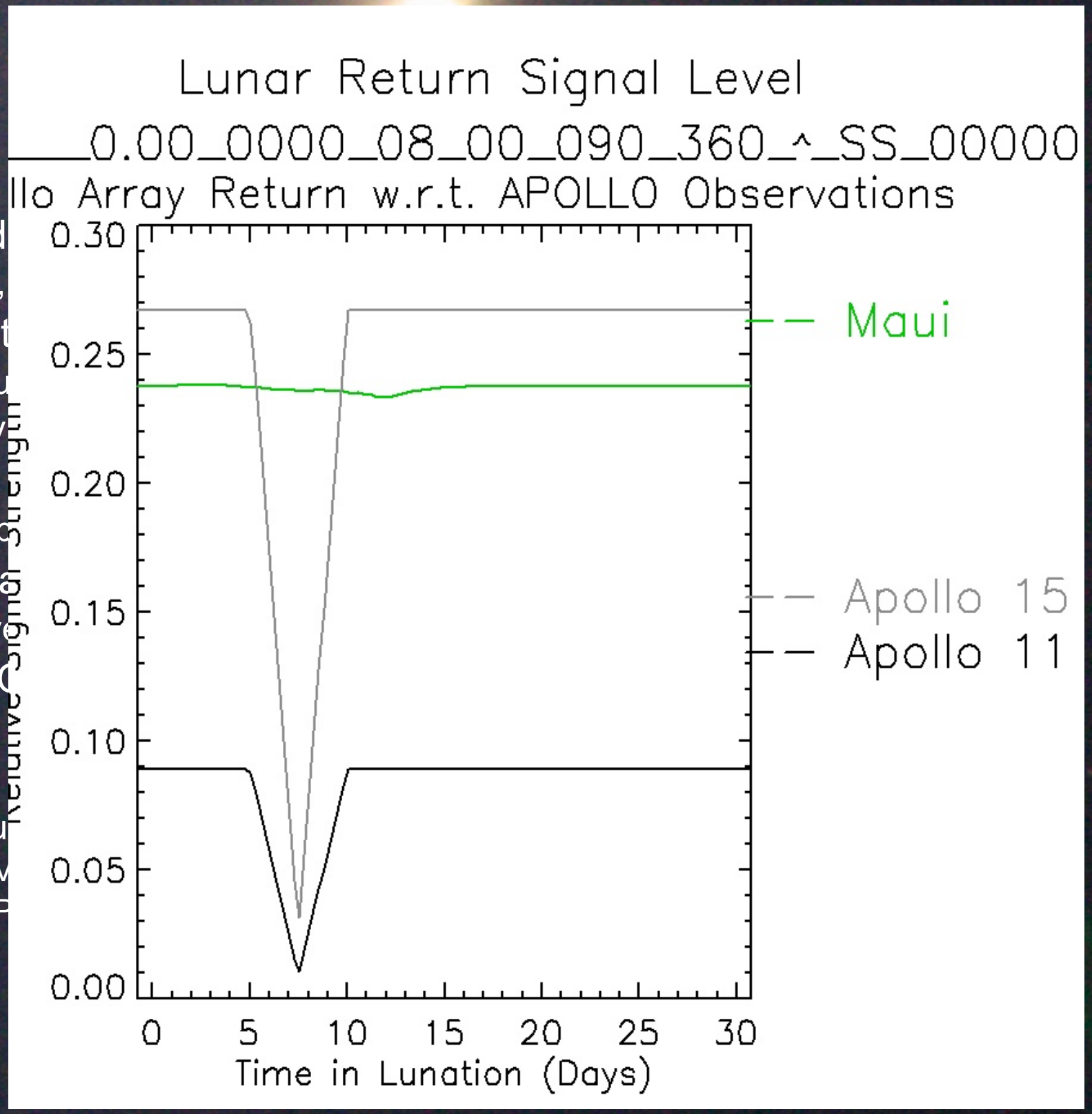
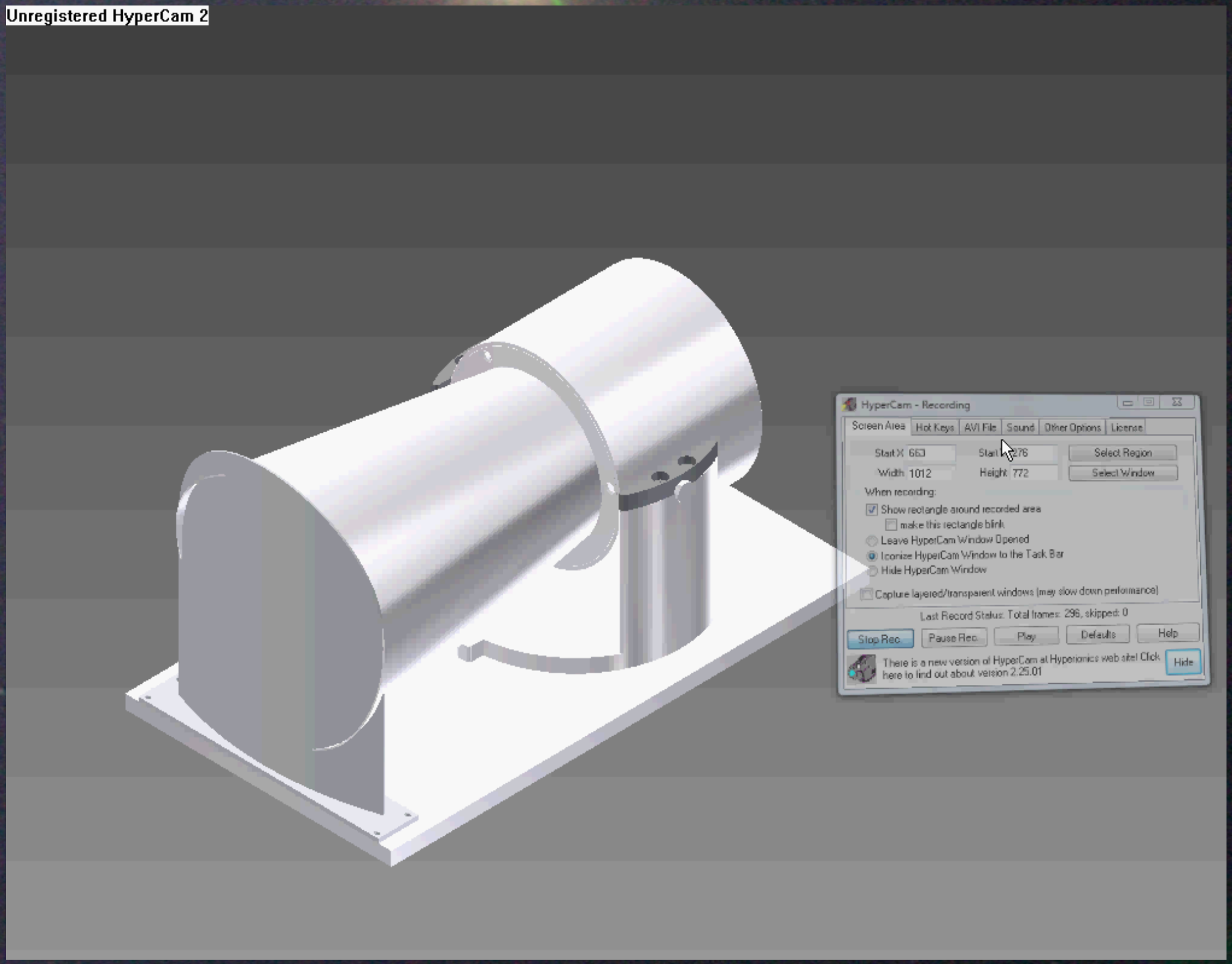
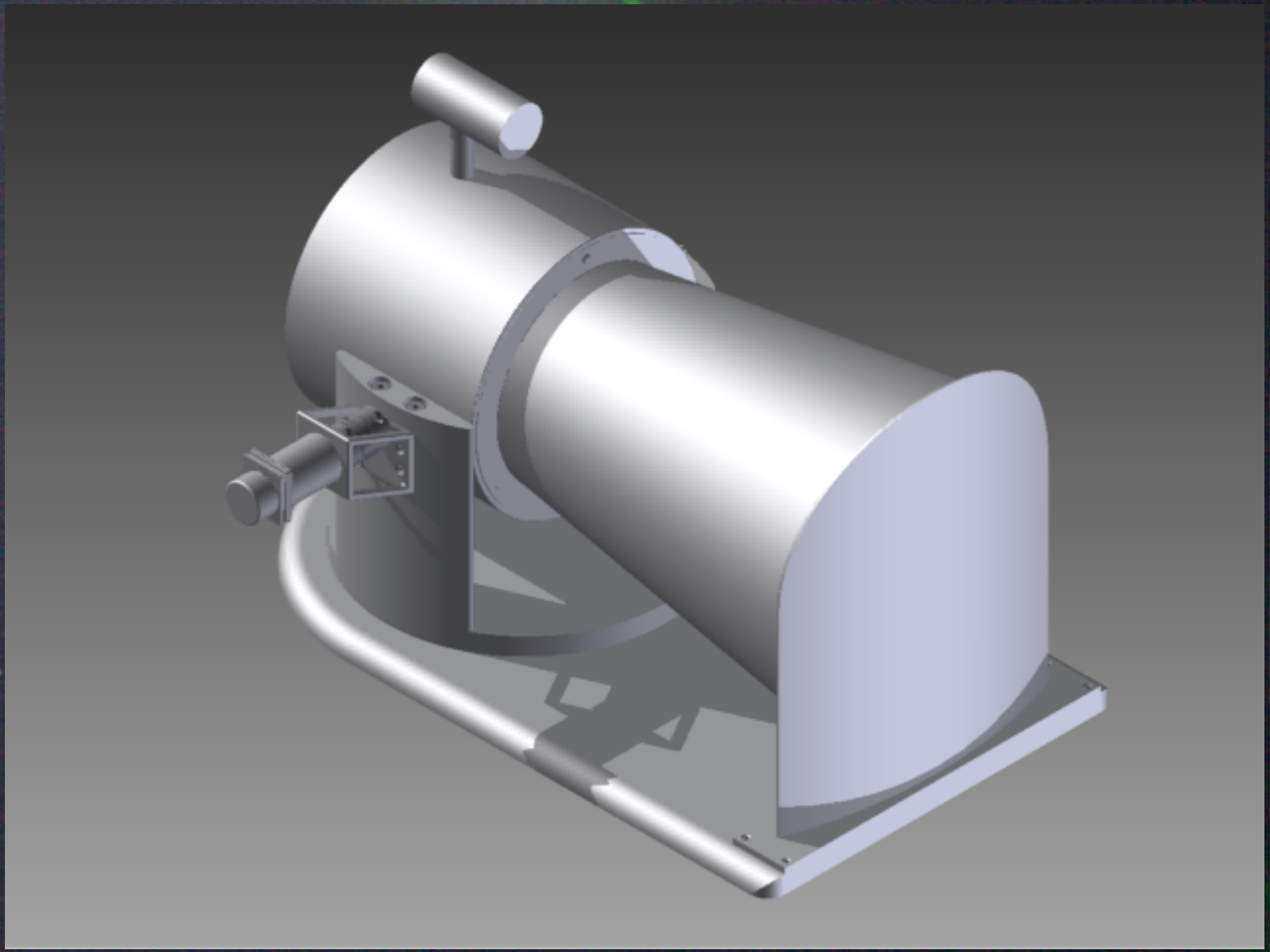


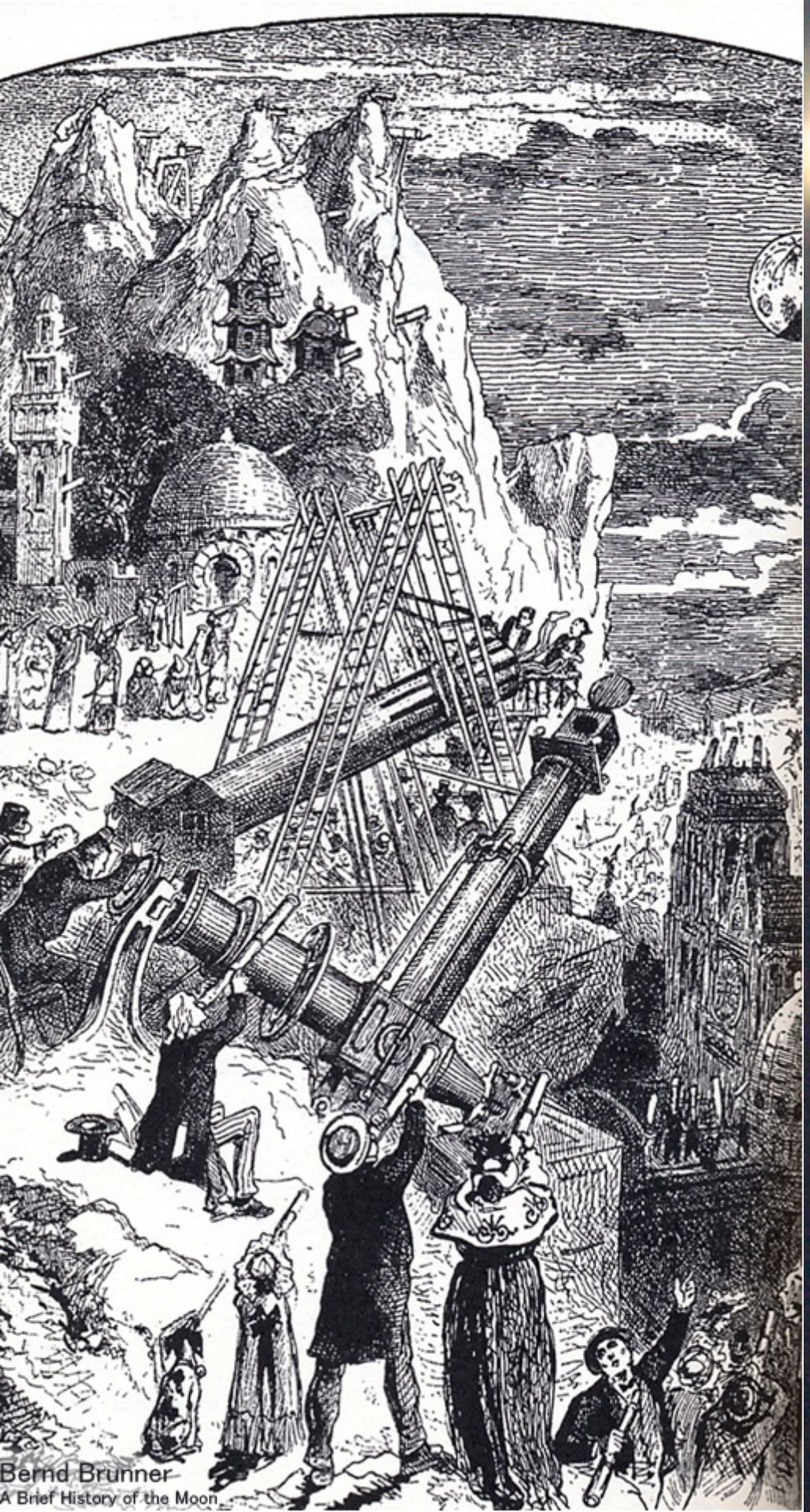
LLLRRA-21 Mounted on MoonEx1

Earth Pointing Maneuver



Camera Sensing Earth Direction





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

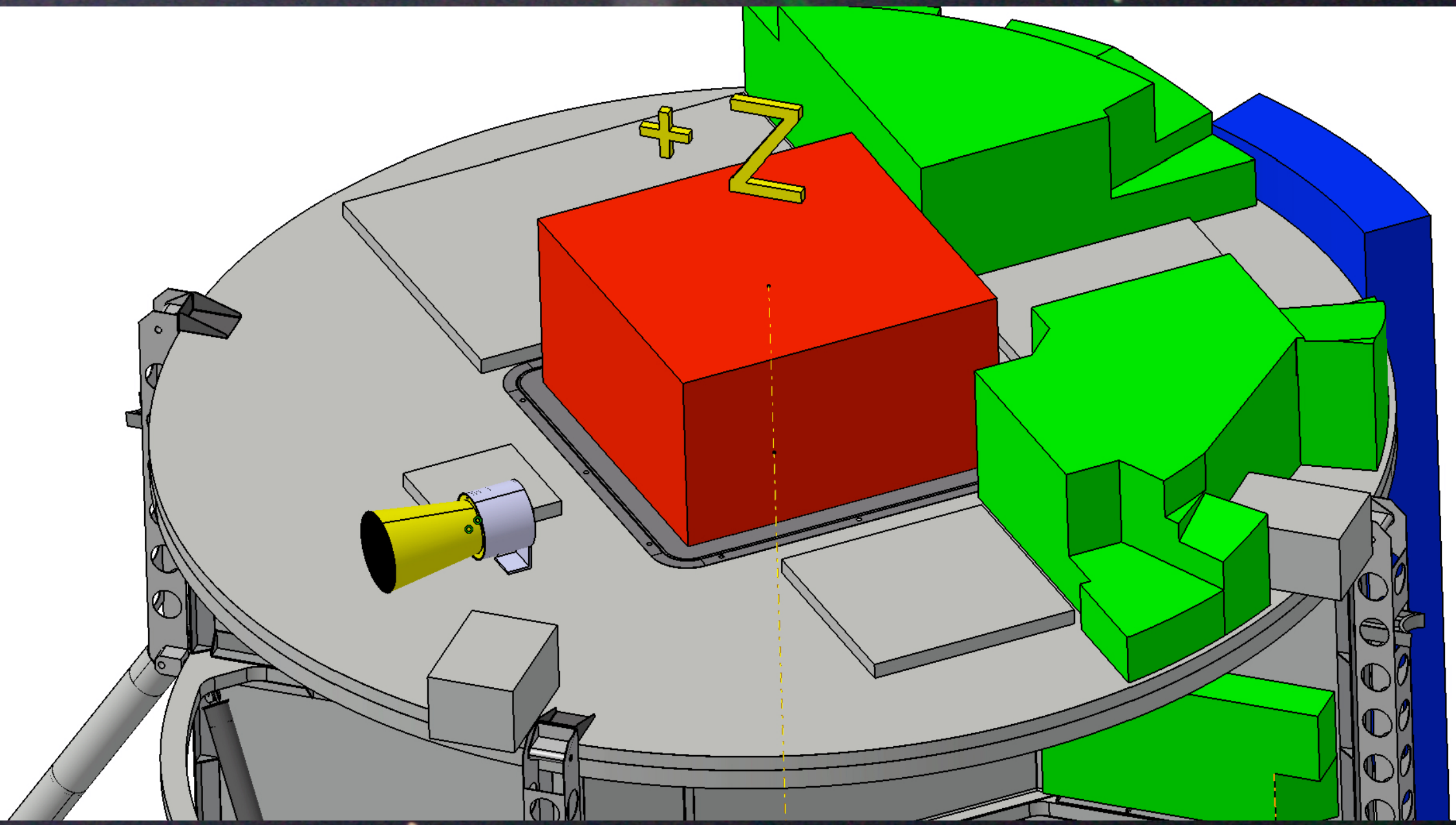
&

LUNAR Team

.

currie@umd.edu

LLRRA-21 Mounted on ESA Lander

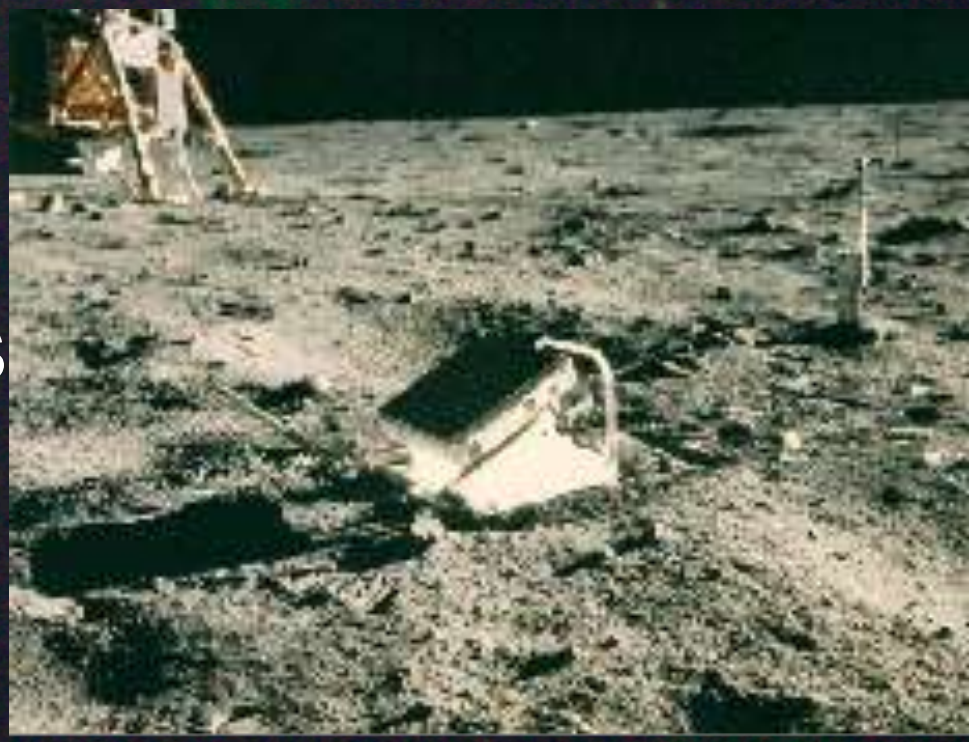


NASA Lunar Science Institute
US Member Teams

- CCLADS — Lunar Dust and Atmosphere
- POLAR — Exploration of Lunar Poles
- CLSE — Evolution via Samples
- **LUNAR** — AstroPhysics From the Moon
  - COSMOLOGY
  - **LUNAR LASER RANGING**
    - UCSD — APOLLO Station
    - Lunar Laser Ranging Retroreflector Array for the 21st Century — University of Maryland, College Park
    - GSFC — Open CCR
  - HELIOPHYSICS
- CLOE — Evolution via Bombardment
- BROWN — Origin of Terrestrial Planets
- DREAM — Dynamics of Exosphere

Brief History of Lunar Laser Ranging

- Operational Procedure
  - Transmit Narrow Laser Pulse from Earth
  - Pulse is Reflected from a Fixed Point on the Moon
  - Measure the Light Travel Time
  - Analyze Time Series of Measurements for Frequencies
- Apollo Range Improvements
  - Kilometers (Radar) to ~300 mm
- Continue for Long Time Series
  - Originally 3 Ranges per Day

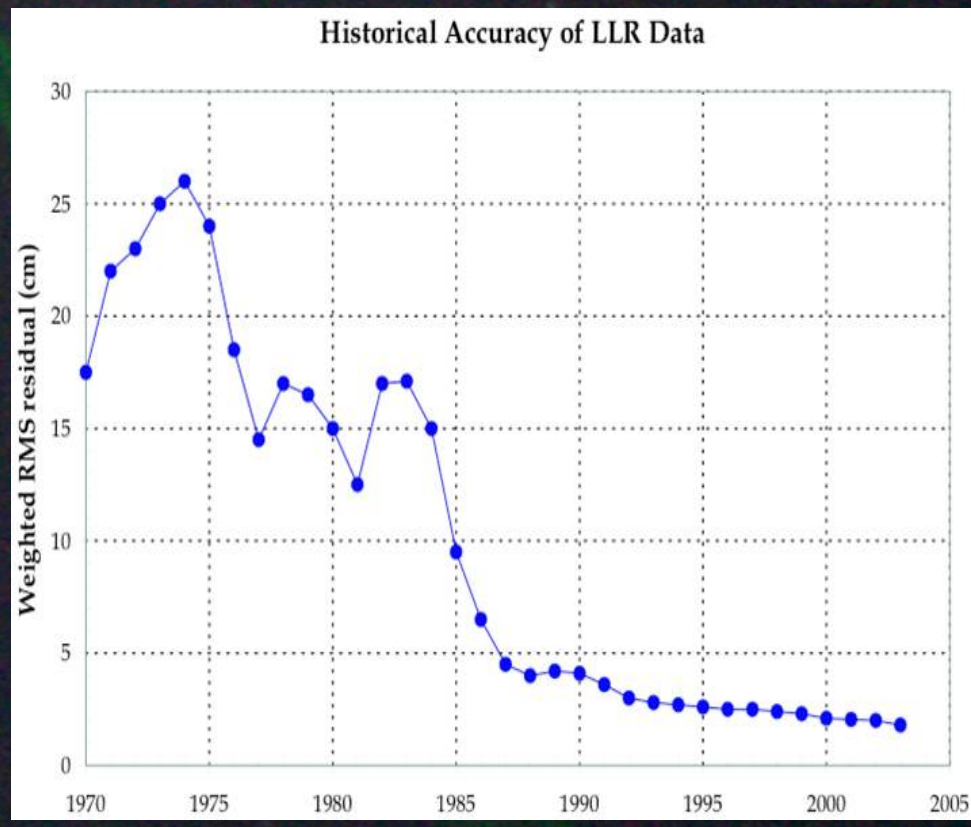


Why Laser Ranging to the Moon

- Ideally Want to Track an Object
  - Which Travels on a Geodesic as in GR
  - That is, Affected only by Gravitation
- Problems with Artificial Satellites
  - Solar Photons Push Satellite to New Orbit
  - Heated Surface of Satellite Emits IR Photons
- Moon has Much Better Mass/Surface Ratio
- Besides, We Learn of the Lunar Interior

SHORT HISTORY of LLRRA-21

- Apollo Lunar Laser Ranging Arrays 1969
  - Thermal and Optical Analysis and Testing
  - McDonald LLR Station
  - 3 Observations/Day
- 2006
  - NASA Considers Return to the Moon
  - We Could Address Accuracy Limit
- 2007
  - LSSO for 100 mm CCR
  - Lunar Science Sortie Opportunities
- 2009
  - NLSI > LUNAR at University of Colorado



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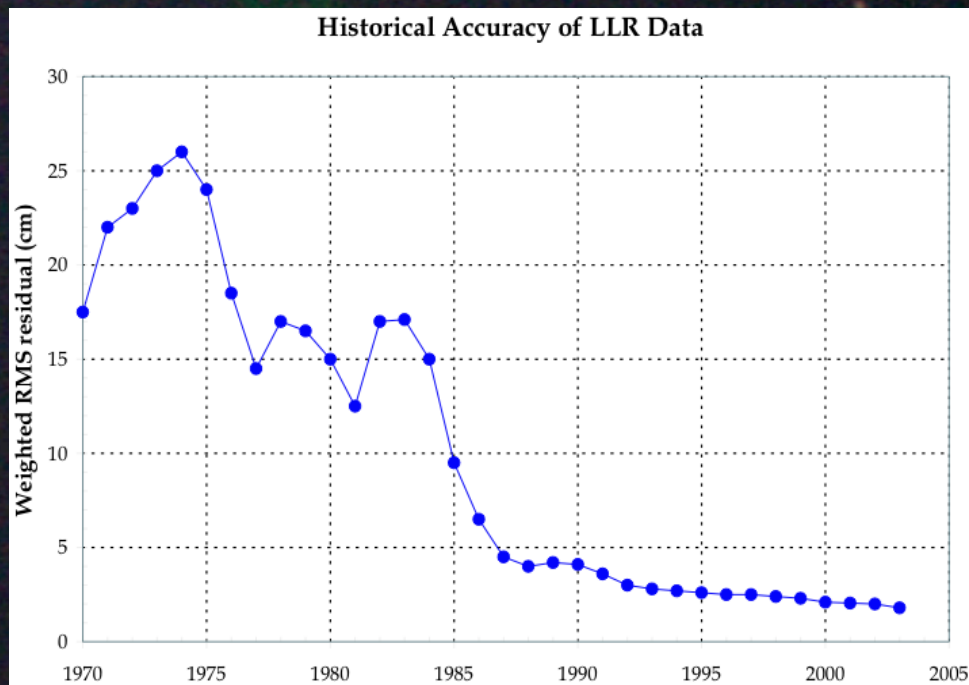
What have the Apollo Arrays Done

- The Earth-Moon System Provides an Ideal System
  - To Evaluate Relativity and Einstein's Theory
  - To Understand the Interior of the Moon
- Moon is Massive enough to Resist Drag/Pressure
- Moon is Far Enough to be in a Solar Orbit (Weakly Bound)
- LLR Currently Provides our Tests of:
  - The Weak Equivalence Principle (WEP)*: $\Delta a / a < 1.3\times10\text{-}13$
  - The Strong Equivalence Principle (SEP): $\eta = 4\beta - \gamma - 1 \quad < 4\times10^{-4}$
  - Time-Rate-of-Change of G to $< 7\times10^{-13}$ per year
  - Inverse Square Law to 3×10^{-11} at 10^{8} m scales
  - Geodetic Precession to 0.6 %
  - Gravitomagnetism to 0.1 %
  - Deviation of of $1/r^2$
    - MOND Theories of Gravitation

LIBRATION PROBLEMS

- Why is there a Problem with the Apollo Arrays
  - Lunar Librations in Tilt Both Axis by 8 degrees
  - Apollo Arrays are Tilted by the Lunar Librations
  - CCRs in Corner are Different Ranges by > 10 cm
  - Even a Very Short Laser Pulse is Spread
  - Thus a Single Photoelectron Range Uncertainty of a few cm
  - APOLLO Station of Tom Murphy UCSD
    - Thousands of Returns per Normal Point
    - Root N to Get Range to 1 – 2 millimeters
    - Needs Large Telescope
    - Hard to get Access for Daily Coverage



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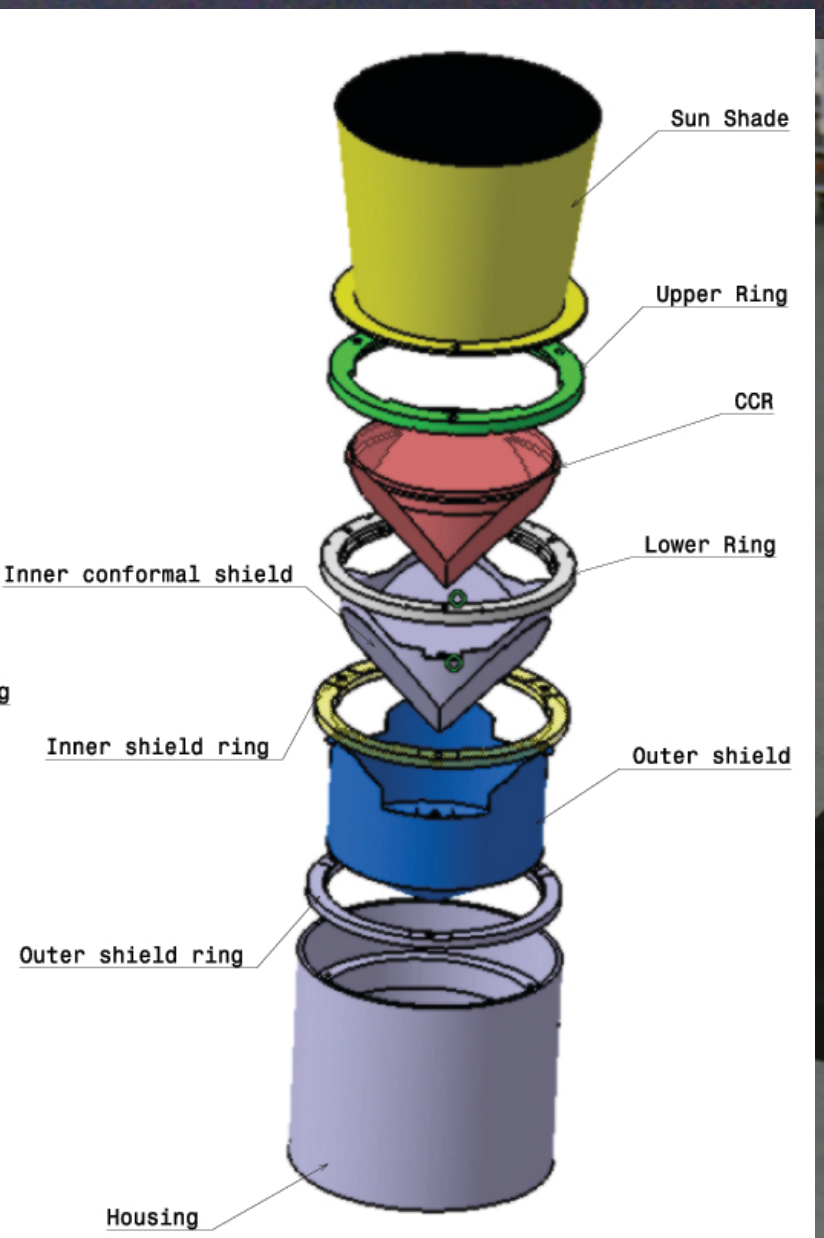
CCR FABRICATION CHALLENGE

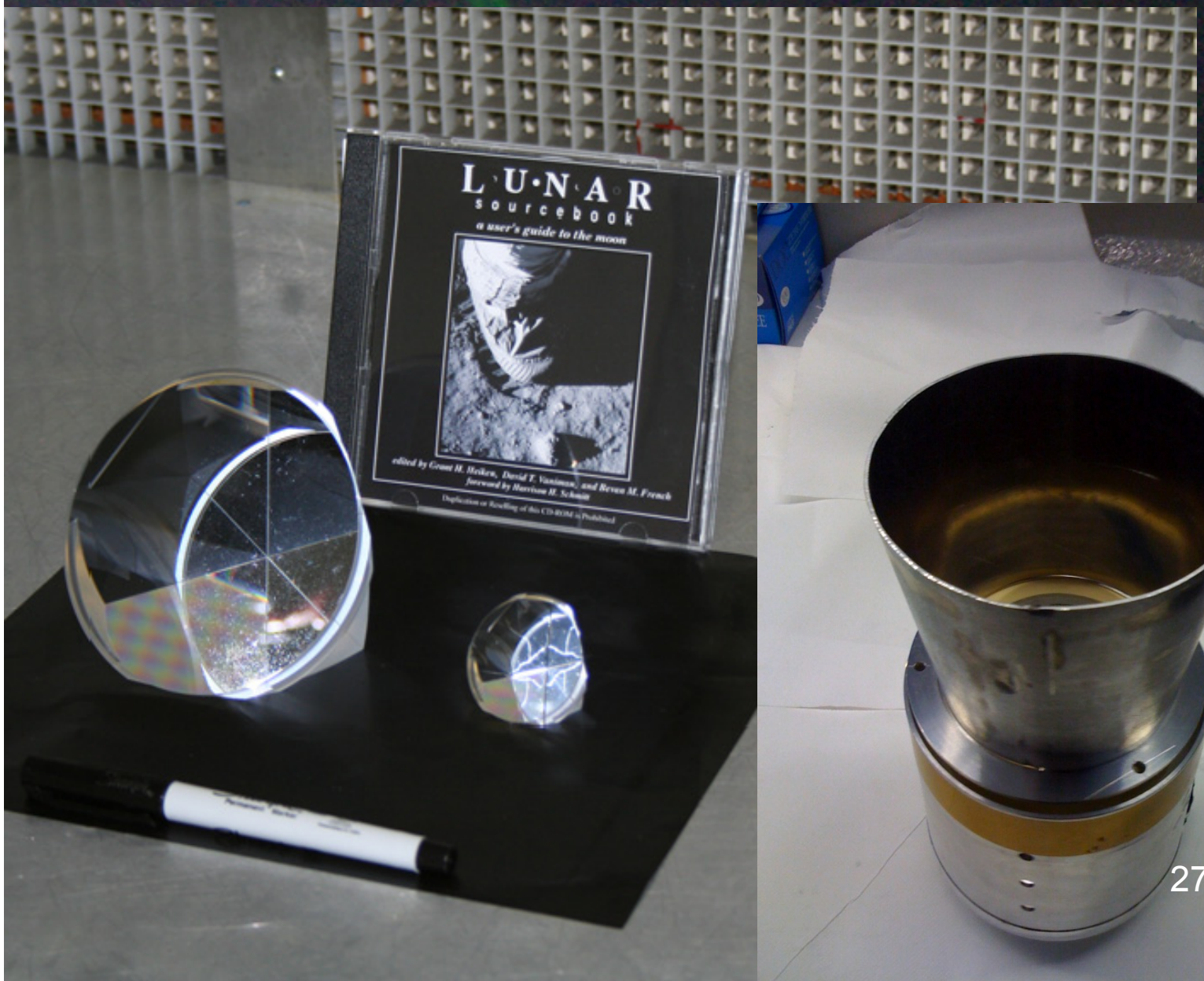
- CCR Fabrication Using SupraSil 1 Completed
- Specifications / Actual
  - Clear Aperture Diameter - 100 mm / 100 mm
  - Mechanical Configuration - Expansion of Our APOLLO
  - Wave Front Error - 0.25 / 0.15 [$\lambda/6.7$]
  - Offset Angles
    - Specification
      - **0.00”, 0.00”, 0.00” +/-0.20”**
    - Fabricated
      - **0.18”, 0.15”, 0.07”**
- Flight Qualified
  - with Certification

University of Maryland, College Park

Lunar Laser Ranging Array for the 21st Century

Nominal Package

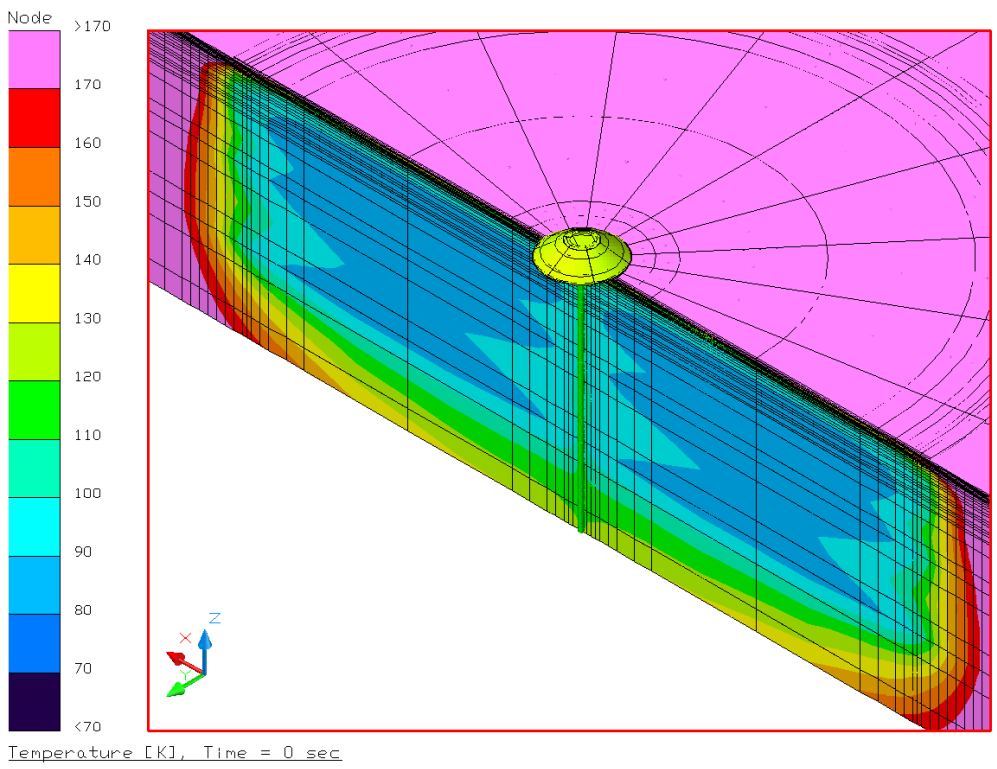


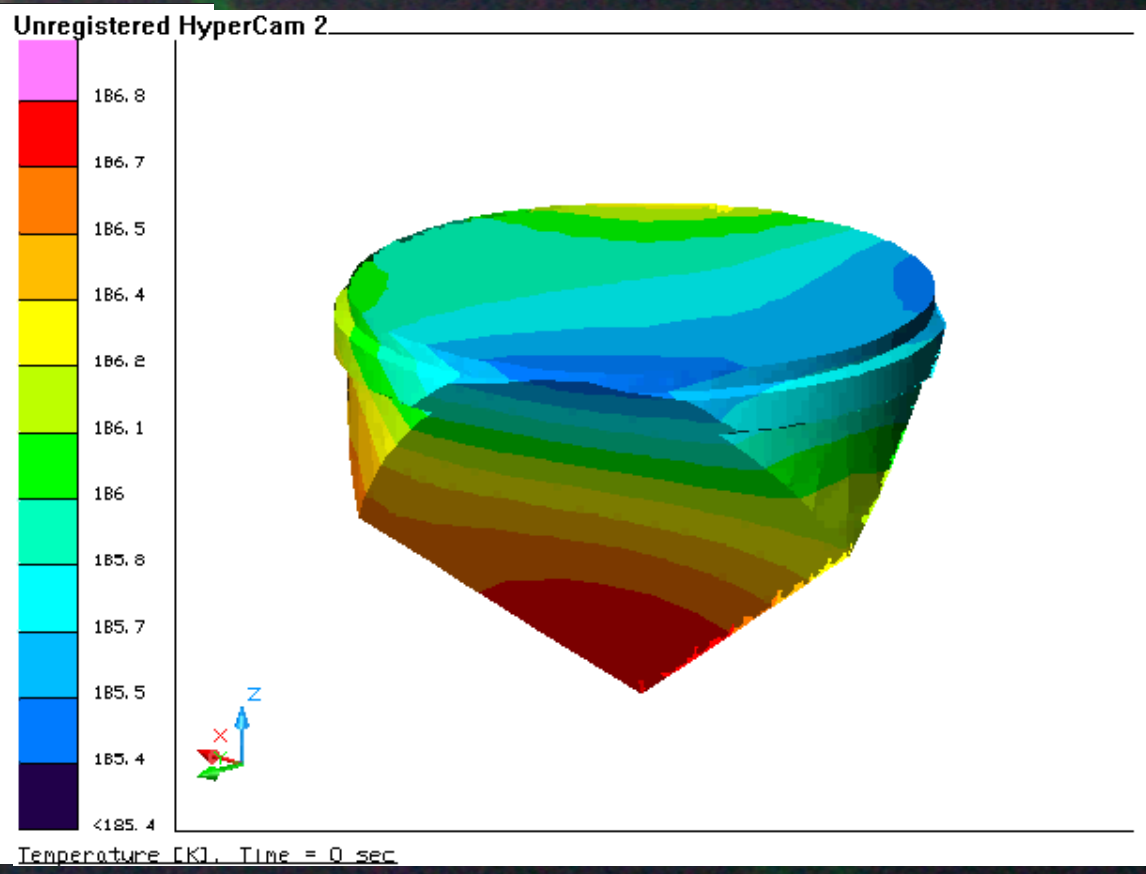


THERMAL ANALYSIS – THEORETICAL
Solar Absorption within CCR

- Solar Heat Deposition in Fused Silica
  - Solar Spectrum – AMO-2
  - Absorption Data for SupraSil 1/311
  - Compute Decay Distance for Each Wavelength
  - Compute Heat Deposition at Each Point
    - Beer's Law
  - Thermal Modeling Addresses:
    - Internal Heat Transport and Fluxes
    - Radiation from CCR to Space
    - Radiation Exchange with Internal Pocket Surroundings
    - Mount Conduction into the Support Tabs

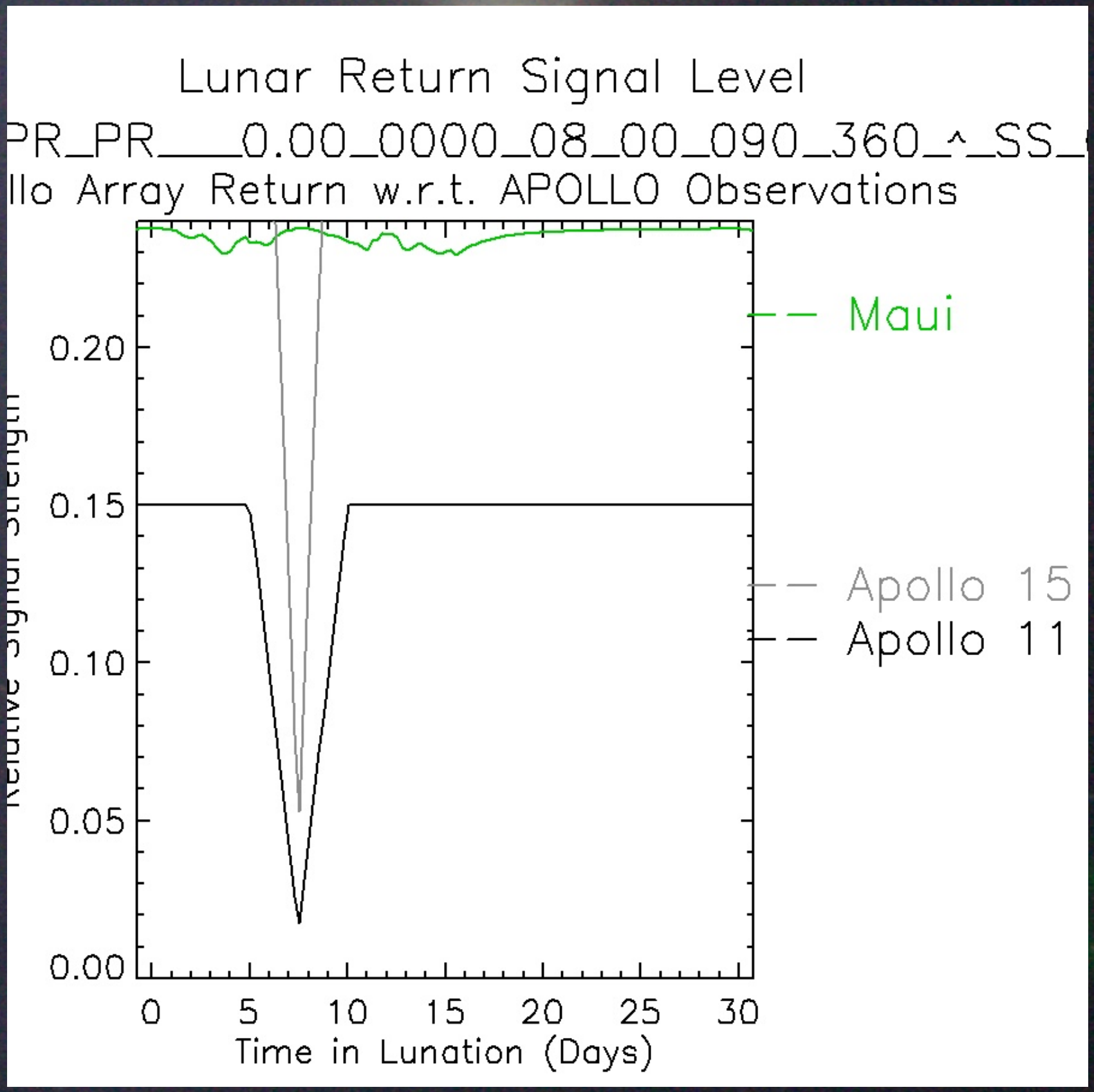
FULL Thermal Simulation





Regolith from Apollo HFE,
Thermal Blanket
Current Design Housing

Temperature Distribution
in CCR and Tip to Face
Temperature Difference


Lunar Return Signal Level
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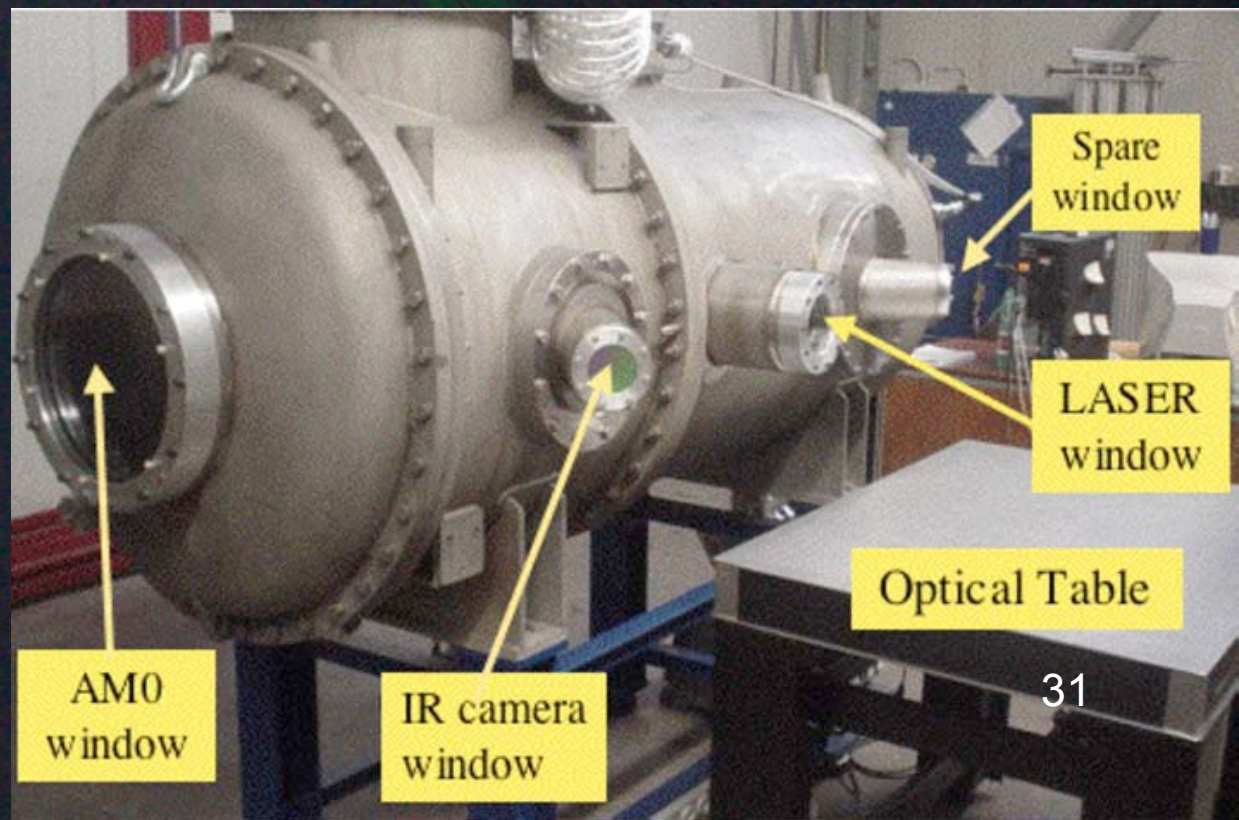
llo Array Return w.r.t. APOLLO Observations
Maui
Apollo 15
Apollo 11
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
Time in Lunation (Days)

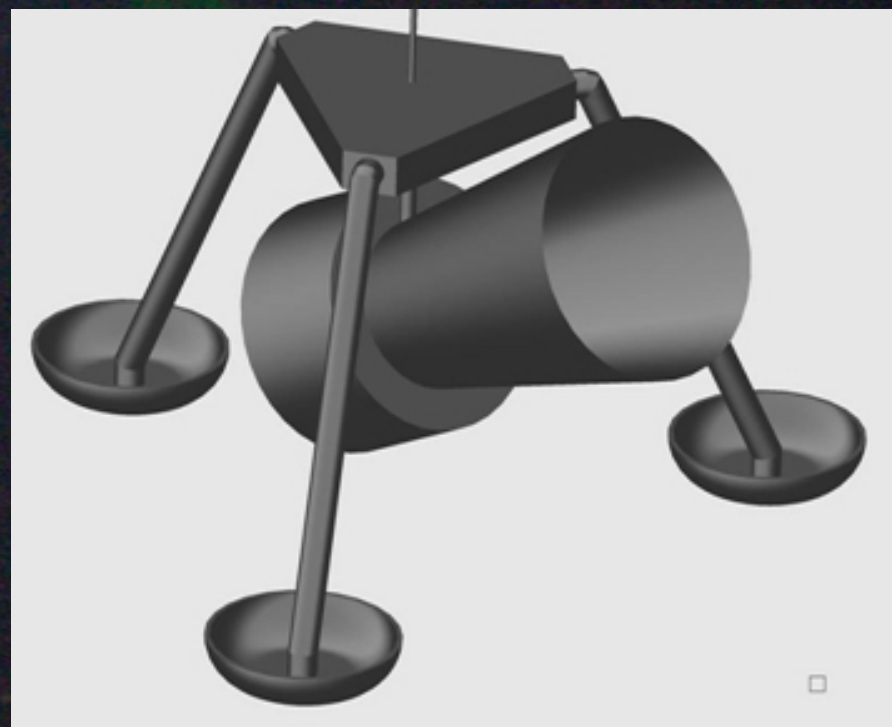
CURRENT STATUS

- Preliminary Definition of Overall Package
- Completed Preliminary Simulations
  - LSSO – Lunar Science Surface Opportunities
  - Thermal (CCR, Regolith, Housing), Optical
- Completed Phase I Thermal Vacuum Tests
  - Solar Absorption Effects on CCR
  - CCR Time Constants –
    - IR Camera – Front Face
    - Thermocouples – Volume
    - Preliminary Optical FFDP



ROBOTIC DEPLOYMENT

- Possible Deployment Methods
  - Lander Mounting
    - Single PhotoElectron Accuracy of a Few Millimeters
    - Thermal Expansion of Lander during Lunation
  - Surface Deployment
    - Single PhotoElectron Accuracy of a Sub-Millimeter
    - Regolith Expansion during Lunation
    - Needs Arm for Deployment
  - Anchored Deployment
    - SPE Accuracy of a Tens of Microns
    - Needs Regolith Drilling Procedure



LLRRA-21 & MoonEx1

LLRRA-21 Teams

- **LSSO Team – NASA**

- Douglas Currie Principal Investigator
  - University of Maryland, College Park, College Park m MD, USA
  - NLSI, Moffett Field, CA, USA &
  - INFN-LNF Frascati, Italy
- Bradford Behr
  - University of Maryland, College Park, MD, USA
- Tom Murphy
  - University of California at San Diego, San Diego, CA , USA
- Simone Dell'Agnello
  - INFN/LNF Frascati, Italy
- Giovanni Delle Monache
  - INFN/LNF Frascati, Italy
- W. David Carrier
  - Lunar Geotechnical Institute, Lakeland, FL, USA
- Roberto Vittori
  - Italian Air Force, ESA Astronaut Corps
- Ken Nordtveldt
  - Northwest Analysis, Bozeman, MT, USA
- Gia Dvali
  - New York University, New York, NY and CERN, Geneva, CH
- David Rubincam
  - GSFC/NASA, Greenbelt, MD, USA
- Arsen Hajian
  - University of Waterloo, ON, Canada

- **INFN-LNF Frascati Team**

- Simone Dell'Agnello PI INFN-LNF, Frascati, Italy
- Giovanni Delle Monache INFN-LNF, Frascati, Italy
- Douglas Currie U. of Maryland, College Park, MD, USA
- NLSI, Moffett Field, CA, USA &
- INFN-LNF, Frascati, Italy
- Roberto Vittori Italian Air Force & ESA Astronaut Corps
- Claudio Cantone INFN-LNF, Frascati, Italy
- Marco Garattini INFN-LNF, Frascati, Italy
- Alessandro Boni INFN-LNF, Frascati, Italy
- Manuele Martini INFN-LNF, Frascati, Italy
- Nicola Intaglietta INFN-LNF, Frascati, Italy
- Caterina Lops INFN-LNF, Frascati, Italy
- Riccardo March CNR-IAC & INFN-LNF, Rome, Italy
- Roberto Tauraso U. of Rome Tor Vergata & INFN-LNF
- Giovanni Bellettini U. of Rome Tor Vergata & INFN-LNF
- Mauro Maiello INFN-LNF, Frascati, Italy
- Simone Berardi INFN-LNF, Frascati, Italy
- Luca Porcelli INFN-LNF, Frascati, Italy
- Giuseppe Bianco ASI Centro di Geodesia Spaziale
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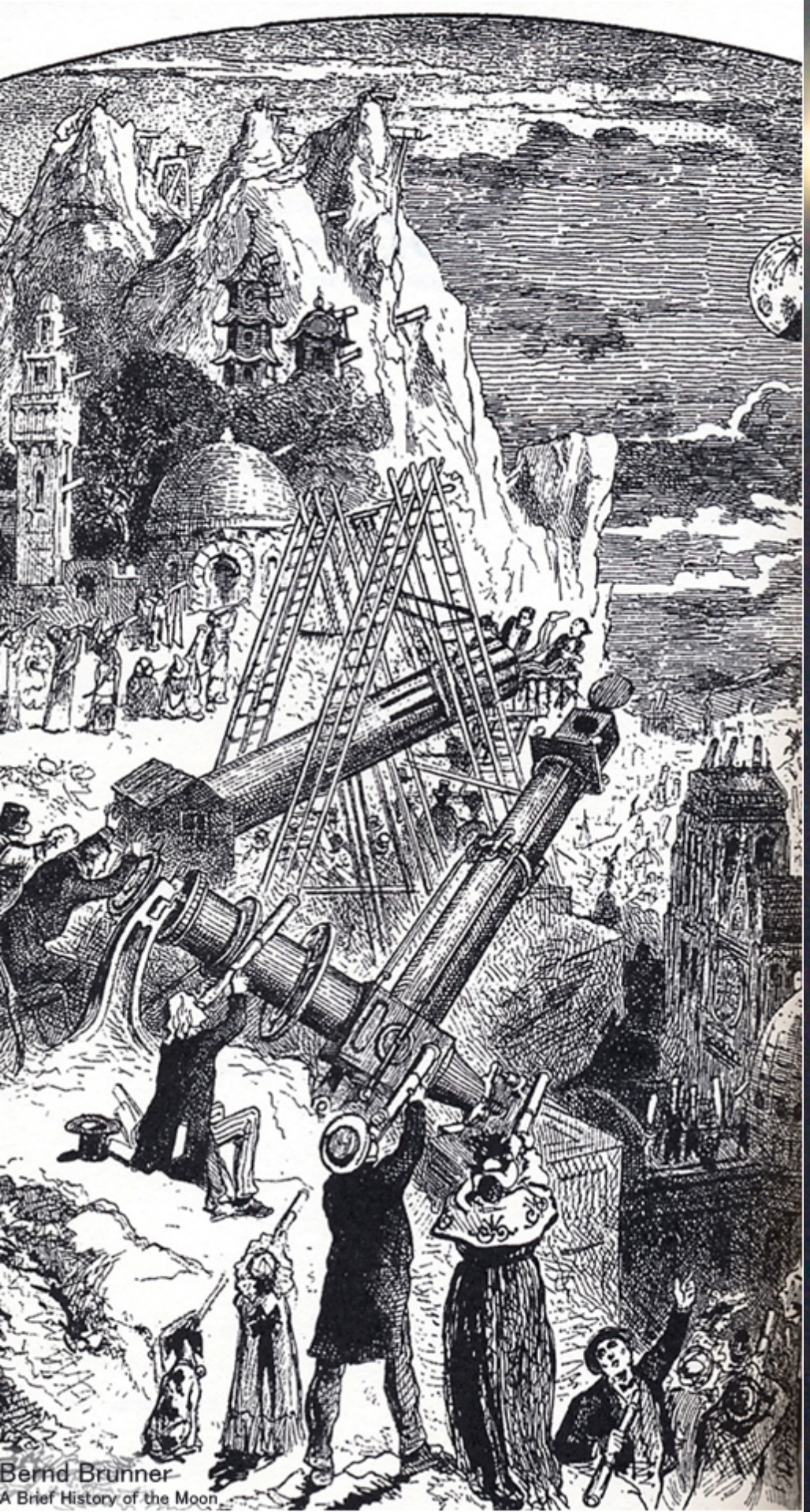
LLRRA-21 CONCLUSIONS

- LLRRA-21 Will Improve Ranging Accuracy
  - By a Factor of 10 to 100
  - Depending Upon Deployment Method
- LLRRA-21 Provides a High Return
  - Many More Observations/Month
  - Many More Laser Ground Stations
- Ready for Flight in Less than a Year
  - Package Weighs Less than 1.5 kilogram
  - No Power or Communication Required
- Google Lunar X Prize
- Extremely Cost Effective for the Quality of Science



Thank You!

any

Questions?

or

Comments?

.

with

Special Acknowledgements

to

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NASA Lunar Science Institute

Italian Space Agency

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LSSO Team

&

LUNAR Team

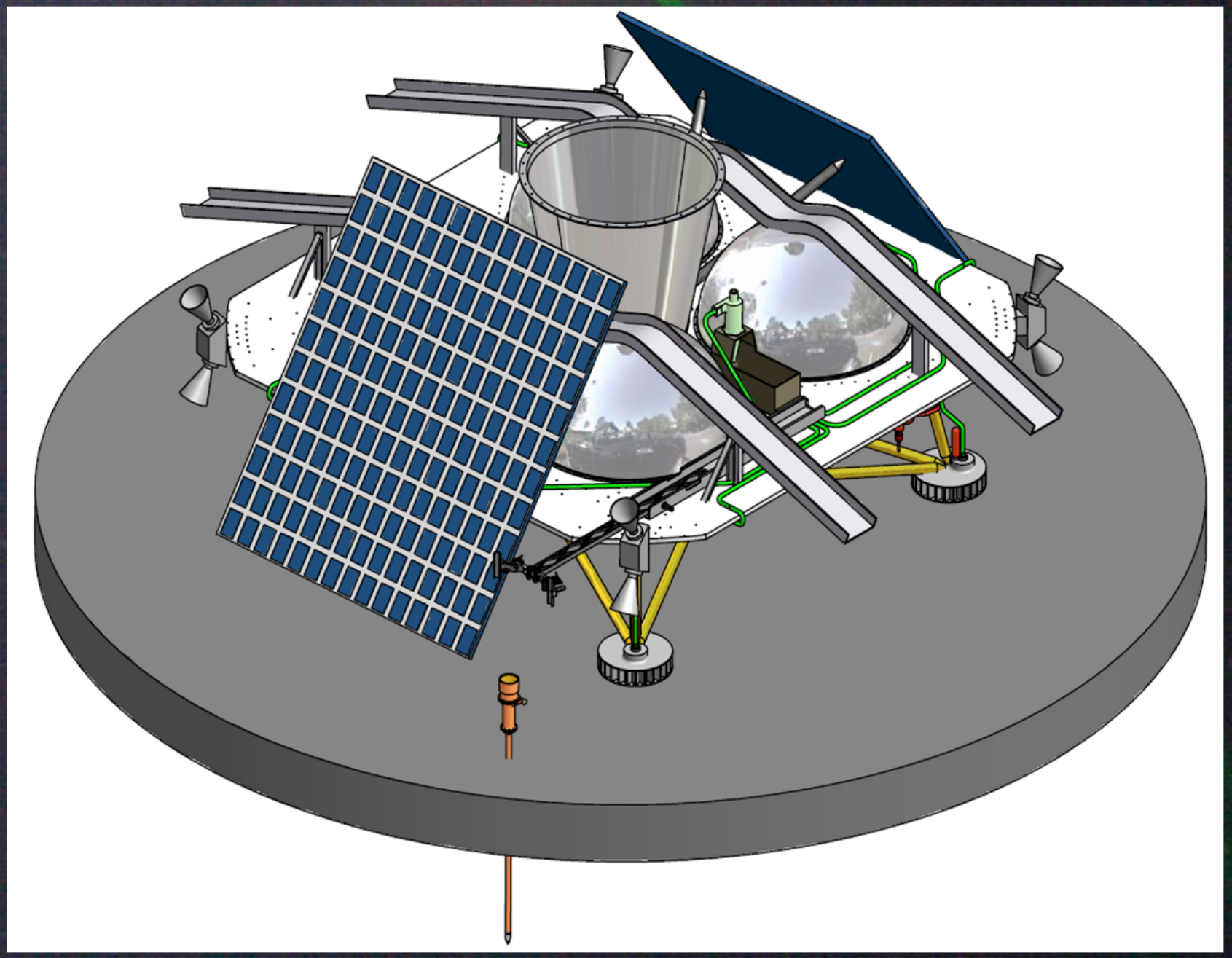
.

currie@umd.edu

Apollo 17 - Drilling
Jack Schmitt & Gene Cernan

PNEUMATIC PROBOSCIS SYSTEM
Chris Zacny – Honeybee, Inc.

Anchored Deployment
Astrobotics & Honeybee



LLRRA-21 PACKAGE