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

History and Current Status

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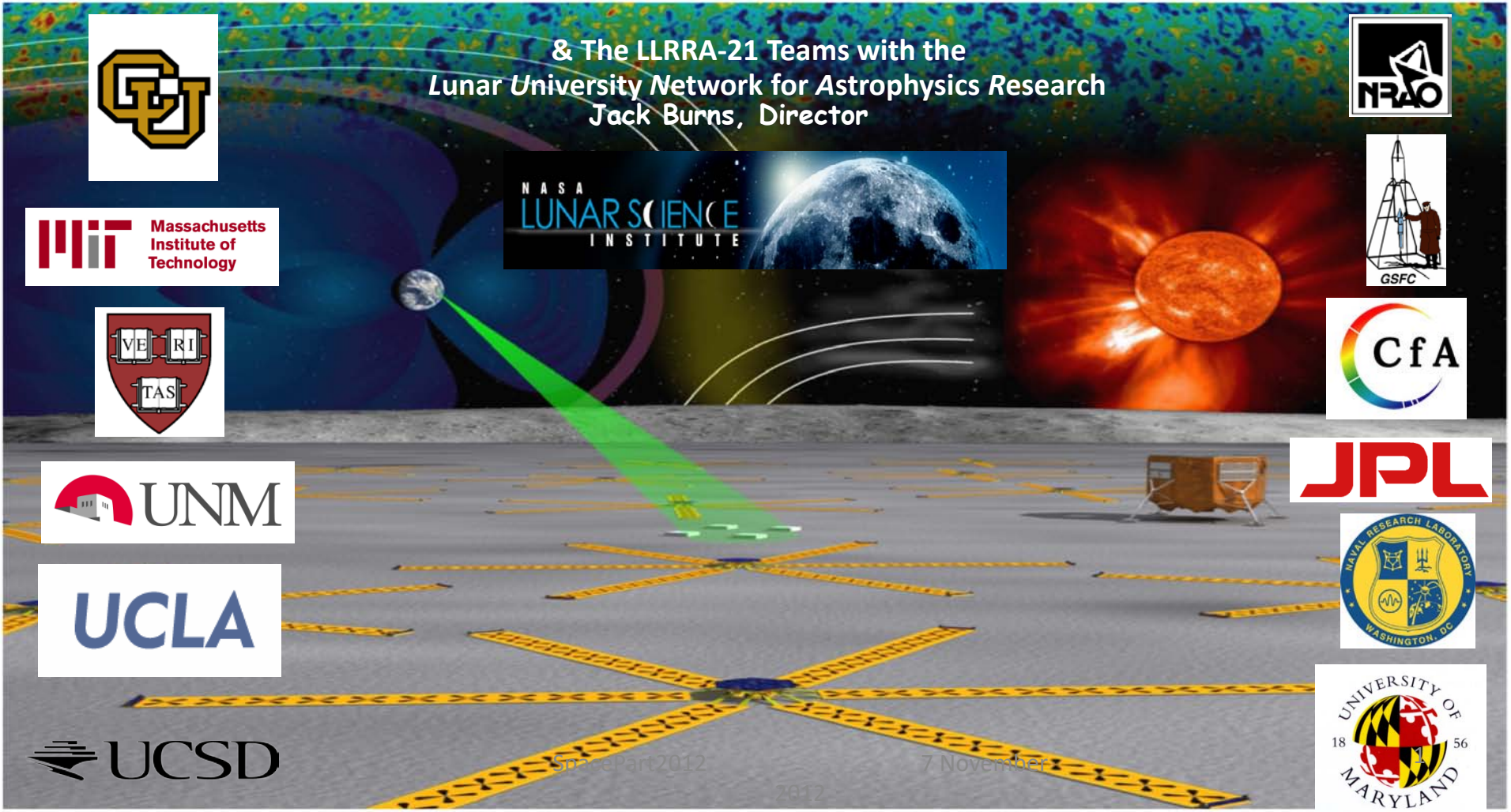

Early Aspects & Motivation

- Historically, the orbit of the moon and its distance
  - has been studied for millennia.
    - Eclipse Calculation
    - Tidal Effects
    - Formation of the Earth-Moon System
- Early in 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 oon
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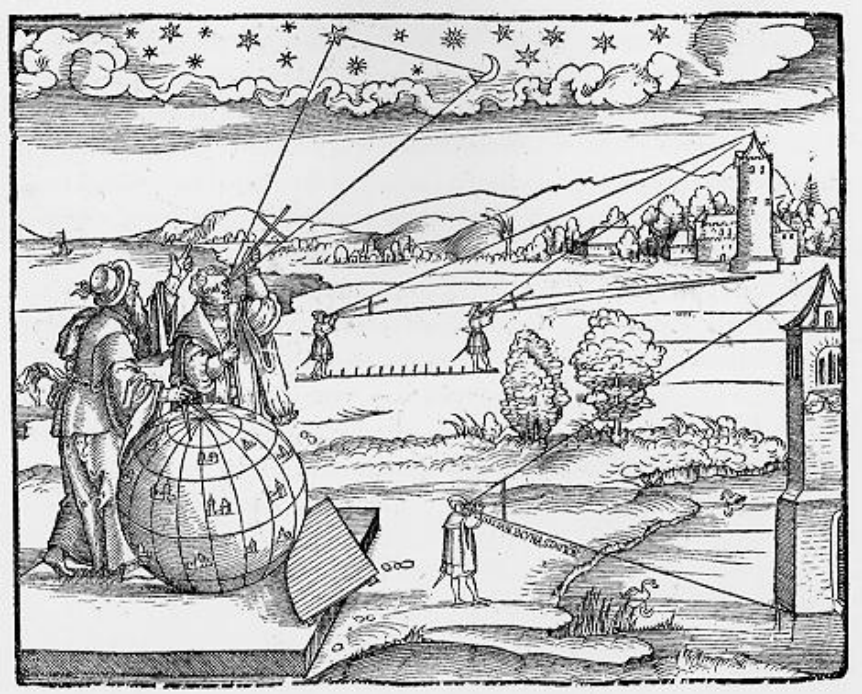
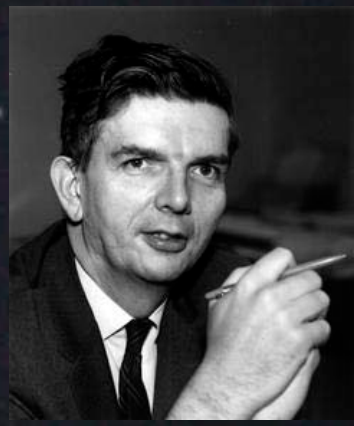
Lunar Distance - PreHistory



- Astronomical Determinatio
  - Early Greek – Hipparchus –
    - Distance to Earth Radius
- Radar Ranging
  - 1959 USNO 150 m
- Orbiting Space Craft
- Optical Ranging
- Problem:
  - Not Accurate enough for General Relativity
  - Not Accurate Enough for Lunar Interior

PreHistory of Dicke Group



- 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 Releativty
  - 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
    - Maiman Demonstrated the Laser
    - Kennedy said We are Going to put a Man on the Moon
  - Accurate Measurements could Finally be Accomplished!!!

Pre-Preparation for Apollo 11

- ALSEP – Major NASA Science Project for the Manned Landing
  - Starting Two Years before Launch
  - Major Set of Scientific Instruments
- Astronaut Input
  - Initial Practice for Deployment
  - Could Sink 30 feet into Dust
- ELSEP – Replacement Program
  - Trivial to Deploy
  - No Power Required
  - No Commination back to Earth
- Initial Feasibility Calculations for Lunar Laser Ranging
  - Bob Dicke's Group at Princeton
- Proposal Submitted to NASA –
  - Accepted for Apollo 11

Preparation for Apollo 11

- Carroll Alley at the University of Maryland takes the Lead
  - Very Short Time for Development, Evaluation and Fabriaction
- Issues Raised in Proposal Review
  - Pointing the Laser with Sufficient Accuracy (~1 arc second)
  - Surveyor Experiment – Successful Demonstration
- Selected Solid Cube Corner Reflectors
  - Uncoated (TIR) CCRs to Survive the Solar Heat Load Effects
  - With Ren-Fang Chang, We made First Analysis of a CCR using TIR
- Arthur D. Little Participated in Analysis for PDR
- Bendix Corporation was Prime Contractor for CDR
- We gave Instructions for Deployment to Buz Aldrin,
  - but Deployment was by Neil Armstrong
- Deployed!!!!!!

Lunar Laser Ranging Observatory

- Lunar Laser Ranging Observatory
  - Carroll and I Made Visits to Several Observatories
    - MacDonald Observatory at Fort Davis, Texas - Primary
    - AMOS on Maui, Hawaii
    - Lick Observatory on Hamilton Mountain, California - Backup
- Developing & Deploying Hardware for Observatory
  - Goddard Space Flight Center – Henry Plotkin
  - University of Maryland - Carroll Alley, Doug Currie, etc.
- Installation at Observatory and Initial Operation
- Successful Ranging at Lick and McDonald

Apollo 14 & Apollo 15

- Successful Deployment, Ranging and Analysis
- We Wanted to Deploy Two Addition Arrays
  - Accurately Measure the Lunar Librations
    - For Lunar Physics - Internal Physical Properties
    - For GR – Determine the Position of the CoM Accurately
  - These were Approved and
    - Apollo 14 and 15 were Deployed
- Apollo Arrays & Two Soviet Union Lunahod Arrays
  - Still Operating and
- New Science Being Produced
  - Jim Williams at JPL

Historical Science Results

- General Relativity Tests
  - Strong Equivalence Principle
    - Different Materials Fall toward the Sun at the Same Rate
  - Inertial Properties of Gravitational Energy
    - Moon is Harder to Push due to Inertia of Gravitational Energy
  - Change of gravitational constant
    - With Time – 1% in the Life of the Universe
    - In Space – No Yakawa Behavior of Gravity Between Earth and Moon
- Lunar Physics
  - Liquid Core – discovery, size, shape
  - "Q" of the Moon – Internal Dissipation

Status, perspective at the LLR sites

- McDonald - lunar tracking at low level
- Matera re-started in spring 2010 - lunar tracking at low level
- APOLLO - good LLR data until end of 2010 (new detector required refined pre-processing → reduced accuracy, i.e. cm instead of mm level), problem fixed in 2012
- Grasse re-started by end of 2009, less returns in 2010/2011, good performance since end of 2011; new offices (2012) for staff far away; more publications needed
- Wettzell will (soon) resume – first attempts, but problems with the new SLR system have to be resolved first

Main research at lunar analysis centers

- Jet Propulsion Laboratory (JPL), Jim Williams recovered
  - lunar interior, lunar core
  - relativity
- Paris Observatory Lunar Analysis Center (POLAC)
  - libration theory
  - reference frames
- Institute of Geodesy (IfE), new project funding
  - relativity
  - Earth orientation
  - lunar interior
- Others: special topics ...

Results - relativity

Parameter	Results
Nordtvedt parameter η (violation of the strong equivalence principle)	$(3 \pm 3.6) \cdot 10^{-4}$
time variable gravitational constant $\dot{G}/G\,[yr^{-1}]$ $\ddot{G}/G\,[yr^{-2}]$ (→ unification of the fundamental interactions)	$(1 \pm 2.5) \cdot 10^{-13}$ $(4 \pm 5) \cdot 10^{-15}$
difference of geodetic precession $\Omega_{GP} - \Omega_{deSit}$ [″/cy] (1.92 ″/cy predicted by Einstein's theory of gravitation)	$(6 \pm 9) \cdot 10^{-3}$
metric parameter γ - 1 (space curvature; γ = 1 in Einstein)	$(4 \pm 5) \cdot 10^{-3}$
metric parameter β - 1 (non-linearity; β = 1) or using $\eta = 4\beta - \gamma_{Cassini} - 3$ with $\gamma_{Cassini}$-1 (~10^{-5})	$(-2 \pm 4) \cdot 10^{-3}$ $(0.8 \pm 1.0) \cdot 10^{-4}$

Müller et al., CQG 2012

Results – relativity (2)

Parameter	Results
Yukawa coupling constant $\alpha_{\lambda=400\,000\ \mathrm{km}}$ (test of Newton's inverse square law for the Earth-Moon distance)	$(3 \pm 2) \cdot 10^{-11}$
special relativity $\zeta_1 - \zeta_0 - 1$ (search for a preferred frame within special relativity)	$(-5 \pm 12) \cdot 10^{-5}$
influence of dark matter δ_{gc} [cm/s^2] (in the center of the galaxy; test of strong equivalence principle)	$(0 \pm 2) \cdot 10^{-14}$
preferred frame effects α_1 α_2 (coupled with velocity of the solar system)	$(-4 \pm 9) \cdot 10^{-5}$ $(2 \pm 2) \cdot 10^{-5}$
preferred frame effect α_1 (coupled with dynamics within the solar system)	$(1.6 \pm 3) \cdot 10^{-3}$

Current Limitations

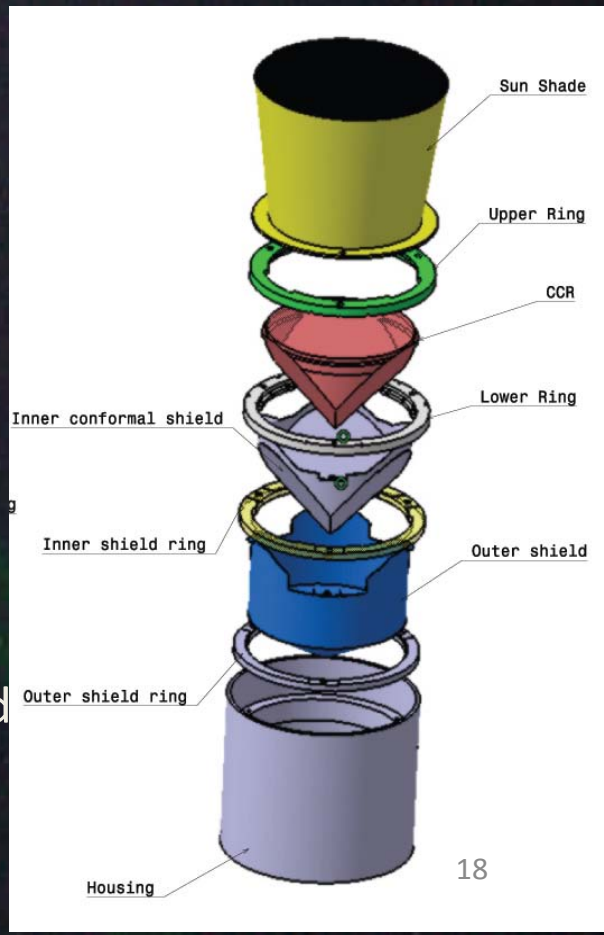
- Why Consider Next Gerenation Retroreflectors?
  - Continual Operation, Continual New Science
- Ground stations have improved by a Factor of 200
  - Arrays Support Only about ~7 cm/Single Shot,
  - 10 to 100 Returns can Create 1-2 for Normal Points
  - Many Thousands of Returns at APOLLO Observatory
    - 1-2 mm a few times a month
- Agreement Between Observations and Fitted Theory has Plateaued
  - ~2 cm – Over the Past Two Decades
- Reason for only ~ 7 cm for Single Shot Precision
  - Lunar Librations Tilt the Arrays, w.r.t. Earth
  - Do not know which CCR in which Corner
    - of the Panel Reflected the Photon ~ 20 cm
- LLRRA-21 Addresses New Science Directions via
  - With Improved Accuracy
  - With More Participating Observatories
  - With More Frequenct Observations

Road to Next Generation RR

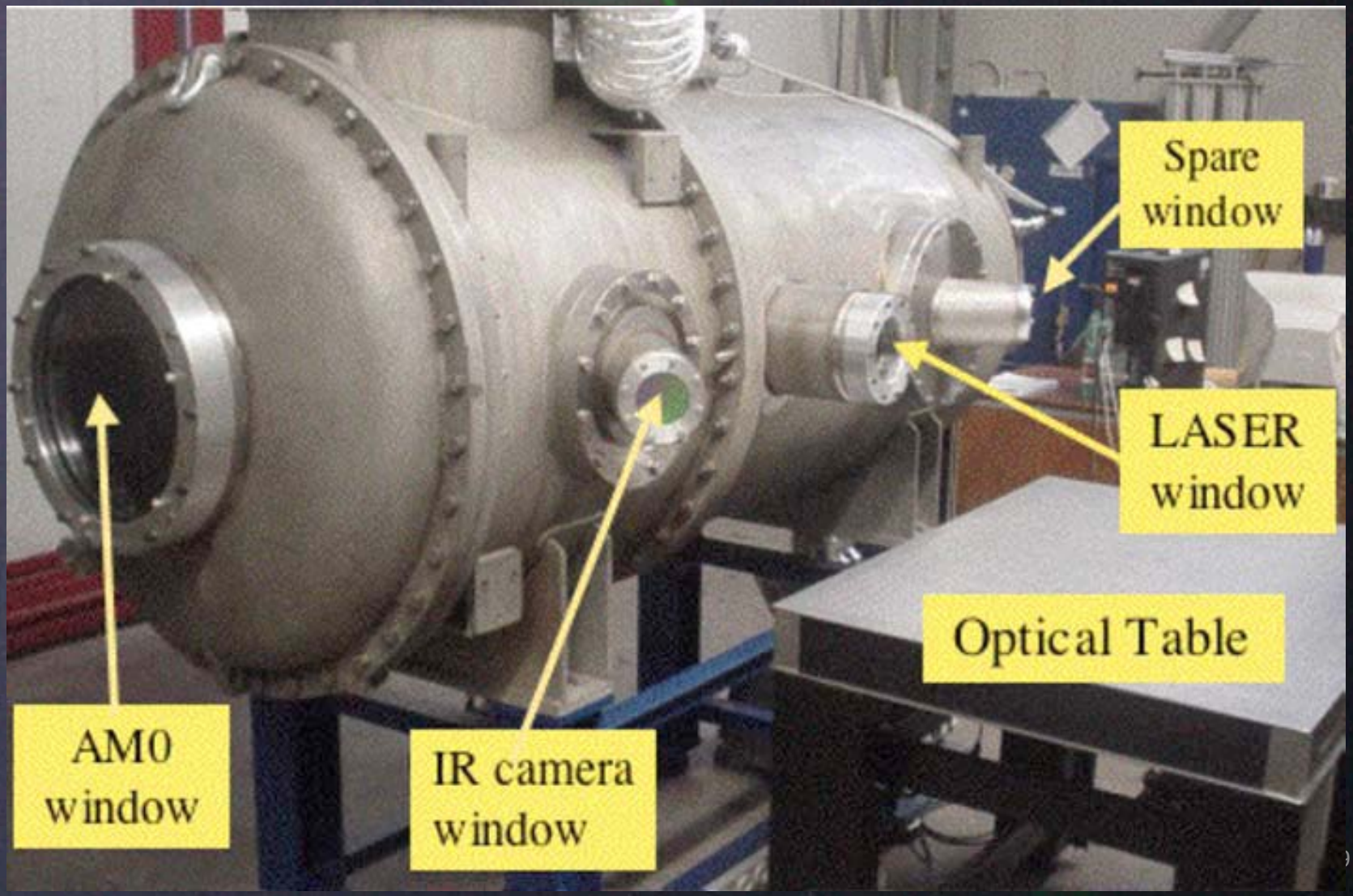
- Historically, Apollo and Lunahod Arrays Consist of:
  - Panels of Small Solid Cube Corner Retroreflectors
- NASA Lunar Science Sortie Opportunities
  - 2007 Program Defining Science for a Manned Landing
  - Start of the
  - Lunar Laser Ranging Retroreflector Array for 21st Century
  - A.k.a. "LLRRA-21"
- NASA Lunar Science Institute
  - Funded Our "LUNAR" Proposal
  - Cosmology, Heliophysics plus GR & Lunar Physics via LLR
- Resulted in a Collaboration with INFN-LNF in Frascati, Italy
  - Unique Facility for the Optical/Thermal/Vacuum Testing
  - Collaboration on Thermal Modeling and Analysis of Ranging Data

Design Objectives of LLRRA-21

- A Large Single Cube Corner Retroreflector
  - Not a Panel of Small CCRs
- LLRRA-21/ MOONLight
  - Single 100 mm Solid CCR
  - Can Support Accuracy of < 0.1 mm
- Very Strong Heritage
  - for Current LLRRA-21 Design
  - Science –
    - Relativity and Lunar Physics Results of Past
  - Technology – Many hundreds of CCRs
    - On Moon and in Space
    - All the Same Design as for Apollo, Just Scaled



SCF_LAB in INFN-LNF in Frascati Develped by Sinone Dell'Agnello



INTERNATIONAL COLLABORATIONS

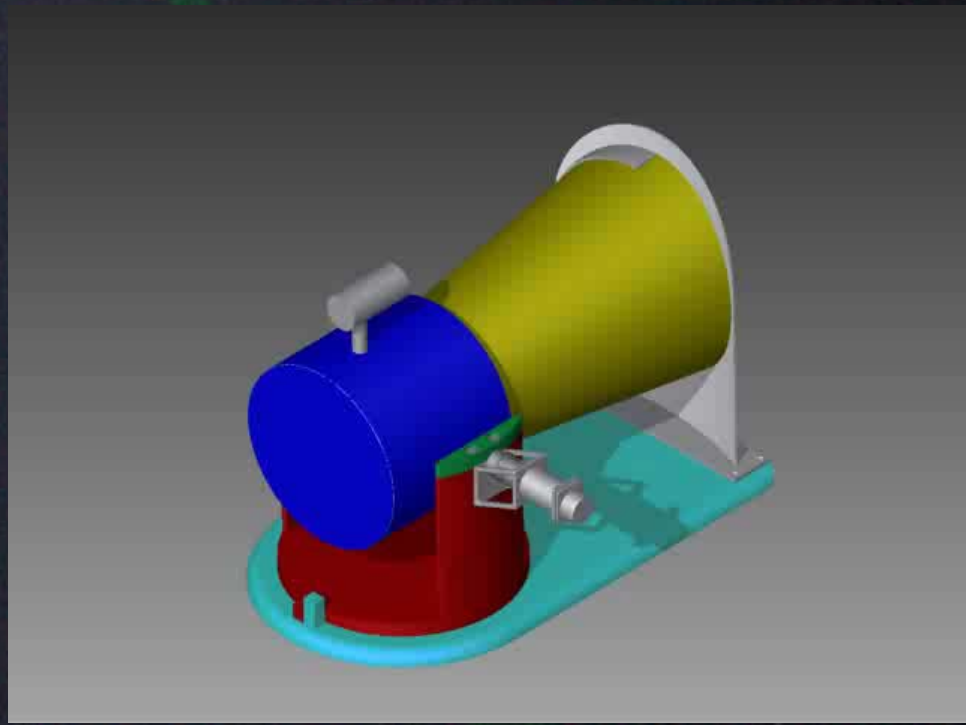
- INFN-LNF and the University of Maryland
- Recently Signed Agreement between
  - Japan Aerospace Exploration Agency (JAXA)
  - National Astronomical Observatory of Japan (NAOJ)
  - INFN-LNF at Frascati and the
  - University of Maryland
- Current Discussions with
  - European Space Agency
  - Their Lunar Lander

Deployments and Flights for LLRRA-21

- Three Methods for Lunar Deployment
  - Lander Deployment Would Support
    - Easiest
    - Day/Night Thermal Motion 1-2 cm
  - Surface Deployment Would Support
    - Needs Arm
    - Day/Night Thermal Motion 1-2 mm
  - Sub-Surface Anchored Deployment Would Support
    - Needs Pneumatic Drilling (Honeybee)
    - Day/Night Thermal Motion < 100 microns
- Possible Flights Currently being Investigated
  - Moon Express – a Google Lunar X Prize Team
  - ESA Lunar Lander – Under Consideration by Ministerial Council

Pointing Requirements

- Need to Point to Center of Libration Pattern
  - About +/- 1 degree
- Landers Lack this Accuracy in Landing Orientation
- LLRRA-21 Needs an Automatic Pointing System
- CMOS Camera for Alignment
- Needs Only a Start Pulse
- Operational Sequence
  - Point to Zenith
  - Take a Camera Exposure
  - Fit Earth Image (On-Board)
  - If Missing -Search off Zenith
- Lock Brakes



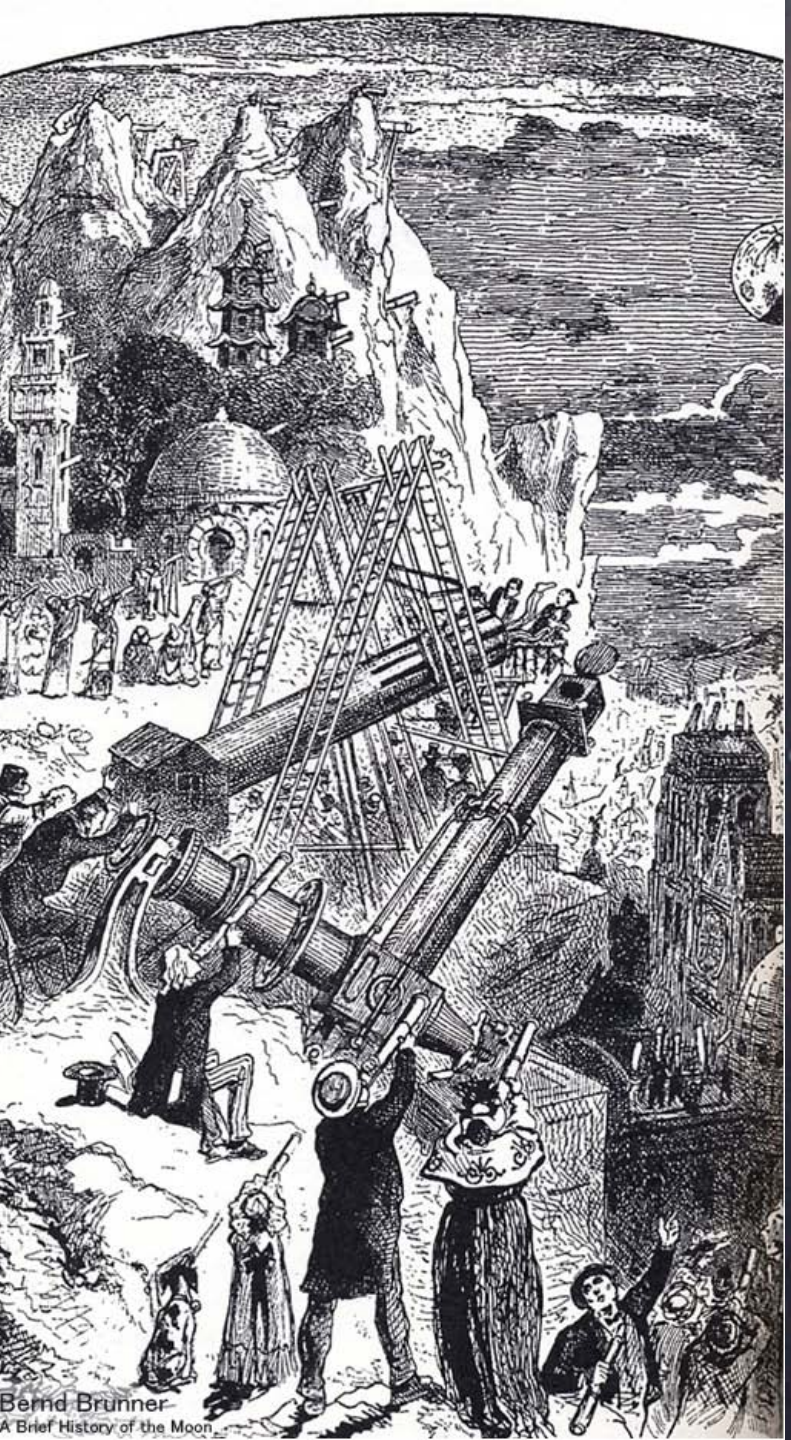
New Science for LLRRA-21

- Ranging Accuracy Improves by factor of 10 to 100
- Enable Multiple Stations to Join Ranging Team
- Evaluate Theories that Address QM-GR Problem
  - Evaluate Alternative Relativity Theories
  - Strong Equivalence Principle - SEP
  - Change of Gravitational "Constant"
    - Temporal (<<1%) and Spatial
- Lunar Physics
  - Core Mantle Properties
  - Inner Solid Core

FUTURE PLANS

- Objectives Over the Next Year
  - Confirm and Obtain Support for Flights
  - Optimize Design for Lander and Landing Site
  - Address Upgrades of Current Lunar Observatories
  - Continue to Upgrade Analysis Programs

- The Next Year will be Exciting



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

.

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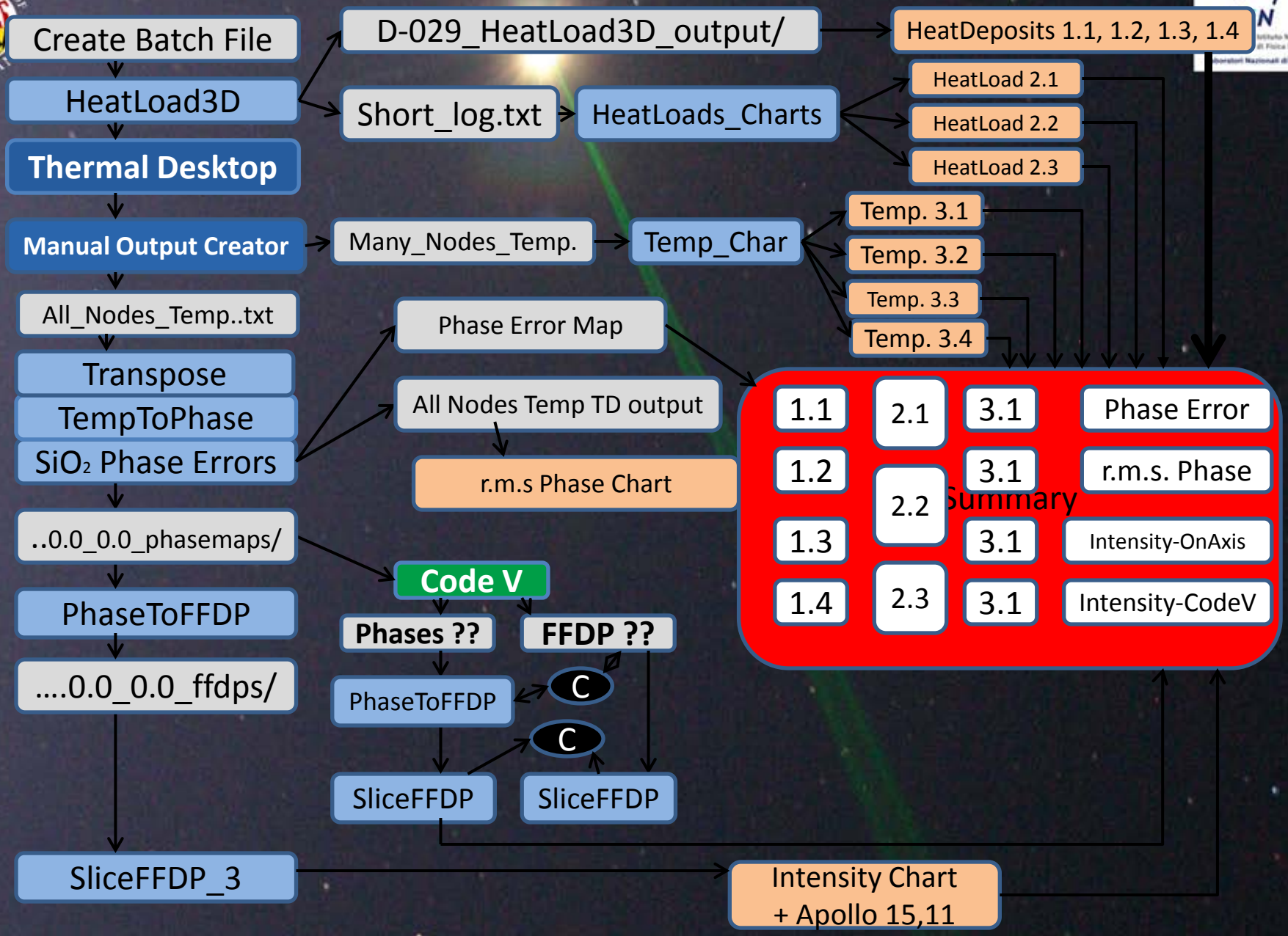
backup

LLRRA-21 Thermal/Optical Simulation



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

CLOE
Evolution via Bombardment

BROWN
Origin of Terrestrial Planets

DREAM
Dynamics of Exosphere

COSMOLOGY

LUNAR LASER RANGING

HELIOPHYSICS

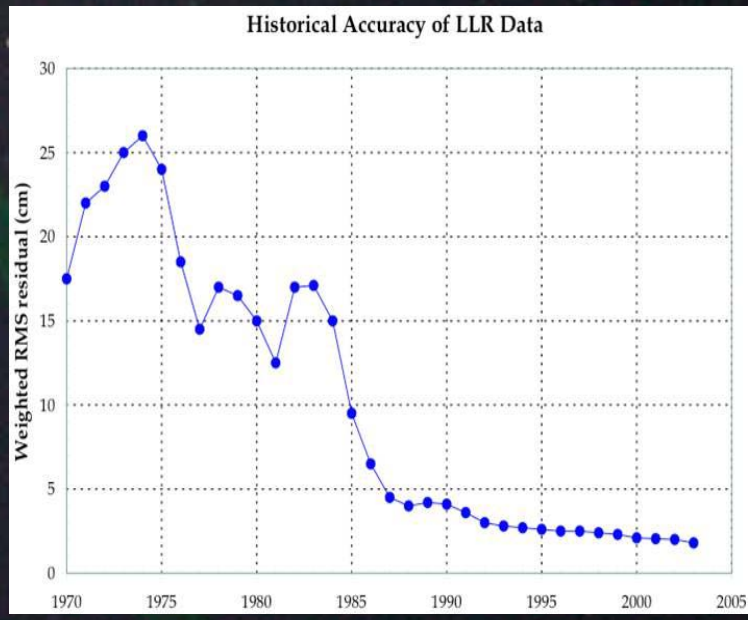
UCSD
APOLLO Station

Lunar Laser Ranging Retroreflector Array for the 21st Century
University of Maryland, College Park

GSFC
Open CCR

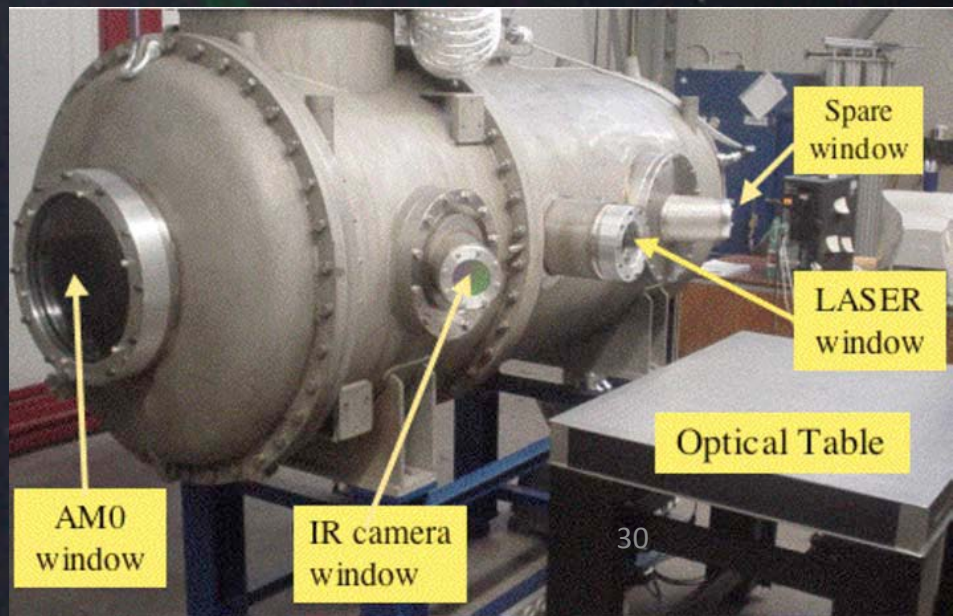
SHORT HISTORY of LLRRA-21

- 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



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



Organization structurre

Simulation program

cosmology