



Frascati Intro

Llrra-21 Design
Cape Photo – scan
Logos on background
Cut Moon

Early Aspects & Motivation

- Historically, the Orbit of the Moon
 - Has been Studied for Millennia
 - Navigation
 - Eclipse Prediction
 - Tidal Tables
 - 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 moon
 - As it relates to the Formation Question

Early Aspects & Motivation

- Perceived as a God or Goddess in Many Cultures
- Historically, the orbit of the moon
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Lunar Distance - PreHistory

- Astronomical
 - 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 Relativity
 - Considered Ranging to the Surface with Spotlight
 - Insufficient Accuracy – Ranging from the Surface
 - Insufficient Signal – 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
 - This could Work!!!





Pre-Preparation for Apollo 11

- ALSEP – 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
- Feasibility Calculations for LLR
 - 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
- Issues Raised in Proposal Review
 - Pointing the Laser with Sufficient Accuracy (~ 1 arc second)
 - Surveyor – Successful Demonstration
- Selected Solid Cube Corner Reflectors
 - Uncoated (TIR) CCRs to Survive the Solar Heat Load Effects
 - With Ren-Fang Chang, I made First Analysis of Return from a TIR CCR
- Arthur D. Little Participated in Analysis for PDR
- Bendix Corporation was Prime Contractor for CDR
- Instructions for Deployment to Buz Aldrin,
 - but Deployment was by Neil Armstrong
 - Quote from Neil
- 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 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 Deployed
- Apollo Arrays & 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 – Between Earth and Moon
- Lunar Physics
 - Liquid Core – discovery, size, shape
 - “Q” of the Moon – Internal Dissipation

Current Limitations

- Why Consider Next Generation 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
- LLRRA-21 Addresses New Science Directions via
 - With Improved Accuracy
 - With More Participating Observatories
 - With More Frequent Observations

