ATMOSPHERIC EFFECTS and the ULTIMATE RANGING ACCURACY for LUNAR LASER RANGING

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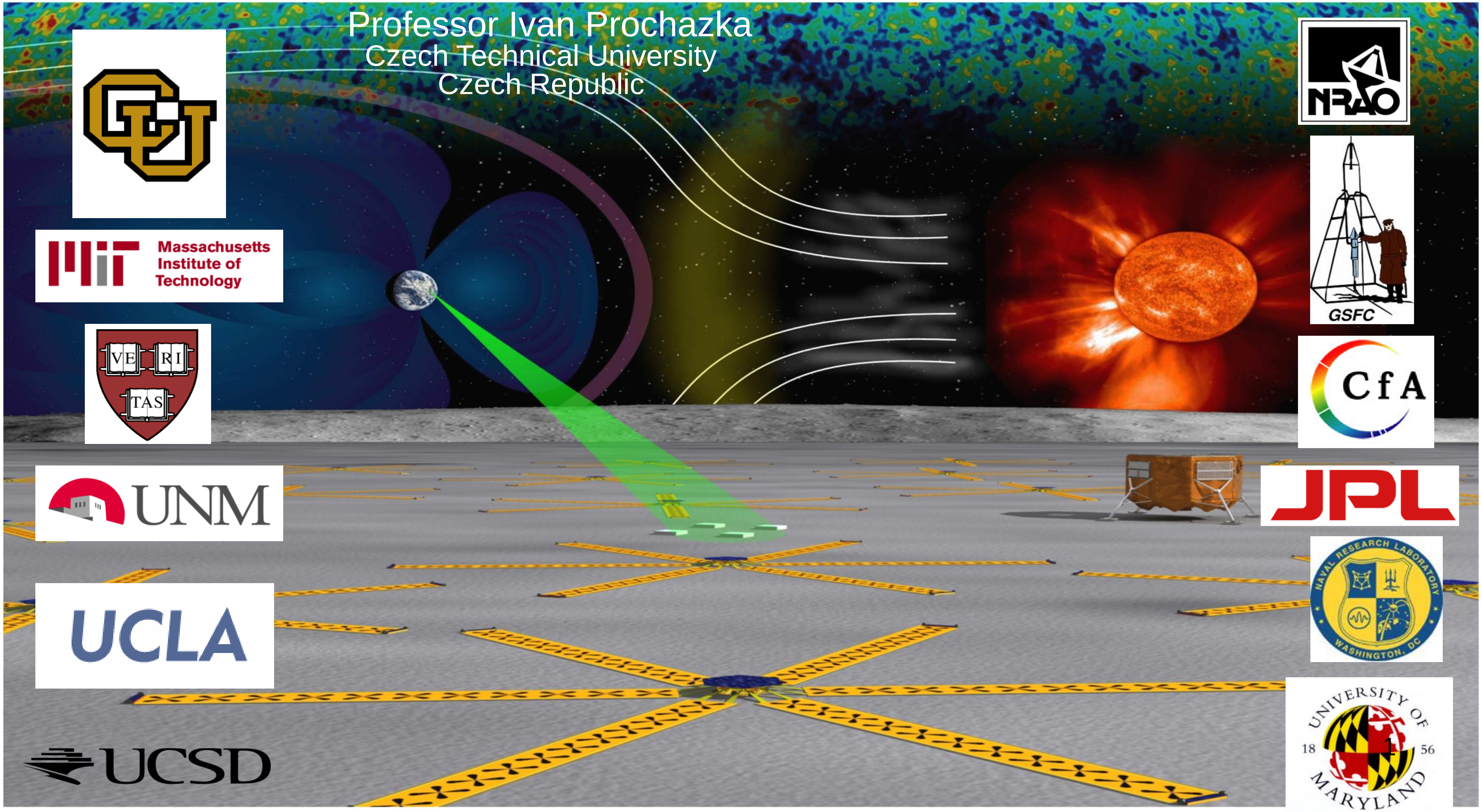


CURRENT SCIENCE ISSUES

- Open Questions in Cosmology and Fundamental Physics
  - Nature of Dark Matter
    - Gravitational Observations are the Only Clue to Date
    - Addressed by the MOND Theories
    - However, For Now – I will Leave This to the Particle Talks
  - Nature of Dark Energy
    - SuperNova Discoveries of Acceleration of Distant Galaxies
    - Einstein' Lambda Constant
    - Quintessence
  - Relation between GR and Quantum Mechanics
    - Attempts toward the Quantization of Gravity
    - String Theory implies Variation of Fundamental Constants

GRAVITATIONAL & GR SCIENCE

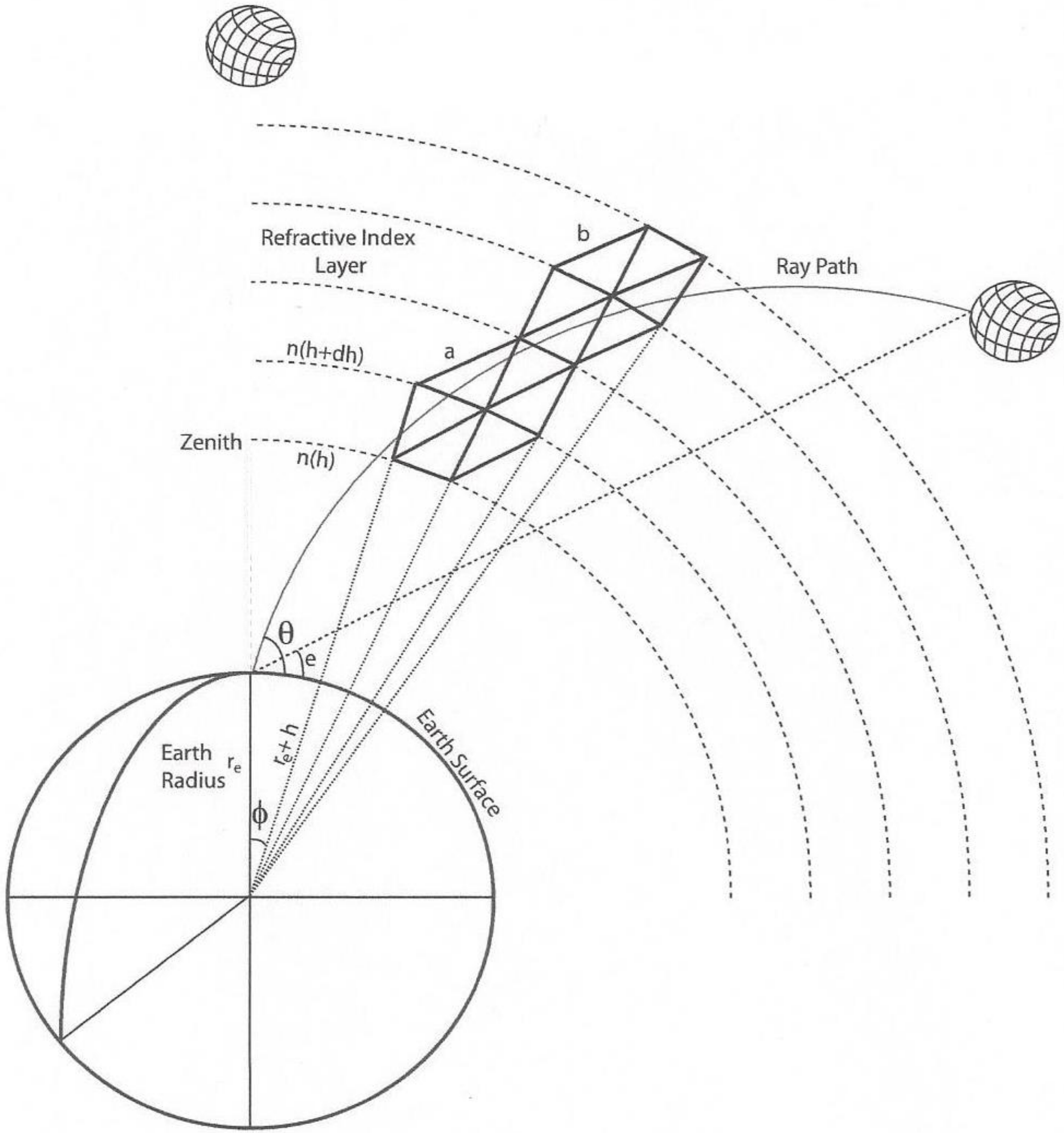
- LLR Currently Provides our Best Tests of:
  - **The Strong Equivalence Principle (SEP)**
  - **Time Rate-of-Change of *G***
  - **Inverse Square Law, Deviation of 1/r**
  - **Geodetic Precession**
  - **The Weak Equivalence Principle (WEP)**
  - **Gravitomagnetism**

CHALLENGES FOR ALLRP

- To Achieve mm and/or sub-mm LLR Accuracy
  – For an Order of Magnitude Improvement in Science
- A) Deploy Three LLRRA-21s on the Moon
- B) Analysis of Upgrade Paths for Current GSs
- C) Improve GS Hardware, Software and Ops
- D) Upgrade Analysis and Scientific Software
- E) Geophysical Effects
- F) **Understanding the Earth's Atmosphere**

ATMOSPHERIC EFFECTS

- During two way path from earth to moon
  - Pulse Spreading Normal to Flight Direction
  - Path of Centroid is Altered – Tilts
  - Temporal Delay - Changing Index of Refraction
- No Comprehensive Data for Combined Effects
- Discussion will Divide into Two Domains
  - Short Term – Local "High Frequency" Effects
  - Long term – Large Scale "Slow", 'Biases"



Refractive Index
Layer
b
Ray Path
a
n(h+dh)
Zenith
n(h)
θ
e
Earth Surface
Earth
Radius
r_e
r_e+ h
ϕ

Pavlis

OUTLINE

- Simulations
  - – Short Term Effects – Normal Points
    - Computations of Turbulence using GLAD
  - – Long Term Effects – Biases
    - Estimates of the Magnitude of the Horizontal Gradinets
- Observations
  - – Short Term
    - Satellite Ranging Observations
  - – Long Term
    - Satellite Ranging Estimates

LUNAR vs. SLR SCIENCE

- SLR Science Observations
  - Need Data Down to 10º Elevation
  - Domain for Most Analysis of Atmospheric Effects

- Lunar Science Observations
  - Gravitation and General Relativity Tests
  - Rotational Properties of the Moon
  - Current Lunar Laser Ranging Ground Stations
  - Observations Conducted between 40º and 30º Elevation

SHORT TERM EFFECTS Simulations

- Shot-to-Shot Variation in Timing of Delay
- Limits Precision of Mean Value of Normal Point
- Theoretical Estimate of Delay using GLAD
  - Ground to Ground
    - 6.0 km Path - Cn2 = 10^-13 – Lo = 10 m
    - RMS of 0.9 mm Shot to Shot
  - Ground to LEO Satellite –
    - 40 degrees Elevation Hufnagfel-Valley Cn2 - Lo = 100m
    - RMS of 0.4 mm Shot to Shot

LONG TERM EFFECTS

- Delay Computed from Met at Ranging Station
  - Pressure, Temperature and Humidity
  - Excellent Accuracy for Zenith Pass
- Zenith Observations Never Possible for Moon
- Almost All Observations at 40º or 30º Elevation
  - Need to Compute Off-Zenith Effects
- Assume Spherically Symmetric Atmosphere
  - But Horizontal Gradients in Pressure, Temperature &H
  - Heat Island, Weather Effects, Wind on Topology
- Need to Evaluate Magnitude of These Effects

LONG TERM EFFECTS Simulations

- Martini & Mendes
  - – Spherically Symmetric Atmosphere
  - – RMS Of Day to Day Estimates of Bias
    - 4.9 mm at 10º – 0.7 mm at 40º – 333 mm at 30º
- Gardner
  - – Radiosondes for Horizontal Gradients
  - – RMS Of Day to Day Estimates of Bias
    - 8.7 mm at 10º – 2.4 mm at 40º – 333 mm at 30º

LONG TERM EFFECTS Simulations

- Hulley and Pavlis – AIRS
  - Satellite Estimation of Horizontal Gradients
  - Ground Resolution ~ 250 km
  - RMS Of Day to Day Estimates of Bias

- Hulley and Pavlis – Weather
  - Surface Estimates of Horizontal Gradients
  - RMS Of Day to Day Estimates of Bias
  - Ground Resolution – ~50 km

MAGNITUDE OF PREDICTIONS

Hulley and Pavlis

Station	Method	N-S Gradient mean 10° mm	N-S Gradient r.m.s 10° mm	N-S Gradient mean 40° mm	N-S Gradient r.m.s 40° mm	E-W Gradient mean 10° mm	E-W Gradient r.m.s 10° mm	E-W Gradient mean 40° mm	E-W Gradient r.m.s 40° mm
McDonald	ART	+0.6	+7.0	+0.0	+0.4	-2.7	+6.0	+0.2	+0.4
Fort Davis,	NRT	-0.2	+0.6	+0.0	+0.0	-1.0	+3.1	+0.0	+0.2
MLRO	ART	-2.1	+4.5	+0.1	+0.3	+1.8	+4.7	+0.1	+0.3
Materia,	NRT	-0.5	+8.4	+0.0	+0.5	-0.4	+7.5	+0.0	+0.5

- Average r.m.s. at 10° for both stations and for both computations 5.36 mm

SHORT TERM EFFECTS Observations

- Ranging Experiments at GRAZ
- Ground to Ground 4.3 km Path - 2" Seeing
  - Shot to Shot - 0.35 mm
    - Compares with GLAD Simulation Prediction
    - 1.8 mm for 6 km path
- Ground to LEO Satellite – 36.6^{o} Elevation
  - Shot to Shot - 0.40 mm
    - Compare with GLAD Simulation Prediction
    - 0.40 mm for 40^{o} elevation and Lo = 100 m

LONG TERM EFFECTS Observations

- Detailed Comparison
  - Computed Results with Observations
  - Day by Day Difference between
    - Laser Ranging and Ray Trace with Horizontal Gradients
  - By Hulley & Pavlis
  - LAGEOS I & II
  - Over Two Years Ranging Experiments

  - 5 mm at 10º – 0.36 mm at 40º – 0.6 mm at 30º

SUMMARY

- Short Term – Shot to Shot Variation in a NP
  - Simulation in GLAD at 40º
    - 0.4 mm for L_o = 100 m
  - Observation at GRAZ at 36.6º
    - 0.4 mm at 36.6º elevation
- Long Term – Bias of a Normal Point
  - Simulation with ARIS and NCEP - DtDay
    - 5.36 mm at 10º – 0.39 mm at 40º – 0.65 mm at 30º
  - Observation with LAGEOS vs. Simulation - wOrb
    - 5 mm at 10º – 0.36 mm at 40º – 0.60 mm at 30º

FUTURE DIRECTIONS

- Obtain Existing Analysis Results
  - E.g., Hulley and Pavlis
  - Integrate into Analysis Structure
- Investigate Better Weather Models
  - Local Topology
    - 1 km resolution (at least for the lower atmosphere)
  - XXX
- Rework Short Term GLAD Analyses
  - Address Existing Lunar Stations
- Investigate Better Measurement Systems
  - E.g., Advanced DIMM Systems

ANCHORED EMPLACEMENT

- Lunar Day/Night Temperature Variation
  - 70 K to 400 K at Equator
  - Expansion of Lander and the Surface of the Regolith
- At 1 meter, Negligible Temperature Change

10-20 -> 5 -> 5 > 3

  - Anchor at depth and INVAR/SiC Support to CCR
- Requires Drilling into Regolith
  - Difficult During Apollo
  - Video from Astronaut Jack Schmidt

Regolith Drilling in Apollo

Kriz Zacny at HoneyBee

19th International Workshop on Laser Ranging
27-31 October 2014
Annapolis, MD

ACCOMPLISHING 0.1 mm

- High Accuracy Short Term
  - Normal Point - 15 Returns – 0.1 mm
- Long High Accuracy Long Term
  - Lidar Data
    - Need Regular Observations
    - Current and French Satellites
  - Need a Program for Regular Reduction of Data
    - In the Manner of Hulley & Pavlis
  - Remote Met Stations
    - Need Analytic Justification & Field Tests

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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