ATMOSPHERIC EFFECTS and the ULTIMATE RANGING ACCURACY for LUNAR LASER RANGING

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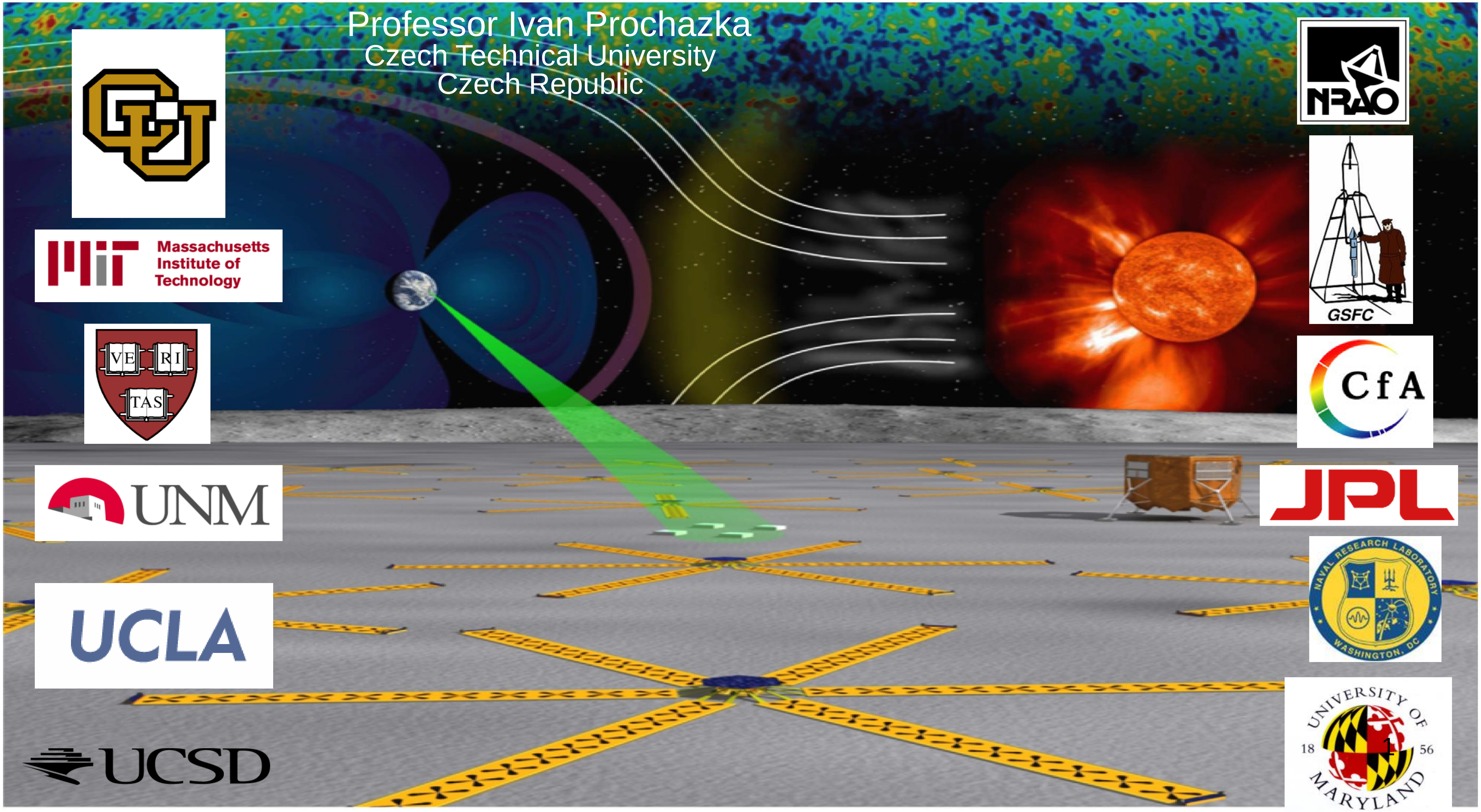


CURRENT SCIENCE ISSUES

- 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
    - This could be Explained by Einstein' Lambda Constant
    - Or Spatial and/or Temporal Changes in Lambda - Quintessence
  - Relation between GR and Quantum Mechanics
    - Attempts toward the Quantization of Gravity
    - String Theory implies Variation of Fundamental Constants

GRAVITATIONAL & GR SCIENCE

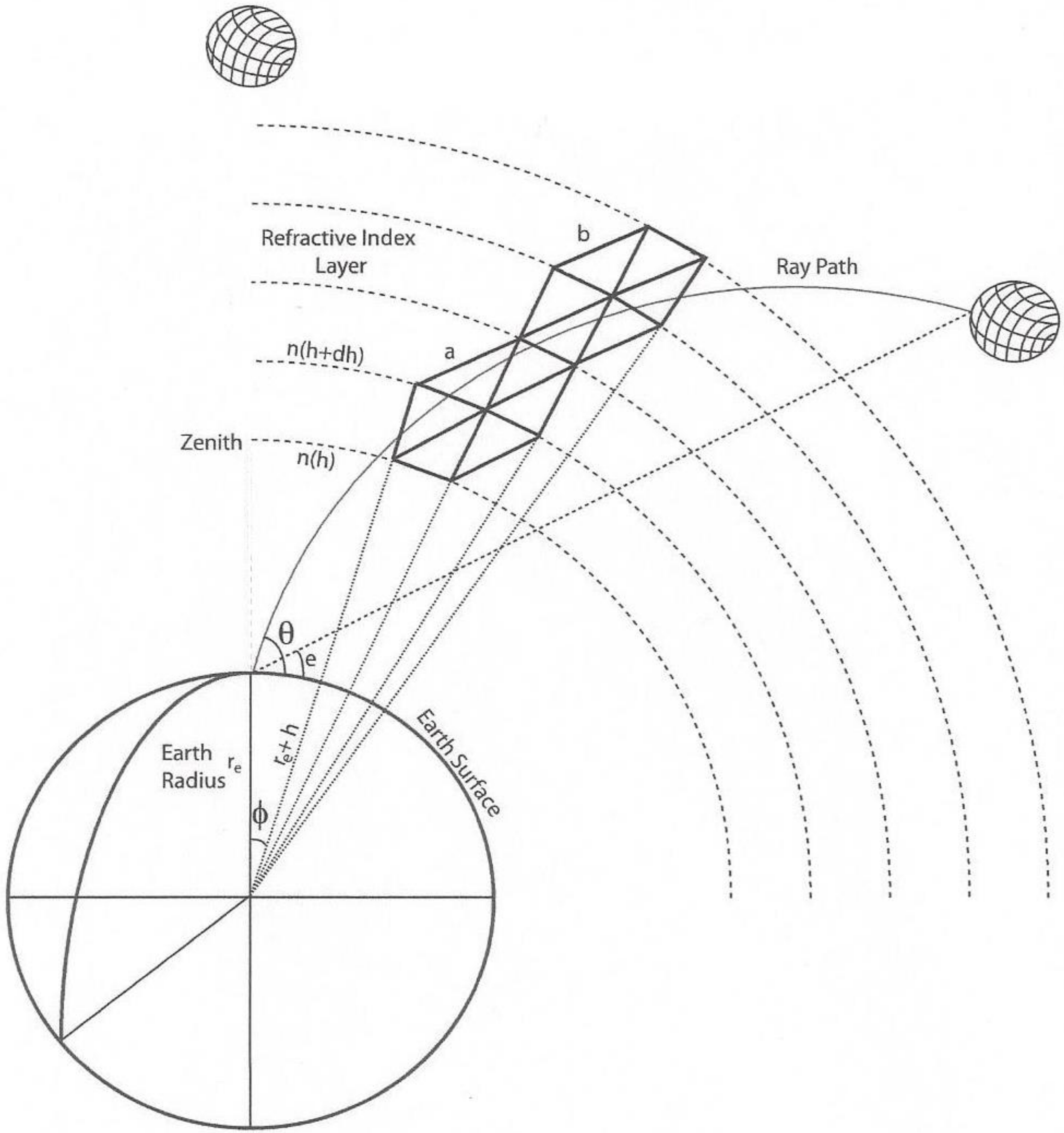
- LLR Currently Provides our Best Tests of:
  - **Strong Equivalence Principle (SEP)   15**
  - **Time Rate-of-Change of *G*   47**
  - **Inverse Square Law, Deviation of 1/r   56**
  - **The Weak Equivalence Principle (WEP)**
  - **Gravitomagnetism**
  - ALLRP Improvement by **XX** over Current by 2030

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) Analyze Upgrade Paths for Current L & S GSs
- C) Improve GS Hardware, Software and Ops
- D) Upgrade Analysis and Scientific Software
- E) Geophysical Effects – Ocean Tides, Rainfall, etc.
- F) **Understanding the Earth's Atmosphere**

ATMOSPHERIC EFFECTS

- During two way path from earth to moon
  - – Pulse Spreading Normal to Flight Direction
  - – Temporal Delay - Path of Centroid is Altered
  - – Turbulence Effects - 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
Radius
r_e
$r_e + h$
ϕ
Earth Surface

Pavlis

OUTLINE

- Simulations
  - Short Term Effects – Achieving Good Normal Points
    - Computations of Turbulence using GLAD
  - Long Term Effects – Biases
    - Estimates of the Magnitude of the Horizontal Gradients
- Satellite Observations
  - Short Term
    - Satellite Ranging Observations of EVISAT
  - Long Term
    - Satellite Ranging Observations of LAGEOS

LUNAR vs. SLR SCIENCE

- SLR Science Observations
  - SLR Science Needs 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
  - Given Locations of Current Lunar Laser Ranging GS
  - 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
  – For a Given Number of Shots
- Theoretical Estimate of Delay using GLAD
  – Ground to LEO Satellite –
    - 40^o Elevation
    - Hufnagfel-Valley
    - $C_n^2 = 10^{-13}$ $L_o = 100$m
  – 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 Observations
- Zenith Observations Never Possible for Moon
- Almost All Observations at 40º or 30º Elevation
  - Need to Compute Off-Zenith Effects
- Could 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

- Gardner
  - Radiosondes for Horizontal Gradients
  - RMS Of Day to Day Estimates of Bias
    - 8.7 mm at 10º – 2.4 mm at 40º

LONG TERM EFFECTS Simulations

- Hulley and Pavlis – AIRS
  - Satellite Estimation of Horizontal Gradients
  - Ground Resolution ~ 50 km
  - RMS Of Day to Day Estimates of Bias

- Hulley and Pavlis – Weather - NCEP
  - Surface Estimates of Horizontal Gradients
  - RMS Of Day to Day Estimates of Bias
  - Ground Resolution – ~250 km

MAGNITUDE OF PREDICTIONS

Hulley and Pavlis

Station	Method	N-S Gradient mean 10º mm	N-S Gradient r.m.s 10º mm	N-S Gradient mean 40º mm	N-S Gradient r.m.s 40º mm	E-W Gradient mean 10º mm	E-W Gradient r.m.s 10º mm	E-W Gradient mean 40º mm	E-W Gradient r.m.s 40º mm
McDonald	ART	+0.6	+7.0	+0.2	+1.9	-2.7	+6.0	+0.7	+1.6
Fort Davis,	NRT	-0.2	+0.6	+0.0	+0.1	-1.0	+3.1	+0.3	+0.8
MLRO	ART	-2.1	+4.5	+0.5	+0.4	+1.8	+4.7	+0.5	+1.3
Materia,	NRT	-0.5	+8.4	+0.1	+0.8	-0.4	+7.5	+0.1	+2.0

- Average r.m.s. at 10º/40º for both stations and for both computations 7.5/2.0 mm

SHORT TERM EFFECTS Observations

- Ranging Experiments at GRAZ Observatory
  - Conducted Ranging to EVISAT Satellite
  - Need to Remove Instrumental Effects

- Ground to LEO Satellite – 36.6^{o} Elevation
  - Observed RMS Shot to Shot Variation - **0.40 mm**

LONG TERM EFFECTS Observations

- Detailed Comparison
  - Between Computed Results with Observations
  - Thus for Each Day This Difference between
    - Laser Ranging and Ray Trace with Horizontal Gradients
  - Analysis Performed By Hulley & Pavlis
  - LAGEOS I & II
  - Analysis of Two Years of Ranging Observations

- 5 mm at 10º – **1.35 mm at 40º** – 1.74 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 – Day to Day
    - **7.2 mm at 10º – 2.00 mm at 40º – 2.50 mm at 30º**
  - Observation with LAGEOS vs. Simulation
    - **5 mm at 10º – 1.35 mm at 40º – 1.47 mm at 30º**

FUTURE DIRECTIONS

- Obtain Existing Analysis Results of Biases
  - E.g., Like Hulley and Pavlis at 10^{o}
  - Integrate This into the Current Analysis Structure
- Investigate Better Weather Models
  - Inclusion of Local Topology and Cloud Patterns
    - 1 km resolution (at least for the lower atmosphere)
  - NCEP -> WRF - World Research and Forecasting System
- Rework Short Term GLAD Analyses
  - Address the Detailed Parameters of Existing Lunar Stations
- Investigate Better Measurement Systems for Turbulence
  - E.g., Advanced DIMM Systems

Thank You!

any

Questions?

or

Comments?

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with

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LSSO Team

&

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