17th ILRS Workshop on Laser Ranging, Bad Kötzing, May 16-20, 2011

Lunar Laser Ranging - Introductory Remarks

Jürgen Müller,

Institut für Erdmessung (Institute of Geodesy)

Leibniz Universität Hannover (University of Hannover)

Germany

Leibniz Universität Hannover

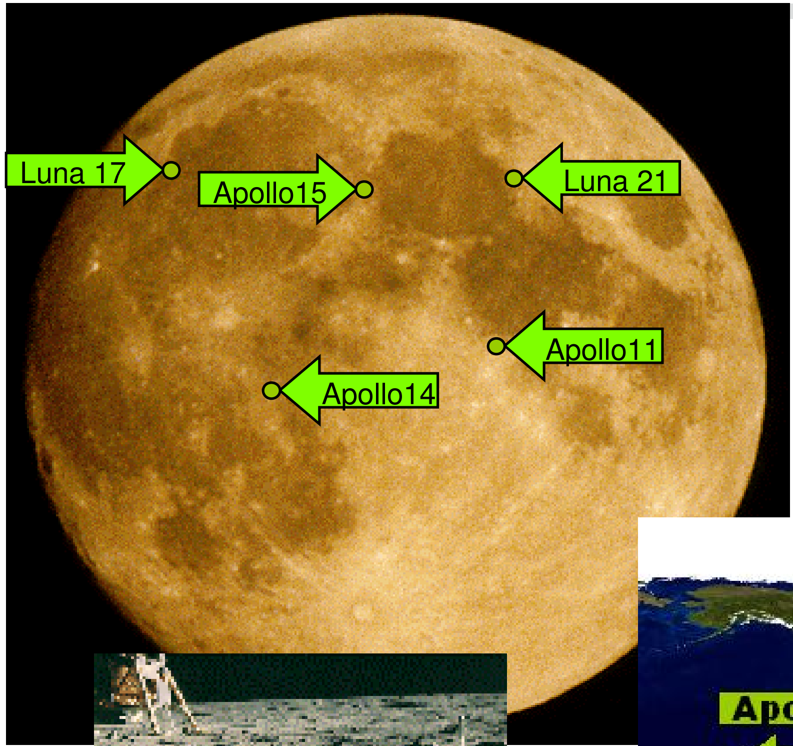
Acknowledgement

Work has been supported by

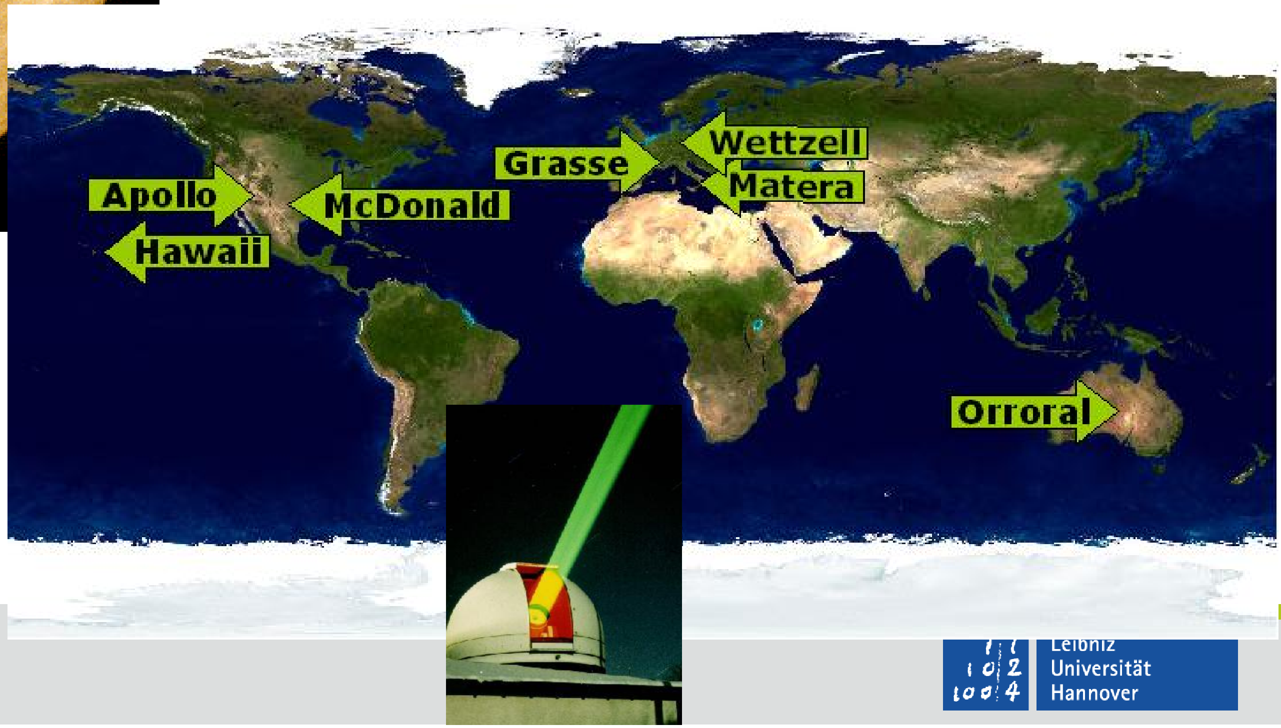
DFG Research Unit FOR584
Earth Rotation and Global Dynamic Processes,
studies by Liliane Biskupek, Xing Fang

and the Centre of Excellence QUEST
(Quantum Engineering and Space-Time Research),
studies by Franz Hofmann

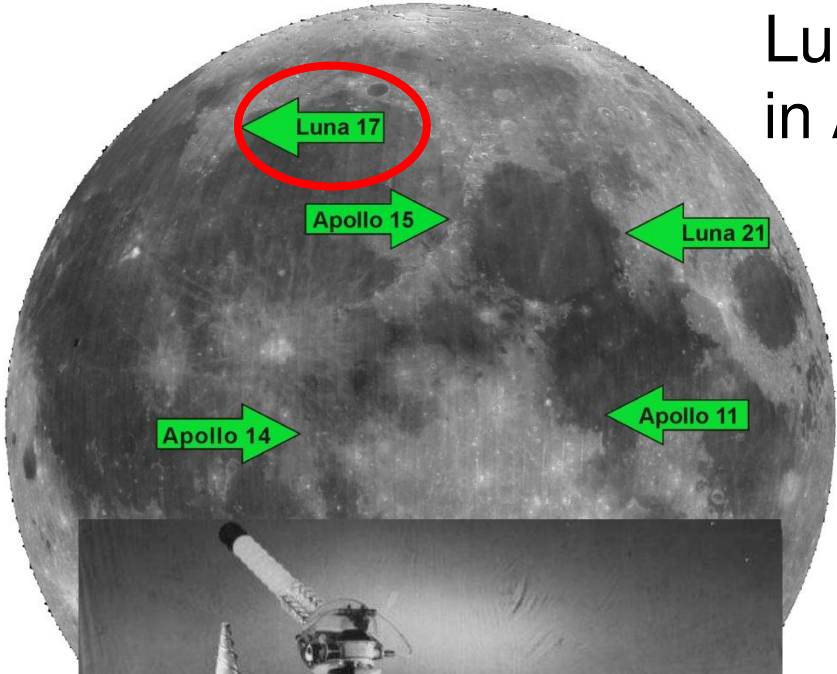
Retro-reflectors and observatories

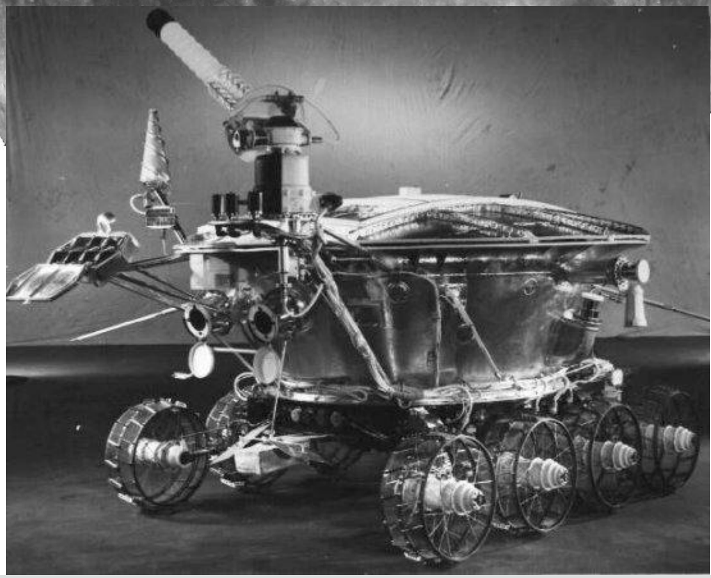


- First reflector deployed on July 21, 1969 (Apollo 11)
- “Continuous” LLR observations for 41 years

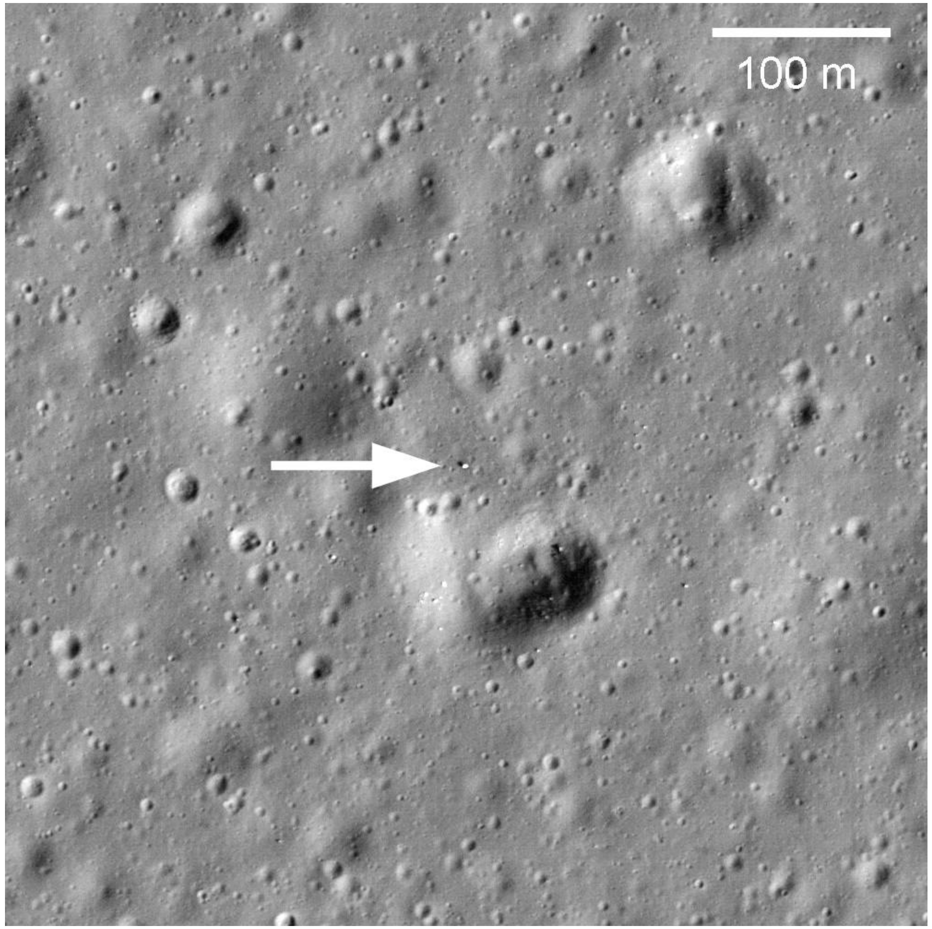


Luna17 retro-reflector



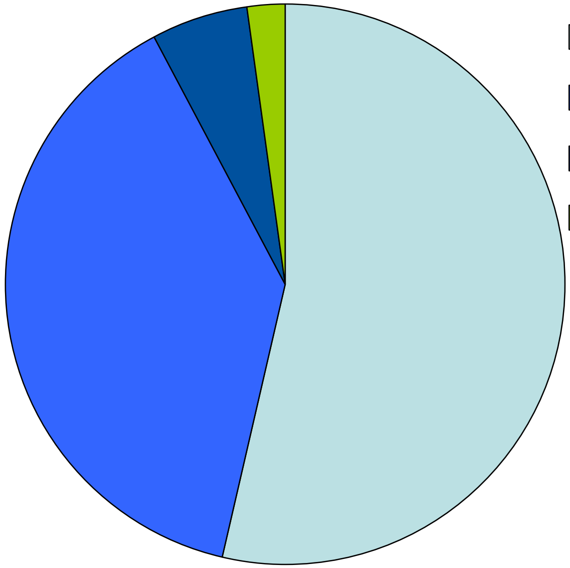


Lunokhod 1 has been re-discovered in April 2010



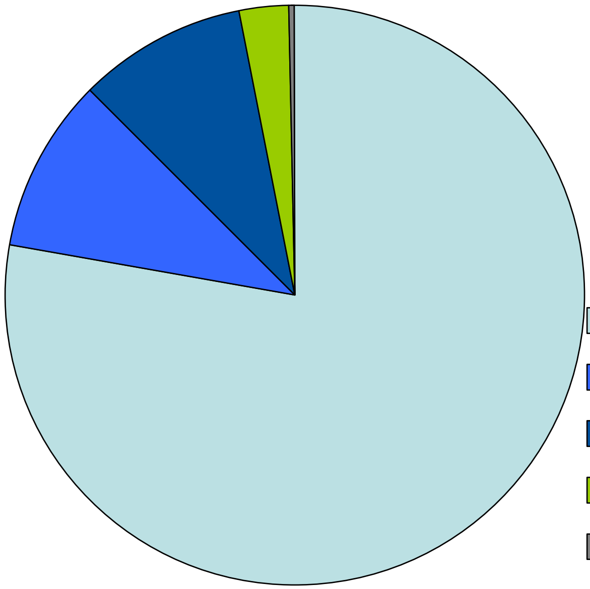
Statistics - reflectors and observatories

Time span 1970-2011



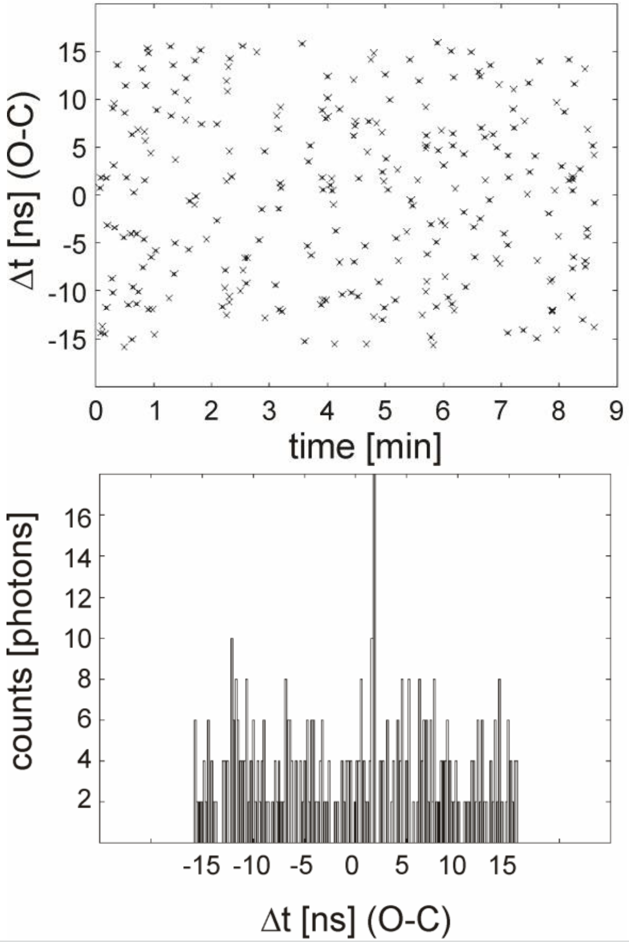
… and a few lunar tracks from

- Orroral
- Wettzell
- Matera

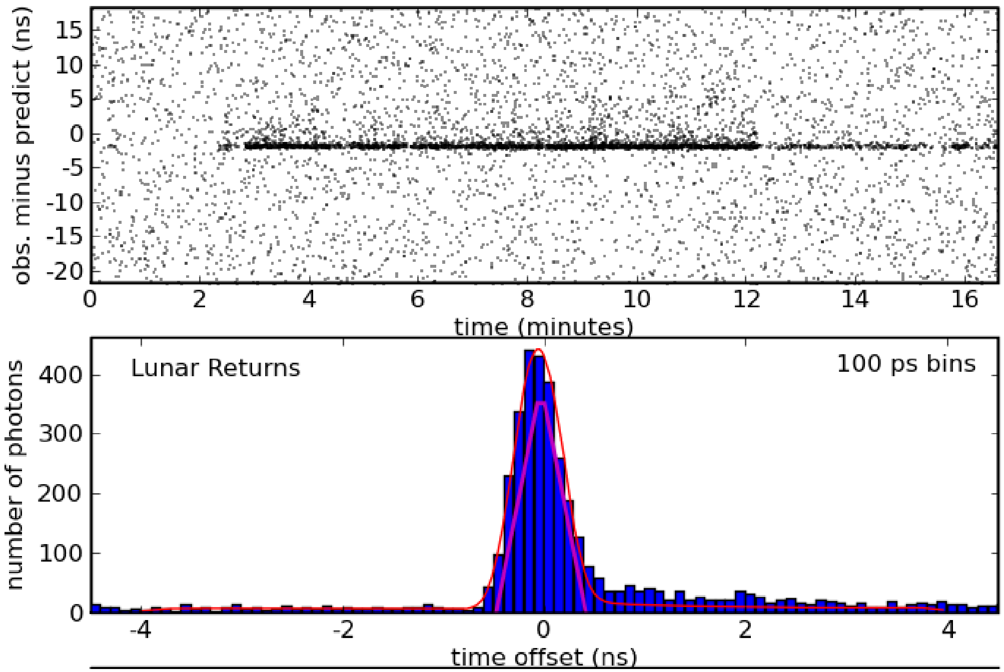


LLR – returned photons

Wettzell, 0.7m telescope



APOLLO, 3.5m telescope



Improvement of functional modelling

Atmospheric corrections (Pavlis …)

Gravity field of Earth and Moon

…

Gravity field of Earth and Moon

Already implemented (Newtonian modelling)

- Translation:

  Earth Y_{2-4}^{0} $\leftrightarrow$ Moon Y_{0}^{0}

  Moon Y_{2-4}^{0-4} $\leftrightarrow$ Earth Y_{0}^{0}

  Earth Y_{2}^{0} $\leftrightarrow$ Sun Y_{0}^{0}

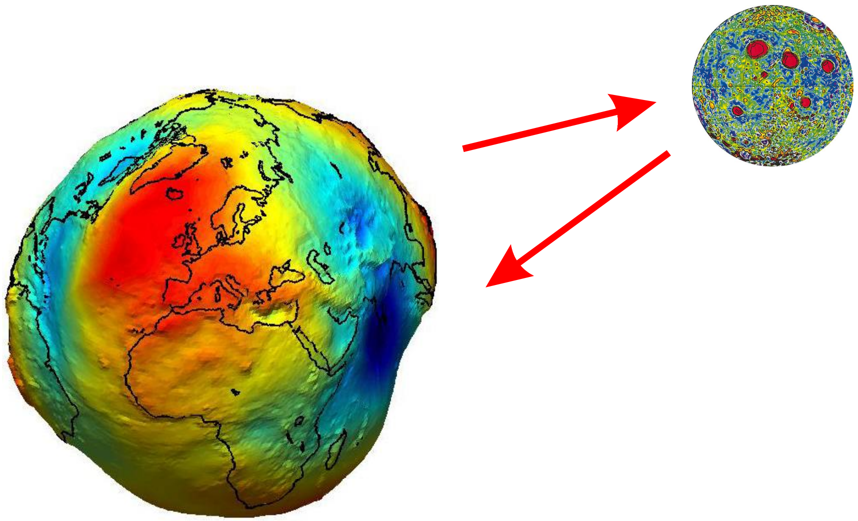
  Moon Y_{2}^{0-2} $\leftrightarrow$ Sun Y_{0}^{0}

- Rotation:

  Earth Y_{0}^{0} $\rightarrow$ Moon Y_{2-4}^{0-4}

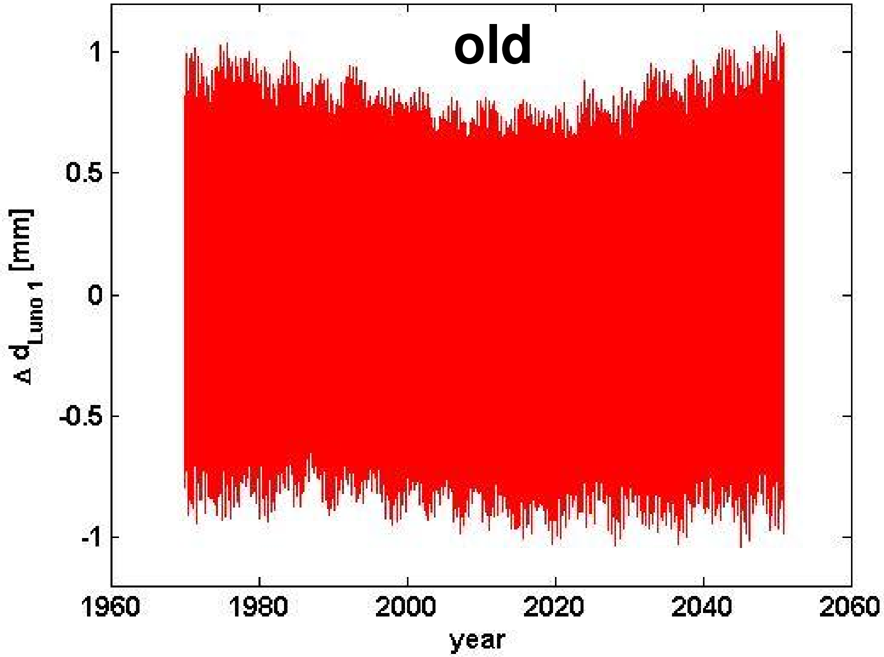
  Sun Y_{0}^{0} $\rightarrow$ Moon Y_{2-4}^{0-4}

  Earth Y_{2}^{0-2} $\rightarrow$ Moon Y_{2}^{0-2}

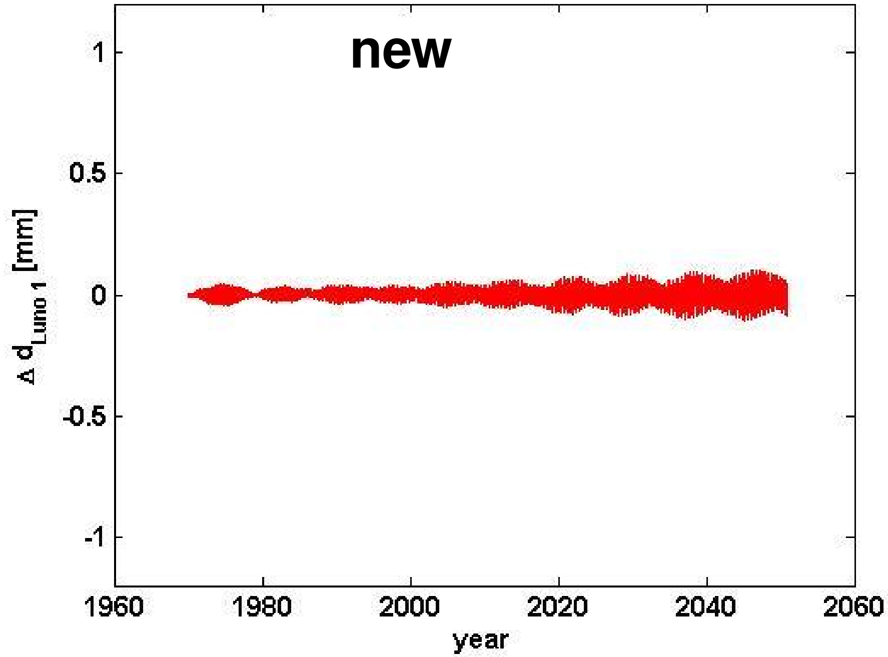


Case: Earth 4 zonal → 4 complete

$\Delta d_{\mathrm{Luno1}}$: l=4 zonal - ref



l=4 complete - ref

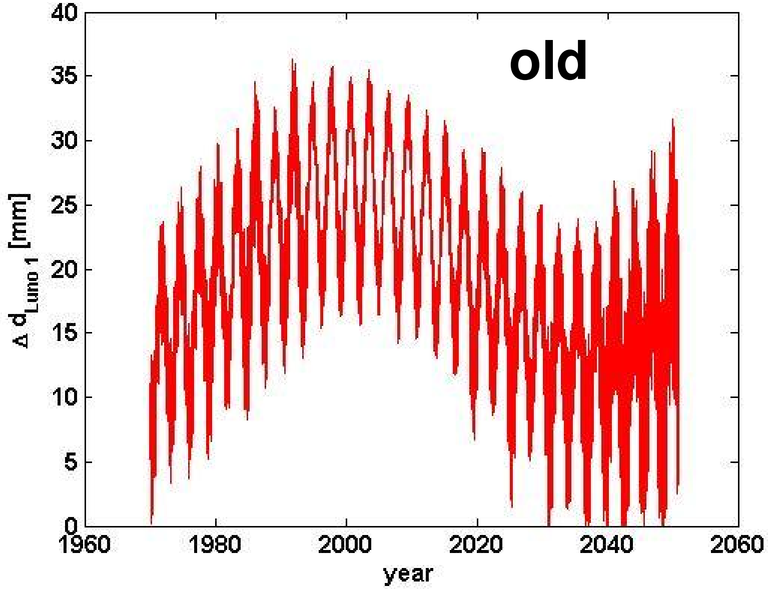


$$\Delta d_{\mathrm{Luno1}} = d_{\mathrm{Luno1\_comp}} - d_{\mathrm{Luno1\_ref}}$$

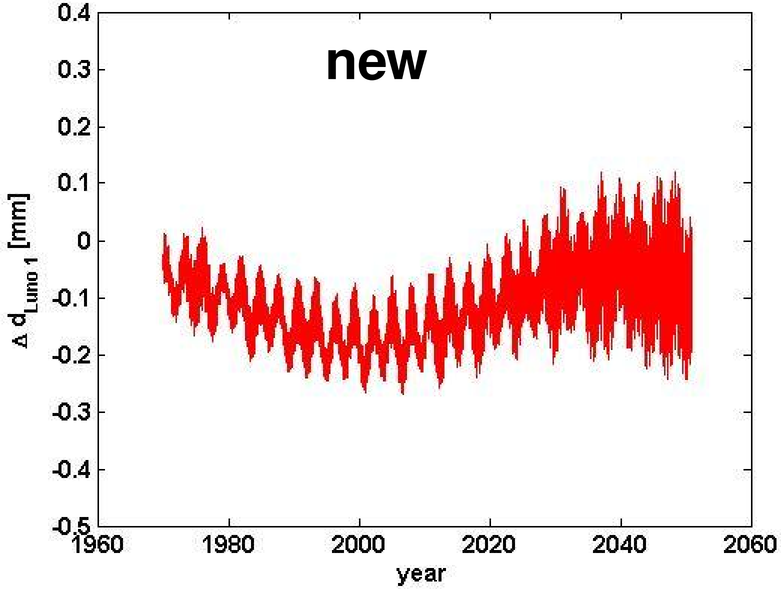
Note: time consuming computation in ephemeris program

Case: Earth + Moon, Luno 1 distance

Δd_{Luno1}: (l_E=4 zonal, l_M=4 complete) - ref



(l_E=4, l_M=5 complete) - ref



- Difference is dominated by lunar gravity field

Improvement of stochastic modelling

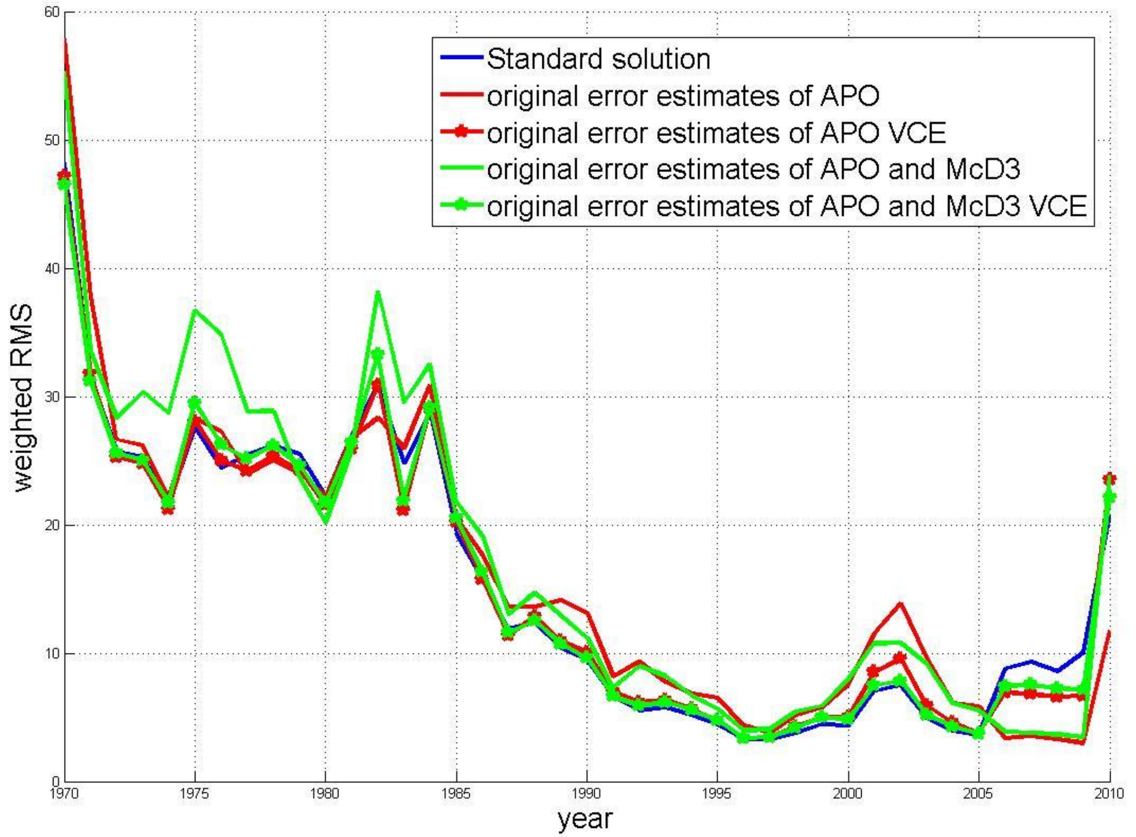
Variance component estimation

Eigenvalue decomposition

Outlier testing

VCE result

Standard solution compared to solutions based on original error estimates from APO resp. from APO and McD3, solutions based on original error estimates plus applying VCE.



New Results

Standard solution

- new reflector (Lunakhod 1)
- new sites (Matera)

Relativistic parameters

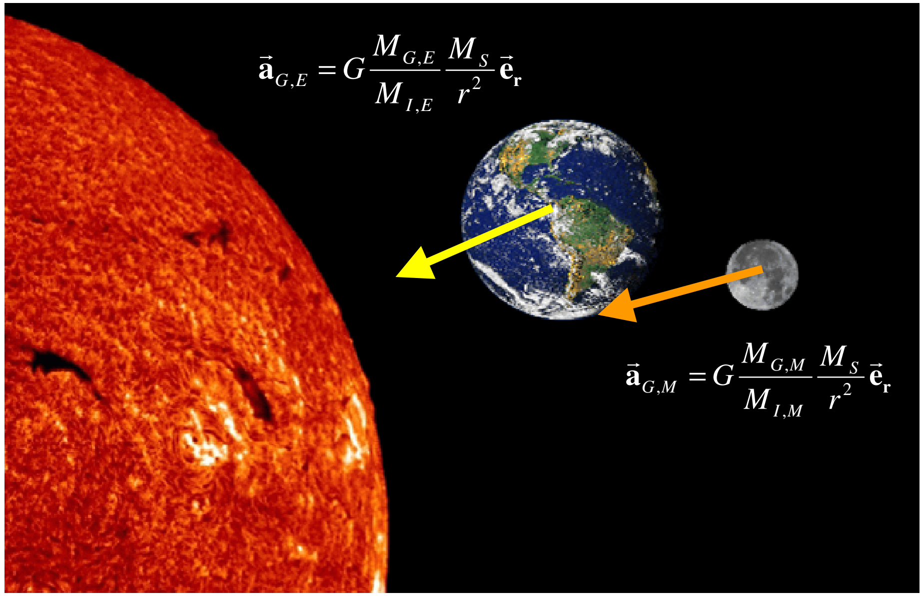
Equivalence principle test with LLR

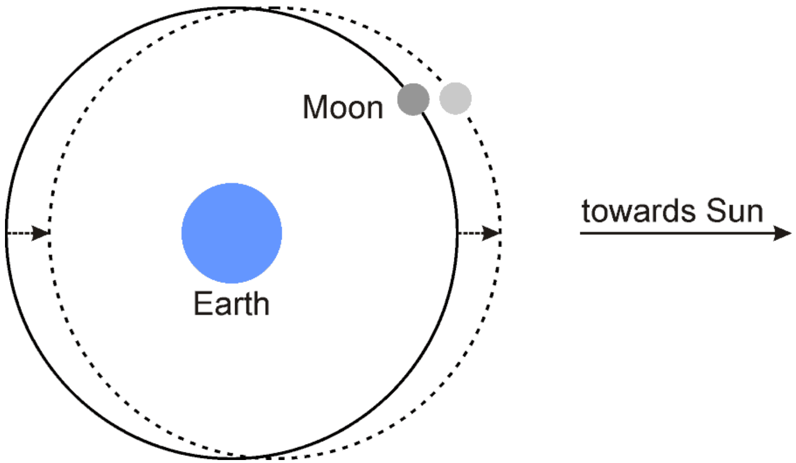
- Earth Moon values:

$$\left(\frac{U}{Mc^2}\right)_{Earth} = -4.64\times 10^{-10}$$

$$\left(\frac{U}{Mc^2}\right)_{Moon} = -1.90\times 10^{-11}$$

- If $\eta \neq 0$
  - Different accelerations
  - Polarisation of lunar orbit





- LLR best technique for lunar orbit determination

→ use Earth-Moon system for testing SEP violation

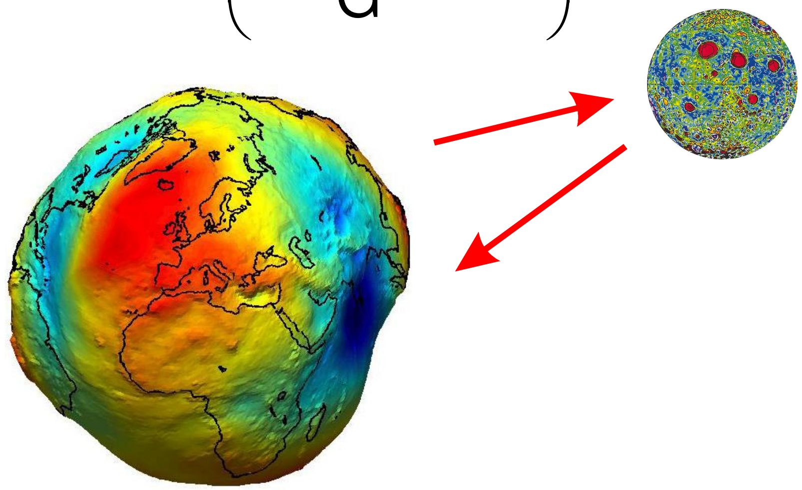
LLR tests of general relativity

Temporal variation of the gravitational constant

$$\frac{\dot{G}}{G} = (1 \pm 4) \cdot 10^{-13}\,\mathrm{yr}^{-1}$$

$$G = G_0\left(1 + \frac{\dot{G}}{G}\Delta t + \ldots\right)$$

Strong equivalence principle



$$\eta = (1 \pm 5) \times 10^{-4}$$

$$\left[\frac{M_G}{M_I}\right]_{SEP} - 1 = (-0.5 \pm 2.3) \times 10^{-13}$$

Factor 2 improvement due to refined modelling and more LLR data

Hofmann, Müller, Biskupek, Astron. & Astroph., 2010

Further activities

ISSI workshop series on LLR modelling and analysis (start 2009)

Boston workshop 2010 on comparison of LLR software packages

ILRS initiative on LLR data qualification

DFG Research unit “Reference systems”

(speaker A. Nothnagel, Bonn)

- Moon related systems
- Barycentric ephemeris

Requirements for LLR data qualification?

Criteria for tracking (new) LLR sites

- number of reflector arrays to be observed:
  at least Apollo15, then LK1, the others if possible
- successful observation days/nights per month: **1 - 4**
- normal points per year: **(~12 to Ap15), but try 100**
- normal point accuracy: **< 0.1 ns** (goal **< 0.05 – 0.01 ns**)
- post-fit residual of single NP to global solution: **< 1 ns**

LLR website

- General rules: tracking and further ILRS criteria
- Checking quality of LLR data (Paris website http://polac.obspm.fr/PaV)

Conclusions

Ongoing activities

- Improved functional and stochastic modelling
- Work on refined LLR data analysis
- Qualification/comparison of data and analysis (exchange in LLR community)

Future steps

- Enhanced studies on lunar interior, earth rotation and relativity
- New LLR experiments (transponders …)