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Lunar Laser Ranging Perspectives

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Lunar Laser Ranging

- Data
- Scientific potential
  + Earth orientation
  + relativity (gravitational constant)
  + …
- Future capabilities (new combined products)

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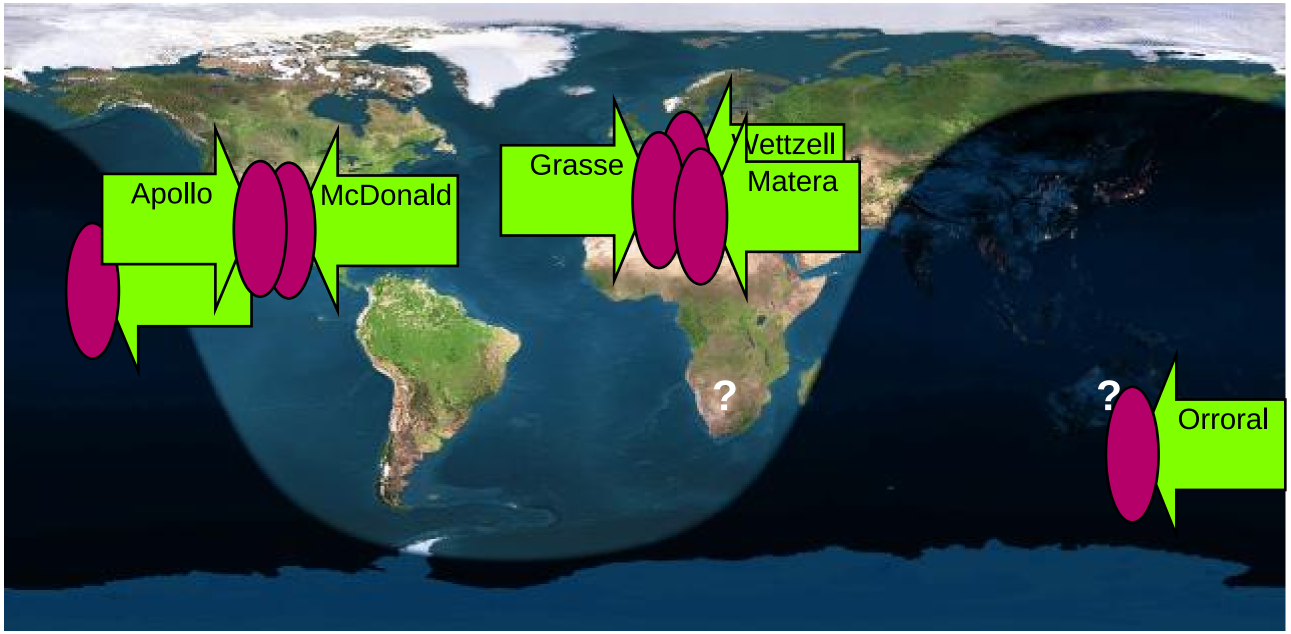
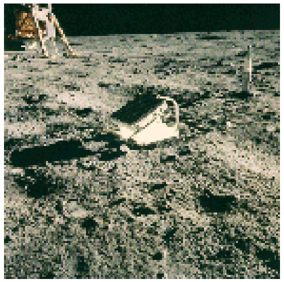
Motivation

- Observations (37 years) and modelling at cm-level
- Long-term stability (orbit, reference frames, EOPs)
- Determination of
  - + Earth-Moon dynamics
  - + relativity parameters

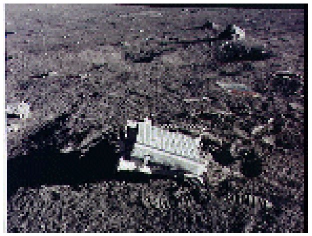
Observatories on the Earth



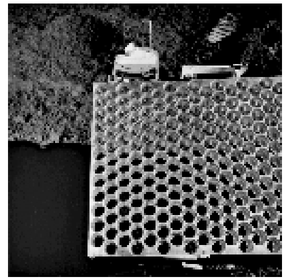
Retro-Reflectors on the Moon



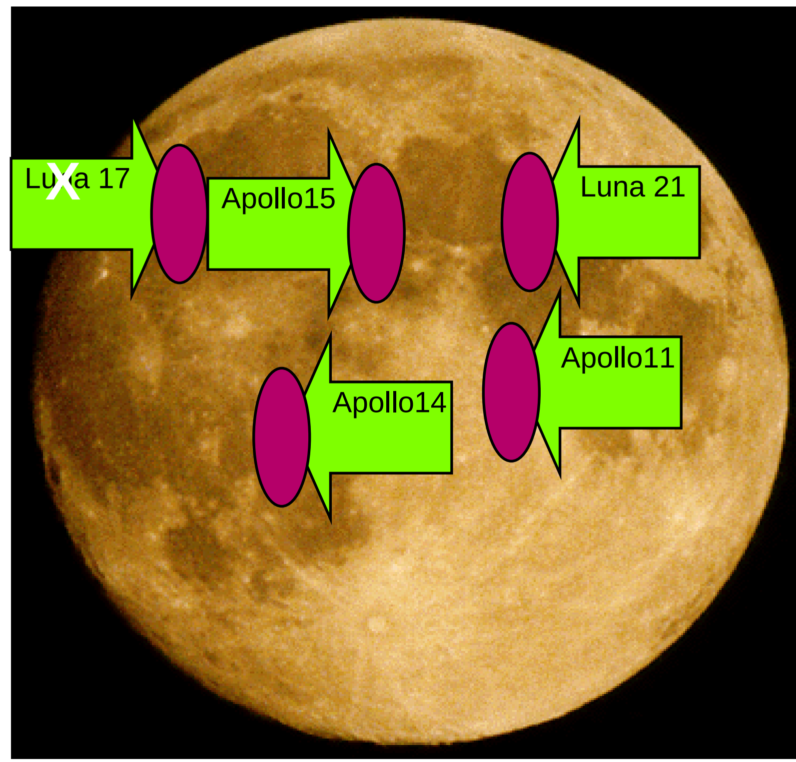
Apollo 11
July 1969



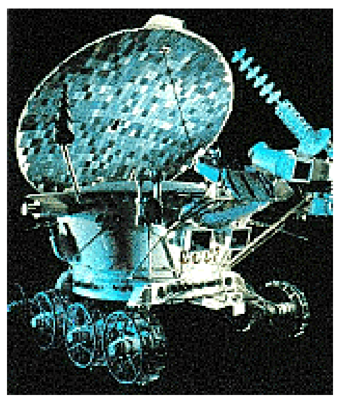
Apollo 14
Jan./Feb.`71



Apollo 15
Jul./Aug.`71



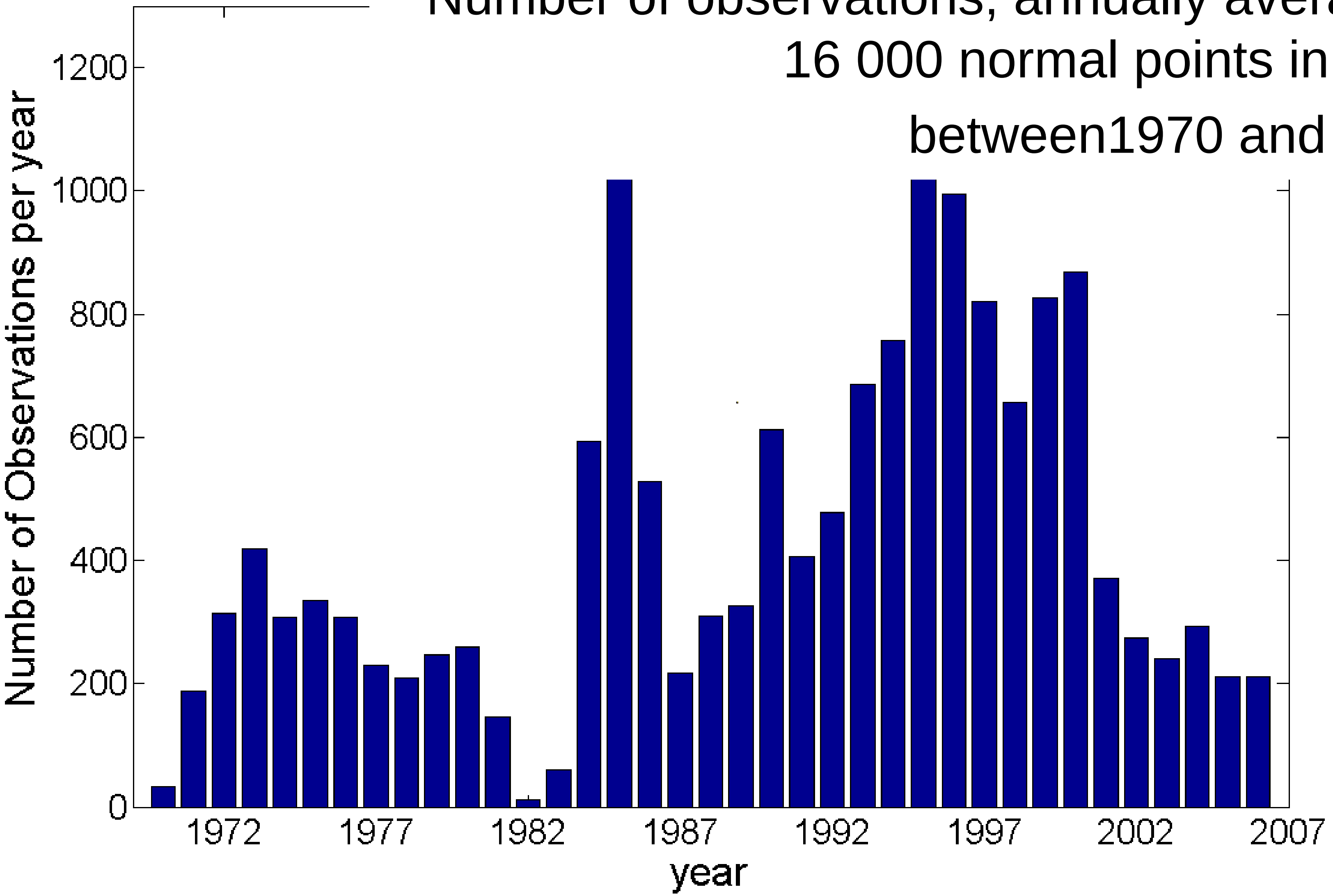
Luna 17
Nov.`70...



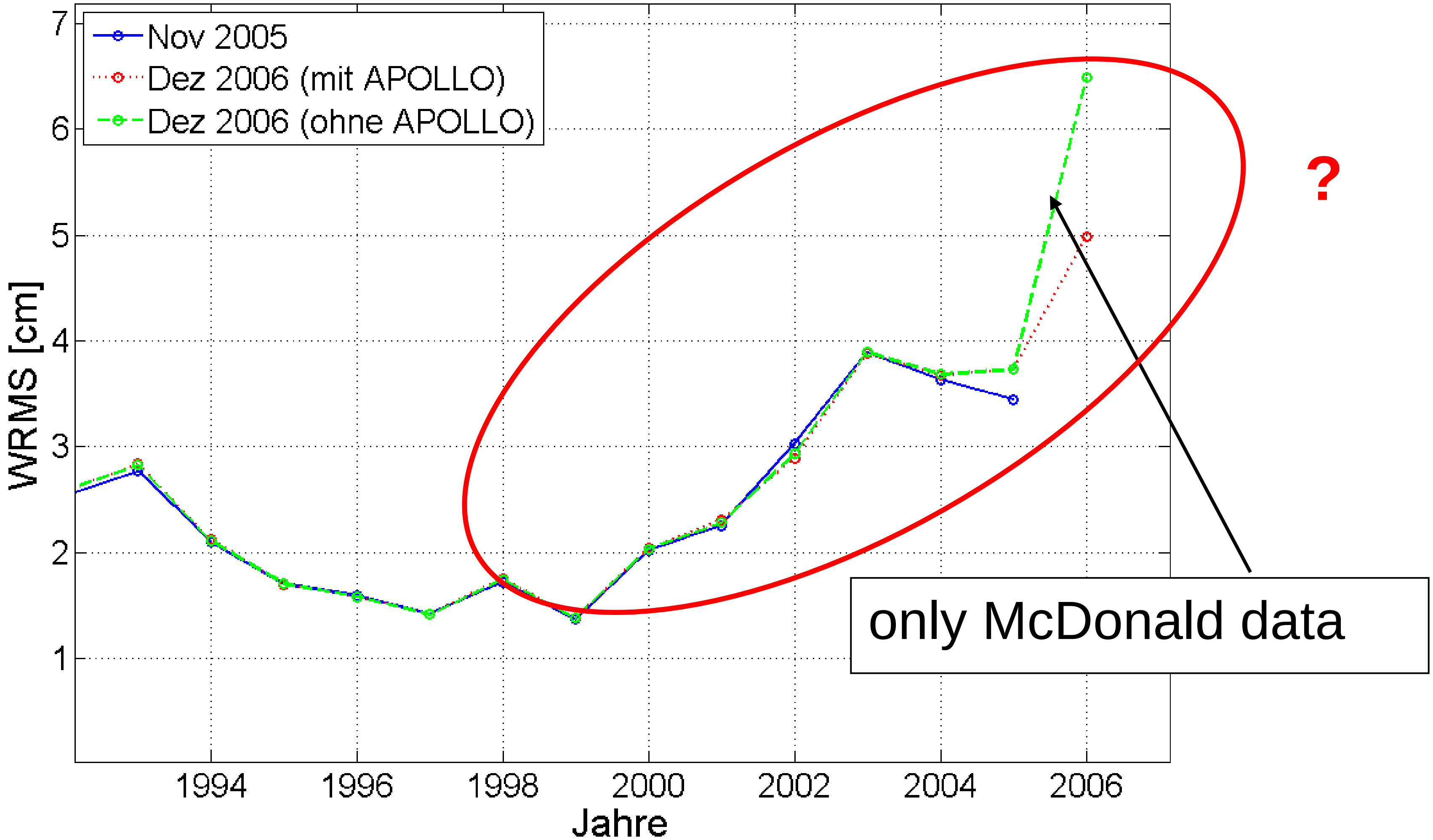
Luna 21
Jan.`73...

LLR Observations per Year

Number of observations; annually averaged;
16 000 normal points in total,
between1970 and 2007



Weighted Annual Residuals



Determination of Earth Rotation (1)

- Two-step procedure
  - Least-squares adjustment, estimation of various LLR parameters
    - Nutation and precession
    - Long-wavelength signals in $\Delta\phi$ (>90 days) are simultaneously estimated for the 1970s

$$\Delta\phi_{LW} = \sum_i A_i \cos(\omega_i t) + B_i \sin(\omega_i t)$$

    - Drift rates for UT1, x_P and y_P

  - Analysis of remaining post-fit residuals
    - daily-decomposition method
    - 1960 ‚nights' with sufficient station-reflector pairs

Determination of Earth Rotation (2)

- Post-fit residuals

$$r(t) = r_{\Delta\phi} + r_{\Delta UT0} + r_n$$

$$r_{\Delta\phi} = 2\,\Delta\phi\, a_E \left(\sin\phi \cos\delta \cos H - \sin\delta \cos\phi\right)$$

$$r_{\Delta UT0} = 2\,\Delta UT0\, a_E \cos\phi \sin H \cos\delta$$

$$\Delta\phi = x_P \cos\lambda - y_P \sin\lambda$$

$$\Delta UT0 = \Delta UT1 + \tan\phi\left(x_P \sin\lambda + y_P \cos\lambda\right)$$

δ declination

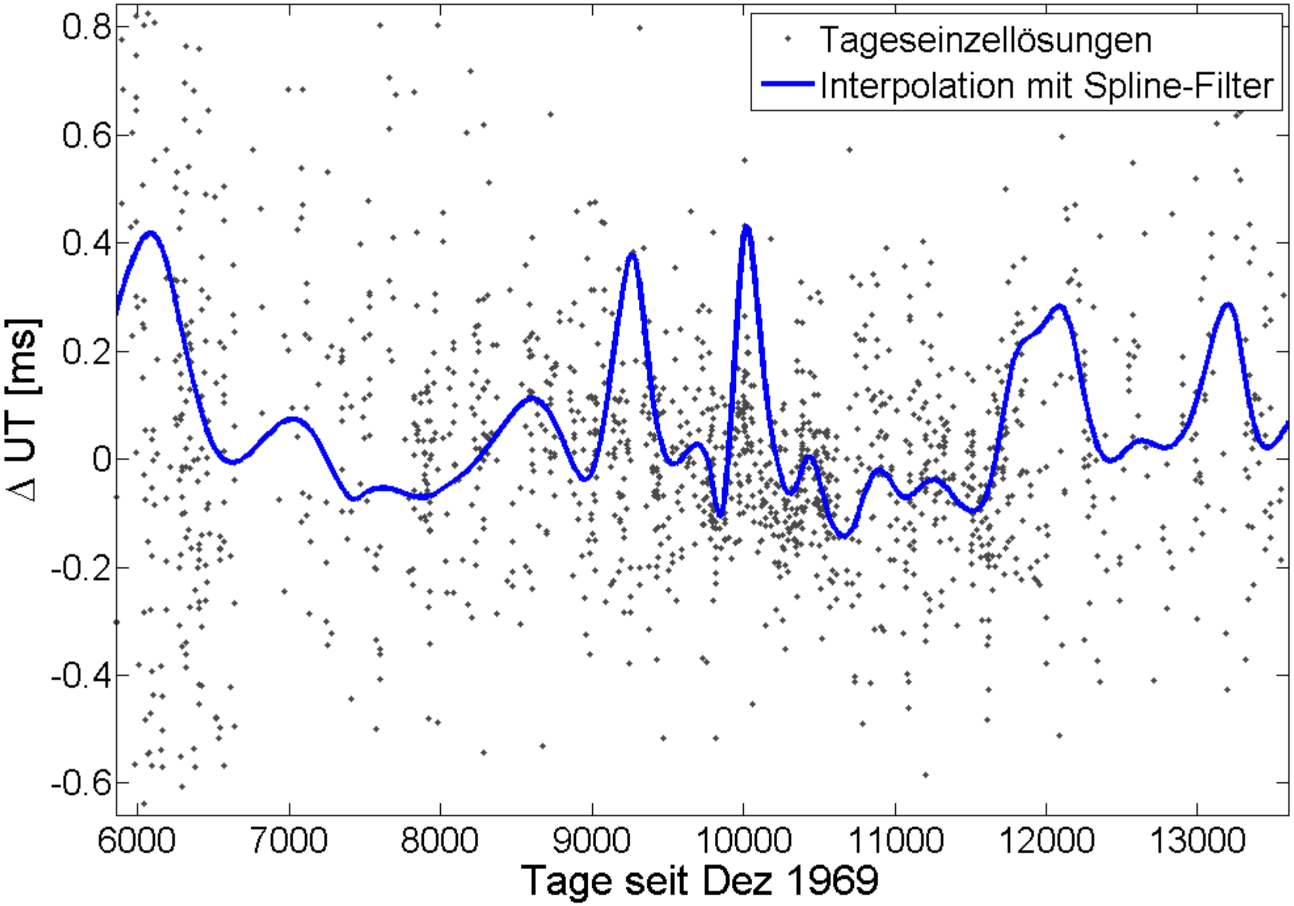
H hour angle

ϕ latitdude

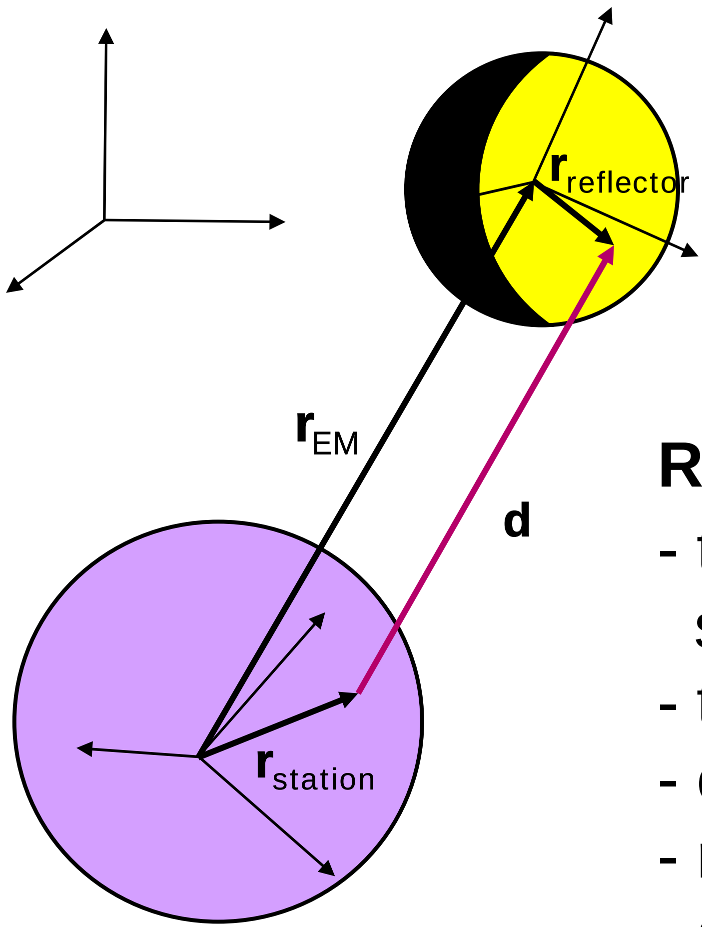
a_E distance to rotation axis

Results for ΔUT0

- Difference to comb2006 solution of R. Gross
- Interpolation by spline filtering



LLR Observation Equation



$$d = c\,\frac{\tau}{2} = \left|\mathbf{r}_{EM} - \mathbf{r}_{station} + \mathbf{r}_{reflector}\right| + c\Delta\tau$$

$$\frac{d^2\mathbf{r}_{EM}}{dt^2} = -\frac{GM_{E+M}}{r_{EM}^3}\,\mathbf{r}_{EM} + \mathbf{b}_{Newtonian} + \mathbf{b}_{Relativity}$$

Relativity in LLR

- transformation between reference systems (Moon, Earth, inertial)
- transformation between time systems
- orbital motion of the solar system bodies
- rotation of Earth and Moon
- gravitational time delay (Shapiro)

- effect: several meters

Example: Gravitational Constant G

Investigation of secular and quadratic variations

$$G = G_0 \left(1 + \frac{\dot{G}}{G} \Delta t + \frac{1}{2} \frac{\ddot{G}}{G} \Delta t^2 \right)$$

Results

$$\frac{\dot{G}}{G} = (2 \pm 7) \cdot 10^{-13} \, \mathrm{yr}^{-1}$$

$$\frac{\ddot{G}}{G} = (4 \pm 5) \cdot 10^{-15} \, \mathrm{yr}^{-2}$$

Results - Relativity

Parameter	Results
Nordtvedt parameter η (violation of the strong equivalence principle)	$(6 \pm 7) \cdot 10^{-4}$
time variable gravitational constant $\dot{G}/G\,[yr^{-1}]$ $\ddot{G}/G\,[yr^{-2}]$ (→ unification of the fundamental interactions)	$(2 \pm 7) \cdot 10^{-13}$ $(4 \pm 5) \cdot 10^{-15}$
difference of geodetic precession Ω_{GP} - Ω_{deSit} [″/cy] (1.92 ″/cy predicted by Einstein's theory of gravitation)	$(6 \pm 10) \cdot 10^{-3}$
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 $\gamma_{Cassini}-1$ ($\sim 10^{-5}$)	$(-2 \pm 4) \cdot 10^{-3}$ $(1.5 \pm 1.8) \cdot 10^{-4}$

New Combined Products

Earth orientation

- UT0 (VLBI)
- Long-periodic nutation, precession (VLBI, GPS, SLR)

Celestial reference frame

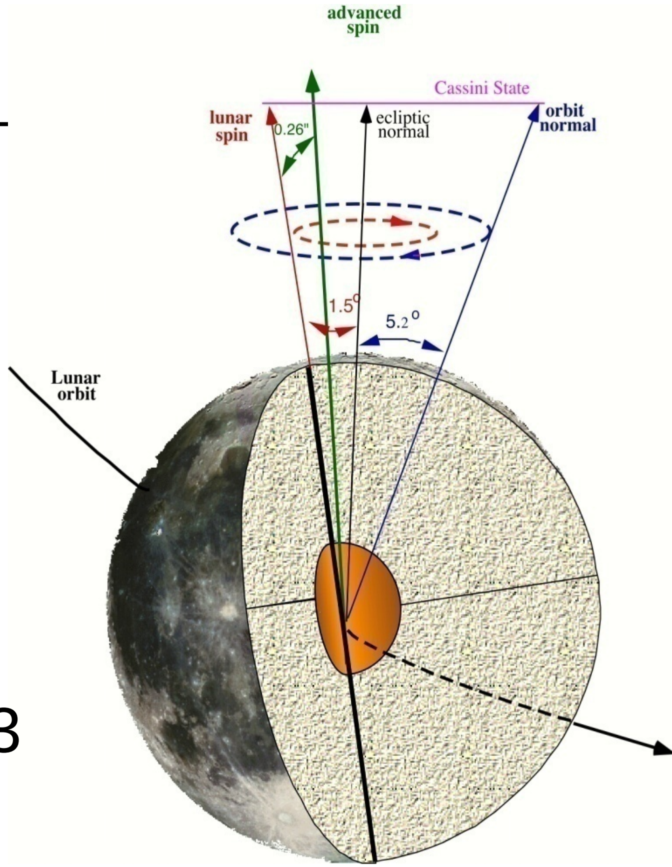
- Dynamic realisation of ICRS, ephemeris
- tie between the lunar network and the radio reference frame (VLBI)

Gravitational physics parameters

- Space curvature (VLBI)
- Lense-Thirring precession (SLR)
- Others (Grav. constant, equivalence principle metric)

Lunar interior

Lunar Interior



Lunar rotation

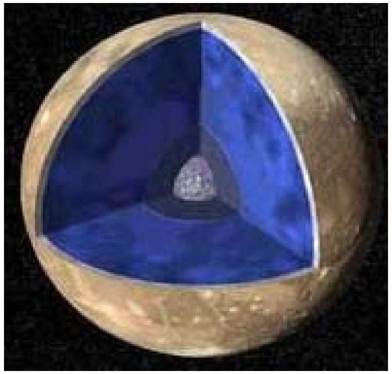
- libration angles, σ = 0.001“
- numerically integrated

Lunar tides

- Love number $k_2 = 0.023 \pm 0.003$

Dissipation from

- fluid core (Rc < 354 km)
- solid mantle, Q = 33 ± 4



Courtesy Turyshev and Williams, JPL

Conclusions

LLR contributes to better understanding of

- Reference frames (ITRF, dynamic ICRF)
- Earth orientation (IERS)
- Earth-Moon system
- Relativity
- Lunar interior
- …

… and supports GGOS

In future: new lunar ranging experiment

(combination with other techniques)

Sensitivity Study for $\ddot{G}$

Sensitivity analysis via

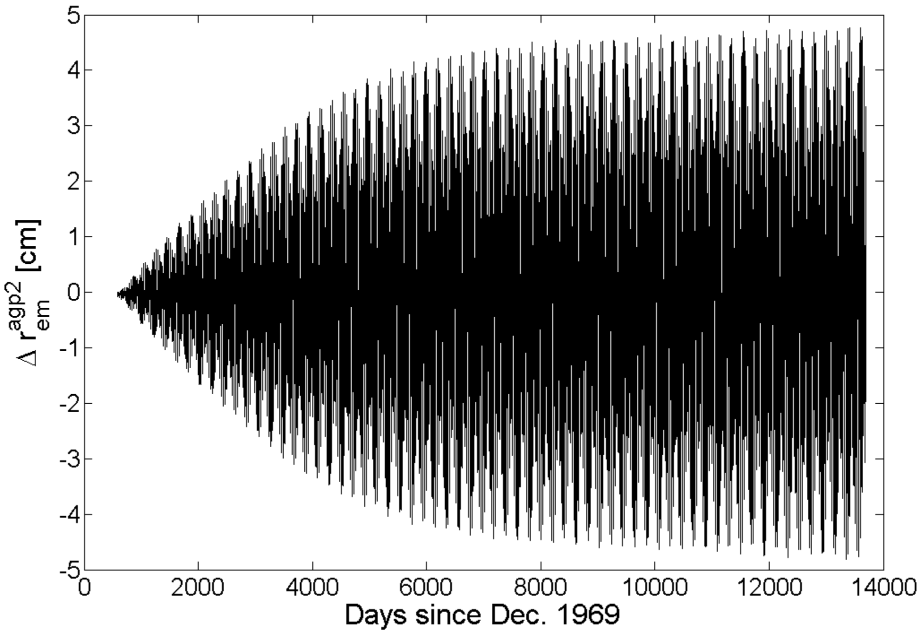
$$\Delta r_{em}(\ddot{G}) = \frac{\delta r_{em}}{\delta \ddot{G}} \Delta \ddot{G}$$

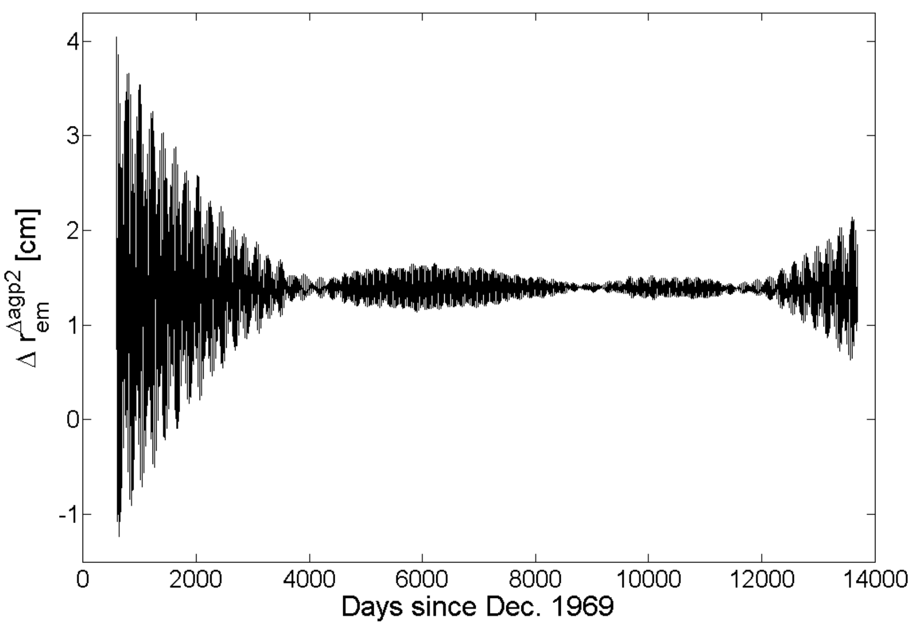
Separation of free and forced terms → two orbit solutions:

1)perturbed,

2)un-perturbed

→ difference





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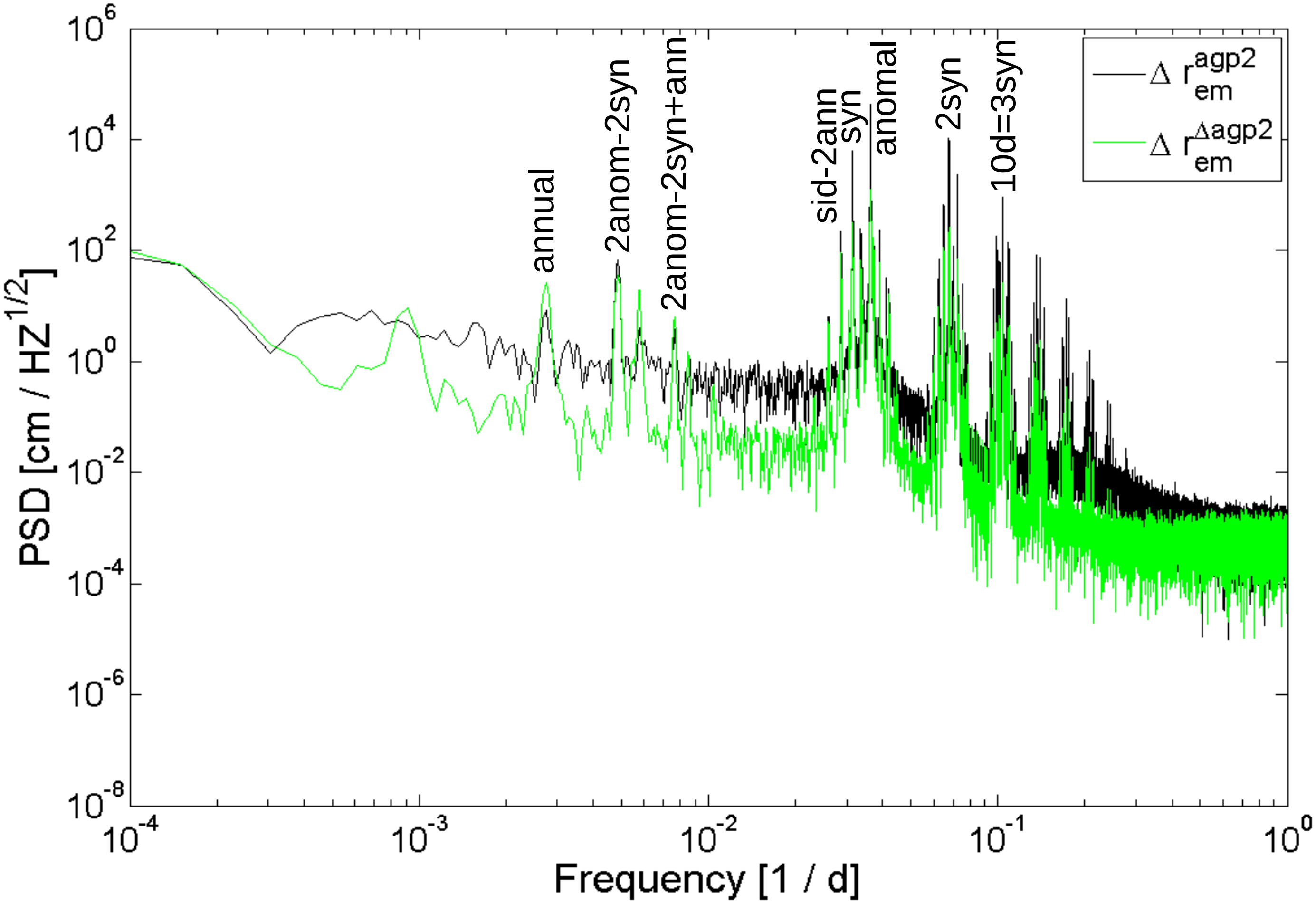
Corresponding Spectrum



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Results – Relativity (2)

Parameter	Results
Yukawa coupling constant $\alpha_{\lambda=400\,000\text{ km}}$ (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)	$(4 \pm 4) \cdot 10^{-14}$
preferred frame effect α_1 (search for a preferred frame within general relativity)	$(-4 \pm 9) \cdot 10^{-5}$
preferred frame effect α_2 (search for a preferred frame within general relativity)	$(2 \pm 2) \cdot 10^{-5}$

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