16th International Workshop on Laser Ranging, Poznan, October 13, 2008

Lunar Laser Ranging - A Science Tool for Geodesy and General Relativity

Jürgen Müller

Institut für Erdmessung, Leibniz Universität Hannover, Germany

Acknowledgement

Work has been supported by

DFG Research Unit FOR584
Earth Rotation and Global Dynamic Processes
(computations by Liliane Biskupek)

and the Centre of Excellence QUEST
(Quantum Engineering and Space-Time Research)

Contents

Introduction

- Motivation

Lunar Laser Ranging

- Data (distribution and accuracy)
- Analysis

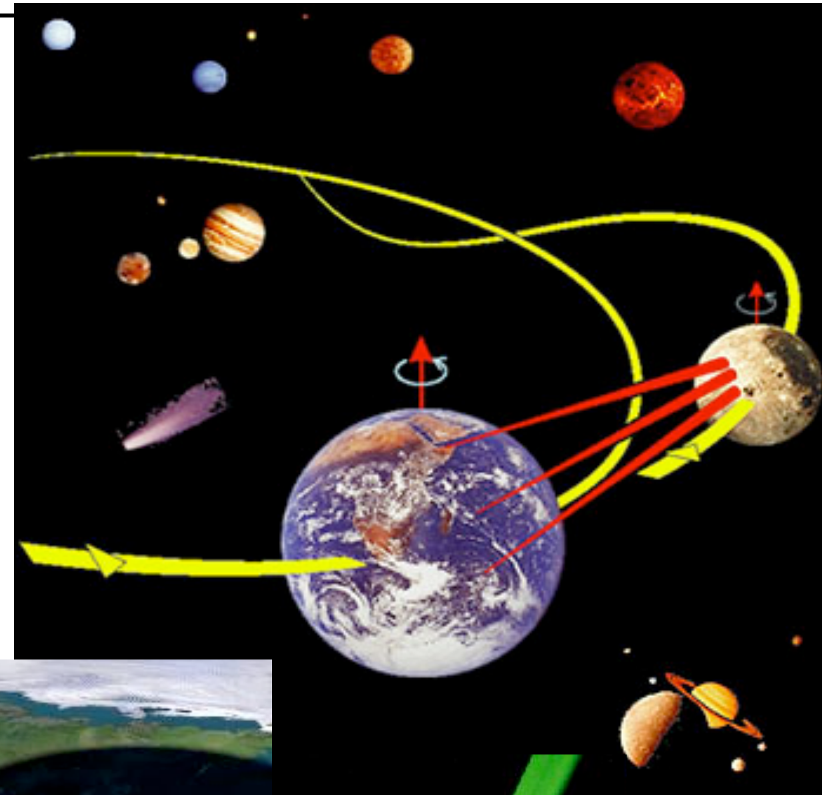
Relativity Tests

Conclusions

- Future capabilities

Lunar Laser Ranging (LLR)

- 38 years of observations
- Modelling so far at cm-level
- Long-term stability (e.g., orbit)
  - → Earth-Moon dynamics
  - → Relativity parameters

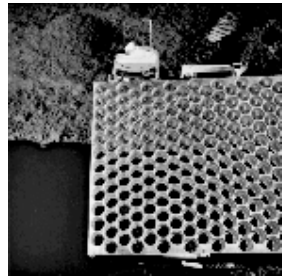


Leibniz Universität Hannover

Retro-Reflectors on the Moon

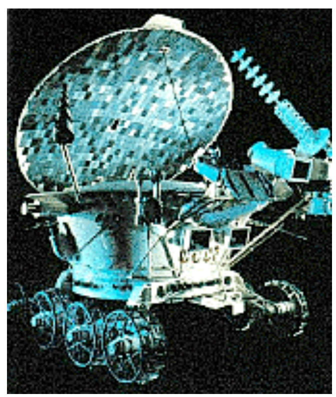
Apollo 11
July 1969

Apollo 14
Jan./Feb.`71

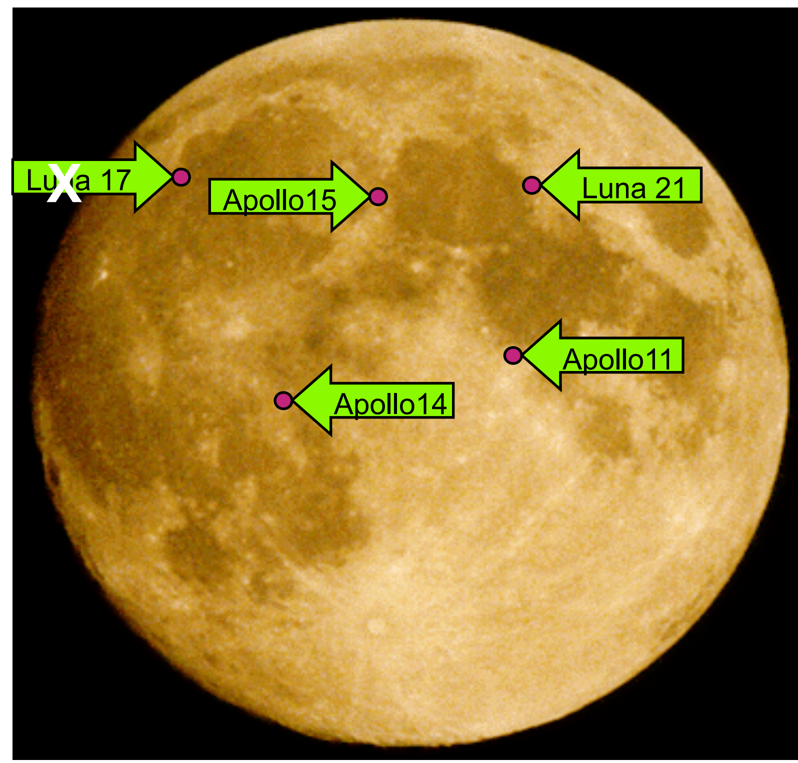


Apollo 15
Jul./Aug.`71

Luna 17
Nov.`70...

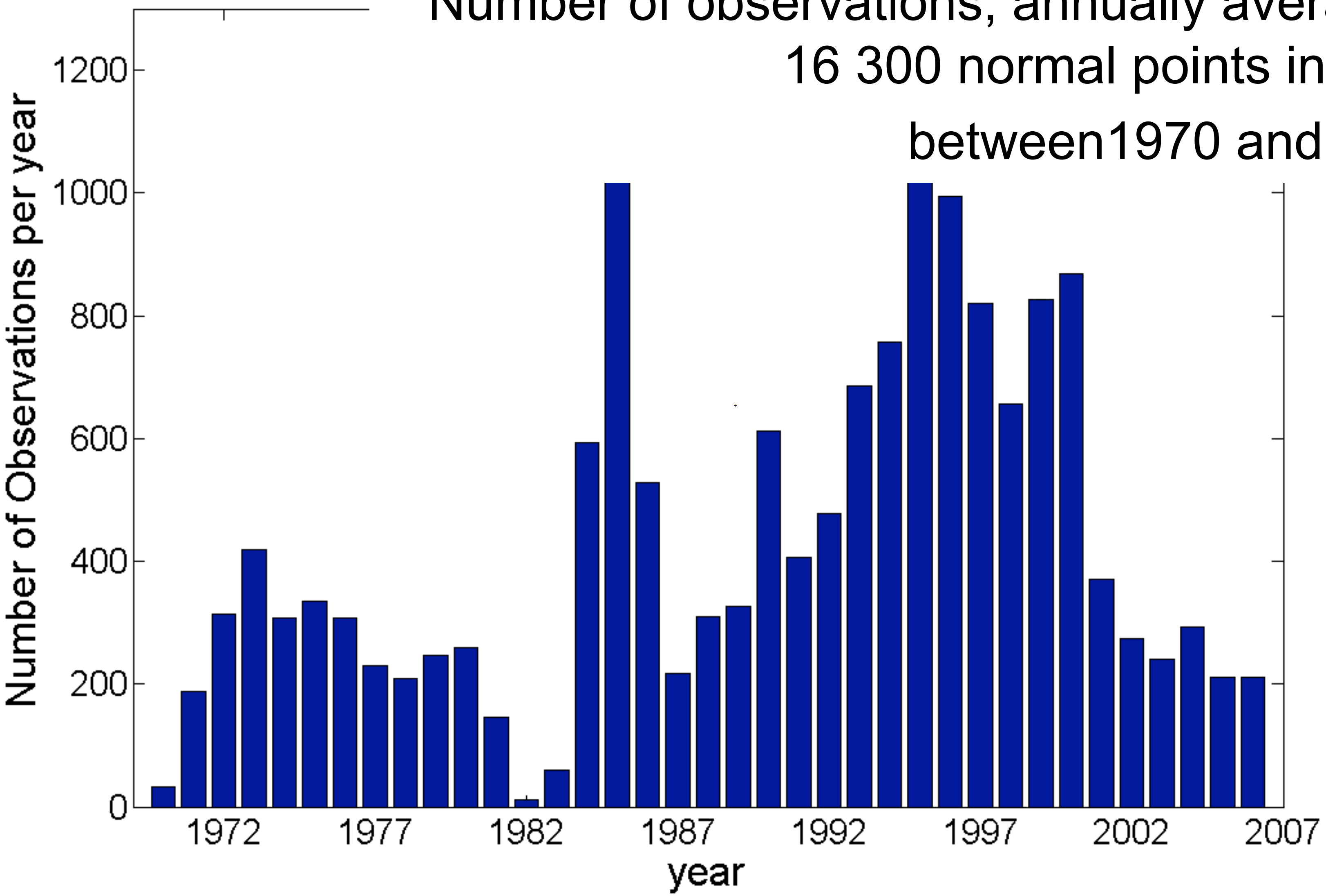


Luna 21
Jan.`73...

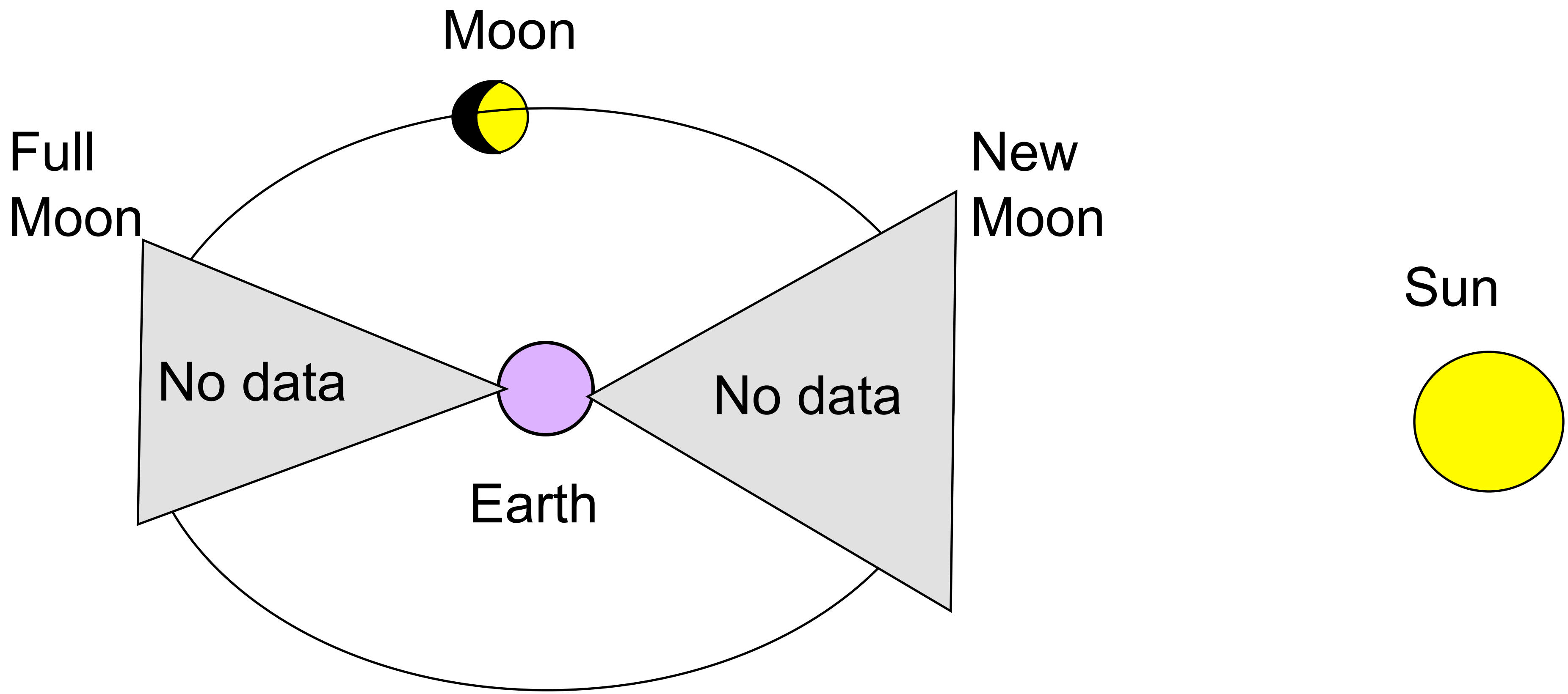


LLR Observations per Year

Number of observations; annually averaged;
16 300 normal points in total,
between1970 and 2008



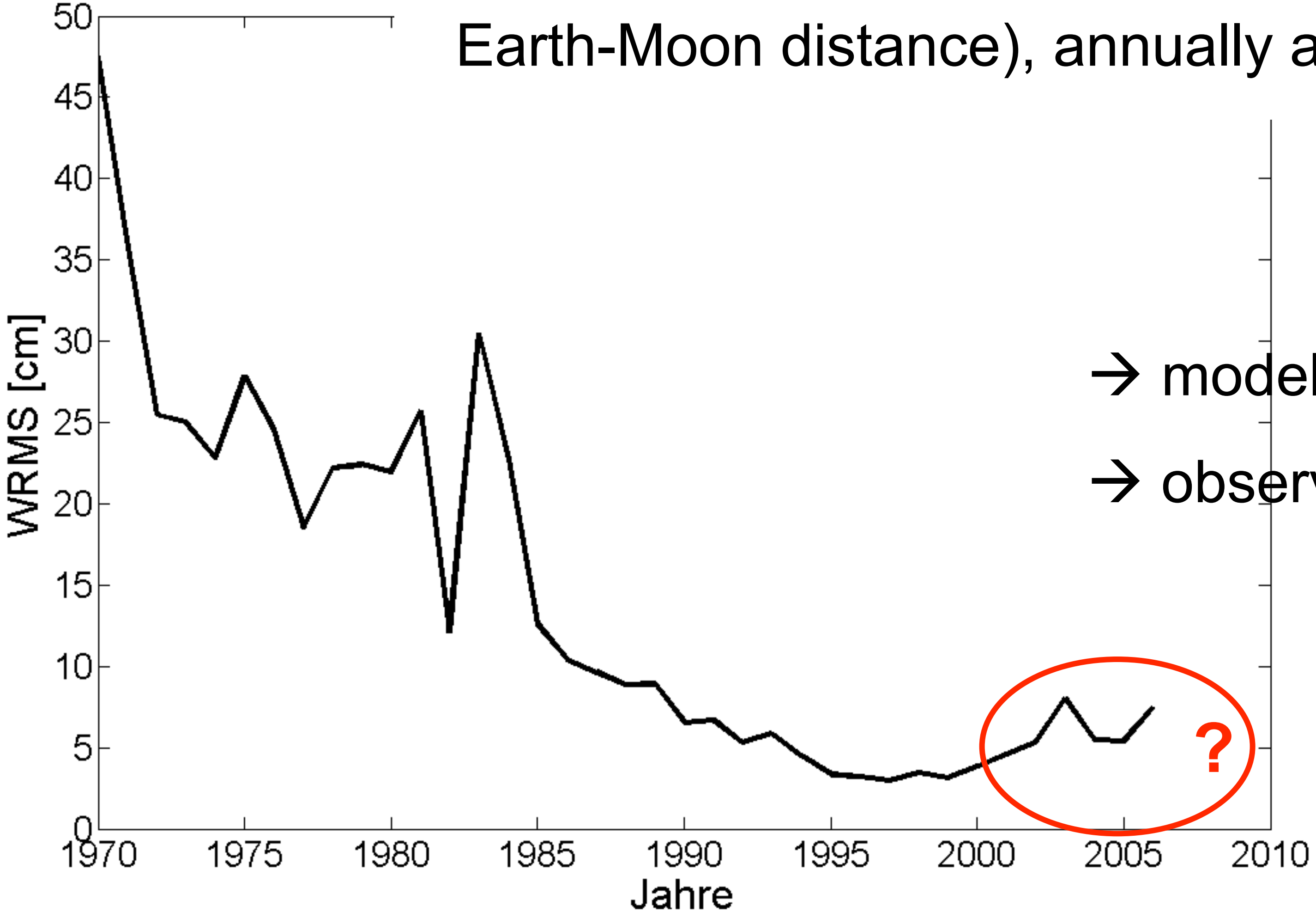
Distribution of Observations per Synodic Month



- large data gaps near Full and New Moon

Weighted Annual Residuals

weighted residuals (observed - computed Earth-Moon distance), annually averaged



→ model?

→ observations?

LLR Results (Theory)

Analysis

- model based upon Einstein's Theory
- least-squares adjustment
- determination of the parameters of the Earth-Moon system (about 180 unknowns, without EOPs)

Results of major interest

- station coordinates and velocities (ITRF2000) - GGOS
- Earth rotation, σ = 0.5 mas (IERS)
- relativity parameters
  (grav. constant, equivalence principle, metric ...)
- ... lunar interior ...

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

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

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

Sensitivity Study for $\ddot{G}$

Sensitivity analysis via

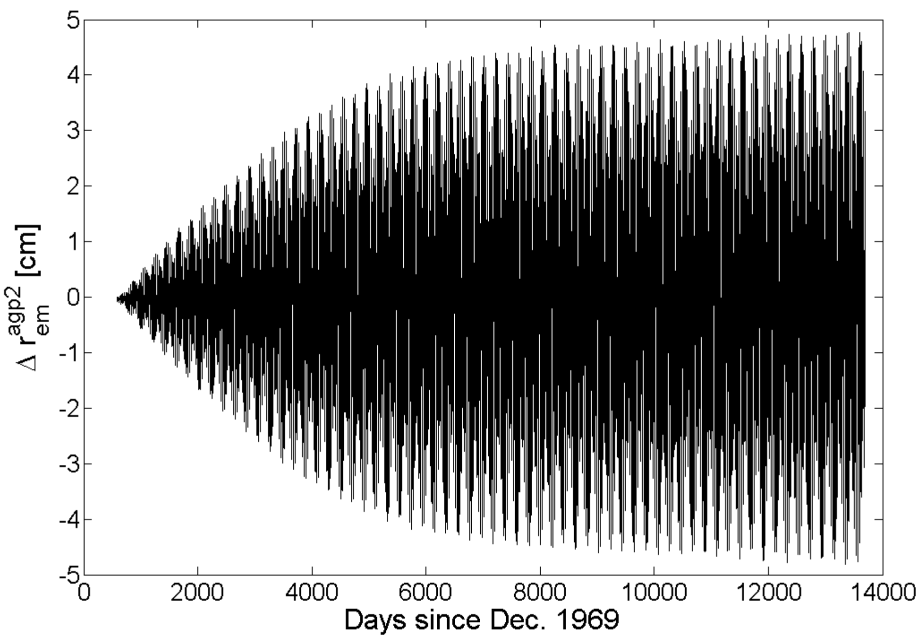
$$\Delta r_{em}(\ddot{G}) = \frac{\delta r_{em}}{\delta \ddot{G}} \Delta \ddot{G}$$

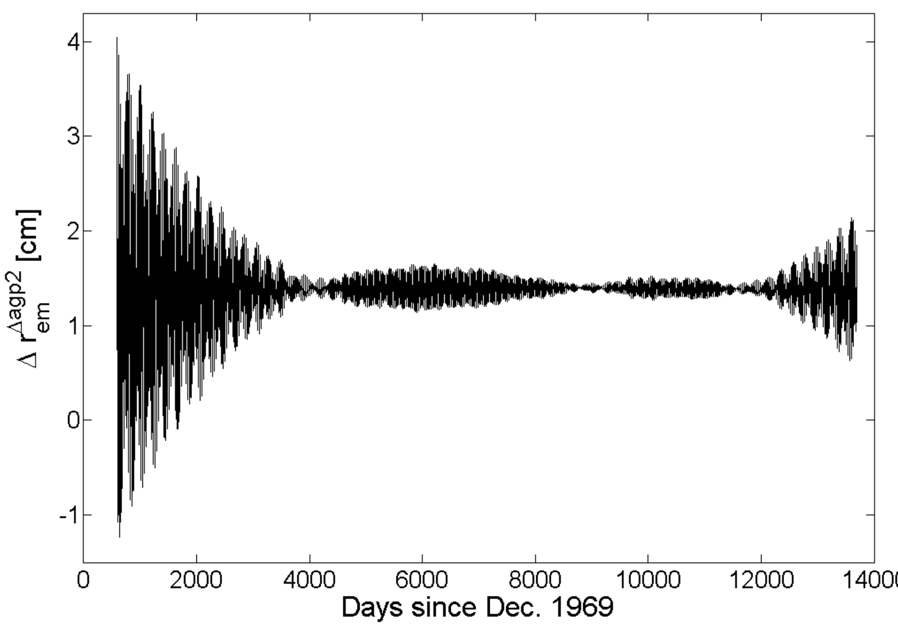
Separation of free and forced terms → two orbit solutions:

1)perturbed,

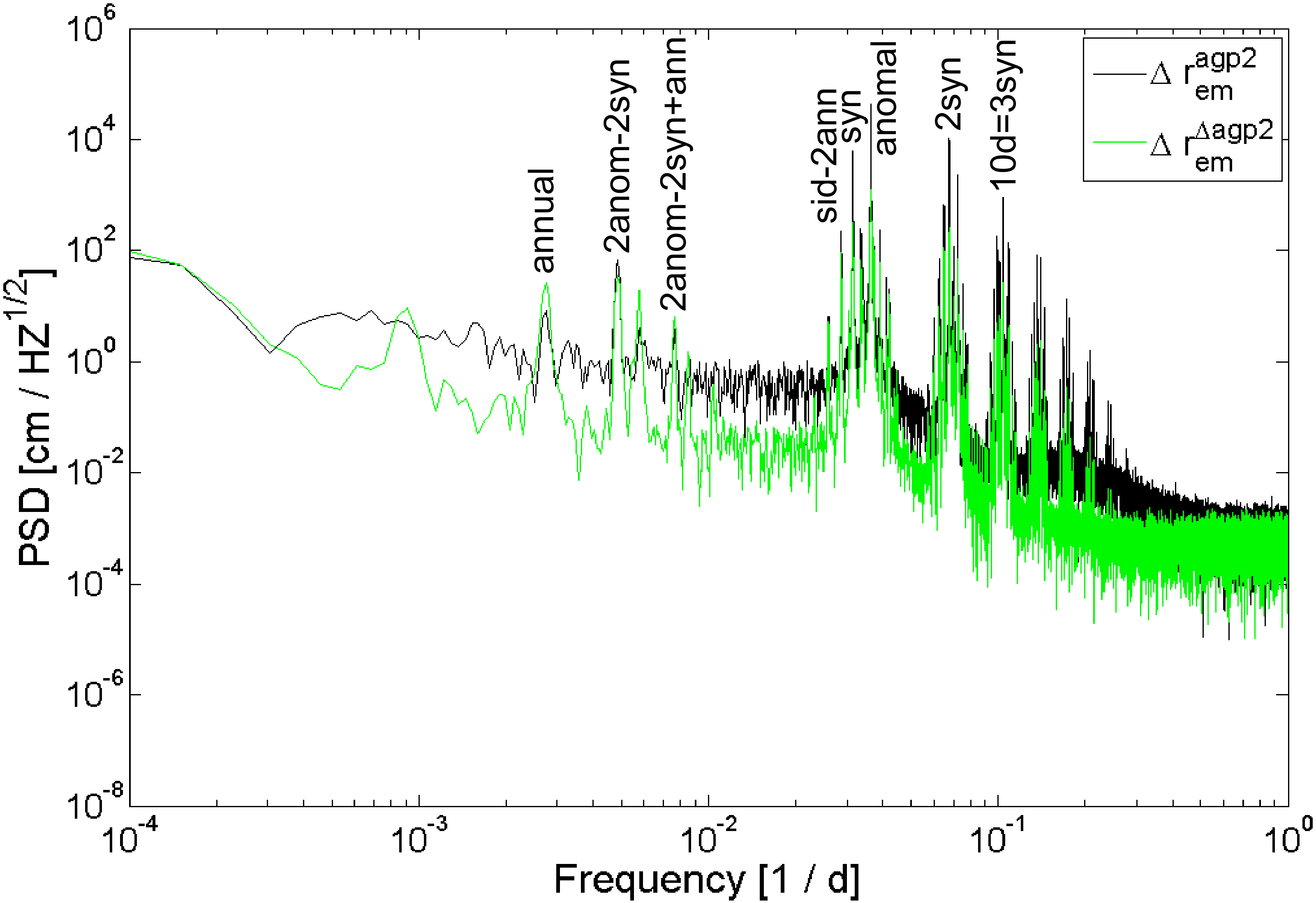
2)un-perturbed

→ difference

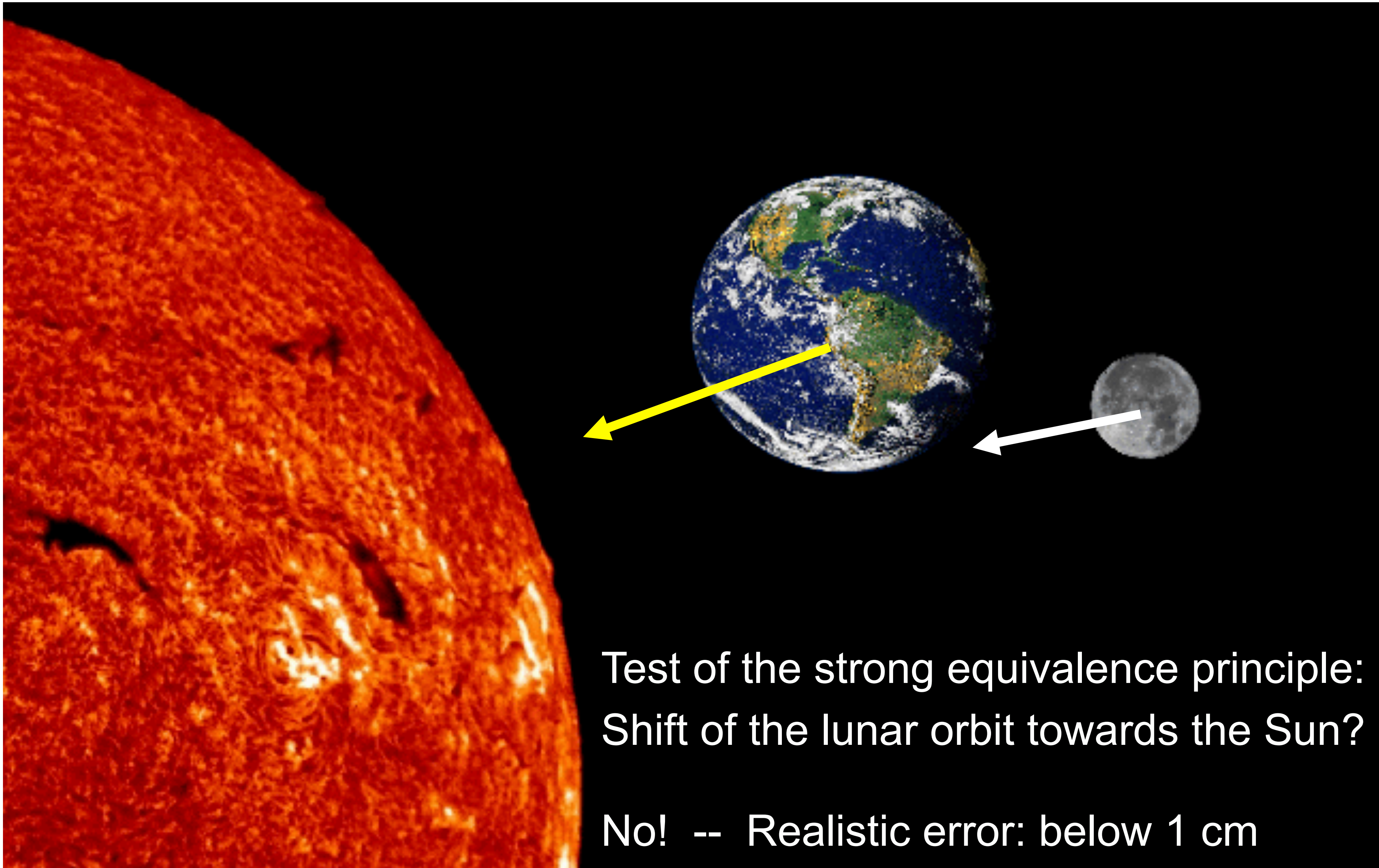




Corresponding Spectrum



Example: Nordtvedt Effect

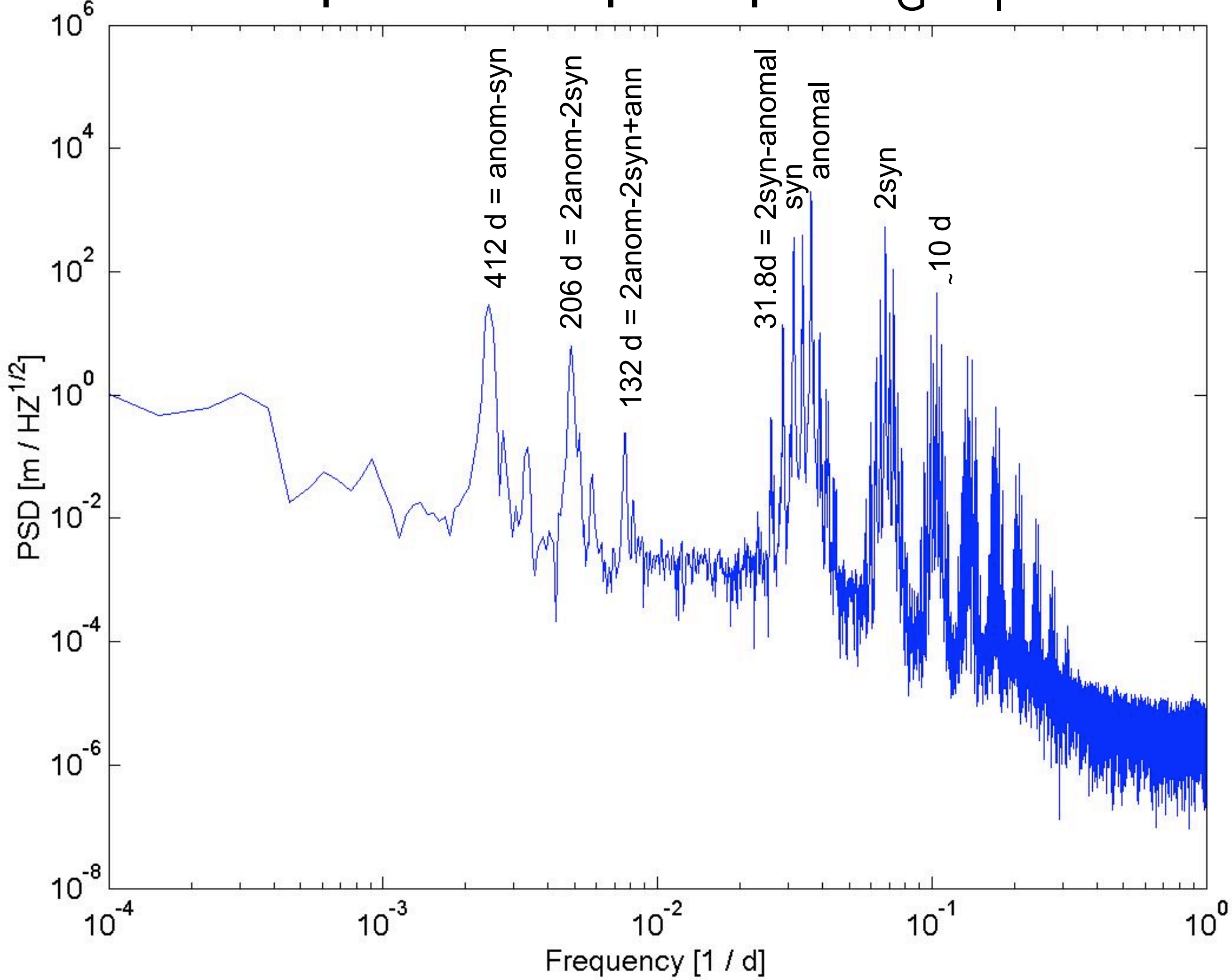


Test of the strong equivalence principle:
Shift of the lunar orbit towards the Sun?

No! -- Realistic error: below 1 cm

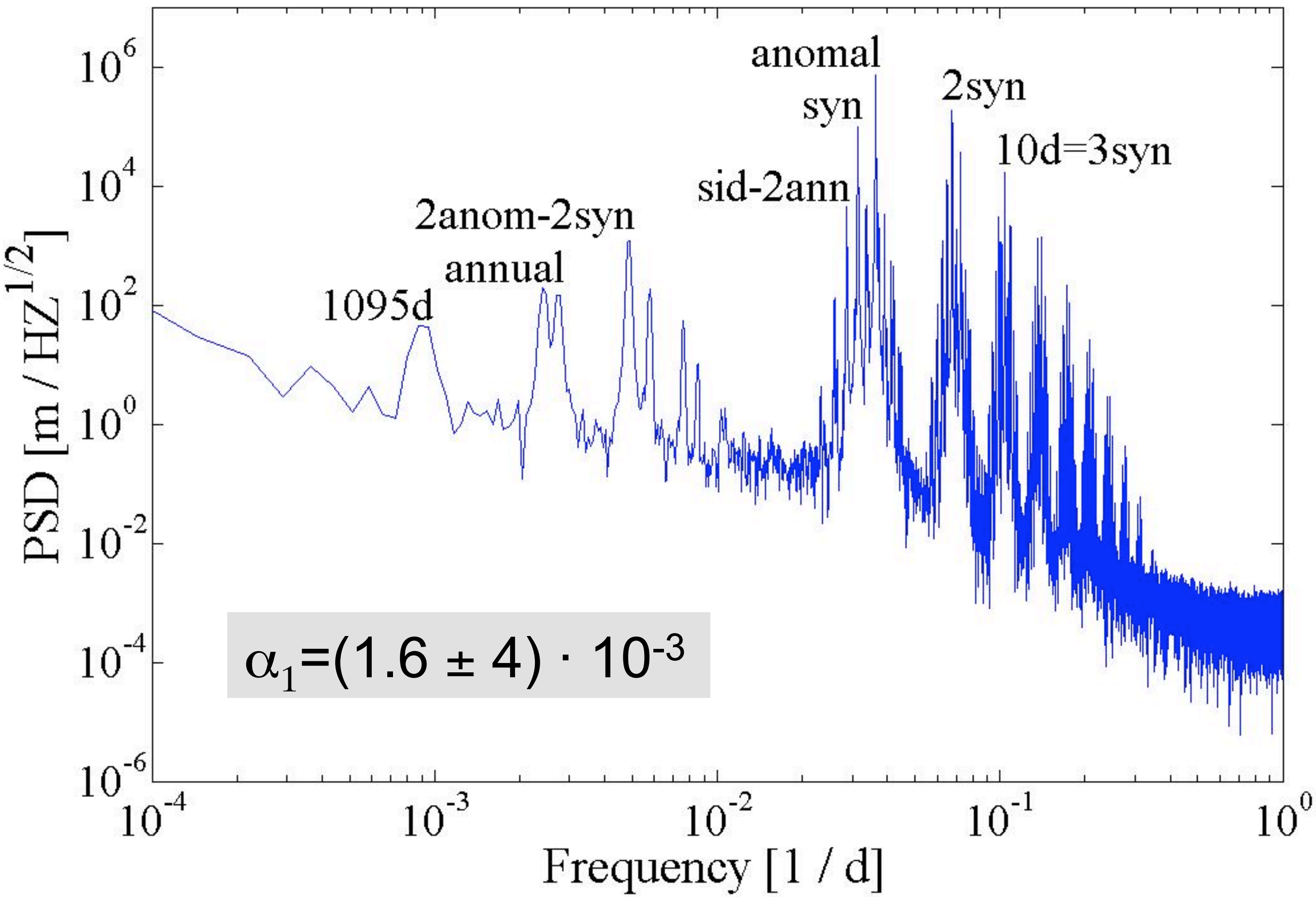
Relativistic Parameters – Power Spectra (1)

Equivalence principle m_G/m_I



Relativistic Parameters – Power Spectra (2)

Gravito-magnetic effect (PPN parameter α_1) in the solar system



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; $\gamma = 1$ in Einstein)	$(4 \pm 5) \cdot 10^{-3}$
metric parameter β - 1 (non-linearity; $\beta = 1$) or using $\eta = 4\beta - \gamma_{Cassini} - 3$ with $\gamma_{Cassini}$-1 ($\sim 10^{-5}$)	$(-2 \pm 4) \cdot 10^{-3}$ $(1.5 \pm 1.8) \cdot 10^{-4}$

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 effects α_1 α_2 (coupled with velocity of the solar system)	$(-4 \pm 9) \cdot 10^{-5}$ $(2 \pm 2) \cdot 10^{-5}$
preferred frame effect α_1 (coupled with dynamics within the solar system)	$(1.6 \pm 3) \cdot 10^{-3}$

Further Applications

Reference frames

- dynamic realisation of the ICRS by the lunar orbit, $\sigma < 0.01''$ (stable, highly accurate orbit, no non-conservative forces from atmosphere)

Earth orientation

- Earth rotation (e.g. UT0, VOL)
- long-term nutation coefficients, precession

see Biskupek/Müller, session 6, Tuesday

Relativity

- test of further theories, Lense-Thirring effect

Combination with other techniques

- combined EOP series and reference frames (GGOS)
- ‚Moon' as long-term stable clock

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

Conclusions

LLR contributes to better understanding of

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

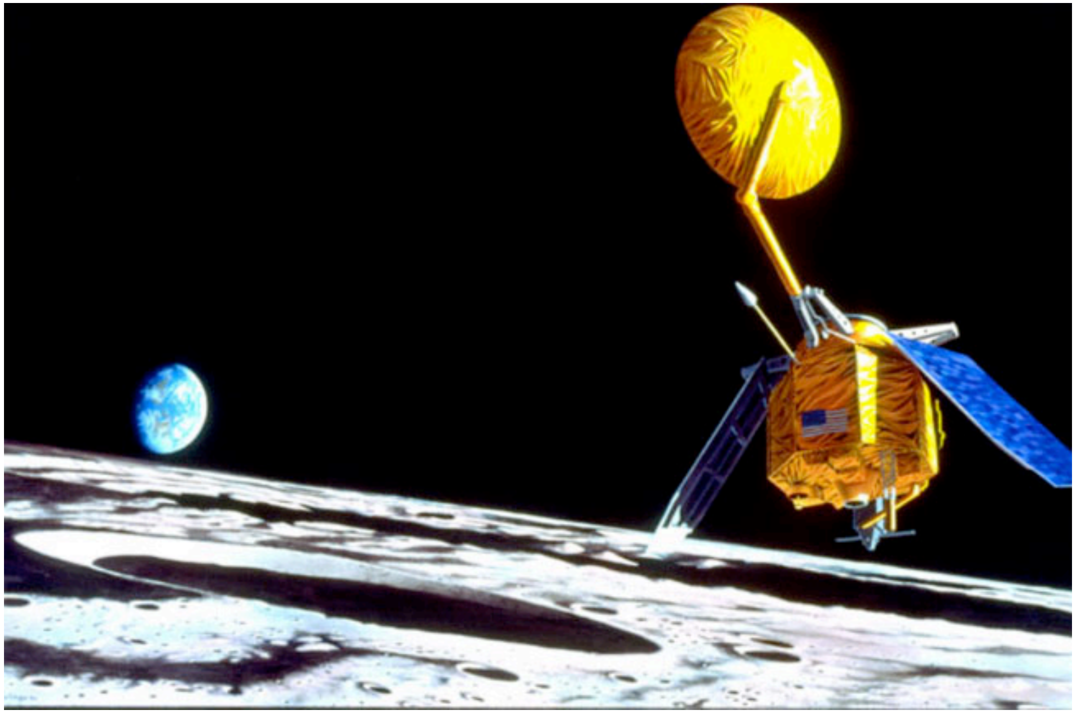
… and supports Global Geodetic Observing System

In future: new lunar ranging experiment

(and combination with other techniques)

Future Lunar Missions

Lunar Reconnaissance Orbiter (LRO)



Deployment of transponders (6 yr lifetime) and new retro-reflectors on the Moon or in lunar orbit

- more observatories

- tie to VLBI (inertial reference frames)

New high resolution photographs of reflector arrays

- better lunar geodetic network

- lunar maps

New Ranging Measurements – Why?

New data needed to constrain lunar interior structure

- improve measurements of forced librations
- measure tidal distortion (amplitude and phase)
- lunar oscillations as response to large quakes or impacts?

Improve on limits of relativistic effects

- time variability of the gravitational constant
- test of strong equivalence principle (Nordtvedt effect)

Improve the tie between the lunar network and the radio reference frame (VLBI)

Above goals require more data, more accurate data, and unbiased measurements!