Benefit of improved Lunar Laser Ranging data for the determination of Earth orientation parameters

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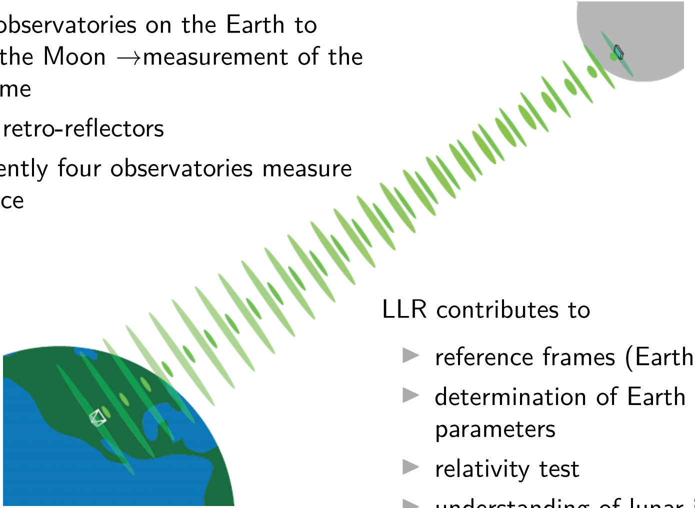
Principle of Lunar Laser Ranging

- Laser pulses from observatories on the Earth to retro-reflectors on the Moon →measurement of the round-trip travel time
- on the Moon: five retro-reflectors
- on the Earth: currently four observatories measure Earth-Moon distance

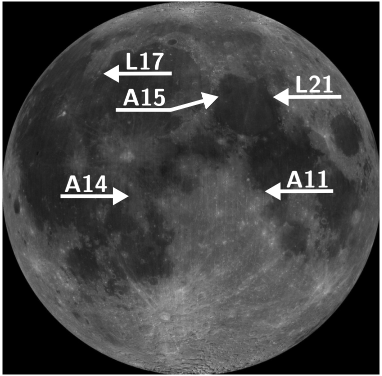


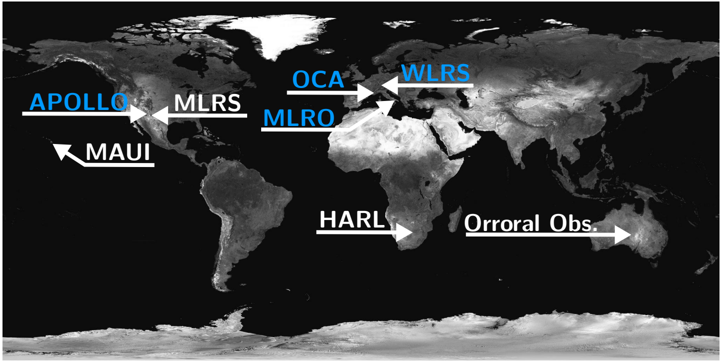
(Murphy, 2013)

LLR contributes to

- reference frames (Earth, Moon, inertial)
- determination of Earth orientation parameters
- relativity test
- understanding of lunar interior

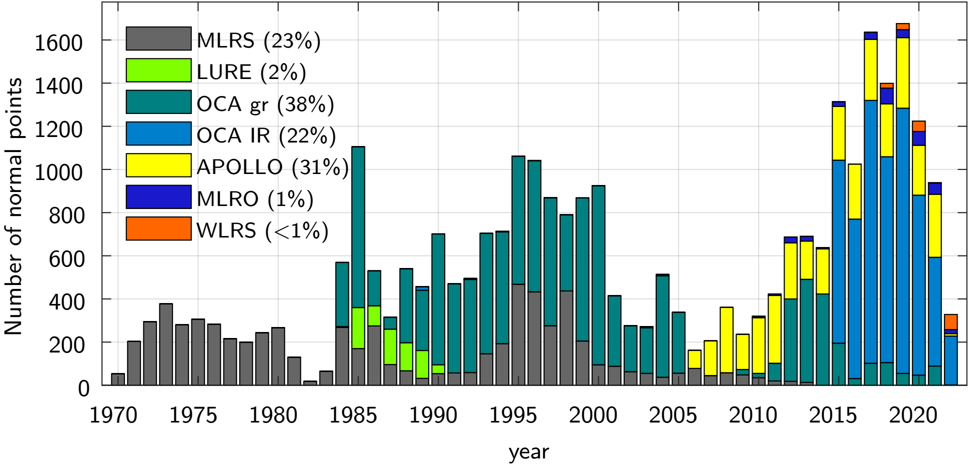
Positions of retro-reflectors and observatories





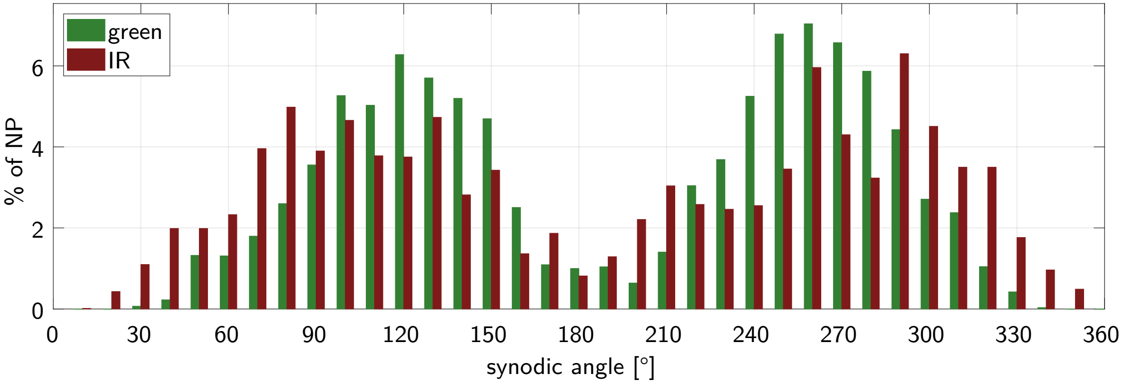
Distribution of the normal points over 52 years

30172 normal points over the time span April 1970 - April 2022



Distribution of the normal points over the synodic month

30172 normal points over the time span April 1970 - April 2022



LLR analysis at IfE

- iterative procedure between ephemeris calculation and parameter estimation
- initial positions and velocities of 8 planets, Sun, Moon, Pluto and asteroids (Ceres, Vesta, and Pallas) from DE440, optional more asteroids
- IERS Conventions 2010
- until 1983 use of the Kalman Earth Orientation Filter (KEOF) series COMB2019
- from 1983 IERS C04 EOP series
- up to 200 parameters can be determined
- as an extension: relativistic parameters (Biskupek et al, 2021)

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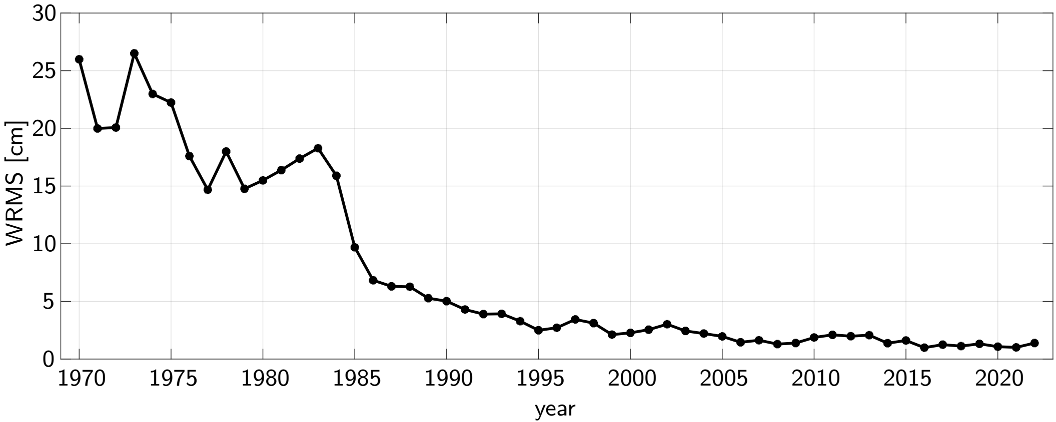
for the Earth

- station coordinates and velocities
- nutation coefficients and precession rate
- x_p, y_p and ΔUT (UT0 apart from VLBI)

for the Moon

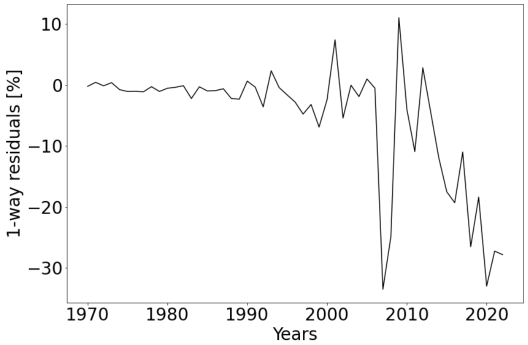
- initial values for orbit and rotation
- reflector coordinates
- dynamical flattening
- lunar core parameters and Love numbers

Residuals from LLR analysis at IfE



Recent updates in the analysis - ephemeris calculation

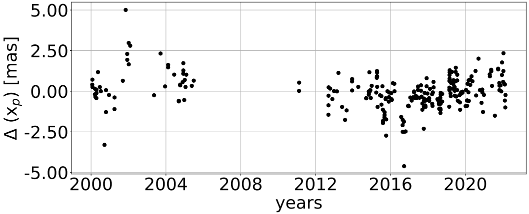
- before: successive calculation from 1969 on (1-way, 1969-2023)
- problem: errors are accumulated over time span (high accurate ephemeris/low accurate NPs ↔ lower accurate ephemeris/high accurate NPs)
- now: ephemeris starting from 2000 (2-way, 2000-1969 and 2000-2023)
- shorter calculation time
- improvement in parameter uncertainty (10 % to 76 %, especially orbit of the Moon, not so much for rotation)
- deterioration in some components of angular velocity lunar mantle and core



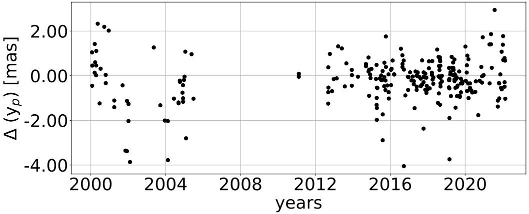
Earth rotation parameters from LLR

- all LLR NPs are used to determine the parameters of Earth-Moon system
- pre-analysis to identify subsets of data with special conditions for ERP determination
- different constellations of stations and the number of NP per night tested
- simultaneous determination of either ΔUT1, x_p or y_p, coordinates of all observatories and other parameters of the Earth-Moon system
- velocities of the observatories fixed to ITRF2014 values
- a-priori ERP from IERS C04 series, fixed for those nights that were not considered
- min. 15 NPs per night for time span starting 01.2000, different cases
- Singh et al (2022), Biskupek et al (2022)

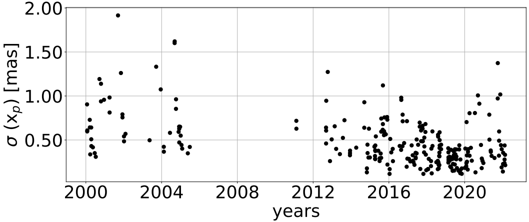
x_p, y_p results - OCA 15 NP, after 2000, 257 nights



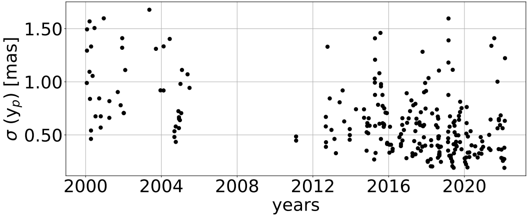
x_p differences to the a-priori IERS C04 EOP series



y_p differences to the a-priori IERS C04 EOP series



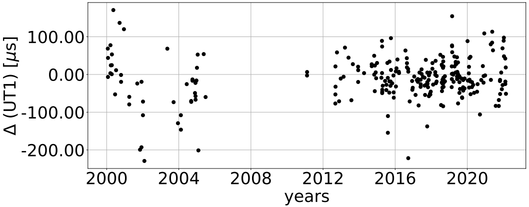
x_p uncertainties with wrms of 0.52 mas



y_p uncertainties with wrms of 0.66 mas

ΔUT1 results

OCA 15 NP, after 2000, 257 nights



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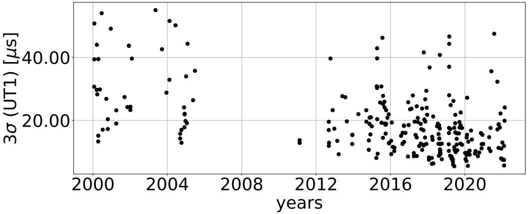

3×ΔUT1 uncertainties with wrms of 20.1 µs

Nutation results

period	results 2018 [mas]	results 2022 [mas]
$A_{18.6y}$	1.42 ± 0.53	0.48 ± 0.18
$B_{18.6y}$	-0.18 ± 0.19	-0.04 ± 0.09
$A''_{18.6y}$	-0.68 ± 0.37	0.38 ± 0.17
$B''_{18.6y}$	-0.06 ± 0.21	0.26 ± 0.10
$A_{9.3y}$	-1.12 ± 0.34	-0.23 ± 0.17
$B_{9.3y}$	-0.27 ± 0.15	-0.15 ± 0.07
$A''_{9.3y}$	-1.55 ± 0.34	0.60 ± 0.16
$B''_{9.3y}$	0.17 ± 0.14	0.13 ± 0.07
$A_{365.3d}$	1.05 ± 0.19	0.14 ± 0.10
$B_{365.3d}$	-0.51 ± 0.09	-0.05 ± 0.05
$A''_{365.3d}$	0.65 ± 0.15	-0.05 ± 0.09
$B''_{365.3d}$	0.04 ± 0.06	-0.09 ± 0.03

period	results 2018 [mas]	results 2022 [mas]
$A_{182.6d}$	0.51 ± 0.17	0.09 ± 0.08
$B_{182.6d}$	-0.06 ± 0.07	0.02 ± 0.04
$A''_{182.6d}$	-0.57 ± 0.14	0.18 ± 0.08
$B''_{182.6d}$	-0.07 ± 0.07	0.09 ± 0.04
$A_{13.6d}$	1.49 ± 0.63	0.39 ± 0.18
$B_{13.6d}$	-0.65 ± 0.26	-0.06 ± 0.08
$A''_{13.6d}$	-1.42 ± 0.81	0.12 ± 0.11
$B''_{13.6d}$	0.27 ± 0.32	-0.09 ± 0.05

(Hofmann et al. 2018)

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- smaller differences to a-priori MHB2000 model compared to 2018 results
- uncertainties (3σ) improved by factor 2
- biggest improvement for 13.6d period, benefit from IR OCA data

Conclusion and outlook

- EOP determination from LLR is possible
- for x_p, y_p uncertainty better then 0.7 mas
- for ΔUT1 from the highly accurate OCA data uncertainty about 20 µs
- determination of nutation coefficients with small differences to a-priori MHB2000 model and improved uncertainties
- LLR analysis benefits greatly from improved LLR data, especially from IR NPs with high number of NPs per night and better distribution over synodic month

next steps:

- implement celestial pole offsets
- combination of VLBI and LLR for validation of EOP

Thank you!