Benefit of the next generation corner cubes for Lunar Laser Ranging analysis

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Introduction

After the deployment of the first retroreflector panel on the Moon by the Apollo 11 crew, measurements of the roundtrip travel times for laser pulses between observatories on Earth and the reflectors (Lunar Laser Ranging – LLR) have been carried out for more than 44 years. Various questions on lunar physics and relativity are addressed. Today, LLR is one of the major tools for tests of General Relativity, e.g. testing the equivalence principle, temporal variations of the gravitational constant $\dot{G}/G$ or geodetic precession (Müller et al. 2014).

Fig. 1: Comparison of the new LLRRA-21 CCR (left) with one single Apollo-era CCR.

In case of the Apollo 11, 14 and 15 mission, each retroreflector consists of 100 or 300 small Cube Corner Reflectors (CCRs). Every panel follows the lunar motion, where the librational movement causes a tilt of the panel w.r.t. the Earth. The angular offset becomes $\pm 8^\circ$ in longitude and $\pm 7^\circ$ in latitude and leads to a temporal spread of the returning pulse due to the different distance of the single CCRs within the panel to the Earth. Nowadays, this is the limiting accuracy factor of LLR measurements.

To overcome this, the Lunar Laser Ranging Retroreflector Array for the 21st Century (LLRRA-21) program has developed a large single CCR (Fig. 1). The advantage of this kind of CCR is the absence of reflection ambiguities which allows the use of much shorter laser pulses to obtain a much more accurate timing of the received signal. This will improve the accuracy of LLR measurements down to the mm-level of accuracy and improve the science by one to two orders of magnitude.

Simulation

To show the effect of additional lunar reflectors of the LLRRA-21 type, we ran simulations on the basis of the last Institut für Erdmessung (IfE) LLR solution. They include all real LLR data up to the end of 2013 and further 27 years of LLR data up to the end of 2030. Fig. 2 shows the timeline of the involved observatories and lunar reflectors within the simulations.

Besides the currently operable LLR stations in France (OCA), Italy (MLRO) and in the USA (APOLLO, MLRS2) we simulated future observations from Germany in Wettzell (WLRS) and South Africa in Hartebeesthoek (HART).

On the lunar side, we started the simulated data with the existing five reflectors of the Apollo missions (denoted with A) and Lunokhod rovers (Lk). The next generation retroreflectors are being developed by Douglas Currie, of the University of Maryland, College Park in collaboration with INFN-LNF in Frascati, Italy (Currie et al. 2013).

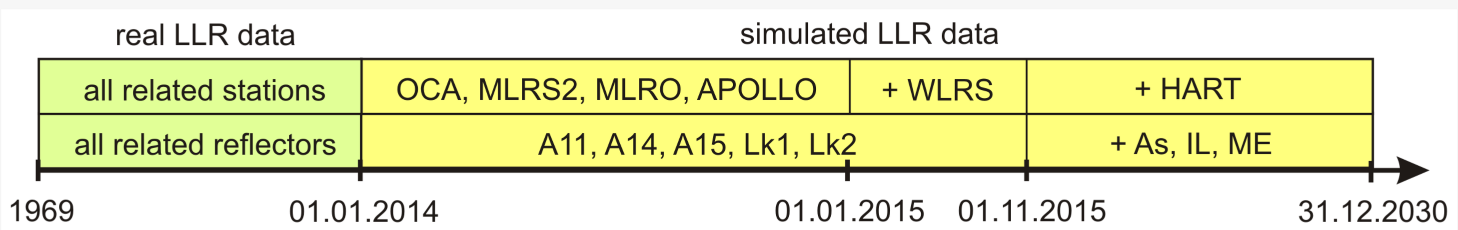

Fig. 2: Timeline of real and simulated LLR data for this analysis

They may be carried to the moon by Astrobotics team (As), the Moon Express team (ME) and the SpaceIL team (IL) (simulated here, see fig. 3) and perhaps other organizations.

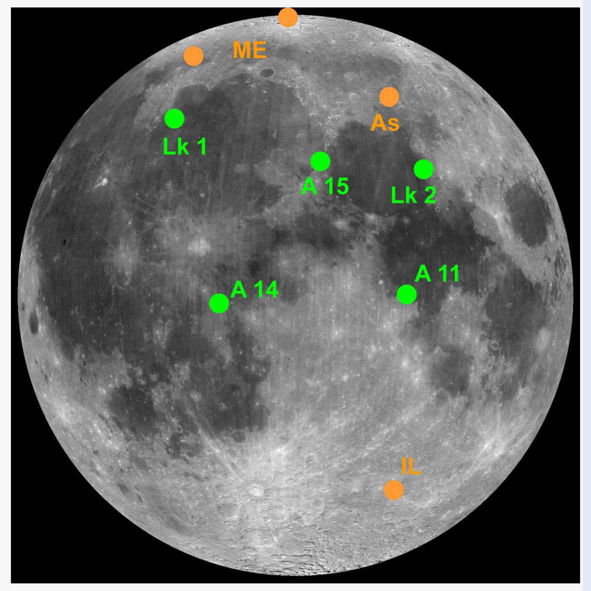

Fig. 3: Distribution of existing (green) and simulated CCRs (orange).

We simulated two scenarios, each with four cases and show the resulting accuracies for $\dot{G}/G$ and the 3D reflector position. The scenarions differ in measurement noise and total number of Normal Points (NP), see tab. 1. In case 1, we just used the existing reflectors. In case 2, all three new CCRs are added, but the IL CCR is just operable during lunar night. In case 3, all added CCRs are operable during lunar day and night and case 4 is the same like case 2, where the ME CCR is positioned in the libration zone near the pole.

Tab. 1: Total number of NP for each analysis interval. Numbers without brackets belong to scenario 1, numbers in brackets are valid for scenario 2.

year	current CCRs	3 CCRs added, IL night	3 CCRs added, IL all time	3 CCRs added, IL night, ME at 87° N
2013	20050	-	-	-
2016	21988 (21151)	22486 (21492)	22601 (21506)	22412 (21406)
2018	23516 (22061)	24836 (22991)	25157 (23054)	24636 (22745)
2020	24966 (22919)	27063 (24373)	27598 (24505)	26861 (23988)
2023	27148 (24242)	30421 (26515)	31241 (26705)	29837 (25872)
2026	29315 (25544)	33714 (28610)	34832 (28872)	32871 (27744)
2030	32256 (27331)	38212 (31465)	39719 (31808)	37002 (30255)

Scenario 1 – high measurement accuracy

In the first scenario, we simulated the optimal case where a measurement accuracy at the mm-level is reached in combination with the new type of CCRs. Even the measurement accuracy to the existing CCRs is pushed into the mm-level, which may be possible with ground based hard- and software updates at the observatories. Tab. 2 shows the applied 1σ noise level to the simulated data.

Tab. 2: Added 1σ noise to simulated LLR data

	existing CCRs	new CCRs
APOLLO	2.5 mm	1.0 mm
other stations	5.0 mm	2.0 mm

The number of annual NP was increased to nearly obtain the doubled amount of NP (approx. 750 NP per year), compared to the present-day rate.

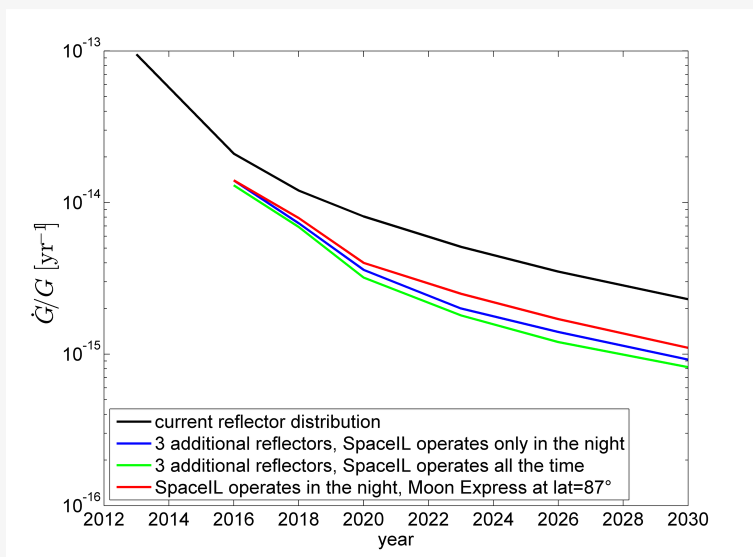

Fig. 4: Simulated accuracy for the determination of the relativistic parameter $\dot{G}/G$.

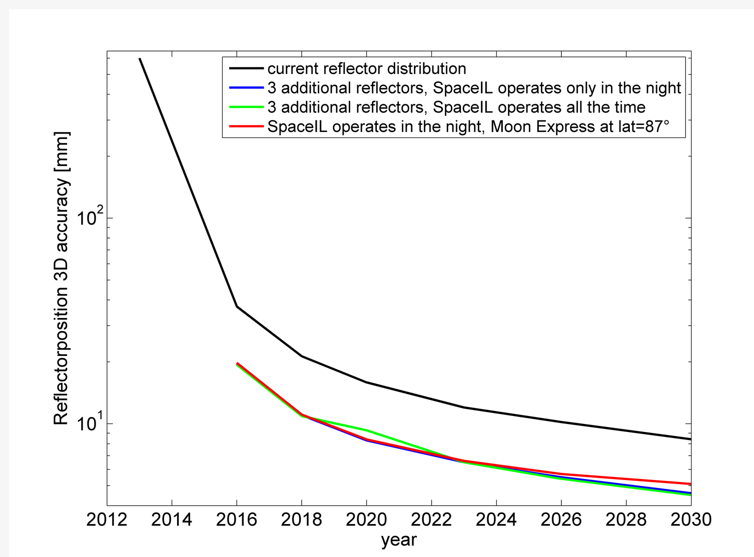

Fig. 5: Simulated 3D accuracy for the lunar reflector coordinates.

Scenario 2 – less measurement accuracy

In the second scenario, we reduced the simulated measurement accuracy to the existing CCRs by a factor of 2, see Tab. 3.

Tab. 3: Added 1σ noise to simulated LLR data

	existing CCRs	new CCRs
APOLLO	5.0 mm	1.0 mm
other stations	10.0 mm	2.0 mm

The number of annual NP was also reduced to the mean level of the observations within the last years, about 400 NP per year to the five existing CCRs, see Tab. 1. This not so optimistic scenario might be the more realistic one.

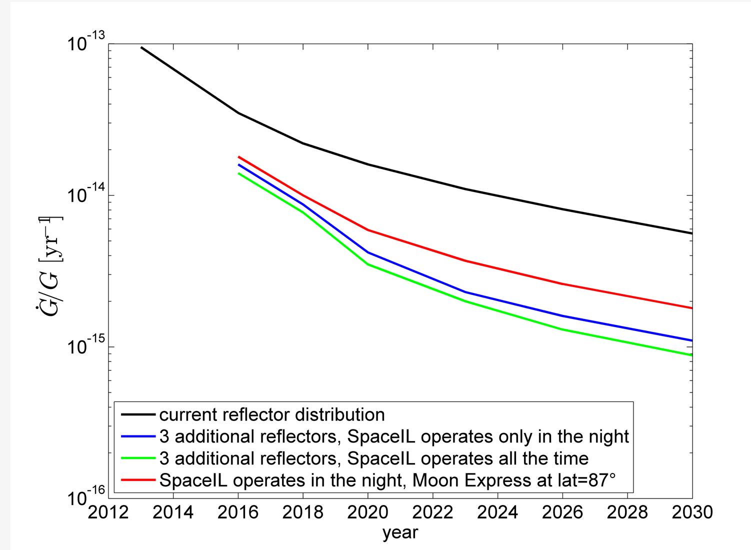

Fig. 6: Simulated accuracy for the determination of the relativistic parameter $\dot{G}/G$.

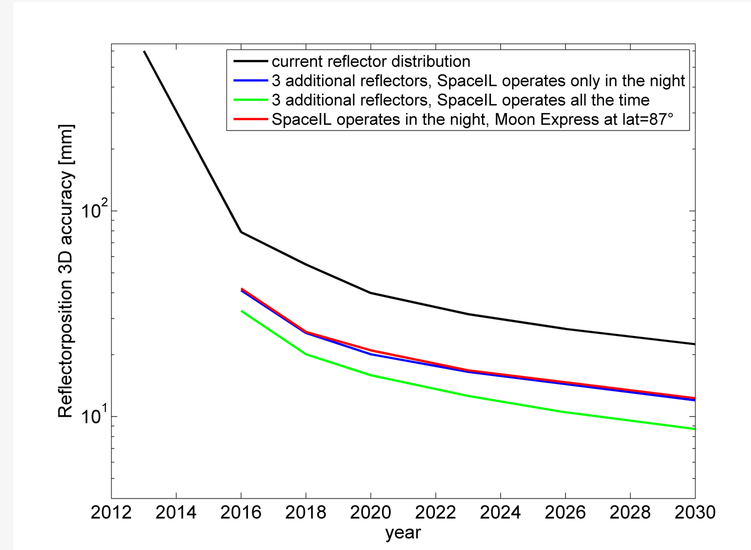

Fig. 7: Simulated 3D accuracy for the lunar reflector coordinates.

Conclusions

For the case of ongoing measurements to the five existing CCRs with an accuracy of some mm, the simulations show an increasing accuracy of the estimated parameter (here exemplarily of $\dot{G}/G$ and CCR position) of about one order of magnitude over the next 25 years. Even a relatively small number of additional precise measurements will have a positive influence on the resulting parameter accuracies.

A further strong enhancement can be reached by the new type of single-prism CCRs. With the possibility to push the measurement accuracy to the 1 mmm level, and under the assumption of a mm-accurate analysis, they will push the accuracy of the resulting parameters by a further factor of 2–3. With the new reflectors, the accuracy level of further 25 years of LLR to 5 CCRs could be reached in a much shorter time, approx. less than 10 years.

References

Currie et al. (2013). A Lunar Laser Ranging Retroreflector Array for the 21st Century. In: *Nuclear Physics B (Proc. Suppl.)*, vol. 243, p. 218-228, http://dx.doi.org/10.1016/j.nuclphysbps.2013.09.007.

Müller et al. (2014). Lunar Laser Ranging and Relativity. In: *Frontiers of Relativistic Celestial Mechanics*, vol. 2, ed. S. Kopeikin, DeGruyter.

Pearlman et al. (2002). The International Laser Ranging Service. In: *Advances in Space Research*, 30, pp. 135–43.

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