Federal Agency for Cartography and Geodesy

Lunar Laser Ranging: A small system approach

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Abstract. *For many decades Lunar Laser Ranging was confined to the single photon detection regime, despite of the application of large telescopes and high power pulse lasers. This means there were only very few stations capable of tracking the moon and the data yield was sparse. When the Apache Point Lunar Laser Ranging facility took up operations, it was the first station that routinely operated with a comfortable link margin, mostly owing to a very large telescope aperture and the high mountain location of the observatory. In contrast, the Wettzell Laser Ranging System is situated at a low elevation of 570 m at a much higher latitude of 49.14° and the telescope aperture diameter is almost 5 times smaller. However, modern high quantum efficiency fast detectors, as well as the operation in the near infrared regime at the 1.06 µm wavelength domain are compensating some of these disadvantages. It allows us to pioneer the application of ultra short laser pulses (10 ps) on the moon, where usually lasers of several hundred ps of pulse width are used. We can now resolve the effective depth of the APOLLO 15 reflector array, which changes as a result of the lunar libration. Owing to the infrared laser frequency, it has become also possible to operate the LLR system during the day time. This paper discusses the results and prospects of high resolution LLR.*

The Wettzell Laser Ranging System (WLRS)

The WLRS was established in the early 90s in order to conduct Satellite Laser Ranging measurements for geodetic purposes. From the beginning the system was designed to also allow for Lunar Laser Ranging. Despite the fairly small aperture of the WLRS telescope and its poor geographical location for a Lunar Laser Ranging facility, first successful attempts were already made in October 1990. However, due to an increasing workload on satellite observations and the poor link efficiency in Lunar observations, these were not continued over the following decades. A few years ago a second SLR system was established next to the WLRS in order to share the workload. This gave the opportunity to re-invent lunar ranging. At the same time with the advent of new single photon detection technologies in the infrared regime, the promise of an increased link efficiency and fast timing became a reality [Eckl] [Courde]. In 2011 the WLRS was also upgraded with the latest generation of passively modelocked high energy ND:YAG lasers. The short pulse width in combination with the fast timing allows to obtain a standard deviation as low as 20 pico-seconds or ~3,5 mm (Figure 1) for local reference target measurements.

In contrast to low intrinsic system jitter standard deviation from APOLLO 15 retroreflector returns is much worse (Figure 2). This is caused by the variable apparent depth of the flat retro-reflector panel in the presence of tilts induced by lunar libration, limiting the standard error to 1 cm.

$$Standard\ Error = \frac{Standard\ Deviation}{\sqrt{N}}$$

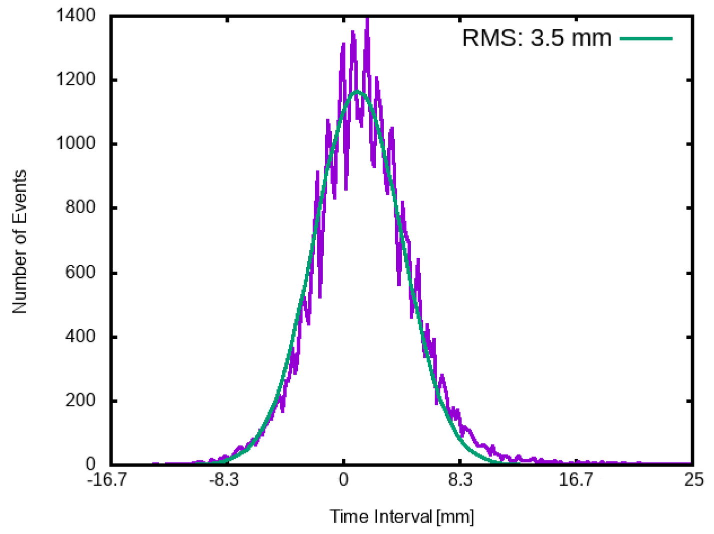


Figure 1: Timing response of the WLRS receiver in local target measurements.

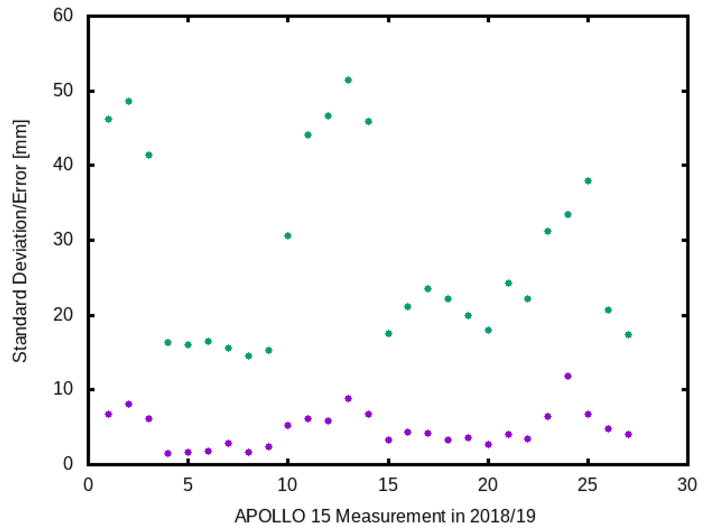


Figure 2: Standard Deviation and Standard Error of APOLLO 15 measurements during 2018 and 2019.

Lunar Laser Ranging

The Laser Link Equation [Degnan] for the optical regime is used to calculate the mean number of expected photo-electrons in the lunar return signal per outgoing laser pulse [Degnan].

$$n_{Pe} \propto \eta_q E_T \lambda G_t \sigma A_r / R^4$$

η_q	Detector quantum efficiency	New	High efficiency InGaAs detector
E_T	Laser pulse energy	Limited	~100 mJ
λ	Laser wavelength	New	Changed from 532 to 1064 nm
G_T	Transmit gain,	Limited	Atmosphere, **Future:** adaptive optics
σ	Reflector optical cross-section	Fixed	Deployed on moon
A_R	Receive telescope aperture	Fixed	0.75 m
R	Distance to the reflector	“Fixed”	Earth-moon distance

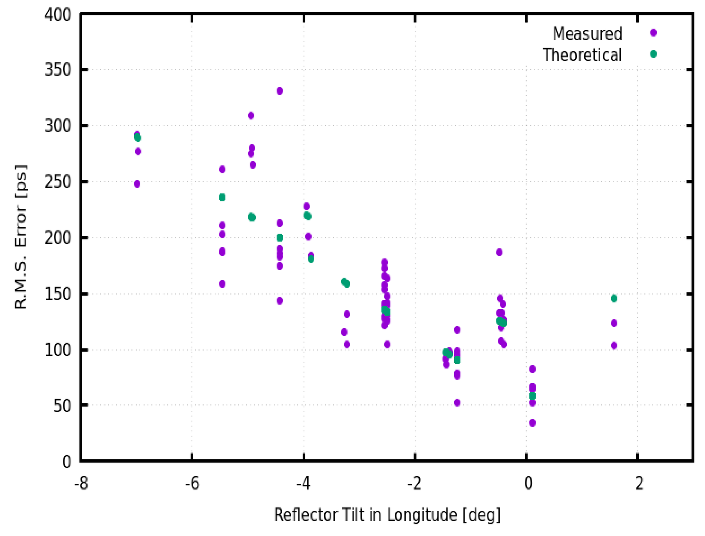
For the WLRS lunar observations a detection probability of up to 0.2 % was obtained, which is in good agreement with the calculated link margin.

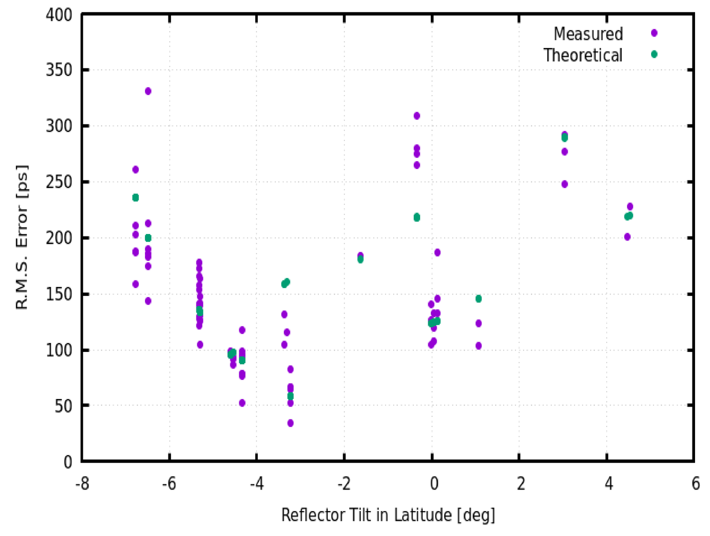
LLR tests, for example the strong equivalence principle (SEP) measure the difference in the accelerations of the Earth and Moon towards the Sun. In the presence of a differential acceleration, the orbit of the Moon – viewed from the Earth – would appear to be displaced, toward or away from the Sun.

$$\Delta r = 13.1\, \eta \ \cos D \ [m],$$

With D the synodic phase of the moon of 29.53 days and η a dimensionsless theory specific parameter. The metric models by Damour and Nordtvedt describe a relaxation of the scalar field strength that today would produce SEP differential accelerations between 5 x 10^{-17} and 10^{-13}.

The present limit on differential acceleration is of the order of $\Delta\alpha/\alpha = \pm(0.5 - 1.3) \times 10^{-13}$, corresponding to a test of the SEP at the level of $|\eta| < 3 \times 10^{-4}$, given the self-energy fraction of the Earth. Lunar laser ranging at the level of ≈ 3 mm would improve sensitivity of the SEP test of Δα/α by one order of magnitude to a precision of 10^{-14} (For details see: [Müller]). This motivates the removal of the apparent target depth.

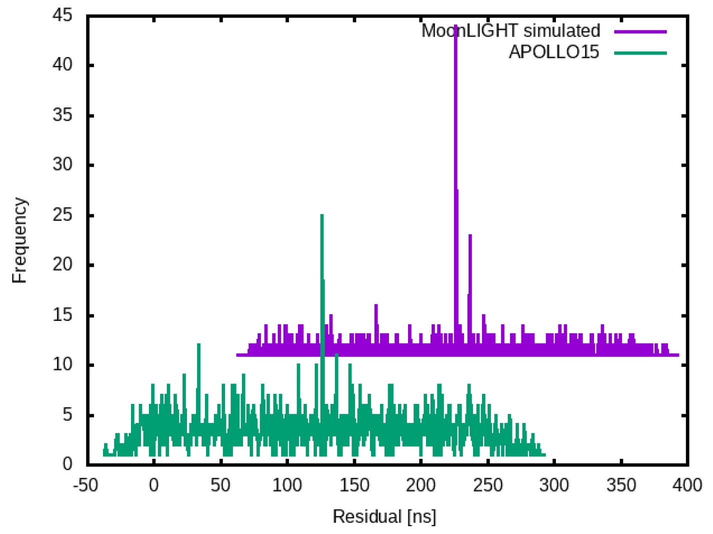




The apparent target depth caused by lunar libration, observed with the ultra-short laser pulses from the WLRS. A “zero signature” reflector will provide the necessary improvement.

MoonLIGHT -zero signature- reflector simulation

A single large retro-reflector, e. g. [Currie], removes any target depth effect and would dramatically improve the range precision over each observation session, independant of the actual lunar libration angle. Furthermore an improved signal to noise ratio can also be expected. A single reflector allows a smaller histogram bin width for the observation. As a result the probability of noise in each histogram bin is reduced, while the lunar returns accumulate coherently. The Figure to the right illustrates this behaviour by a simulation of the proposed MoonLIGHT reflector echoes. For this illustration the widely scattered observations from the APOLLO 15 target were corrected by the reflector response of the MoonLIGHT reflector.



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