Lunar laser ranging utilizing a highly efficient solid-state detector in the near-IR

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ABSTRACT

Ranging to the moon in the optical domain sets high demands on the tracking station. Apart from precise pointing and tracking with error tolerances of less than 1 second of arc, it also requires the capability for single photon event timing in the presence of significant background light levels. As a consequence of this technological challenge, there are only very few laser ranging stations like the McDonald Laser Ranging Station (MLRS) and the MeO station near Grasse in France that have successfully tracked the moon over the last almost 50 years. The Geodetic Observatory Wettzell is a fundamental station for Global Geodetic Observing System (GGOS) and therefore combines all the major measurement techniques of space geodesy collocated in one place. While the Wettzell Laser Ranging System (WLRS) has obtained a few observations of the Apollo 15 target in the past, the data volume was too sparse to make a significant contribution.

Recent progress in the development of highly sensitive IR photon counting detectors has provided a new generation of diodes that offer high quantum efficiency at the fundamental wavelength of Nd:YAG at 1.064µm and very short signal rise times at the same time. Furthermore they exhibit a very low intrinsic detector noise level. Together with a 75 mJ pulse energy and a laser pulse width as small as 10 picoseconds, the WLRS has now repeatedly observed the Lunokhod 1 and the Apollo 15 target with a good signal to noise ratio, so that the remaining measurement error is limited to the effective reflector depth of the respective lunar targets in the presence of the libration of the moon. This talk outlines the station characteristics and discusses the detector performance for this high demanding application.

Keywords: Lunar Laser Ranging, Satellite Laser Ranging, Single Photon Detection, Time-Correlated Single Photon Counting

1. INTRODUCTION

Almost 50 years ago, on the 20th of July in 1969, the NASA APOLLO 11 mission succeeded for the first time in taking human beings to the moon. Besides several other scientific instruments the astronauts also deployed a Laser Ranging Retro-reflector (LRRR) during their visit on the lunar surface. In contrast to all other experiments, including those of any other APOLLO missions, the only experiment, which is still operational is Lunar Laser Ranging. This is possible, because the segment on the moon is purely passive and consists of solid glass corner cube reflectors only. The complexity then of course is on the ground side. In lunar laser ranging time-of-flight measurements to the LRRRs on the moon are made using strong lasers in combination with large optical telescopes. These are necessary because of the high attenuation in the optical transmission link between ground up to the moon and back to ground. Due to the high precision of such measurements a relative accuracy of less than 5×10^{-11} can be achieved nowadays. This means that employing this technique, the distance to the moon can be measured with an accuracy and precision of as low as few centimeters [9]. Because of that lunar laser ranging still is a leading technique to verify the predictions of general relativity and to study the earth-moon system [8, 9]. In contrast to all other Lunar Laser Ranging Systems the Wettzell Laser Ranging System (WLRS) may be called a hybrid lunar laser ranger because it was designed to cover the whole range from ranging low earth orbiting satellites up to the currently farthest target, the moon. Indeed most of the observation time of the WLRS is spent on satellite laser ranging, what makes this system one of the most productive systems in the International Laser Ranging Service [15]. Furthermore the WLRS is part of the Geodetic Observatory Wettzell, which is

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a core site of the Global Geodetic Observing System. At the Observatory the space geodetic techniques are co-located. As a result the coordinates of the reference point of the WLRS are very well known in the international terrestrial reference frame. Currently also much effort is spent on further improving the quality of this data by combining the solutions of the different space geodetic techniques [1, 8]. Therefore the lunar laser ranging data gained with the WLRS is very well referenced. To cope with the requirements on the accuracy and precision for satellite laser ranging the system is optimized for best timing performance. This is realized by utilizing a pulsed laser with a pulse-width of only 10 picoseconds. Together with a single photon detector that is also optimized for best timing performance a single shot ranging precision of 19 picoseconds with very close to Gaussian distributed noise can be achieved (Figure 1). Converted to precision in ranging this gives a root-mean-square value of 3.3 millimeter. In the following after a detailed description of our single photon sensitive detector package our recent achievements in Lunar Laser Ranging in terms of the measurement process, the link budget and the accuracy that can be expected will be illustrated.

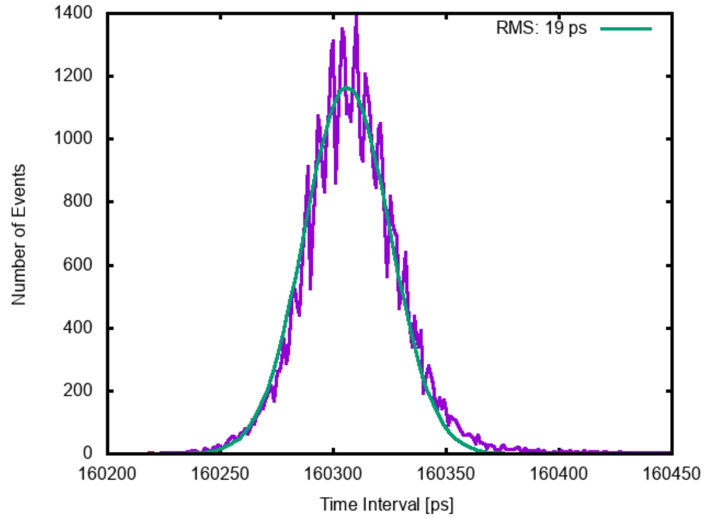

Figure 1. Residual histogram of ranging a local single reflector target with the WLRS.

2. EXPERIMENTAL SETUP

As already mentioned the WLRS may be called a hybrid lunar laser ranging system. Typical parameters of LLR systems with the highest productivity through the last years compared to the WLRS can be found in Table 1. The most important parameters with respect to signal strength are optical aperture of the telescope, laser single pulse energy and the atmospheric parameters. This can be understood when analyzing the radar link budget equation [4]. Considering just both of the former parameters the WLRS already lacks about one order of magnitude in signal strength compared to state of the art lunar laser ranging systems. The contribution of the atmosphere cannot be given directly, because these parameters are changing and the situation at other sites is not known exactly. However both of the other lunar laser ranging systems are situated at astronomical sites with typically good conditions whereas the WLRS is not. Instead the WLRS is situated in southeast Germany in the Bavarian Forest at an elevation of about 665 m. Typically humidity as well as atmospheric turbulence are high in this region. Because of the resulting high loss in signal strength it would not make sense to perform lunar laser ranging at the second harmonic wavelength of the laser, which is traditionally used for satellite laser ranging. Ranging at the fundamental wavelength of the laser makes the second harmonic generation process unnecessary and because of that a gain in the laser pulse energy of a factor of 2 can be obtained. Furthermore the energy content of a single photon is proportional to the inverse of its wavelength. Therefore the amount of photons in one laser pulse raises again by a factor of two. First attempts to perform satellite laser ranging at the fundamental laser wavelength of a Nd:YAG laser at 1064 nm were conducted in the 90s [13, 12]. However, the detectors available at that time were lacking sensitivity. Ten years later, in 2001, first attempts with a new kind of compound single photon avalanche diode were made in Prague [11]. Such compound diodes consist of an InGaAs absorption layer with a low band gap, which is sensitive in the near-infrared spectrum of light together with a multiplication layer with a large band gap to reduce the noise, see e. g. [17]. The devices analyzed in Prague had a fairly small active area of 30 to 50 micrometer only and could not provide the high demands in timing precision and dark count rate. Therefore, they could not compete with single photon avalanche diodes composed of silicon. As a result silicon devices were and are still used in satellite laser ranging applications. Then a few years later upgraded versions of such diodes became available with an active area of as large as 80 micrometer [17]. Furthermore these devices are optimized to provide highest efficiency at a wavelength of 1064 nanometer using anti-reflective coatings. In 2013 they were investigated for their suitability in satellite laser ranging applications with promising results [5]. Just recently the detectors were used for lunar laser ranging with great success for the first time at the Grasse MeO station [2]. Now also first successful attempts in lunar laser ranging utilizing InGaAs/InP single photon avalanche diodes during the year 2018 at the Geodetic Observatory Wettzell can be reported.

Table 1. Overview of relevant parameters of the most productive Lunar Laser Ranging Systems compared to the WLRS from the International Laser Ranging Service Station Site Log data. The Grasse Lunar Laser Ranging System is capable of performing lunar laser ranging in both laser wavelength.

	APOLLO	**Grasse MeO**	**WLRS**
Telescope Aperture [m]	3,5	1,54	0,75
Laser Pulse Energy [J]	0,115	0,3 (0,2)	0,075 & 0,05
Detection Efficiency [%]	30	20 (20)	30
Wavelength [m]	0,532	1,064 (0,532)	1,064
Elevation [m]	2788	1323	665

Before going into detail of the lunar laser ranging process itself the scheme and some relevant properties of the InGaAs/InP single photon avalanche diode, the model PGA-080u-1064TOT from Princeton Lightwave Inc. (now Argo AI) installed at the WLRS shall be outlined. One fundamental issue of using single photon avalanche diodes with a usually small active area together with large optical telescopes is to focus the collected light onto the active area. For that purpose we use an aspherical lens with a very short focal length of only 12 millimeter to eventually achieve a field of view of 18 seconds of arc. Of course this value is specific for our individual setup. Anyway such a field of view is sufficient to perform lunar as well as satellite laser ranging but requires careful alignment and a stable setup over time.

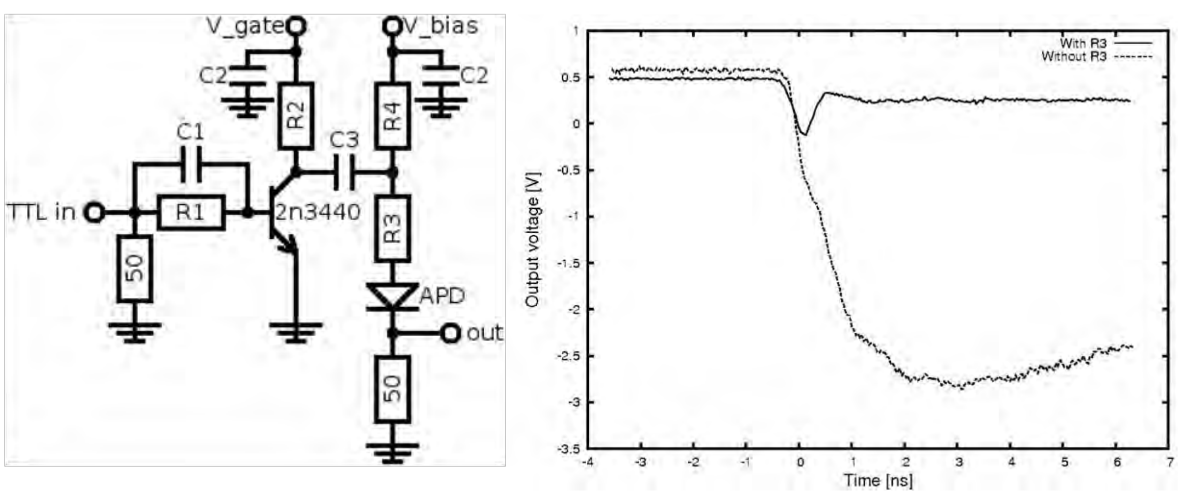

Figure 2. a) Passive quenching circuit used for applying the bias voltage to the InGaAs/InP single photon avalanche diode at the WLRS. b) Output pulse shape of an avalanche breakdown of the single photon avalanche diode applying identical bias voltage with and without the resistor R3.

To apply the required bias voltage to the device we use the same electronic circuit that we have already presented in a previous publication [6]. The circuit is displayed in Figure 2 a). It is a simple passive quenching circuit with an additional resistor R3. This resistor causes the diode to be decoupled from the current source, which is the capacitor C3 during biasing the diode above its breakdown voltage. As a result the amount of current during the breakdown process of the diode is reduced. Therefore the quenching process takes place before complete ionization of the depletion layer of the diode has happened. As a result a separation of the current arising from the avalanche process taking place in the semiconductor and that of the current flowing through ionized parts of the semiconductor is visible. Figure 2 b) illustrates this behavior. It can also be seen, that the total amount of current flowing during a breakdown is reduced. This in principle also reduces the afterpulsing effect that can be seen in such devices [14]. However in our application the repetition rate of activating the device is only 20 Hz and therefore afterpulsing is not visible anyway. For us it is more important that the additional resistor allows us to apply a higher bias voltage since the heat introduced into the semiconductor and the bonding wires is reduced during a breakdown. Figure 3 outlines the relative detection efficiency for a signal that is expected 100 nanoseconds after the diode is switched to active mode at different bias voltages above breakdown. It is visible that this parameter becomes highest at a value of about 14 to 18 Volt. In particular this is the case for a chip temperature of 220 Kelvin. This again is the minimum temperature that can be reached with the thermoelectric cooler that is already installed on the chip. For the measurements of Figure 3 the device was mounted in a cryostat to also reach lower temperature regions. This however makes the experimental setup much more complicated, especially when taking the above mentioned demanding requirement on the alignment of the diode into account. During the measurements the signal level of the pulsed laser source as well as the optical alignment were kept constant all the time.

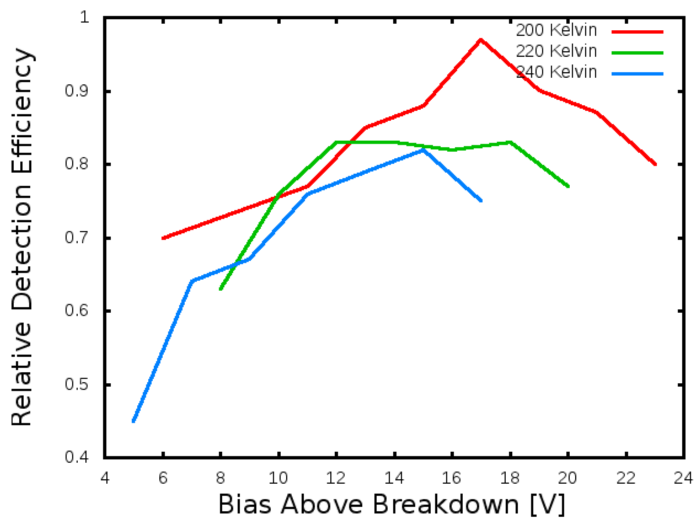

Figure 3. The relative detection efficiency for the InGaAs/InP single photon avalanche diode used at the WLRS.

Besides the detection efficiency also the timing behavior of the device is of concern, of course. Figure 4 outlines the root mean square jitter of the device with respect to the bias voltage above breakdown at a chip temperature of 220 Kelvin. Because of restrictions of the time-tagging electronics the trigger level necessarily needed to be -125 millivolt. During the measurement the signal rate of impinging photons triggering the avalanche was kept at a level of about 5 percent. As a result only single photo-electrons were seeding the avalanche breakdown. It is visible that the jitter clearly goes down up to a bias voltage of 20 Volt. To optimize the timing performance on the one hand side and to maintain the best possible detection efficiency on the other hand, a bias voltage of 18 Volt above breakdown was chosen in the final setup. This is 8 Volt above the maximum rating given by the manufacturer.

In satellite laser ranging applications the arrival time of the reflected photons is usually known to a few 10s of nanoseconds. Therefore to reduce the noise and as a consequence to optimize the detector efficiency, the detector should be activated as close as possible to the expected satellite echoes. Hence the time interval that is required to stabilize the detector bias voltage is of concern. From Figure 4 it can be seen that this process takes about 60 to 70 nanoseconds. After this time interval the systematic error in the time-interval measurement is reduced to below few picoseconds. To also account for the uncertainty in the photon arrival time mentioned above it is wise to activate the detector around 100 nanoseconds in advance to that point of time.

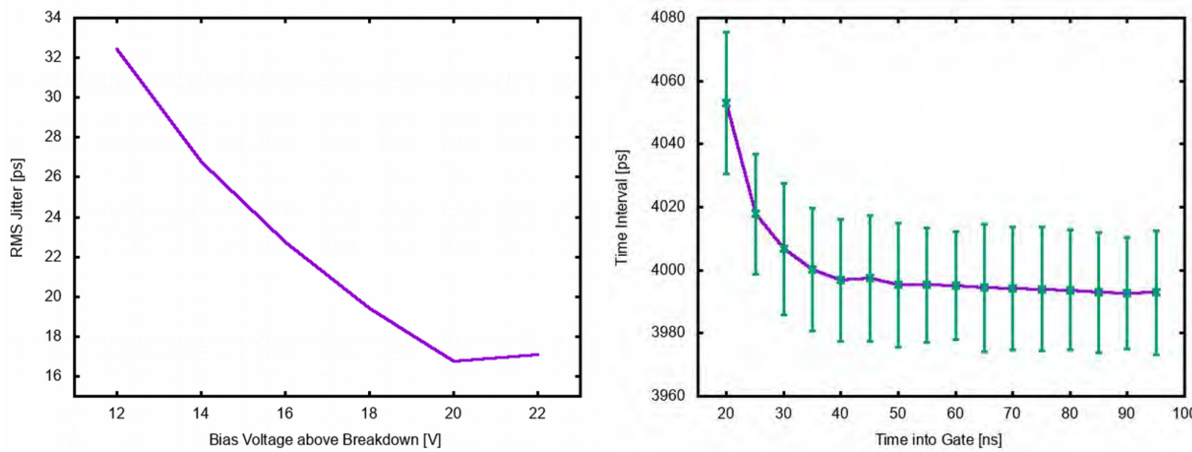

Figure 4. a) The root mean square jitter of the InGaAs/InP single photon avalanche diode at a chip temperature of 220 Kelvin and at a trigger level of −125 millivolts when the avalanche breakdown is seeded by single photo-electrons only. b) The measured time interval as a function of the time interval after activation of the InGaAs/InP single photon avalanche diode.

3. OBSERVATION STRATEGY

A detailed analyses of the radar link budget equation gives a maximum return rate of only 0.2 percent for the parameters of the WLRS. Because of the low signal strength and the poor atmospheric condition in Wettzell lunar laser ranging is only reasonable at an elevation of the moon of more than 50 degree. However, despite of that the WLRS still lacks one order of magnitude in signal strength compared to state of the art lunar laser ranging systems. To anyway perform lunar laser ranging the drawback of low link efficiency had to be overcome. Thus an observation strategy was developed that allows for lunar laser ranging without direct feedback. Usually satellite laser ranging systems give feedback that indicates success close to real-time employing sophisticated analysis of the ranging residuals [7]. The underlying challenge without feedback then is to establish the link between the ground station and LRRR and to keep this link established during one observation interval. One has to keep the demanding requirement on the pointing here in mind. The pointing has to be stable to less than 1 second of arc to be able to successfully perform lunar laser ranging. Therefore our tracking strategy consists of two steps. The first step is to detect the telescope pointing error and subsequently the second step is to track the LRRR with an automatic correction of the telescope pointing. The first step is possible because highly accurate lunar crater positions are provided by the Paris Observatory Lunar Analysis Center, which serve as a reference for initiating the telescope pointing offset (Figure 5 a)). After this referencing step, the reflector ephemeris are used to move the telescope towards the LRRR position. To initiate the ranging procedure the azimuth and elevation offset values found during crater referencing are used. Then another reference in the field of view of the telescope camera is used to keep the telescope pointing stable. This reference may be an illuminated mountain slope or a partly illuminated crater. After this second reference is assigned the telescope automatically tracks this point regarding the initial offset. This can be seen in Figure 5 b) where the mountain slope is visible in the black square. Inside the square pixels with low intensity are blacked out and then the expectation value of the residual pixels is calculated. The telescope is commanded in such a way, that the black reference cross, that indicates the initial offset, coincides with this expectation value. During the first lunar ranging attempts however this second step was performed manually. One fundamental requirement for the whole procedure of course is, that the ephemeris are accurate to less than 1 seconds of arc with respect to the telescope reference point. To give an idea what can be expected from such an approach the tracking performance on the example of tracking a star is outlined in Figure 6. Besides the noise also a periodic modulation is visible. This modulation arises from the gears of the telescope drives of the WLRS and therefore has no impact on the tracking performance of the telescope. Reducing these modulations from the data gives a remaining root mean square pointing error of less than 1 second of arc. Eventually it is assumed that our approach should also allow for lunar laser ranging without the need of high precision telescope drives.

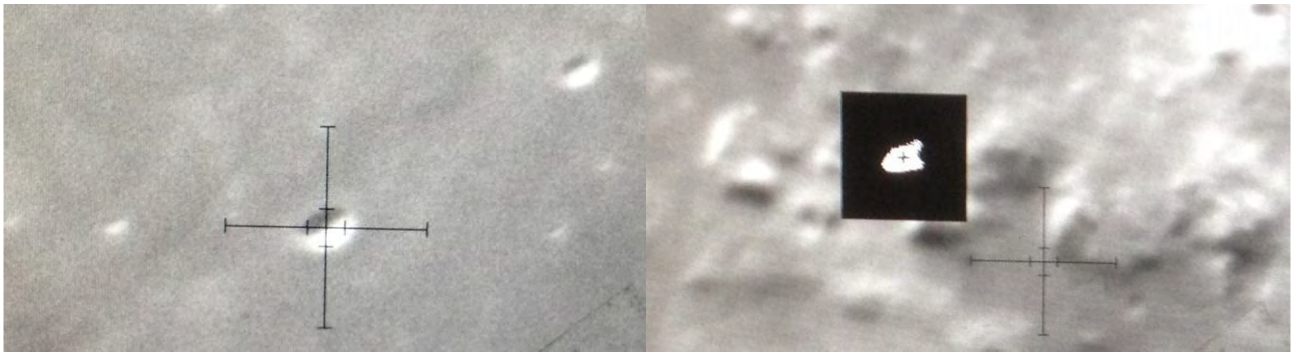

Figure 5. a) The telescope reference cross-hair pointing towards Reiner crater on the moon to detect the telescope pointing error. b) The telescope reference cross-hair pointing towards the APOLLO 15 LRRR together with the reference point (an illuminated mountain slope), which is automatically tracked.

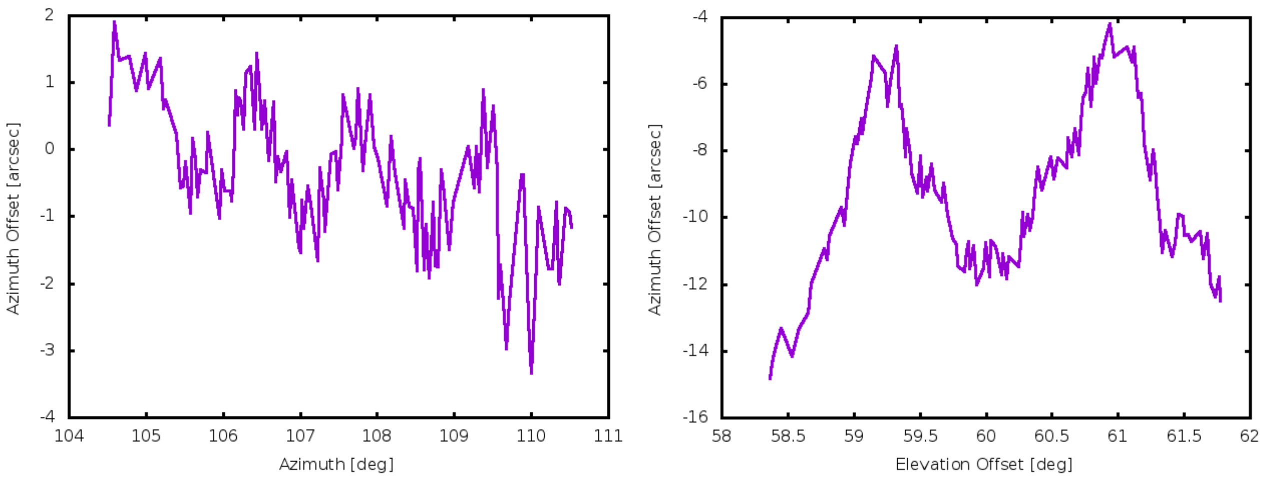

Figure 6. Offset pointing correction of the WLRS telescope in automatic tracking mode in Azimuth and Elevation on the example of tracking a star.

One further important point to conduct lunar laser ranging is to reduce the detector noise. This can be done by filtering unwanted straylight or by optimizing the utilized single photon avalanche diode towards a low dark count rate. The latter can be done by reducing the bias voltage of the detector. However as already mentioned above a reduction of the bias voltage does not necessarily improve its detection efficiency. To also keep the timing performance of the detector at the highest level it was chosen not to optimize the detector with respect to the dark count rate. Anyway, the detector noise is not the limiting factor. The dark count rate of the detector is 180 kHz whereas the noise arising from solar photons scattered on the surface of the moon is with 3 MHz by more than one order of magnitude higher in the case of the WLRS. This might be clarified by the fact that with an apparent magnitude of up to -12.9 the moon is the second-brightest object in Earth's sky after the sun [16]. Therefore, careful filtering of straylight is required. In case of the WLRS the field of view of the detector is limited to 10 seconds of arc during lunar laser ranging. In addition the detector is activated about 100 nanoseconds before the lunar echo is expected. As mentioned above this gives just enough time to stabilize the detector bias voltage. Eventually, a spectral filter is implemented to prevent photons of a different wavelength regime compared to that of the laser to reach the detector.

4. RESULTS

With the system prepared in that way 6 successful passes of the APOLLO 15 and 5 of the LUNA 17 reflector were tracked during 2018. Then, by the end of 2018 in total 380 echoes could be received from the APOLLO 15 reflector and 177 from the LUNA 17 reflector. From these echoes 13 and respectively 9 averaged residuals were formed, each at an averaging time interval of approximately 1000 seconds. It was found that the return rate was close to the expected maximum value of 0.2 percent (Figure 7), with an average return rate of 0.144 for APOLLO 15 and 0.095 for LUNA 17.

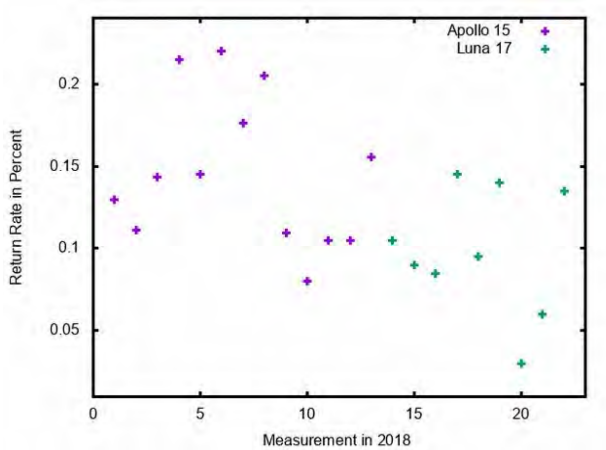

Figure 7. Return Rate of the individual averaged residuals for ranging the APOLLO 15 and LUNA 17 reflector with the WLRS.

From a metrological point of view and assuming a normal distributed signal noise the precision of an averaged residual can be calculated using the simple formula:

$$\text{averaged residual precision} = \frac{\text{single shot precision}}{\sqrt{\text{number of events}}} \tag{1}$$

From Figure 1 it can be seen, that the raw system noise is close to that of a normal distributed signal. However, this measurement was performed to a single reflector target, without any geometrical contribution from the target. The reflectors on the lunar surface on the other hand consist of many of those corner cube reflectors arranged in a flat panel. During deployment these panels where arranged in that way, that the normal vector of each panel the panels is pointing towards the earth on average. However lunar libration causes a tilt and as a result a geometrical depth of the panels. Therefore, a normal distributed signal noise is only valid when the reflector panel is oriented properly. Anyway, Formula 1 gives a good estimation of the precision of each of the averaged residuals (Figure 8). On average a precision of the order of 5 mm could be achieved. This is of the same order that current state of the art LLR systems can provide [10].

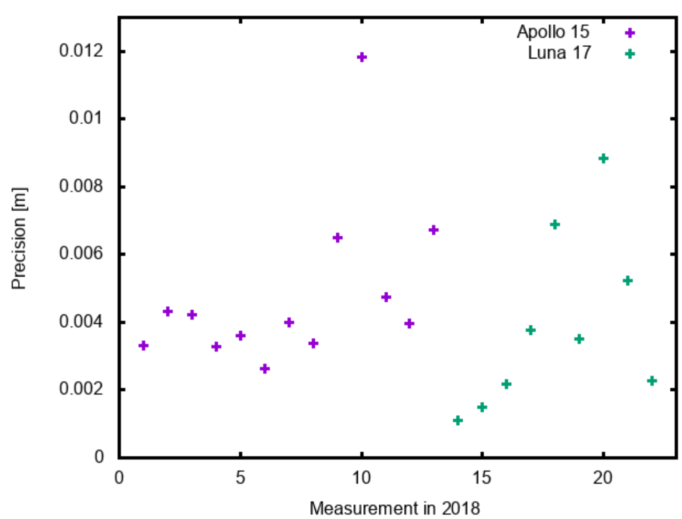

Figure 8. Precision of the averaged residuals achieved during measurements of the APOLLO 15 and LUNA 17 reflector with the WLRS.

To verify our results the current state of the art models of the earth-moon system had to be adjusted to our data. One of them is the ELPN01 model of the Paris Observatory Lunar Analysis Center. This model is kindly provided via a web-based interface (http://polac.obspm.fr/PaV/) and is a simple and helpful tool for that purpose. Also the analysis center of the Jet Propulsion Lab provided the residuals of our data with respect to their current model. The results of both can be seen in Figure 9. For the data from the Paris Observatory Lunar Analysis Center also error bars are drawn in the plot. The residuals there are of the order of 10 mm shifted towards positive values. The peak to peak scatter is of the order of 25 mm. On the other hand side the residuals from the Jet Propulsion Laboratory model are centered around zero with a higher peak to peak scatter of 80 mm. The reason for the increased scatter most probably is that some effects of the earth moon system are not considered in this model, yet. In both cases our data is of a similar quality compared to that of state of the art lunar laser ranging systems.

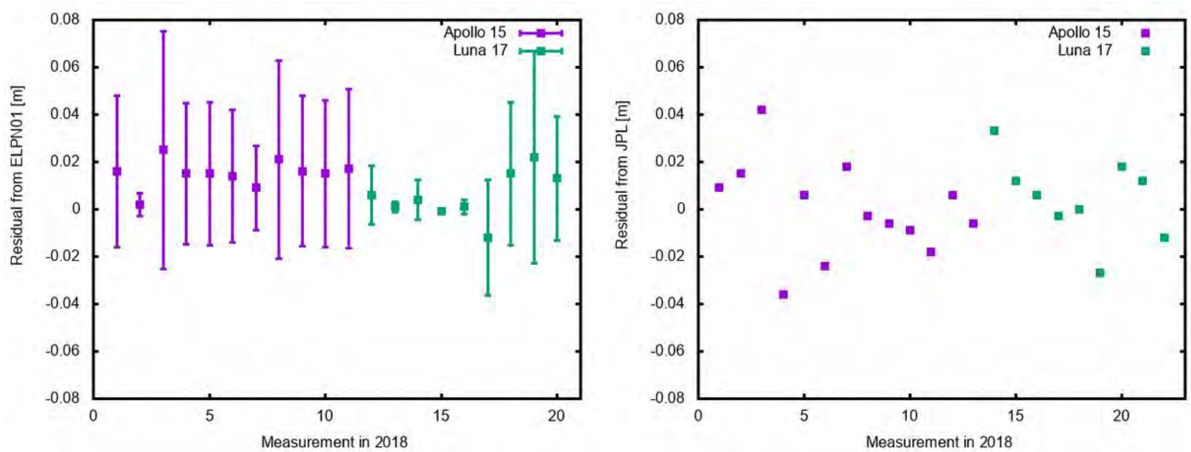

Figure 9. Residuals of the lunar laser ranging data measured with the WLRS with respect to a) the ELPN01 model of the Paris Observatory Lunar Analysis Center and b) with respect to the current model of the Jet Propulsion Lab.

Since the scatter of daylight in the atmosphere is far lower at a wavelength of 1064 nanometer compared to 532 nanometer quite an amount of data could be gained during daytime. This especially concerns the data of the Luna 17 reflector, where all of the passes were tracked during the morning hours. Some of the data could be acquired at an elevation of the sun of 33 degree with a distance from sun to moon of 55 degree. Ranging during daytime implies that the lunar phase is close to new moon and this again is important for verifying Einstein's postulate of the universality of the free fall in a gravitational field, known as the strong equivalence principle [9]. During one pass of the Luna 17 reflector only 16 percent of the surface of the moon was illuminated.

Because of the geometrical structure of the corner cube reflector arrays on the moon, the potential in ranging precision of the WLRS cannot be utilized. Employing the next generation of corner cube reflectors on the surface of the moon would allow for that. With this kind of reflectors a precision of less than 1 mm can be achieved during a pass segment of 1000 seconds. Furthermore, such a target would facilitate a better feedback for recognizing photon echoes from such a reflector. This is possible because when applying a histogram analysis on the residuals during a lunar laser ranging session the histogram bin-width can be reduced. As an example, a histogram of the original APOLLO 15 data of one pass segment together with simulated data from a single corner cube reflector target is depicted in Figure 10. Such a single corner cube target could be realized by the MoonLIGHT next generation lunar laser ranging reflectors [3]. For both graphs in Figure 10 the same data was used. The only difference is the bin-width of the histogram and that the scatter of the real APOLLO 15 measurement was reduced artificially in case of the MoonLIGHT reflector. For a better visibility the simulated graph was shifted by 100 nanoseconds in the abscissa and by 10 in the ordinate. The simulation verifies an improved signal to noise ratio by a factor of 2.5. However, in case of the WLRS it is important that the optical cross section of such a new kind of reflector should be similar to at least that of both of the Luna reflectors.

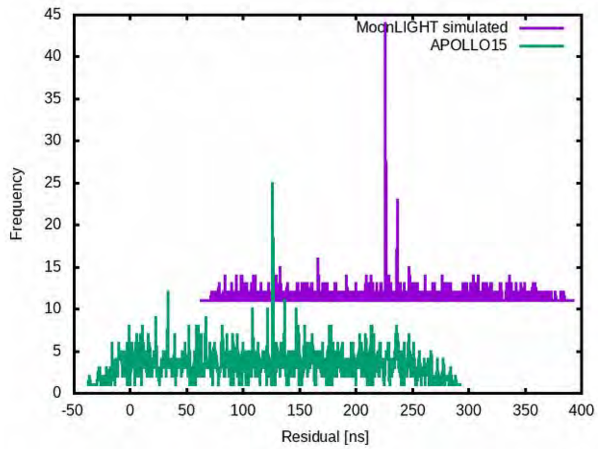

Figure 10. Histogram plot of the residuals during one pass segment of ranging APOLLO 15 together with a simulated histogram of a possibly future MoonLIGHT pass segment.

5. CONCLUSION

It could be shown that lunar laser ranging is possible with satellite laser ranging systems comprising a fairly small optical telescope and moderate laser pulse energy. Furthermore, in the case of the Wettzell Laser Ranging System a pulsed laser with a pulse width of as short as 10 picoseconds is utilized. Together with an optimized single photon avalanche diode a single shot root mean square measurement precision of 3.2 mm is provided, when ranging a single retro-reflector target. The data gained so far from Lunar Laser Ranging measurements with that system is of the same quality to that provided by state of the art Lunar Laser Ranging Systems. With an improved target structure of the retro-reflectors on the moon sub millimeter ranging precision during a pass segment of 1000 seconds is possible. This can be achieved by deploying the MoonLIGHT retro-reflector on the surface of the moon.

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