SLR link budget and retroreflector optical cross section evaluation

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Abstract

The network of satellite laser ranging stations is expanding every year, which is partly driven by new applications such as space traffic management as well as new companies that commercialize the technology. For the design of new ground segments, it is important to find the balance between an optimization of the link budget, e.g., through the utilization of high-power lasers, large telescopes, etc., and the mass, the volume, and the overall costs of such systems. A key uncertainty in the estimation of the link budget is the optical cross section of the satellites that are equipped with retroreflectors. The objective of this study is the derivation of the practical "in-orbit" optical cross section from satellite laser ranging measurements. The analysis shows that only a few stations provide useful data for the evaluation. Further, the derived values from selected satellites exhibit discrepancies to the theoretical values, which are beyond the variances of the measurements. Nevertheless, this study provides optical cross sections of satellites that can be used for first signal estimations of new compact ground systems, such as the miniSLR®.

1. Introduction

The demand of Satellite Laser Ranging (SLR) systems is continuously growing. In the last decades the number of satellites supported by the International Laser Ranging Service (ILRS) network increasingly advanced and this will increase further if all future Global Navigation Satellite System (GNSS) satellites are equipped with retroreflectors [1]. SLR may also become a powerful tool for space surveillance and tracking (SST), as more and more payloads get equipped with retroreflectors [2].

However, the current SLR network faces a few challenges. First of all, the global coverage of SLR stations remains uneven, whereby most of the stations are located on the upper hemisphere [1]. On the other hand, many stations are already at or beyond their limit in terms of tracking requests [2]. Accordingly, it is necessary to further expand the SLR network by introducing new ground segments. With that said, to this date legacy systems feature one major problem. The systems are integrated in individual buildings, occupied by a dome and thus require elaborate infrastructure, are expensive, and mostly require on-site staff for operation [3, 2], which impede the expansion of the network. In order to meet the demand of objects to be tracked, the technology has to become more accessible. This leads to the need for small, inexpensive and autonomous systems that can be transported and placed anywhere on the globe, such as the miniSLR® [4] system, which is being developed at the German Aerospace Center (DLR) in Stuttgart (see Figure 1).

Figure 1: miniSLR® system (DLR in Stuttgart).

In order to construct such systems as small as possible, they only contain the necessary elements. Accordingly, the power and hardware are limited. Powerful lasers and large telescopes require a lot of space and energy. The systems must therefore be optimized for the application and performance. The performance of a system can be estimated by the link budget, which defines the received signal strength. However, a key uncertainty in the link budget remains the Optical Cross Section (OCS) of the satellites that are equipped with retroreflectors.

This study contributes to the derivation of the “in-orbit” OCSs of satellites from SLR measurements. Hereby we pursue the goal to expand the state of the literature values and provide OCSs for the wavelength of 1064 nm, which is essential for the miniSLR® and future applications. In comparison, theoretical mean values are considered for a selection of satellites, which serve as a first reference and evaluation.

2. The SLR Link Budget

As mentioned above, for the estimation of a systems performance, link budgets are employed (see Equation (2)) [5].

$$N_s = \frac{E_p \cdot \lambda}{h \cdot c} \cdot \frac{8}{\theta_d^2} \cdot e^{-2\left(\frac{\Delta\theta_p}{\theta_d}\right)^2} \cdot A_R \cdot \tau_R \cdot \tau_T \cdot \eta_q \cdot \sigma \cdot \left(\frac{1}{4\,\pi R^2}\right)^2 \cdot \tau_{Atm}^2(\alpha, \lambda) \cdot \tau_C^2 \quad (1)$$

These determine the generated photoelectrons in the receiver per fired laser pulse N_s, i.e. the received signal strength. The link budget depends on several system specifications, such as the laser pulse energy E_p, the wavelength λ, the beam divergence θ_d, the pointing accuracy $\Delta\theta_p$, the detector efficiency η_q, the telescope diameter A_R, and the transmission efficiencies of receiver τ_R and transmitter τ_T, respectively. Further influences are the atmosphere ($\tau_{\text{atm}}, \tau_c$), depended on the elevation angle α, but also the space segment, i.e. the slant range R and the utilized retroreflectors by the OCS σ.

The return rate determines the probability of a photoelectron being generated in the receiver per pulse. In general, this follows the Poisson distribution for a given period of time. When the intensity of the returned pulse is limited so that in general no more than an individual photoelectron is generated in the detector, the operational mode remains in single photon. In this case the number of generated photoelectrons per pulse can directly be assigned to a return rate P_d by Equation (2) [6].

$$P_d = 1 - e^{-N_s} \tag{2}$$

3. Data collection and selection

Data for this study is obtained from measurements of stations that are part of the ILRS network, which is provided by the EUROLAS Data Center (EDC) [7]. In total, data from 51 stations in the period from 2007 to 2022 is obtained, which operate at the wavelength of 532 nm and 1064 nm. Further measurements are obtained with the in-house developed miniSLR® system in the period of March to August 2022.

The necessary return rate resolves from the generated normal points. These comprise filtered range measurements of fixed time frames that are compressed into a single data point [8], which are part of the Consolidated Range Data (CRD) format. Dividing the received echoes by the total number of fired pulses, yields the return rate of one normal point frame, which can be converted to the number of generated photoelectrons by Equation (2).

Investigating the site log and CRD files reveals that 17 ILRS stations do not provide all necessary system specifications for the evaluation of the link budget, which can be seen in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

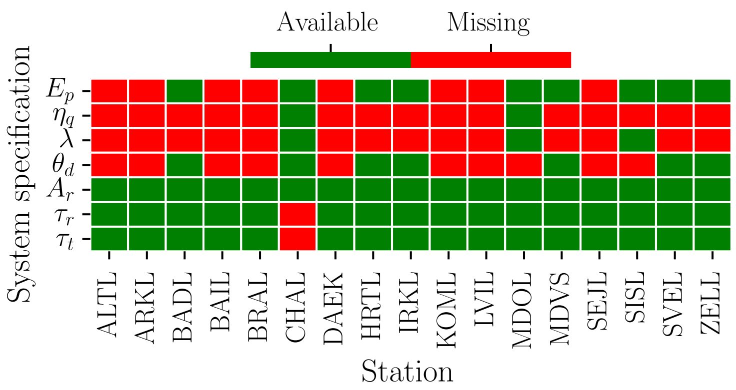

Figure 2: Missing specifications of ILRS stations.

As shown in this figure, most of the stations do not provide necessary information regarding the detector and the laser. Consequently, 34 ILRS stations provide sufficient information for the analysis.

Further relevant for the analysis are stations that operate in single photon mode, for which the Poisson distribution is known. In order to identify stations that operate in this mode, the data of each individual station is clustered by the applied system specifications, which may alter over time. Furthermore, the data is clustered by the observed satellites, since the space segment has significant impact on the signal strength. For single photon operation a threshold of 15% return rate [9] is considered. Data sets that exhibit a mean return rate below the threshold are declared as single photon measurements. The ones remaining above the threshold are removed. After filtering, data of 28 stations remains.

To enable the identification of any systematics and stations that are capable of return rate control, we qualitatively compare the resulting OCS from measurements of the single photon operating stations for a set of common ranged satellites. In Figure 3 this is exemplarily shown for Lageos-1. In the figure the resulting OCS is displayed, split by the ranging wavelength of 532 nm and 1064 nm.

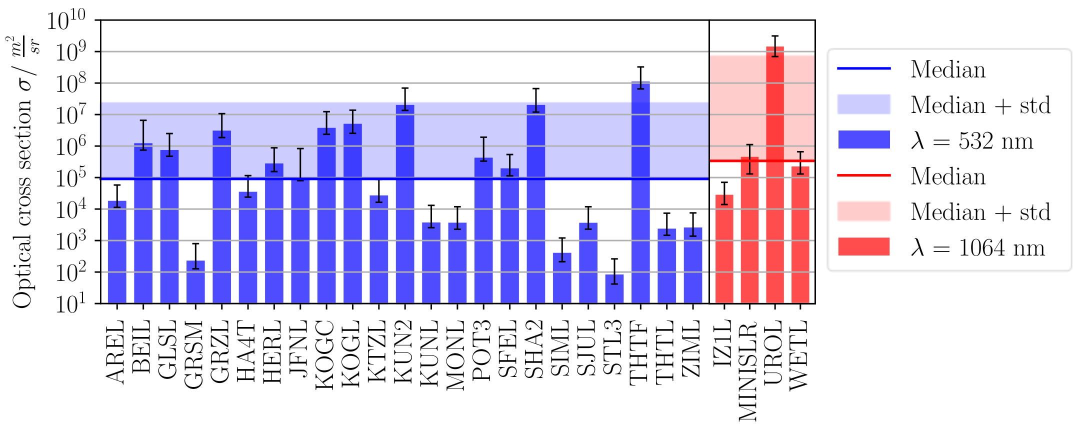

Figure 3: Derived OCS of measurements from single photon operating SLR stations for Lageos-1.

It can be seen that several stations yield relatively low and some relatively large values. This might imply that the stations feature larger or lower losses in reality, which can be attributed to the tracking uncertainties and the beam divergence, since these have a large influence on the received signal (see Equation (1)). Further, the application of return rate control may cause these discrepancies since the signal attenuation is not logged in the data. In order to identify data from useful stations we introduce the range of the median and one standard deviation to the median, as shown in the figure.

By investigating multiple satellites in different orbit altitudes, we identified stations that feature any systematics or return rate control. Systematics are identified by investigating Medium Earth Orbit (MEO) satellites and return rate control by Low Earth Orbit (LEO) satellites, which is most likely to occur for these types of satellites. The inspected satellites include Lageos-1/-2, Etalon-1/-2, Glonass, Galileo as MEO targets and Ajisai, BeaconC, Starlette and Swarm as LEO targets. It shows that five stations provide useful data for LEO satellites and above and an additional four stations for MEO satellites and above, which are summarized in Table 1. The latter stations imply return rate control or larger tracking uncertainties for LEO satellites.

Table 1: Stations that provide useful data for the further evaluation of the OCS.

	532 nm																								1064 nm			
Station	AREL	BEIL	GLSL	GRSM	GRZL	HA4T	HERL	JFNL	KOGC	KOGL	KTZL	KUN2	KUNL	MONL	POT3	SFEL	SHA2	SIML	SJUL	STAL	STL3	THTF	THTL	ZIML	IZ1L	MINISLR	UROL	WETL
LEO and above	☒	✓	✓	☒	✓	☒	☒	☒	☒	✓	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	✓	☒	☒
MEO and above	☒	✓	✓	☒	✓	☒	✓	☒	☒	✓	☒	☒	☒	☒	✓	☒	☒	☒	☒	☒	☒	☒	☒	☒	✓	✓	☒	✓

4. Results

The measurements of the selected stations are then summarized and used to derive the OCSs of the remaining satellites in the data, which can be seen in Figure 4 over the mean orbit altitude. In total the OCSs of 76 satellites are derived, whereby larger constellations utilizing the same array types are summarized. In the upper part of the figure several selected satellites and their corresponding theoretical values are displayed.

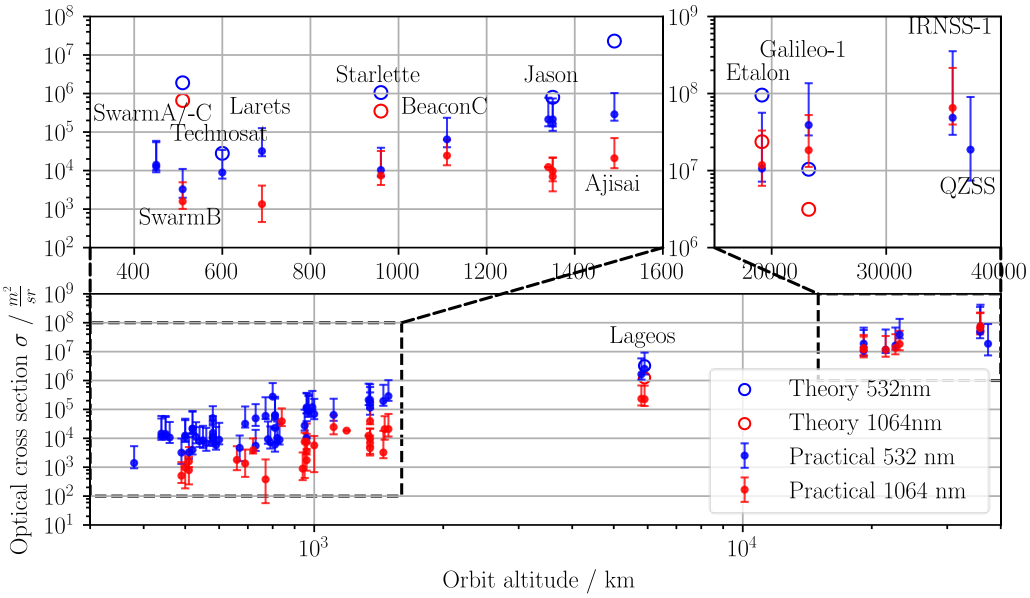

Figure 4: Practical and several theoretical OCSs over mean orbit altitude.

It is clearly visible that the theoretical values trend to lie up to two orders of magnitude above the practical values, whereas the measurements of one satellite can feature variances up to one order of magnitude in total. The large variances among one satellite can be attributed to variances in weather conditions, tracking dynamics, and the change of incident angle of the beam with respect to the reflectors. On the other hand, the discrepancies towards the theoretical values might arise from degradation of the retroreflectors or imply that in general larger losses arise, which have to be considered in the design of new systems. Consequently, the practical derived values should be considered as lower achievable limits or margins of a factor of ten or greater need to be contemplated.

Nevertheless, these values can be utilized to generate signal estimations for e.g. the miniSLR®, shown in Figure 5.

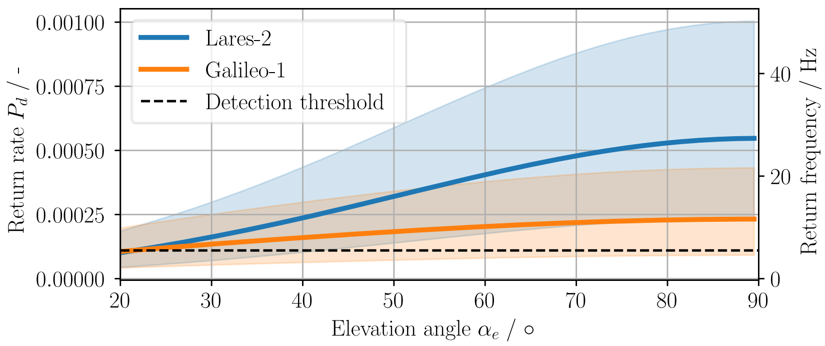

Figure 5: Signal estimation for the miniSLR®.

In this figure the mean estimated return rate over the elevation angle is displayed for Lares-2 and Galileo. The colored areas illustrate the variations in the signal that can arise from the above-mentioned uncertainties and variations. Yet, it can be clearly seen that the signal of both satellites is beyond the limiting detection threshold along the elevation angle and therefore a sufficient signal can be expected, ranging from a few detections per second to some tens of detections.

5. Conclusion

This study has shown that several stations do not provide sufficient data for the link budget analysis and others either exhibit systematic errors in their available specifications or apply return rate control. Further, it showed that the derivation of the OCS from SLR measurements is conflicted with several uncertainties, which arise variances of one order of magnitude. Moreover, the utilized model reveals discrepancies to the theoretical values that are beyond the variations of the measurements. This outcome might imply that the stations feature larger losses in general and that it is required to include a margin of a factor of ten or greater in the dimensioning of new ground segments. Nevertheless, this study provides OCSs for signal estimations, which can help to evaluate the performance of compact ground segments, e.g. for the miniSLR®.

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