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Compact Ground Station for Satellite Laser Ranging and Identification

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Abstract

Satellite Laser Ranging (SLR) is a key technology for keeping track of satellite positions and precisely determining their orbits around Earth. We are taking this technology one step further and have developed a laser-optical method, which allows for the identification of satellites. This tagging technology makes use of space qualified corner cube reflectors (CCRs) that alter the polarization state of retroreflected light. Such a passive 'number plating system' is operating independently of on-satellite energy sources, i.e. it allows for identification and tracking even if the satellite is malfunctioning. This technology can be especially useful for small satellites (CubeSats) that are often launched in clusters, have a high dead-on-arrival (DOA) rate and cannot easily be identified by existing space situational awareness (SSA) / space traffic management (STM) systems. This method will be implemented in our research platform 'miniSLR®', an automated, small, autonomous and transportable SLR station. By incorporating many off-the-shelf components into a standardized station with only a 1.5 m by 2 m base area, availability and affordability are ensured. The design of the system allows for an operation with small servicing effort, enabling a placement even at remote locations. With the miniSLR® prototype having now reached the field-testing stage, we confidently demonstrated optical closed-loop tracking capability up to GNSS orbits and, in addition, have received laser return signals from several LEO satellites. With the integration of a new, highly repetitive laser source with sub-ns pulse duration in the next months, the precision is expected to be reduced to the mm range, based on calculations and experience from our previous SLR station. Launching new satellites, especially constellations, requires better space traffic monitoring for collision avoidance. SLR can provide this essential mission support, but the necessary extension of the ground station network by using large observatories is expensive. A configuration of small SLR stations like the miniSLR® placed around the globe has the potential to extend the existing SLR network capacity at a fraction of the typical installation and operational costs of common, large SLR observatories.

Keywords: Satellite Laser Ranging, Retroreflectors, Space Situational Awareness

Acronyms/Abbreviations

Corner Cube Reflector (CCR), Consolidated Laser Ranging Data Format (CRD), Consolidated Prediction Format (CPF), Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center (DLR), Follow On (FO), Global Navigation Satellite System (GNSS), Global Positioning System (GPS), International Laser Ranging Service (ILRS), Left Circular (LC), Liquid Crystal Variable Retarder (LCVR), Low Earth Orbit (LEO), Optical Cross Section (OCS), Original Equipment Manufacturer (OEM), picosecond (ps), Polarization State Analyzer (PSA), Polarization State Generator (PSG), Receiving (Rx), Right Circular (RC), Root Mean Square (RMS), Satellite Laser Ranging (SLR), Transmitting (Tx), Two Line Element (TLE), Universal Serial Bus (USB)

1. Introduction

Developed in 1964 [1,2], laser ranging is a method to determine the distance from a fixed target on Earth to an object in space. Therefore, a laser light pulse is sent from the ground station to the space object, reflected back and detected. The distance is then calculated from the runtime of the light. High accuracy range measurements require correcting for atmospheric effects. The return rate can be estimated via the radar link equation [3,4], which includes several parameters of the SLR station (e.g. the efficiency of transmitting/receiving optics, the receiving aperture area, the detector efficiency, the laser pulse energy and the laser beam divergence), but also atmospheric losses or the optical cross section (OCS) of the target are considered.

In the beginning, laser ranging accuracy to satellites was in the order of meters [5]. Today the position of cooperative targets, satellites equipped with retro reflectors, can be determined down to the mm range, due to pulsed picosecond (ps) laser sources [3]. An early scientific goal was "refining the size and shape of the earth" [5]. While space geodesy with tectonic plate motion or crustal deformation is still the heart of SLR technology, new fields such as precise orbit determination for collision avoidance or supporting Earth observation satellites are emerging [1,5].

In this paper, an updated version of the small SLR ground station "miniSLR®" [6] is first presented and its functionality demonstrated. It was developed to show that SLR on a small scale is a viable way for cost-effective operation. The first goal is to hand over a functioning system to a partner in the industry for series production. Part of this endeavour was the successful admission to the ILRS as an engineering station. In a next step a new method to identify satellites will be tested with the miniSLR® after laboratory measurements are finished. Therefore, polarimetric CCRs, which are essential for this tagging technology, are developed in parallel at the Institute of Technical Physics [7] to fly as scientific payload on Cube Sat missions. This new identification method can then be added as an extension of the current system, increasing the attractiveness of equipping small satellites with retro reflectors. Satellite operators could even afford their own ground station network with the advantage of identifying their satellites.

1.1 miniSLR® Concept

Typically, SLR stations are whole observatories, expensive and large buildings exclusively for SLR. In contrast, the miniSLR® (see Fig. 1) follows the concept of a minimal SLR station, consisting only of the necessary components and occupying minimal space, but at the same time doesn't rank behind the regular SLR observatories in terms of precision.

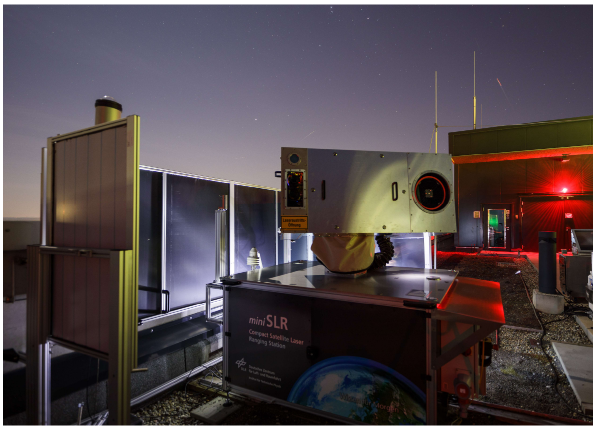

Fig. 1. miniSLR® at its current location on the roof of the institute building in Stuttgart, Germany. Version 3.0 is completely enclosed, waterproof and air conditioned with detachable lids on the front and the sides of the top compartment to easily access the optics behind (image credit: Paul Wagner / DLR)

There are about 40 stations operating worldwide, most of them located on the northern hemisphere [1]. The measurements could be improved by collecting more data, especially on the southern hemisphere. But for observatories lots of infrastructure and money is needed, which is why the miniSLR® can provide remedy. With its small footprint and autonomous operation, it can be placed at remote locations without personal surveillance.

1.2 Polarimetric SLR concept

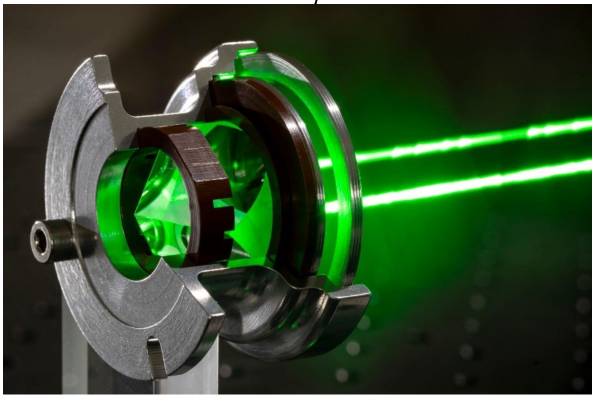

Fig. 2. CCR for the identification of Satellites with polarimetric SLR (image credit: Frank Eppler / DLR)

Polarimetric CCRs (see Fig. 2) are currently under development and can be provided to satellite operators in the future. They alter the polarization state of the incoming laser light. Together with polarisation changing and analysing optics at the laser ranging ground station, in theory there are seven distinguishable CCR assemblies possible [7]. As each satellite can be equipped with more than one CCR, there are enough tags for identification even if a flock of Cube Sats is launched.

The SLR ground station transmits (Tx) right circular (RC) or left circular (LC) polarized light, while the receiving side (Rx) allows only RC or LC polarized light to pass through to the detector. The polarisation states are switched on short timescales, e.g. using a Liquid Crystal Variable Retarder (LCVR). As there are four different combinations of LC/RC at Tx/Rx, four different intensities can be measured for each CCR assembly [7].

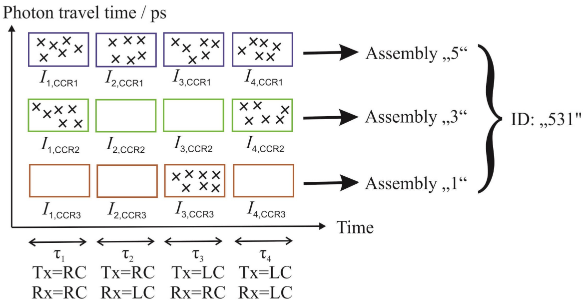

Fig. 3. Example of polarimetric identification with satellite laser ranging. The crosses represent return signals, while the boxes stand for certain assemblies over different time intervals τ [7]

Fig. 3 shows schematic, polarization-dependent SLR data that can be used for the polarimetric identification of a space object: On the x-axis the short time periods τ in between which the polarisation state is changed as well as said states are depicted. On the y-axis there is the photon travel time for the different CCR assemblies, leading to one row for each assembly due to the distance of the CCRs on the satellite. The crosses inside the boxes indicate detected photo-electrons. The signal is used to derive relative, polarization-dependent intensities for each CCR assembly mounted to the satellite. In Fig. 3, the satellite carries three different CCR assemblies to generate the ID “531” [7].

Because this is a passive way to identify and distinguish different satellites or different retroreflectors on the same satellite, it works even if the satellite is malfunctioning or reached its end of life.

2. Experiment/System and Setup

The miniSLR® has been developed for about four years, with continuous improvements and several versions. At the moment version 3.0 is placed on the roof of the institute building in Stuttgart, Germany. On the upside it can be easily accessed for maintenance or observations. On the downside, this also means a high level of laser safety has to be maintained, not only for aircraft protection but also the residents nearby. This is resolved by laser safety walls around the system as seen in Fig. 1 and Fig. 4, a datastream from the German air traffic control and an infrared camera with software that automatically analyses the images and closes the shutter when something is in the line of sight.

Fig. 4. Open view of the miniSLR® 3.0. The lids are detached on the front and side to allow a glimpse inside the miniSLR®. In the top compartment the left side encloses the transmitter, the right side the telescope and in between mainly laser, parts of the receiver and USB electronics are placed. The bottom compartment holds computers and mount controller on the left and electronics for e.g. timing, GPS and internet on the right

2.1 *System Overview*

Together with the new design of version 3.0, there were several changes made to the system as announced in [8]. Main improvements are the new mount for higher tracking accuracy and the design featuring detachable lids for easy access to the optics behind. Furthermore, the system is completely enclosed and air conditioned, which makes it waterproof and increases stability.

The most important system parameters are listed in Table 1.

Table 1. miniSLR® 3.0 system specification overview

Size (L x W x H)	(2.3 x 1.3 x 2.0) m
Mass	600 kg
Ranging wavelength	1064 nm
Pulse energy	110 µJ
Pulse duration	4 ns
Repetition rate	27 kHz
Apertures (Rx/Tx)	20 cm / 7 cm
Beam divergence	~ 50 µrad
Tracking accuracy	25 µrad

2.2 Key Components

While most controlling electronics such as GPS or timing electronics are placed in the base compartment, the top compartment encloses mainly the optics of transmitter and receiver (see Fig. 4). It is encapsulated and on top of an Alt-Az. telescope mount to be able to move freely. The receiving telescope has a diameter of 20 cm, whereas the laser beam is about 5 cm wide at the exit of the transmitter. Light received by the telescope is coupled into a multimode fibre and detected by a single photon counting device. Table 2 gives an easy overview of all relevant components.

Table 2. miniSLR® 3.0 key components

Mount	Astelco NTM600
Laser	nLight M30
Detector	Aurea OEM
Event Timer	Swabian Instruments Time Tagger Ultra
Telescope	ASA Astrograph 8H
Rx Camera	Andor Zyla 5.0
Tx Camera	Atik 414ex
Clock	Meinberg GPS180

Due to its small aperture, the miniSLR® makes use of a highly repetitive, high pulse energy laser source to compensate the loss on the receiver side. As shown in [4], a higher pulse energy linearly increases the return rate, whereas a higher repetition rate increases it under the square root. Another important quality of the laser source is a short pulse duration, leading to more precise measurements. This will be achieved with the integration of a new laser in the coming months.

2.3 Polarimetric laboratory setup

To validate the working principle, an experiment was designed and built up in the laboratory, shown in Fig. 5. The ground station is simulated with a SLR demonstrating experiment to be as close to a real SLR station as possible.

Fig. 5. Laboratory setup to validate the working principle of polarimetric laser ranging. On the left side there is a SLR demonstrator with telescope (including mount), laser, PSG in front of the laser and PSA behind the telescope. On top of the optical bench on the right the CCR with two quarter waveplates is built up

At the transmitter, a linear polarizer, a quarter waveplate (λ/4) and a LCVR form the polarization state generator (PSG) to control the emission of either RC or LC polarized light. On the receiving end, behind the telescope, another combination of a quarter waveplate and LCVR controls the transmission of either RC or LC polarized light, acting as a polarization state analyser (PSA).

The satellite side is simulated with a metal coated retroreflector and polarizing optics corresponding to the desired design in front of it, similar to the CCR shown in Fig. 2. This could either be two quarter waveplates or a quarter waveplate and a polarizer, rotated to specific angles to simulate the different assemblies.

3. **Measured Data**

3.1 Tracking ability

Compared to version 2.0 [8], tracking capability has improved due to the new NTM600 Mount from Astelco. With the 20 cm telescope, most CubeSats down to a size of 3U and geostationary satellites can be tracked in closed loop, meaning a passive optical tracking, correcting Rx continuously to the satellite while it is moving. This is done by evaluating the image from the tracking camera, where the satellite is imaged as a bright spot when illuminated by the Sun. If the satellite cannot be seen through the telescope, e.g. because it is in the Earth's shadow, and optical closed loop tracking is not possible, the procedure is called blind tracking.

The NTM600 has a specified absolute positioning accuracy of < 5 arcsec RMS ("full sky blind pointing") [9]. For the miniSLR® and site conditions this results in 5 arcsec – 10 arcsec, depending on the pointing model. This accuracy is good enough for blind tracking, as shown in Fig. 6, if the target satellite has exact predictions.

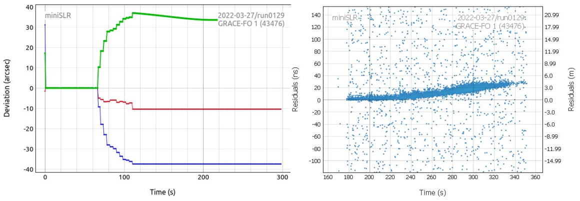

Fig. 6. Blind tracking capability of the miniSLR® shown for the satellite Grace-FO. On the left-hand side, there is the deviation from the target in arcsec over time, showing that Grace-FO went in Earth shadow and the tracking did not readjust after about 100 s. On the right-hand side, the corresponding ranging data during blind tracking is displayed.

3.2 Ranging ability

Being fully operational since February 2022, the current version 3.0 of the miniSLR® has ranged to many different satellites. Most targets are in LEO, but some GNSS targets were successful as well. This will improve with a new laser. In the following sections, some measurements sorted by orbit height are displayed.

Orbit predictions either stem from radar or laser ranging data. In general, the latter is more precise. There are two common data formats called consolidated laser ranging prediction format (CPF), officially used by the ILRS, and two line element (TLE).

In general, the plots show the deviation of measurement and prediction. Therefore, the trail of returns does not necessarily need to be at zero and this does not correspond to the precision of the measurement. If the returns are inclined, as seen in Fig. 7, it corresponds to a time bias. When the returns are shifted from zero in y, as seen in Fig. 9, it corresponds to a range bias. Also, no conclusions about the absolute distance to the satellite, which changes over one complete pass, can be drawn. The left y-axis shows the deviation from the prediction in time, whereas the right y-axis shows this deviation in space, both over the time of the flyover on the x-axis.

3.2.1 Low Earth orbit targets

Satellites in low Earth orbit (LEO) are the closet ones to Earth with orbit heights up to 2000 km [10]. This proximity makes them easier to range, but at the same time harder to track, because their orbital speed is higher. With about 1 to 5 minutes duration, a pass is short and the telescope needs to move faster.

Fig. 7 shows a three-minute sample of the ranging data for the satellite Starlette. Here the predictions had both, a time bias as well as a range bias, as explained in section 3.2. During this pass the distance of Starlette to the miniSLR® varied between 800 km and 3400 km. The mean return rate was 0.83%.

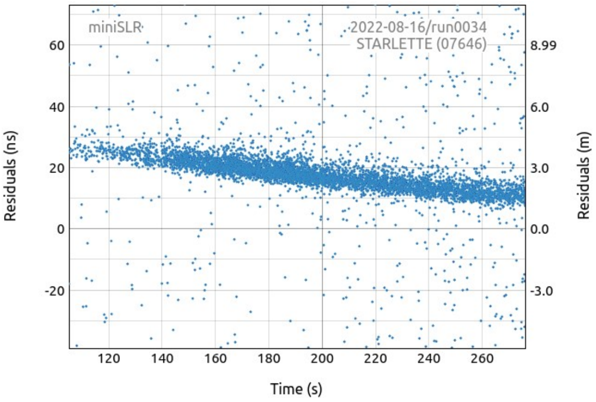

Fig. 7. Ranging data of Starlette. Orbiting at a maximum altitude of over 1100 km [11], the mean return rate for this run is 0.834%. From the inclination and position of data points a time bias and a range bias of the predictions can be deduced.

Another example of a cooperative target in LEO is Sentinel 6. The ranging data is shown in Fig. 8. This is another way how a range bias and a small time bias can look like. At a range distance from 1600 km to 4000 km to the miniSLR®, the mean return rate is 0.38% and clearly distinguishable from the background noise. During time intervals with no data points, the shutter was closed due to an aircraft flyby.

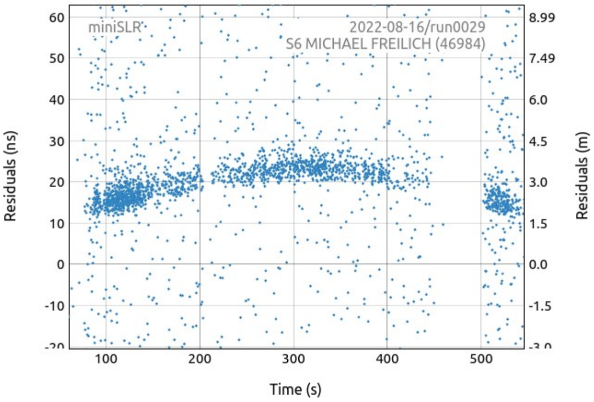

Fig. 8. Ranging data of Sentinel 6. Clear returns with mean return rate of 0.380% at distances up to 4000 km, while showing mainly range bias. During time intervals with no data points, the shutter was closed due to an aircraft flyby.

Comparing the ranging plots of Starlette (Fig. 7) and Sentinel 6 (Fig. 8), the influence of many retroreflectors can be seen. Both satellites were approximately equidistantly from the ground station, but Starlette as a geodetic target yielded more than twice the return rate of Sentinel 6.

3.2.2 GNSS targets

With an apogee between 18100 and 24300 km [10], navigation satellites are the outermost targets successfully observed by the miniSLR®.

Fig. 9 shows returns from Cosmos 2024 at distances to the miniSLR® between 20800 km and 21000 km. Due to this high distance, the return rate is only 0.017% and return data points cannot be clearly separated from the background. Therefore, GNSS targets are the range limit for this small system.

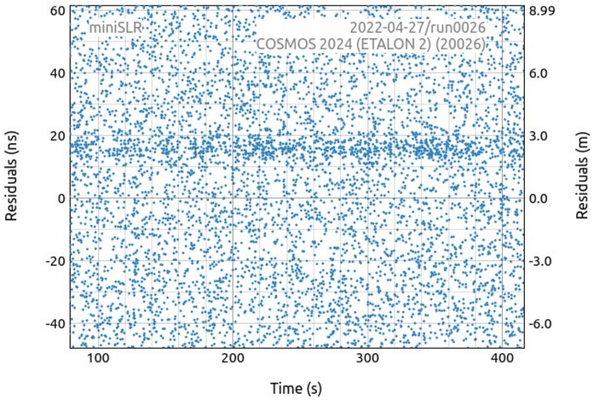

Fig. 9. Ranging data of Cosmos 2024. At a distance ten times further away than Starlette, the return rate is with 0.017% visibly worse and marks the distance limit of such a small SLR system.

3.2.3 Other targets

Most important for calibration purposes in SLR are the geodetic satellites such as Lageos, EGS/Ajisai, Lares, as explained in the following section 4. Due to their high mass at relatively small sizes, their orbit is very stable. Additionally, they are continuously ranged by the ILRS and thus have very precise orbit predictions. Equipped with reflecting surfaces all over, their quantity of returns mainly depends on their distance.

Fig. 10 shows ranging data from Lageos 1, one of the most important geodetic satellites in space. The distance to the miniSLR® ranged between 6200 km and 8200 km for this run.

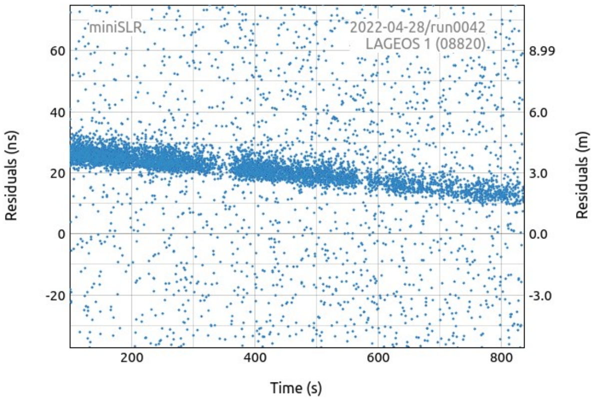

Fig. 10. Ranging data of Lageos 1. Strong returns with a mean return rate of 0.160% at distances over 6000 km to the ground station.

4. Results and Discussion

Overall, the modifications of the miniSLR® payed off and improved the system. Tracking accuracy in closed loop is below 1 arcsec, while the blind pointing accuracy is between 5 arcsec and 10 arcsec, depending on the pointing model. This enables blind tracking of satellites, which was successfully demonstrated.

Ranging capability of the miniSLR® was presented on the basis of LEO satellites like Starlette up to GNSS targets like Cosmos 2024.

To verify the ranging precision, an external station evaluates the ranging data from the miniSLR®, more precisely data from geodetic satellites. This is then compared to the data from other ILRS ranging stations to get the precision in relation to them. In this case the evaluation was done by Prof. Toshimichi Otsubo from the Hitotsubashi University in Japan.

The first evaluation of seven passes yielded a mean precision of 10 mm, ranging between 9 mm and 21 mm. The analysed satellites were Ajisai, Lares, Lageos 1 and Lageos 2. A precision in the low, single-digit cm range is very encouraging, given that the current laser has a pulse duration of 4 ns and therefore a single shot rms of 30 cm.

5. Conclusions and Outlook

This paper has given an overview of the miniSLR® version 3.0, its structure and built in electronics. Furthermore, several ranging plots demonstrate the capability of such a small system. With the new mount, the tracking capability improved to enable blind tracking in some cases. It is confidently ranging to cooperative targets in LEO plus several navigation satellites. Geodetic satellites are ranged with a precision of about 2 cm. Therefore, the system performs very well with the given instruments and can be used to extend the current SLR network on a low-cost basis.

With the integration of a new laser source with pulse duration of less than 500 ps, the precision is expected to improve accordingly to the mm range.

Furthermore, the polarimetric satellite identification will be tested with the miniSLR® and a specifically designed CCR on a Cube Sat that is to be launched.

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