The miniSLR®: A low-cost, high-performance laser ranging system for the ILRS

Daniel Hampf (1,2), Felicitas Niebler (1), Nils Bartels (1), Wolfgang Riede (1)

(1) German Aerospace Center (DLR e.V.), Institute of Technical Physics, Stuttgart, Germany (daniel.hampf@dlr.de)
(2) DiGOS Potsdam GmbH, Potsdam, Germany

Abstract

The miniSLR® has been developed as a low-cost, high-performance alternative to conventional SLR systems. It is completely integrated into a movable container of less than 2 x 2 m² footprint. Using a 500 ps laser at 50 kHz repetition rate, it achieves sub-centimetre precision. Long-term stability has been considered as integral part of the design and is facilitated by a full encapsulation, air-conditioning, short cable lengths and a calibration target on the main support structure. While the focus is on LEO targets including Lageos, all targets including GNSS constellations can be ranged.
The main advantages of such a small, highly integrated system are rather obvious: Low production cost, reduced engineering effort, shorter commissioning times. The system can be constructed and validated at the factory, before it is transported to its final observation site. At the site, no civil works are required and no building permits need to be obtained. Yet the system can be connected firmly to the ground, and using an appropriate site survey, local ties can be established in the same way as for conventional systems.
At DLR in Stuttgart, tests with an improved miniSLR® prototype have commenced in March 2022. Minor modifications for improved stability and reliability are underway. In July 2022, the system has been accepted into the ILRS as engineering station. It is planned to regularly deliver data to the ILRS to validate the system performance and stability. Furthermore, DLR will use the system as a test platform for its own research, including experiments with smart retroreflectors which can be used for satellite identification.

1. Introduction

The miniSLR® has evolved out of the idea to make SLR a more accessible and widely used technology. The goal has been to develop a simple, compact and relatively inexpensive laser ranging system, that nevertheless can achieve the accuracy, stability and range of conventional state-of-the-art SLR stations. Its design is focused on its one and only purpose – highly accurate laser ranging to cooperative targets in Earth orbit – and streamlined to contain only the absolutely necessary components. In this sense, the "mini" in miniSLR alludes to both the system's small size, as well as its minimal complexity.

Such a minimal, transportable and compact system offers a range of advantages:

- Reduced costs of ownership, maintenance and operation
- Simpler operation and repair due to less complex technology
- The system can be fully assembled, commissioned and validated at the factory before transportation to its final observation site

- No building (and building permit) is required, it can sit on a simple concrete platform that is sufficiently well connected to the bedrock

One of the system's rather unique features is its complete encapsulation. During stand-by or operation, no part of the system is exposed to outside temperature or humidity. Both receiver and transmitter are enclosed in air-conditioned aluminium boxes, equipped with high-quality optical windows with antireflective coatings. This design offers additional advantages over a traditional slit or all-sky dome:

- No systematic timing effects due to temperature gradients within the system
- No shut-down is required to move the system into a safe state, therefore it is inherently safe even in catastrophic system failures such as power loss, mechanical blockage or connection loss (important for unattended operation)
- Less moving parts, reduced complexity and better accessibility

Obviously, the above-mentioned advantages come at a certain price. Due to the small receiver size, a rather strong laser source is needed to obtain sufficient returns from all targets between LEO and GNSS orbits. On the other hand, the absence of a coudé path requires the laser, or at least the laser head, to be installed onto the moving part of the telescope. This poses some challenges for the selection of the laser source, and requires some novel approaches to reach the desired performance.

While the miniSLR can be used for basically any SLR related task, we foresee four main areas of application:

- Expansion of the ILRS network to sites in the global south, for improved satellite geodesy and mission support
- Support of existing SLR systems (co-location) in order to increase tracking capacity
- Facilitation of new SLR applications, such as Space Traffic Monitoring
- Dedicated mission support network for constellations of satellites

The current version of the miniSLR has been in experimental operation since February 2022 on the roof the DLR institute's building in Stuttgart, Germany. During this time, a few hundred satellite passes have been recorded in order to test and improve the design of the system. This paper describes the system set-up (section 2), the design specifications (section 3), and first results of the test campaigns (section 4).

2. System Set-up

The whole system is integrated in and on a custom-made aluminium enclosure with a footprint of about 130 x 180 cm. It carries not only the mount with the optical bench, but also the calibration targets, weather stations and antennas (see figure 1).

The top compartment contains optical breadboards for flexible set-ups and mechanical stability of all components. It is carried on an Astelco NTM-600 direct drive mount. Using a custom mount model with up to 18 parameters, a satellite blind tracking accuracy of 5 – 10 arcsec is achieved. A guiding camera for closed loop tracking is available and is regularly used for visible passes of objects with poor predictions.

Figure 1: The miniSLR on the roof of the DLR Institute of Technical Physics, in July 2022

Up until late October 2022, an nLight M30 laser system was used for ranging. After that, it has been replaced by a Standa MOPA-4 laser with a shorter pulse duration. The laser parameters can be found in table 1. Both systems feature a small laser head with a size of less than 10 cm x 10 cm, so they can easily be integrated into the top compartment of the miniSLR. The cooling is realized with thermoelectric coolers (TECs).

A laser with a relatively high repetition rate laser of 50 kHz has been chosen because it enables a sufficiently large average power of 5 W, while maintaining a small footprint and low weight. Achieving the same 5 W with a system of e.g. 5 kHz and 1 mJ pulse energy would have resulted in a much bulkier and heavier laser. The same reasoning has led to the decision for a pulse duration of 500 ps. This pulse duration is close to the minimum available in commercial Q-switched lasers. In order to go to even shorter pulses, the laser would need to be based on mode-locking, which again would have resulted in a much larger laser head at the same pulse energy and average power. In this way, the chosen laser parameters exactly fit into the niche required with the miniSLR: A rather high average power, low weight, small size, and sufficiently short pulses for competitive ranging precision (for more details on the ranging precision please see section 3).

Table 1: Laser system specifications. The nLight M30 has been used from February to October 2022, when it has been replaced by the Standa MOPA-4, with the goal to improve the ranging precision.

	nLight M30	Standa MOPA-4
Repetition rate	12 kHz	50 kHz
Pulse energy	200 µJ	100 µJ
Pulse duration FWHM	5 ns	500 ps
Operating wavelength	1064 nm	
Divergence full angle	50 µrad / 10 arcsec	

With its diffraction limited divergence of 50 µrad / 10 arcsec, the beam constitutes a hazard to human eyes for a distance of up to ten kilometres (nominal ocular hazard distance in accordance with norm EN-60825-1:2014). A multi-layer airspace safety system is integrated into the system, based mainly on live data from the German Air Traffic Control Service and ADS-B data. A thermal IR camera is used additionally to detect heat signatures from airborne objects. In case of an approach of less than ten to twenty degrees between the pointing direction and an aircraft, the laser beam is automatically shut off by two independent shutters, and redirected into a beam block. One of the shutters is designed in a "closed-by-default" mode and closes automatically if no "clear" signal is received from the software for more than three seconds.

The system contains a single attenuator in the transmit path, which is used for time calibration. Whenever the system is pointing below a defined azimuth-dependent elevation mask, the attenuator is automatically inserted for additional safety. No attenuator is integrated in the receive path. Due to the low pulse energy and the small receiver, the system inherently maintains single-photon levels for all targets without the need for return rate control.

The receiver telescope is an ASA H8 Newton telescope with an aperture of 20 cm. To improve transmission at 1064 nm, the corrector lens has been removed. It feeds both the visual camera and the single photon detector, distributing the light over a dichroic mirror.

Returning photons are detected by an Aurea OEM InGaAs SPAD sensor, which can be operated in either free-running or gated mode. It features a maximum detection efficiency of up to 30% at the wavelength of 1064 nm, and a timing jitter of about 120 ps RMS. It is coupled to the receive telescope over a multi-mode optical fibre with a 105 µm core diameter. A 1 nm wide spectral filter is used before the fibre coupler to reduce ambient light. The system has a flat acceptance curve up to about 150 µrad / 30 arcsec full angle, thus enabling blind tracking even in case of mediocre predictions.

Signals from the start photodiode and the single photon detector are recorded by a Swabian Instruments Time Tagger Ultra. Frequency and Time are derived from a Meinberg GPS 180 GNSS-controlled atomic clock. A range gate system for the 50 kHz operation is currently under development. Meanwhile, all data is recorded in free running mode, therefore operation is currently only possible in darkness.

A Reinhardt DFT 55V weather station is used to record temperature, humidity and pressure. It is installed on the same height as the system's invariant point. The absolute measurement error of the weather station is given as 0.8 hPa. In the light of recent discussions in the ILRS about the importance of exact barometric measurements, the weather station may be replaced by a more accurate one in the future.

3. Design Specifications

The miniSLR is designed as single-photon station. Typical return ratios measured during the test runs in 2022 range from 0.01% for GNSS targets, 0.2% Lageos and up to 3% for highly reflective LEO satellites such as Grace-FO. Given the high repetition rate, these return ratios nevertheless result in large numbers of returns, up to 1 kHz for LEO satellites and still about 5 Hz for GNSS targets. Transmit and receive apertures of the system are around 80 cm apart from each other, thus atmospheric backscatter into the receiver is inherently avoided and dedicated pulse collision avoidance is not required.

In order to achieve millimetre precise measurements without the need for a large and heavy picosecond laser, the miniSLR relies on averaging single returns within a normal point. With the current 500 ps laser, the single shot precision should be about 7.5 cm FWHM. All other system components exhibit a much smaller time jitter and do not contribute significantly to the overall jitter.

Assuming a purely statistical process, the normal point precision σ_{NP} is given by

$$\sigma_{NP} = \frac{\sigma_{Shot}}{\sqrt{N}}$$

Where σ_{Shot} is the single-shot precision and N is the number of measurements in a normal point. By design, the system should receive at least 3,000 data points per normal point, in order to achieve an improvement by a factor of 50 relative to the single shot precision. This should result in a normal point precision of 1.5 mm FWHM. For GNSS targets, the goal has been set to 300 data points, and an improvement of a factor of 17 (~5 mm).

Further design specifications are listed in table 2.

Table 2: The miniSLR design specifications

System size	130 cm x 180 cm footprint ~ 200 cm height
System mass	~ 600 kg total
Power supply	3 phase 230 V, up to 5 kW
Rx aperture	20 cm
Tx aperture	7.5 cm
Blind tracking accuracy	< 10 arcsec
Guided tracking accuracy	< 3 arcsec
Range	400 km to 25,000 km (cooperative targets)
Precision (goal)	< 2 mm (LEO, Lageos, Lares-2) < 5 mm (GNSS)
Accuracy (goal)	< 10 mm

4. Test Operation and First Results

A site survey has been conducted for the miniSLR in August and September 2022. Table 3 shows the coordinates of the system invariant point (intersection of vertical and horizontal mount axes).

For testing the system, numerous passes of typical current and past ILRS targets have been recorded with the nanosecond laser system between March and August 2022. Time calibration has been performed regularly (every 1 to 2 hours during observation), using the calibration loop on the miniSLR frame. Most passes have been recorded using visual tracking, when possible, but blind tracking passes have been recorded as well. So far, all data has been recorded in darkness, since no suitable range gate generator has been available yet and the detector had to be used in free running mode. The data has been filtered and reduced to normal points following the standard ILRS procedure.

Two sets of data recorded with the nanosecond laser, from April 2022 and August 2022, have been analysed by Toshimichi Otsubo in comparison with other SLR data for a first estimation of the accuracy [1]. The two SLR-derived 3D positions for the invariant point agree within about 20 cm with each other, and with the coordinates from the site survey. Likewise, a range bias of about 20 cm has been found. The pass to pass biases have been on the order of 10 cm, with a normal point precision of about 3 cm. The single shot RMS within the normal points has been measured to about 1700 ps, or 25 cm, which is expected from the used 5 ns laser.

Table 3: Reference point coordinates

DHDN90 (German geodetic system), GK-coordinates	WGS84	ITRF2014 cartesian
x: 3507619.813 m y: 5401267.813 m h: 484.907 m (DHHN12 height normal)	N: 48.748893982° E: 9.102599520° H: 533.240 m	x: 4160755.242 m y: 666638.631 m z: 4772593.195 m

While these numbers should improve with the new laser, they also hint at some systematic errors. Most probably, these revolve around the calibration procedure. A number of issues, mainly multiple reflections and a high number of accidental multi-photon events due to insufficient attenuation have already been discovered and are currently being addressed.

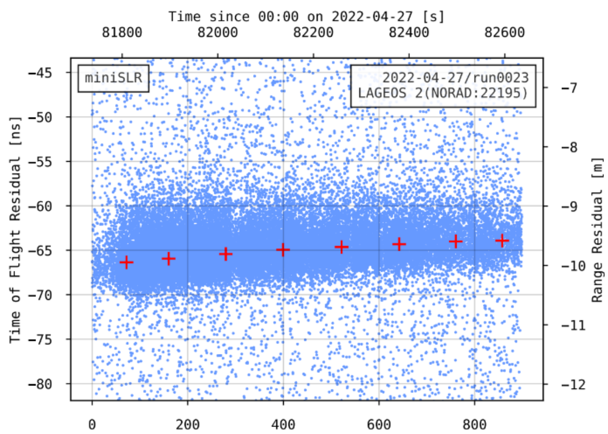

Figure 2: Lageos-2 range residuals measured with the nLight M30 nanosecond laser.

In any case, the taken data does confirm the assumed data rates. For Lageos, more than 3000 data points per normal point could be obtained routinely. For GNSS targets, some 300 to 400 data points have been achieved per normal point. For LEO satellites, often several ten thousand returns have been recorded for each normal point. Figure 2 shows a longer Lageos-2 run from the April 2022 measurement campaign.

Meanwhile, the Standa MOPA-4 laser has been integrated, and a number of passes have been recorded with it. Figure 3 shows an Ajisai pass recorded in mid-November. The normal points contain around 3,000 data points each, with an RMS of about 500 ps or 8 cm. While this is a significant improvement over the previous laser system, it is not quite at the level expected from the specifications. Tests and adjustments are on-going to investigate possibilities for improvement.

For the near future, a new pass by pass analysis is envisaged to understand the improvement in system accuracy due to the new laser and an improved calibration procedure.

As soon as the test data reveals a satisfactory accuracy and performance, a regular data delivery to the ILRS is foreseen. However, the miniSLR will remain an engineering station. The data from public ILRS analysis is envisaged to provide an independent validation to the achieved system accuracy.

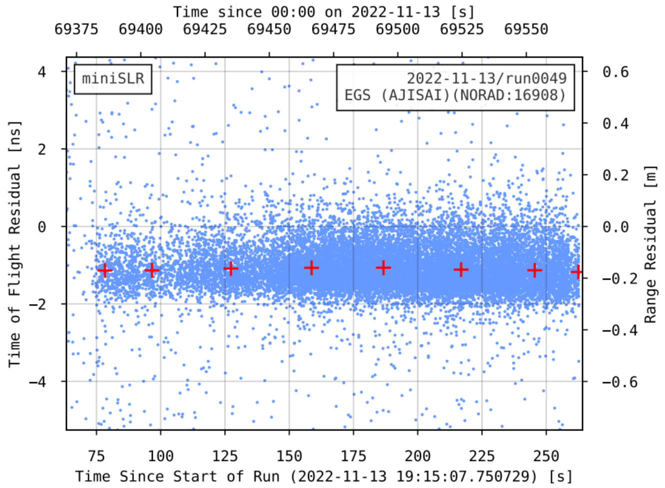

Figure 3: An Ajisai pass recorded with the Standa picosecond laser.

4. Conclusion and Outlook

The development of the miniSLR has led to a very promising new SLR system with numerous applications in the context of satellite laser ranging. Reliable tracking and ranging operation has been achieved with a compact and minimal set-up. Data has been taken regularly throughout the year of 2022, and operation and system development are on-going.

For the near future, the main goal is to demonstrate a sub-centimetre system accuracy, in line with the design specifications. For that, improvements in the calibration procedure and further tests with the new picosecond laser are being carried out.

For the year of 2023, we plan to further improve the operation by implementing daylight ranging, further automation and possibly a better system sensitivity (improved optical transmission). Data delivery to the ILRS is currently being prepared and should commence in the first half of 2023.

In the long term, DLR intends to use the miniSLR platform not only for SLR operation, but also to test novel technologies such as identification of laser ranging targets through polarimetric ranging [2]. In parallel, the miniSLR will be developed into a commercial product, which can be obtained as a ready-to-use system, in cooperation with DiGOS Potsdam GmbH.

References

[1] Otsubo, T., Müller, H., Pavlis, E.C. et al. Rapid response quality control service for the laser ranging tracking network. J Geod 93, 2335–2344 (2019). https://doi.org/10.1007/s00190-018-1197-0

[2] Bartels, N., Hampf, D., Heidenreich, B. et al. Polarimetric satellite laser ranging. Proc. International Workshop of Laser Ranging, Yebes, 2022.