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Satellite Laser Ranging at 100 kHz Pulse Repetition Rate

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Abstract Current satellite laser ranging (SLR) systems work at laser repetition rates of some 10 Hz up to about 10 kHz. However, using a laser repetition rate of 100 kHz offers several advantages: First, a laser with lower pulse energy can be used, while nevertheless the same amount of returns is received for a given target. Second, a poor single-shot precision (e.g. due to a long laser pulse) can be counteracted, as the statistical error decreases with the number of individual measurements. These two factors increase the number of options concerning the laser source, and may also help to make the system inherently eye-safe. Lastly, it may also help to gather data more quickly and thus increase the number of targets that can be tracked per system.

A high repetition rate SLR system has been installed at the Uhlandshöhe observatory in Stuttgart, Germany. Using an effective repetition rate of 100 kHz and a pulse energy of 50 μJ, various typical SLR targets could be ranged successfully, including LAGEOS and global navigation system satellites at altitudes of around 20,000 km. A comparative orbit analysis, using data taken by other SLR stations at the same time, shows that a normal point scatter in the order of 1 cm is achieved despite the rather poor single-shot precision of about 60 cm.

These results show an interesting potential especially for future low-cost SLR systems, that may utilize this technique to achieve competitive performance with small, low-energy lasers.

Keywords Satellite laser ranging · Satellite ground station

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1 Introduction

1.1 Development of the SLR network

Traditionally, SLR systems were operated with pulse energies on the order of 100 mJ at repetition rates of around 10 Hz. In 2004 NASA's SLR2000 system and the Graz SLR station demonstrated that laser ranging at kHz repetition rates could offer improvements in normal point accuracy [21, 18]. Since then, the International Laser Ranging Service (ILRS) network has now split into two paradigms: Low repetition rate, high pulse energy, multi-photon detecting systems, and high repetition rate systems which measure few or single photons per pulse. This split is illustrated in figure 1.

Despite kHz level ranging now being commonplace, and although 100 kHz level ranging had been considered for some time [16], SLR had not yet been performed at 100 kHz repetition rates due to a number of technical challenges (see section 2). In this paper we show that there are compelling reasons for wanting to overcome these challenges, and demonstrate a satellite laser ranging experiment at 100 kHz effective repetition rate.

1.2 Motivation

Using very high repetition rates offers two main advantages, which will be explained in more detail in this section: First, the pulse energy can be decreased while the sensitivity, or maximum range, of the system is retained. Second, longer laser pulses (nanoseconds rather than picoseconds) can be used while retaining the precision of the distance measurement. Combined, these two advantages relax the demands on the laser and thus enable novel applications, as will be lined out in section 1.3.

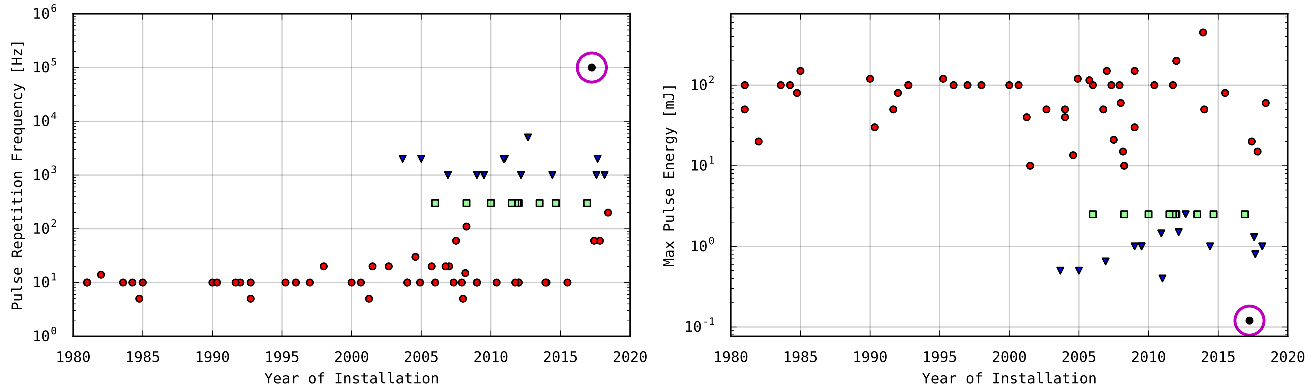

Fig. 1 The plots above show the properties and dates of installation of the lasers at *Active Stations* in the ILRS network [6]. After 2004, a new approach to SLR becomes popular: Using high pulse repetition rates with low energy pulses. The circular and triangular data points represent these two approaches while the square data points represent the Russian SLR network, which takes an intermediate approach. The Uhlandshöhe Research Observatory, in Stuttgart, which is an ILRS *Engineering Station*, is highlighted by a circle.

1.2.1 Sensitivity

The mean number of photoelectrons, n_{pe}, received by an SLR system per pulse is given by the radar link equation, adapted for use in SLR [10]:

$$n_{\mathrm{pe}} = \left(E_{\mathrm{T}} \frac{\lambda}{hc} \right) G_{\mathrm{t}}\ \sigma_{\mathrm{ocs}} \left(\frac{1}{4\pi R^2} \right)^2 A_{\mathrm{r}}\ T_a^2\ T_c^2\ \eta_{\mathrm{t}}\ \eta_{\mathrm{r}}\ \eta_{\mathrm{d}} \qquad (1)$$

where:

- E_{T}, the energy of a single pulse
- $\frac{\lambda}{hc}$, inverse of the energy of a single photon at a wavelength of λ (h Planck's constant)
- G_{t}, the transmit gain, a term which accounts for the finite beam divergence, and inaccuracies in pointing
- σ_{ocs}, the optical cross section of the target
- $\left(\frac{1}{4\pi R^2} \right)^2$, two-way losses along the slant range R
- A_{r}, the aperture area of the receiving optics
- $T_{\mathrm{a}}^2, T_{\mathrm{c}}^2$, the two way losses for atmospheric absorption and cirrus clouds.
- η_{t}, the efficiency of the transmitting optics
- η_{r}, the efficiency of the receiving optics
- η_{d}, the detector efficiency

For a single photon counting detector, the probability of a particular outgoing pulse yielding a detected return, P_{d} is a function of n_{pe} [9]:

$$P_{\mathrm{d}}(n_{\mathrm{pe}}) = 1 - \exp\left(-n_{\mathrm{pe}}\right) \qquad (2)$$

At high mean photoelectrons per pulse, $P_{\mathrm{d}}(n_{\mathrm{pe}})$ tends towards 1. But at low mean photoelectrons per pulse, which is typical of single photon counting SLR, $P_{\mathrm{d}}(n_{\mathrm{pe}}) \approx n_{\mathrm{pe}}$. The frequency of detected returns f_{d} at these levels is therefore directly proportional to the laser pulse repetition frequency f_{p}:

$$f_{\mathrm{d}} = f_{\mathrm{p}}\, n_{\mathrm{pe}} \qquad (3)$$

As described in equations 1 and 3, ranging at very high repetition rates (100s of kHz) can be used to compensate for larger losses in the SLR system. For example, a decrease in pulse energy E_{T} can be compensated by an increase in repetition frequency f_{p}, yielding in result the same amount of received return photons f_{d}. It should be noted that an increase in laser repetition rate will usually also increase the noise rate of the system by the same amount. However, the sensitivity of the system will nevertheless improve with increasing f_{p}, usually by a factor of $\sqrt{f_{\mathrm{p}}}$ (for more detail, see section 2.3).

1.2.2 Precision

The single shot precision of an SLR system can be estimated by convolving the impulse responses of the components which make up the system. If we assume that all of the impulse responses are Gaussian and independent of each other, then the single shot precision can be estimated by summing the standard deviation of the individual uncertainties in quadrature (adapted from [9]):

$$\sigma_{\mathrm{single}} = \sqrt{\sigma_{\mathrm{L}}^2 + \sigma_{\mathrm{D1}}^2 + \sigma_{\mathrm{D2}}^2 + \sigma_{\mathrm{ET}}^2 + \sigma_{\mathrm{S}}^2} \qquad (4)$$

Where the σ terms are the standard deviations of the following:

- σ_{L}, the time uncertainty due to the laser pulse form (related to the pulse duration)
- σ_{D1}, the time uncertainty due to the precision of the start detector
- σ_{D2}, the time uncertainty due to the precision of the stop detector
- σ_{ET}, the time uncertainty in the response of the event timer
- σ_{S}, the impulse response of the target which is being ranged.

When many single measurements are combined, the overall precision of a normal point σ_{np}, is related to the number of measurements, N, in the following way:

$$\sigma_{\text{np}} = \frac{\sigma_{\text{single}}}{\sqrt{N}} \tag{5}$$

The number of measurements N is itself directly proportional to the rate of returns f_{d} during the observation, therefore increasing pulse repetition frequency by a factor of Δf_p results in an improvement in precision of $\sqrt{\Delta f_p}$. Thus, it can help to achieve highly precise measurements despite larger uncertainties in some of the contributing terms.

It should be noted that increasing N will only reduce the statistical (rather than the systematic) error of the measurement. Regular calibration measurements to monitor the stability of all involved devices are of the same importance as in traditional sub-kHz SLR systems.

1.3 Applications

Using very high repetition rates enables the use of lasers with nanosecond pulses and / or low pulse energies. With this, several new approaches to SLR become viable. Among other possibilities, some technologies which are of interest are:

1. *On-Mount Compact Lasers*:
   Modern compact lasers typically are small and stable enough that they can be mounted directly to the telescope mount, instead of using a coudé path to direct the light from the laser to the transmitting optics [17]. The downside to these lasers is that they are typically only capable of providing low pulse energies. Equation 1 shows that the detection rate is linearly dependent on the pulse energy, since this determines the number of photons emitted per pulse. Increasing the pulse repetition rate would therefore allow an equivalent reduction in pulse energy for no overall change in detection rate, making this type of laser viable for SLR.

2. *Optical Fibre-Coupled Transmitters*:
   The use of a coudé path can also be avoided by coupling the transmitting optics to the laser source with an optical fibre [15]. This configuration has several benefits over on-mount lasers: The orientation of the laser stays constant throughout operation, the laser optics are not exposed to the weather and the design is simple enough that it can be used to convert existing telescopes to SLR stations without much modification.
   Fibre-coupled SLR is conducted using relatively long duration pulses to reduce the peak power of a pulse and avoid damage to the optical fibre. An increase in pulse duration deteriorates the precision of the laser (σ_{L} in equation 4) and so deteriorates the single shot precision. As shown previously (equation 5), the lower single shot precision can be compensated by increasing the pulse repetition rate.

3. *Improved Laser Safety*:
   Lasers which have short pulse duration usually have very high peak power. The high peak power density produced by such a laser has the potential to cross damage thresholds that a laser with an equivalent average power, but longer pulse duration would not. High repetition rate SLR allows ranging to be performed with lasers that have longer duration pulses and so allows the system to be operated at higher average power while having less potential to cause damage.
   Lasers with wavelengths longer than 1.4 μm have the benefit that they can be operated at higher average power while remaining eye-safe. It is envisaged that such lasers could be used to build an SLR system which is inherently eye-safe. Currently, most lasers which are commercially available at these wavelengths have long duration pulses or low pulse energy and would need to be operated at high repetition rate to be viable for SLR.

4. *Improved Data Yield*:
   Stations which already have good single shot precision are able to achieve mm level accuracy with less than a few hundred observations per normal point [6]. In these cases, data rate is not a limiting factor but operating at higher repetition rates can increase overall data yield by making it possible to complete the measurement of a single normal point faster and allowing the system to move on and observe multiple satellites within one standard normal point interval (as permitted by the 2012 amendment to the ILRS's standard normal point algorithm [4]).

The equipment required to achieve very low single shot precision is complex and expensive and places a barrier to accessible and accurate SLR. In comparison, increasing repetition rate is relatively easy and inexpensive. The experiment described later in this paper demonstrates the positive effect of a very high repetition rate on both the sensitivity and the precision of an SLR system.

2 Technical challenges

There are several challenging issues associated with laser-ranging at very high repetition rates, which need to be addressed and which determine to some extent the limits of this approach.

2.1 Ambiguity

The limit of ambiguity applies to any ranging experiment using a regularly pulsed source: If the repetition interval is shorter than the ToF (time of flight), an assumption of the expected distance must be used to properly correlate time-stamps of outgoing and incoming pulses. In satellite laser ranging, the expected ToF is usually derived from CPF predictions available from the ILRS website [5]. Their accuracy is often better than ten meters for regularly tracked targets, but may become larger than 100 meters for less tracked targets or objects at very low altitudes that are seriously affected by atmospheric drag. If no ILRS predictions are available, two line element (TLE) predictions can be used [8]. In this case, the range uncertainty is often several hundred meters.

For this discussion, we will assume the ToF as

$$\mathrm{ToF} = 2R/c \tag{6}$$

where R is the range and c the speed of light in vacuum. Atmospheric effects increase the ToF by some ten nanoseconds [20] but, for simplicity, these effects are not considered here.

To avoid ambiguity in the received returns, the pulse interval I_p should be greater than the uncertainty of the prediction. If ΔR denotes the largest expected prediction error in one direction, the minimum repetition interval is given by

$$I_\mathrm{p} > 4\frac{\Delta R}{c} \tag{7}$$

and the maximum repetition rate by

$$f_\mathrm{p} < \frac{c}{4\Delta R} \tag{8}$$

For a distance uncertainty of up to ±100 m, this yields a maximum repetition rate of 750 kHz. In the experiment configuration described here, a maximum distance uncertainty of ±350 m can be tolerated due to the trigger rate of 200 kHz.

These numbers show that the problem of ambiguity does not pose a strong limit on the maximum allowed pulse rate for usual SLR scenarios. Nevertheless it should be noted that the ambiguity can be resolved completely if the pulse rate is varied during the measurement. Changing I_p by some ten nanoseconds a few times during the measurement will produce clearly visible jumps in the lines of all incorrectly correlated pulses and only leave the correct line unaffected. When using this pulse rate variation, ambiguity poses virtually no limit at all.

2.2 Pulse collision avoidance

A pulse collision happens if the laser is fired a short time before the detector expects a return from the satellite. A part of the laser light is scattered in the atmosphere and reflected back into the detector, thus increasing the noise. For a regularly pulsed laser, this happens (roughly) when the ToF is an integer multiple of the pulse interval. Traditionally, a pulse collision is avoided by delaying the laser pulse by some 100 µs for those times at which a temporal overlap of outgoing and incoming pulses is expected.

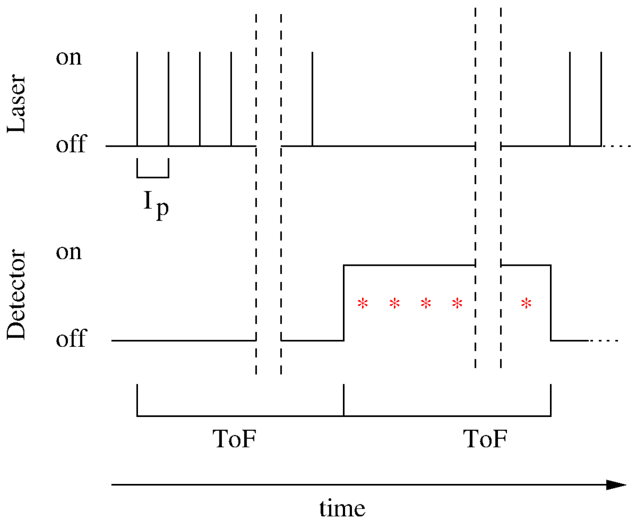

Fig. 2 Illustration of burst mode pulse collision avoidance: The laser is fired at its nominal repetition rate ($1/I_p$) for the duration of one time of flight (ToF). Subsequently, the laser remains off for another ToF while the detector is activated to receive the returning photons. The stars mark times at which photons can be received – if the return ratio is below one, only some of those will actually be detected.

While this scheme works well up to a few kHz repetition rate, it cannot be used at very high repetition rates where pulse intervals of only a few microseconds are used. Instead, *Burst Mode* pulse collision avoidance can be used (see also figure 2): In this mode of operation, the laser is fired at its nominal repetition rate for a duration of one ToF, while the detector remains off or closed. Before the first return pulses arrive at the detector, the laser is switched off and the detector starts receiving. After another full ToF, the pattern starts over again. A small extra gap of around 100 µs is inserted between firing and receiving periods to accommodate for the thickness of the atmosphere. While the ToF ranges from a few milliseconds up to several hundred milliseconds, depending on the distance to the target, I_p is typically only a few microseconds (5 µs in the described experiments, see section 3). Each burst therefore contains several thousands of individual pulses.

Overall, this scheme reduces the effective repetition rate to about 50% of the trigger rate. Under some circumstances, it might be more beneficial to run at the full trigger rate and ignore the increased noise level. Specifically, this might work well if receiver and transmitter apertures are positioned a few meters apart and the geometric overlap of the two apertures only starts high up in the atmosphere. In our set-up, however, the burst mode scheme proved to be essential to the success.

2.3 Increased noise

In SLR, noise usually means events registered by the detector which are not due to reflections on the target. There are two main types of noise: First, dark noise or thermal noise, which is generated in the detector itself even if it is completely in the dark. Second, afterpulses caused by charge carriers not drained during a detection. Third, actual photons that trigger the detector, but are not due to laser returns. Sources of this light can be sunlight scattered in the atmosphere (especially when measuring during the day) or reflected on the object, or laser light scattered in the atmosphere. The total rate of noise events N_{noise} can thus be written as

$$N_{noise} = N_{dark} + N_{a.p.} + N_{sky} + N_{object} + N_{backscatter} \quad (9)$$

All these rates depend greatly on the conditions of the experiment, and actual noise rates can range from some 100 Hz to several 100 kHz. Typically, a detector will be operated in gated mode, i.e. only be active for a short time period before and after the expected return signal. The measured noise rate therefore depends also on the duty cycle of the detector, D, which is the product of the repetition frequency and the duration of each active period, GW:

$$N_{noise,meas} = N_{noise} * D = N_{noise} * f_p * GW \quad (10)$$

High noise rates are problematic for two reasons: First, every detector has a typical deadtime, that effectively disables it for some time after each detection. For SPADs, this time may be anywhere between a few 10 ns [1] and a few 10 μs [3]. Assuming a dead time of 10 μs as in our current set-up, the maximum detector rate is 100 kHz. Since real events are lost in the deadtime even well below this rate, it is desirable to keep the detector rate (real events plus noise) well below 50 kHz in this case.

Second, a high noise rate impedes the detection of weak return signals. As in any number counting experiment, the significance S of a detection is defined as [19]:

$$S = \frac{N_{on} - N_{off}}{\sqrt{N_{on} + N_{off}}} = \frac{N_{signal}}{\sqrt{N_{signal} + 2N_{noise}}} \quad (11)$$

In this equation, N_{on} and N_{off} are the number of events in the signal and in the background region, respectively. $N_{signal} = N_{on} - N_{off}$ is the number of actual signal events, and $N_{noise} = N_{off}$ the number of actual noise events. Often, a significance of more than five is required to accept a signal as real. In any case, a high noise rate N_{noise} must be balanced by a high signal rate N_{signal} to obtain a sufficient significance.

To judge the effect of increasing the repetition rate on the significance of detection, we note that N_{signal} increases linearly with repetition rate f_p, if all other experimental parameters are unchanged (e.g. the laser pulse energy). Assuming an efficient pulse collision avoidance which eliminates backscatter noise, the noise level will also increase linearly with f_p (see eq. 10).

Therefore, equation 11 yields

$$S \propto \frac{N_{signal}}{\sqrt{N_{noise}}} \propto \sqrt{f_p} \quad (12)$$

In conclusion: The significance of a detection, and therefore the sensitivity of a laser-ranging system, increases with the square root of the repetition rate. However, care must be taken to keep the detector rate (the sum of signal and noise events) well below its maximum count rate determined by its dead time.

2.4 Daylight ranging

Many current SLR stations are able to perform ranging measurements during the day, albeit at the cost of an increased noise rate. With the system described in this paper, this has not yet been possible due to detector saturation at higher noise rates. However, this problem seems to be caused mainly by incidental design choices of the system rather than the high pulse rates: First, a 6 nm wide spectral filter is used for the single photon detector, which is rather broad compared to other systems. Second, the detector comes with a rather long deadtime of about 10 μs, in effect limiting the maxmimum detection rate to below 100 kHz.

Generally, it would seem that high rate systems do not suffer from increased background from daylight any more than conventional systems. In both cases, the sensitivity will deteriorate compared to night time measurements due to the increased sky brightness (increased N_{sky} in equation 9). However, as long as the increased noise rate can be handled by the detector and the data acquisition system, daylight ranging will be possible regardless of the repetition rate.

2.5 High data rates

Laser-ranging at very high repetition rates requires a fast data acquisition system and processing system. In the described set-up, we used the PicoQuant HydraHarp event timer, which is capable of registering up to 12.5 million counts per second. Other modern event timers usually employed in SLR, such as the Eventtech A033-ET (Riga) or the Guidetech GT668SLR are also specified for data rates above one million counts per second [11, 12]

The software evaluating and displaying the data must also be tuned to high efficiency. For our experiments we used the SLR software OOOS (Orbital objects observation software, [14]). It uses separate threads for reading the timestamps, calculating the expected time of flight, correlating

Table 1 Specifications of the laser system

Fundamental wavelength	1062 nm
Ranging wavelength	1062 nm
Spectral bandwidth FWHM	6 nm
Pulse energy (at laser)	80 μJ
Pulse energy (at transmitter)	50 μJ
Pulse duration	10 ns
Repetition rate	200 kHz

the outgoing and incoming timestamps, saving the timestamps and displaying the results. Despite using an ordinary office PC and a rather slow network storage, this approach works well up to 100 kHz effective repetition rate. To work at even higher rates, some further development of the software might be needed.

OOOS is published under GPL3 [2] and is available free of charge on the project's website [7]. The authors would appreciate feedback from anyone using this software for their SLR experiments.

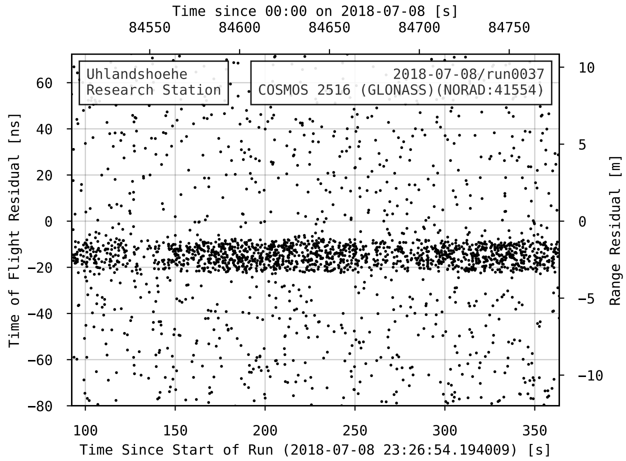

Fig. 3 Ranging plot showing a pass of satellite COSMOS 2516 (Glonass 136) at a distance of approximately 19,700 km. About 1,600 return events have been recorded (post-filter) in about 250 seconds, which corresponds to a return ratio of about 6×10^{-5}.

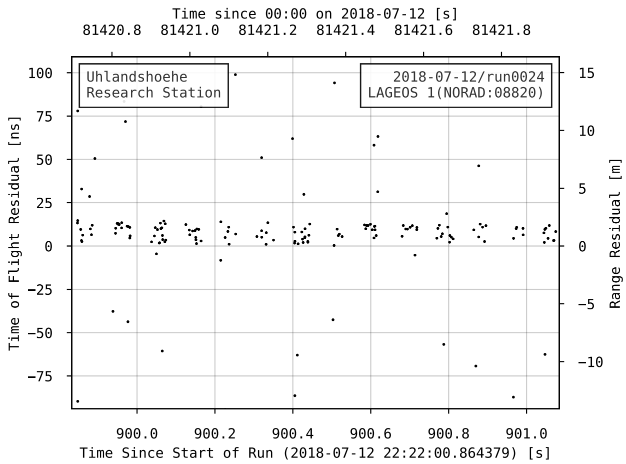

Fig. 4 Ranging plot showing a one second segment of a Lageos 1 pass at a distance of about 6,900 km. Roughly 100 return events per second (post-filter) could be detected.

3 Experimental set-up

The experiments described here were conducted using the Stuttgart SLR station at the observatory Uhlandshöhe (ILRS code UROL). The fundamental wavelength of 1062 nm from a Jenoptik fibre laser (Jenlas fiber ns 10-70) is used for ranging (see table 1 for specs). While the laser offers a range of different pulse shape settings and a maximum energy of 70 W at a repetition rate of 1 MHz, it is operated at 8 W and an effective repetition rate of 100 kHz (80 μJ per pulse). Due to losses in the optical system, the pulse energy at the output of the transmitter amounts to about 50 μJ.

In contrast to the usual coudé path set-up used for SLR, this system employs an optical fibre to direct the light from the stationary laser to the transmitter on the telescope mount. Laser trigger and detector gate pulses are generated by a White Rabbit FMC-DEL card, which is synchronised to UTC using a White Rabbit Switch as grandmaster clock and a Jackson Labs Fury GPS as time source. Event timing is done with a PicoQuant HydraHarp event timer, synchronised with a Meinberg GPS 180 clock. Both trigger and event timer are capable of working at data rates up to several hundred kilohertz. More details about the set-up can be found in [15].

For the current measurements, the system was operated at a trigger rate of 200 kHz, which results in an effective ranging rate of 100 kHz due to the burst mode duty cycle of 50%. Measurements were taken during four nights in the first half of July 2018.

4 Results

During the campaign, efforts have been concentrated on ranging to spherical geodetic satellites for an analysis of the system's performance. However, other LEO targets and also some GNSS satellites could be ranged successfully as well. Due to the low pulse energy, the returns consist only of single photon events, with mean return ratios (detected returning photons per outgoing pulse) between 0.1 for some LEO satellites with large reflectors down to 10^{-4} for GNSS satellites.

Figure 3 shows a ranging measurement to Glonass satellite 2516 (NORAD ID: 41554) at a distance of 19,700 km. Despite a very low return ratio of only 6×10^{-5}, a clear return signal is visible.

Table 2 Typical amounts of data recorded from various targets, shown as data points used per normal point (NP)

Name	ID	NP time	data points per NP	Return ratio
Swarm B	39451	5 s	20k - 40k	4% - 8%
Explorer 27	01328	15 s	up to 100k	6%
Larets	27944	30 s	100k	3%
Lageos	08820	120 s	10k - 20k	0.1%
Glonass	e.g. 41554	300 s	1k	0.003%

Figure 4 shows a short section of a ranging measurement to Lageos 1 (NORAD ID: 8820). At a distance of 6,900 km a return ratio of about 10^{-3} is achieved, thus collecting some 10,000 data points per normal point (120 seconds average). In the zoomed in view, the effect of the burst mode can clearly be seen, as the returns come in clusters of about 45 ms duration.

Table 2 shows some typical values for the number of data points obtained per normal point (NP) for different satellites. As can be seen, the number of data points is quite high in most cases despite low return ratios. This is particularly useful to counteract the large range uncertainty caused by a long pulse duration laser.

To quantify the precision achievable with this approach, the data were analysed at Hitotsubashi University where rapid quality check analyses are routinely conducted for a number of SLR satellites [22]. Combined with the worldwide SLR observations, ten runs from these experiments are tested in their precise orbit determination. Applying a provisional station position of the Stuttgart SLR station, the data aligned well in the determined orbits and the pass-by-pass range bias and time bias are at cm- and microsecond-level respectively. Despite the fact that the single-shot RMS of about 60 cm is much higher than at other stations (a few mm to a few cm), it should be emphasized that the scatters of NP data are in the range of 5 to 15 mm RMS which is promising for sub-cm precision orbit determination.

In summary, these measurements show that the anticipated benefits of very high laser repetition rates can be realised in practice: Despite a rather low pulse energy of only 50 µJ, clear returns can be seen from targets up to GNSS orbits. On the other hand, averaging over a large number of returns for each normal point successfully counteracted the poor single-shot precision caused by the 10 ns long laser pulses, and resulted in a normal point precision in the order of 1 cm.

5 Conclusion & Outlook

In this paper, the challenges and benefits of using very high repetition rates for SLR have been examined in theory and practice. The results show that laser ranging at 100 kHz is not only possible, but indeed a very useful technique for systems that are limited in their choice of laser. Both a low pulse energy and a long pulse duration can be compensated, and a large range and a good precision can be achieved nonetheless.

The current set-up at the Uhlandshöhe Observatory is not yet the ideal 100 kHz SLR system. The use of a multimode optical fibre results in a rather large laser beam divergence of about 100 µrad half angle. The use of a single-mode fibre could decrease this number and thus increase the number of returns from distant targets significantly. With an improved fibre, or an on-mount laser, somewhat higher pulse energies and thus even more returns would be possible. Also, it should be noted that 100 kHz do not mark the end of the development, and rates up to 500 kHz or more seem feasible.

With these possible improvements in mind, it seems likely that SLR at very high repetition rates will become more common in the future. For existing systems, it may offer a gain in sensitivity, precision and / or data yield at a moderate cost. Since it enables the use of laser at wavelengths above 1.4 µm, it may also help in the development of inherently eye-safe systems. For new systems, it may supersede the traditional coudé path approach, as on-mount laser systems or fibre-coupling become competitive alternatives. The German Aerospace Center will further pursue this approach not only with the Uhlandshöhe SLR system, but also with the new miniSLR system currently under construction, which will incorporate a whole SLR system with a multi-kHz on-mount laser into a small box [13].

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