Satellite Laser Ranging with a fibre-based transmitter

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Abstract

The experimental satellite laser ranging station in Stuttgart has commenced operations in January 2016. Its modular, flexible and cost-efficient design uses only readily available components and is therefore well suited for an upgrade of existing astronomical observatories to SLR stations. One of its key features is the laser light transmission via an optical fibre, thus avoiding the need for a coudé path mount. Currently, the transmitter achieves an output pulse energy of about 25 µJ at 5 kHz (125 mW) and is operated at the fundamental Nd:YAG wavelength of 1064 nm. The complete system, including IT hardware and observer workplaces, is fitted into a 12 feet dome.

With the current configuration, many cooperative targets in LEO and beyond (up to LAGEOS) have successfully been observed, with usual return rates of several hundred counts per second. Since the tracking relies on visual guiding, no accurate CPF predictions are needed, and out-of-service SLR targets like GEOS 3 can be observed as well using public TLE data.

In the future, the system is envisaged to operate at much higher repetition rates to further increase the performance. In the long-term, the goal is to approach current ILRS standards in terms of precision, maximum range and availability (daylight ranging) with this design. This contribution describes the technology, first results and planned upgrades.

The Stuttgart SLR station

The SLR station in Stuttgart has been established in 2012 and is intended solely for the development of new SLR technology. It is based on site of the city's historic observatory at 48.78240° N, 9.19641° E, and at a height of 354 m above sea level. The system design is focused on a small, modular and inexpensive set-up, in line with the idea of a "minimal SLR" system. It employs a 500 mW solid state laser (Innolas AOT piccolo MOPA), an optical fibre for the transmission of the laser light to the transmitter, a standard amateur astronomy direct-drive mount, and a standard telescope. The trigger and DAQ system uses the White Rabbit technology developed by CERN (especially the WR FMC-DEL card) and the PicoHarp 300 event timer by PicoQuant. As receive detector, an idQuantique id400 module is mounted in the focal plane of

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the main telescope. Some specs of the system are summarised in table 1. A detailed description of the system can be found in *(Hampf, et al., 2016)*.

Laser power	~ 500 mW
Repetition rate	5 kHz
Pulse duration	3 ns
FoV detector (side length)	10 arcsec / 50 µrad
Beam divergence (full angle)	80 arcsec / 400 µrad
Detector dark noise	2 kHz

Table 1: System specs

The fibre-based transmitter technology

Commonly, a coudé mirror system is used in SLR to guide the light from the stationary laser onto the transmitter telescope. While being a flexible and well established approach, it is also a cost driver for small SLR systems, since it requires a special design telescope mount. Two ways to avoid a coudé path and use a standard telescope mount have been devised in recent years: The placement of the whole laser system onto the telescope (Kirchner, et al., 2015), and the use of an optical fibre in the transmitter line, as described here (Humbert, et al., 2015).

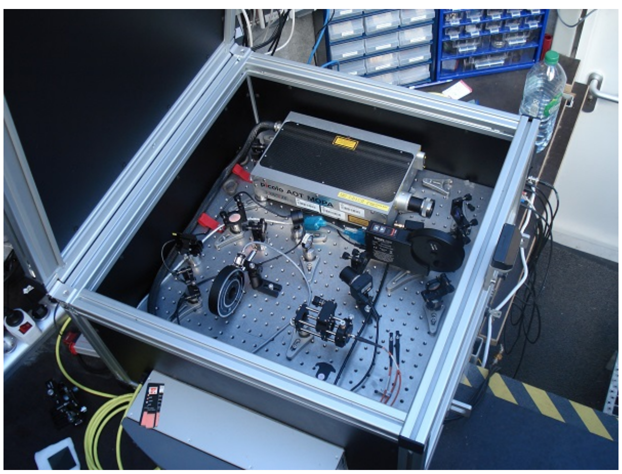

Figure 1: Laser set-up with Nd:YAG laser, energy and start pulse sensors, and fibre coupling stage

Figure 1 shows the optical set-up including the laser source and the fibre coupling stage. For our current configuration, a stable manual stage proved to be good enough to ensure a coupling efficiency of 50 to 70%. Even though the environment is not climate-controlled, re-alignment of the fibre coupling is required only occasionally (~ once per month).

In our experience, the main challenge when using a fibre in an SLR transmitter is the rather high peak power produced by short (picosecond to nanosecond) laser pulses, especially when focused into a small fibre core. Above a certain energy density threshold, which depends on the pulse duration and the type of fibre used, surface damage is inflicted onto the entry facet.

Two ways to avoid fibre damage are the use of longer pulses (nanoseconds rather than picoseconds) and larger fibre core diameters. In our set-up, stable operation has been achieved using 100 µJ pulses of 3 ns duration and an inexpensive 50µm multi-mode fibre.

While the pulse energy of 100 µJ is sufficient for a high repetition system, it would be desirable to decrease the pulse duration and, even more importantly, to switch to single mode operation in order to decrease the beam divergence significantly. Currently, the system's maximum range is limited to about 6000 km due to the large divergence of about 400 µrad. In preliminary tests with a 25 µm single mode fibre a divergence of 140 µrad was achieved, however at a reduced pulse energy to avoid damage.

To overcome these limitations, the dynamic research and development in the field of fibre optics offers various interesting approaches. In cooperation with Stuttgart University, our group is currently testing single-mode transmission through a multi-mode fibre with a core diameter of 50 to 70 µm, which would combine the advantage of a low beam divergence with a high damage threshold (Austerschulte, et al., 2012). Novel fibre concepts, such as hollow core fibres, promise even much higher damage thresholds and could be very well suited even for picosecond laser ranging with high energy lasers. In lab experiments, pulses with up to 30 mJ (30 ns) have been transmitted successfully through such a fibre (Dumitrache, et al., 2014). Assuming the damage threshold to depend on the square root of the pulse duration (Tien, et al., 1999), this corresponds to about 1 mJ at 30 ps.

First successful measurements

In its current set-up, the system is able to perform satellite laser ranging to most cooperative LEO targets and – in good conditions – up to LAGEOS. Typical return ratios are in the order of 0.1 to 10 percent, which yields a very clear signal considering the laser repetition rate of 5 kHz and a typically rather low noise rate of about 2 kHz. Since the tracking currently relies on visual acquisition, measurements can only be taken during dusk or dawn. Usually, TLEs are used as tracking predictions, so the tracking is not limited to standard SLR targets.

Two examples of successful measurements are shown in figures 2 and 3. During these early measurements, no pulse collision avoidance mechanism was available; therefore clear signatures of atmospheric backscatter are visible.

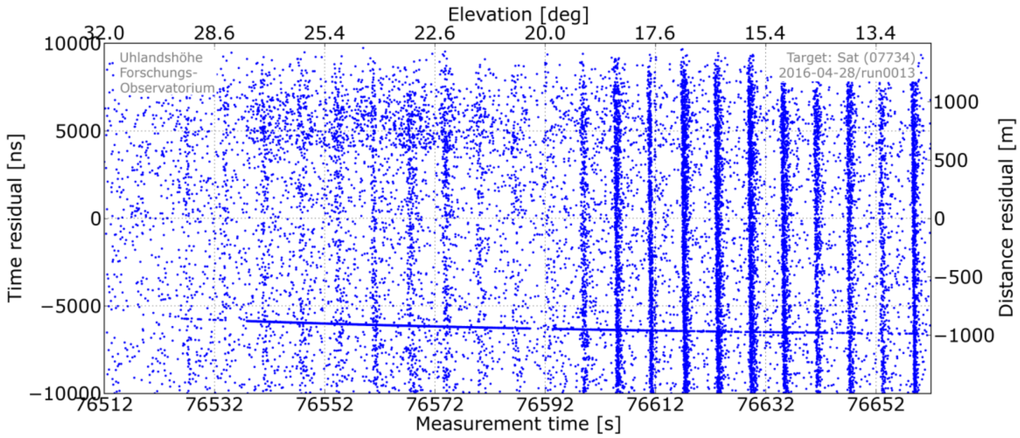

Figure 2: Ranging to satellite GEOS 3, using TLE predictions and a gate of 20 µs .The average return ratio is 1 to 2%.

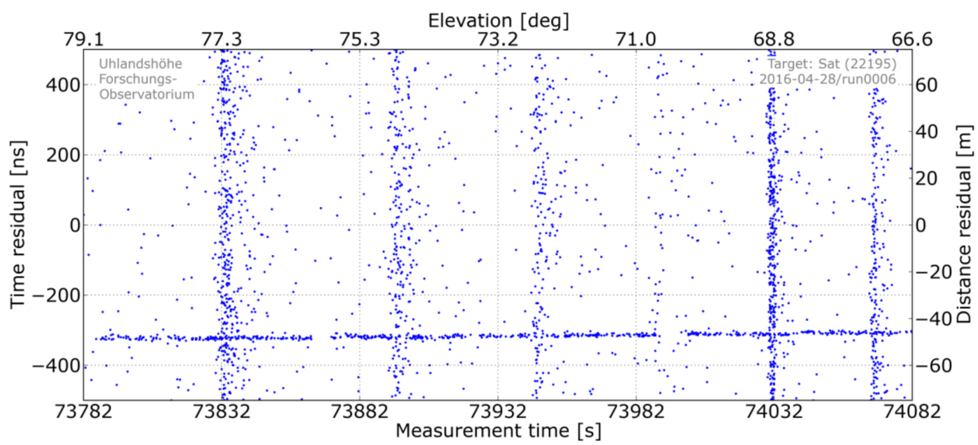

Figure 3: Ranging to Lageos 2, using CPF predictions and a gate of 2 µs. The average return ratio is about 0.05%.

Planned improvements of the system

Following the successful proof of principle, the SLR system will now be upgraded with the ultimate goal of approaching current ILRS standards. Currently, the main challenges in this respect are the limited range, a poor precision and the limitation of the observations to dusk / dawn periods. It is believed that all three limitations can be overcome without compromising the principle design goal of using inexpensive, standard components.

To increase the operating range, three options exist: Increase the pulse energy, increase the repetition rate (at constant pulse energy), and reduce the beam divergence. Since the fibre imposes a rather severe energy limit (which can however be increased somewhat by novel type fibres, as discussed above), the next upgrades will focus on an increase of the repetition rate (see next section) and the reduction of the beam divergence by improving the beam quality at the end of the fibre. Additional measures are a PC controlled divergence control (currently only manual and rather coarse) and a re-coating of the transmitter lenses for better transmission at 1064 nm.

To increase the measurement precision, proper calibration schemes will be developed. This includes the definition of the system invariant point, and the automatization of the calibration procedure. Additionally, a new event timer system (Guide Tech GT668) will replace the current PicoHarp 300, which has repeatedly shown problems with drifts against UTC.

To enable all-night and daylight tracking, the mount control software and especially the pointing model will be completely rewritten. First tests using the TPOINT software show a potential of reaching a blind pointing accuracy somewhere around 5 to 10 arcseconds. Combined with an efficient search and hold algorithm, which is already under development, this might be sufficient to enable blind tracking.

Towards 100 kHz laser ranging

As discussed before, the pulse energy of a fibre-based system is intrinsically limited. However, the average power transmitted can be increased almost indefinitely by increasing the pulse repetition rate. In a signal limited situation, this increases the data yield linearly; in the more common case of a noise limited measurement, the data yield increases with the square root of the pulse rate.

Suitable hardware is required for this upgrade: A high repetition laser, a fast detector, a data acquisition system that can handle high data rates, and fast PCs. Also, the software must be written with a focus on efficiency, to read, analyse, save and display the data in real time. Currently, an upgrade of the Stuttgart SLR station is underway with the goal of achieving repetition rates well above 10 kHz, potentially up to 100 kHz.

The current laser will be replaced by a Jenoptik JenLas fibre laser, which can be triggered with rates from 1 kHz to 1 MHz. Both the current PicoHarp and the new Guide Tech event timer are capable of acquiring more than 1 MHz of data rate. The ranging software is currently being rewritten to allow true multiprocessing, to exploit the full potential of a multi-core PC.

To avoid problems with atmospheric backscatter, the pulses will be generated in bursts (or pulse trains). These bursts last for $ToF - t_{margin}$, and are separated by a quiet period of $ToF + t_{margin}$, in which returning echoes are being received. In this, ToF is the expected light travel time, and t_{margin} $(\ll ToF)$ accommodates for uncertainties and the time the light needs to leave the atmosphere. Figure 4 illustrates the pattern. In this mode, which has already been implemented in our system, no pulse collisions occur at any laser rate.

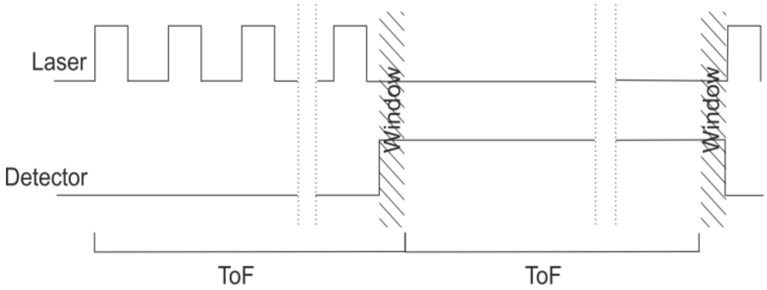

Figure 4: Pulse generation pattern for burst mode measurements. ToF: Expected time of flight for the laser pulses (~ a few 10 ms). Window: Safety margin for the distance measurement, to accommodate for distance uncertainty and the time the light needs to leave the atmosphere (~ a few 10 µs)

Conclusions

The experiments described here have shown that SLR is possible with an optical fibre as replacement for the coudé path in the transmitter line. This greatly reduces system costs, as it enables the use of a standard amateur astronomy mount. It should be emphasised that such a system has only been made possible by many technological advances in recent years, such as small and inexpensive solid state lasers, high performance optical fibres, precise direct drive amateur astronomy mounts and affordable event timers capable of handling multi-kilohertz data rates.

The system offers an interesting, cost-efficient alternative to consider when planning new SLR stations. The hardware of the whole system described here can be purchased for less than 200 k€, which already includes all described upgrades. Due to its small size, the rather low complexity, and the high degree of automatization, the system should also be moderate in its operation costs. Due to its modular design, it is also well suited for an adaption to other scenarios, e.g. to upgrade a standard optical telescope to an SLR system.

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