A PATH TOWARDS LOW-COST, HIGH-ACCURACY ORBITAL OBJECT MONITORING

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ABSTRACT

In an increasingly crowded space environment, precise predictions of space object trajectories are of paramount importance in order to avoid collisions and unnecessary evasive manoeuvres. Laser-optical range measurements are a promising approach to attain the high quality input data required for good predictions. However, while laser ranging to space debris objects is possible and has been demonstrated by several observatories, the technique requires expensive, high-power lasers and large aperture telescopes, to detect the faint diffuse reflections from the surface of the targets.

Therefore, we propose to routinely equip satellites, rocket bodies and potential mission related debris with small laser retroreflectors. With these, precise position measurements can be obtained much more easily, not only during the operational phase, but also after the mission. Such equipment could possibly be mandated by regulatory bodies like number plates in road vehicles. However, if the additional impact and cost of the technology is small enough, satellite owners and operators may even choose to include retroreflectors in their designs voluntarily and for their own benefit. This seems especially likely in the case of large constellations, in which a precise tracking of defunct satellites is of great importance to protect the other objects in the constellation.

In this contribution we will present recent developments at DLR Stuttgart to facilitate a more wide-spread introduction of this technology. The miniSLR system is a small, fully automated laser ranging ground station that can be used to track and range to objects equipped with retroreflectors. It is completely integrated in a box of $120\ \mathrm{cm}$ by $180\ \mathrm{cm}$ footprint and can be transported to a remote observation site after full integration and testing at the home institution. If produced in a small series, it may become the backbone of a global low-cost satellite laser ranging network for space traffic monitoring services.

Furthermore, new types of retroreflectors are currently under development, which may allow a unique identification of space objects using laser ranging. In combination, these technologies can contribute to a more controlled and thus safer space environment.

Keywords: Laser Ranging; Retroreflectors; Precision Measurements.

1. INTRODUCTION

Satellite laser ranging (SLR) is an established technology used for various scientific applications. Originally developed as a geodesy tool, it is now also used by many Earth observation missions, gravimetry experiments, time transfer experiments, and navigation satellite systems (GNSS) [20]. A network of around 40 stations around the world routinely records range data to almost 100 satellites and provides it openly to scientists, mission operators and the general public (International Laser Ranging Service, ILRS) [10].

On the satellite, a small and lightweight retroreflector provides enough backscatter towards the ground station. Being a completely passive system, these reflectors can often be incorporated into the satellite bus without much impact on the overall design.

On the other hand, most of the SLR ground stations are of unique design and are being developed and constructed by local scientists and engineers. A handful of NASA and Roskosmos stations share a similar design, but nevertheless building a new SLR station is a costly and time-consuming process [8, 12]. In this paper we will present current activities to develop a less complex, ”minimal” SLR system that may facilitate a much wider range of uses and applications for SLR (section 3).

An interesting and promising new application of SLR is its use in space traffic monitoring, as part of the general space surveillance. In the early 2000s, the newly constructed laser ranging station in Mt Stromlo, Australia, for the first time succeeded in ranging to diffusely reflecting targets without retroreflectors [16]. This technology, often dubbed space debris laser ranging (SDLR), has since been employed by several European and Chinese SLR stations in experimental campaigns [18, 21]. Meanwhile, EOS in Australia is working towards a routine SDLR service [2]. Similar efforts are underway in Europe under coordination of ESA [14].

However, SDLR remains a complex and expensive technology, mainly due to the use of very high power lasers. Retroreflectors commonly achieve effective optical cross sections of about one million square metres or more [1]. For diffusely reflecting targets, the effective optical cross section is only a fraction of their actual size, i.e. a few square metres for large rocket bodies and well below one square metre for the majority of space debris objects. This has to be compensated by a combination of very high power lasers, large telescope apertures and very precise beam pointing with a small divergence.

If, however, more space vehicles were equipped with laser retroreflectors, existing standard SLR stations could be used for monitoring their trajectories. Especially, new "minimal" SLR systems as presented in section 3 could be installed specifically for space traffic monitoring. Such a system could provide cm to mm precise positions of orbital objects, during and after their operational lifetime. Even considering the costs to install retroreflectors on satellites, the overall costs of such a system would be just a fraction of SDLR or radar systems of comparable performance.

On top of that, advanced retroreflectors may provide means to identify targets uniquely. With little effort, retroreflectors can be modified to reflect back a target signature using properties of the laser light such as wavelength or polarisation (section 4). This can help to quickly identify targets from launches with multiple payloads, but also to trace back the origin of tracked objects even decades after their launch.

2. USING LASER RANGING FOR SPACE TRAFFIC MONITORING

2.1. Advantages of using SLR for space traffic monitoring

Currently, laser ranging to cooperative targets (i.e. targets with retroreflectors) is not used for space traffic monitoring purposes. However, it offers a range of advantages:

- High accuracy: Sub-cm range accuracy to the reflector (distance to centre-of-mass may be a little less well known, depending on the knowledge of the mass distribution in the target).
- Low-cost ground stations: Satellite laser ranging is an established and well-known technology. Recent technical advances enable the development of small, low-cost SLR systems that can achieve competitive performance (see section 3).
- Minimal impact on satellite: Retroreflectors are small, lightweight, require no power and produce no heat. As such, they can easily be integrated into the satellite bus with little impact on the overall design.
- Added value during mission: Already during the active operations of the satellite, the mission may benefit from high resolution position data, without complex on-board technology that consumes power and space.
- Additional information: With little extra effort, retroreflectors may be modified to project back extra information about the object, e.g. serve as an ID tag for the satellite (see section 4).

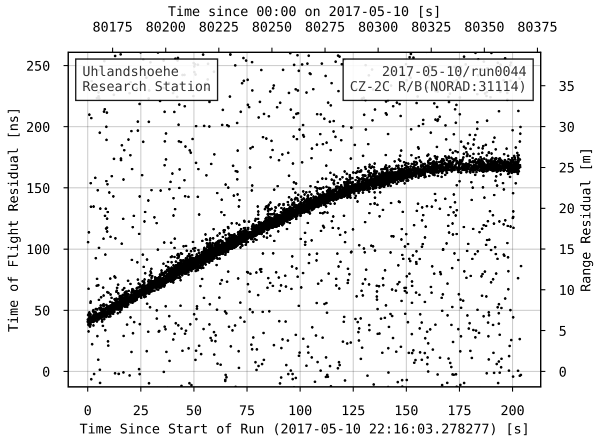

Figure 1. Ranging data of a Chinese rocket body (CZ-2C R/B, NORAD ID 31114)) recorded at the Stuttgart SLR station "Uhlandshoehe" in May 2017, using a 300 μJ *laser at* 10 kHz *repetition rate.*

2.2. SLR as part of a sensor network

An efficient and successful space surveillance network will employ sensors of different type. Radar systems and passive-optical telescopes will be required to collect routine data on the general space situation. However, in case of a predicted close conjunction, on-demand laser ranging measurements can provide valuable high-precision information about the likelihood of a collision.

In case of uncooperative targets, such as debris from a breakup, this will have to be done by an SDLR station. However, about 40% of the "debris" objects actually are rocket bodies, intentionally released components (e.g. adapter rings), or defunct but structurally intact payloads [6]. All these could easily be equipped with retroreflectors to enable standard SLR measurements. In fact, some rocket bodies of Chinese origin already carry retroreflectors, and several standard SLR stations have been able to obtain ranging data of them (one example is shown in Fig. 1).

A simplified work flow diagram is shown in Fig. 2: Radar and passive optical sensors are used to detect new objects, which are not yet catalogued, and to keep the catalogue up-to-date with regular measurements. In case an upcoming close conjunction between two objects is detected (and at least one of the objects is controllable), follow-up measurements with laser systems can be conducted to

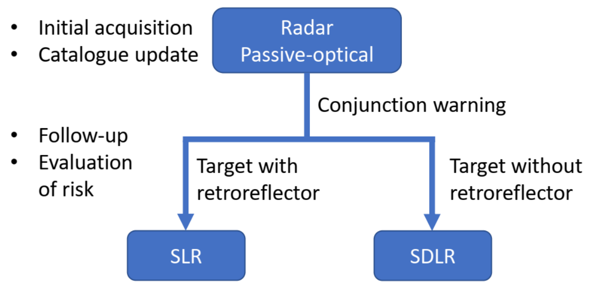

Figure 2. Flow chart of space surveillance tasks.

evaluate the need for collision avoidance measures.

It should be noted that uncertainties in the orbit predictions cause many false alarms, that may trigger unnecessary evasive manoeuvrers. ESA estimates that even with the best currently available predictions, about 99% of the alarms are in fact false alarms [7]. Reducing this number will save money, reduce required man-power, and extend mission time. Laser ranging (i.e. SDLR and, where possible, SLR) is the most cost-effective and accurate option to significantly reduce the number of false alarms.

2.3. Preparing the satellites

With SDLR systems, laser ranging to all targets in orbit is possible in principle. Minimum size and maximum distance of the objects depend on the system parameters. SLR, on the other hand, requires the satellite constructors to include retroreflectors on all their space objects (payloads, rocket bodies, mission-related debris). In turn, as long as retroreflectors are available, SLR works well even on very small targets and over large distances.

We hope that the advantages outlined in section 2.1 will encourage satellite operators and constructors to consider the inclusion of retroreflectors in their bus designs. The benefits should be especially obvious for operators of satellite constellations. With many objects on similar orbits, defunct satellites are an immediate threat to the rest of the constellation. De-orbit manoeuvres may not always be possible before a critical malfunction. Frequent evasive manoeuvres for active members of the constellation may be avoided if the failed satellites can be tracked with very high accuracy.

In 2019, a group of satellite operators, manufacturers and associated companies have published a set of "best practices" to ensure the sustainability of space operations [17]. Among other measures, they recommend the inclusion of laser retroreflectors on vessels to enhance tracking possibilities. In an ESA study that has investigated various means to improve the visibility of small spacecraft, laser retroreflectors have been found to be the best available technology [4]. In a recent review, Mark A. Skinner has pointed out the urgent need for improved tracking and identification means on small satellites such as CubeSats, and suggested retroreflectors as one option to achieve this [13].

Figure 3. The miniSLR prototype on the roof the DLR institute in Stuttgart (Image: Tim Bourry / DLR).

However, the successful adoption of SLR for space surveillance will also depend on the regulations, guidelines and incentives imposed by the large space agencies and regulatory bodies (e.g. the FCC in the U.S.). Ultimately, satellite operators may be forced or encouraged to include tracking aids on all their orbital objects, just as cars and bicycles are required to be equipped with headlights and cat's eye reflectors to increase road safety.

3. THE MINISLR SYSTEM

3.1. Design goals

The miniSLR system has been developed to make SLR a more accessible and affordable technique. The complete system (including mount, telescopes, laser, event timer, time and frequency generators etc.) is integrated into one container of approximately 120 cm by 180 cm footprint (see Fig. 3). The design offers some substantial advantages over traditional SLR stations:

- The system can be built and tested at "factory", so there is no need to bring experts and engineers to a possibly remote SLR site.
- The assembled system can be transported to its observation site using a transporter van and a forklift.
- The design is kept simple and only absolutely necessary hardware is incorporated, to obtain low failure rates and facilitate maintenance.

- A well-proven and established control software is used to run the system fully autonomously.
- The whole set-up is sealed and air-conditioned (not yet in the picture), thus no component is exposed to harsh environment. All components are kept at lab-typical temperatures, which increases the measurement stability.
- Since the system is inherently rain-proof, even a catastrophic failure (like a power failure) does not require immediate attention.
- The small footprint and relatively low weight (about 500 kg) substantially reduce infrastructure costs compared to traditional SLR stations that require their own building.
- Short signal lines and stable environmental conditions decrease possible sources of changing system time bias. Continuous calibration will be performed to eliminate remaining sources of shifts.

By carefully designing the system parameters, the critical performance figures are comparable to those of established SLR stations:

- Measurement range from LEO up to GNSS satellites
- Nominal normal point ranging precision of 1 mm (LEO) / 5 mm (GNSS)
- Long-term stability

With these specifications, the miniSLR will be not only highly useful in scientific SLR settings like geodesy and mission support, but may also pave the way for new applications, for which SLR currently is too expensive or too experimental. If retroreflectors on satellites become more common, a small network of standardized miniSLR systems around the world could provide extremely accurate orbital data at very competitive costs.

3.2. Technology

To simplify the system while keeping the required performance, the miniSLR focuses on achieving a very good time resolution by averaging over many laser pulses, rather than per individual pulse. During an interval of 5 to 300 seconds (depending mainly on satellite altitude), several ten thousand single photon returns are collected. Each individual pulse achieves a time resolution of about 400 to 500 picoseconds (corresponding to about 7 centimetres). By averaging these measurements into a *normal point*, a standard procedure which is also routinely employed by other SLR stations [15], the time resolution is improved by about two orders of magnitude (1 mm).

This approach relaxes the demands on several critical system components such as the laser, the single photon detector and the event timer. A laser with a pulse duration of 400 ps can be constructed much more compact and lightweight than a 10 ps laser with similar pulse energy (due to the significantly lower peak power).

Table 1. Specifications of the new miniSLR prototype currently under construction.

Laser pulse duration	400 ps
Laser pulse power	150 µJ
Laser repetition rate	75 kHz
Operating wavelength	1064 nm
Beam divergence	50 µrad
Telescope aperture	20 cm
Tracking accuracy	25 µrad

Additionally, the laser is further simplified by decreasing the pulse energy compared to conventional SLR systems. In turn, to achieve sufficient return signals, the laser is operated at much higher repetition rates than otherwise used in SLR. This *very high repetition rate SLR* has first been developed for the SLR station in Stuttgart ("Uhlandshöhe") [5], and is currently also being explored by other groups in the SLR community [3, 19].

Such a sub-nanosecond, low-pulse-energy laser can be mounted on a relatively small platform, which can be installed on a small and relatively inexpensive telescope mount. In consequence, this simplifies the whole infrastructure supporting the ranging system, and ultimately enables the integration into a small, transportable container.

Table 1 lists the main specifications of the new miniSLR prototype. With these specs, the return rates should be high enough to achieve the envisaged ranging precision of one to five millimetres per normal point.

3.3. Development

The first miniSLR prototype has been operational in September 2019. During a short test campaign, laser ranging could successfully be demonstrated to various targets. However, serious problems with the telescope mount impeded continued operation. Currently, the miniSLR is being refurbished with a new mount and a more powerful laser. Additionally, air-conditioning and waterproofing is improved to allow fully unattended operation in all weather conditions. First operation of the new miniSLR prototype is expected for late 2021.

DLR is currently negotiating with private sector companies to prepare a commercial product based on the miniSLR prototype.

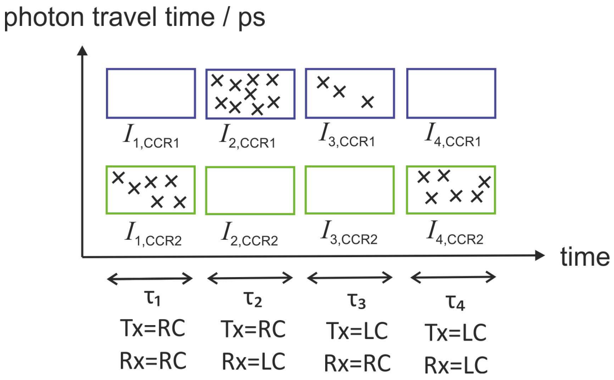

Figure 4. Detection principle for the identification of a satellite via polarimetric SLR. The polarisation of the transmitted (Tx) and the detected (Rx) signal is modulated between right-circular (RC) and left-circular (LC) during the time intervals τ_1 to τ_4. The relative intensity obtained for each retroreflector assembly (in this case CCR1 and CCR2, which are separated in space and thus have a different photon travel time) during τ_1 to τ_4 can be used to identify the satellite.

4. RETROREFLECTORS AS IDENTIFICATION TAGS

Recent effort in our group focuses on developing novel retroreflector arrays that allow not only for a precise orbit determination via SLR, but also for an identification of the satellite (satellite with "numberplate"). In this approach the satellite is equipped with one or more passive-optical assemblies that consist of a retroreflector(-array) and additional polarization optics. The change of polarization induced by these assemblies can be retrieved from ground by performing polarization-modulated SLR measurements. This requires that the SLR ground station is equipped with a fast-switching polarisation state generator (PSG) and a polarization state analyser (PSA). The time-resolved, relative signal strength detected for different polarization states on the PSG and SPA allows for the identification of the space object (see Fig. 4).

A major advantage over other strategies for space object identification [9, 11] is that the retroreflector assembly is completely passive optical, which allows for a simple integration into the satellite. Since the assembly does not require electricity, it will furthermore even work in case of a satellite outage. The concept has been validated with initial laboratory tests and a flight module is planned to be launched onboard of the DLR satellite Compact-Sat 2.

5. SUMMARY

A comprehensive sensor network for space surveillance requires sensors for different tasks: Wide field-of-view radar and passive-optical systems are well suited to detect new objects and to regularly update orbital parameters for all objects. In case of a predicted close conjunction, very accurate position data is required to evaluate the need of an evasive manoeuvre. Laser ranging (SDLR or SLR) is ideally suited for that due to its very high precision. Especially SLR (laser ranging to targets with retroreflectors) offers a particularly cost-effective way to obtain high-precision orbital data.

The miniSLR is a compact and powerful new laser ranging system which is ideally suited for space traffic monitoring SLR. Due to its low cost, high degree of automation, and its small size, it is a competitive alternative to existing sensors.

Using SLR for space traffic monitoring requires the integration of retroreflectors on payloads, rocket bodies and mission-related debris. Satellite operators may consider to equip their vessels with retroreflectors due to their usefulness during the mission, their minimal impact on the satellite design and the need to protect their other own satellites. Rules and guidelines from regulatory bodies may further encourage a more wide-spread adoption. Enhanced retroreflectors which can uniquely identify objects are under development and may further increase the potential of SLR for space surveillance.

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