SPACE DEBRIS LASER RANGING: MOVING FROM EXPERIMENTS TO OPERATION

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ABSTRACT

Over the last twenty years, it has been shown in numerous experiments that Space Debris Laser Ranging (SDLR) can be a powerful tool for determining the position of objects in orbit. With a relatively simple and well-established technology, the distance between a ground station and an object in orbit can be derived with an accuracy of a few decimetres. In turn, these measurements can be used to produce highly accurate predictions of orbits for the timespan of one to a few days.

Consequently, this technology has the potential of having a great impact on different aspects of Space Situational Awareness (SSA), and in particular on the assessment of short- and mid-term conjunction warnings. With targeted laser ranging observations, uncertainties about the orbits of defunct objects can be reduced by orders of magnitude, enabling operators to make clear and well-informed decisions about evasive manoeuvres. In a vast majority of cases, manoeuvres can be avoided completely thanks to the high fidelity of the prediction.

Unfortunately, this potential of laser ranging for SSA has so far been exploited poorly. A number of reasons can be put forward, but the lack of availability of easy-to-obtain laser ranging data seems to be at the core. So far, all SDLR efforts in Europe have been conducted in the context of research and studies. For SSA service providers and satellite operators there exists no straightforward way to obtain SDLR data.

To improve this situation, DiGOS has launched a new web platform called "Commercial Laser Ranging Data Exchange" (CLRDE). This activity, which is co-funded by the Competitiveness Segment of the Space Safety Programme of ESA, provides an easy-to-use gateway for SSA service providers and other data users to obtain laser ranging data from numerous ground stations. The organisational and technical overhead, which is usually associated with receiving laser ranging data from ground station operators directly, is minimised. To support the introduction of the service to the market, ESA acts as test customer and provides access to data generated with the Izaña laser ranging system in Tenerife.

Meanwhile, the Izaña station is being upgraded to develop and test new technologies in laser ranging. To improve data yield, the system is enhanced with functions for autonomous operation. A light curve detector with high temporal resolution has been integrated for object characterisation. Also, a new camera-based aircraft detection system is being tested.

The largest upgrade, however, is the addition of a second laser transmitter system specifically for non-cooperative targets. First successful measurements have been taken to defunct satellites and rocket bodies. A special camera system and corresponding software allow automated guiding of the telescope to enable observation of objects with poor orbit prediction. To enable observations also during the day and increase operation time, the guiding camera system is capable of detecting objects also in daylight.

During the years of 2025 and 2026, the station will be available as makerspace platform for experiments in the domain of laser ranging and related fields. A number of experiments with different partners have already been planned. Parties interested in participating are invited to contact DiGOS or ESA about it.

Keywords: Space Debris, Laser Ranging, Light Curves, Daylight Tracking.

1. INTRODUCTION

The use of laser ranging data for high-precision orbit determination of satellites and space debris has significantly evolved in recent years. While Satellite Laser Ranging (SLR) with retroreflective targets has long been an established method in geodesy and science [1, 2], Space Debris Laser Ranging (SDLR) is gaining increasing importance for the precise monitoring of non-cooperative objects in Earth orbit [3, 4, 5].

Laser ranging offers a huge potential for applications in

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the domains of space situational awareness (SSA) and space safety. In particular, it can complement existing networks of radar and passive-optical ground stations with a high-accuracy component: Due to the inherent accuracy of the measurements in the sub-metre regime, predictions based on laser ranging can be orders of magnitude more accurate than those done based on other technologies. In particular, this can help with:

- Conjunction warnings and risk estimation
- Collision avoidance planning
- Catalogue keeping
- Maneuver detection
- Re-entry predictions
- Support of de-orbit or nudging operations (e.g. laser momentum transfer)

However, despite promising study results, laser ranging data is so far not used operationally for space situational awareness (SSA) and space safety applications. We assume two main reasons for this:

1. There is so far no clear and easy-to-use interface to task laser ranging stations and collect their data. Projects so far often relied on direct contact and communication between individual data users and ground station operators. Data formats and interface details have to be negotiated individually for each project, causing a significant overhead.
2. Although there are several SDLR laser ranging stations operating in Europe (and Asia), none of them is operated primarily for space safety applications[1]. Observation time and efforts always have to be shared with other usages of the ground stations. Observations are done on a best-effort basis, and it is difficult for data users to anticipate the amount of data they will receive upon an observation request.

Two initiatives to improve the situation, and to bring laser ranging closer to an operational use in the space safety domain, are presented in this paper. The CLRDE (Commercial Laser Ranging Data Exchange) is a web platform that facilitates the exchange of data between data users and data providers (see section 2). In terms of hardware, the ESA Laser Ranging Station Izaña at Tenerife has been upgraded to enable space debris laser ranging, to develop and test techniques to improve data yield, usability and response time (see sections 3 and 4). Section 5 presents a short outlook of planned activities in these projects.

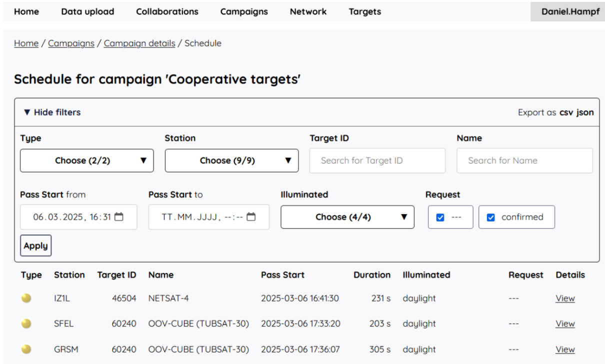

Figure 1. Screenshot of the CLRDE web platform, displaying an example of the automatically generated schedule for one configured campaign.

2. COMMERCIAL LASER RANGING DATA EXCHANGE

While the ILRS (International Laser Ranging Service) offers a system to request observations from laser ranging stations, and distribute the resulting data, it is not compatible with the requirements of space safety applications. Adding a satellite to the ILRS tracking lists can take several months, requires manual review by the ILRS Governing Board, and will only be granted to missions of scientific interest. Parties interested in acquiring laser ranging for commercial or operational use cases have to approach ground station operators individually, negotiating data formats, interfaces, workflows, data exchange methods and other details.

To fill this gap, the Commercial Laser Ranging Data Exchange (CLRDE) project was launched, co-funded under the European Space Agency's (ESA) Space Safety Programme. The goal of this initiative is to provide a central platform that facilitates the exchange of laser ranging data between ground stations and users such as satellite operators and Space Situational Awareness (SSA) service providers. CLRDE represents a paradigm shift from purely experimental applications to an operational "Laser Ranging as a Service" (LRaaS) model. It is noted that similar goals are pursued with "Debris Laser Tracking Network" [6], which is currently developed by GMV.

The technical infrastructure of CLRDE is based on a modern web-based platform with various interfaces for flexible data utilization. In addition to a graphical user interface for interactive operation, a RESTful API is available for automated requests, as well as an SFTP interface for direct file uploads. The platform enables the management of observation campaigns, planning of measurement tasks, and assignment of specific observation targets. The collected data is provided in the standardized CRD (Consolidated Ranging Data [7]) format and can be

[1] The stations built and operated by EOS in Australia are a notable exception. However, the data seems to be used mainly internally, and the state of the operations is not obvious.

directly integrated into existing SSA systems.

A key aspect of CLRDE is the provision of laser ranging data as a commercial service. Users can access high-precision measurement data as needed without having to operate costly infrastructure themselves. This opens up new possibilities for satellite operators in terms of precise orbit monitoring and collision avoidance. Observation requests can be scheduled both long-term and on short notice for specific passes.

CLRDE also offers new opportunities for operators of laser ranging stations to use their existing capacity more efficiently. Until now, these stations have been primarily utilized for scientific or government-funded projects. By integrating into the CLRDE network, they can now deploy their measurement capacities more flexibly. In the long term, the existence of a working market place for laser ranging data may incentivise the construction of new laser ranging ground station, dedicated to a commercial provision of LRaaS.

Since the beginning of 2025, the CLRDE platform is online[2] and available for testing by any interested party. Currently, it is used in small scale operation for two research projects which involve collecting and distributing laser ranging data from European laser ranging stations to various data users.

3. UPGRADE OF IZAÑA LASER RANGING STATION

The ESA station Izaña (IZN-1 or IZ1L) is located at the Observatorio de Teide on the Spanish island of Tenerife. It is a multi-purpose optical ground station for satellite observation, position measurements and communication. The telescope carries the SLR package for ranging to cooperative targets equipped with retro reflectors. Currently, on the two Nasmyth foci the laser ranging detector package and the laser communication terminal are installed. Additionally on one of the two optical ports a space debris observation camera is installed for passive optical space debris observations.

As part of the upgrade of the IZN-1, the functionality of the system has been extended with a very compact space debris laser ranging transmitter for ranging to non-cooperative targets during night and day time. The space debris laser system has been installed in a separate slit dome of about 2 m in diameter with a cylindrical base (IZN-2), on a compact Alt-Azimuth direct-drive mount. This so called bistatic configuration uses two mounts for the laser ranging measurements synchronized such that both are tracking the same target. The laser pulses are emitted from the newly installed transmitter system (Tx), and the returns are received by the existing main telescope (Rx) with its unmodified laser ranging detector package. Such a system can be installed adjacent to any

[2]https://clrde.digos.eu

Figure 2. ESA laser ranging Izaña at Tenerife. The larger structure on the left is IZN-1, the full conventional SLR system. The smaller dome on the right (IZN-2) houses the high-power laser transmitter for space debris.

SLR station, enabling it to perform Space Debris Laser Ranging (SDLR) without modifying the main SLR system. The space debris laser ranging station concept is based on capable off-the-shelf hardware to the widest extent possible.

The main components of the space debris laser ranging subsystem are the pulsed laser source for laser ranging to non-cooperative targets, the transmitting refractor telescope and a optical guiding system consisting of a wide-field reflecting telescope, a CMOS camera and filters for daylight operation. The space debris laser package, the telescope and the guiding system are mounted on a rigid plate which is fixed on the mount. The primary wavelength of a high-power Nd:Yag (1064 nm) is used for ranging. The repetition rate is 200 Hz, the pulse energy 200 mJ (equivalent to an average power of 40 W) and a pulse width of 7 ns. The exit aperture of the transmitting telescope has a diameter of 20 cm, the laser beam diameter when exiting the front lens of the transmitting telescope has a diameter of 14 cm.

Since available space debris predictions are often rather inaccurate, a visual guiding system for Tx and Rx is mandatory for successful ranging. Due to backscatter effects of the outgoing laser beam and achromatic aberration effects (the optical design is only optimised for a wavelength of 1064 nm) the transmitter telescope cannot be used as guiding telescope in many cases. The requirements for the additionally installed guiding telescope are diverse, which is why a compromise had to be made in the choice of the hardware. On the one hand, the visualisation of targets with larger angular offsets (e.g. in case of re-entry scenarios) should be possible, on the other hand the guiding system should also visualise space debris targets in day light conditions. The choice was a 20 cm f/2.4 reflecting telescope in combination with a camera using a backside illuminated CMOS sensor with a sensor size of $36 \times 24\,\mathrm{mm}^2$ and a pixel size of 3.76 µm. The resulting FOV is 4.3° x 2.9° and a pixel scale of 1.6”/pixel. First tests show that targets down to a magnitude of 5.5 can be visualised during day light (elevation of the sun $> 10°$), if additional long pass filters are used for reducing the sky background. This value corresponds to a spherical target with a diameter of 1 m in a distance of 600 km, assuming an albedo of 0.2.

For the Rx telescope the camera installed in the laser detection package can be used for guiding purposes. Since the FOV is very small (0.3°) compared to that on IZN-2, relatively accurate predictions are required for the target to be visible in the FOV. However, this system offers the advantage of higher sensitivity during the day (approx. 1 mag). To ensure that the object is within the FOV of the Rx guiding camera, a time bias correction is calculated by the Tx guiding system and sent to the Rx telescope. Afterwards both guiding systems apply independently additional pointing corrections to keep the laser beam on the target (Tx) as well as in the FOV of the receiving SPAD (Rx) with a FOV of 20" (full angle).

To increase the amount of data that can be generated per month, the software has been upgraded with improved assistance systems, with the final goal of enabling autonomous operation without operator control. This will be a major step towards a highly productive system, as it increases the potential operating time significantly, independent of staff availability. As an intermediate step, the system has been operated for the last several months in a supervised-automation mode. The software is operating the system fully automatically, including target selection by a priority-based scheduler, while the operator intervenes only occasionally in case of error or problems. Tests and improvements are on-going to improve the reliability and efficiency of the automation systems.

The detector package at IZN-1 has been upgraded with an additional single-photon detector to enable high temporal resolution light curve recording simultaneously with the ranging measurements. Light curves (LC) is a common method to extract physical and dynamical characters of various targets. The application of LC on satellites or space debris is to collect the solar radiation reflected by the surface of the object, and LC shows the brightness variation of an object over a period of time. The signal density is firmly connected to the geometry relations between observer, object and sun, cross-section and the reflectivity of object.

A station protection function is already available for the existing IZN-1 station and has been extended to IZN-2 for protecting the space debris station as well. The laser safety functionality ensures that persons inside and outside the station as well as airplanes and other "flying objects" in the local airspace are not exposed to hazardous laser light emitted by the system. In addition to the existing ADS-B (Automatic Dependent Surveillance - Broadcast) receiver a thermal infrared camera has been integrated to improve detection of objects without ADS-B. As the area above the observatory is a prohibited airspace, warnings for aircraft approximations are extremely rare.

The completion of the hardware installation has been achieved towards the end of 2024. Extensive observations campaigns started in January 2025, with the goal to verify the system performance. The current manual operation for SDLR is to be gradually converted to hands-off automated operation.

4. OPERATIONAL SPACE DEBRIS LASER RANGING

During tests campaigns in the first quarter of 2025, over fifty passes of non-cooperative space debris targets have been tracked with the IZN-2 system. The tests have shown that the system can be operated continuously for several hours, and obtain returns signals from non-cooperative objects with a high chance of success. Within a single day (2025-02-28, 11:00 until 22:00 hours local time) over 20 passes of non-cooperative targets have been recorded. Several of the passes have been recorded during daylight, up to a sun elevation of 40°. Daylight space debris ranging, first shown by [11], is considered a major milestone towards more productivity, as it significantly increases the time during which observations can be made.

Tracking was based on public TLE data, and used the camera system for visual correction of the tracking. The tests have focused on rocket bodies and defunct satellites with a radar cross section[3] between 0.05 m^2 (Calsphere 4A (NORAD ID 1520)) and about 20 m^2 (Envisat (27386) and Adeos (24277)). The maximum distance at which an object was tracked was about 3800 km.

The maximum return rate achieved in the successful passes varies from about 2 Hz to 170 Hz, which corresponds to a return ratio of 1% to 85%. Low return rates are typically seen in small and more distant objects; conversely, higher return rates are seen in larger and less distant targets. According to the radar link equation formulated by [9] and [10], the expected return rate is proportional to the object's cross section, and inversely proportional to the fourth power of the distance R. As the optical cross section is not widely known for most targets, typically the radar cross section (RCS) is used as an approximation. Thus, the achieved return rates are shown in Figure 3 as a function of RCS / R^4.

The lowest return rates are seen for targets Calsphere 4A (1520) at 1500 km distance (a white sphere of 36 cm diameter), and CZ-3C R/B (38954) at a distance of 2955 km (a rocket body of 18 m^2 RCS). The highest return rates are seen by some Ariane and Long March (CZ) rocket bodies, at distances of 700 km to 900 km. While a general trend is visible, it is notable that some objects with a large RCS and small distance nevertheless exhibit a very low return rate. Reasons for this may be poor tracking, but also unfavourable orientations of the object, a low reflectivity of the surfaces, or a strong specular component of the reflection, which deflects the return photons to other directions than the ground station.

[3] All radar cross sections of this section have been extracted from [8]

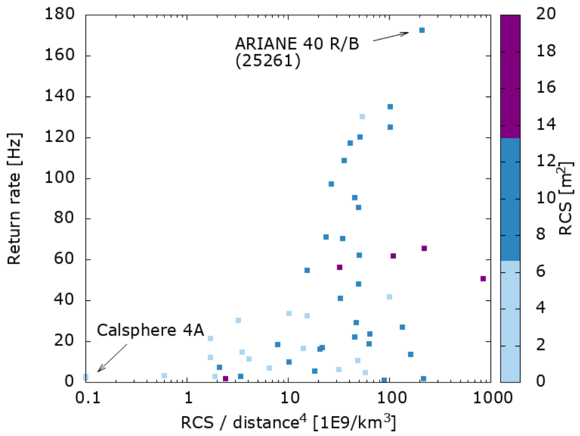

Figure 3. Maximum return rate versus size / distance factor, as explained in the text. The radar cross section of the target is given in colour code. In total, 55 passes are included in the graph.

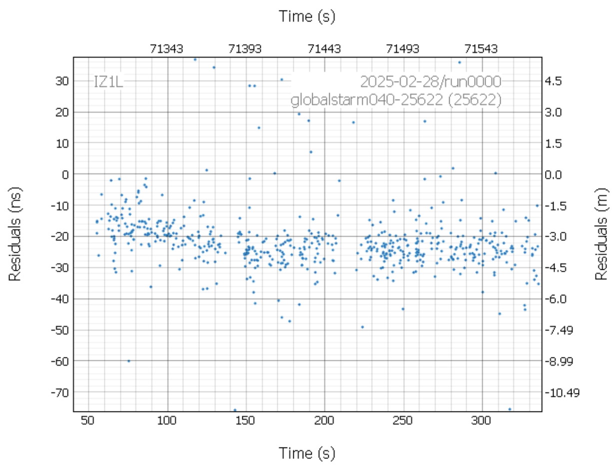

Figure 4. Ranging plot of Globalstar M040 satellite (NORAD ID: 25622), which has a radar cross section of 2.2 m^2 *and an orbital altitude of about* 1400 km.

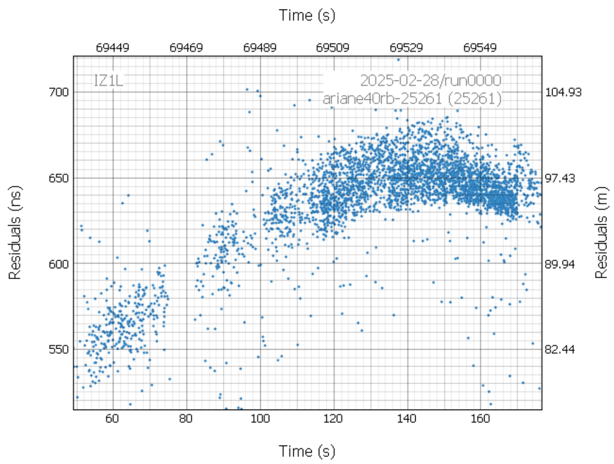

Figure 5. Ranging plot of an Ariane 40 rocket body (NORAD ID: 25261), which has a radar cross section of 12.2 m^2 *and an orbital altitude of about* 770 km.

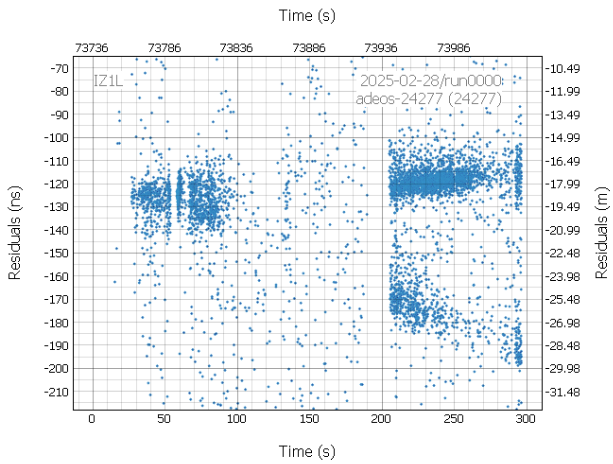

Figure 6. Ranging plot of Midori / Adeos (NORAD ID: 24277), a former ILRS target. Towards the end of the pass, two reflecting surfaces can be distinguished clearly.

Figure 4 shows the plot of Globalstar M040 satellite (NORAD ID: 25622), one of the faintest objects tracked so far. Its radar cross section is listed as 2.2 m^2. About 600 returns have been recorded in about 4 minutes, corresponding to a 2.5 Hz return rate, or 1.2% return quota.

Figure 5 shows ranging to an Ariane 40 rocket body (25261) with a radar cross section of 12.2 m^2. With about 11,000 returns in about 2 minutes, it is one of the stronger targets tracked (average return rate: 90 Hz; peak return rate 172 Hz). The line has a thickness of about 20 ns, corresponding to about 6 metres. Comparing to the plot of Figure 4, which has a width of only 5 ns, this is a clear indication of a target signature: Different photons of the laser pulses are reflected on different surfaces of the object, which are up to 6 metres apart from each other in the line of sight.

Figure 6 shows ranging plot of Midori / Adeos (24277), with a radar cross section of 22 m^2. It also carries a single hollow cube retroreflector with an effective diameter of 50 cm. Since the satellite is out of control since June 1997 ([12]), it can be assumed that the object may tumble and the retroreflector will, in general, not always be visible from the ground. Towards the end of the measurement, a signature of two reflecting surfaces appears, which move apart from each other and reach a distance of over 10 m. A clear interpretation of this is not yet available, and it cannot be said if one of the two traces is produced by the retroreflector. Given the size of the bus of 4 x 4 x 5 metres, the large separation can best be explained with a reflection on parts of the solar module, which has a length of 13 m [12]. Similar signatures of object size and shape in SDLR data have been seen by [13].

Figure 7 shows the corresponding light curve, recorded simultaneously by the new SPAD light curve detector. It exhibits an irregular behavior, which cannot be connected in a trivial way to a rotation. A broad peak can be seen at around 73930 seconds, indicating the reflection of sun-light by a larger area. The very short peak at 73789

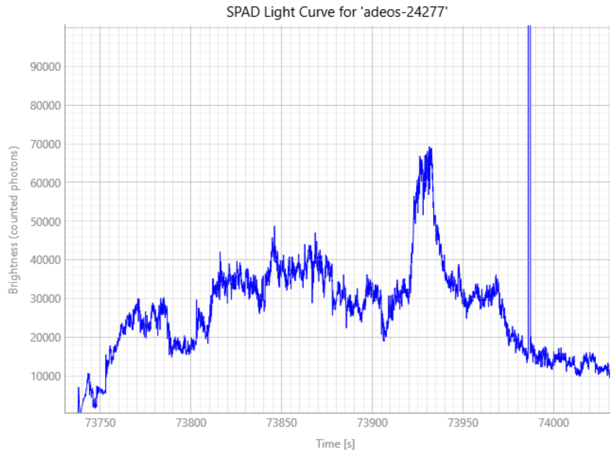

Figure 7. Lightcurve recorded during the same pass shown in Figure 6.

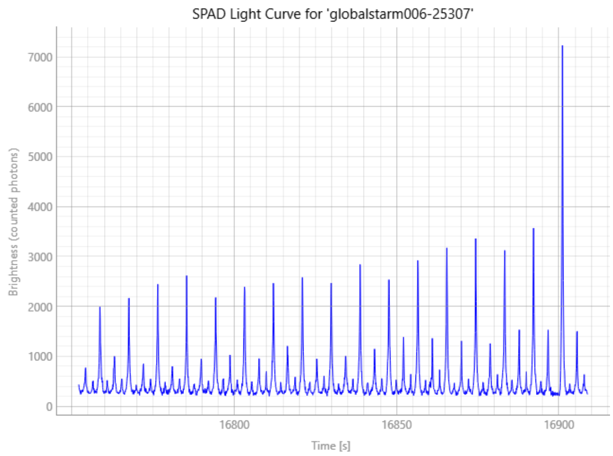

Figure 8. Lightcurve recorded of satellite Globalstar M006 (NORAD ID: 25307) on 2025-02-25. A regular pattern is clearly visible, indicating a fast and stable rotation.

seconds lasts for about one second and reaches a brightness almost a hundred times larger than the baseline at this point (intentionally cropped in the figure). It can best be explained with a specular reflection of sunlight by a large, even surface, potentially the solar module. A more sophisticated analysis can be achieved by taking the sun-object-observer geometry into account during the pass, and by simulating the situation with a ray-tracing software. Studies along these lines are planned as part of the makerspace actvitiy (see section 5).

As a last example, a light curve of Globalstar M006 (NORAD ID: 25307) is shown in Figure 8. It exhibits a regular pattern with a four peak structure: large, small, medium, small. It may be assumed that these four peaks correspond to four sides of different sizes and reflectivity (albedo). Using an auto-correlation function, the period is determined to (8.8 ± 0.1) s.

5. OUTLOOK AND FURTHER ACTIVITIES

To further advance space debris laser ranging into a technology that can be used operationally for space safety applications, the two approaches described in this paper are pursued further:

The CLRDE website will be improved further with feedback from the community. Test operation will be extended to more potential customers and data providers, to evaluate interfaces, functions, and documentation. As part of this, integration into EU-SST will also be investigated. Furthermore, it will be attempted to estimate the potential market value of certain amounts of laser ranging data, in order to understand the economic viability of constructing and operating laser ranging stations dedicated only to operation space safety applications.

The upgraded Izaña laser ranging system will be used within different on-going projects to test out new techniques and applications. As part of a "makerspace" activity, the data will be used by various cooperation partners for AI-driven conjunction warning analysis, attitude determination and shape reconstruction, and improved orbit predictions. One particular area of interest is the combination of simultaneous laser ranging and light curve data. This "makerspace" actvity is on-going, and new requests for cooperation are welcome.

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