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Laser measurements to space debris from Graz SLR station

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Abstract

In order to test laser ranging possibilities to space debris objects, the Satellite Laser Ranging (SLR) Station Graz installed a frequency doubled Nd:YAG pulse laser with a 1 kHz repetition rate, a pulse width of 10 ns, and a pulse energy of 25 mJ at 532 nm (on loan from German Aerospace Center Stuttgart – DLR). We developed and built low-noise single-photon detection units to enable laser ranging to targets with inaccurate orbit predictions, and adapted our standard SLR software to include a few hundred space debris targets. With this configuration, we successfully tracked – within 13 early-evening sessions of each about 1.5 h – 85 passes of 43 different space debris targets, in distances between 600 km and up to more than 2500 km, with radar cross sections from >15 m^2 down to <0.3 m^2, and measured their distances with an average precision of about 0.7 m RMS.

Keywords: Laser ranging; Space debris

1. Introduction

Space debris is created by rocket bodies, upper stage engines, decommissioned satellites, and fragmentation due to break-ups, collisions, explosions of non-empty tanks etc. The number of space debris objects is increasing rapidly, and could reach – in the most populated LEO orbits between 800 km and 1200 km – within a few years a run-away point, called *Kessler Syndrome* (Kessler and Cour-Palais, 1978): Due to increasing debris population, the collision probability increases to a level at which more debris is created – due to collisions – than is removed due to atmospheric drag and following re-entry of LEO debris. This scenario is predicted even for the very unlikely case that all future launches are stopped.

This poses increasing hazards to manned and unmanned space flights and space operations: There have been already several collisions in space, some of them with minor consequences (Jason-1, March 2002 (NASA: Orbital Debris Quarterly News (2011))), some of them catastrophic (Iridium33 collision with Cosmos 2251 in 2009), and some of them even intentionally: China destroyed its own, aging Fengyun-1C weather satellite via an anti-satellite test, increasing the total radar traceable amount of debris objects by 22%.

The estimated number of space debris objects – down to a size of about 1 cm – is in the order of >600.000. While particles smaller than about 1 cm could be handled by proper shielding of spacecrafts, collisions with larger objects are most likely catastrophic due to the high kinetic energy involved at speeds above 8 km/s, and have to be

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avoided by proper manoeuvres – which are costly in terms of available propellant. Space debris has caused already 12 collision avoidance manoeuvres of the ISS since October 1999 (Orbital Debris Quarterly News).

2. Space debris orbit predictions

Space debris orbits are determined by tracking at least the larger objects (about 22.000) with rather big radar stations (U.S. Space Surveillance Network, 2012; ESA: Meteoroid, 2012), TIRA (Tracking and Imaging RAdar) near Bonn (Fraunhofer Institute), or by passive optical tracking with telescopes (Shell, 2010; Milani et al., 2011).

The main problem is the relatively low accuracy of these methods (up to some 100 m for small objects). Improving the predicted orbit accuracy is necessary to avoid unnecessary anti-collision manoeuvres, or even to remove space debris by laser ablation (Schall, 1991; Phipps et al., 2012).

An evolving method to improve space debris orbit predictions uses strong laser pulses to measure the distance to the objects; the few results reported up to now used kW lasers (Greene et al., 2002) or more recently a 2 J/20 Hz laser (Zhang et al., 2012).

At SLR Graz, for the first time a laser with kHz repetition rate, with relatively low energy per pulse (25 mJ) and relatively low power (25 W) was used to measure distances to space debris objects.

3. SLR graz setup for space debris measurements

With our standard SLR laser in Graz (532 nm, 10 ps pulse width, 0.4 mJ/pulse and 2 kHz repetition rate – which gives a power of 0.8 W) it is not possible to range to debris objects: Calculated return rates are too low to identify any results. This was confirmed by several internal tests and experiments. Therefore, a cooperation was initiated from German Aerospace Center (DLR: Deutsches Zentrum für Luft- und Raumfahrt) Stuttgart, where the Institute of Technical Physics had started calculations of expected return rates from laser ranging to space debris, and already had acquired a dedicated laser system for space debris laser ranging: 532 nm, 25 mJ/pulse, 10 ns pulse width, 1 kHz repetition rate. This laser system was installed at Graz SLR station at the end of 2011, and integrated into the hardware and software of the station.

As single photon detector, we first tested our standard 200 μm diameter C-SPAD: Single Photon Avalanche Diode, Peltier-Cooled version (Kirchner et al., 1998; Gibbs and Wood, 2000). Although we got first returns from debris objects with this detector, its intrinsic high dark noise (>400 kHz @ kHz repetition rates) proved to be a big challenge: The weak orbit predictions require detector gating times of 50 μs and more, while the high dark noise allows for a few μs only. Another detector (Micro Photon Devices) was also tested successfully, but was more difficult to handle due to its relatively small size (100 μm diameter): Detector alignment (*all* incoming photons should impinge on the diode) becomes significantly more difficult, and telescope pointing and tracking accuracy is more difficult to handle.

To improve both operational constraints and the link budget, we designed and built several low-noise single photon detector units, optimized for space debris detection: We used the 500 μm diameter avalanche diode SAP 500 (Stipcevic et al., 2010), with <10 kHz dark noise, and a quantum efficiency of 50% at 532 nm. For these tests we used passive quenching of the diode. Using the standard radar link equation (Degnan, 1985; Zhang et al., 2012; Voelker et al., 2011), we calculated expected return rates of at least 4 photoelectrons per second for a 'standard' 3 m^2 target in 800 km distance.

We selected more than 200 debris objects in stable, near-circular orbits of 600 km altitude or higher (up to about 1500 km), and with Radar Cross Sections (RCS) from <0.1 m^2 to 15 m^2. Optical reflectivity – or albedo – of space debris objects is not easily available or accessible. However, in most cases it corresponds sufficiently well with microwave RCS values (Kessler and Jarvis, 2011). The RCS values have been obtained from Space-Track.Org; however, the values given there are not a constant, but indicate an actual value as a result during radar measurements. Because most objects are tumbling along their orbit, they show varying cross sections, and thus also varying albedo (Nakajima et al., 2006). For a few objects, RCS values – and/or at least the object dimensions – have been obtained also from the (ESA DISCOS Data Base, 2012).

SLR requires a priori information to track satellites. This is needed not only for accurate telescope pointing, but also to activate/gate the detector as short as possible (about 65 ns in Graz) before arrival of the reflected photons, to minimize the amount of 'noise detections'. The two line elements (TLE) used for space debris orbit predictions are essentially parameters for a Kepler orbit. Space debris TLEs are mostly derived from radar measurements. Since the accuracy of these measurements is not very high – with time biases up to ±1 s, and range biases up to ±1 km, this poses problems on our SLR station: Instead of our usual range gates of 200 ns to 400 ns, we need at least some tens of μs for space debris – at least during the initial search phase.

These problems also required some upgrade of our ranging software, to allow for automatic identification of possible returns out of high background noise in real time, with larger time bias and range bias values requiring large range gates, and larger measurement RMS of space debris targets, as compared to SLR satellites.

Due to these problems, we scheduled test sessions of about 1.5 h only during early evening, with the orbiting objects still in sun light, but with the Graz SLR station in darkness. This allowed us to visualize the objects with cameras in the main receiver telescope, to correct the telescope pointing for the relatively large time and range biases, and to adapt range gate positions and offsets accordingly.

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4. SLR graz space debris ranging: results, problems, solutions

Between Dec. 11th, 2011 and May 10th, 2012 we scheduled 13 such sessions, during which we successfully tracked 85 passes of 43 different space debris targets (Fig. 1 shows residuals of a typical pass), in distances between 600 km and up to more than 2500 km (Fig. 2), and with radar cross sections from >15 m^2 down to <0.3 m^2. Average precision was ≈0.7 m RMS. Up to 16 passes were tracked during a single evening session. In most passes, we collected several 1000 returns; average was about 5100 returns per pass. This compares fairly well with the predicted return rates of ≈4 photoelectrons/second.

The relatively strong laser with its 1-kHz repetition rate creates an inherent overlap problem between transmitted pulses and returning photons: At kHz repetition rates, there are always several pulses simultaneously in flight. If a return is expected at the same time when another laser pulse is transmitted, the high atmospheric backscatter of the transmitted pulse eliminates any chance to detect a single photon returning from the target: The detection system

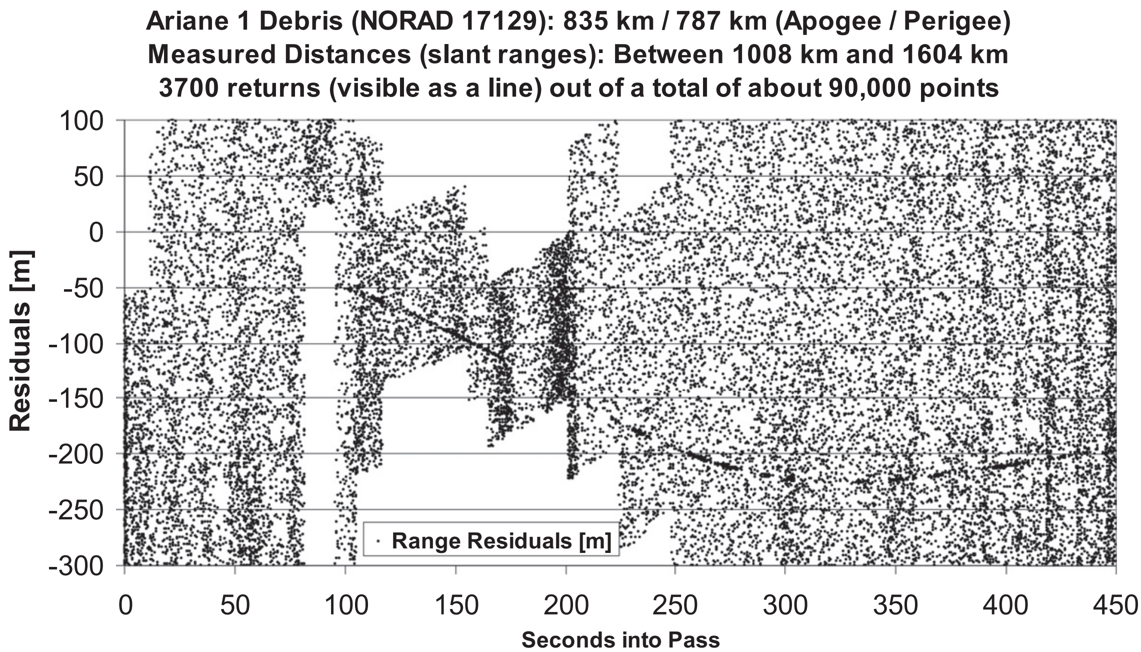

Fig. 1. A typical (*not* our best) space debris pass: Ariane 1D (NORAD 17129): about 3700 valid returns, at a mean distance 1650 km, starting/ending at low elevation (17°/19°). For clarity of the plot, only each 3rd point is plotted.

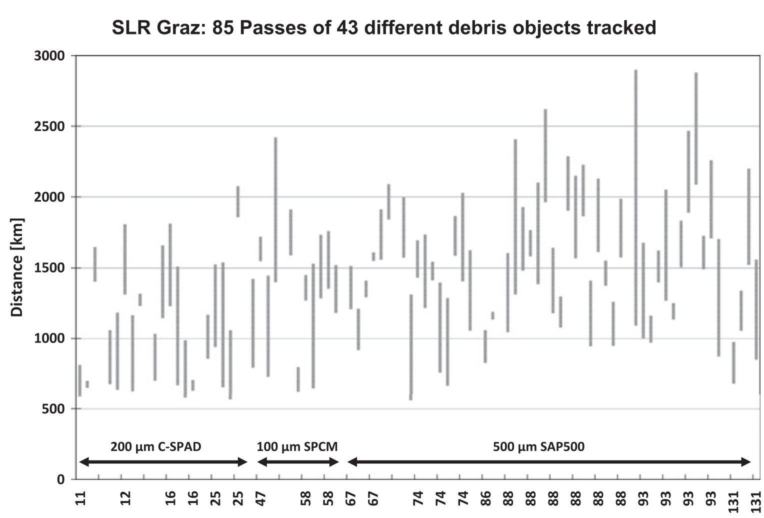

Fig. 2. Graz Debris Ranging Results: 85 successfully tracked passes, with objects in distances from 600 km up to more than 2500 km. Detectors with different diameters were used: 200 µm C-SPAD, 100 µm SPCM (Single Photon Counting Module, of Micro Photon Devices), 500 µm SAP500.

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is simply blinded. To avoid such overlaps, we used our overlap avoidance circuitry, which was already implemented in our SLR system: The exact laser firing times are slightly shifted back and forth to avoid such overlap situations at all. The average repetition rate however remains at the specified 1 kHz.

5. Conclusion, outlook, future plans

We successfully demonstrated laser ranging to space debris objects in distances between 600 km and more than 2500 km, using a 1 kHz repetition rate/25 mJ per pulse/10 ns pulse width/532 nm frequency doubled Nd:YAG laser. Average precision was about 0.7 m, basically independent of object size, as opposed to radar measurements. The radar cross section RCS of the targets was between 0.3 m^2 and 15 m^2. Using actually available TLE predictions, we were able to measure up to 16 passes per 1.5-h evening session.

As the only upgrade of our SLR station were the Laser, a low-noise detector, and some upgrade of our SLR software to include space debris objects, it seems to be relatively easy for *any other* SLR station to range to space debris objects. Due to operational limits of the SLR stations, this might not be a potential solution e.g. to establish and maintain a complete space debris catalogue, but it could be well suited for precise orbit determination of any object with predicted collision course within a few days: With accurate laser-determined orbits, it might help to avoid anti-collision manoeuvres, saving fuel and extending life times of active satellites.

As a next step, we are going to test bi-static and/or multi-static laser ranging: While Graz fires to a space debris object, other stations within a few hundred km distance from Graz will try to detect diffuse reflected ‘Graz’ photons, thus determining additional distances from target to SLR stations. This would allow – by simple geometry – an accurate 3D coordinate determination of the orbit, with consequently significantly improved accuracy.

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