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Multistatic Laser Ranging to Space Debris

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Abstract. *Using a strong laser (200 mJ @ 532 nm, 3 ns pulse length, 80 Hz) borrowed from DLR Stuttgart, the SLR station Graz tracked space debris targets up to distances of > 3000 km. Several cooperating SLR stations within Europe – synchronized to the Graz laser firing times - successfully detected and time-tagged also these Graz photons, diffusely reflected from the space debris targets. These quasi-simultaneously measured distances from several laser stations to the same orbital arc should allow for better and faster orbit determination using only few passes of such non-cooperative targets.*

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, Cour-Palais, 1978). This scenario is predicted even for the unlikely case that all future launches are stopped. This poses increasing hazards to manned and unmanned space flights and space operations. ENVISAT, one of the largest space debris objects will be in orbit for about 150 years until re-entry; and it will pass within 200 metres of 2 catalogued other objects every year. In case of a collision - given its mass, volume and shape - it might generate a cloud of debris large enough to populate the whole orbit, eventually making space operations difficult or even impossible, and possibly preventing access to space for future human generations (Space News, 23 July 2010).

2. Laser Ranging to Space Debris Targets to improve Orbit Predictions

Space debris orbits are determined by tracking at least the larger objects (> 22.000) with big radar stations (U.S. Space Surveillance Network), TIRA (**T**racking and **I**maging **RA**dar) near Bonn, or passive optical tracking with telescopes (Shell, 2010; Milani et al, 2011).

Main problem is the relatively low accuracy of predictions determined with these methods (1 km or more for small objects). Improving this is necessary to avoid unnecessary anti-collision manoeuvres, or even to remove space debris by laser ablation (Phipps et al, 2012).

An evolving method uses strong laser pulses to measure the distance to the objects; the 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), or a 2 J / 10 Hz laser at the lunar laser ranging station in Grasse / France (Courde et al, 2012). Adding laser ranging data of only few passes (usually 2 passes) to the standard TLE (Two Line Elements) predictions, significantly improves prediction accuracy (Bennet et al, 2013)

At SLR Graz, initially a diode-pumped 25 W laser with 1 kHz repetition rate, with relatively low energy per pulse (25 mJ), and 10 ns pulse width was used to measure distances to space debris objects (Kirchner et al, 2012). This laser has been replaced in 2013 by a flash lamp pumped laser with 99.9 Hz maximum repetition rate, and 200 mJ per pulse (3 ns pulse width) at 532 nm. With both lasers, we tested the feasibility of bistatic and multistatic laser ranging to space debris targets.

3. MultiStatic Space Debris Laser Ranging: Setup

Details about problems arising from - and solutions applied for - successful laser ranging to debris objects from Graz SLR have been published earlier (Kirchner et al, 2012); the necessary adaption cover both hardware (laser, a new 500 µm diameter single photon detection package using an SAP500 diode (Stipcevic et al, 2010)) and software (pointing, target acquisition with low accuracy predictions, real-time return identification in noisy conditions and others).

Fig.1: Graz fired to debris targets flying over Middle Europe, the diffusely reflected photons were detected in all 4 stations (Graz; Zimmerwald: 600 km; Wettzell: 400 km; Herstmonceux: 1200 km)

Mainly due to low accuracy predictions, we scheduled test sessions of about 2 hours only during early evening, with the orbiting objects still in sun light, but with Graz and the participating SLR stations 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. Including other SLR stations for multistatic laser ranging reduces these short available time slots again, because e.g. in stations west of Graz the sun set occurs later (up to almost half an hour for Zimmerwald., and up to a full hour for Herstmonceux)

The Graz photons are diffusely reflected from the body of space debris targets. These photons should be detectable from other stations within some distance around Graz. As possible candidates for such multistatic ranging the SLR stations of Zimmerwald (Swiss; 600 km), Wettzell (Germany, 400 km), and Herstmonceux (England, 1200 km) were identified (fig. 1), and agreed to adapt their tracking and ranging programs and procedures accordingly.

To be able to gate their single photon detectors, these stations have to be synchronized to the Graz laser firing times, down to at least a few hundred nanoseconds. To achieve this, Graz SLR fired the strong debris laser at fixed epoch times, known in advance to all participating stations. These firing epochs start with a fixed offset (285.050 µs) from the 1 pps, and are repeated within each full one-second frame.

First tests revealed that the DLR laser – specified for 100 Hz max repetition rate – only could fire with 99.9 Hz; therefore we selected a repetition rate of exactly 80 Hz, allowing repeatable firing epochs within each one–second frame.

All participating stations – including Graz - had to disable their internal overlap avoidance procedures, because these apply delays in their firing times, or slightly change their repetition rates, to avoid overlaps between transmitted laser pulses and arriving photons of earlier shots.

4. MultiStatic Space Debris Laser Ranging: First Results

In March 2012, the Swiss SLR station in Zimmerwald for the first time detected Graz photons, emitted from the 1 kHz / 25 mJ / 10 ns laser in Graz, and diffusely reflected from the body of the satellite ENVISAT (fig. 2). This satellite was selected for first tests because of well known orbit – due to routine SLR by ILRS stations – and because of its large Radar Cross Section (RCS; ≈ 19 m^2).

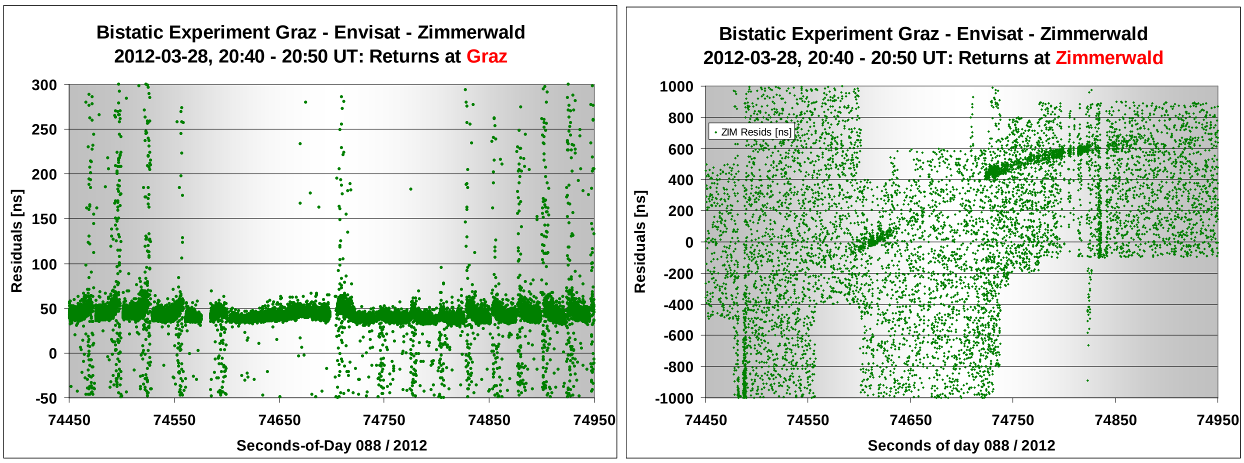

Fig. 2: First success: Graz fired to ENVISAT, and received strong echoes from its retro-reflectors (left); Zimmerwald received Graz photons, diffusely reflected from the satellite body (right)

In this pass, Graz ranged to the retro-reflectors of ENVISAT (fig. 2, left) with the strong debris laser (1 kHz, 25 mJ) and without applying any overlap avoidance procedures. Strong backscatter within repeating overlap periods was overloading heavily the detector (C-SPAD), resulting in the observed variations in data density. Zimmerwald was operating in its standard 100-Hz-mode;even disregarding 90% of the Graz shots, about 1500 returns out of 9500 events were recorded, with an RMS of 2.6 m – mainly due to the large satellite body. The average return rate – within the slots of success – was about 5% (fig 2, right).

In 2013, these tests were continued with the 100 Hz / 200 mJ / 3 ns flash lamp pumped laser of DLR Stuttgart; in addition, the SLR stations in Wettzell / Germany and Herstmonceux / England also adapted their software accordingly and participated in these tests. In several bistatic sessions Wettzell tracked up 6 passes per session, detecting Graz photons (fig. 3); similar results were obtained with Zimmerwald. In one session, all 3 stations (Graz, Zimmerwald, Wettzell) successfully tracked ENVISAT (the satellite already was debris at this time) with Graz photons only.

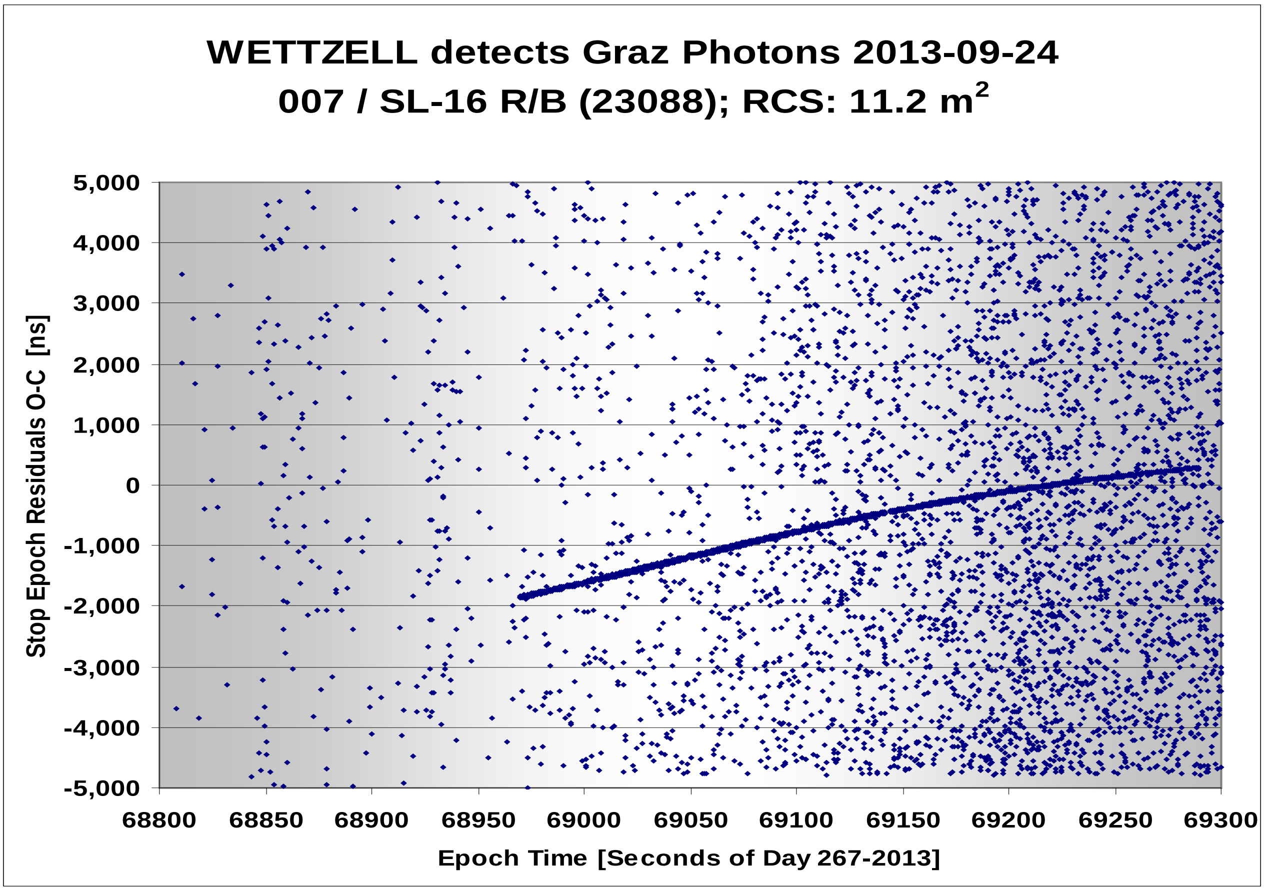

Fig. 3: Graz photons – diffusely reflected from an old rocket body (NORAD 23088) and detected at the SLR station Wettzell; shown are residuals, ZERO is the predicted time-of-flight (Graz – Target – Wettzell)

Towards the end of this test period, the SLR station Herstmonceux also joined the experiment; after a few technical test sessions, in the first operational session – with 80% clouds in Herstmonceux, and 30 % clouds in Graz – Graz photons reflected from NORAD 39014 (a rocket body with 7.7 m^2) were detected also at Herstmonceux.

5. Problems and Solutions

The biggest obstacle definitely was weather; considering a standard probability for laser ranging weather in middle Europe (as example: 50%), the probabilities will multiply when more stations are involved; with 4 stations involved, this can be estimated with 0.5^4 (about 6%), coinciding well with our session scheduling experiences. However, in the conclusion section some ideas for possible improvements are listed.

For convenience, only sessions at early evening were scheduled; possible sessions at very early morning times were omitted☺. The end of each session (for the transmitting station Graz) was dictated when most debris targets had entered the Earth shadow. Due to the low accuracy of the TLE predictions, after that time it was not possible anymore to reliably hit the invisible target; and due to the lack of retro-reflectors, there is no real feedback.

The situation is a bit better during summer months with shorter nights in Graz, when such targets might be continuously in sun shine for 4 hours or more, which allows to track 2 or 3 passes of one target in one night. As demonstrated by (Bennet et al, 2013), tracking at least 2 passes of the same target within 24 hours allows more precise orbit predictions (10 to 20 arc seconds) for the next 24 to 48 hours.

The accuracy of multistatic laser ranging itself is affected by several contributors, which are much smaller – or do not exist at all - in standard SLR:

- Target size: While standard SLR operates to well defined retro-reflectors, achieving an accuracy of a few millimetres, space debris targets can have dimensions of several meters; photons can be reflected from any surface, resulting in up to several meters uncertainty;
- Laser pulse length: 10 to 100 picoseconds for standard SLR, but several nanoseconds for space debris ranging; due to mainly single-photon ranging, this adds to the overall RMS;
- Differences in time scales at different stations: Below 100 nanoseconds, and usually within a few tens of nanoseconds. For SLR, this is no problem, because this is needed for epoch times only; and satellites move less than 1 mm within 100 nanoseconds. For multistatic laser ranging, time scale differences directly affect the distance measurement: 10 nanoseconds translate into 1.5 m distance bias;

The first two contributors are also valid for debris laser ranging at a single station; in such a setup, we have measured an average RMS of 820 mm, with a minimum RMS of 155 mm, and a maximum RMS of more than 4 meters (ENVISAT, the largest target).
Different meteorological data sets at the participating stations must be included in the calculations.

5. Conclusion. Outlook, future plans

Synchronizing the SLR stations of Zimmerwald (Swiss; 600 km), Wettzell (Germany; 400 km) and Herstmonceux (England; 1200 km) to the Graz laser firing times, all participating stations could detect Graz photons, diffusely reflected from rocket bodies. The Graz laser fired 532 nm pulses with 80 Hz, 200 mJ/shot and 3 ns width per pulse.

Using quasi-simultaneous laser ranging to space debris targets should allow for more accurate orbit determination (10-20 arc seconds for the next 24 or 48 hours) in significantly shorter time (24 hours) needing less passes (e.g. 2).

The 4 SLR stations involved in the experiment – including Graz - are located in 4 different weather zones; this reduces heavily the probability for acceptable laser ranging weather at all sites. As a consequence, only during 1 out of 9 sessions we got triple ranges (Graz, Zimmerwald AND Wettzell). Weather simply was the main limitation for successful multistatic sessions.

There are several possible ways to improve this limitation:

- More participating *passiv*e stations (i.e. receive-only); Potsdam, Borowiec, Riga, Grasse and Matera have already expressed their interest;
- More participating *active* stations (transmitting strong pulses): More limited here, because more expansive add-ons are necessary (strong laser);
- Adding a few receive-only stations within e.g. 200 km of a transmitting station:
  - o It is more likely to have consistent weather conditions within shorter distances;
  - o These stations could be much cheaper than a complete SLR station (no laser, no Coudé); remote-controlled / automatic; no costs for operators; no laser / aircraft problems etc.

Future plans include tests with at least 3 or 4 stations simultaneously – supposing that more European SLR stations will be available -, and to verify orbit prediction accuracy using the resulting data of only 1 or 2 passes for a specific target. In addition, we intend to look for photons of other stations, diffusely reflected from standard ILRS satellites, during standard ranging from Graz SLR; the data will be used again to check possible improvements for POD, using only sparse data sets.

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