SPACE DEBRIS LASER RANGING AT GRAZ

Georg Kirchner(1), Franz Koidl(2), Daniel Kucharski(3), Martin Ploner(4), Wolfgang Riede(5), Uwe Voelker(6), Ivo Buske(7), Fabian Friederich(8), Oliver Baur(9), Sandro Krauss(10), Harald Wirnsberger(11)

(1)Austrian Academy of Sciences, Lustbuehelstrasse 46, A-8042 Graz, Austria; Email: Georg.Kirchner@oeaw.ac.at
(2)Austrian Academy of Sciences, Lustbuehelstrasse 46, A-8042 Graz, Austria; Email: Franz.Koidl@oeaw.ac.at
(3)Korea Astronomy and Space Science Institute, Space Science Division,776, Daedeok-Daero, Yuseong-Gu, Daejeon, 305-348, South Korea; e-mail: daniel@drdk.org, daniel@kasi.re.kr
(4)University Bern, Sidlerstrasse 5, CH-3012 Bern; Email: Martin.Ploner@aiub.unibe.ch
(5)German Aerospace Center, Pfaffenwaldring 38-40, D-70569 Stuttgart; Email: Wolfgang.Riede@dlr.de
(6)German Aerospace Center, Pfaffenwaldring 38-40, D-70569 Stuttgart; Email: Uwe.Voelker@dlr.de
(7)German Aerospace Center, Pfaffenwaldring 38-40, D-70569 Stuttgart; Email: Ivo.Buske@dlr.de
(8)German Aerospace Center, Pfaffenwaldring 38-40, D-70569 Stuttgart; Email: Fabian.Friederich@dlr.de
(9)Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria; Email: Oliver.Baur@oeaw.ac.at
(10)Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria; Email: Sandro.Krauss@oeaw.ac.at
(11)Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria; Email: Harald.Wirnsberger@oeaw.ac.at

ABSTRACT

The Graz Satellite Laser Ranging (SLR) station usually measures distances to retro-reflector equipped satellites with an accuracy of few millimetres, using short laser pulses with 10 ps pulse width, a low energy of 400 µJ, and a repetition rate of 2 kHz. To test laser ranging possibilities to space debris, we installed two stronger lasers (a diode-pumped 25 mJ / 1 kHz / 10 ns / 532 nm laser, exchanged later to a flash lamp pumped 150 mJ / 100 Hz / 3 ns / 532 nm laser) – both on loan from DLR / German Aerospace Centre Stuttgart –, and built low-noise single-photon detection units. With this configuration, we successfully tracked ≈100 passes of almost 50 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 accuracy of 0.7 m (10 ns laser) resp. ≈ 0.5 m (3 ns laser) RMS.

The resulting data will be used to calculate improved orbits of the tracked debris objects, and to compare them with radar-based TLE (two-line element) orbits. As demonstration experiment, here we provide findings for ENVISAT normal point analysis. As a next step, we plan to additionally taking pointing information into account. Potentially, the joint analysis of both ranges and orientation angles further improves space debris orbit accuracy. Orbit determination and prediction was done with the GEODYN software package.

In addition, we successfully tested a 'bi-static' mode: Graz fired laser pulses to ENVISAT; while Graz detected photons reflected from the retro-reflector, the Swiss SLR station Zimmerwald detected the photons diffusely reflected from the satellite body.

1 INTRODUCTION

With our standard laser in Graz – 532 nm, 10 ps pulse width, 400 µJ per pulse, 2 kHz repetition rate – we are ranging routinely to retro-reflector equipped satellites to distances of almost 40 000 km, and with an accuracy of 2 – 3 mm. However, with its low power of 0.8 W it is NOT possible to range to uncooperative – i.e. without retros - debris objects. Therefore, a cooperation was initiated with the German Aerospace Centre (DLR) 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, diode pumped laser system for space debris laser ranging: 532 nm, 25 mJ / pulse, 10 ns pulse width, 1 kHz repetition rate. This laser system was integrated into the hardware and software of Graz SLR station at the end of 2011. In November 2012 it was replaced with a flash lamp pumped 200 mJ / pulse, 3 ns pulse width, 100 Hz laser, also from DLR Stuttgart.

2 DETECTION

As a single photon detector, we first used our standard 200 µm diameter C-SPAD (Single Photon Avalanche Diode, Peltier-Cooled version) [1, 2]. 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 gate times only. Another detector (Micro Photon Devices, [3]) 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) became significantly more difficult, and telescope pointing and tracking accuracy was more difficult to handle.

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

To improve both operational constraints and the link budget, we designed and built several low-noise single photon detector units, optimized for such space debris detection: We used a 500 µm diameter avalanche diode (SAP 500; [4]), 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 [5,6], we calculated expected return rates of at least 4 photoelectrons per second for a 'standard' 3 m^2 target in 800 km distance.

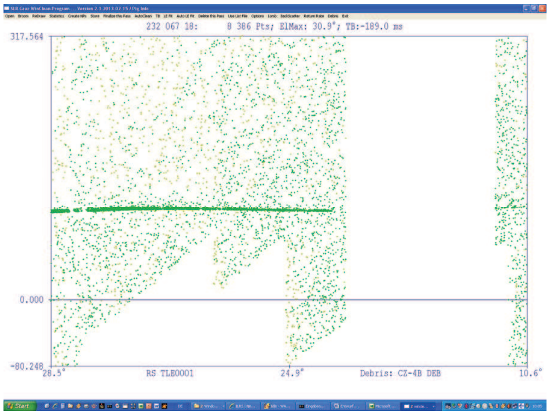

Figure 1: CZ-4B DEB (COSPAR 37182): 3700 valid returns (≈ solid line); 480 mm RMS; 1100-1900 km; RCS ≈ 5 m^2; Laser: 100 Hz / 200 mJ / 3 ns / 532 nm; 2013-03-08.

3 OPERATIONAL ISSUES

We selected about 300 debris objects in stable, near-circular orbits between 600 km altitude and 1500 km, and with Radar Cross Sections (RCS) from < 0.1 m^2 to 15 m^2. Optical reflectivity of space debris objects is not easily available or accessible. However, in most cases it corresponds sufficiently well with microwave RCS values [7]. The RCS values have been obtained from www.Space-Track.Org; however, the values given there are not a constant, but indicate an actual value: Because most objects are tumbling along their orbit, they show varying cross sections, and thus also varying albedo [8]. For a few objects, RCS values - and / or object dimensions – have been obtained also from the ESA DISCOS database.

SLR requires a priori information to track objects. 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 their accuracy is not very high, and measurements might have been taken only in long intervals, this may result in time biases of up to ±1 s, and range biases of up to ±1 km of the predicted orbit, which 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 hours 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 relatively large time and range biases, and to adapt range gate positions and offsets accordingly.

4 RESULTS, PROBLEMS, SOLUTIONS

Between December 2011 and March 2012 (10 ns laser) and in March 2013 (3 ns laser) we scheduled 16 such sessions, during which we successfully tracked almost 100 passes of about 50 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 for the 10 ns laser, and ≈ 0.5 m RMS for the 3 ns laser. 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 (10 ns / 1 kHz laser) resp. about 3200 returns per pass (3 ns / 100 Hz laser). This compares fairly well with the predicted return rates of ≈ 4 photoelectrons / second.

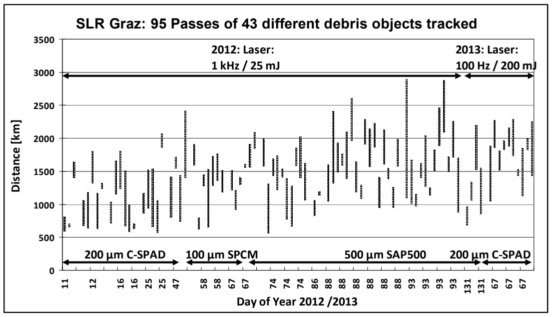

Figure 2: Summary of Graz Debris Laser Ranging; 2 different lasers, 3 different detection packages

The relatively strong lasers, together with their high repetition rates, create inherent overlap problems between transmitted pulses and returning photons: At higher 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 single photons returning from the target: The detection system 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 resp. 100 Hz.

5 BISTATIC RANGING

The photons of the Graz lasers are reflected diffusely from debris objects; thus they could be detected also by other stations within a few 100 km distance from Graz.

To test such scenarios, the Swiss SLR station in Zimmerwald was synchronized to the Graz SLR station: Knowing the exact firing times of the Graz laser in advance, they could calculate the expected arrival times of the Graz photons in Zimmerwald, and activate their detector accordingly. Using ENVISAT as a test target with its big RCS and its well known orbit, Graz photons could be detected in Zimmerwald, thus measuring the distances to the satellite from the 2 sites simultaneously.

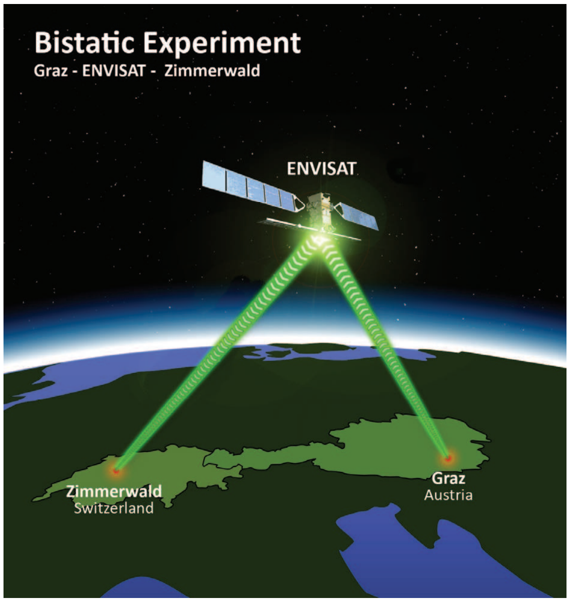

Figure 3: Bistatic laser ranging Graz – Zimmerwald; diffuse reflection of laser photons on ENVISAT (graphics: Astronomical Institute Bern)

Due to the diffuse reflection on the targets, it would be easy to extend this method to more stations: Because they only need a receive telescope and no laser, they would be relatively cheap. They could be autonomous, and remotely controlled. More such receive-only stations would also help to relax the weather problem significantly, while still resulting in a high probability for 3-D coordinate determination of the debris object, with consequently significantly improved accuracy.

6 TOWARDS INCREASED DEBRIS ORBIT PREDICTION ACCURACY

SLR tracking has the potential to considerably improve both orbit determination and orbit prediction of debris objects. In order to demonstrate this potential, we conducted a series of investigations based on ENVISAT data from the two-day period August 26-27, 2011. The estimated parameters include initial values, air drag coefficient, and 3D linear empirical accelerations. Against the background of a more realistic debris tracking scenario, we did not make use of any satellite macro model for non-gravitational forces handling; furthermore, for orbit prediction only normal points (NPs) from the Graz SLR station have been considered.

Figure 4a depicts differences between the ENVISAT orbit we determined over the whole two-day period (referred to as reference orbit in the sequel) with SGF (NERC Space Geodesy Facility) predictions (CPFs) provided via the ILRS. The differences are up to a few tens of meters (see Table 1 for statistics), and hence they are in the accuracy range of CPF-based orbit predictions. The differences between the reference orbit and radar-based TLE orbits, in contrast, exceed one kilometre, with a position RMS value of 453.7m (Fig. 4b, Table 1).

Figure 4c reveals that in the presence of SLR NP data for one day, orbit prediction over the subsequent day is well below the 100m-level. Most notably, for these computations the initial state vector for orbit determination and prediction has been taken from TLE information. The results in Fig. 4c may be considered as over-optimistic provided that the number of NPs (120 in August 26) and their quality is possibly superior to real space debris tracking. As such, the SLR-based orbit prediction improvement by one to two orders of magnitude over TLE orbits should be taken as upper bound.

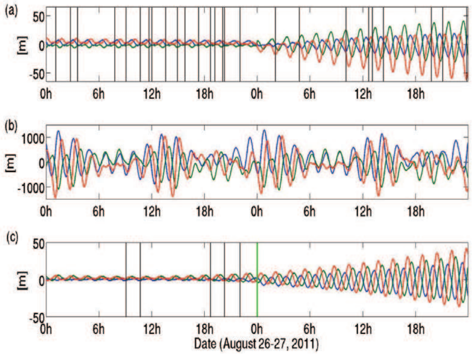

Figure 4: ENVIST orbit differences (x: blue, y: green, z: red) between reference orbit (derived from SLR NPs of 12 stations over the period August 26-27, 2011; black vertical lines indicate data availability, the total number of NPs is 531) and (a) SGF CPF orbits, (b) TLE-based orbit, (c) orbit determination (August 26) with subsequent orbit prediction (August 27) considering NPs from the Graz SLR station only; black vertical lines indicate data availability (the total number of NPs for August 26 is 120), green vertical line indicates separation between orbit determination and orbit prediction

Table 1: Orbit determination (August 26-27) and prediction (August 27) statistics (differences RMS in meter)

Case	x	y	y	total
Fig. 4a	7.2	12.7	16.7	12.8
Fig. 4b	452.9	393.6	507.5	453.7
Fig. 4c	10.9	13.1	16.9	13.8

7 CONCLUSION, FUTURE PLANS

We successfully demonstrated laser ranging to space debris objects in distances between 600 km and more than 2500 km, testing 2 frequency doubled (532 nm) Nd:YAG lasers: 1) A diode-pumped, 1 kHz / 25 mJ per pulse / 10 ns laser; 2) A flash lamp pumped, 100 Hz / 200 mJ per pulse / 3 ns laser . Average precision was about 0.7 m resp 0.5 m RMS, 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 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 Lasers, 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 will not be a potential solution e.g. to establish and maintain a complete space debris catalogue, but it may be well suited for precise orbit determination of a selected 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 far as orbit prediction is concerned, we are currently working on the determination and processing of pointing information (azimuth and elevation angles) in addition to range observations. For this purpose, we plan to use telescope pointing information and passive optical imaging of the debris objects against background stars. Both methods should allow deriving pointing angles with an accuracy of a few arc seconds. We expect the joint analysis of both data types (ranges and orientations) will result in more reliable and more precise orbit determination/prediction of debris objects. Moreover, we started to assess the benefit of bi-static and multi-static ranges in the framework of simulation studies.

8 REFERENCES

1. Kirchner, G., Koidl, F., Prochazka, I., Hamal, K.: SPAD Time Walk Compensation and Return Energy Dependent Ranging. Proceedings of 11th Int. Laser Ranging Workshop, Deggendorf 1998, pp421-525.
2. **G**ibbs, P., Wood, R. The C-SPAD a a single-photon detector. Proceedings of the 12th International Laser Ranging Workshop, Matera, 2000
3. http://www.microphotondevices.com/
4. Stipcevic, M., Skenderovic, H., Gracin, D.: Characterization of A Novel Avalanche Photodiode for Single Photon Detection in VIS-NIR Range. Optics Express, Vol. 18, Issue 16, pp. 17448-17459, 2010; http://dx.doi.org/10.1364/OE.18.017448
5. Degnan, J. J. Millimeter Accuracy Satellite Laser Ranging; A Review; AGU Geodynamics Series 25, pp 133-162
6. Zhang, Z.P., Yang, F.M., Zhang, H. F., Wu, Z.B., Chen, J. P., Li, P., Meng, W. D. The use of laser ranging to measure space debris. Research in Astronomy and Astrophysics (RAA), Vol 12, No 2, 2012
7. Kessler, D. J., Jarvis, K. S. Obtaining the Properly Weighted Average Albedo of Orbital Debris from Optical and Radar Data. Pesasi-B1.4-0023-02
8. Nakajima, A., Kurosaki, H., Fukaya, T. Space Debris Optical Observation System in JAXA/IAT. http://www.amostech.com/TechnicalPapers/2006/Orbital_Debris/Nakajima.pdf