Two-color and multistatic space debris tracking

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Abstract

Collisions with space debris in orbit are a growing threat to operational satellites and manned space missions. Optical observations, providing directional information and radar tracking providing mainly range are the currently established methods for maintaining a valid catalog of space debris items and their orbits. From this catalog one can obtain the probability of collisions and appropriate collision avoidance maneuvers can be scheduled. SLR (Satellite Laser Ranging) can provide both, range information and pointing angles at the same time, thus improving the orbit determination process of space debris targets as well as providing a better forecast of the respective orbit. In order to investigate the potential of the SLR technique the ESA project "Accurate Orbit Determination with Laser Tracking/Tasking" was started in 2014. We report on the technical progress achieved during the project by introducing improved visual tracking, simultaneous ranging at two different wavelengths (1064nm and 532nm) and a new tracking site in Stuttgart. Furthermore, it was possible to intensify the multi-static ranging including Graz, Wettzell and Stuttgart. These results are also presented and discussed.

Introduction

Since the first space mission in 1957, namely the launch of Sputnik 1, satellites have a great impact on our daily life. Modern navigation, communication and Earth observation are just examples of the wide range of possible space-based applications. But beside active satellites, a lot of inactive objects populate the near-Earth orbits. All these non-functional man-made objects and fragments of these objects (for example caused by collisions) in outer space are called space debris.

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The currently most complete database of LEO objects, the USSTRATCOM catalog, contains 17729 published objects (July 2016)[1], which should include the majority of particles above 10cm size. This database is mainly based on measurements using radar facilities like the FPS-85 located in Eglin, Florida.

In the ESA project, an optical approach is pursued to determine the orbital positions of space debris. Therefore, the technique of satellite laser ranging as performed since the early 1960s, was adapted to the requirements of a non-cooperative target.

Such an active optical approach for determining the position of an orbital object has various advantages compared to radar based observations:

- The used wavelength is much smaller than the object size. Thus no Rayleigh scattering effects occur when the electromagnetic wave is reflected at the object.
- Due to the shorter wavelength, the diffraction induced beam broadening is smaller. Even for much smaller aperture diameters a typically narrower beam is obtained. Thus the angular coordinates can be measured more accurately.
- The time of flight influencing atmospheric effects on the electromagnetic wave propagation in the optical regime are much smaller compared to radar waves. Thus high precision range information can be extracted easily from measured data.
- Since the accuracy of optical measurements do not depend on signal strength, accurate position determination is also possible for small objects.

To investigate the various benefits of the optical technology, the SLR station in Wettzell (operated by the Federal Agency for Cartography and Geodesy and the Technical University Munich) was modified and supplemented with a suitable laser to perform laser ranging to space debris. Measurement campaigns were performed to evaluate the performance of the system. Besides the standard single station two-way ranging, several other measurement configurations were examined. This includes multistatic ranging with the SLR station Wettzell as transmitter of 1064nm photons and the SLR station in Graz (operated by the Space Research Institute of the Austrian Academy of Sciences) and the experimental SLR station in Stuttgart (operated by the German Aerospace Center, see [3]) as additional receivers of the diffusely scattered photons. Furthermore, simultaneous two-way ranging was performed at a wavelength of 532nm by the SLR station in Graz. Thus it is possible to compare different measurement scenarios regarding the achievable orbit accuracy.

Hardware set-up

There are mainly two big differences between standard SLR and space debris laser ranging:

- Space debris objects are (mostly) not equipped with retro reflectors. Thus their effective cross sectional areas are several orders of magnitude smaller compared to cooperative targets. To compensate for this, lasers with increased pulse energy are required.

LASER PARAMETERS OF PARTICIPATING STATIONS

	Wettzell	Graz	Stuttgart
Type	Coherent Infinity	Coherent Infinity	Innolas AOT MOPA
Wavelength [nm]	1064	532	1064
Pulse energy [mJ]	200	200	0.1
Repetition rate [Hz]	20	100/80	5000
Pulse duration [ns]	3	3	3
M^2	1.5	1.5	1.5

Table 1 Parameters of the lasers operated at the different observatories.

DETECTOR PARAMETERS OF PARTICIPATING STATIONS

	Wettzell	Graz VIS	Graz IR	Stuttgart
Type	PGA-200-1064 Princeton Lightw.	C-SPAD	PGA-200-1064 Princeton Lightw.	ID400 id Quantique
Wavelength [nm]	1064	532	1064	1064
DE [%]	25*	25*	25*	30
DCR [kHz]	180	100	60	2
Diameter [µm]	80	200	80	80

Table 2 Parameters of the used detectors. The values marked with an asterisk denote guessed values.

- The publicly available orbit predictions for space debris objects (in two line element format) have accuracies in the order of several 100m [2], making blind tracking impossible. Therefore, a camera with a rather wide field of view (about 0.1°x0.1°) is necessary to image the sunlight reflected from the target. This information can be used to correct the telescope pointing in order to successfully track arbitrary objects. It should be noted that this only works during the terminator period.

These points were taken into account when setting up the space debris laser ranging stations for the GSTP project. Table 1 summarizes the parameters of the lasers operated at the different observatories, whereas Table 2 shows the detector properties. In the following paragraphs, the unique features of the three participating stations are explained in more detail. The measurement configurations realized with these three stations are shown in Figure 1 and explained in Table 3.

A) Wettzell observatory

The same telescope aperture with a diameter of 75cm is used for transmitting the laser pulses at a wavelength of 1064nm and receiving the scattered photons. Due to this monostatic optical set-up a mechanical shutter is required to switch between the transmitting and receiving path. This limits the maximal repetition rate to 20Hz. Thus the average optical power used for ranging in the IR was only 4W.

B) Graz observatory

A telescope with a diameter of 50cm is used to capture the infrared photons transmitted from

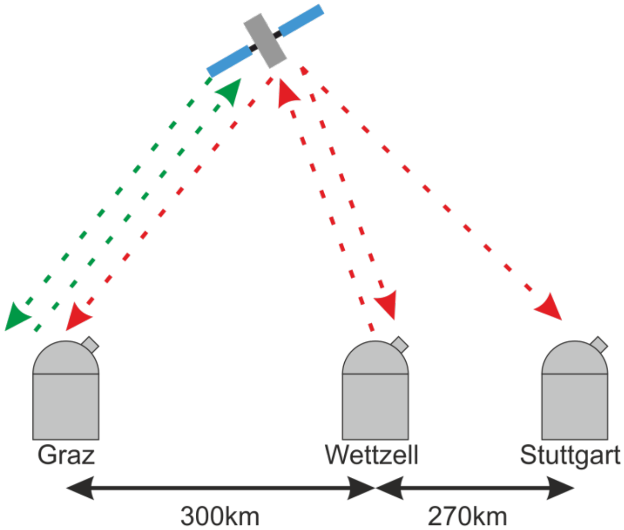

Figure 1 Realized measurement configurations. Red arrows indicate ranging at a wavelength of 1064nm, whereas green arrows indicate ranging at a wavelength of 532nm.

MEASUREMENT CONFIGURATIONS

Config	Transmitter	Receiver
A	Wettzell →	Wettzell
B	Wettzell →	Wettzell Stuttgart
C	Wettzell →	Wettzell Graz
D	Wettzell →	Wettzell Stuttgart Graz
E	Wettzell → Graz →	Wettzell Graz
F	Wettzell → Graz →	Wettzell Graz Graz

Table 3 Realized measurement configurations. The red font indicates ranging at 1064nm, whereas the green font indicates ranging at 532nm.

Wettzell and the 532nm photons provided by the laser placed in Graz. The detection package, attached directly to the telescope, is able to measure both wavelengths simultaneously. The transmitter optic, realized as a separate refractive telescope, is used to expand the laser beam to a diameter of about 6cm. Due to this biaxial optical set-up, high repetition rates are possible.

C) Stuttgart observatory

Since the pulse energy of the laser operated in Stuttgart is limited to 100µJ, ranging is only possible to cooperative targets. Nevertheless, the station is capable to contribute to multistatic experiments. In this configuration the receiver telescope captures the IR photons scattered by the space debris object.

Measurements

More than 150 passes of dozens of objects were tracked with a success rate of 60% (config A). Objects as small as 1.3m^2 were tracked at a distance of 1200km. Return events from larger objects are visible up to a range of 2000km. Besides the single-station ranging, multi-station experiments were performed with Wettzell acting as transmitting station. In 70% of the successful ranging attempts from Wettzell, returns are also visible in Stuttgart. A similar number of 56% is achieved for bistatic ranging with Graz as additional receiver.

The statistics of the different measurement configurations are summarized in Table 4. Since only three objects were ranged using all three stations at the same time, no statistic is given for this configuration (D).

STATISTICAL RESULTS OF DIFFERENT CONFIGURATIONS

	A	B	C	E	F
Objects tracked	169	107	32	43	32
Successful Wettzell	107 (60%)	51 (60%)	23 (72%)	-	-
Successful attempts	107 (60%)	36 (70%)	13 (56%)	29 (67%)	12 (38%)
Smallest object [m²]	1.3	6.2	6.2	6.2	6.2

Table 4 Statistical results of the different measurement configurations. The object cross sections are extracted from ESAs DISCOS catalog.

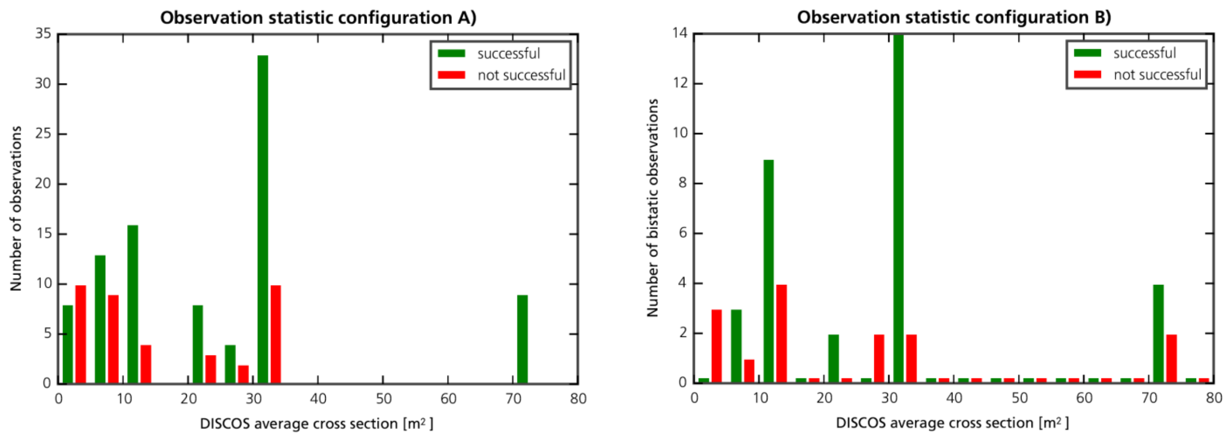

Figure 2 Successful/not successful ranging attempts as function of the average object cross section for configuration A and B. The target cross sections are extracted from ESAs DISCOS catalog.

Figure 2 shows the histogram of measured objects as function of the average cross section as given by the DISCOS catalog for configuration A and B. Objects as small as 1.3m² were measured from Wettzell. The smallest object measured in the bistatic configurations has an average area of 6.2m². This lower sensitivity for smaller objects in bistatic configuration, which is also visible in the histograms of figure 2, can be explained by the different aperture areas of the receiver telescopes (Wettzell 0.44m², Stuttgart 0.15m²).

Figure 3 shows residual plots of two different objects which may provide further information about the object. The residual plot of object 40358 for example shows a distinct double line originating from the two dominant backscatter areas of the target. The lines are separated by about 35ns, which corresponds to 5.25m, indicating the shape and size of the object.

In contrast the residual plot of object 39679 shows an oscillation with a period of 11.5s and an amplitude of 30ns. Due to the high signal strength, only photons reflected from the first surface of the object are detected. Thus the distance oscillation is probably caused by an object rotation. Besides the rotation period, the object dimension can be estimated from the amplitude.

Conclusion

Laser ranging to space debris objects in low earth orbit was comprehensively investigated at two

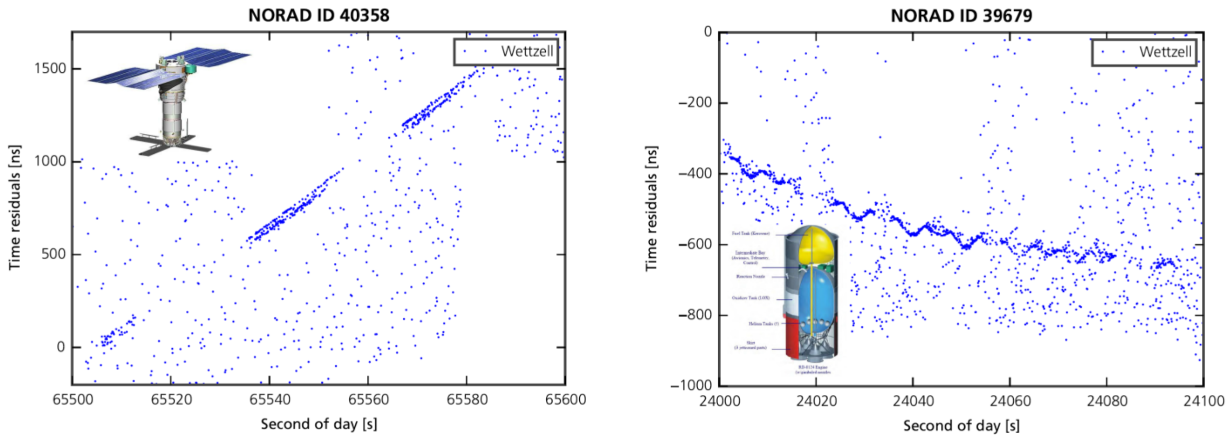

Figure 3 Left: Residual plot of object 40358. Two distinct lines are visible, which are separated by about 35ns. Inset from [4] Right: Residual plot of object 39679. An oscillation is visible with an amplitude of 30ns and a period of 11.5s. Inset from [5].

different wavelengths (1064nm and 532nm). Objects as small as 1.3m² were tracked in standard single station two-way ranging at 1064nm by Wettzell with an overall success rate of 60%. Furthermore, multistatic experiments were performed with the SLR stations in Graz and Stuttgart as additional receivers. Moreover, the observatory in Graz ranged simultaneously at a wavelength of 532nm to the same objects. This enables the comparison of the achievable orbit accuracy of the different measurement configurations. More information about this can be found in [6].

Apart from orbit determination, laser ranging data can be used to provide further space debris properties. The presented residual plots show very interesting features indicating the shape, dimension or rotation behavior of the objects. Further investigations are required in this area to identify the full potential of laser ranging.

Acknowledgement

This work was funded by the European Space Agency (RFQ/3-14099/14/D/SR).

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