

FIRST RESULTS FROM AN ESA STUDY ON ACCURATE ORBIT DETERMINATION WITH LASER TRACKING OF UNCOOPERATIVE TARGETS

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ABSTRACT

Within the framework of ESA's General Support Technology Program (GSTP) the project "Accurate Orbit Determination with Laser Tracking" was successfully launched at the end of 2014. The participating institutions comprise the German Aerospace Center, Institute of Technical Physics, Stuttgart, the Austrian Academy of Science, Space Research Institute, Graz, the Technical University of Munich, Research Facility Satellite Geodesy, Munich and the Federal Office for Cartography and Geodesy, Geodetic Observatory, Wetzell. The scope of this project encompasses the establishment of new tracking techniques for uncooperative, space-borne targets: Simultaneous 2-way laser ranging from two sites at two laser wavelengths (Wetzell: 1064 nm; Graz: 532 nm); and simultaneously multi-static ranging, where the stations in Graz and Stuttgart detected the diffuse radiation of Wetzell, backscattered from the space debris targets. Results are presented unveiling the rotational behaviour of rocket bodies as well as improved accuracy of orbit predictions due to the multi-static observation geometry. For laser ranging to uncooperative targets, the radar cross section of the smallest objects detected so far are about 0.4m², and the largest distances are about 3000 km.

Key words: Space Debris, Laser Ranging, Multistatic Observation.

1. INTRODUCTION

Since the first space mission in 1957, namely the launch of Sputnik 1, mankind benefits in various ways from the outer space. Satellites for example have a great impact in our daily life. But beside active satellites a lot of inactive objects populate the near-Earth orbits. All these non-functional man-made objects and fragments of such objects (for example caused by collisions) in outer space are called space debris. 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 by radar facilities like the FPS-85 located in Eglin, Florida. In the ESA GSTP 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 range 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.

2. HARDWARE SETUP

The measurements described in this paper have been realized by a network of telescopes in Graz, Wettzell and Stuttgart. The stations in Graz and Wettzell are operational satellite laser ranging (SLR) stations, whereas the station in Stuttgart is exclusively used for research and diagnostic purposes. 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.
- 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 $0.1^\circ \times 0.1^\circ$) 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 in twilight conditions.

These points were considered when setting up the space debris laser ranging stations for the GSTP project. Tab.

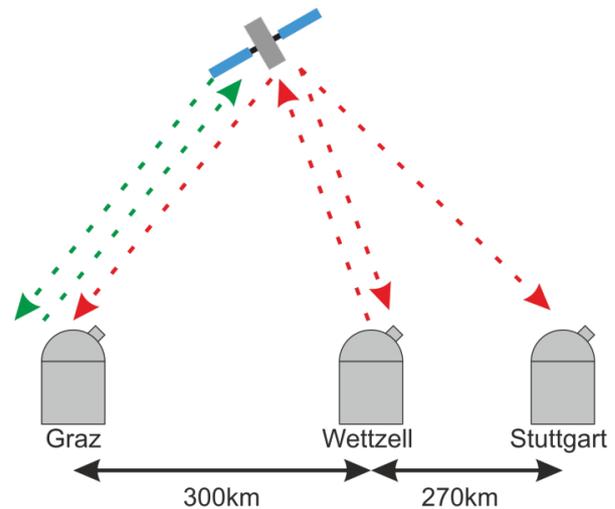


Figure 1. Realized measurement configurations. Red arrows indicate ranging at a wavelength of 1064nm whereas green arrows indicate ranging at a wavelength of 532nm.

1 summarizes the parameters of the lasers operated at the different observatories whereas Tab. 2 shows the detector properties. The measurement configurations realized with these three stations are shown in Fig. 1 and explained in Tab. 3.

The hardware setup at each station is outlined in the subsequent paragraphs.

2.1. Hardware setup in Wettzell

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 setup 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. The setup is illustrated in Fig. 2.

2.2. Hardware setup in Graz

A telescope with a diameter of 50cm is used to capture the infrared photons transmitted from 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. This circumstance enables for higher repetition rates as the setup in Wettzell.

	Wetzell	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
Beam parameter M^2	1.5	1.5	1.5

Table 1. System parameters for the transmit laser at network observatories Wetzell, Graz and Stuttgart. The beam parameter M^2 indicates the departure from the diffraction limit.

	Wetzell	Graz VIS	Graz IR	Stuttgart
Type	PGA-285 Priceton Lightw.	C-SPAD	PGA-200-1064 Princeton Lightw.	ID400 id-Quantique
Wavelength/nm	1064	532	1064	1064
DE/%	30*	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 are estimated values. DE: Detector efficiency. DCR: Dark count rate.

MEASUREMENT CONFIGURATIONS		
Config	Transmitter	Receiver
A	Wetzell	Wetzell
B	Wetzell	Wetzell Stuttgart
C	Wetzell	Wetzell Graz
D	Wetzell	Wetzell Stuttgart Graz
E	Wetzell Graz	Wetzell Graz
F	Wetzell Graz	Wetzell Graz

Table 3. Realized measurement configurations. Red arrows indicate ranging at a wavelength of 1064 nm, whereas green arrows indicate ranging at a wavelength of 532 nm

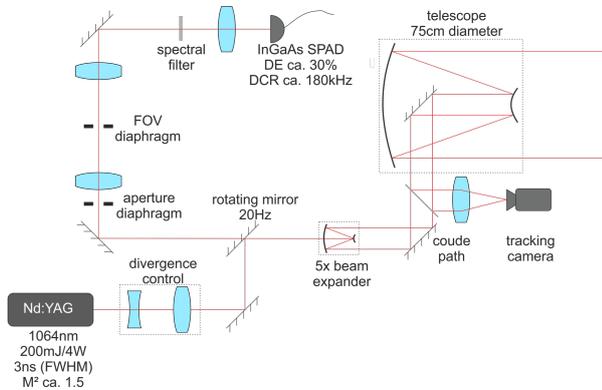


Figure 2. Experimental setup in Wetzell

2.3. Hardware setup in Stuttgart

Since the pulse energy of the laser operated in Stuttgart is limited to 100 μJ , ranging is only possible to cooperative targets. Nevertheless the station is capable to contribute to multistatic experiments. In this configuration the receiver telescope with an aperture of 40cm captures the IR photons scattered by the space debris object.

3. MEASUREMENTS

More than 150 passes of dozens of objects were tracked with a success rate of 60% (config A). Objects with an optical cross section as small as 1.3m² 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 Wetzell acting as transmitting station. In 70% of the successful ranging attempts from Wetzell, 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 Tab. 4. Since only three objects were ranged using all three stations at the same time, no statistic is given for this configuration (D).

Fig. 3 and Fig. 4 show the histograms of measured objects as a function of the average cross section as given by the DISCOS [8] catalog for configuration A and B respectively. It should be noted that the DISCOS catalog lists optical cross sections rather than radar cross sections as available from [7] and covers only a fraction of the objects available from the latter source. The smallest tracked object as available from the DISCOS catalog was 1.3m². The smallest object measured in the bistatic con-

	A	B	C	E	F
Objects tracked	169	84	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/m ²	1.3	6.2	6.2	6.2	6.2

Table 4. Statistics of the different measurement configurations which have been realized in the observation campaigns. The object cross sections are extracted from ESAs DISCOS [8] catalog.

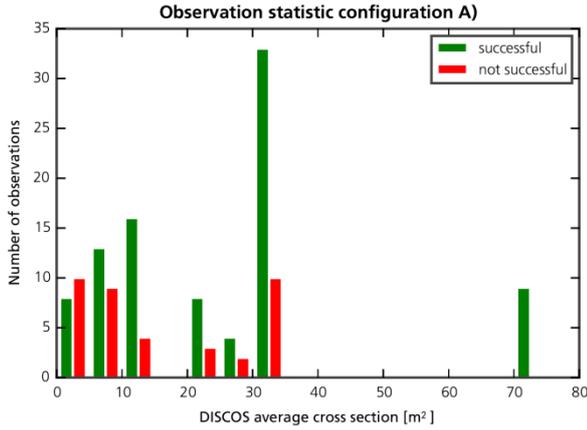


Figure 3. Successful/not successful ranging attempts as function of the average object cross section for configuration A. The target cross sections are extracted from ESAs DISCOS [8] catalog.

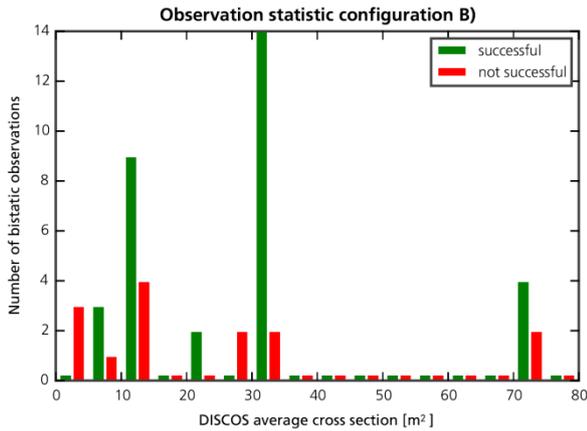


Figure 4. Successful/not successful ranging attempts as function of the average object cross section for configuration B. The target cross sections are extracted from ESAs DISCOS [8] catalog.

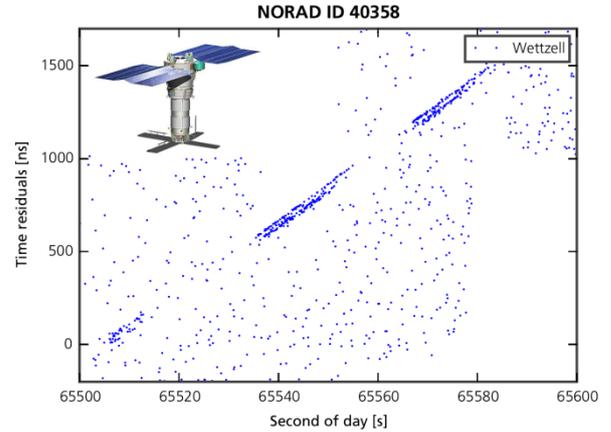


Figure 5. Residual plot of object 40358. Two distinct lines are visible, which are separated by about 35ns. Inset from [4].

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 Fig. 3 and 4, can be explained by the different aperture areas of the receiver telescopes (Wettzell 0.44m², Stuttgart 0.15m²). Fig. 5 and 6 show residual plots of two different objects which may provide further information about the object. The residual plot of object 40358 (Fig.5) 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 (Fig.6) 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.

4. LINK BUDGET CONSIDERATIONS

In order to evaluate the system performance of the laser ranging system in Wettzell in terms of debris object coverage, the Celestrak catalog [7] is used to extract the perigee height and the radar cross sections of the up to date objects in earth orbit (status 02-09-2016). The catalog encompasses a total of 117661 orbiting debris objects

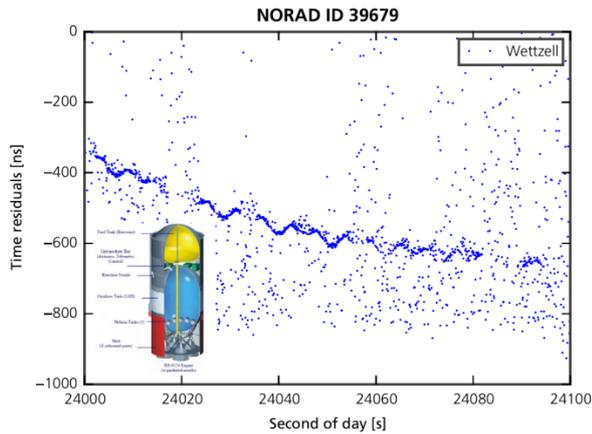


Figure 6. Residual plot of object 39679. An oscillation is visible with an amplitude of 30ns and a period of 11.5s. Inset from [5].

with radar cross sections larger than 1cm^2 and perigee heights ranging from 250km to 40000km. Fig. 7 shows the individual debris objects marked as red dots with their radar cross section and perigee height respectively. The blue asterisks mark the objects which have been tracked by the laser ranging system during the various campaigns. The green line indicates the radar cross section as a function of perigee height, where the expected received photon number per second equals the dark count rate of the employed detector, i.e. where a signal to noise ratio of 1 is achieved. Under the best observing conditions (maximum atmospheric transparency and observing elevation angle of 90 degree) all objects above the green line are within reach of the system. These are approximately 30 percent of all cataloged debris objects. As the successfully tracked objects are acquired usually under elevations smaller than 90 degree and the perigee is generally not passed during the observation of the object, the slant range during observation is considerably higher. This is the reason for the spacing between the dark count limited link budget (green line) and the successful tracked objects marked in the data plot. As can be depicted from Fig. 7 the smallest tracked object in terms of radar cross section is 0.4m^2 at a height of 800km.

5. CONCLUSION

Laser ranging to space debris objects in low earth orbit was comprehensively investigated at two different wavelengths (1064nm and 532nm). According to the DISCOS catalog objects with an optical cross section as small as 1.3m^2 were tracked in standard single station two-way ranging at 1064nm by Wetzell with an overall success rate of 60%. The radar cross section of the smallest observed object was 0.4m^2 orbiting at a perigee height of 800km. Furthermore multistatic experiments were performed with the SLR stations in Graz and Stuttgart as additional receivers. Moreover the observatory in Graz

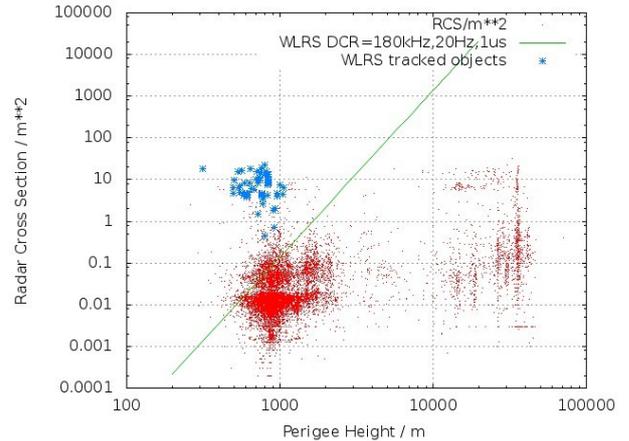


Figure 7. Darkcount rate limited link budget for the Wetzell Laser Ranging System and the cataloged debris objects as a function of perigee height. The blue asterisks mark the successfully tracked objects.

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.

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