# INNOVATIVE TECHNOLOGIES FOR OPTICAL GROUND STATIONS

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## ABSTRACT

There is a growing interest in the development of ground station technology for catalogue maintenance or ad-hoc measurements of orbital objects like space debris or satellites for initial orbit prediction. Optical methods are providing efficient solutions for space situational surveillance in order to support catalogue maintenance. The Institute of Technical Physics already operates a laser ranging station with a fiber-based laser transmitter and another transportable one built in a 20 ft ISO container which is in progress. The setup of both stations will be briefly presented. Furthermore the exploitation of the ranging data which can contain not only the slant range but also information about the dimension and rotation of an orbital object is discussed in this work.

## 1 INTRODUCTION

A fast growing population of satellites (especially of nano and micro satellites) as well as the planned installation of so called mega-constellations is a concern for all space-faring nations. Dysfunctional satellites may break up, collide with each other or space debris and hence increase the population of space debris and making certain orbits inhabitable for future missions.

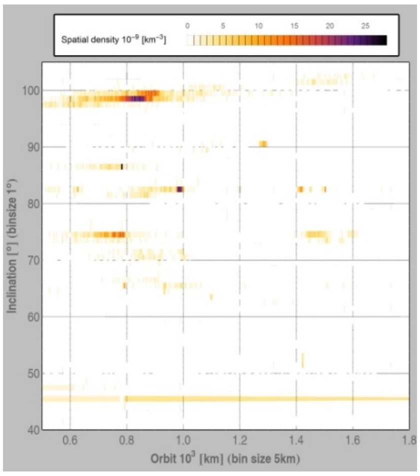


*Figure 1. The spatial density of LEO objects versus the objects' average orbit height and inclination. Particularly orbits at an inclination of 98° between 700km and 1000km are very densely populated.*

In low Earth orbits (LEO) the spatial density of orbital objects reaches a maximum at an inclination of 86.5° and heights of 782.5 km, as it can be seen in Fig. 1. Radar stations are mainly used for monitoring the orbital population of satellites and space debris in low Earth orbits. A worldwide net of radar stations operated by USSTRATCOM maintains a catalogue of about 28.000 objects of which approximately 15.000 are open for public interest. Rader based space surveillance is a well-established technique which can be complemented by laser based ranging [5]. This technique is routinely performed by a few ten stations (currently 49 active stations) linked together within the network of the International Laser Ranging Service (ILRS) [3]. Major tasks of the ILRS are of geodetic nature like monitoring tectonic plate activity and probing the gravitational field of the Earth to name some. In various campaigns specific satellites are frequently ranged during a station's overpass and the data is processed and shared among attending stations. As a result of this cooperation blind tracking and ranging of these satellites is possible during day and night time through sophisticated data acquisition and filtering techniques. Blind tracking of space debris with TLE based a priori information is generally unfeasible, since the orbits are insufficiently determined and the uncertainty of the along track and cross track prediction can be as large as a few mrad and up to kilometres in the radial direction. However, this prediction can be used for coarse tracking of an object and a fine tracking algorithm, which makes use of the object's backscattered solar light during dusk and dawn. At the Institute of Technical Physics we seek ways to combine the desire to monitor space debris with the precision and accuracy of laser ranging. This technology is not expected to replace radar based observations but rather to support catalogue maintenance and provide the capability of ad-hoc precise orbit determination.

## 2 TECHNOLOGY DEVELOPMENT

The Institute of Technical Physics already operates a laser ranging station at the center of the city of Stuttgart/Germany [1,2] while there is work in progress to build a second one. The first one is a stationary laser ranging station, Uhlandshöhe Forschungs-

*Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office*
*Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)*

Observatorium (UFO) Fig. 2, with a fiber based laser transmitter dedicated for ranging cooperative targets and testing new technologies. Whereas the second one is a transportable laser ranging station in a 20 ft ISO container, called Surveillance Tracking and Ranging-Container (STAR-C) Fig. 3, which will be capable to track and range space debris.

### 2.1 UFO

UFO operates routinely and attended already some conjoint campaigns with nearby ranging stations [4]. Although the fiber based laser transmitter lacks the possibility to guide high peak powers it can be partially compensated by a higher repetition rate of the ranging laser. Following this concept, range measurements were taken at repetition rates up to 10 kHz. Currently we focus on increasing the overall performance of the station and to automise its operation.

*Figure 2. At UFO a bi-static setup is assembled on an equatorial mount. On top of the main 17inch telescope is an auxiliary telescope with an aperture of 10cm. For the ranging the pulses are guided by a passive optical fiber to the auxiliary telescope.*

At the observatory there is a bi-static setup on an equatorial mount (NTM 500 by Astellco) within a 12 ft clam shell dome. The mount carries a telescope with an aperture of 17inch for tracking and ranging and on top of it a telescope with an aperture of 10 cm for transmitting an infrared laser beam. At the back of the 17 inch telescope is attached a beam splitter which transmits the visible light on the tracking camera (Andor Zyla) and reflects the infrared light on a single photon detector (id-Quantique 400). In standard conditions the closed loop tracking accuracy can be as small as 2 arcsec (RMS) which is limited by the atmospheric turbulence. A 5m long passive optical fiber guides a fraction of light from a Nd:YAG laser to the transmitter telescope. On the one hand this comes at the advantage of a simple light weight construction, but on the other hand it limits the available pulse energy. As a multimode fiber guides the pulses to the laser transmitter the final full beam divergence is approximately 280 µrad, which can be improved by a factor ten using single mode fibers or suppressing higher modes. Smaller core diameters increase the fluence which increases the risk of damaging the fiber material. However, times of flight measurements to stationary corner cube reflectors (CCR) as well as on satellites were taken.

### 2.2 STAR-C

STAR-C is planned to begin its operation during the second half of this year at a site of the Deutscher Wetterdienst (German Weather Service) located within the vineyards of Stuttgart/Germany. At this site we will gradually increase the performance and capability of the station. Closed loop tracking of orbital objects during dusk and dawn is the first step towards tracking and ranging of space debris. Afterwards a low energy laser will be used for testing, diagnosis and first ranging measurements to well-known targets, stationary as well as orbiting, in order to characterise the overall performance of the experiment. Later a high energy laser will be implemented to reach the full capacity in order to range space debris. Since the whole set up of the laser ranging station is built into a 20 ft ISO-container, it can be deployed to nearly any site worldwide.


*Figure 3. The entire hardware of the transportable laser ranging station is built into a standard 20ft ISO-container. On one end of the container is a platform that raises a bi-static setup on an alt-azimuth mount above the roof of the container. A 17inch telescope is used of the tracking and ranging (further details, see text).*

The whole station will be assembled and tested at a convenient site and when ready to be shipped it can be transported by train, truck or ship. At the desired site the station will be ready to operate with little effort and an operator will have full control either from inside the container or remotely via a network connection. Before the observation one opens a retractable roof and a platform raises two telescopes for the transmit and receive channel in a bi-static setup on an alt-azimuth mount above the roof of the container. Each axis of the alt-azimuth mount is driven with direct drives, where absolute encoders give a theoretical angular resolution of 0.1µrad (1/50 arcsec). On the transmit channel we will use a Nd:YAG laser operated at the fundamental wavelength of 1064 nm. A coudé-train through the axes of the alt-azimuth mount guides the light of the laser to the transmitting telescope with an aperture of 10 cm. An active beam stabilization will keep the beam at the center of the last mirror which is used for the fine steering of the pointing. On the receive channel there is a telescope with an aperture of 17 inch with a beamsplitter to separate the visible light for tracking and the infrared for the time of flight measurement. In the focal plane of the visible light is a low noise CMOS camera (Andor Zyla) with a field of view of approximately 0.3° which will be used for tracking. A fiber-coupled SPAD with either a 50 µm or 100 µm core diameter of a multimode fiber yields a native field of view of 16 µrad (3.5 arcsec) or 33 µrad (7 arcsec) respectively, which can be increased with a relay lens. In a first step the STAR-C will be equipped with a low energy laser ($f_{rep}$ / $E_p$ / $\tau_P$ ) = (1 kHz / 30 µJ / 1 ns), which will later be replaced by a laser with an average power of several Watts. For taking the time tags of the time of flight measurement we will use the event timer AO33-ET by Eventech.

## 3 EXPLOTATION OF RANGE MEASUREMENTS

For laser ranging of far distant and fast moving objects it is essential to have a coarse prediction of the object's slant range in order to determine the actual distance at the time of the measurement. From the taken data the range residuals are calculated in its simplest form by $t_{res}=t_i-t_{i,p}-t_{cal}$, where $t_i$ is the measured TOF and $t_{i,p}$ the predicted TOF at the epochal time $i$ and a systematic temporal offset $t_{cal}$ caused by the time tagging electronics. More sophisticated models take account for atmospheric delays or time delays based on the amount of light impinging the detector at the epochal time $i$ triggering an event. An example of such a measurement is shown in Fig. 4, where the clear signal arises from a CCR array around the altimeter antenna at the bottom of the TOPEX satellite. After a malfunction in January 2006 the satellite became dysfunctional and tumbles in an orbit of 1330 km. A return ratio can be defined as the ratio of the number of valid events over the number pulses sent within the same time. For sufficient return ratios the range residuals not only contain the actual distance but can also exhibit information about the size and rotational state of the object, as seen in the observers' line of sight. A closer look at the range residuals in Fig. 4 show that there is an oscillation of the range residuals during the observation which becomes more clearly towards the end.

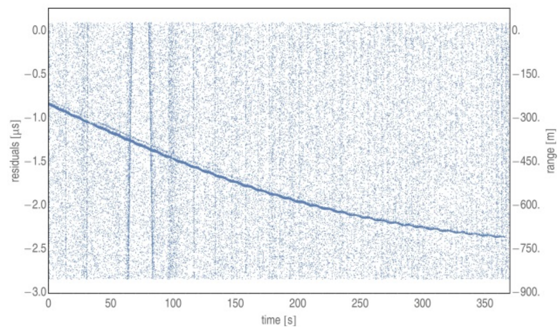


*Figure 4. Range residuals against TLE predictions of the dysfunctional satellite TOPEX slowly rotating in an orbit of 1330 km. The temporal width of the range residuals decreases from the beginning of the observation towards the end and an oscillation can clearly be seen.*

### 3.1 Rotation

Consider a rotating object predominantly reflecting from a particular surface of higher reflectivity than the remaining object (see Fig. 5), for example a solar panel. Further consider that this surface is displaced by a distance $d$, greater than the single shot accuracy, from the instant center of rotation. In such a scenario the range residuals show a periodic signature, where the period is related to the rotational frequency and the amplitude to the surface's displacement to the instant center of rotation.

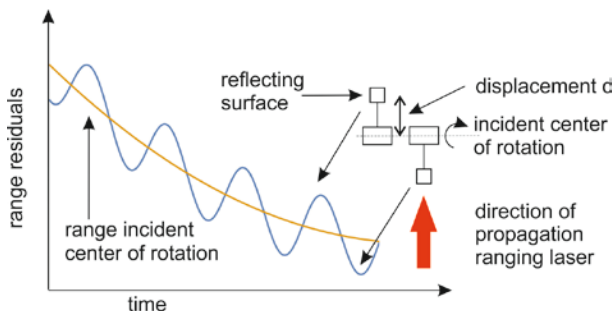


*Figure 5. A schematic plot of the range residuals when observing a rotating object with a reflecting surface which is displaced from the incident center of rotation. The apparent range oscillates as the surface appears closer and further at the frequency of the rotation.*

When taking the first derivative of the range residuals as shown in Fig. 6 the rotation of the TOPEX satellite can be clearly seen. The period of this rotation was determined to 10.67 ± 0.004 s.

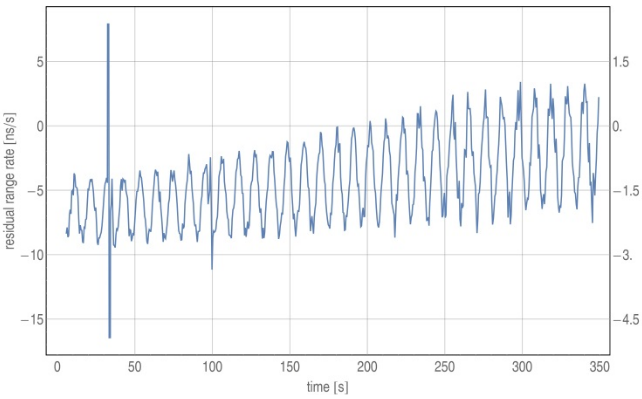


*Figure 6. The residual range rate of the range residuals clearly show an oscillation of 10.670± 0.004 s.*

## 4 SUMMARY

The effort of this work shows promising solutions for cost efficient optical ground stations for laser ranging of objects in LEO. In future UFO will be extended with other fiber technology in order to increase the available pulse energy delivered to the laser transmitter and decrease the laser beam divergence. Additionally we develop a transportable laser ranging station capable to track and range space debris. Both stations, however, are also building blocks of a network [6] of stations to either provide a greater coverage or to operate in multi-static campaigns in order to increase the accuracy for orbit predictions.

## 5 REFERENCES

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