Space Debris Orbit Predictions using Bi-Static Laser Observations.
Case Study: ENVISAT.

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Abstract. Space debris objects in the Low Earth Orbit (LEO) segment pose an increasing threat to all spacefaring nations. One of the most relevant issues in the framework of collision avoidance or the removal of space debris objects is the quality of orbit predictions. It has recently been demonstrated that laser ranging has the potential to significantly contribute to the reliability and accuracy of orbit predictions. However, a severe limitation of the technique is the sparse network of SLR-stations that are able to track uncooperative targets, and hence the sparseness of tracking data. In order to mitigate this limitation, the concept of mulit-static laser ranging has been established. These observations refer to the tracking of objects from one active SLR-station and the detection of diffusely reflected photons at several passive stations. If only one passive station is involved, the concept is referred to as bi-static. In this contribution we shed light on orbit predictions of the defunct ENVISAT satellite. Against the background of sparse tracking data, we found that the concept of bi-static laser observations improves the prediction accuracy by one order of magnitude compared to the results based on "conventional" two-way laser ranges only.

Introduction

Objects which no longer serve any useful purpose are referred to as space debris, including decommissioned satellites, upper stages, and fragmentation due to break-ups explosions and collisions. Only around 5 % of the tracked objects belong to operational satellites. According to Liou (2006), the debris population is densest in the LEO segment, ranging from around 200 km to 2000 km, particularly at inclinations between 80° and 100°. One of the most massive abandoned intact satellites is ENVISAT with an orbital altitude of around 770 km and an inclination of 98°, consequently being a critical object (equipped with Laser Retro Reflectors).
The reliable and accurate orbit determination, respectively orbit prediction, of debris objects is of crucial importance for any effort towards orbit conjunction analysis and taking measures for collision avoidance. Hitherto, debris monitoring is performed by space surveillance networks using ground-based radar tracking and passive optical tracking with telescopes. Recent studies successfully demonstrated SLR to be an alternative to track abandoned satellites and upper stages at LEO altitude (Kirchner et al., 2013a; Zhang et al., 2012). Based on these technological developments, Bennett et al. (2013) achieved significant improvement of the accuracy of orbit predictions. Though, only sparse tracking data is available for uncooperative targets, due to advanced technological requirements.
Against this background, we propose to extend the existing SLR network by passive telescopes in combination with multi-static observations. Multi-static observations means that an object is tracked by only one active SLR-station, but the diffusely reflected photons are detected at several passive stations. In case of only one passive station the measurements are referred to as bi-static.

In this contribution we focus on this new observation type in combination with two-way laser ranges in case of orbit determination and prediction of the defunct ENVISAT satellite.

Data and Methods

The bi-static measurements to ENVISAT have been collected during a multi-static measurement campaign in 2013 with Graz as active station and Herstmonceux, Zimmerwald and Wettzell as passive stations. The laser used for these experiments (provided by DLR) emitted high energy pulses with 200 mJ at a wavelength of 532 nm and pulse length of 3 ns. The time synchronization between the stations was realized using GPS receivers and is significantly less than 100 ns. More details about the technical realization can be found in Kirchner et al. (2013b).
As a first possible approach to use bi-static observations within dynamic orbit determination, we separate the observation (t_{stop}-t_{start}) in uplink time-of-flight (τ_u) and downlink time-of-flight (τ_d). This is achieved by cubic interpolation of the measured round-trip time (Δt) at the active station, cf. Figure 1. Noteworthy, the time synchronization between the participating stations is essential, since it affects directly the observations. The estimation of a pass-wise measurement bias can account for imperfect time synchronization. Eventually, the separated observations are considered in the dynamic orbit determination process in addition to "conventional" two-way laser ranges.

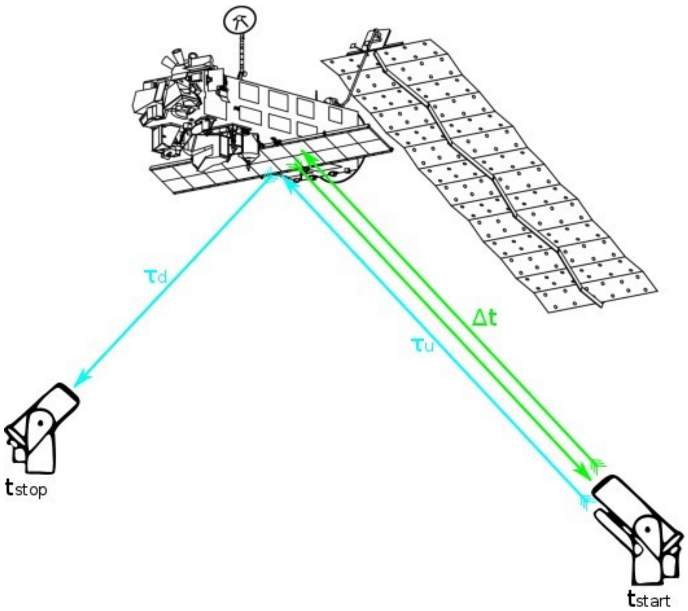


Figure 1. *Concept of bi-static laser observations*

The software package GEODYN-II (Pavlis et al., 2006), developed at NASA's Goddard Space Flight Center, has been used to perform dynamic orbit computations. It provides a batch least-squares estimation algorithm, which minimizes the weighted sum of squared observation residuals (observed minus computed). Within the dynamic orbit determination process the initial state vector, as well as force model parameters, are estimated iteratively.
Eventually, the force model together with the estimated parameters are used to predict the trajectory. A listing of the applied force model components is presented in Table 1. The following parameters are adjusted within the dynamic orbit determination process: initial state vector,

atmospheric drag coefficient, solar radiation pressure coefficient, empirical accelerations (constant, once per revolution) in along-track direction, and measurement bias per pass. One of the most challenging problems related to space debris orbit determination is the unknown attitude information, especially in the context of non-conservative forces modelling.

Table 1. *Adopted force models and standards*

conservative force model	
central body	EIGEN5s up to d/o 150
third body	JPL DE-403
solid earth tides	IERS conventions 2003
ocean tides	GOT 4.8
pole tides	IERS conventions 2003
non-conservative force model	
atmospheric density model	MSIS-86
solar radiation	Cannonball, cylindrical shadow model
reference frames	
inertial reference frame	J 2000.0
terrestrial reference frame	SLRF2008
tidal loading displacement	no atmospheric pressure loading
measurement correction	
tropospheric refraction model	Mendes-Pavlis, Elevation cut-off 10°
center-of-mass correction	not applied

Realistic tracking scenario

In order to reflect realistic data availability scenario for space debris objects, we composed three different data observation subsets collected during a period of 3 days:

(a) all available two-way laser ranges (10 passes collected by 6 stations, 115 Nps)

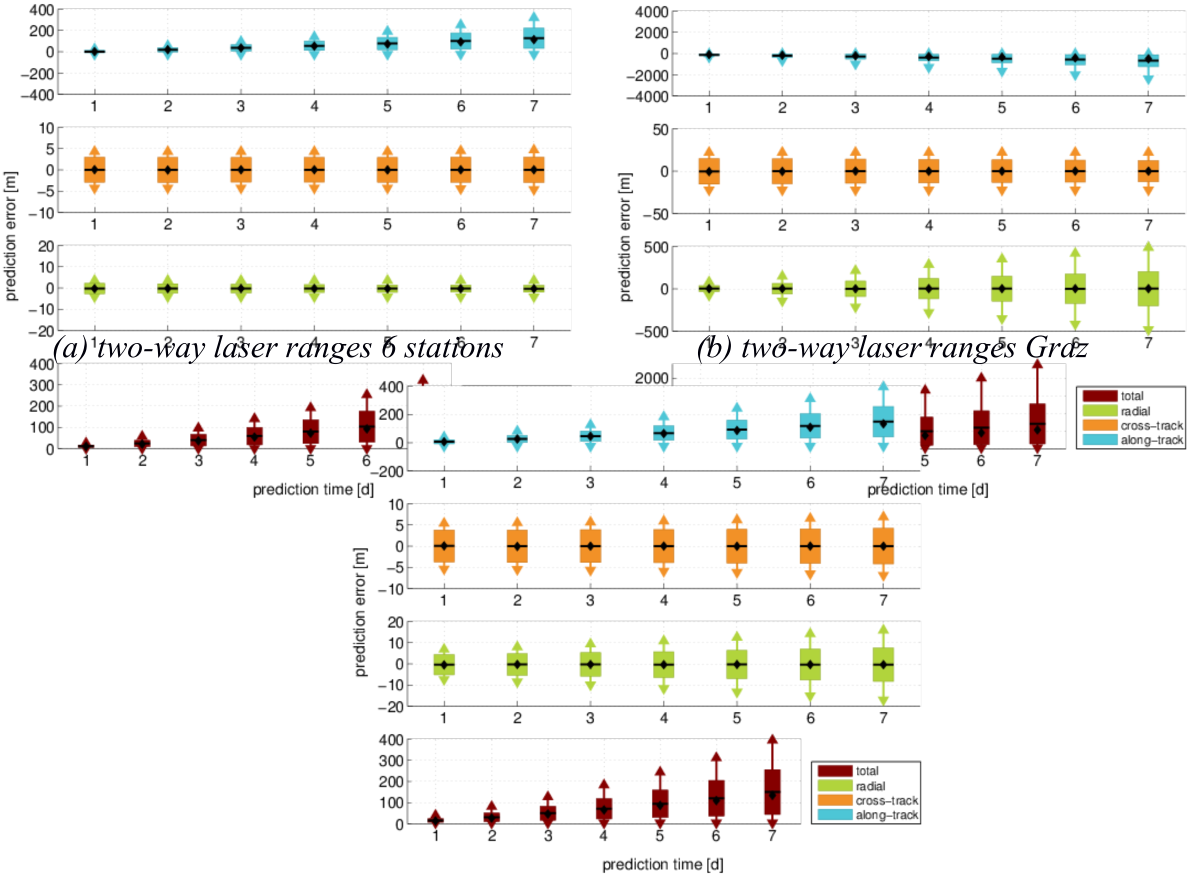
(b) two-way laser ranges from a single station (3 passes collected by Graz, 57 NPs)

(c) observation set (b) and additional 3 passes of bi-static observations (bi-static measurements between Graz and Wettzell, 155 NPs)

The accuracy of predictions based on the observation subsets (a) – (c) was assessed by comparison with a reference orbit. This reference orbit was derived from all available two-way laser ranges during the prediction period (acquired by 12 SLR-stations). The RMS of post-fit observation residuals amounts to 1.1 m, which is superior to any of our orbit prediction results. Consequently, the adopted reference orbit indeed is an adequate reference for quality assessment. Furthermore, observed ranges and computed ranges based on derived predictions are used to form (a posteriori) laser tracking residuals. These observed minus computed residuals provide an independent and unambiguous validation tool (Luthcke et al., 2003).

Quality of orbit predictions

The validation of orbit predictions with reference orbit demonstrates that the incorporation of bi-static observations considerably improves the prediction accuracy. As indicated by Figure 2, the improvements are about one order of magnitude compared to the results using "conventional" two-way laser ranges only. At a prediction time of three days, the total errors are at the level of 1000 m for two-way laser ranges only (Figure 2b), and 150 m for two-way laser ranges and additional bi-static observations (Figure 2c). The quality of orbit predictions based on the laser tracking data from one active station is comparable to that using two-way laser ranges from 6 SLR-stations, compare Figure 2a versus 2c.



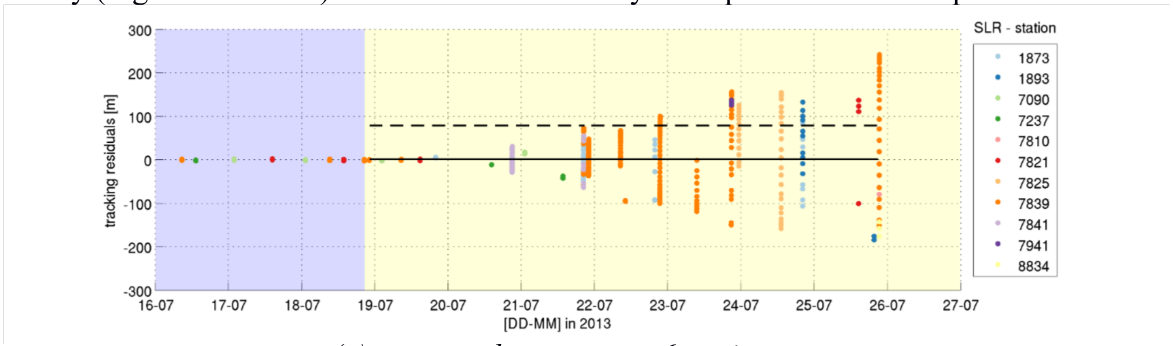
(a) two-way laser ranges 6 stations

(b) two-way laser ranges Graz

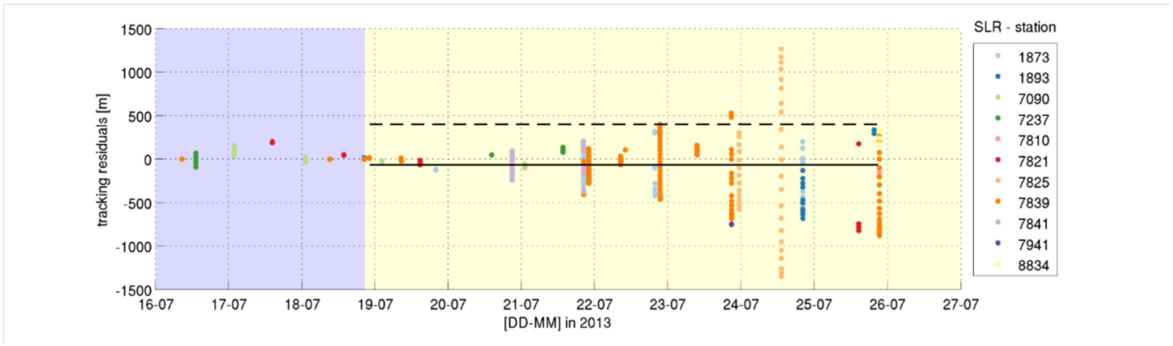
(c) two-way laser ranges Graz + bi-static

Figure 2. Orbit prediction errors for ENVISAT w.r.t. an a posteriori determined reference orbit derived from laser tracking data. Box: two-sided standard deviation; blackline: mean; black diamond: median; arrows: minimum and maximum values. The panel indications (a), (b) and (c) refer to the scenarios as mentioned in the text.

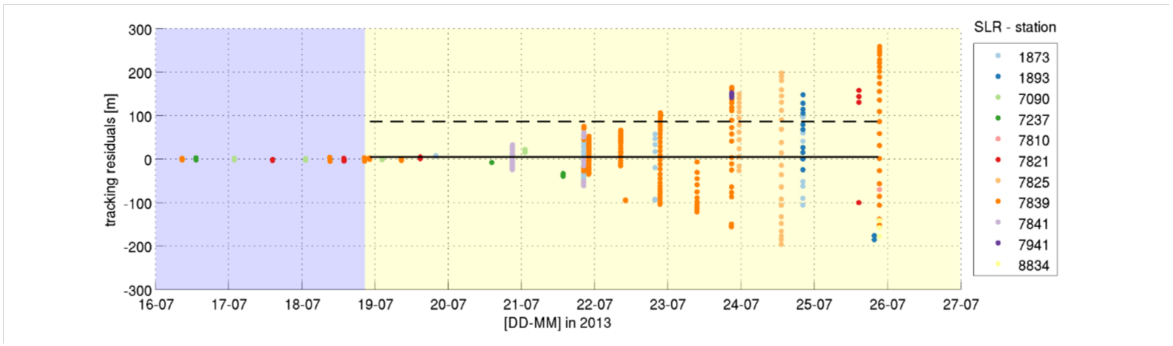
Laser tracking residuals are well suited to validate orbit solutions, see Figure 3. Especially, Figure 3b reveals that orbit determination/prediction using only 3 passes of single-station two-way laser ranges results in large tracking residuals. This is in particular the case for laser tracking data from SLR-stations which have not been involved in the orbit determination process. During the prediction period the residuals reach a maximum value of 1350 m. For the scenarios (a) and (c), on the other hand, the maximum laser tracking residuals amount to only 240 m and 260 m, respectively (Figure 3a and 3c). Both observation sets yield equivalent residual patterns.



(a) two-way laser ranges 6 stations



(b) two-way laser ranges Graz



(c) two-way laser ranges Graz + bi-static

Figure 3. Validation of orbit predictions for ENVISAT using all available two-way laser ranges during the period of investigation. Blue section: orbit determination; yellow section: orbit prediction; solid line: median; dashed line: RMS.

Conclusions

We found that in case of ENVISAT the incorporation of bi-static laser observations can improve the orbit prediction accuracy, against the background of sparse tracking data. The improvements are about one order of magnitude compared to single-station results. Since the prediction errors are comparable to using 10 passes collected by 6 SLR-stations, we propose to extend the existing SLR network by passive telescopes in combination with multi-static observations. The extension of the presented work to a wider range of (uncooperative) space debris objects, e.g. upper stages, is planned for the near future. Though, it has to be mentioned that it is not the intention to maintain a catalogue of debris objects using laser-based observables. Instead, SLR has to be seen as a technique to refine the prediction accuracy of selected objects.

References

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