ACCURATE ORBIT DETERMINATION OF SPACE DEBRIS WITH LASER TRACKING

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ABSTRACT

Accurate orbit determination of space debris is a topic of great and ever-growing importance, particularly in view of the increasing number of objects in populated orbit regimes with high densities of operational satellites. To this end, debris laser ranging, which can be established on the basis of on an existing network of stations and associated expertise, is considered as a promising concept to provide timely and accurate observations. Moreover, the combination of high laser pulse energies and generally irregular shapes of debris objects facilitates bi- or multi-static ranging, thereby maximizing the obtainable information content. This paper delivers insight into the technologys capabilities and limitations by drawing on experience gained and real data obtained within the framework of an ESA study. In particular, we analyze orbits products resulting from different observation scenarios in a network of three central-European stations and emphasize the impact of additional bi-static laser ranging data. Eventually, we assess the quality of the orbit products by employing cross-validation studies and highlight the potential of fusing laser ranging with Two-Line-Element (TLE) data.

Keywords: Orbit Determination, Laser Tracking, Bistatic Ranging, Sparse Data, High Precision.

1. INTRODUCTION

The increasing amount of space debris in Earth orbits poses a growing threat to manned and unmanned space flight. Hence, spacecraft operators are faced with challenges like conjunction analyses, collision avoidance planning and active debris removal. In this regard, reliable and accurate orbit prediction of space debris is a crucial issue. Currently, the US Space Surveillance Network (SSN) maintains the largest catalog of orbit data corresponding to more than 15,000 trackable objects with the majority being debris. These orbits are provided in the form of Two-Line-Elements (TLEs), which are essentially orbit determination products based on radar and passive optical tracking data and work with particular analytical propagators [1]. However, TLE based predictions are generally too inaccurate regarding the challenges named above ([2, 3]).

The present study emerges from an ESA project, in which an active optical approach was pursued to determine space debris orbits. To this end, the technique of satellite laser ranging (SLR) as performed since the early 1960s was adapted to the requirements to range to non-cooperative targets. This was motivated by the fact that laser ranging has recently demonstrated the potential to significantly improve the quality of orbit determination giving rise to better predictions in terms of both accuracy and uncertainty [4, 5]. Moreover, depending and the object's shape the strong laser pulses are generally reflected diffusely. Hence, detecting these photons with several cheaper receive-only stations in bi- or multi-static ranging scenarios is a promising concept to further increase the data yield and the observability of the parameters of interest with limited numbers of object passes. First results of successful experiments of bi-static laser ranging to space debris are presented in [6, 7, 8]. Besides its higher ranging precision, such an active optical approach has various further advantages as compared to radar tracking of space debris:

- The used wavelength is much smaller than the object size. Thus no Rayleigh scattering effects occur when the electromagnetic wave is reflected by the object.
- Narrower beams are obtained due to smaller diffraction-induced beam divergence, even for very small aperture diameters. Hence, it is straightforward to record accurate angular observations.
- The atmospheric effects on the electromagnetic wave propagation in the optical regime are comparatively small and can be modelled very well. Therefore, high precision range information can be extracted easily from the measurements.
- Since the accuracy of optical measurements does not depend on signal strength, accurate orbit determination is also possible for small objects.
- The required observation sites are cheaper than radar stations in terms of both acquisition and operation costs by at least one order of magnitude.

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Specifically, the SLR station in Wettzell (operated by the Federal Agency for Cartography and Geodesy and the Technical University of Munich) was modified and supplemented with a suitable laser to perform laser ranging to space debris. Besides the standard single station two-way ranging, several other measurement configurations were examined. This included multi-static ranging with the SLR station Wettzell as transmitter of 1064 nm 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) as additional receivers of the diffusely reflected photons. Furthermore, simultaneous two-way ranging could be performed at a wavelength of 532 nm by the SLR station in Graz. Thus, it is possible to compare different measurement scenarios regarding the achievable orbit determination accuracy. The geographic locations of the three involved stations are shown by Figure 1.

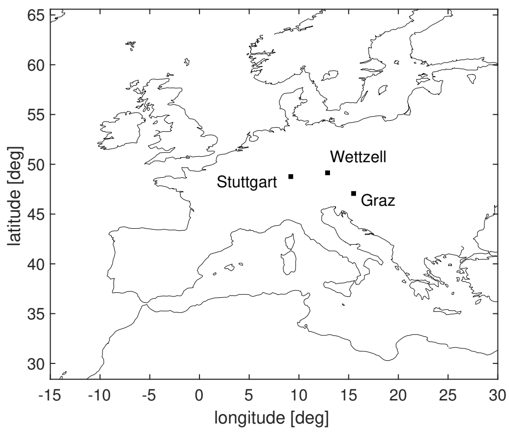


Figure 1: Geographic locations of the three laser ranging stations involved in the ESA study that is the basis of this work. Wettzell and Graz conducted mono-static laser ranging. In addition, bi-static laser ranging from Wettzell to Stuttgart and from Wettzell to Graz was performed.

The remainder of this paper is organized as follows: First we briefly recall the basic principle of satellite and debris laser ranging and introduce the obtained tracking data. In this context, a method for filtering the noisy raw observations is presented and some major constraints and limitations are discussed. After that we describe our approaches to address typical problems related to orbit determination of space debris based on sparse mono- and bi-static laser ranging. This encompasses state and force model parameter initialization using TLE data and a discussion of feasible solution parameter sets. Eventually, we present first orbit products resulting from various orbit determination scenarios. In doing so, we provide insight into post-fit and cross-validation residuals (as a surrogate measure for the orbit prediction accuracy) and analyze an approach of data fusion with TLEs as pseudo-observations. We finish this paper with some concluding remarks.

2. DEBRIS LASER RANGING

2.1. Measurement principle

Observations in SLR are typically time-of-flight measurements of short laser pulses from the transmitting station to the satellite and back. We refer to this concept as mono-static ranging, which can be applied for ranging to space debris objects with properly modified hardware. In a bi- or multi-static ranging scenario one station is equipped with a transmitting laser and one or several other stations can receive the diffusely reflected laser pulses. Hence, we are provided with additional time-of-flight measurements, informally referred to as bi-static range measurements in the present work. In this case clock offsets may have to be estimated along with the orbit as the transmit and receive epochs are recorded by separate timers connected to remote and generally not sufficiently accurately synchronized clocks. Depending on the stability of the involved clocks these offsets may have to be estimated for every object pass individually as it is done in this study.

2.2. Available data

For this study two dedicated tracking campaigns were conducted during August 13-27 and September 7-14, respectively. As already indicated above, these campaigns involved the experimental laser ranging network comprising the three stations as shown by Figure 1. New hardware was installed at all sites as described in detail by [7]. Only mono- and bi-static range measurements were obtained during these campaigns but it is planned to additionally record angular telescope pointing data in future experiments. In the first campaign 32 objects were tracked successfully amounting to ranging data for 54 passes over all involved stations. Even more data, 162 passes of 35 objects, were obtained in the second tracking campaign. Most tracked objects are rather large rocket upper stages. Whereas bi-static tracking at the laser wavelength of 1064 nm was only performed from Wettzell to Stuttgart in the first campaign, it was additionally accomplished from Wettzell to Graz in the second campaign. The involved stations even succeeded in performing multi-static ranging to an upper stage on September 14 and to another upper stage on September 13 and 14, where both Graz and Stuttgart detected the photons transmitted by Wettzell simultaneously. For both objects Graz performed interleaved mono-static ranging at 532 nm yielding an unprecedented set of tracking data, namely two-color and multi-static laser ranging data (see also [8]).

2.3. Data filtering

Very sensitive detectors (e.g. single photon avalanche diodes) are employed to facilitate detecting a reasonable amount of signal echoes. Hence, in spite of spectral and temporal filters as well as a very narrow telescope field-of-view, the ratio of signal to noise counts is commonly very small. Object illumination, atmospheric background scattering, detector dark counts, and many other factors may render the signal track in the range residual plots merely recognizable. To retrieve these signals a filtering procedure that is well-established in satellite laser ranging is adopted, which iterates two successive steps until convergence: First, the orbit (e.g. initialized by the latest TLE) is adjusted by polynomials in radial, in-track, and cross-track directions based on the mono- or bi-static ranges of a single object pass. Second, the remaining residuals undergo 2.3 sigma screening. In case of bi-static range observations, clock offsets and clock offset variations having the approximate form of polynomials of equal or lesser degree than the orbit corrections are mapped into these corrections. Hence, they do not need to be estimated or modelled explicitly.

2.4. Limitations

The major constraints of laser ranging to space debris are related to weather, object and station illumination conditions, and operator and system availability. Comparing the number of tracked passes of a particular object with the total number of actual passes over several years may serve as a metric to coarsely quantify these constraints. To this end, we analyzed the tracking statistics of GOCE (about 230 km altitude), representative for very low LEO objects, and LAGEOS1 (about 5900 km altitude), representative for MEO objects, for the stations in Graz (Austria), Herstmonceux (UK), Zimmerwald (Switzerland), and Yarragadee (Australia). These two targets were included in the tracking schedules of the SLR stations during the entire considered time horizon without particularly high or low priority. Note that for these objects blind tracking (no particular illumination conditions required) was possible due to accurate orbit predictions and GOCE flying a sun-synchronous dawn-dusk orbit. We discuss illumination constraints, i.e. object visibility in the terminator/twilight zone, in the second part of this section.

Table 1 and Table 2 summarize the results of our analyses. Besides the total number of passes during the considered time horizon, the number of successfully tracked passes, and the relative share of successfully tracked passes with respect to the total number of passes are given. While the stations in Graz and Herstmonceux tracked a similar percentage of GOCE passes (about 10%), Zimmerwald was the considerably most productive among these European stations with nearly twice the relative amount of tracked GOCE passes (about 18%) - also in terms of absolute numbers. All this does not come close to the tracking statistics of the SLR station in Yarragadee, which successfully tracked about 44% of all passes. Hence, obviously weather conditions are the predominantly limiting factor in SLR. The generally higher number as well as the higher share of tracked LAGEOS1 passes may be attributable to its significantly longer pass times, during which only partial tracking may have been performed (interleaved with other targets). The overall pattern is very similar to the one obtained for GOCE. The European stations tracked between about 20 and 34% of all passes with Zimmerwald being the most productive one. Again, Yarragadee is in a class of its own with a share of nearly 90% of successfully tracked passes but a lower total number of passes owing to the targets orbit. Hence, for a station at mid-latitudes one may expect to track between 10 and 20% of all passes of a low LEO object and between 20 and 30% of all passes of a MEO object, when blind tracking is possible.

Table 1: Number of actual and observed GOCE passes between mid 2009 and end 2013. The right column contains the fraction of observed passes.

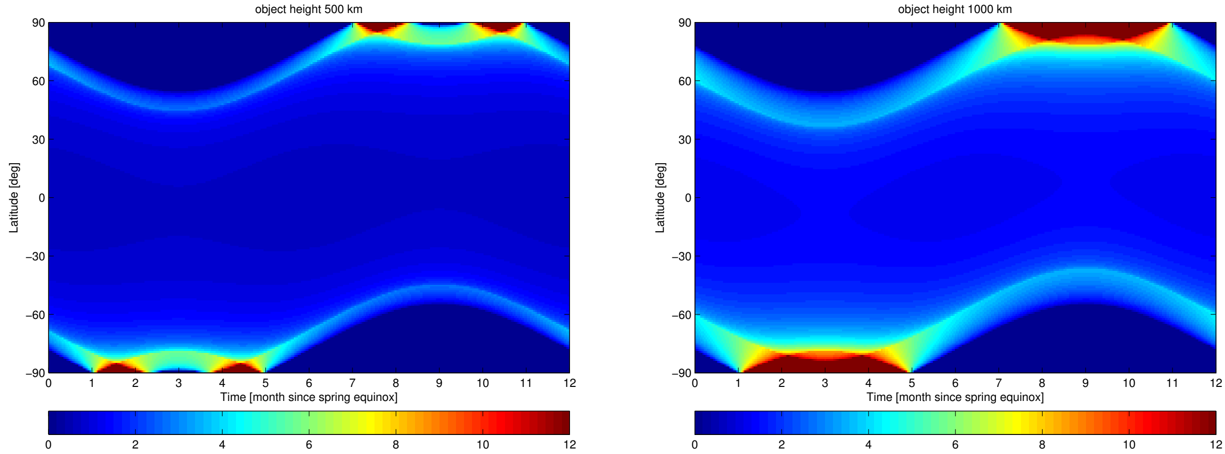
station	# total	# observed	obs./total
Graz	3263	326	10.0%
Hers	2047	240	11.7%
Yarr	2487	1094	44.0%
Zimm	2276	410	18.0%

Table 2: Number of actual and observed LAGEOS1 passes between Jan 2009 and Dec 2016. The right column contains the fraction of observed passes.

station	# total	# observed	obs./total
Graz	14710	2863	19.5%
Hers	13618	3419	25.1%
Yarr	9738	8427	86.5%
Zimm	14137	4760	33.7%

These numbers may reduce considerably as tracking is commonly limited to the terminator zone (about two hours at dusk and dawn, respectively) because of too inaccurate orbit predictions. In such cases active optical tracking of uncooperative objects must be guided by correcting the telescope pointing. This is possible when the tracking station is on the night side of the Earth or in twilight while the object is illuminated by the Sun. The duration of the evening visibility is thus the interval from the time when the sun is below the horizon of the station (by a certain angle) and the time when the object enters the Earth's shadow. This holds in reverse order for the morning visibility interval.

Figure 2 shows the dependency of the (morning or evening) visibility period as a function of time of year and station latitude for different object heights (500 km and 1000 km) for Sun elevation of -12°. It is assumed that the object is in zenith direction above the station and that observations are not yet possible in civil twilight but in nautical twilight. A Sun elevation of -12° is thus considered as the beginning (in evening) or ending (in morning) of the observation interval. We observe an increase of visibility duration for higher satellite altitude (due to the fact that they stay longer in sunlight), an increase of the visibility period for increasing latitude (due to the fact, that the duration the object is in sunlight increased faster



(a) (b)

Figure 2: Duration of the morning or evening visibility period as function of time and geographic latitude for an object at 500 km height (a) and 1000 km height (b) for the beginning/end of civil twilight, Sun 12° below horizon. Visibility duration is color coded in hours.

than the decrease of the duration of the night at the station), and a rapid decrease to vanishing visibility period for stations further north (as there is no longer night close to solstice).

With this limitation in mind, research into tracking outside the twilight zone will be highly relevant. A promising approach is the use of advanced CCD cameras, with which objects are visible from a station in daylight. Also, improving predictions based on previous tracking data (from the same or other laser ranging stations) and data fusion utilizing complementary sensors such as tracking radars may allow for blind tracking. Eventually, we consider automatic search and hold strategies based on realistic orbit uncertainty modelling as another approach to this problem.

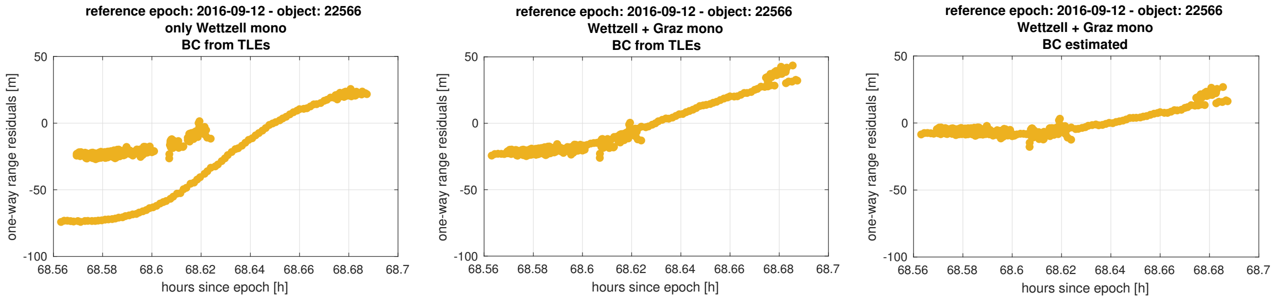
3. ORBIT DETERMINATION

Based on literature findings ([9, 10]) and our own processing results we state that obtaining reliable orbit predictions is very difficult when ranging data is sparse because the entire orbit determination process is weakly constrained. This is usually the case for laser ranging to debris objects, for which only limited data over a very local region might be available as in the present study. Much more stable solutions may be obtained when the force model parameters are not part of the estimation parameter set. Therefore, depending on the data at hand we choose to estimate only the object state vector (position and velocity) at a fixed epoch to avoid the risk of overfitting, which results from non-resovable parameter correlations. To this end, force model parameters for atmospheric drag and solar radiation pressure are derived from historical TLEs as described in [11]: The change rate of the semi-major axis is expressed as a function of atmospheric drag, which in turn is subject to the ballistic coefficient. Eventually, the problem is solved for the latter using numerical integration, a high-fidelity atmospheric density model, and the semi-major axis time-series data. Based on the ballistic coefficient a very rough estimation of the area-to-mass ratio and the solar radiation pressure coefficient is derived. Concerning the estimation of the ballistic coefficient, we apply a small modification to this method as we observe oscillations in semi-major axis time-series from historical TLEs in LEO regimes above 700 km altitude. Our approach fits a non-decreasing polynomial to the semi-major axis time-series, which replaces the original TLE-derived values. It demonstrates superior performance as compared to the cited method in our studies.

Moreover, fitting a high-fidelity orbit model to several TLEs as pseudo-observations results in improved initial values for the object state vector. Eventually, we found that orbit predictions might be particularly unreliable for parts of the orbit that are not observed by a local tracking scenario such as in the present study. The reason is that the generated orbits are only constrained in small arcs that are observed by the stations. This problem can be effectively tackled by fusing the ranging data with TLEs as pseudo-observations constraining the orbit globally as we will illustrate below. For the actual orbit determination we make use of high-fidelity force and observation models, which are commonly used in geodetic applications demanding even higher accuracies. The solutions are obtained in a common least-squares adjustment with a Levenberg-Marquardt optimization engine.

4. FIRST ORBIT PRODUCTS

The observations used to produce the orbits that are presented in this section were exclusively obtained during evening visibility intervals. Hence, the temporal spac-

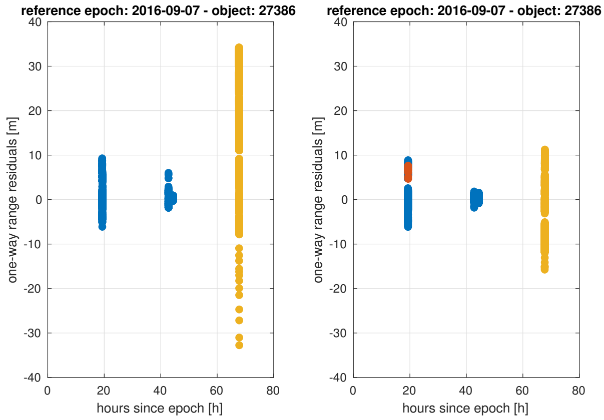


(a) (b) (c)

Figure 3: Third day prediction residuals from two-day orbit fit. Three Wettzell passes in fit (a); three Wettzell and two Graz passes in fit (b); same as (b) but ballistic coefficient (BC) estimated from data. The broad/narrow residuals correspond to Wettzell/Graz range residuals.

ing of tracked passes is always close to mutiples of 24 hours. Typically, no accurate reference orbits are available for space debris objects, which could be used to assess the quality of the orbit products computed on the basis of laser ranging data. Moreover, all of our post-fit residuals are in the range of the observation noise plus object size revealing no information about orbit inconsistencies. Leaving pass-wise observation data sets out and predicting orbits based on the retained data at these epochs allows to derive prediction residuals. This approach is essentially a variant of cross-validation and shall serve as a meaningful measure to quantify orbit product quality. However, we stress that with the terminator-induced, nearly 24-hour observation sampling and the poor observation geometries due to the spatially close tracking stations, the product quality may likely be worse in orbit regions farther away from mid-latitudes in the northern hemisphere. All plots presenting residuals show one-way residuals for mono-static ranges and residuals divided by two for bi-static ranges.

Figure 3 shows prediction residuals of object 22566 (NORAD ID) on day three following a two-day orbit adjustment. The adjustment incorporates data of three passes tracked in mono-static mode by Wettzell (a) and two additional passes tracked in mono-static mode by Graz (b). The third scenario (c) is identical with (b) except that the ballistic coefficient is estimated based on the sufficient amount of available laser tracking data for this object. The broad residual plots belong to Wettzell and the narrow residual plots belong to Graz as their data underwent a sort of low-pass filtering in pre-processing. While TLE-based one-day range predictions have commonly errors in the range of a few hundred meters, our predictions are considerably smaller. Including mono-static ranging data from Graz (b), the predicted residuals further improve and become more consistent. Even smaller residuals with an adjusted ballistic coefficient underpin the fact that this data set is indeed suitable for estimating this parameter without overfitting. The effect of adding range data from a second station is confirmed by the whole range of blue (Wettzell) and red (Graz) mono-static post-fit residuals with the resulting prediction residuals (yellow) for ENVISAT (27386) as given by Figure 4.

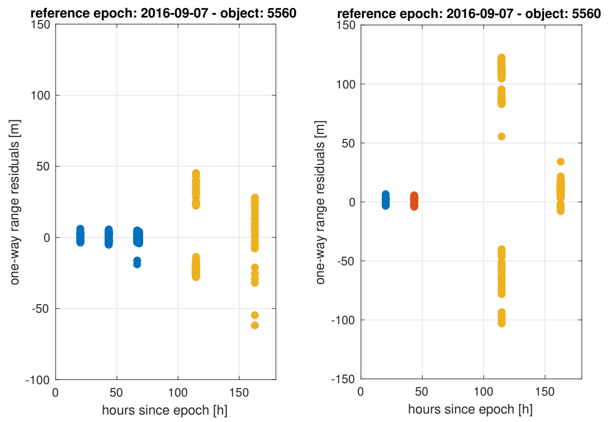


(a) (b)

Figure 4: Mono-static post-fit range residuals corresponding to Wettzell (blue) and Graz (red) and prediction residuals (yellow). Adding mono-stating ranging data from a second station (b) improves the prediction residuals, and thus, at least the associated orbit arc.

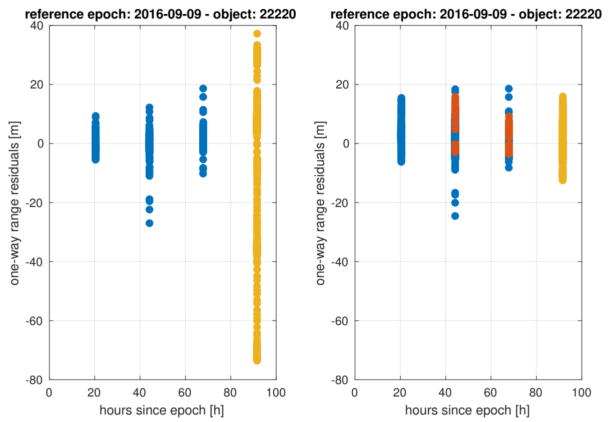
The benefits of bi-static ranging data shall be demonstrated based on two other objects and data sets. First, one may be faced with a situation of very sparse data, for example owing to the aforementioned tracking limitations. While no meaningful orbit can be computed with the mono-static tracking data shown in Figure 5 (b) (blue), adding some bi-static ranges renders orbit determination possible. Beyond that, the resulting predictions are still clearly superior to TLE predictions and not even much worse than the ones that can be produced with the convenient situation given by Figure 5 (a).

Second, Figure 6 shows how adding bi-static ranging data can further improve an orbit solution that is based on mono-static ranging data only. In the shown scenario one-day range prediction errors can be reduced from about 80 m to less than 20 m, which is about the amplitude of system noise plus object dimensions. Note that there is not even an active transmitter necessary at the receiving site to obtain these bi-static observations.



(a) (b)

Figure 5: Blue residuals correspond to mono-static ranges (Wettzell), red residuals correspond to bi-static ranges (from Wettzell to Graz), and yellow indicates residuals (Wettzell) predicted on the basis of the orbit product from the first three days. (a) Favorable situation with a sufficient tracking data. (b) Too little tracking data does not allow for orbit determination until at least some bi-static observations are added.



(a) (b)

Figure 6: Additional bi-static range observations (red) may help to significantly improve orbit predictions (yellow) based on purely mono-static laser ranging data (blue).

CPF files contain orbit predictions derived from SLR data in a standardized format. These predictions are commonly used by SLR stations for their tracking operations. The defunct satellite ENVISAT is equipped with retro-reflectors, whose visibility can be well predicted due to its relatively stable spin axis. Therefore, it is tracked by many SLR stations as a (partially) cooperative target. Comparisons of our ENVISAT orbit products with the best available CPF predictions, which are produced from more globally distributed laser ranging data, shall serve as an indicator for the absolute orbit accuracy. Figure 7 illustrates that during observation epochs both products

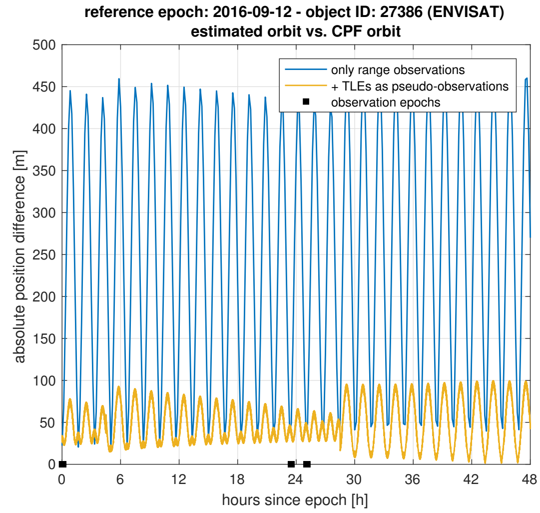


Figure 7: Absolute position differences between our laser-only solution as well as a combined laser-TLE solution and a CPF orbit of ENVISAT computed from laser ranging data of the global ILRS network. Discontinuities result from CPF boundaries, i.e. concatenating subsequent CPF files.

come very close (blue curve). By contrast, in areas of the orbit, which are far away from our three tracking stations, the orbit position differences reach their maximum. In addition, the remarkable effect of data fusion with TLEs as pseudo-observations becomes apparent in these differences (yellow curve). Importantly, for very sparse tracking data, e.g. single pass ranges, data fusion with TLEs may be the only way to utilize the laser observations for improved prediction if no other complementary data is available.

5. CONCLUSIONS

This paper presented laser tracking as an observation technique for accurate orbit determination of space debris on the basis of real range measurements. We stressed its outstanding benefits like high precision independently of target distance and size and low costs as compared to radar tracking. In addition, we analyzed its inherent constraints, namely tracking limited to cloudless skies and convenient object illumination conditions in the terminator zone. In this regard, we proposed using advanced CCD cameras to make the objects visible in daylight conditions, developing automatic search and hold strategies based on realistic orbit uncertainty products, and improving orbit predictions by means of heterogeneous sensor data fusion. With the latter idea in mind and the sparse data at hand, we stated a method to regularize the weakly constrained orbit determination problems by deriving force model parameters from TLE data. That followed, we demonstrated the notable range prediction accuracies derived from single-station mono-static ranges as well as additional mono-static ranges from a second station. We presented results highlighting the benefits of bi-static ranging data to further improve predictions or to make the solution of an otherwise singular orbit determination problem possible. Eventually, we indicated the potential of fusing laser ranging with TLE catalog data to regularize the problem and obtain orbits that are meaningful also in regions that are not observed by our spatially close tracking network. We conclude that further data fusion with additional observations such as angular encoder data, which can be recorded during laser ranging, or data from tracking radars is a promising direction of further research.

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