Validation and Assessment of Space Debris Orbits based on Two-Color and Multi-Static Laser Ranging

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Abstract. *In the framework of the ESA GSTP study "Accurate Orbit Determination of Space Debris with Laser Tracking / Tasking" both two-color and multi-static laser tracking data was acquired. We validate these observations and assess orbits computed on their basis. In this context, we deliver insight into the technology's accuracy and precision by comparing observed versus computed measurements from reference orbits and by assessing their high-frequency components with regard to object geometries. Moreover, based on post-fit and cross-validation residuals of our orbit products we validate the overall processing procedure which comprises data filtering, estimating force model coefficients from Two-Line-Elements (TLEs), as well as the actual orbit determination process. Eventually, further comparisons with external orbit data support our statements about the validity and quality of our data and orbit products, respectively.*

1 Introduction

The rapidly growing number of space debris objects poses an increasing threat to operational satellites and manned space missions. Accurate orbit determination forms the basis of most fundamental activities such as contingency analyses and collision risk assessments. To this end, the concept of debris laser tracking is a promising extension of SLR to provide timely and accurate data with the technology's well-known advantages. In addition, the combination of high pulse energies and generally irregular shapes of debris objects facilitates bi- or multi-static ranging, thereby maximizing the obtainable information content. In the framework of the ESA GSTP study "Accurate Orbit Determination of Space Debris with Laser Tracking / Tasking" we successfully performed multi-static laser ranging to debris objects with mono-static ranging interleaved at a second wavelength.

We report on our validation studies concerning both the measurements themselves and the orbit products computed on their basis. To this end, we first introduce the data available from our tracking campaigns and the subsets considered in this paper. In this context, we describe a method for filtering noisy bi-static range observations. Subsequently, we detail our approaches to address typical issues in orbit determination of space debris based on sparse and ill-distributed range measurements, namely the estimation of an initial orbit as well object-specific force model parameters based on TLE data. We split the actual validation studies in two logically connected parts – validation of the range measurements and validation of the orbit products. The former presents range residuals w.r.t. benchmark orbits (absolute ranging accuracy) and w.r.t. kinematic single-pass solutions (validation of high-frequency components). The latter introduces the orbit determination scenarios, gives insights into the post-fit range residuals, presents cross-validation range residuals, and discusses orbit solutions with respect to external orbit data.

2 Data

For this study two dedicated tracking campaigns were conducted during August 13-27 and September 7-14, respectively, which involved the SLR stations in Wettzell and Graz as well as a new debris laser ranging station set up in Stuttgart. New hardware was installed at all sites as described more in detail in [1]. 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, spent upper stages of rocket bodies. Whereas bi-static tracking at the laser wavelength of 1064 nm (vs. 532 nm in mono-static mode) 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 the upper stage with NORAD ID 18187 on September 14 and to the upper stage with NORAD ID 22566 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. For orbit determination, and hence for our validation studies, the temporal distribution of the data is at least as important as its mere amount. In this regard, the outcomes of the second campaign are particularly convenient. Table 1 shows the temporal distribution of successfully tracked passes of the objects 22220, 22566 (both large SL-16 rocket bodies), and the object 23768 (Envisat). The subsets that serve as the basis for most of our validation tests are highlighted by bold frames. The shaded background in the middle row indicates successfully performed multi-static ranging.

22220 (SL-16 R/B)	2016-09-09	2016-09-10	2016-09-11	2016-09-12	2016-09-13	2016-09-14
Wettzell	X		X	X	X	X
Graz				X	X	X
Graz bi					X	X
Stuttgart bi				X		

22566 (SL-16 R/B)	2016-09-09	2016-09-10	2016-09-11	2016-09-12	2016-09-13	2016-09-14
Wettzell				X	XX	X
Graz				X	X	XX
Graz bi					X	X
Stuttgart bi				X	X	X

27386 (Envisat)	2016-09-07	2016-09-08	2016-09-09	2016-09-12	2016-09-13	2016-09-14
Wettzell	X	X	X	X	XX	X
Graz				X		X
Graz bi						X
Stuttgart bi		X	X		X	

Table 1. Temporal distribution of the tracked passes of the objects 22220, 22566 (both SL-16 R/B), and Envisat (23768) by the three stations in Wettzell, Graz, and Stuttgart.

To filter bi-static time-of-flight data we iterate two alternating steps until convergence: First the orbit (initialized by the latest TLE) is adjusted by polynomials in radial, in-track, and cross-track directions based on the bi-static ranges of a single pass. Secondly the remaining residuals undergo 2.3 sigma screening. Informally, this procedure assumes that the signal-to-noise-ratio is high enough to form a recognizable track in the residual plot. Moreover, clock offsets and clock offset variations, which can be modeled by polynomials of equal or lesser degree than the TLE orbit corrections, are mapped into the orbit, and hence, do not need to be estimated or modeled.

3 Orbit determination

We found that estimating force model coefficients from two-day data sets as processed in our validation studies may considerably corrupt the orbit validity. The reason is that the orbit determination process is only weakly constrained by sparse and localized data as available from our tracking campaigns. Hence, considering 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. Force model parameters for atmospheric drag and solar radiation pressure are derived from historical TLEs as described in [2]. 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 700km 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. Eventually, fitting a high-fidelity orbit model to several TLEs as pseudo-observations results in improved initial values for the object state vector.

To validate resulting orbit products we define two scenarios for object 22566, which is a large SL-16 rocket body, as well as the defunct satellite Envisat, respectively (see Table 2). Here we note that statements derived from the orbit products may only be valid in the context of these scenarios, but may be good indicators of the validity of our data as well as the associated data processing pipeline. There is a relatively large amount of data available for both objects and for the latter we even have orbit predictions in the form of CPF data from the ILRS for comparisons. For each object we define one full orbit determination scenario, which incorporates all data in the orbit determination process, and one validation scenario (in brackets in Table 2), which omits a certain portion of the data for cross-validation purposes.

Object	Scenario	2016-09-12	2016-09-13	2016-09-14
22566	#1	W	2 x W	W
(SL-16 R/B)		G	G	2 x G
	#2	W	2 x W	[W] (cross-val.)
		G	G	[2 x G] (cross-val.)
23786	#1	W	2 x W	W
(Envisat)		G		G
	#2	W	2 x W	[W] (cross-val.)
		G		[G] (cross-val.)

Table 2. Orbit determination scenarios with mono-static ranges from Wettzell (W) and Graz (G).

4 Approach

Our validation studies are split into four parts, of which the first two are concerned with the mere measurements and the latter two with the resulting orbit products:

- <u>Absolute range validation:</u> This is to verify that the observations measure what they are intended to measure with the desired accuracy. Geodetic laser satellites provide highly accurate reference orbits for this purpose.
- <u>Relative range validation:</u> Kinematic single-pass solutions based on mono-static tracking data are obtained. The kinematic post-fit range residuals can be used to analyze noise as well as high-frequency signal components.
- <u>Cross-validation:</u> Subsets of the tracking data are left out in the orbit determination process. Subsequently, they are compared to the theoretical observations as one would obtain from the resulting orbit product.
- <u>Comparison of orbit products against external orbits:</u> In this context, we analyze the orbit products for Envisat, for which relatively good CPF orbit predictions are publicly available for comparisons.

5 Results

Absolute range validation: To validate the absolute ranging accuracy and stability against theoretical values from accurate orbits we are limited to geodetic targets, which were not part of our tracking campaigns. For all other tracked objects, no reference orbit products are available with accuracies serving this purpose. Figure 1 shows the range residuals of mono-static ranges from Stuttgart with respect to a LARES orbit. LARES is a geodetic laser satellite with convenient orbit and object properties facilitating precise orbit determination. Figure 1 clearly demonstrates that the observed ranges are consistent with this orbit to the 2m level. In addition, the resulting RMS does not exceed the expected RMS of the tracking system. Consistent results were found for mono-static laser ranging data from the debris lasers in Wettzell and Graz.

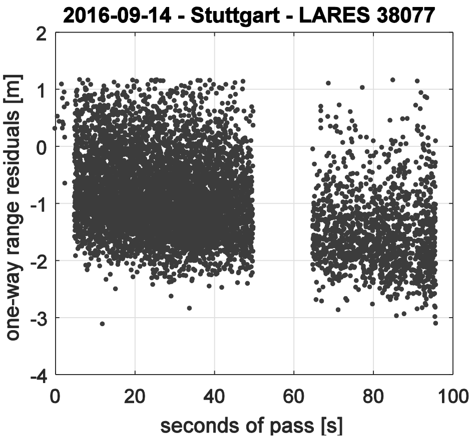

Figure 1. Range residuals w.r.t. a LARES benchmark orbit.

	SL-16 R/B	SL-8 R/B
Length [m]	10.4	6.0
Diameter [m]	3.9	2.4
Mass [kg]	8300	1400

Table 3. SL-16 and SL-8 R/B properties.

Relative range validation: Two object types provide a good basis for these validation studies, namely the SL-16 and the SL-8 rocket bodies. The reason is that these are very typical debris objects, which differ significantly in their geometrical dimensions. Moreover, most tracking data from our two campaigns is related to such objects, for which Table ***3*** lists some basic properties. We expect a dependency of the kinematic post-fit residuals on object dimensions as the object will be viewed from different angles due to attitude motion and varying pass-geometry. Moreover, the points of pulse reflection on the object surface will be randomly distributed causing larger post-fit RMS values for larger objects. Exemplarily, the left and center plots of Figure 2 show kinematic post-fit residuals of the two described objects for mono-static range data from Wettzell. Both figures demonstrate that these residuals are well within the expected bounds. Moreover, a nice result is the clearly recognizable correlation with object size. In addition, the right plot of Figure **2** shows kinematic post-fit residuals of Envisat passes, for which the retro-reflectors were visible from Wettzell. This results in very small post-fit residuals as expected.

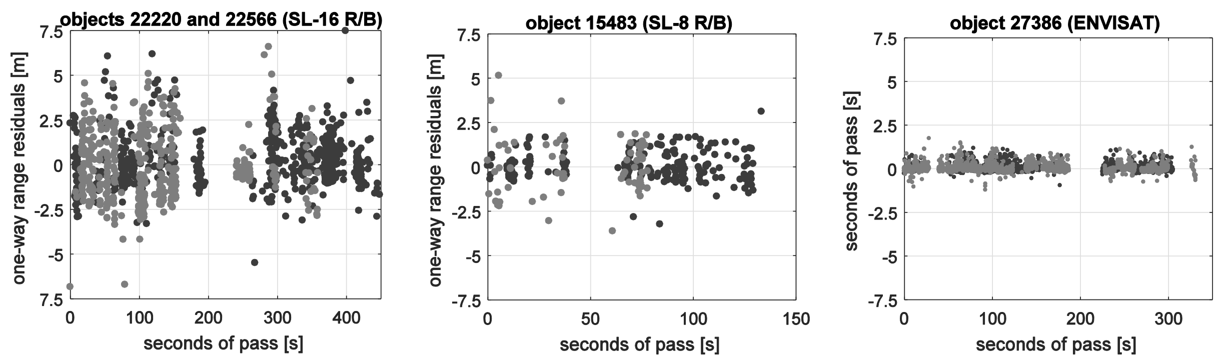

Figure 2. Kinematic single-pass range residuals for mono-static ranges from Wettzell.

Post-fit range residuals: Post-fit range residuals for the full-data orbit determination scenarios of Table 2 indicate how well all components – real data, observation models, and dynamics models – fit together. Ideally, these residuals should be equal to the mere observation noise implying perfect system modeling.

Not least in view of unknown laser pulse reflection points as well as unmodeled object geometry and attitude dynamics this will never be the case. In addition, setting force model parameters to their TLE-derived values contributes to this fact. With that in mind, Figure 3 and Figure 4 illustrate remarkably small post-fit range residuals for both objects and scenarios as defined in Table 2. Besides the obvious difference in noise levels between FRD (Wettzell) and NPT data (Graz), these results even give a hint on the differences of dominant reflection points w.r.t. the objects' center of masses as seen by the two stations.

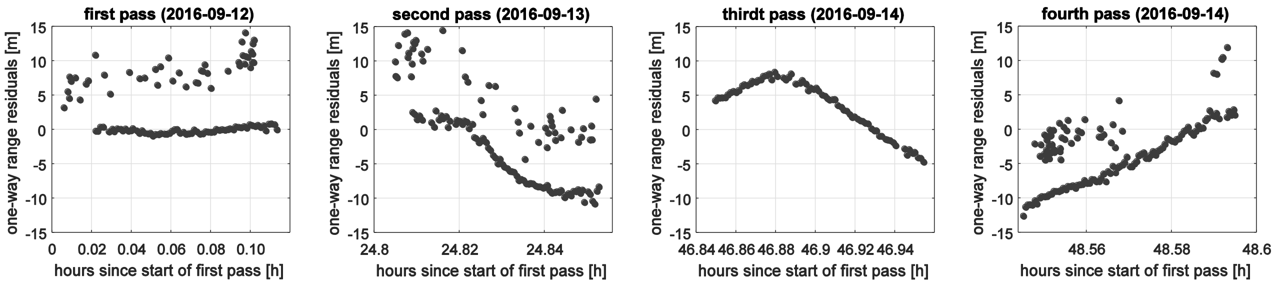

Figure 3. Post-fit range residuals for scenario #1 of object 22566 (see Table 2).

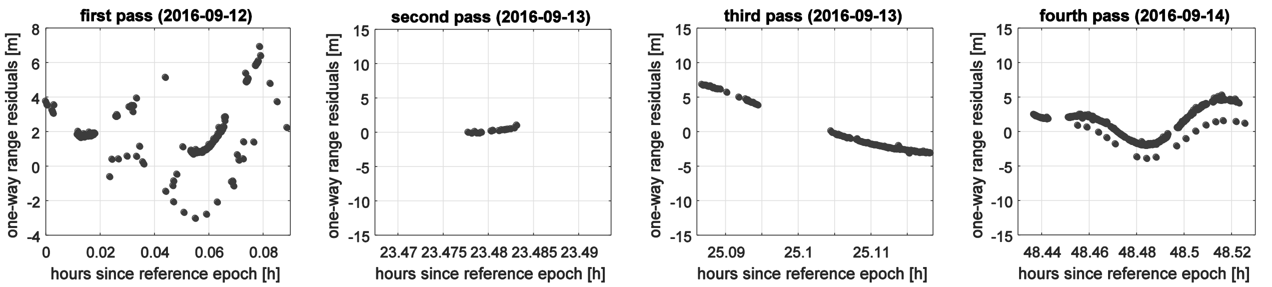

Figure 4. Post-fit range residuals for scenario #1 of object 27386 (see Table 2).

Cross-validation: First we address cross-validation results for scenario #2 of object 22566 and Envisat, respectively (see Table 2). In both cases, all available observations from the first two consecutive days are included in the data set for orbit determination. Figure 5 (left and center) shows the predicted residuals of our two-day orbit and the TLE prediction along with the post-fit residuals of the three-day orbit for scenario #1 of object 22566 (see Table 2). While the TLE residuals are in the range of several hundred meters, the predicted range residuals resulting from our two-day fit spans are always well below 50m, thus constituting a remarkable improvement. It may further be noted that the predicted range residuals are very close to actual post-fit residuals with differences smaller than 30m. The same holds for scenario #2 of Envisat, which is illustrated by Figure 5 (right). In this case, the difference between predicted range residuals and actual post-fit range residuals is even smaller, amounting to no more than 15m. Remarkably, our laser ranging based predictions are even better than the CPF predictions provided by the ILRS, which build on a much higher number of tracking SLR stations.

Next we present a representative cross-validation test for our bi-static ranging data. Orbit determination is performed once for the standard scenario #2 of object 22566 (see Table 2) and once for the same scenario but with additional bi-static ranging data from Wettzell to Graz during the object's first pass over Central Europe on the second day in the fit span. The mono- and bi-static post-fit range residuals for both cases indicate how well the two different data types can be matched in a unified processing framework (see Figure 6, left). Moreover, for both cases the accuracy of the predicted range data on the third day (i.e. the validation passes) is assessed (see Figure 6, right). To some extent, this reveals the contribution of the bi-static ranging data to improve range predictions at future epochs, i.e. that the range prediction accuracy can be slightly improved by additionally incorporating bi-static ranging data.

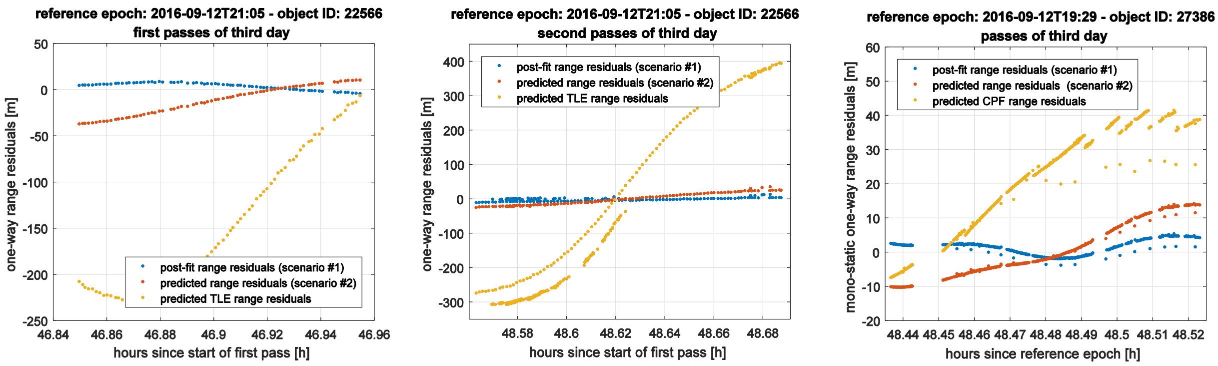

Figure 5. Mono-static range residuals for object 22566 (left and center) and 27386/Envisat (right).

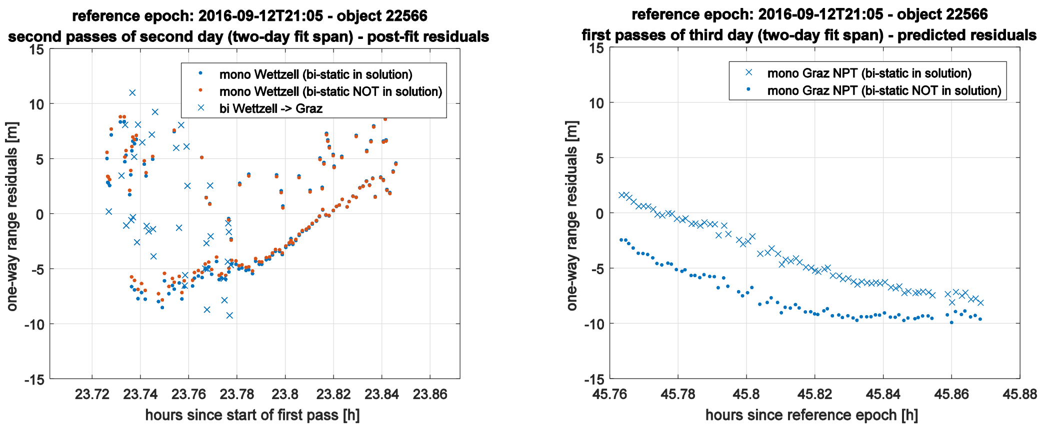

Figure 6. Post-fit (left) and cross-validation residuals (right) including bi-static range data.

Comparison of orbit products against external orbits: Comparisons of our Envisat orbit products with the best available CPF predictions from DLR, which are produced from more globally distributed laser ranging data, shall serve as an indicator of the overall orbit validity. Figure 7 (left) shows that during observation epochs of scenario #1 (see Table 2) both products come very close implying both the suitability of the CPFs as a coarse reference and the increased accuracy of our solution whenever laser ranges were recorded. By contrast, in areas of the orbit, which are far away from the tracking stations, the orbit position differences reach their maximum, which is still considerably smaller than the maximum of the differences w.r.t. the TLE orbit. Figure 7 (right) further reveals that the main improvement of our orbit product with respect to TLEs is due to the particularly improved along-track component.

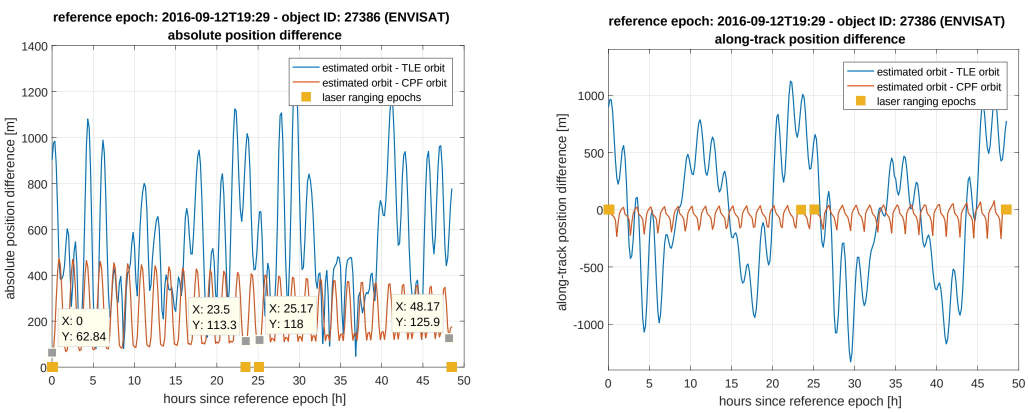

Figure 7. Absolute (left) and along-track (right) orbit differences of our Envisat product (scenario #1).

6 Conclusions

In our studies we first validated the absolute ranging accuracy with RMS values of less than 1.0m with respect to geodetic reference orbits. With respect to known debris targets (large upper stages and spent satellites) we additionally showed that amplitudes of the high-frequency signal components are not merely due to system noise but also due to varying points of pulse reflection, and hence, due to object geometry. Our orbit determination efforts revealed that obtaining reliable orbit products and predictions is very difficult when tracking data is sparse and obtained by a spatially close set of stations as in this study because the orbit determination process is only weakly constrained. Much more stable solutions were obtained when the force model parameters were not part of the estimation parameter set. The resulting orbit products still yielded acceptably small post-fit residuals and considerably improved predictions as compared to TLEs. Remarkably, being in the order of few tens of meters our predictions of Envisat were even distinctly smaller than CPF predictions (DLR), which are produced from more globally distributed laser ranging data. The cross-validation studies further revealed that adding bi-static observations can further reduce range prediction errors. Eventually, comparisons of our Envisat orbit products with the best available CPF predictions underlined the absolute orbit validity.

Acknowledgement

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References

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