Validation & Qualification of Space Debris Laser Systems at the Expert Centre for Space Safety

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Abstract

To pave the way towards a sustainable use of the outer space, the Expert Centre for Space Safety (ExpCen) co-ordinates data acquisition and exchange for passive and active sensors operating in different spectral regions, and configurations, aiming at diverse target objects. Within the optical regime, ongoing efforts address the validation and qualification (V&Q) of passive optical and space debris laser ranging sensors, which is an integral service that comprises the interfacing and tasking of the candidate sensor, in addition to retrieving and post-processing the acquired observations to ensure the compliance with predefined quality metrics. The candidate sensor will be certified for participating in future campaigns, after successful completion of V&Q, besides being provided with technical support and system-related feedback to successfully complete the V&Q.

Regarding active optical systems, the ExpCen does not only profit from the profound legacy from the Satellite Laser Ranging (SLR) community, but the outcome of different activities conducted within the development and establishment of the ExpCen.

In this presentation, we will describe the architecture of the ExpCen laser ranging processing engine, including algorithms, new in-house developments and future improvements. Furthermore, after the compilation of results and lessons learnt from past activities, we redefine the requirements for validation and qualification of candidate sensors.

Introduction

The uncontrolled proliferation of human-made objects in the outer space prevents the exploitation of the latter in a sustainable way. Any remediation activity towards its sustainable use needs information about an extended state vector comprising not only the position and velocity of the target object of interest, but also information regarding its physical characteristics. The quality of the ranges observed with laser ranging systems has the potential to improve the knowledge of the orbit significantly. Within this context, the analysis of space debris (SD) laser systems becomes imperative. In this work we focus on determining the quality, performance and stability of a given space debris laser system to ensure an optimal exploitation of the observable.

Problem Statement

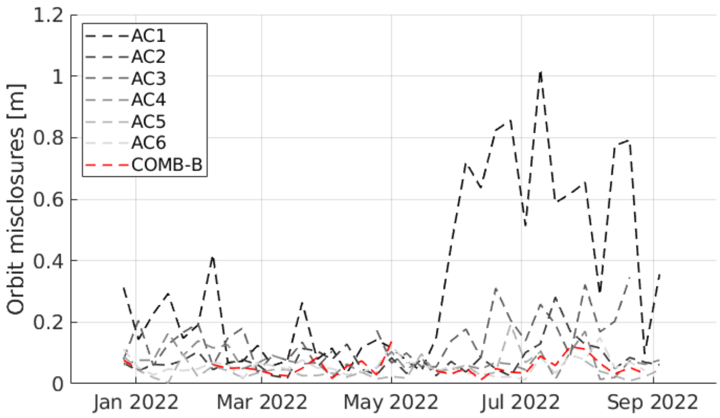
Given single passes from a single station derive quantitative figures for the assessment of the quality of the observable. In a first instance, we shall inspect our modelled one-way range as:

$$\rho = \|X^S(t) - X_R(t)\| + Tro + Sys + CoM + Rel + Rb + \varepsilon.$$

Where X^S are the coordinates of the satellite, X_R the coordinates of the station, *Tro* the tropospheric path delay, *Sys* the system delay, *CoM* the centre of mass correction, *Rel* the general relativistic correction, *Rb* the range bias and ε the inherent measurement error. All terms in units of length. Next, we will focus on the error contribution per each term in the modelled range.

Satellite Coordinates

To assess the error of the orbits, we took all 7-day-arc Lageos-1 solutions available from the beginning of 2022 until September 2022, from the different Analysis Centres (AC) from the International Laser Ranging Service (ILRS). Those orbits are co-estimated with station coordinates and Earth orientation parameters. During the analysis of the different solutions, we noticed that only few ACs propagate the solution until the first entry of the next solution, which is a requirement for assessing the so-called orbit misclosures. For those solutions where there was no overlap, we propagated the orbit using Lagrange polynomials of 12th degree. To control the error committed by extrapolating the state, we took the 13 entries prior to the last entry, performed the extrapolation and compared against the last entry, which was found tolerable, i.e. < 5 cm, until 6 minutes after the last propagation. We show the results in the next figure.



We took as a reference (red) the solution provided by the combination of all solutions provided by all analysis centres. We found the average misclosures value to be of about 10 cm. In a second step, we wanted to validate how good were the predictions provided in the form of Consolidated Prediction Format (CPF), since those are generated with a higher latency. Overall, after comparing different solutions in time, the average error was found to be of 30 cm. This value will determine which other corrections are needed to correct the data.

Station Coordinates and Eccentricities

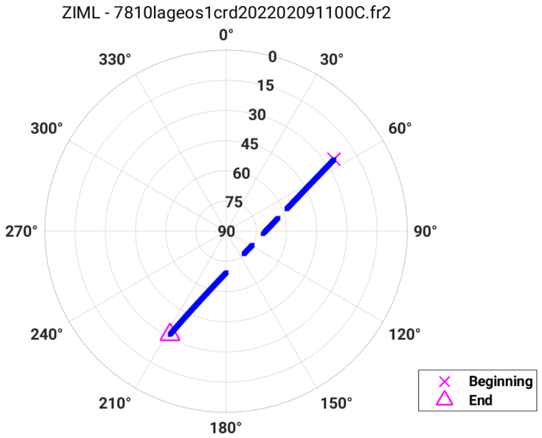
For this term, we distinguish two scenarios:

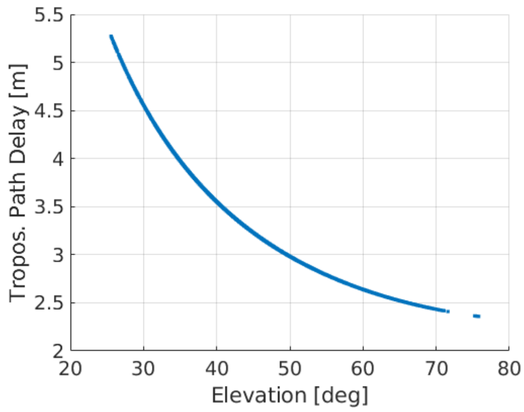
a) Coordinates are estimated within the ILRS framework: the station is included within the network of stations that define a reference frame. If the station of interest passes the internal qualification requirements from the ILRS, there will be available coordinates, velocities with their respective formal errors. Note that the Expert Centre applies corrections to the station coordinates, such as post-seismic deformations, tidal effects, etc., within the V&Q only when their impact is larger than 30 cm.

b) SD laser systems have a typical pulse width at the nanosecond level. The inclusion of these systems within the existing network will worsen the overall solution from the different AC of the ILRS. One possibility to avoid that impact would be to create a pipeline in collaboration with an AC in which we may obtain coordinates using the ILRS reference frame, but without affecting their released solutions. On the other hand, systems that wish to be agnostic to any existing network may consider that for the time being we rely on the reference frame provided by the ILRS, the reason being the profound existing legacy. Nevertheless, the Expert Centre is able to perform conversions between different reference frames.

Tropospheric Path Delay

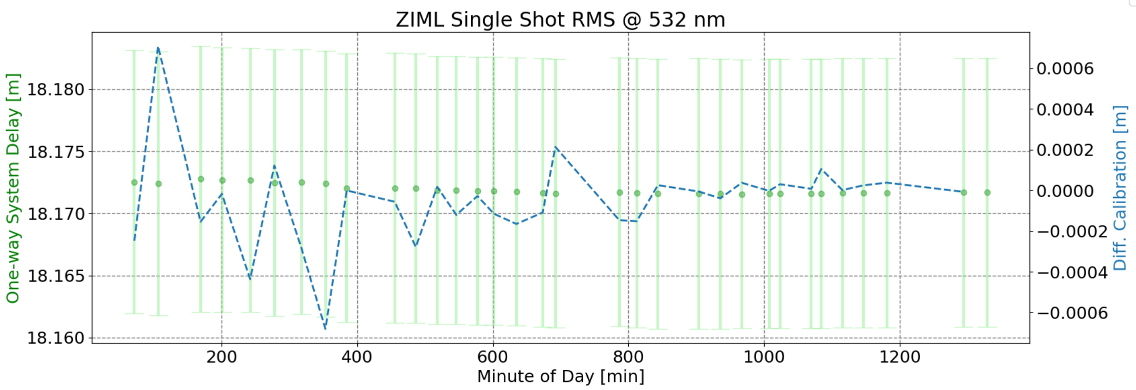
An example of the path delay from an observed pass at the SwissOGS Zimmerwald is provided in the next figure. The delay depends on the relative geometry of the observed pass, the employed wavelength and meteorological information available at the epoch of observation. At the Expert Centre, we have implemented two well-known models: Marini-Murray and Mendes-Pavlis.





System Delays

By definition, the system delays are the residuals after subtracting a fiducial range from the ToF measurements to a so-called calibration target. In the next plot, we see the corresponding system delays available after one day of observations at the SwissOGS Zimmerwald.



From such a historical set, we can verify certain aspects such as the agreement between the pulse width and the scattering of the single shot measurements, besides the stability of the system delays over time. Note that ideally, we would request potential sensors undertaking the V&Q procedure to provide a longer time span analysis to have a more representative figure.

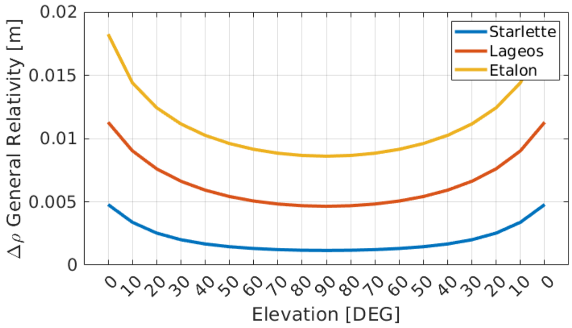
Centre of Mass Correction

During the validation and qualification procedure at the Expert Centre, the two procedures include ranging to targets carrying a retroreflector – for the validation – and ideally targets without any known reflecting element. Note that in the last case we shall include those decommissioned cooperative satellites, which do not have a controlled attitude or even rocket bodies from which evidence was gathered pointing into the existence of even more than one reflective element.

In general, for selected target objects, and stations, the centre of mass correction is provided by the ILRS. For SD laser systems, we consider only the geometrical correction when using geodetic cannon ball like satellites for the validation of the candidate station. One typical fiducial target is Lageos-1 for which we use only the standard centre of mass correction of 251 mm.

Other corrections

Other corrections due to the so-called Sagnac effect, the light travel time, or the light path bending due to general relativity are applied. In the next figure, we show the impact of the light path bending on the observed range for satellites orbiting at different altitudes.

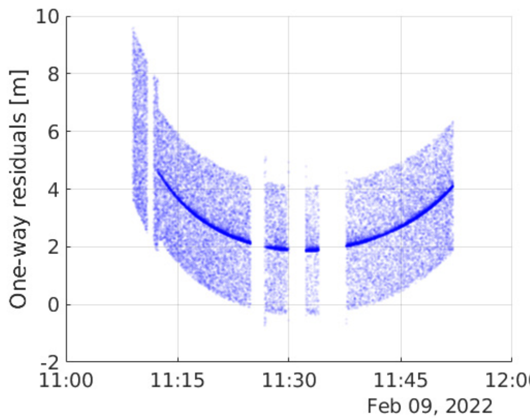


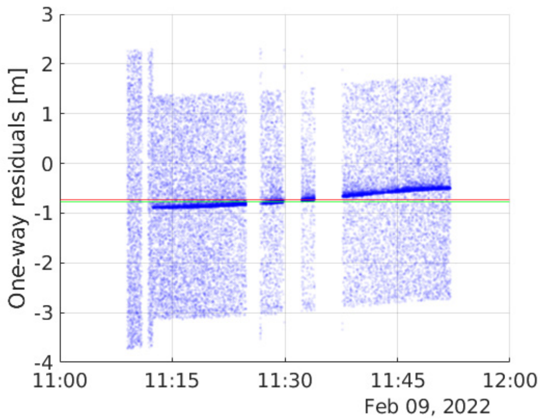
Note that if compared to the error that we obtain from the orbits, the order of magnitude of the correction due to general relativity will not play a crucial role. Furthermore, it is highly correlated with the tropospheric correction.

Example

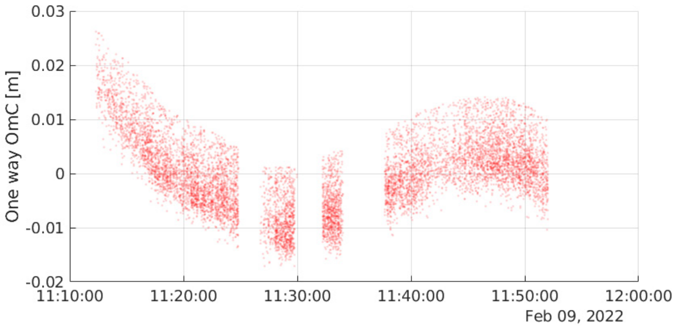
In the next figure, we show the detected signal from Lageos-1 observed at the SwissOGS.

On the left, we see the measurements after correcting only for the calibration constant, while on the right we





show the final residuals after applying all corrections. In green and red, we show the mean and median of the data set respectively. Even after the corrections, we see that the residuals are not centred on zero, suggesting a potential range bias, and that there is a symmetrical trend indicating a potential time bias. One way to model those effects is by expanding the observable in Taylor series of 1^{st} order. Next, we show the residuals after filtering the detections from the backscattered signal of the object together with the estimation of the so-called time and range biases.



The results show that we can improve the residuals, however, one should notice the slight trend on them. This trend may be further removed if we modelled it as variations in the coordinates of the satellite, i.e. the orbit. Additionally, if there are available subsequent passes, we can check the consistency of the estimated range and time bias if we use the same set of ephemerides.

Road map

This subsection summarizes our current procedures and protocols for the post-processing of satellite laser ranging data at the Expert Centre for Space Safety. We define the post-processing segment as the sequence of operations conducted from the retrieval of observations and predictions until the delivery of observables in specific formats. The final products are:

- Filtered full-rate data (Level-0): Once the raw data from one pass is available, we correct for system delays and atmospheric refraction. For those corrections, we make use of the values obtained in the specific entries of the CRD file format. To correct for the atmospheric propagation error, we use the standard model developed by Marini and Murray to compute the time-of-flight delay. Note that some stations perform the corrections by themselves, thus enabling us to skip this step. With the corrected time-of-flight measurements, and predictions, we can form differences and compute the so-called observed minus computed (OmC) term. The main goal of this processing level is to identify photoelectrons coming from the target. In statistical terms, the problem corresponds to a binary classification: an entry can be either signal or noise. In order to discriminate the signal from the noise there are two main methods available: geometrical and dynamical binning. The geometrical method makes use of the dispersion of successive measurements in the OmC space. It is the usual approach implemented in many traditional SLR stations. To account for non-flat signatures on the signal, we enhance the method and perform differential binning. Differential binning exploits the fact that the difference between successive OmC entries will remain constant, within a reasonable time span, for those photoelectrons coming from the target. The dynamical approach consists of the orbit improvement of only one orbital element: the perigee passing time. The estimation of the perigee passing time makes use of the variational equations, i.e. how much does my observable change due to a variation in the perigee passing time. We compute such variations per observation, applying conveniently the chain rule, and construct a measurement window with n observations where we finally perform a Majority Voting step to discriminate, which observations come from the target.

- Normal-point/full-rate data (Level-1): The Level-0 data will contain false-positives detections e.g. in situations with a strong background such as daytime. Furthermore, flattening of the signal for the generation of normal points is imperative. In order to remove trends and false positives, the satellite-fixed reference frame is used for representing OmC entries. The method used for detrending is usually a polynomial fitting that rejects data values with a residual that exceed the a posteriori 3-sigma criterion. For the generation of Level-1 data, we do, instead of polynomial fitting, an orbit improvement using the pointing direction of the telescope for enabling the estimation of differential corrections to the a priori six Keplerian elements that define the orbit. If a particular station does not provide pointing information, we can retrieve it from the predictions. Appropriate handling of the weighting becomes critical when using pointing information. The rejection of outliers and detrending is crucial for the normal point formation according to the Herstmonceux normal point definition. The output of the Level-1 are either normal points, cleaned full rate, or both in the CRD or TDM format. Note that due to the observed short arcs, mainly in non-cooperative target passes, we recommend to use cleaned full-rate data instead of normal points for space debris targets. The use of full-rate data will turn critical if further attitude and attitude motion analysis will take place.

So far, only data from one pass was analysed. If several passes are available, we can validate that the measurements come from the same target and generate improved ephemerides that will allow for even a comparison against a reference orbit (if available). We define a new processing level as consistency check; within it, we distinguish the following sublevels:

- Consistency Check (Level-2.0): This consistency check evaluates the estimated time bias (along-track error) and range bias (radial error)for successive passes observing all of them using the same set of predictions. It proved to be useful when observing passes close to each other so that the ephemerides have not changed significantly due to the different perturbations acting on the target. For our case, we estimate the time bias using the variational equation for the perigee passing time, as in the dynamic filtering used in Level-0.

- Consistency Check (Level-2.1): If more than few hours have passed and the Level-2.0 does not qualify the observation campaign, a different approach may be used. The main features of this level of processing is the orbit improvement of several arcs merging pointing angles and ranges. The use of pointing angles aims at the improvement of the otherwise weakly constrained orientation of the orbital plane. The tool used for this qualification is the in-house software tool SATORB. The convergence of the least-squares solution implies that there is an orbit to which the observed arcs fit minimizing the mean squared error. If more than two passes are available, one pass will be left out of the orbit improvement and compared against the predicted measurements that will come from the orbit improvement using the other two or more passes.

- Consistency Check (Level-2.2): if more than one station is observing the same target during a specific campaign, the fusion of observations coming from different stations, in a single orbit improvement batch, shall qualify the observed passes for all stations that provide measurements. Note that this level of qualification would be granted instead of the Consistency Check (Level-2.0) for single passes, if all stations involved in the campaign make use of the same set of ephemerides and the elapsed time between observed passes has not yet degraded the quality of the ephemerides, in case of multiple passes.

From the solution provided by the least-squares adjustment, we can validate the precision of the measurements. Finally, in the pursuit of a figure of merit for the accuracy, we will compare the solution provided by the propagated improved orbit against an external reference. Currently, we have the capabilities to generate reference orbits if there are enough measurements evenly distributed along the orbit and time. As a reference, orbital arcs of at least two days will be used for the generation of reference orbits. We define this level of qualification as Accuracy Assessment (Level-3).

References

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