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) coordinates 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.

1. 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.

2. 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.

3. 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 Figure 1.

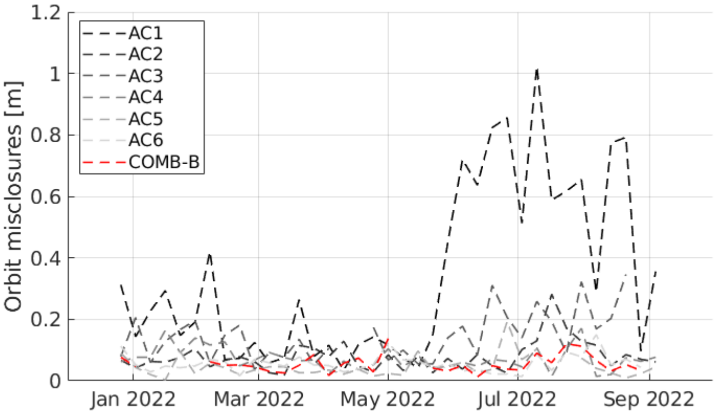

Figure 1 - 7-day-arc Lageos-1 solutions from the beginning of 2022 until September 2022, from the different International Laser Ranging Service (ILRS) Analysis Centres (AC).

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.

4. 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.

5. Tropospheric Path Delay

An example of the path delay from an observed pass at the SwissOGS Zimmerwald is provided in Figure 2. 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.

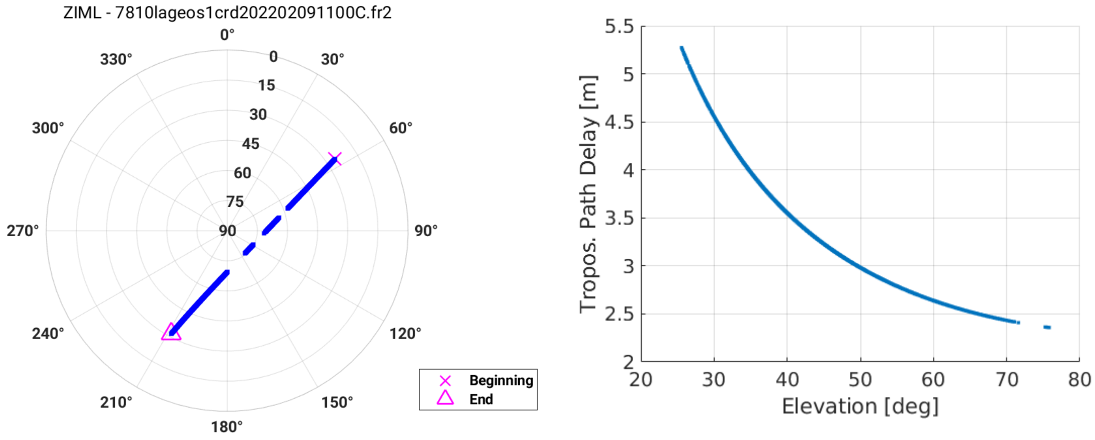

Figure 2 - Path delay from an observed pass at the SwissOGS Zimmerwald.

6. 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 Figure 3, 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.

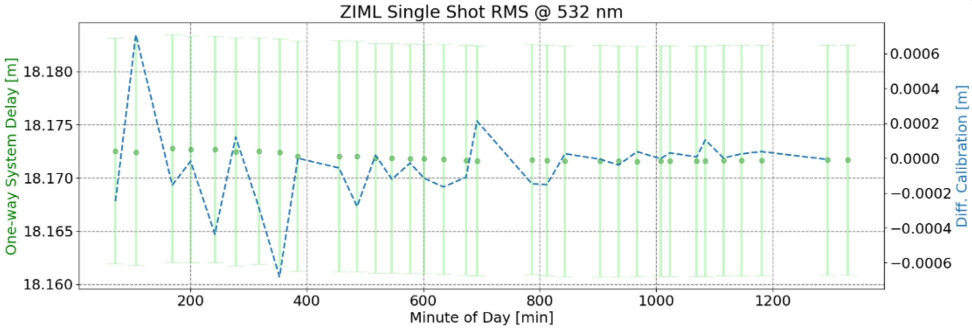

Figure 3 - System delays available after one day of observations at the SwissOGS Zimmerwald.

7. 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.

8. 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.

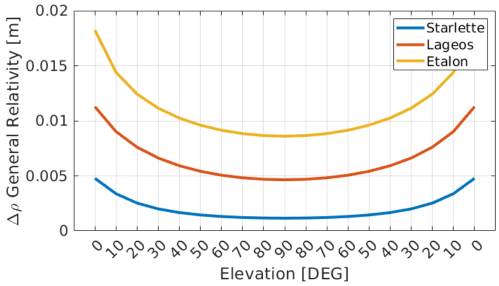

Figure 4 - impact of the light path bending on the observed range for satellites at different altitudes (Starlette, Lageos and Etalon).

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.

9. Example

In Figure 5, we show the detected signal from Lageos-1 observed at the SwissOGS.

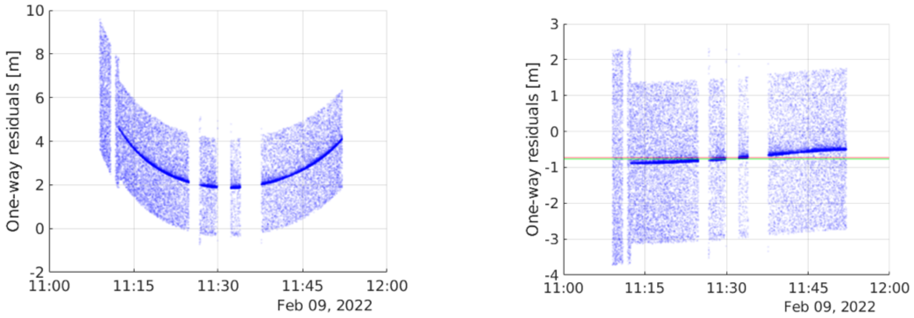

Figure 5 – Detected signal from Lageos-1 observed at the SwissOGS. Left: corrected only for calibration constant. Right: Final residuals after applying all corrections.

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 1st order. Next, in Figure 6, 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.

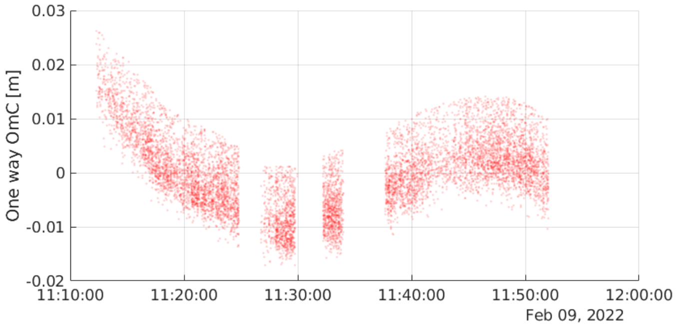

Figure 6 – Residuals after filtering detections from the objects' backscattered signal and with the estimation of time and range biases.

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.

References

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