LASER RANGING DATA PROCESSING ENGINE 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 paper, 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.

Keywords: Expert Centre for Space Safety; Laser Ranging.

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. OBSERVATION EQUATION

Given single passes from a single station, we want to derive quantitative figures for the assessment of the quality of the observable. To do so, in a first instance, we shall inspect the modelled one-way range as:

$$\rho_{obs}^{1-way}(t) = ||X^S(t) - X_R(t)|| + T(*)_{del} \quad (1)$$
$$+S(*)_{del} + CoM(*) + Rel(*)_{corr} + Rb(*) + \xi,$$

where X^S are the coordinates of the satellite, X_R the coordinates of the station, $T(*)_{del}$ the tropospheric path delay, $S(*)_{del}$ the system delay, $CoM(*)$ the centre of mass correction, $Rel(*)_{corr}$ the general relativistic correction, $Rb(*)$ the range bias and ξ the inherent measurement error. All terms in units of length. The symbol $*$ represents a dependency with respect to the observed target, relative geometry, or system characteristics, among others.

3. THE TOOL

The tool consists of a highly modular software suite. The different programming languages used in different parts of the tool were wrapped to be called from a single main file in MATLAB for generating graphic visualization output. In addition, the adopted programming paradigm was object oriented since the problem may be very well described by objects such as *the station*, or *the engine*. The latter abstraction may be very useful for the general conceptualization of the software tool by, e.g., UML diagrams.

In Figure 1, we show a general overview of the workflow of the tool. The tool itself was designed to be included within the current software architecture of the ExpCen

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in a harmonic fashion. However, the tool may as well be deployed as a Standalone program. By doing so, the tool may be adapted to any other generic software suite as a *plug-in*.
In the following, we start describing the workflow the tool assuming a Standalone use. During the installation of the tool, a defined directory structure is created, which will be accessible to the different operating modes of the tool.

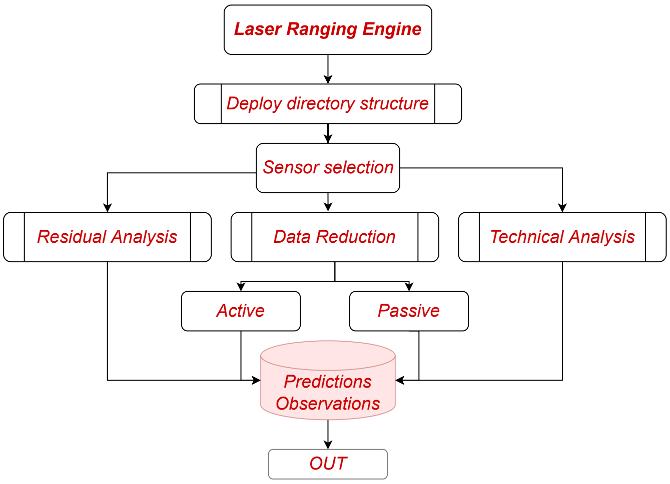

Figure 1. Schematic of the laser ranging engine at the Expert Centre for Space Safety.

The directory contains the information of the available sensors within the tool, the status of each sensor corresponding to a log file that includes all the history from every time that a new process was run, the datum definition, the technical specifications, and all relevant information that is needed for any postprocessing of the raw data. A schematic of the directory structure is shown in Figure 2. Once the directory structure is deployed and available to

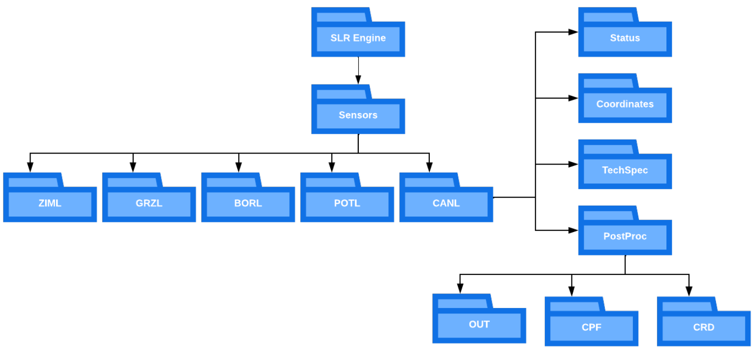

Figure 2. Directory structure needed by the laser ranging engine at the ExpCen.

the engine, we may start using the tool for different purposes. Regardless of the mode that you choose to run the tool, i.e. fully automated or manual, the tool requires as input that the user defines the station that will be used for the processing of the data, the observation mode, i.e. active or passive, and the type of analysis that the operator wants for the executed run.
Within the scope of this paper, we fill focus on the type of analysis that the operator may do. In particular, we will describe the Residual Analysis, Data Reduction and Technical Analysis procedures.

3.1. Data Reduction

This procedure is the backbone of the tool, since it is the one used for the V&Q of SD laser systems. The ranges that are acquired with SD laser ranging systems are derived after the timing of a laser pulse from emission until on-ground detection. If the system is active, the timing unit measures the roundtrip from emission until detection. On the other hand, if the system is passive, the two stations must be synchronized in time and firing frequency so that *listening* stations, different from the one emitting the pulses, can detect the reflected photons by the space segment. Bearing this is mind, for active systems, the first critical correction corresponds to the one applied after the calibration of the timing unit with an external reference distance. This information may be provided in specific entry lines within the so-called Consolidated Range Format (CRD).
In Figure 3, we show the one-way residuals after cor-

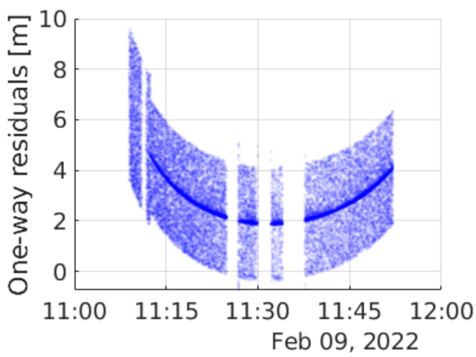

Figure 3. Raw measurements to Lageos-1 from the SwissOGS corrected from system delays.

recting for system delays using the so-called calibration constant. The ranging station in this example is the SwissOGS, and the fiducial target object corresponds to Lageos-1. Note that the impact of this correction, $S(*)_{del}$, should correspond to a bias on the y-axis, assuming that there are no timing jitters in the other components constituting the SD laser system.
Other corrections such as the tropospheric path delay $T(*)_{del}$, the centre of mass correction $CoM(*)$, and the general relativistic correction $Rel(*)_{corr}$, are also applied. It is important to keep in mind the order of magnitude of the corrections. In previous research activities, we have estimated an lower-bound error of about 10 cm coming from the reference orbits. In that regard, only corrections that exceed this value will become noticeable

while post-processing the data. In Figure 4, we show the raw measurements from the SwissOGS to Lageos-1 after correcting for all remaining error sources. By inspection

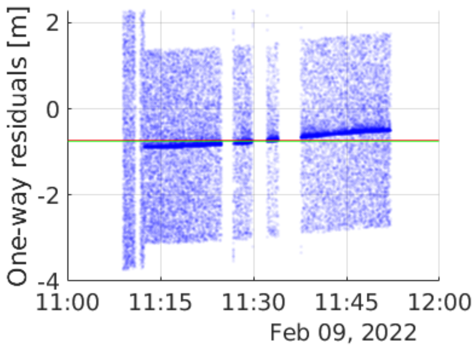

Figure 4. Raw measurements to Lageos-1 from the SwissOGS corrected from the remaining error sources.

of Figure 4, we see that in spite of correcting for known error sources, we still have a noticeable trend in the concentration of returns. The trend suggests a possible range bias, shown by the green (mean) and red (median) line of the depicted residuals, besides a time bias potentially explaining the symmetry of the highly concentrated returns along the observed pass. In a following step, we model those by expanding the residuals using a Taylor series expansion of first order and proceed with the estimation of the range and time bias. The results after applying this step together with a filtering phase are shown in Figure 5. We see in Figure 5 that the order of magnitude of

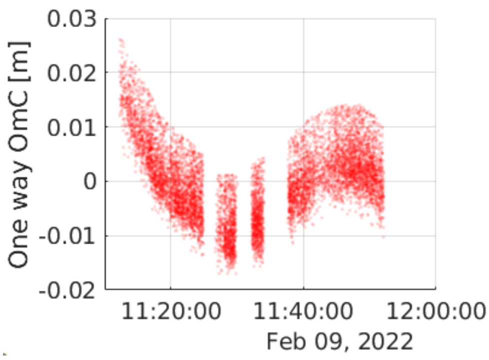

Figure 5. Residuals after the estimation of a time and range bias using the data after applying all corrections.

the residuals become smaller. However, we still see a trend indicating that the previous parametrization, which maps errors in the along-track and radial components is not enough to model the variations of the observations with respect to the orbit. To further remove this trend, we include the variations of the observable with respect to the orbit. The results after an orbit improvement are shown in Figure 6. Once the residuals have been flattened, we may proceed with the statistical evaluation of the residuals, compare the results with the specifications of the observing systems, and compress the data in the so-called normal points for further processing steps.

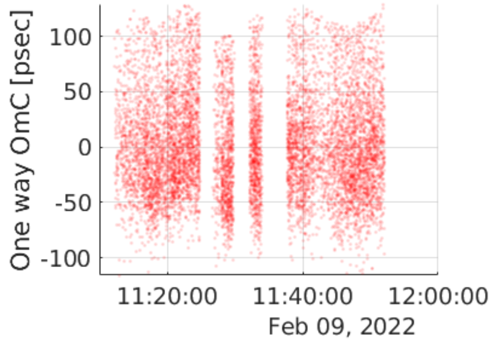

Figure 6. Residuals after the orbit improvement.

3.2. Residual Analysis

This procedure aims at providing attitude information about the observed target object. Specifically, we subtract the acquired laser ranging measurement against their predicted vales, i.e. the residuals, to estimate the synodic period of the target object. In the following, we present a test case for Envisat, a defunct satellite from which we have available several passes from the SwissOGS.
In Figure 7, we show the observed ranges minus the predicted ones, in addition to those detections that were classified as signal. Notice that the order of magnitude of the residuals are significantly higher if we compare the results with the ones obtained previously for Lageos-1, since the predictions available for this pass come from the latest Two-Line Element orbital set. Once we have

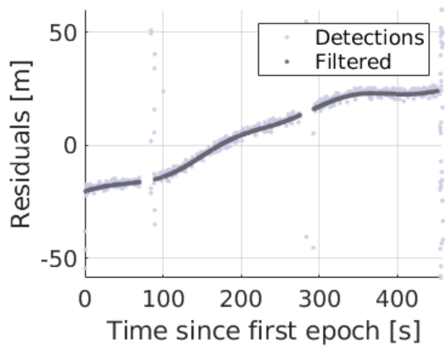

Figure 7. Residuals and signal filtering for the observed pass of Envisat from the SwissOGS.

the detections, we proceed with the removal of the main trend of the residuals, which is preventing us to see the oscillating pattern corresponding to the rotation of the retroreflector onboard the defunct satellite with respect to its main rotation axis. In Figure 8, we show the resulting detrending using two different approaches: a generic polynomial and the estimated time bias corresponding to an along-track error in the orbit used for this analysis. In Figure 8, we see that both methods yield similar results for the first two peaks. Nevertheless, the third peak shows a variation in the amplitude if compared to the more reg-

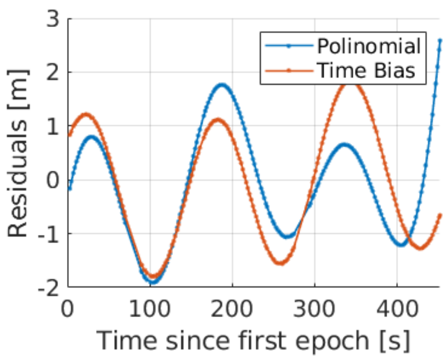

Figure 8. Residuals after detrending using two methods: a generic polynomial and a time bias corresponding to an along-track error in the orbit used for this analysis.

ular amplitude achieved when detrending using the time bias approach. Moreover, when using the generic polynomial, we see that the last branch suffers from the so-called *Runge's Phenomenon*. This instability at the edges may affect the estimation of the synodic period. To test for that, we computed the synodic period using the Lomb-Scargle method. The results are shown in Figure 9. By

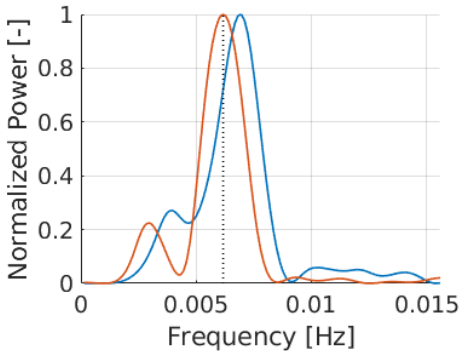

Figure 9. Estimated periods using the Lomg-Scargle method after detrending the original residuals using two different approaches: a generic polynomil (blue), and an estimated time bias (orange). The dotted line provides the ground-truth, which was retrieved from the literature.

inspection of Figure 9, we may conclude that there was an impact on the estimated period when the main trend was removed using a generic polynomial. However, in some other cases, we have seen how the polynomial performs better than the time bias removal by constraining it with functional boundary conditions, i.e. imposing the derivative of the polynomial to be zero at the boundaries. This improvement became noticeable for those passes with gaps in between observations. Note that the availability of the two methods allow us to choose and to compare the results from both checking the consistency of the provided solutions.
Finally yet importantly, besides identifying the oscillating pattern in the observed signal, we might be interested in the representation of the measurements in different reference frames, which is possible if we have available ephemerides, besides all other needed parameters to convert between frames. For example, to visualize the object from a given observing station, we may use the Earth-Centred-Earth-Fixed reference Frame. Nevertheless, there are other interesting representations that may provide us with further information that could be used for complementary analysis. An example of such representations, is the so-called Satellite-Fixed reference frame, depicting on one of the axis the along-track direction, and the on the other the normal to the orbital plane. The presented pass analysed before was represented on that frame and the resulting relative geometry can be seen in Figure **??**.

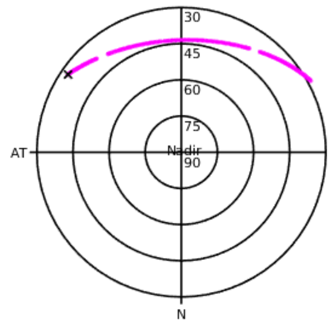

Figure 10. Relative geometry between Envisat and Station represented in the Satellite-Fixed reference frame. AT stands for along-track, while N corresponds to the normal to the orbital plane.

3.3. Technical Analysis

The Technical Analysis procedure is the last one currently available within the tool. The highlight of this part of the tool is the capability to process data comprising a relative long time span of, e.g., years efficiently. This procedure contain several options:

- Temporal analysis of calibration measurements.
- Comparison of theoretical vs. estimated return rates.
- Spatial distribution of return rates.
- Analysis of meteorological data.
- Analysis of time and range biases for selected targets.
- Long term analysis of reference orbits.

For the time being, we are increasing the list of products that we may offer. An example of such product is depicted in Figure 11. In this analysis, we provide a monthly summary of the time and range biases estimated from each observed pass. We provide the monthly

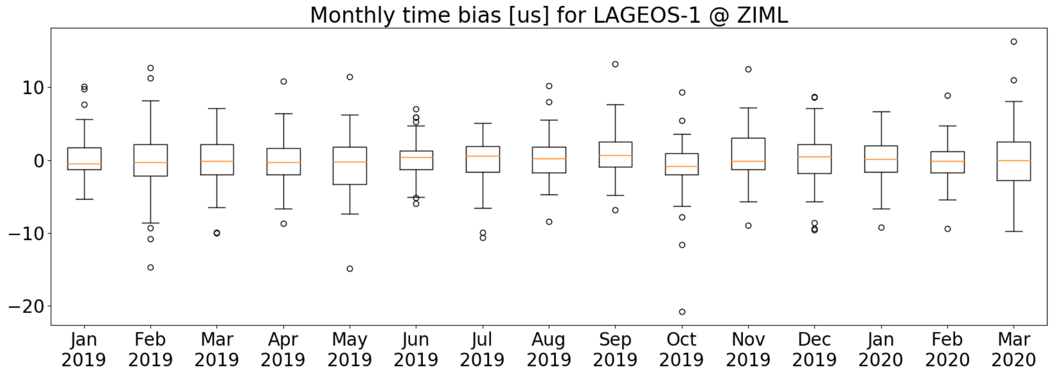

Figure 11. Time series analysis of the estimated time and range biases for the SwissOGS, from passes to Lageos-1. The outliers correspond to passes with poor relative geometry and only few measurements available. The applied procedure corresponds to the one that the ExpCent currently uses for the V&Q of new sensors.

summary as a Box plot including the estimated values that were classified as outliers. The time bias and range bias estimated for such cases corresponded to passes with poor relative geometry between observing station and satellite, or only few measurements available for that specific pass. In addition, Figure 11, provides critical information for the assessment of the system's stability. These type of products may be compiled in the for of *key performance indicators* guaranteeing the full exploitation of accurate, precise and reliable observations acquired with SD laser systems.

4. SUMMARY

In this paper, we presented the laser ranging data processing engine available at the Expert Centre for Space Safety. With the development of new SD laser systems, new standards and methods, homogenizing the acquired data by heterogeneous world-wide distributed systems becomes a necessity. Different quality metrics defined by the user community shall guarantee the use of measurements from new systems for Space Situational Awareness and Space Traffic Management. In that context, the Expert Centre provides a service that consists of validating and qualifying new systems aiming at building a fully certified network of stations capable of providing precise, accurate and reliable data. Within the active optical domain, we have developed an internal software tool that processes raw laser ranging data. The tool currently offers three main processing strategies: Data Reduction, Residual Analysis and Technical Analysis. Within the Data reduction procedure, we apply the needed corrections to the raw data, estimate a time and range bias and ultimately, we perform a single-pass orbit improvement. Within the Residual Analysis procedure, we want to extract periodic information from the target object of interest. To do so, we detrend the initial residuals using two different approached, and finally we estimate the synodic period using the Lomb-Scargle method. In addition, we have implemented the representation of state vectors in different reference frames to derive more information from each pass and correlate it other information available, e.g., from passive optical. Finally, the Technical Analysis procedure provides extensive analysis of the different components constituting the SD laser system.
Current deliverables within the laser ranging engine include a full characterization of the precision, accuracy and received signal of the system. The stability of the system is evaluated with respect to observations conducted to specific fiducial target objects, from which we estimate range and time biases per observed pass. Furthermore, the tool ensures compliance with current formats and standards promoting them to ensure interoperability between different stations. For attitude related studies, we are currently able to process data containing periodic patters. We have conducted extensive testing for passes of defunct satellites carrying a retroreflector onboard. In the near future, we are planning to conduct a campaign with a special focus on non-cooperative targets, from which we can perform an end-to-end test to further validate our tool. Additionally, we are currently developing robust and sophisticated algorithms for signal detection based on statistical hypothesis testing.

REFERENCES

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