Accuracy assessment of CoM corrections for Etalon geodetic satellites

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Abstract

Present-day Satellite Laser Ranging (SLR) systems are in principle capable of providing ranges with an accuracy and precision approaching the millimetre level. This capability is best utilised if the error budget contributions of the multiple factors affecting the laser observations are minimised and do not exceed the inherent accuracy of the ranging measurements. Centre of mass values (CoM), used to relate the ranges to the satellites to their centre of mass, depend on the characteristics of the target, the detection hardware in use at the tracking stations, the intensity of the returned laser pulses, and the post-processing strategy employed to reduce the observations. Station-, and time-dependent CoM corrections are available for the geodetic targets used by the ILRS for its contribution to the realisation of the ITRF. These values are based on theoretical considerations, empirical determination of the optical response functions of each satellite, and knowledge of the tracking technology and observation policies employed. We have computed reference frame solutions using ILRS observations to the LAGEOS and Etalon satellites for the period 1995-2014, estimating range errors along with station coordinates. We find unexplained, cm-level positive biases for the Etalon satellites in the case of many stations, in particular those operating at high energy return levels. This, along with analysis of the range bias time series of stations that have undergone transitions through different modes of operation provide evidence suggesting that the current CoM values for some systems are inadequate. We point out the factors limiting the accuracy of the current CoM modelling and discuss some improvements, which are relevant not only for the specific Etalon case discussed here, but also for the CoM corrections for other targets.

1 Introduction

The ILRS contribution to the realisation of the International Terrestrial Reference Frame (Altamimi et al., 2016) consists in the combination, by the official ILRS combination centres ASI and JCET, of the laser station coordinates and Earth Orientation Parameters computed from orbital dynamics solutions provided by individual ILRS Analysis Centres [1]. To date, these solutions are exclusively based on satellite laser ranging observations made by the ILRS network of tracking stations to the geodetic satellites LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2. It is therefore imperative that any factors affecting the quality of the observations to these spacecraft are understood and minimised, in order to ensure that the product delivered by the ILRS as a whole and its unique contribution to the realisation of the reference frame is of the utmost accuracy and scientific value.

Critical parameters that impact directly on the accuracy of SLR observations are the satellite centre of mass corrections (CoM). These are the vectors from the reflection points of the retroreflector arrays to the centres of mass of the spacecraft, linking the ranging measurements to the computed orbits

[1] http://ilrs.gsfc.nasa.gov/science/analysisCenters/index.html

of the satellites. Due to their rotational symmetry, in the case of geodetic spheres such as LAGEOS and Etalon, the CoM correction is simply the distance from the reflection point to the centre of mass. Unfortunately, at accuracy levels approaching a centimetre, the CoM values depend not only on the characteristics of the target, but also on the detection hardware in use by the tracking stations, their mode of operation, intensity of returned pulses, and the reduction procedures employed to form the normal point data which ultimately encapsulate the SLR observable. This fact was readily recognised as the laser ranging technique evolved and the accuracy of the observations improved, with many early studies devoted to assess the impact of the so-called satellite signature effect on the ranging measurements collected by different hardware setups (see, e.g. Sinclair (1995).

For the LAGEOS satellites, extensive optical ground testing and simulation work was conducted before launch in order to quantify the most adequate CoM values for different systems (Fitzmaurice et al., 1977; Minott et al., 1993). Notably, therein it was already recognised that fixed CoM values could not be prescribed, for the characteristics of the ground network change as it evolves and new technology is adopted. For the pair of Russian Etalon satellites, no ground testing was conducted. A value for the CoM correction valid for centroid detection systems was determined and published some years after launch (Mironov et al., 1993). Unfortunately, a single, fixed CoM value is not adequate for the heterogeneous network of ground stations, and a system-dependent set of corrections was required. Later on, the determination of the impulse response functions for the satellites LAGEOS, Etalon and Ajisai by Otsubo and Appleby (2003) allowed for the computation of the current CoM tables used by analysts of SLR data to correct the raging measurements to these targets (Appleby and Otsubo, 2013).

2 Etalon range bias analysis

In order to assess the accuracy of laser ranging measurements to the Etalon satellites, we have conducted orbital dynamics computations where range bias (RB) parameters to these spacecraft were estimated. We had performed this exercise previously for the LAGEOS and LAGEOS-2 targets, revealing the presence of systematic errors at a few millimetre level in a considerable number of stations of the network (Appleby et al., 2016). Measurement or mismodelling errors in the Etalon satellites will have a low impact on the SLR product (station coordinates and Earth Orientation Parameters) and its contribution to the realisation of the reference frame, as the data yield of the network for these satellites is and has been historically quite low. However, the identification and minimisation of any potential errors is of great interest both on its own, to enhance the quality of these observations, and for the possible knock-on improvements derived from their discovery and mitigation.

We computed weekly combined LAGEOS + Etalon solutions for the period 1995–2014, where we estimated orbit initial conditions, station coordinates, Earth orientation parameters (pole coordinates Xp and Yp, and length of day LOD), as well as range biases. Both station coordinates and range biases were constrained at the level of 1 m. Combined LAGEOS + LAGEOS-2 and Etalon-1 + Etalon-2 range bias parameters were estimated, since both satellite pairs orbit at very similar heights and their construction is identical. Although no special weighing scheme was employed in the computations, given that the quantity of the available Etalon data is much lower than that for LAGEOS (about 10%), observation to the latter dominate the solutions. Thus, the extent to which the Etalon data contribute to the determination of station coordinates is relatively minor. The modelling standards and other details of the computation were identical to those followed by the NSGF Analysis Centre for its contribution to the ILRS combined solution for the ITRF2014 reprocessing, and are detailed elsewhere (Appleby et al., 2016).

As we are focusing our attention on the specific case of the Etalon observations, in particular potential inaccuracies in the centre of mass values for these satellites, we computed the differences between the range bias time series estimated for Etalon and LAGEOS. The rationale is that in this manner possible issues at the station level (e.g. local survey inaccuracies, hardware problems) will

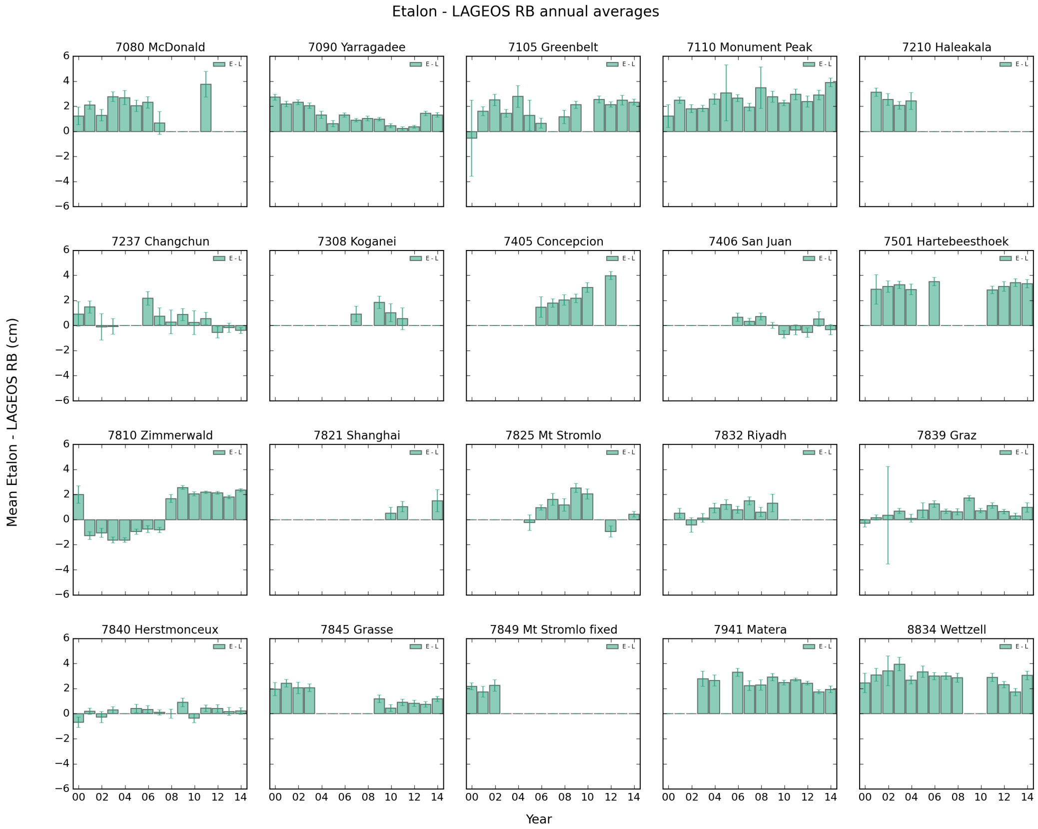

Figure 1 – Annually averaged range bias differences between Etalon and LAGEOS. The error bars represent the standard errors of the differences.

cancel out and the resulting differential bias will reflect only satellite-specific errors. These may indicate both centre of mass modelling deficiencies as well as other factors that could be different between targets and have the potential to impact the range measurements (e.g. intensity levels of the returned laser pulses). It must be stressed that the difference in range bias does not in itself offer information on the correctness of the CoM corrections for either satellite: a small difference could be caused by consistent, but equally inadequate CoM values for both targets.

2.1 RB results

The results of the range bias analysis are summarised in figure 1, where annual weighted averages of the range bias differences, with their standard errors, are shown for twenty stations of the network. A minimum threshold for the number of yearly observations available was introduced to avoid displaying values with low statistical significance. Notably, the great majority of the range bias differences (Etalon minus LAGEOS) are found to be positive, with magnitudes reaching 2–3 cm in many cases. These range bias differences, or “excess Etalon bias”, appear to be greater and more consistent in the case of stations operating at multi-photon levels of signal return, using PMT and MCP/PMT detectors. On the other hand, stations operating in the single-photon mode employing SPAD detectors show lower differential biases, at least for stations for which a long time series of observations is available. Although only some of these stations operate explicitly in the single-photon mode, the distances involved when ranging to Etalon (19,120 Km perigee) and the inverse dependence of the intensity of returns with the fourth power of the range mean that even stations that do not actively control their received energy are in fact working at a level of at best a few photons.

We note that in some cases there are clear interannual inconsistencies in the range bias differences. For example, the averaged difference between Etalon and LAGEOS range biases estimated for Mc Donald 7080 (USA), Yarragadee 7090 (Australia) or Mt Stromlo 7825 (Australia) show significant variations throughout the period of analysis. This points to changes at the station level that introduced a difference between the range measurements obtained for these two satellites. The ultimate cause of these changes is worth investigating, possibly making use of the detailed system changes files in a collaborative effort involving analysts, station operators and system engineers. That is not the object of the present study. Here we limit our attention to the most obvious positive offsets at the centimetre level mentioned above.

The results shown in figure 1 are very consistent and significant. It is extremely unlikely that all the stations for which a large range bias difference has been obtained are all somehow consistently flawed in a similar fashion, throughout more than ten years in some cases. In addition, the observed correlation with detection technology also points to a problem in the way the observations produced by these stations are handled. The primary suspects in this case are the applied centre of mass corrections, and ultimately the modelling assumptions from which they are derived.

3 CoM modelling

The centre of mass corrections in use by the SLR analysis community consist of a series of tabulated values available, at the moment of writing, for the laser targets LAGEOS, Etalon and Ajisai (Appleby and Otsubo, 2013). These values have been determined for each station taking into account the detection hardware in use and observation policy followed at different epochs. The models and assumptions underlying the computation of these CoM corrections are detailed in Otsubo and Appleby (2003). Briefly, empirical impulse response functions for each satellite were derived by ray-tracing using the locations and characteristics of the individual corner cubes on the surfaces of the satellites. The response functions were tuned to the specific reflectivity of each satellite using single-photon tracking range residuals. The impulse response functions can then be employed to compute the probability distribution of the intensity of reflected laser pulses for any arbitrary laser pulse-length, and CoM values derived taking account of the various detection systems, provided that their characteristics are known. Identical considerations were employed to obtain the impulse response functions and CoM corrections for Starlette, Stella and LARES (Otsubo et al., 2015), whose full system-specific tables of values have been recently derived and made available.

3.1 Shortcomings in the current modelling

The kind of computation described above can be readily performed for systems operating at the single-photon level, as only the optical part of the detection process needs to be taken into account. This is so because the detection and timing of the electric signals generated by the photodetector are independent of the characteristics of the reflected pulses. Provided the intensity of returns is controlled and limited, on average, to single-photons, the behaviour of the receiver hardware is identical between detections. Thus, the specific point within the signal at which the timing device is triggered stays constant and is therefore cleanly calibrated out. By accumulating repeated observations of the same target during a tracking session (or ground calibration), the resulting distribution of residuals maps the physical geometry of the laser retroreflector array as sampled by a laser of finite width.

For stations operating at intensity levels involving multiple photons returned per fired pulse using MCP/PMT detectors, the behaviour of the receiver systems is more involved. Instead of a single photon behaving like a delta function, in this case the returned pulses contain tens of photons, each

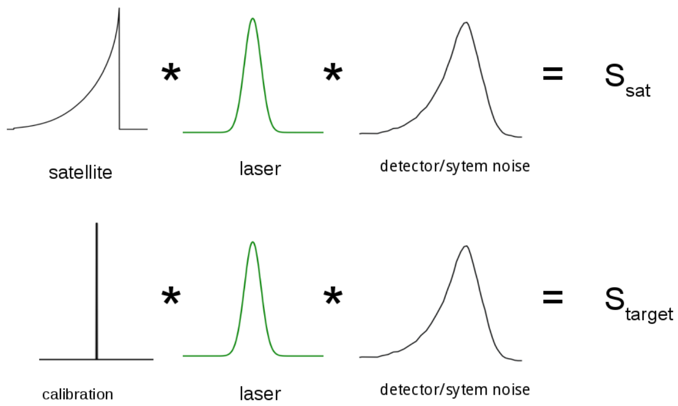

Figure 2 – Convolution steps performed to determine centre of mass corrections in this work. The signal from satellite tracking is obtained by convolution of the impulse response function, a Gaussian function representing the laser beam, and the detector response. For ground calibrations, the impulse response is replaced by a delta function.

generating an electrical signal in the photocathode, the superposition of which is the received pulse that is to be timed to obtain the time of flight measurement. Factors critical for the timing consistency of the received signals include potential amplitude differences as well as some knowledge of their temporal behaviour, such as pulse width and rise time. As this kind of information is not readily available unless dedicated measurements are performed, some pragmatic assumptions were adopted in the development of the CoM correction tables. Among these, the whole response of the detection systems was modelled with a single Gaussian function, the "pulse width" of which was that of the only component known with reasonable certainty for *all* the stations of the network: the optical pulse length of the transmitted laser. Other necessary simplifications that made the problem more tractable include assuming that the intensity of the returned pulses is sufficiently high at all times regardless of target characteristics, weather conditions, time of the day and satellite elevation; that stations operate in a consistent way without introducing unreported changes in their systems; that appropriate calibration practices are followed that take into account the differences in intensity expected from different retroreflector arrays; that some sort of pulse amplitude calibration is in place to minimise residual time-walk effects in the detectors.

A consequence derived from the application of the simplifications described above is that the pulse transformations caused by the electronic multiplication process and signal amplification, electronic and timing jitter were previously only approximately estimated. In addition, the only parameter of the CoM model relevant for multi-photon detection systems, the "pulse width", was underestimated because only the optical contribution was considered. An outcome from these considerations is that the introduction, in some form, of the additional electric pulse lengthening taking place during the detection process will tend to reduce the computed CoM correction values, in agreement with what the range bias analysis in the previous section suggest. The negative relationship between the pulse width (optical, electrical) of the detected signal and the CoM correction is a result that follows from the definition of the CoM as the difference in the timing reference points between a single-point ground calibration and an actual target of finite depth. See, for instance, Arnold (2016), in these proceedings, for theoretical results showcasing the CoM dependence on pulse width.

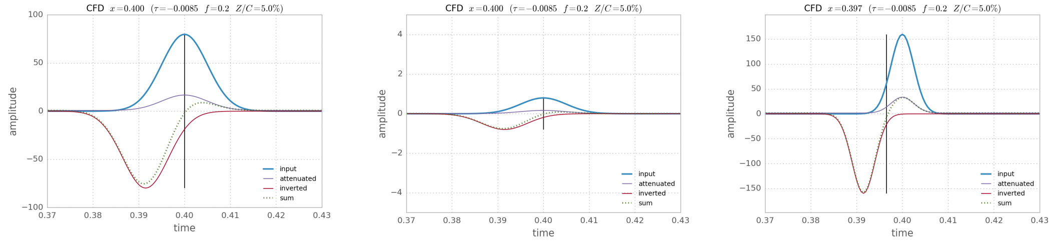

Figure 3 – Examples of constant fraction timing. The figures display the ideal signals generated in a constant fraction discriminator and the resultant reference points. The first two plots show identical input curves (Gaussian functions) timed and referenced consistently, regardless of a 100x amplitude difference. The width of the input signal in the third plot is shorter by a factor of two, and the timing reference obtained is clearly displaced (identical delay and attenuation settings in all three cases).

3.2 Estimating CoM corrections: the impulse response function approach

There are various methods of obtaining satellite target signatures; that is, functions describing the shape of the reflected laser pulses with respect to the centre of mass of the targets. These include detailed computer simulations of the far-field diffraction patterns (FFDPs); convolution of theoretically or experimentally derived impulse response functions; analysis of empirically obtained FFDPs; and laboratory measurements with ultra-short pulsed lasers using either streak cameras or detectors similar to those deployed for actual ranging operations (Minott et al., 1993). As discussed in section 3, the CoM correction tables currently in use have been derived by convolution of empirical impulse response functions and Gaussian functions describing the laser beams (Otsubo and Appleby, 2003). The same approach is followed here, with the addition of a further convolution describing the response of the detection system, as graphically summarised in figure 2.

Detector response The system response information required to extend the current modelling is not readily available from the current ILRS system logs and station information. A possible approach is to assume that the detector response for each station is reasonably well approximated by a Gaussian function with matching rise time to that noted in the system logs. An alternative is using information available elsewhere (e.g. technical reports, manufacturer specifications, unpublished testing) describing the behaviour of the hardware as measured under controlled conditions. This kind of testing is not performed routinely and requires the use of some specialised equipment (e.g. fast oscilloscopes and very short-pulsed lasers), but it is available in some cases. Under the following assumptions, a convolution approach including empirically determined detector responses is a valid one:

- system response measurements obtained with short laser pulses
- measurements obtained at the multi-photon level
- normal ranging operations performed under similar conditions to experiments (gain, thresholds, no extra equipment employed)
- satellite tracking return rates consistently kept at the multi-photon level

Timing reference points In order to compute the centre of mass correction for a particular target as observed with a particular detection system the appropriate timing reference point must be chosen. This is simply the point in the received signal at which a timing measurement is triggered. Typical reference points are the peak, leading edge, and some fraction of the peak. Constant fraction timing is a popular choice for precise timing and event counting applications. The equipment employed to perform constant fraction timing are constant fraction discriminators. These devices split the input

Table 1 – Etalon CoM results for two example configurations

	CoM (mm)	
	current value	this work
150 ps FWHM ITT F4129f	603(5)	587
50 ps FWHM Photek210	610(3)	600

signal in two, attenuate one part and invert and delay the other; the point at which the addition of these two signals changes sign (the zero crossing) is the reference point (see, e.g. ORTEC). This technique minimises amplitude dependent time-walk effects as long as the shape of the input signal is similar. Discriminators require careful setting up for the shape of the expected signals in order to operate optimally.

The reference point employed in this work was determined with simple simulations of the zero crossing of a virtual discriminator tuned up for the synthetic signals obtained via the convolution process detailed above. Examples of the constant fraction timing employed here are shown in figure 3. The timing differences between following this approach and simply triggering at same fraction of the peak are not great; however in this manner we can take into account possible effects arising from imperfect (or simply fixed) discriminator settings.

3.3 CoM results

We limited ourselves to testing the convolution method extended with the system response for two example receiver configurations:

- 150 ps FWHM laser, ITT F4129f MCP/PMT (350 ps rise time, 550 ps FWHM)
- 50 ps FWHM laser, Photek210 MCP/PMT (128 ps rise time, 191 ps FWHM)

Detection systems similar to these are or were in the past used in several stations of the ILRS network. The first system, with an older, slower detector package and a relatively long laser pulse length, is a good representative of the kind of systems in use in the 1990-2000s for multi-photon mode tracking (e.g. the NASA SLR network). The second one, with a short laser pulse length and a fast-response MCP should be representative of systems such as Matera 7841 (Italy) or Wetzell 8834 (Germany). Detector responses for these devices are available in Varghese et al. (1993) and Milnes and Howorth (2005), from which the relevant curves were digitised for this work. Both systems were assumed to be working at pure multi-photon levels of return, using constant fraction discriminators with perfect settings tuned for *each* [2] satellite so that they operate in the true constant fraction timing mode at all times, triggering at a fraction of 0.2.

Etalon The values obtained for the CoM of Etalon are detailed in table 1, as well as the current CoM corrections and their estimated uncertainties. For both systems the CoM values computed in this work are shorter than the current ones, by 16 mm in one case and 10 mm in the other. The use of these CoM values would therefore reduce the estimated range biases for Etalon for these systems (although it would not eliminate them completely). Given that these values were computed following an approach that takes into account a more detailed view of the detection process, and that the effect of their application is in good agreement with what the orbital dynamics results indicate, there is a good incentive to compute new CoM corrections following this approach for other systems as the required information becomes available.

[2] This is not possible in practice. The authors ignore the precise settings at which discriminators are operated, but assume near-optimal conditions.

Table 2 – LAGEOS CoM results for two example configurations

	CoM (mm)	
	current value	this work
150 ps FWHM ITT F4129f	249(1)	245
50 ps FWHM Photek210	250(2)	248

LAGEOS An immediate implication derived from a change of modelling standards for CoM computation is that the values for other satellite targets would have to be revised. In order to get an indication of the magnitude of the changes implied by the newer modelling we calculated the CoM corrections for LAGEOS for the two example configurations considered (results shown in table 2).

As LAGEOS has a smaller radius than Etalon, the changes in CoM corrections are smaller. However, the 4 mm change obtained for one of the systems is very significant, especially given the small uncertainty previously assumed for the current model (±1 mm in this case). For the second system (50 ps laser, Photek210 detector), the difference is only 2 mm, which lies within the presumed uncertainty limits of the current value.

Limitations We note that although the work presented here attempts to include more effects that have an impact on the CoM value adequate for specific targets and detection systems, it is not an exhaustive modelling of all the relevant components involved in the detection process. For instance, the time response characteristics of some other devices that may be in use in the receiver chain have not been modelled (e.g. pre-amplifiers and timing amplifiers, if present). These additional components, if not taken into account, will contribute with their own signature to the detected signals, generally stretching them if their time response is not fast enough.

Crucially, we have assumed that the return rates of the systems under consideration are consistently in the multi-photon regime; if this were not the case, and as the intensity of returns approaches the single-photon level, the statistics of detection at the photocathode must be taken into account. In addition, if the operating conditions at the tracking stations change in terms of hardware settings (e.g. use of amplifiers for certain targets, detector gains, thresholds) a single CoM correction value may not be adequate.

4 Conclusions

Examination of the range biases estimated for the Etalon satellites reveals apparent systematic errors at the level of 2–3 cm. These appear more conspicuous and consistent in "high-energy" systems operating at the multi-photon level, although other systems are *not* exempt of biases. A significant part of the range errors for Etalon are suspected to be caused by deficiencies in the centre of mass modelling underlying the current tables in use by the SLR analysis community. Other contributions to the overall error budget include unreported system changes; operational inconsistencies; failure to follow strictly the observation policy in use at the stations (single-photon, multi-photon); and possible hardware issues e.g. non-linearities in the timing devices. Taking into consideration the response of the detectors in addition to the optical pulse stretching, we can generate new CoM corrections that accommodate to a substantial extent—although not fully—the range biases found from orbital dynamics computations. A number of simplifying assumptions must be adopted in order to compute an average CoM value for each system, which in all likelihood means that mm-level CoM corrections can not be achieved for the Etalon targets. These assumptions apply as well to the case of other satellites, such as LAGEOS, for which initial results subject to revision, suggest a system-dependent change for some systems in the range of 2–4 mm relative to the current values if this modelling were adopted.

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