Detection of various SLR systematic errors for mm accuracy

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Quick QC and Slow QC

The measurement quality of state-of-the-art satellite laser ranging (SLR) systems has easily exceeded 1 cm precision and they currently aim at 1 mm precision. It is not always possible for a station to monitor the quality of their own data, and therefore the analysis institutes have become involved in the quality assessment in various ways.

Due to a malfunction in the local observation system including software and operation, we, analysts, sometimes see a large deviation from the best-fit orbits. Two of the active examples are the 6-hourly pass-by-pass quality control (QC) at Hitotsubashi University, Japan (Otsubo et al., 2013):

http://geo.science.hit-u.ac.jp/slr/bias/

and the NP (normal point) residual plots of long-arc and short-arc analyses at NERC Space Geodesy Facility, UK:

http://sgf.rgo.ac.uk/analysis/nporbit.html and http://sgf.rgo.ac.uk/qualityc/

both of which have been routinely viewed by SLR stations. We should reduce or even remove such anomalous data from the ILRS (International Laser Ranging Service) data archive, and such rapid feedback is found to be effective.

Such quick QC is a powerful tool to detect a large (roughly > 10 cm for high quality stations) error, but we also have to deal with much small size error. The following part of this paper is dedicated for precise systematic behavior of SLR data using a one-year (July 2015 to June 2016) data set, and, in particular, the calibration procedure is focused on.

Is Calibration Properly Done?

Raw SLR measurements include the excess delay, but the point-to-point distance between a telescope reference point and a satellite is the value to be used by analysts. Therefore, the calibration procedure is required at each station by measuring the two-way range to a known-distant target, and the raw SLR measurements are subtracted by the excess delay that is provided as the “system delay” record in the CRD (Consolidated Laser Ranging Data) format.

Fig. 1 shows a one-year time series of the system delays of Herstmonceux, UK. An annual

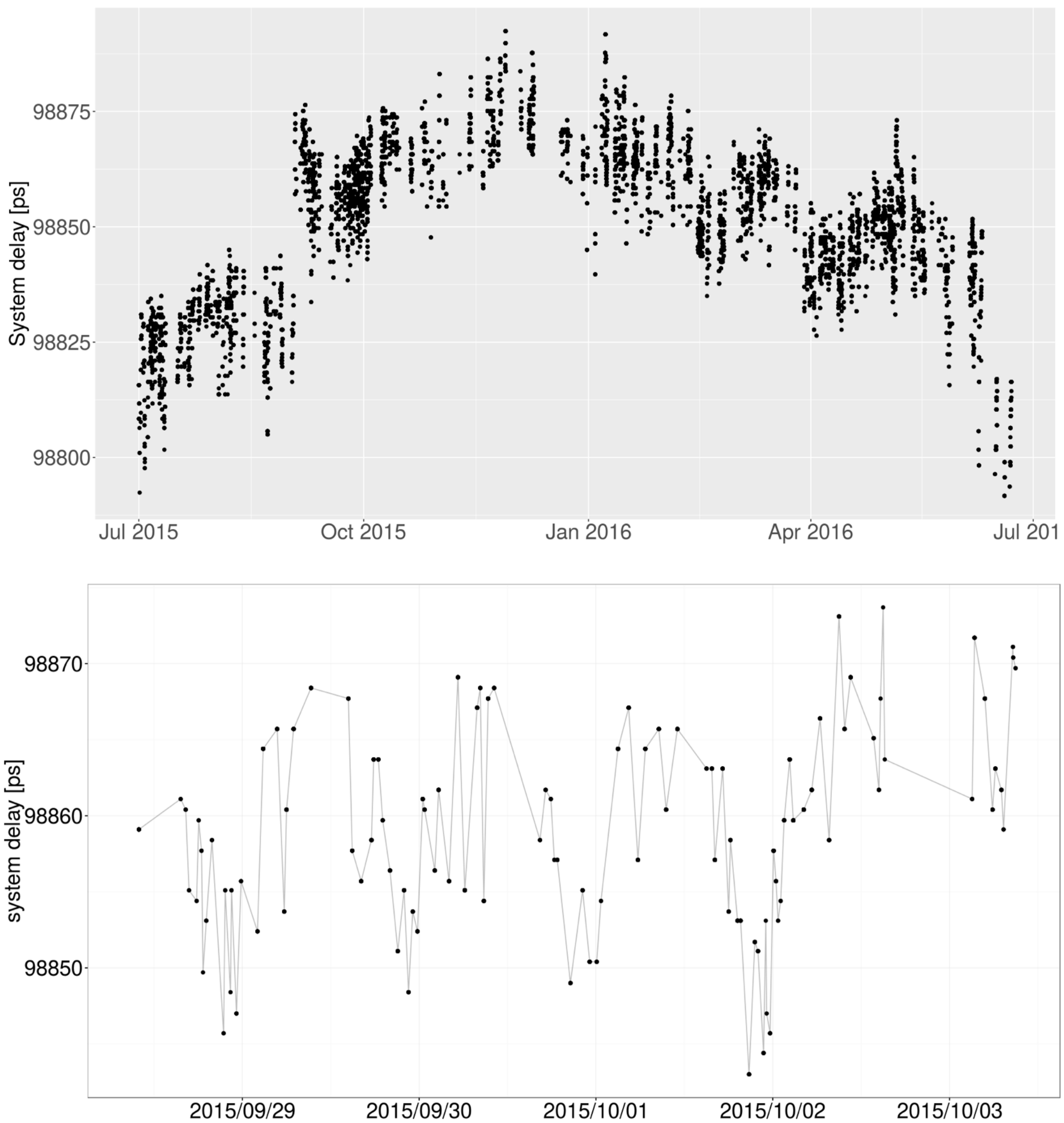

Fig. 1. One-year (July 2015 to June 2016; top) and five-day (bottom) time series of the system delay observed at Herstmonceux, UK.

signature is clearly seen, and, if it is zoomed in like Fig. 2, a daily pattern is also seen. The system delay is often sensitive to the air temperature, especially because the detector and a part of cables are exposed to the open air at Herstmonceux. For almost all SLR stations, the graphs for one-year and five-day-clipped time series are available at:

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/CalTimeSeries1y.pdf

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/CalTimeSeries5d.pdf

Now let us relate the stability of the system delay with the quality of SLR. In theory, no matter

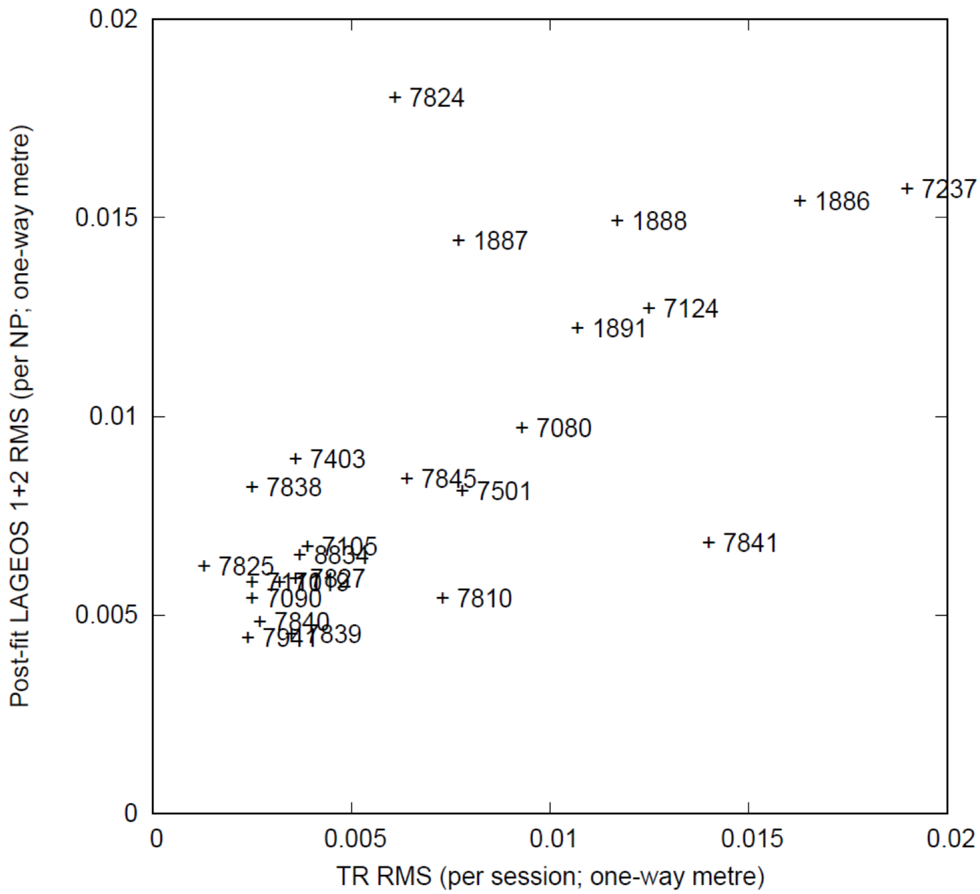

Fig. 2. Correlation between the system delay stability RMS and the post-fit RMS of LAGEOS-1 and LAGEOS-2. TR: Terrestrial Ranging.

how large the system delay varies, the SLR quality should not be affected as long as it is calibrated properly. Fig. 2, however, indicates a clear positive correlation between the RMS of one-year system delay measurements and the post-fit residual (NP) RMS of the two LAGEOS satellites in the same period. Software “c5++” is used for the one-year precise orbit determination. There are also zoomed-out versions of this:

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/DelayVsLag.pdf

to see the behavior of more SLR stations. The SLR stations with high-precision (small RMS) LAGEOS NPs nearly always have good stability in the calibration. There are a few exceptional stations like Zimmerwald (7810) and Potsdam (7841) where the calibration RMS is significantly larger than the LAGEOS RMS, and these are examples that indicate good calibration procedures. On the other hand, there are several stations with relatively large RMS values for both parameters,

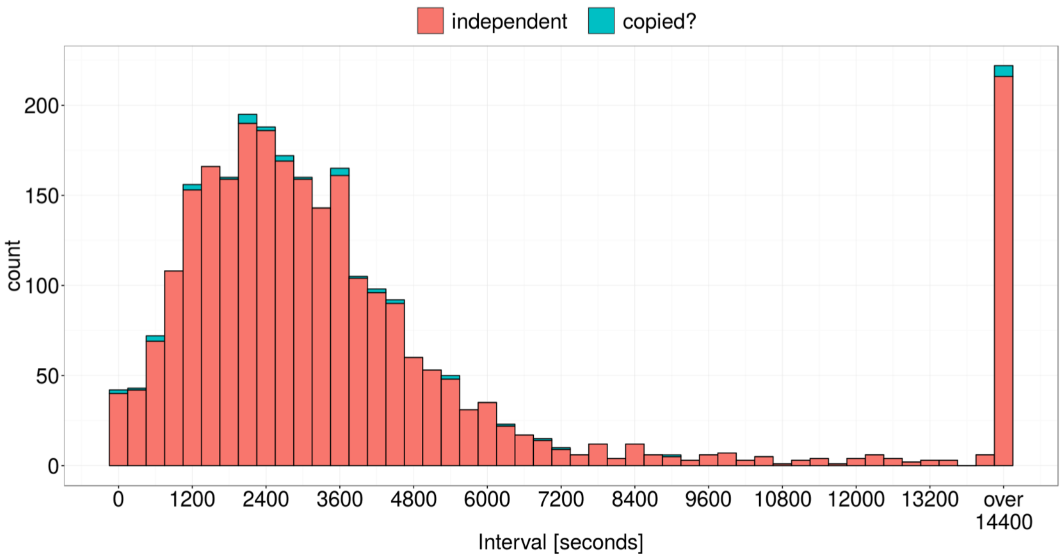

Fig. 3. The time interval between the two adjacent system delay measurement. The blue ("copied?") part is the case when an identical record are given for the two adjacent data sets.

and the improvement in the calibration stability may improve the LAGEOS quality for these stations. It is highly recommended for every station to pay attention to its own system delays, and understand the short-term and long-term behaviours and the cause of the variation.

The LAGEOS quality may improve if one does the calibration more often especially during the time when the system delay is expected to change. Using the SLR data to all satellites tracked by Herstmonceux, we simply calculate the time intervals between the two adjacent system delay measurements and the result is given in Fig. 3. The plots for other stations are available at:

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/CalInterval.pdf

The calibration frequency should be carefully chosen by examining the short-term calibration variation (ex. Fig. 1 bottom). It should be noted that there are a number of stations with which the identical values are given for the two adjacent measurements and we suspect the time tag of the calibration record may not be true.

Post-fit residuals of LAGEOS-1+2, Ajisai, Starlette+Stella and LARES data are plotted with respect to the applied system delay. The analysis procedure is common with Otsubo (2014). The graphs are:

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/SortDelay6.pdf

and it will be ideal if there are no positive/negative trends. A negative 1:1 trend indicates that the variation in calibration would not be common to its satellite tracking.

Other Potential Error Sources

Likewise, the post-fit residuals are examined with respect to other parameters.

(1) Number of single-shot returns per NP bin (intensity)

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/SortIntensity6.pdf

where some stations (especially with C-SPAD) show a negative trend that is caused by intensity-dependent range measurements.

(2) Single-shot RMS of NP bin

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/SortRms6.pdf

where several stations show a positive trend that can partly be linked with the intensity dependence (above) and also can be caused by the variation of the tail clipping point (Wilkinson et al., 2016).

(3) Elevation of the Sun

http://geo.science.hit-u.ac.jp/slr/bias/2016sp/SortSunEl6.pdf

which is aimed to detect a day/night offset that can be shown at the zero elevation of the Sun.

Conclusions

There are a number of potential error sources in SLR measurement, and some of them are revealed from the one-year SLR data set. In particular, the system delay measurement and its procedure are likely to affect the SLR quality at a number of stations.

The majority of systematic errors detected in this study can be eliminated by careful tests at a station. It is important for every station to suspect, detect and remove any error sources even at the 1 mm level.

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