Systematic Error Mitigation in SLR Products for ITRF2020

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Errors affecting the SLR technique

• SLR data provide a direct measure of the station-satellite distance at specified measurement times. Systematic errors in range are commonly called range biases, and systematics affecting the epoch of the observations are known as time biases.

• The nature of the errors affecting the SLR technique can be divided into 3 categories:
  1. ranging machine errors
     • calibration and/or synchronization issues
     • hardware malfunctioning
     • intrinsic device limitations
  2. timing errors (station clock issues)
  3. modeling errors (e.g. satellite center of mass offsets, force model deficiencies, etc.).

• Following good practices and procedures at the ground stations should help to identify and minimize errors of the first two categories.

• Time biases for most ground stations are relatively small and stable. There are sporadic episodes of very large clock errors. The impact of time biases in the geodetic products is mainly restricted to the horizontal components of station coordinates (east-west component), which can reach a few mm.
ILRS Activities to Control Systematic Errors

• ILRS characterizes the quality of the data produced by its network before releasing them to the user community. To achieve this, a number of “check points” are in use:
  • The first level of quality control (QC) is always performed at the station collecting the data
  • Daily analysis for quality control (QC) of range and time biases
  • Quality Control Board (QCB) addressing laser ranging data quality issues via bi-monthly telecons

• These efforts are very successful in detecting major problems and system malfunctions, but they lack the ability to detect varying errors below a threshold of 1-2 centimeters.

• The ILRS ASC paid attention to the systematic error handling from the very beginning of its activities in order to provide ILRS products as free from systematic errors as possible and to monitor the long-term performance of stations at the mm level maintaining a record of known problems in the “Data Handling” file...
Station Systematic Error Monitoring Report

Since 1998 ILRS has used the Global Report Card to evaluate and monitor the station performance [https://ilrs.cddis.eosdis.nasa.gov/network/system_performance/]

- The short term stability is the standard deviation of the pass-by-pass range biases during the last 3 months
- The long term stability is the standard deviation of the pass-by-pass range bias estimates during the past year.
Station Systematic Error Monitoring History

Now available online (http://geodesy.jcet.umbc.edu/ILRS_REPORT_CARD) separately for each site, averaged over the five AC series along with a std. dev.
The “Data Handling” file:

- SITE/ID
  - SOLUTION/DATA_HANDLING
    - CODE PT_UNIT T_DATA_START __DATA_END M E-VALUE STD_DEV COMMENTS
  - list of sites with mandatory arc dependent biases to be estimated
    - 1664--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 1668--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 1953--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 7080--- mm A 16:106:000 0:00:00:000 0:00:00:000 E
    - 7548--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 7388--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 7810--- mm B 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 7945--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 E
    - 7483--- mm A 10:265:000 0:00:00:000 0:00:00:000 E
    - 8334--- mm A 10:319:000 0:00:00:000 0:00:00:000 E
    - 7280--- mm A 12:001:000 0:00:00:000 0:00:00:000 E
    - 8321--- mm A 09:148:000 10:069:000 0:00:00:000 E
    - 7249--- mm A 12:067:000 0:00:00:000 0:00:00:000 E

- SITE/ID
  - list of new sites with preliminary coordinates (not included in ITRF2014)
    - 1674--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 V
    - 1891--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 V
    - 7394--- mm A 15:218:000 0:00:00:000 0:00:00:000 V
    - 7407--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 V
    - 7627--- mm A 0:00:00:000 0:00:00:000 0:00:00:000 V

- SITE/ID
  - list of mandatory range biases to be applied on observation (ILRS/ASC Oct 2007)
    - * with updates from ILRS/ASC reprocessing results
      - 1873--- mm A 95:001:000 0:00:001:000 0:00:000:000 R
      - 7080--- mm A 88:001:000 89:349:000 0:00:000:000 R
      - 7080--- mm A 90:001:000 93:168:000 0:00:000:000 R
      - 7080--- mm A 95:005:000 96:026:000 0:00:000:000 R
      - 7080--- mm A 96:026:000 96:116:000 0:00:000:000 P
      - 7080--- mm A 96:116:000 96:330:000 0:00:000:000 P
      - 7109--- mm A 0:000:000 88:347:000 0:00:000:000 R
      - 7109--- mm A 97:009:000 97:918:000 0:00:000:000 R
      - 7110--- mm A 84:001:000 84:136:000 0:00:000:000 R
      - 7110--- mm A 87:300:000 87:625:000 0:00:000:000 R
      - 7110--- mm A 96:240:000 96:277:000 0:00:000:000 R
      - 7110--- mm A 84:122:000 87:074:000 0:00:000:000 R

...
ILRS Activities to Control Systematic Errors (cont.)

- The ILRS ASC is going to adopt a new model for the range biases strongly motivated by the need to remove the VLBI-SLR scale difference. The model will be obtained estimating RB simultaneously with all other parameters.

- A Pilot Project is currently ongoing with the data reanalysis performed by the ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, JCET, NSGF):
  - Weekly estimation of coordinates, EOP and range biases RB
  - Time frame: 1993-2018
  - Data: LAGEOS, LAGEOS 2, Etalon 1&2
  - Time series with separate range biases for LAGEOS, combined for Etalon
  - Combination of the time series estimated by the ILRS ACs
  - Computation of mean range biases over medium/long time scale

An example of the estimated RB is given in the next figure on the right where the blue dots are the weekly combined RB estimates for GRAZ.
The SLR data provide a direct measure of the station-satellite distance at specified measurement times. Systematic errors in range are commonly called range biases, and systematics affecting the epoch of the observations are known as time biases.

Time biases for most ground stations are relatively low and stable. There are sporadic episodes of very large clock errors. The impact of time biases in errors, for example, is particularly problematic and their removal often non-trivial. Highly correlated with station height estimates over short periods, the precision of individual SLR observations and normal point data exceeds that of currently available modelling standards. Individual retroreflector

The ILRS ASC is going to adopt a new model for the range biases. The first level of quality control (QC) is always performed at the station collecting the data points. The ILRS ASC paid attention to the systematic error handling from the very beginning of its activities in order to provide ILRS products as free from intrinsic device limitations devoted all its efforts to develop, evaluate and implement the new approach that will continuously monitor the systematic errors at all ILRS sites in the future. The presentation will demonstrate the level of improvement with respect to the previous ILRS product series and a glimpse of what we can expect for the future.

**ILRS Activities to Control Systematic Errors**

- Computation of mean range biases over medium/long time scale
- Combination of the time series estimated by the ILRS ACs
- Data: LAGEOS, LAGEOS 2, ETALON1-2
- Time frame: 1993-2018
- Weekly estimation of coordinates, EOP and range biases RB

An example of the estimated RB is given in the figure on the right. The model will be obtained estimating RB simultaneously with other parameters (coordinates, EOP) included in the ILRS products.

The ILRS Analysis Standing Committee (ASC) completed the re-analysis of the modern-era data set with improved modeling and the newly adopted new model for the range biases. The results show that real biases can be recovered and that the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases usually involving stations with poor or sparse data records. As an example, the figure below on the left shows the case of a known, existing range bias in the data from station MLRO (Matera Laser ranging Observatory, Italy) in 2007, close to a value of 25 mm as determined by the station engineers, with a 2-3 mm uncertainty. The estimated biases are represented in the plot both as running averages of each 6.5±0.5

The monitoring of systematic errors is an ongoing task to keep the ILRS operational. Use of the updated data handling file for all the official ILRS products, ITRF included. Start of the operational service to routinely keep the table updated.

**Impact on the Reference Frame**

The ILRSA with estimated RB

**Impact on the ILRSA Scale w.r.t. ITRF2014**

<table>
<thead>
<tr>
<th>Year</th>
<th>TX [mm]</th>
<th>TY [mm]</th>
<th>TZ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>20</td>
<td>-10</td>
<td>-40</td>
</tr>
<tr>
<td>2000</td>
<td>6.5±0.5</td>
<td>-20</td>
<td>-10</td>
</tr>
<tr>
<td>2005</td>
<td>14.4±0.2</td>
<td>-20</td>
<td>-10</td>
</tr>
<tr>
<td>2010</td>
<td>7.2±0.2</td>
<td>-10</td>
<td>-20</td>
</tr>
<tr>
<td>2015</td>
<td>20</td>
<td>-10</td>
<td>-40</td>
</tr>
</tbody>
</table>

Green line represents the actual bias value used in the analysis, as reported in the adopted data handling file.

**Impact on the ILRSA TX/TY/TZ w.r.t. ITRF2014**

- TX: deviation from the ITRF2014 reference frame.
- TY: deviation from the ITRF2014 reference frame.
- TZ: deviation from the ITRF2014 reference frame.

**Mean values in mm**

- TX: 6.5±0.5 mm
- TY: 7.2±0.2 mm
- TZ: 14.4±0.2 mm
The results show that real biases can be recovered and that the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases involving stations with poor or sparse data records.

The figure on the right shows the case of a known, existing range bias in the data from station MLRO (Matera Laser Ranging Observatory, Italy) in 2007, close to a value of 25 mm as determined by the station engineers, with a 2-3 mm uncertainty.

The estimated biases (running averages of each AC’s time series) and of the combined time series, named ILRSA. A few sporadic discrepancies at the sub-centimeter level notwithstanding, the identification and quantification of a systematic range error is satisfactory.
Results of the SSEM PP – Main Sites

- The general agreement among the solutions provided by the ILRS ACs is more clearly shown in the figure below on the right with the histogram of the mean biases over the entire 2005-2008 period, for the top 20 most prolific stations in the SLR worldwide network during these years. It is worthwhile to underline that this estimation process cannot yield millimeter accuracy in each single estimation but it can nevertheless reach such an accuracy in the mean value. The mean biases estimated for LAGEOS and LAGEOS-2 have very similar values, as expected from their nearly identical construction and similar orbits.

![Weighted averages of LAGEOS-1/2 RB 2005.0-2009.0](image-url)
Results of the SSEM PP – Active Sites

- The graph shows the mean estimates for LAGEOS and LAGEOS-2 bias for all active stations in the SLR worldwide network during the years 1993-2018. **Red arrows indicate Core Sites.**
Impact on the Reference Frame - Origin

- The impact of the new approach on the reference frame was investigated by looking at the translations and scale of the loosely constrained combined time series with respect to ITRF2014 in comparison with the values obtained with the standard approach, i.e., with the application of the corrections listed in the Data Handling file.

- The origin translations are not significantly different, except for a slight smoothing of the annual component and general reduction of some extreme values.
Impact on the Reference Frame - Scale

- While the origin translations are not significantly different, the offset in the scale is significantly reduced, as shown in the figure. Furthermore, the mean change that is of the order of ~1 ppb is towards a closer agreement with the ITRF2014 scale, indicating a reduction in the scale difference between the SLR and VLBI future realizations of the TRF.
Operational phase

• The monitoring of systematic errors is an ongoing task to keep the ILRS operational product at a high quality standard, maintaining close contact with the onsite engineers.

• Items to be considered towards an operational phase:
  • New satellite Center of Mass (CoM) model - just delivered (mid-November ‘18)
  • Full reanalysis to take into account the new satellite CoM corrections
  • Mean station systematic errors inserted into the ILRS Data Handling file
  • Start of the operational service to maintain the table routinely updated
  • Use of the updated Data Handling file for all the official ILRS products, ITRF2020 included.

• Expected operational by this summer...
Changes in SLR Data Analysis

• Once ILRS adopts the new Data Handling file with the results from the current reanalysis, the users of SLR data will have to:
  • Adopt the new systematics and apply them *a priori* for each tracking site
  • Use the new satellite Center of Mass (CoM) model for supported targets
  • Use the same station coordinates as those used by ILRS in the reanalysis (SSEM PP)
  • Interrogate the Data Handling file (often, daily) to ensure there are no changes in the adopted mean biases or new additions (DH file carries a time stamp which changes with each release).
Thank you!