We investigate the impact of adding Satellite Laser Ranging (SLR) data to Global Positioning System (GPS) ground and low-earth orbiting (LEO) observations for the determination of the geocenter coordinates and the terrestrial scale, along with their stability. To obtain an independent measure of inter-technique site ties, we impose no a priori constraint on the ties between collocated SLR and GPS ground stations. Challenges with integration of SLR data stem from the relative scarcity of SLR tracking data and presence of uncalibrated SLR biases. We present results from a simulation as well as preliminary results from the combined processing of ground GPS tracking data, Jason-2 GPS tracking data and SLR observations to Jason-2 and LAGEOS (LAG) 1 and 2 from mid-2010 to end of 2014. We discuss our methodology and the various approaches taken to quantify the effect of SLR data on the quality of our frame solution and highlight some of the challenges encountered in exploiting space-based collocations to improve the terrestrial reference frame. In particular, we show that while the formal errors retrieved from our estimation process suggest that including SLR observations should significantly improve geocenter determination and the stability of the reference frame, practical issues prevent us from achieving the levels of stability and accuracy expected based on a covariance analysis.

### Highlights

- **Strategy:**
  - 40 GPS stations and 16 SLR stations
  - 7-day orbit arc for GPS and LEO satellites
  - Error sources added to simulated truth: pass-dependent bias modeled as random walk and white measurement noise added to SLR observations
  - Perform fiducial-free network and reduced-dynamic orbit solution
  - Reference frame determination error measured as Helmert transformation between the estimated network position and the truth network position
  - Final error assessment drawn from average of 4 7-day realizations over a year, separated by 3 months.

- **Results:**
  - Down-weighting the SLR data relative to the GPS observations helps reduce errors in the determination of the geocenter coordinate.

### Methodology

- Weekly LAGEOS orbits obtained from ILRS BKG (Bundesamt fur Kartographie und Geodasie) analysis center.
- Weekly Jason-2 orbits generated from week-long arc Jason-2 reduced-dynamics precision orbit determination using GIPSY-OASIS software.
- Inability to estimate station-dependent biases in the core network solution process a priori coarse estimation of station-dependent biases based on time series of prefit residuals.
- Data pre-processing: exclusion of some SLR stations from processing based on prefit residuals scatter; correction of estimated site-dependent at the observation level prior to core estimation process.
- Network selection: 40 globally distributed GPS sites, number of SLR stations ranging from 1 to 16 depending on arcs for both GPS+IA2 and GPS+LAGEOS cases depending on arc,
- SLR data weight: 5 mm; GPS data weight: 2 mm (LC), 20 cm (PC)
- A priori station position deviation: 1km for GPS sites, 10 m for SLR sites
- IGS antenna calibrations are used for this investigation.

### Simulation setup and results

#### Impact of adding SLR dataset to GPS dataset measured by:

- Impact on frame parameters determined by GPS sites only (fig. 1, table 2): only the GPS sites are used to build a frame and compare with JPL’s realization of ITRF08 (JL08PB).
- Formal errors analysis (table 1): additional satellites and/or measurements should theoretically improve the frame solution.

- Scatter is greatly increased when SLR observations to J2 only are added to GPS data, esp. in TX and TZ: suggesting that J2 is not enough of a tie on its own to properly constrain the solution. Adding SLR observations to J2 and the 2 LAGEOS satellites strengthen the space tie, reduces the scatter and visiblyimproves the frame solution; suggesting the deficiencies observed in the GPS+IA2 SLR/GPS case arise from the relative scarcity of SLR data to J2.

- Adding J2 helps all geocenter components, esp. TZ. Adding SLR measurements for J2 degrades the overall solution, esp. TZ. Adding SLR observations to J2 and the LAGEOS satellites resolves the issues noted with SLR observations to J2 only. Adding SLR measurements for LAGEOS do not affect the GPS sites significantly due to the lack of space and ground tie.

### Table 1: Results of fit to IJ0LBP frame from frame built using GPS sites only. Units are mm and mm/yr for rates.

<table>
<thead>
<tr>
<th></th>
<th>GPS ground only</th>
<th>GPS ground+J2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset</td>
<td>TX</td>
<td>TY</td>
</tr>
<tr>
<td></td>
<td>-5.945</td>
<td>0.862</td>
</tr>
<tr>
<td>Offset sigmas</td>
<td>0.081</td>
<td>0.084</td>
</tr>
<tr>
<td>White noise</td>
<td>0.052</td>
<td>0.052</td>
</tr>
</tbody>
</table>

### Table 2: Statistics on estimated frame parameters resulting from fit of solution to IJ0LBP frame. Units are mm. Colors added for readability.

- 800 observations for IJ0LBP frame.
- Results are averaged over 4 7-day realizations.
- The most significant improvements are observed in TX and TZ.
- S suggests the deficiencies observed in the GPS+IA2 SLR/GPS case arise from the relative scarcity of SLR data to J2.

### Future prospects:

- Comparing using ground ties only, J2 as a space tie only, a combination of ground and space ties:
- Implementation of site-dependent bias estimation in filtering process - investigation of SLR data weight impact on frame determination.

### Results:

- SLR pass-dependent bias (2 mm/pass random walk).
- SLR white noise for measurement point (1 mm).

### Performance analysis

- Impact of adding SLR dataset to GPS dataset measured by:
  - Impact on frame parameters determined by GPS sites only (fig. 1, table 2): only the GPS sites are used to build a frame and compare with JPL’s realization of ITRF08 (JL08PB).
  - Formal errors analysis (table 1): additional satellites and/or measurements should theoretically improve the frame solution.

- Scatter is greatly increased when SLR observations to J2 only are added to GPS data, esp. in TX and TZ: suggesting that J2 is not enough of a tie on its own to properly constrain the solution. Adding SLR observations to J2 and the 2 LAGEOS satellites strengthen the space tie, reduces the scatter and visiblyimproves the frame solution; suggesting the deficiencies observed in the GPS+IA2 SLR/GPS case arise from the relative scarcity of SLR data to J2.

- Adding J2 helps all geocenter components, esp. TZ. Adding SLR measurements for J2 degrades the overall solution, esp. TZ. Adding SLR observations to J2 and the LAGEOS satellites resolves the issues noted with SLR observations to J2 only. Adding SLR measurements for LAGEOS do not affect the GPS sites significantly due to the lack of space and ground tie.

### Context:

- We investigate combining SLR and GPS data by performing precise orbit determination (POD) for the GPS constellation, Jason-2 (J2) and the LAGEOS (LAG) 1 and 2 satellites. We show results from a simulation targeting the effects of SLR systematic and random measurement errors on the determination of the frame parameters as well as from real data inversion.

- **Objective:**
  - To quantify the impact of SLR data when combined with GPS observations on the determination of the reference frame; to gain insight into the need for ground, space or combined ground/space ties when determining the geocenter position and TRF scale parameter.

- **Approach:**
  - Weekly arcs corresponding to SLR weeks from May 2010 through Dec. 2014 are processed. GPS and LEO satellite states and clocks are estimated simultaneously with station positions, tropospheric delays and other parameters.
  - 5 cases are considered:
    - GPS ground data only,
    - GPS ground+IA2 data,
    - GPS ground+LAG data,
    - GPS ground+LAG data+IA2 SLR data,
    - GPS ground data+LAG SLR data, GPS ground data+IA2 GPS/SLR+LAG SLR. No ground ties are used.

- **Conclusion:**
  - Ties are needed to connect GPS and SLR datasets; J2 serves as a space tie but challenges associated with SLR data editing and station-dependent biases estimate lead to degraded performances when combining GPS and SLR observations to J2 only.
  - SLR observations to the LAGEOS satellites significantly improve the multi-technique solution but further investigation is required to assess which of the GPS-only or multi-technique solution is preferred. Simulation results suggest relative data weights are critical for mitigating frame errors.

- **Future prospects:**
  - Comparing using ground ties only, J2 as a space tie only, a combination of ground and space ties:
    - Implementation of site-dependent bias estimation in filtering process - investigation of SLR data weight impact on frame determination.