Performance of dynamic and ambiguity-fixed GNSS-derived LEO orbits in SLR validation and network calibration

Daniel Arnold 1  Stefan Schaer 1,2  Ulrich Meyer 1  Linda Geisser 1  Adrian Jäggi 1

1 Astronomical Institute, University of Bern
2 Swiss Federal Office of Topography, Wabern

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Motivation

• Numerous geodetic satellites are in low Earth orbit (LEO)
• Precise orbit determination (POD) by GNSS (GPS), some tracked by Satellite Laser Ranging (SLR)
• GNSS-based LEO POD has witnessed remarkable quality improvements in recent past (e.g., more accurate modeling of gravitational and non-gravitational forces, single-receiver ambiguity fixing, ...)
→ cm accuracy and precision possible
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SLR to LEO satellites

- allows for independent validation of GNSS-derived orbits
- allows to measure orbit errors not only in radial, but also in lateral directions
- can be used to calibrate SLR stations (coordinates, range and timing biases) if we have confidence in GNSS-derived orbits
GPS-based POD of LEO satellites

- Bernese GNSS Software v5.3
- State-of-the-art models
  - Macro models for non-gravitational forces
  - In-flight calibrated GPS antenna phase patterns
  - Spacecraft parameters (attitude, CoM, sensor locations, etc.)
- Carrier phase ambiguity fixing:
  - Single-receiver ambiguity resolution using GPS products of Center for Orbit Determination in Europe (CODE), including new signal-specific satellite phase biases
  - Ties LEO orbit to IGSxx reference frame
  - Horizontal components benefit most, only weak constraint in vertical direction
Ambiguity-fixed GNSS clock corrections and phase bias products (enabling undifferenced ambiguity-resolution) of CODE available:

- Operationally generated
- IGS Final product line:
  - ftp://cddis.gsfc.nasa.gov/pub/gnss/products
  - Starting from 1 January 2019
- MGEX product line:
  - ftp://cddis.gsfc.nasa.gov/pub/gnss/products/mgex
  - Starting from 1 July 2018
- See also ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT
Models used for POD

- Earth gravity field: GOCO05S ($120 \times 120$)
- Solid Earth tides: IERS2010
- Pole tides: IERS2010
- Ocean pole tides: EOT11a ($50 \times 50$)
- Atmospheric densities/horizontal wind model: DTM2013 / HWM14
- Earth reflectivity/emissivity: CERES 2007
- Transmitting antenna PCO/PCV: igs14.atx
- Receiver antenna PCV: in-flight calibration (iterative residual stacking)
Satellites considered

**Swarm-A/B/C:**
- Magnetic field
- Launched: 22 Nov 2013
- Altitude: 460 km (A/C), 510 km (B)

**Sentinel-3A/B:**
- Altimetry
- Launched: 16 Feb 2016 (A), 25 Apr 2018 (B)
- Altitude: 810 km

**GRACE Follow-On C/D:**
- Gravity field
- Launched: 22 May 2018
- Altitude: 500 km
Analysis of LEO SLR data

- Compute SLR residuals based on
  - known LEO satellite orbit, attitude, geometry, LRA characteristics
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  - satellite position (in RTN or s/c body frame)
  - station position (in NEU frame)
  - SLR range and timing bias
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• From partials and residuals, form/solve normal equations
  • Correlations (station height and radial orbit component; time offset and along-track component)
  • A priori constraints or well observable set of parameters
SLR residuals Swarm-B, (reduced-) dynamic

SLR observations of 14 high-performance SLR stations, SLRF2014 station coordinates used, no parameters estimated.

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Kinematic orbits: Purely geometrically derived from GPS observations, fully independent on the force models used for dynamic LEO POD.

Amb.-float (16.5 mm)
SLR residuals Swarm-B, kinematic

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- Amb.-float (16.5 mm)
- Amb.-fixed (9.9 mm)
SLR residuals Swarm-B, kinematic

Kinematic orbits: Purely geometrically derived from GPS observations, fully independent on the force models used for dynamic LEO POD.

SLR STD comparable to ambiguity-fixed dynamic orbits (9.1 mm)!

→ limitations of SLR?
SLR residuals GRACE-FO, (reduced-) dynamic

Amb.-float, no non-grav. modeling

Amb.-fixed, no non-grav. modeling

Amb.-fixed, non-grav. modeling
SLR residuals GRACE-FO, (reduced-) dynamic

Noticeable offset for reduced-dynamic orbits, more pronounced for GRACE-FO C.

Amb.-float, no non-grav. model

Amb.-fixed, no non-grav. model

Amb.-fixed, non-grav. model
Noticeable offset for reduced-dynamic orbits, more pronounced for GRACE-FO C.
K-band validation for GRACE-FO

Daily RMS values of K-band range residuals (additional independent validation):

- Reduced−dynamic, float (mean: 5.06 mm, median: 4.73 mm)
- Reduced−dynamic, fixed (mean: 1.77 mm, median: 1.44 mm)
- Dynamic, fixed (mean: 1.47 mm, median: 1.17 mm)
### Estimated corrections w.r.t. SLRF2014

Coordinate and range bias corrections from 435 days of dynamic, ambiguity-fixed Swarm-A/B/C, Sentintel-3A/B and GRACE-FO C/D orbits:

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Estimated corrections w.r.t. SLRF2014 (2)

Corrections for station **Monument Peak (71100412)** from different orbit types:

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<td>Float</td>
<td>$-3.3 \pm 0.2$</td>
<td>$-10.5 \pm 0.2$</td>
<td>$-21.8 \pm 0.9$</td>
<td>$-2.5 \pm 0.5$</td>
</tr>
<tr>
<td>Fixed</td>
<td>$-3.2 \pm 0.2$</td>
<td>$-7.8 \pm 0.2$</td>
<td>$-12.4 \pm 0.9$</td>
<td>$0.8 \pm 0.5$</td>
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<td>Fixed + NG</td>
<td>$-2.8 \pm 0.2$</td>
<td>$-7.5 \pm 0.2$</td>
<td>$-10.7 \pm 0.9$</td>
<td>$0.3 \pm 0.5$</td>
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Reduction of residuals (1)

Monument Peak (71100412), all satellites:

Without corrections

![Graph showing residuals over time with Monument Peak data and a deviation of 6.4 ± 10.8 mm]
Reduction of residuals (1)

Monument Peak (71100412), all satellites:

With corrections

![Graph showing residuals](image-url)
Reduction of residuals (2)

Without corrections

Swarm-B

Residuals [mm]

Date

Jul 18
Sep 18
Nov 18
Jan 19
Mar 19
May 19
Jul 19

1.0 ± 9.1 mm
Reduction of residuals (2)

With corrections

<table>
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<tr>
<th>Satellite</th>
<th>Residuals [mm] with corrections</th>
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<td>Swarm-A</td>
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<td>Swarm-B</td>
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<tr>
<td>GRACE-FO D</td>
<td>+1.7 ± 10.6</td>
<td>+0.0 ± 8.3</td>
</tr>
</tbody>
</table>

Date:
- Jul 18
- Sep 18
- Nov 18
- Jan 19
- Mar 19
- May 19
- Jul 19

Residuals [mm]
SLR residuals (mean ± std.) of dynamic and ambiguity-fixed orbits with and without corrections:

<table>
<thead>
<tr>
<th>Orbits</th>
<th>w/o corr.</th>
<th>w/ corr. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swarm-A</td>
<td>+3.1 ± 9.6</td>
<td>+1.0 ± 7.7</td>
</tr>
<tr>
<td>Swarm-B</td>
<td>+1.0 ± 9.1</td>
<td>−0.9 ± 7.2</td>
</tr>
<tr>
<td>Swarm-C</td>
<td>+2.2 ± 9.6</td>
<td>+0.0 ± 7.7</td>
</tr>
<tr>
<td>Sentinel-3A</td>
<td>+1.5 ± 10.3</td>
<td>+0.0 ± 7.8</td>
</tr>
<tr>
<td>Sentinel-3B</td>
<td>+1.1 ± 10.2</td>
<td>−0.7 ± 7.4</td>
</tr>
<tr>
<td>GRACE-FO C</td>
<td>+3.4 ± 10.1</td>
<td>+1.7 ± 7.9</td>
</tr>
<tr>
<td>GRACE-FO D</td>
<td>+1.7 ± 10.6</td>
<td>+0.0 ± 8.3</td>
</tr>
</tbody>
</table>
Conclusion

- SLR to LEO satellites not only sensitive to radial, but also to 3-dimensional orbit errors, as well as station positions and range (and timing) biases.
- Dynamic ambiguity-fixed LEO orbits have reached a quality level that is interesting to validate/calibrate the SLR station network. Needs good knowledge of satellite geometry (antenna and reflector locations).
- Station parameter corrections sometimes at 1 cm level even for high-performance SLR stations.
- Corrections remove mean offsets in SLR residuals for individual stations and reduces standard deviation.
- Kinematic orbits profit a lot from ambiguity fixing. SLR now sees hardly any differences to the (superior) dynamic orbits.
• For methodology and further results, see

• For CODE’s phase bias products, see

Thank you for your attention!