Rigorous propagation of Galileo-based terrestrial scale

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Tour de l’IGS
Technical Mini-Workshop Series
June 02, 2021
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   - Background
   - Motivation

2. Method
   - Data
   - Preliminary step
   - Model fit
   - Back-substitution

3. Results
   - Scale factors w. r. t. IGSR3
   - Scale factors w. r. t. ITRF2014

4. Conclusions
   - Summary and outlook
Scale of previous ITRF solutions

- So far available GNSS satellite phase center offsets (PCOs) estimated with fixed ITRF scale, and depend conventionally on SLR and VLBI scale
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Rigorous propagation of Galileo-based terrestrial scale – Background

Scale of previous ITRF solutions

- So far available GNSS satellite phase center offsets (PCOs) estimated with fixed ITRF scale, and depend conventionally on SLR and VLBI scale
  - No independent scale realization possible by GNSS
Rigorous propagation of Galileo-based terrestrial scale – Background

**Scale of previous ITRF solutions**

- So far available GNSS satellite phase center offsets (PCOs) estimated with fixed ITRF scale, and depend conventionally on SLR and VLBI scale
  - No independent scale realization possible by GNSS

**Unique opportunity**

- European GNSS Agency disclosed metadata including z-PCOs for Galileo satellites
  - Realize independent scale in multi-GNSS solutions and possibly contribute to ITRF2020 scale
Preliminary work

Shortcoming of igsR3.atx z-PCOs

- A single correction to all igs14.atx GPS z-PCOs was estimated (same for GLONASS) based on preliminary multi-GNSS solutions for the period 2017-2018.
- Like in all other ANTEX files, satellite z-PCOs are constant (except for R730 & R737), with no uncertainties available.
Preliminary work

Shortcoming of igsR3.atx z-PCOs

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- Like in all other ANTEX files, satellite z-PCOs are constant (except for R730 & R737), with no uncertainties available.
- No constraining with appropriate weighting possible (satellite z-PCOs fixed in repro3 solutions).
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New approach in this study
Rigorous propagation of Galileo-based terrestrial scale

New approach in this study

- Fit deterministic and stochastic model to time series of GPS/GLONASS z-PCO estimates of repro3 AC solutions
- Derive piecewise linear models of z-PCOs
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- Fit deterministic and stochastic model to time series of GPS/GLONASS z-PCO estimates of repro3 AC solutions
- Derive piecewise linear models of z-PCOs
  → Introduce time-variable z-PCOs with realistic uncertainties for scale estimation
Outline

1. Introduction
2. Method
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**Data**

<table>
<thead>
<tr>
<th>IGS repro3 SINEX solutions of four ACs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CODE (Center for Orbit Determination in Europe):</strong> 1994-01-02 to 2019-12-31</td>
</tr>
<tr>
<td>- From 2002-01-01 GLONASS; From 2013-01-01 Galileo</td>
</tr>
<tr>
<td><strong>ESA (European Space Agency):</strong> 1995-01-01 to 2020-12-31</td>
</tr>
<tr>
<td>- From 2009-01-01 GLONASS; From 2015-01-01 Galileo</td>
</tr>
<tr>
<td><strong>GFZ (GeoForschungsZentrum):</strong> 1994-01-02 to 2020-12-31</td>
</tr>
<tr>
<td>- From 2012-01-01 GLONASS; From 2013-12-21 Galileo</td>
</tr>
<tr>
<td><strong>GRGS (Groupe de Recherche en Géodésie Spatiale):</strong> 2000-05-03 to 2020-12-31</td>
</tr>
<tr>
<td>- From 2008-11-04 GLONASS; From 2016-12-31 Galileo</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Preliminary step: When does Galileo-based scale become precise and stable enough?</th>
</tr>
</thead>
</table>

CODE

ESA

GFZ

GRGS

→ Steady level after May 2017 when at least 17 Galileo satellites are included
**Preliminary step:** When does Galileo-based scale become precise and stable enough?

**CODE**

**GFZ**

**ESA**

**GRGS**

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Preliminary step: When does Galileo-based scale become precise and stable enough?

→ Steady level after May 2017 when at least 17 Galileo satellites are included
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z-PCO time series

Determination of time series of GPS+GLONASS satellite z-PCO estimates
Determination of time series of GPS + GLONASS satellite z-PCO estimates

- After May 2017
  - Fix Galileo satellite z-PCOs (except for E102)
- Before May 2017
  - “no-net-translation” constraints of selected GPS and GLONASS satellite z-PCOs w. r. t. igsR3.atx
Determination of time series of GPS+GLONASS satellite z-PCO estimates

- After May 2017
  - Fix Galileo satellite z-PCOs (except for E102)
- Before May 2017
  - “no-net-translation” constraints of selected GPS and GLONASS satellite z-PCOs w. r. t. igsR3.atx
- Initial screening procedure: elimination of data before 1997, data with large formal errors, short time spans
Diverse features: periodicities, offsets, outliers, slow non-linear variations
Fit deterministic and stochastic models to all z-PCOs

Initial model: Single linear trend + variable white noise
Then: Iterative model refinement by adding more deterministic and noise components
Fit deterministic and stochastic models to all z-PCOs

Initial model: Single linear trend + variable white noise
Then: Iterative model refinement by adding more deterministic and noise components

Example ESA AC R730 – Fit after 33 iterations
Model fit – periodogram: GFZ

- grey: average periodograms of residuals from complete deterministic models
- red: white + flicker noise fit
- black: average periodograms of residuals from piecewise linear models
Back-substitution

Long-term stacking of GPS+GLONASS z-PCO time series

Estimation of daily “transformation parameter” before May 2017 to remove initial “no-net-translation” constraint and get piecewise linear z-PCO models independent from igsR3.atx, with realistic uncertainties.

New piecewise linear z-PCO models are then back-substituted into the daily AC SINEX solutions, and their scale is compared to that of the IGSR3 reference frame.

→ Result: Galileo-based scale independent of igsR3.atx (and SLR/VLBI)

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Scale fit w. r. t. IGSR3, Example: GFZ

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**Scale factors w. r. t. IGSR3**

IGSR3 reference frame - repro3 solution based on igsR3.atx file

<table>
<thead>
<tr>
<th></th>
<th>scale offset @2010.0 [mm]</th>
<th>scale rate [mm/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cod</td>
<td>-0.1 +/- 0.7</td>
<td>0.04 +/- 0.05</td>
</tr>
<tr>
<td>esa</td>
<td>0.8 +/- 0.8</td>
<td>0.06 +/- 0.07</td>
</tr>
<tr>
<td>gfz</td>
<td>0.5 +/- 0.9</td>
<td>-0.04 +/- 0.07</td>
</tr>
<tr>
<td>grg</td>
<td>-0.1 +/- 0.8</td>
<td>0.01 +/- 0.07</td>
</tr>
</tbody>
</table>
### Mean scale offsets at epoch 2010.0 and scale rates w.r.t. ITRF2014

<table>
<thead>
<tr>
<th>AC</th>
<th>scale offset @2010.0 [mm]</th>
<th>scale rate [mm/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGS repro</td>
<td>7.6 +/- 0.2</td>
<td>0.20 +/- 0.02</td>
</tr>
<tr>
<td>cod</td>
<td>7.8 +/- 0.7</td>
<td>0.23 +/- 0.05</td>
</tr>
<tr>
<td>esa</td>
<td>8.7 +/- 0.8</td>
<td>0.25 +/- 0.07</td>
</tr>
<tr>
<td>gfz</td>
<td>8.4 +/- 0.9</td>
<td>0.15 +/- 0.07</td>
</tr>
<tr>
<td>grg</td>
<td>7.8 +/- 0.8</td>
<td>0.20 +/- 0.07</td>
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</tbody>
</table>

→ 4 ACs agree within 1 mm for scale offset; 0.1 mm/yr for scale rate
Scale factors w. r. t. ITRF2014

Comparison with the other space geodetic techniques

- VLBI contribution to ITRF2014
- SLR test ASI solutions
- DORIS contribution to ITRF2014
- GNSS repro3 constant z-PCO
- GNSS repro3 GFZ pwl z-PCO

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Rigorous re-evaluation of all GPS and GLONASS satellite z-PCOs
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Rigorous re-evaluation of all GPS and GLONASS satellite z-PCOs

- Piecewise linear models of GPS and GLONASS z-PCOs (vs. igsR3.atx with constant z-PCOs)
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- Piecewise linear models of GPS and GLONASS z-PCOs (vs. igsR3.atx with constant z-PCOs)
- Back-substitution to repro3 solutions → refined Galileo-based scale:
Conclusions

Rigorous re-evaluation of all GPS and GLONASS satellite z-PCOs

- Piecewise linear models of GPS and GLONASS z-PCOs (vs. igsR3.atx with constant z-PCOs)
- Back-substitution to repro3 solutions → refined Galileo-based scale:
  - Differences to igsR3.atx-based scale are essentially linear
  - 4 ACs (CODE, ESA, GFZ, GRGS) agree within 1 mm for scale offset; 0.1 mm/yr for scale rate w. r. t. ITRF2014
  - Refined AC-specific estimates agree with scale of IGS repro3 solutions within same level
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Rigorous re-evaluation of all GPS and GLONASS satellite z-PCOs

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→ Contribution to ITRF2020 scale?
Thank you very much for your attention.

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Model fit – periodograms: CODE

- grey: average periodograms of residuals from complete deterministic models
- red: white + flicker noise fit
- black: average periodograms of residuals from piecewise linear models
Model fit – periodograms: ESA

- black: average periodograms of residuals from piecewise linear models
- grey: average periodograms of residuals from complete deterministic models
- red: white + flicker noise fit
Model fit – periodograms: GFZ, GRGS

GFZ

GRGS
Appendix

Free vs. constrained scale

**Free scale**

- Unreliable scale trends which differ a lot among ACs
- Reasons:
  - Remaining trends in z-PCOs?
  - 3.6 yr Galileo too short for 20 yr time span?

Example: ESA

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Free vs. constrained scale

Constrained scale

- Additional assumption: no-net-rate constraint over selected subset of GPS z-PCOs
- Shortcoming? In case of actual non-zero average trend → propagation of these trends into scale

Example: ESA
Appendix

Scale factors w. r. t. IGSR3

CODE

ESA

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Appendix

Scale factors w. r. t. IGSR3

GFZ

GRGS

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