Evaluation of
the IGS terrestrial frame solutions
since the switch to IGS14/igs14.atx

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(with contributions from Ralf Schmid, Jim Ray & Wei Chen)
Outline

• Transition to IGS14/igs14.atx: reminder

• Recent daily SINEX combination results (→ this afternoon)

• Impact of the switch to IGS14/igs14.atx on:
  – Alignment of daily IGS SINEX solutions to ITRF
  – Scale of daily IGS SINEX solutions
  – Accuracy of IGS station positions

• ITRF2014 post-seismic deformation models: 2.5 years after (→ this afternoon)

• Comparison of I/D/JTRF2014 polar motion series with geophysical excitation data
Transition to IGS14/igs14.atx

- **Reference frame switch**
  - IGS14 = subset of 252 well-suited RF stations from ITRF2014 (i.e., with long and stable position time series)
  - **New: post-seismic deformation models** now part of reference coordinates
  - IGS14 “core” network = 51 homogeneously distributed clusters of stations designed for the alignment of global GNSS solutions

*Distribution of the IGS14 and former IGS08 RF stations*

*51 primary stations of the IGS14 core network*
**Transition to IGS14/igs14.atx**

- Reference frame switch: IGb08 → IGS14
- Ground antenna calibration updates:
  - additional ROBOT calibrations for 17 antenna types
  - additional COPIED calibrations for 2 antenna types
  - updated ROBOT calibrations for 19 antenna types (more antenna samples)
  - updated COPIED calibrations for 11 antenna types

<table>
<thead>
<tr>
<th></th>
<th>igs08.atx</th>
<th>igs14.atx</th>
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<tbody>
<tr>
<td>Absolute calibration</td>
<td>428 (84.9%)</td>
<td>457 (90.7%)</td>
</tr>
<tr>
<td>Converted field</td>
<td>31 (6.2%)</td>
<td>11 (2.2%)</td>
</tr>
<tr>
<td>Uncalibrated radome</td>
<td>45 (8.9%)</td>
<td>36 (7.1%)</td>
</tr>
</tbody>
</table>

Antenna calibration status of the 504 current IGS stations, based on either igs08.atx or igs14.atx

Absolute calibrations now available for >90% of the IGS stations
Transition to IGS14/igs14.atx

- Reference frame switch: IGb08 → IGS14
- Ground antenna calibration updates: igs08.atx → igs14.atx
- Satellite antenna calibration updates:

**Satellite (radial) z-PCOs:**
- Daily estimates derived from the repro2 contributions of 7 ACs
  (SINEX files unconstrained, then inverted under NNR+NNT+NNS constraints wrt IGS14)
- z-PCO time series trend-corrected to epoch 2010.0 before computing weighted averages
- Mean change from igs08.atx to igs14.atx ≈ −6 cm
  → net scale change of the IGS terrestrial frame solutions ≈ +0.5 ppb (+3 mm)

**Satellite x- and y-PCOs:**
- Daily estimates derived from the repro2 contributions of 6 ACs
- But stability and inter-AC agreement too poor to derive reliable values
- Updates for the GPS Block IIR satellites only, based on pre-flight calibrations (Dilssner et al., 2016)
Transition to IGS14/igs14.atx

- Reference frame switch: IGb08 → IGS14
- Ground antenna calibration updates
- Satellite antenna calibration updates: igs08.atx → igs14.atx

IGS14/igs14.atx framework adopted by the IGS starting with products of GPS week 1934 (29 January 2017) [IGSMail-7399]
Recent daily SINEX combination results

Spikes in JPL residuals due to numerical issues during the preprocessing of JPL solutions (problem now solved)
Recent daily SINEX combination results

- GRGS solved an ANTEX-related bug.
- JPL hasn’t switched to IGS14/igs14.atx yet.
- Slight decreases of vertical WRMS for SIO, then MIT (unknown reasons)

Smoothed WRMS of station position residuals from daily IGS SINEX combos
Alignment of daily IGS solutions

Top and bottom left: WRMS of the residuals of 6-parameter similarity transformations between daily IGS solutions and (a) the IGb08 core network, (b) the IGS14 core network

Bottom right: Number of available IGb08/IGS14 [core] stations in daily IGS solutions

Notable improvement with IGS14 after 2010, i.e. when IGb08 coordinates are extrapolated

« Full » IGS14 network already declining

IGS14 « core » network rather stable, for now
Scale of daily IGS solutions

• How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGSyy)?
Scale of daily IGS solutions

• How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGSyy)?

  – Mean scale depends on *conventional* (igsyy.atx) satellite z-PCOs (igsyy.atx z-PCO values derived so as to give access to ITRFyyyy scale)
Scale of daily IGS solutions

- How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGSyy)?

  - Mean scale depends on *conventional* (igsyy.atx) satellite z-PCOs
  - Scale rate determined by the use of *constant* satellite z-PCOs
    → « intrinsic GNSS scale rate » vs. ITRFyyyy scale rate (Collilieux & Schmid, 2013)
Scale of daily IGS solutions

• How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGSyy)?

  – Mean scale depends on *conventional* (igsyy.atx) satellite z-PCOs
  – Scale rate determined by the use of *constant* satellite z-PCOs
  – Seasonal variations due to aliasing of non-linear deformations of the station network into daily scale factors (network effect)
Scale of daily IGS solutions

- How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGSyy)?

- Mean scale depends on *conventional* (igsyy.atx) satellite z-PCOs
- Scale rate determined by the use of *constant* satellite z-PCOs
- Seasonal variations due to aliasing of non-linear deformations of the station network into daily scale factors (network effect)
- Systematic errors due to imperfections in igssy.atx z-PCO values combined with changes in the satellite constellation (Ge et al., 2005)
Scale of daily IGS solutions

Mean scale (determined by igsyx.atx satellite z-PCOs):
- igs08.atx: −0.3 ppb bias wrt ITRF2008 scale due to recent orbit modeling changes
- igs14.atx: coincides with ITRF2014 scale at epoch 2010.0

Scale rate (determined by the use of constant satellite z-PCOs, i.e. ”intrinsic GNSS scale rate”):
- closer to ITRF2008 scale rate (−0.004 ppb/yr) than to ITRF2014 scale rate (+0.026 ppb/yr)

Non-linear scale variations:
- Similar seasonal variations (i.e. network effect) with IGb08/igs08.atx and IGS14/igs14.atx
- Non-linear, non-seasonal variations less scattered with igs14.atx thanks to improved z-PCOs, esp. for recently launched satellites
The 0.03 ppb/yr scale rate difference between ITRF2014 and ITRF2008 clearly shows up when confronting the IGS daily solutions with both RFs.

The “intrinsic GNSS scale rate” based on constant z-PCO values is closer to the ITRF2008 than to the ITRF2014 scale rate.

The scale of igs14.atx-based GNSS solutions matches the ITRF2014 scale at epoch 2010.0, but progressively diverges with time.

Schematic representation of the scale and scale rate differences between ITRF2008, ITRF2014 and GNSS solutions based on either igs08.atx or igs14.atx
Accuracy of IGS station positions

• Biases in IGS station positions are evidenced by equipment-related discontinuities:

→ What is the magnitude of equipment-related discontinuities in the IGS repro2 station position time series?
→ What does it tell about the accuracy of IGS station positions?
→ Do antenna change discontinuities get smaller with igs14.atx?

MAS1 (Maspalomas, Spain)
Cyan: Detrended repro2 station position time series
Blue: piecewise linear + annual + semi-annual fit
Accuracy of IGS station positions

- What is the magnitude of equipment-related discontinuities in the IGS repro2 station position time series?

Histograms and empirical cumulative distribution functions (CDF) of 985 equipment-related discontinuities estimated during the long-term stacking of the daily IGS repro2 solutions.
Accuracy of IGS station positions

• What is the magnitude of equipment-related discontinuities in the IGS repro2 station position time series?

Histograms and empirical cumulative distribution functions (CDF) of 985 equipment-related discontinuities estimated during the long-term stacking of the daily IGS repro2 solutions

Best fitting Student’s t-distributions:
• East: \( \nu = 2.02; \sigma = 2.85 \) mm
• North: \( \nu = 2.10; \sigma = 2.74 \) mm
• Up: \( \nu = 1.88; \sigma = 7.45 \) mm
→ Discontinuity sizes aren’t normally distributed, but show “heavy tails”.

Tried to identify different sub-categories:
– antenna changes / receiver changes,
– uncalibrated radomes,
– problematic antenna types...
but without success.
Accuracy of IGS station positions

• What does it tell about the accuracy of IGS station positions?

Discontinuity sizes = station position biases – station position biases
Accuracy of IGS station positions

• What does it tell about the accuracy of IGS station positions?
Accuracy of IGS station positions

- What does it tell about the accuracy of IGS station positions?
  - Equipment-related biases in IGS station positions follow heavy-tailed distributions (modelled here as Student’s t-distributions).
  
→ Confidence intervals grow « fast » with confidence levels.

<table>
<thead>
<tr>
<th></th>
<th>Student's t params</th>
<th>confidence intervals [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \nu )</td>
<td>( \sigma ) [mm]</td>
</tr>
<tr>
<td>East</td>
<td>1.75</td>
<td>1.61</td>
</tr>
<tr>
<td>North</td>
<td>1.80</td>
<td>1.56</td>
</tr>
<tr>
<td>Up</td>
<td>1.66</td>
<td>4.17</td>
</tr>
</tbody>
</table>
Accuracy of IGS station positions

- Do antenna change discontinuities get smaller with igs14.atx?

Subset of 346 antenna change discontinuities involving at least one antenna with updated calibration from igs08 to igs14.atx

- Apply PPP-derived position corrections to compute expected discontinuity sizes with igs14.atx

→ « igs08.atx to igs14.atx » position corrections have marginal impact on discontinuity sizes.

→ Errors in type-mean antenna calibrations do not seem to be a major contributor to current IGS station position biases.
ITRF2014 PSD models: 2.5 years after

- IGS daily station position time series vs. propagated ITRF2014 coordinates: two examples

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- daily IGS station position time series
- propagated ITRF2014 coordinates
- ± 3σ confidence intervals

end of ITRF2014 input data
ITRF2014 PSD models: 2.5 years after

- PSD model prediction errors
  - depend on each individual case, but generally on:
    - age of the last earthquake,
    - amplitude of the post-seismic deformations,
    - (presence of other non-linear deformations)
  - are mostly comparable with prediction errors of classical linear ITRF2014 coordinates:

Differences between IGS daily station position time series and propagated ITRF2014 coordinates
- Stations without PSD model
- Stations with PSD model
ITRF2014 PSD models: 2.5 years after

- PSD model prediction errors
  - depend on each individual case, but generally on:
    - age of the last earthquake,
    - amplitude of the post-seismic deformations,
    - (presence of other non-linear deformations)
  - are mostly comparable with prediction errors of classical linear ITRF2014 coordinates,
  - especially for IGS14 stations (whose selection took the PSD model formal errors into account):

Differences between IGS daily station position time series and propagated ITRF2014 coordinates
- IGS14 stations without PSD model
- IGS14 stations with PSD model
Inter-comparison of I/D/JTRF2014 polar motion series

Detrended polar motion differences

Power spectra of polar motion differences
Inter-comparison of I/D/JTRF2014 polar motion series

- Background noise in PM differences approximately flicker

- JTRF $y_p$ series shows spectral peaks at 52.18 cpy (7d) and harmonics, due to using weekly ig2 solutions as input

- JTRF $y_p$ [semi-]annual signals different from both others, due to filter approach used

- JTRF different from both other series at low frequencies (<5 cpy), due to filter approach used

- DTRF slightly different from both other series at mid frequencies (5-70 cpy)

- ITRF slightly different from both other series at high frequencies (> 70 cpy)

<table>
<thead>
<tr>
<th>[µas]</th>
<th>DTRF – ITRF</th>
<th>JTRF – ITRF</th>
<th>JTRF - DTRF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_p$</td>
<td>$y_p$</td>
<td>$x_p$</td>
</tr>
<tr>
<td>182.625 d</td>
<td>2.390</td>
<td>1.399</td>
<td>1.535</td>
</tr>
<tr>
<td>7.00000 d</td>
<td>0.090</td>
<td>0.130</td>
<td>0.172</td>
</tr>
<tr>
<td>3.50000 d</td>
<td>0.122</td>
<td>0.056</td>
<td>0.159</td>
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<tr>
<td>2.33333 d</td>
<td>0.132</td>
<td>0.042</td>
<td>0.041</td>
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<tr>
<td>5-70 cpy</td>
<td>4.551</td>
<td>4.531</td>
<td>3.227</td>
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<tr>
<td>&gt; 70 cpy</td>
<td>3.099</td>
<td>3.127</td>
<td>2.977</td>
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RMS of the total pairwise polar motion difference series, of the periodic signals fitted to each difference series, and of their low-, mid- and high-frequency residuals
I/D/JTRF2014 polar motion series vs. geophysical excitation data

- Convert polar motion series into “geodetic excitation” series by the “gain adjustment” method of Chen et al. (2013)

- Compare geodetic excitation series with geophysical (LDC) excitation series derived from GRACE, SLR, plus atmospheric, oceanic and hydrological models (Chen et al., 2013)

Differences between “X – LDC” and “ITRF – LDC” excitation difference power spectra, offset by multiples of 50 mas²/d² for clarity

• Negative values mean: closer to LDC than ITRF
• Positive values mean: further from LDC than ITRF
I/D/JTRF2014 polar motion series vs. geophysical excitation data

<table>
<thead>
<tr>
<th>[] [mas/d]</th>
<th>ig2 – LDC</th>
<th>IG2 – LDC</th>
<th>IG2_s – LDC</th>
<th>ITRF – LDC</th>
<th>DTRF – LDC</th>
<th>JTRF – LDC</th>
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<tbody>
<tr>
<td></td>
<td>$\chi_1$</td>
<td>$\chi_2$</td>
<td>$\chi_1$</td>
<td>$\chi_2$</td>
<td>$\chi_1$</td>
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<tr>
<td>corr coeff</td>
<td>0.971</td>
<td>0.984</td>
<td>0.971</td>
<td>0.984</td>
<td>0.971</td>
<td>0.984</td>
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<tr>
<td>365.250 d</td>
<td>1.223</td>
<td>0.513</td>
<td>1.220</td>
<td>0.516</td>
<td>1.218</td>
<td>0.517</td>
</tr>
<tr>
<td>182.625 d</td>
<td>1.149</td>
<td>1.039</td>
<td>1.149</td>
<td>1.041</td>
<td>1.147</td>
<td>1.037</td>
</tr>
<tr>
<td>13.6600 d</td>
<td>1.408</td>
<td>1.046</td>
<td>1.404</td>
<td>1.043</td>
<td>1.404</td>
<td>1.043</td>
</tr>
<tr>
<td>7.000000 d</td>
<td>0.212</td>
<td>0.110</td>
<td>0.211</td>
<td>0.116</td>
<td>0.211</td>
<td>0.116</td>
</tr>
<tr>
<td>&gt; 70 cpy</td>
<td>5.132</td>
<td>5.521</td>
<td>5.135</td>
<td>5.517</td>
<td>5.135</td>
<td>5.517</td>
</tr>
</tbody>
</table>

Correlation coefficients between geodetic and LDC excitation series; RMS of the “geodetic – LDC” excitation difference series, of the periodic signals fitted to each difference series, and of their low-, mid- and high-frequency residuals

- Total RMS significantly larger for DTRF ($\chi_2$) and JTRF
- ITRF & IG2_s globally show best agreement with LDC at [semi-]annual periods; JTRF globally worst
- ITRF shows better agreement with LDC than DTRF & JTRF at high frequencies
Thank you for your attention!