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
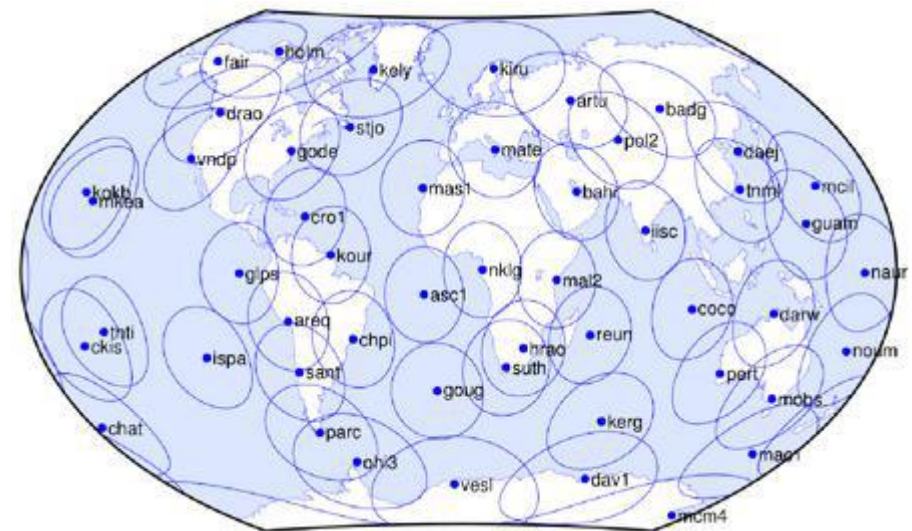
- **Reference frame switch**   **IGb08 → IGS14**

    - **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**
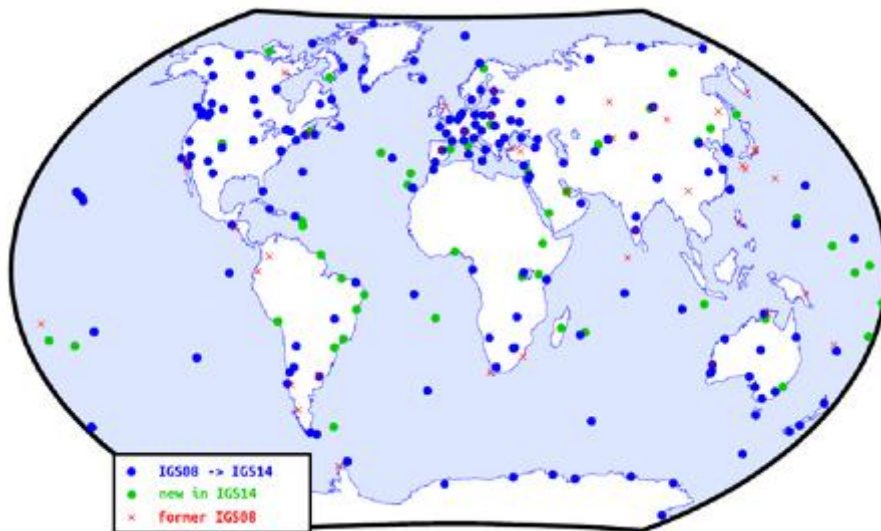
Distribution of the IGS14 and former IGS08 RF stations

51 primary stations of the IGS14 core network

3

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**

	igs08.atx	igs14.atx
Absolute calibration	428 (84.9%)	457 (90.7%)
Converted field calibration	31 (6.2%)	11 (2.2%)
Uncalibrated radome	45 (8.9%)	36 (7.1%)

Absolute calibrations now available for >90% of the IGS stations

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

Transition to IGS14/igs14.atx

- **Reference frame switch**   **IGb08 → IGS14**

- **Ground antenna calibration updates**   ⎤
- **Satellite antenna calibration updates** ⎦ **igs08.atx → igs14.atx**

- **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

WRMS of station position residuals from daily IGS SINEX combinations
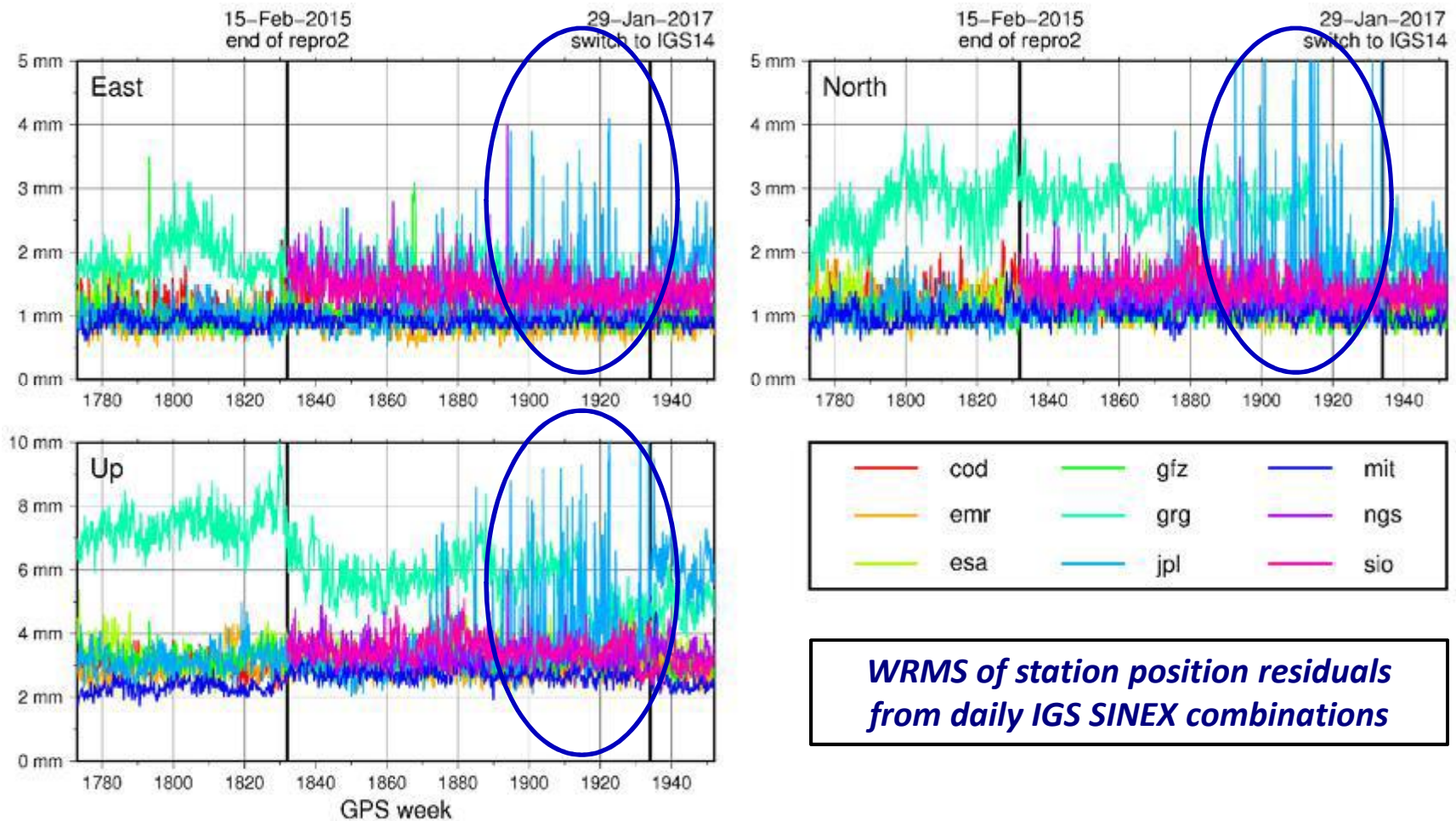
– **Spikes in JPL residuals due to numerical issues during the preprocessing of JPL solutions (problem now solved)**

Recent daily SINEX combination results

Smoothed WRMS of station position residuals from daily IGS SINEX combos
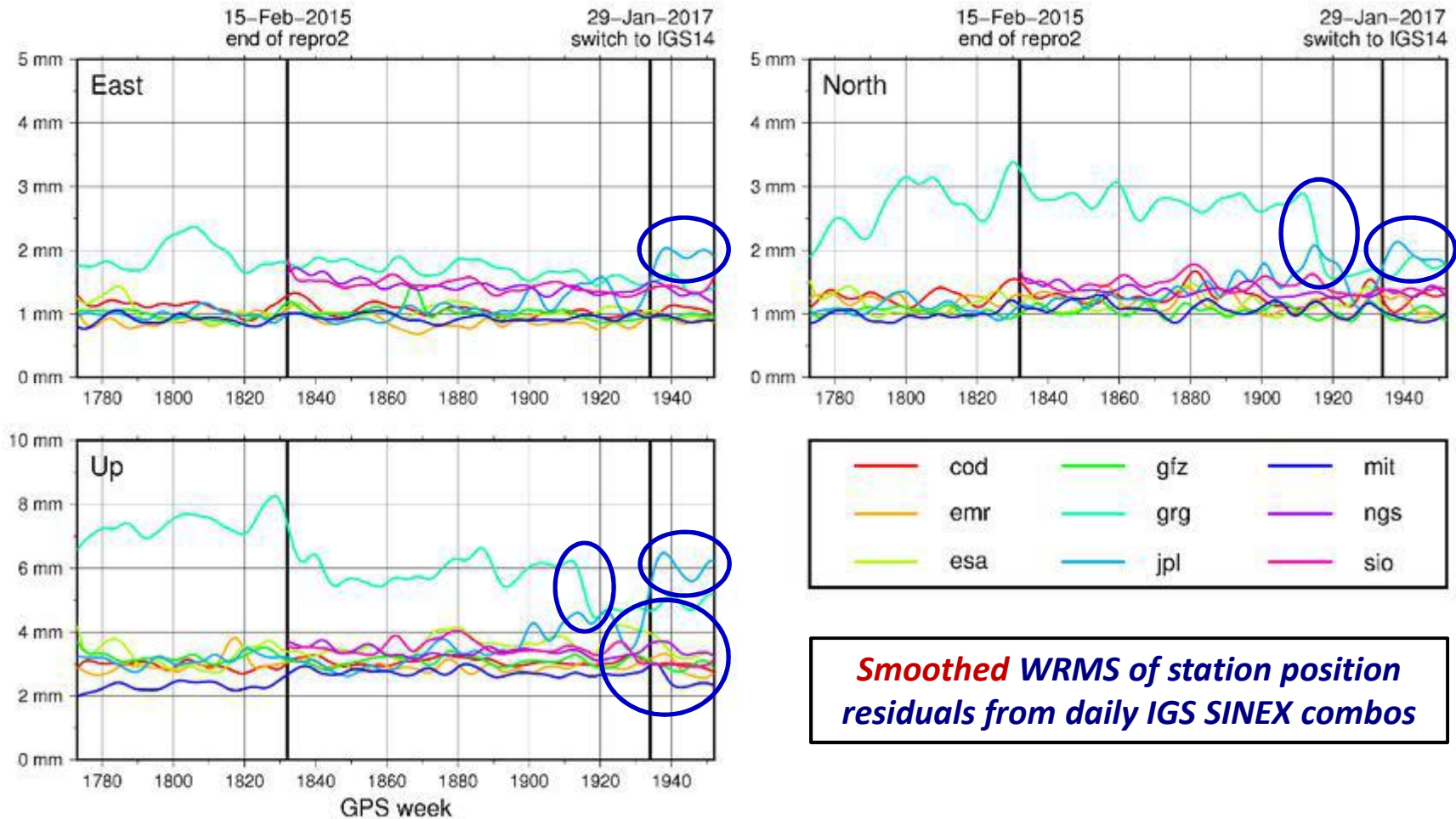
- GRGS solved an ANTEX-related bug.
- JPL hasn't switched to IGS14/igs14.atx yet.
- Slight decreases of vertical WRMS for SIO, then MIT (unknown reasons)

8

Alignment of daily IGS solutions
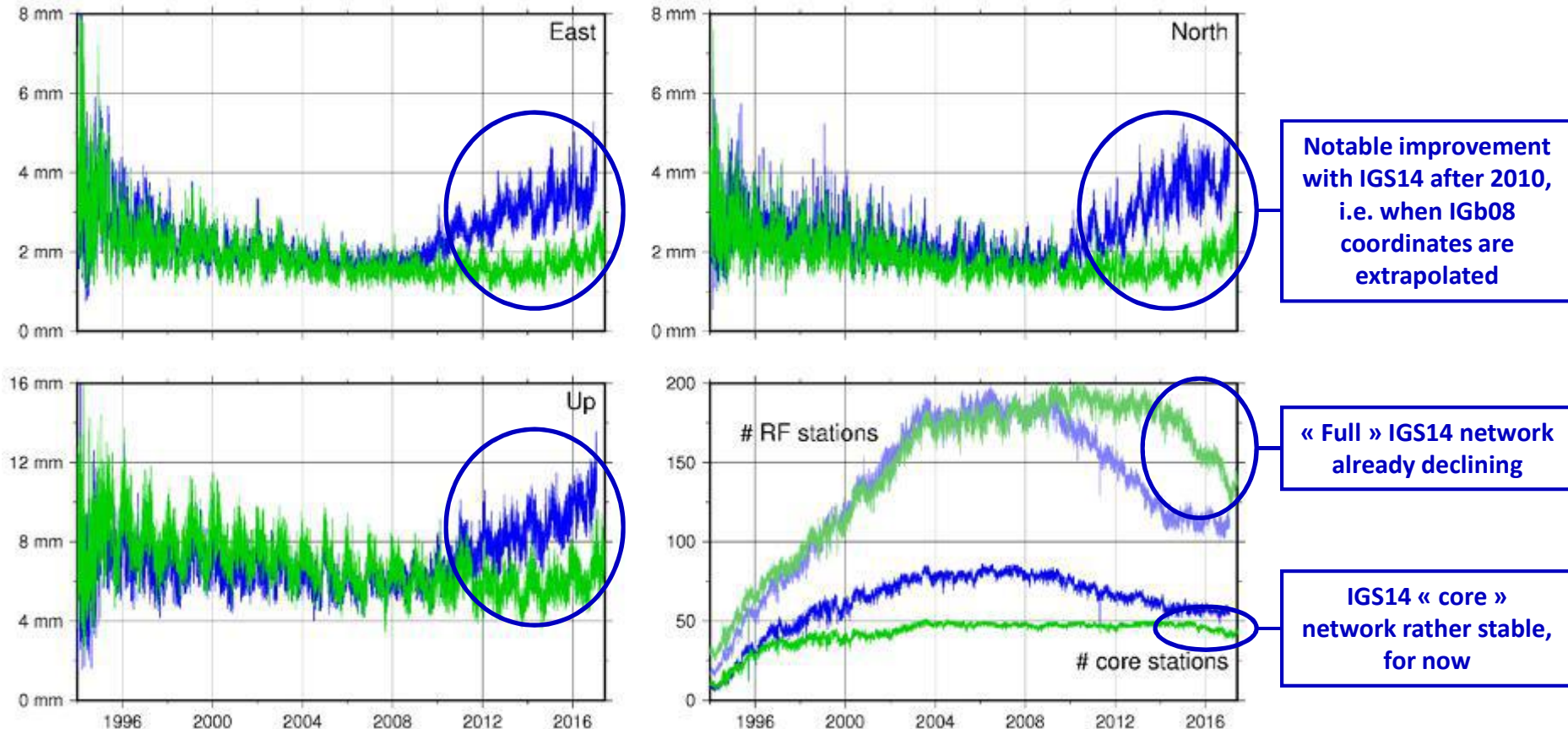
**Notable improvement with IGS14 after 2010, i.e. when IGb08 coordinates are extrapolated**

« Full » IGS14 network already declining

IGS14 « core » network rather stable, for now

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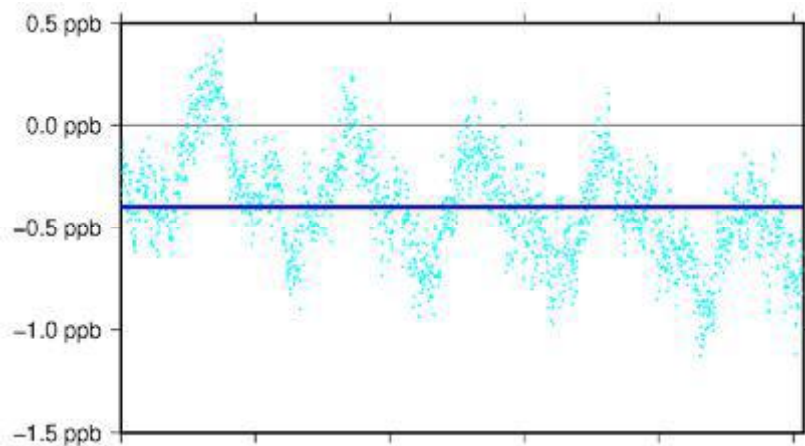*Bottom right: Number of available IGb08/IGS14 [core] stations in daily IGS solutions*

9

Scale of daily IGS solutions

- **How to interpret the scale factors estimated between daily IGS solutions & a linear reference frame (IGS*yy*)?**
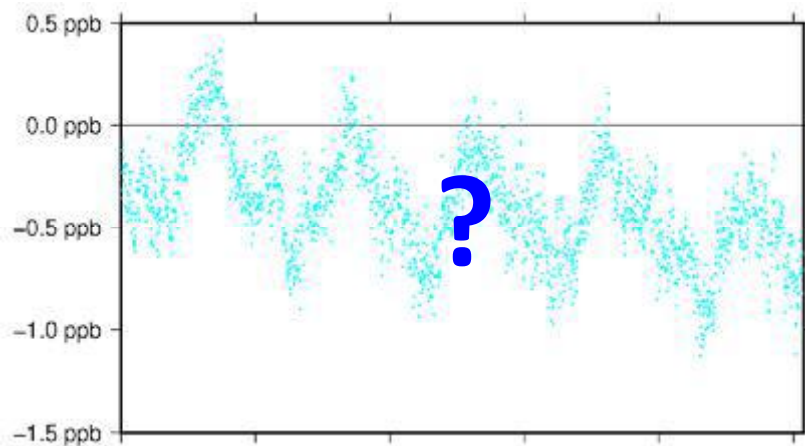
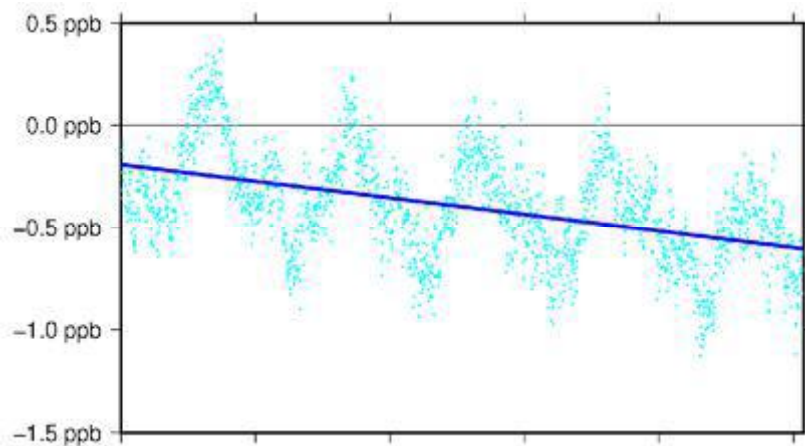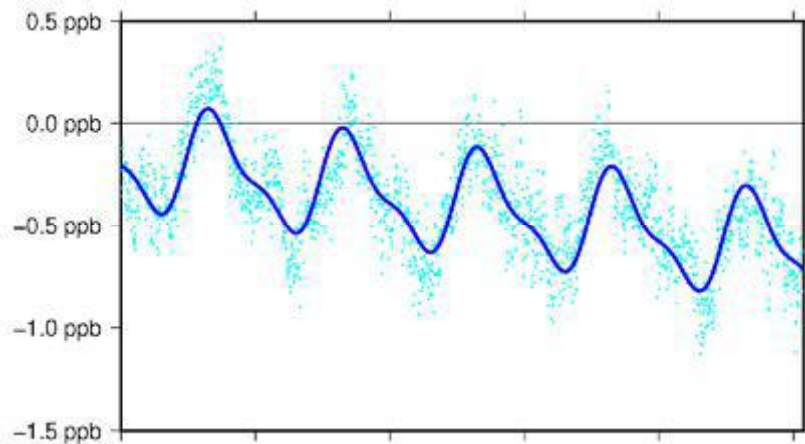# Scale of daily IGS solutions

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

  - **Mean scale depends on _conventional_ (igs*yy*.atx) satellite z-PCOs** (igs*yy*.atx z-PCO values derived so as to give access to ITRF*yyyy* scale)

Scale of daily IGS solutions

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

- – **Mean scale depends on _conventional_ (igs*yy*.atx) satellite z-PCOs**
- – **Scale rate determined by the use of _constant_ satellite z-PCOs**
  - → **« intrinsic GNSS scale rate » vs. ITRF*yyyy* 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 (IGS*yy*)?**

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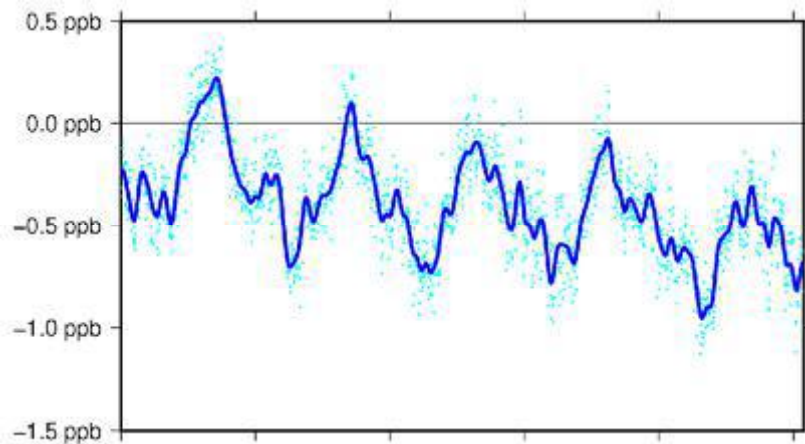
- – **Mean scale depends on *conventional* (igs*yy*.atx) satellite z-PCOs**
- – **Scale rate determined by the use of *constant* satellite z-PCOs**
- – **Seasonal variations due to aliasing of non-linear deformations of the station network into daily scale factors (network effect)**
- – **Systematic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

Scale of daily IGS solutions
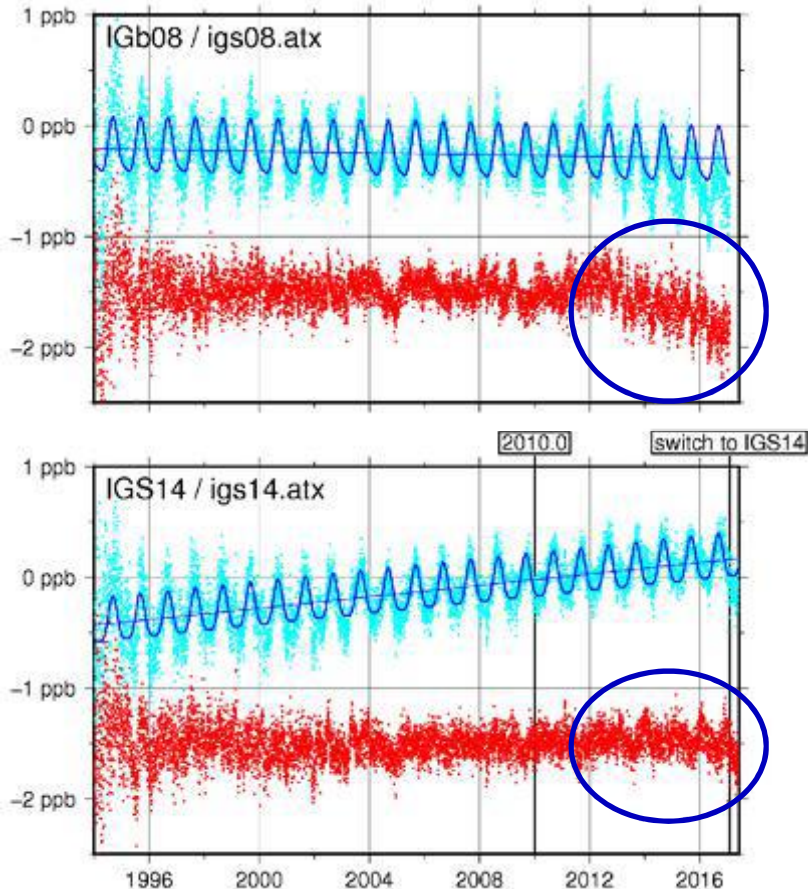
*Cyan: Scale factors between IGb08/igs08.atx-
(resp. IGS14/igs14.atx-) based daily solutions
and IGb08 (resp. IGS14)
Blue: linear trend [+ annual and semi-annual signals]
Red: residuals of the fits, shifted by -1.5 ppb*

Mean scale (determined by igs*yy*.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**

15

# Scale of daily IGS solutions

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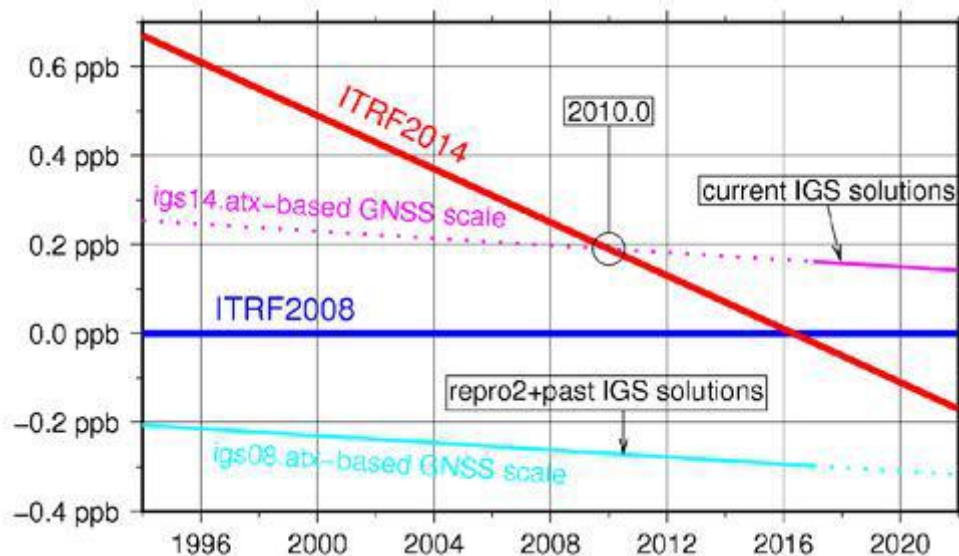
Schematic representation of the scale and scale rate differences between ITRF2008, ITRF2014 and GNSS solutions based on either igs08.atx or igs14.atx
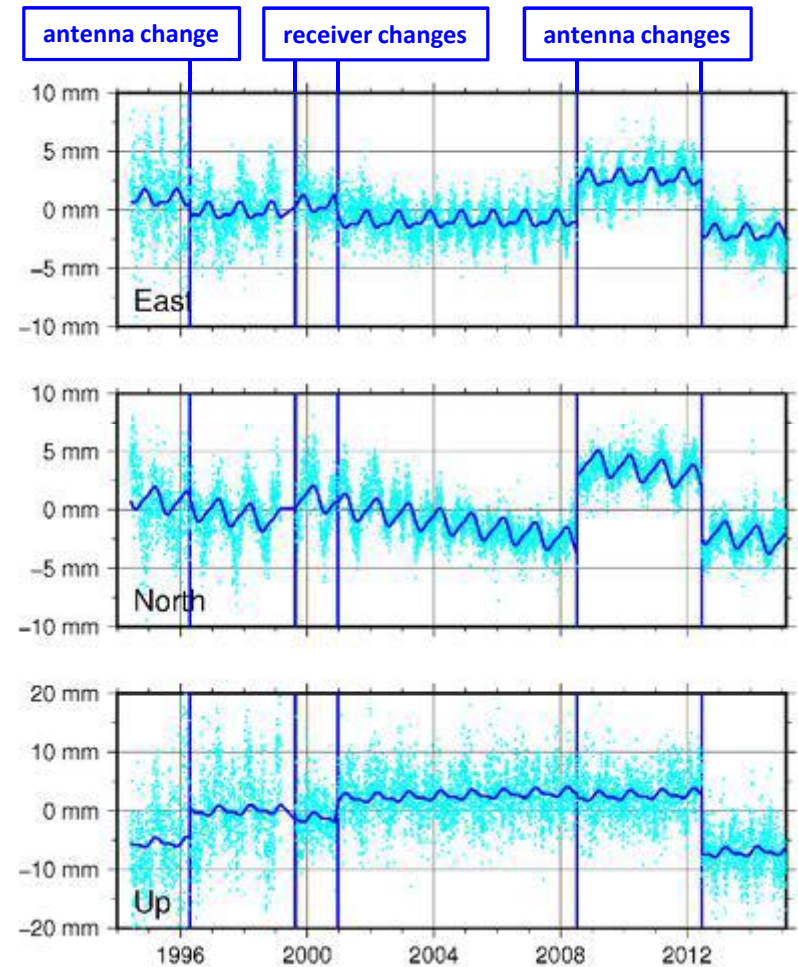
Accuracy of IGS station positions

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

Unknown: 425 (20%)

Equipment changes: 1019 (49%)

Earthquakes: 646 (31%)
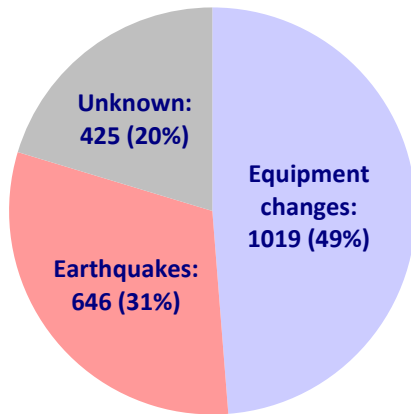
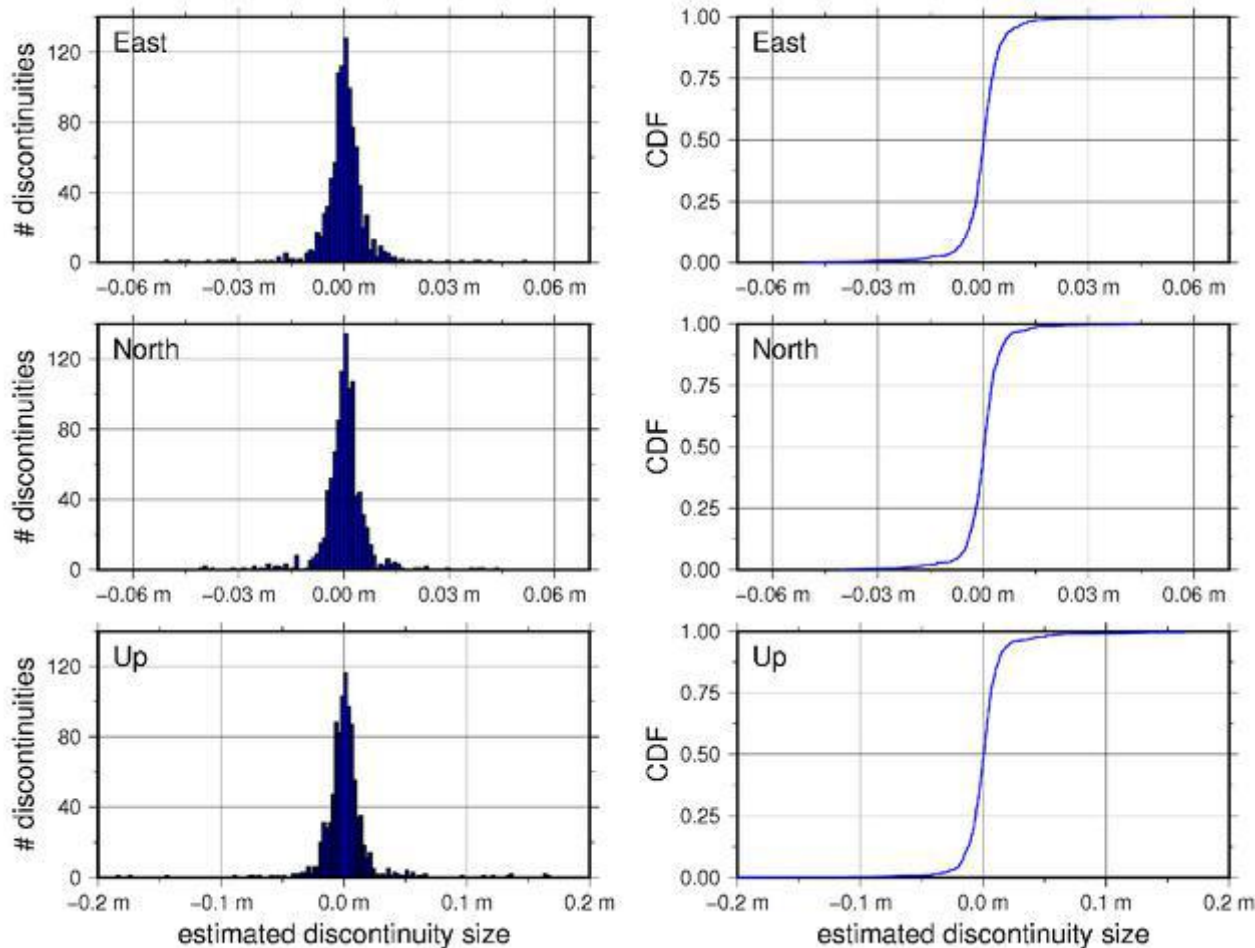*Distribution of identified discontinuity causes in IGS repro2 station position time series*

→ **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?**

antenna change   receiver changes   antenna changes

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

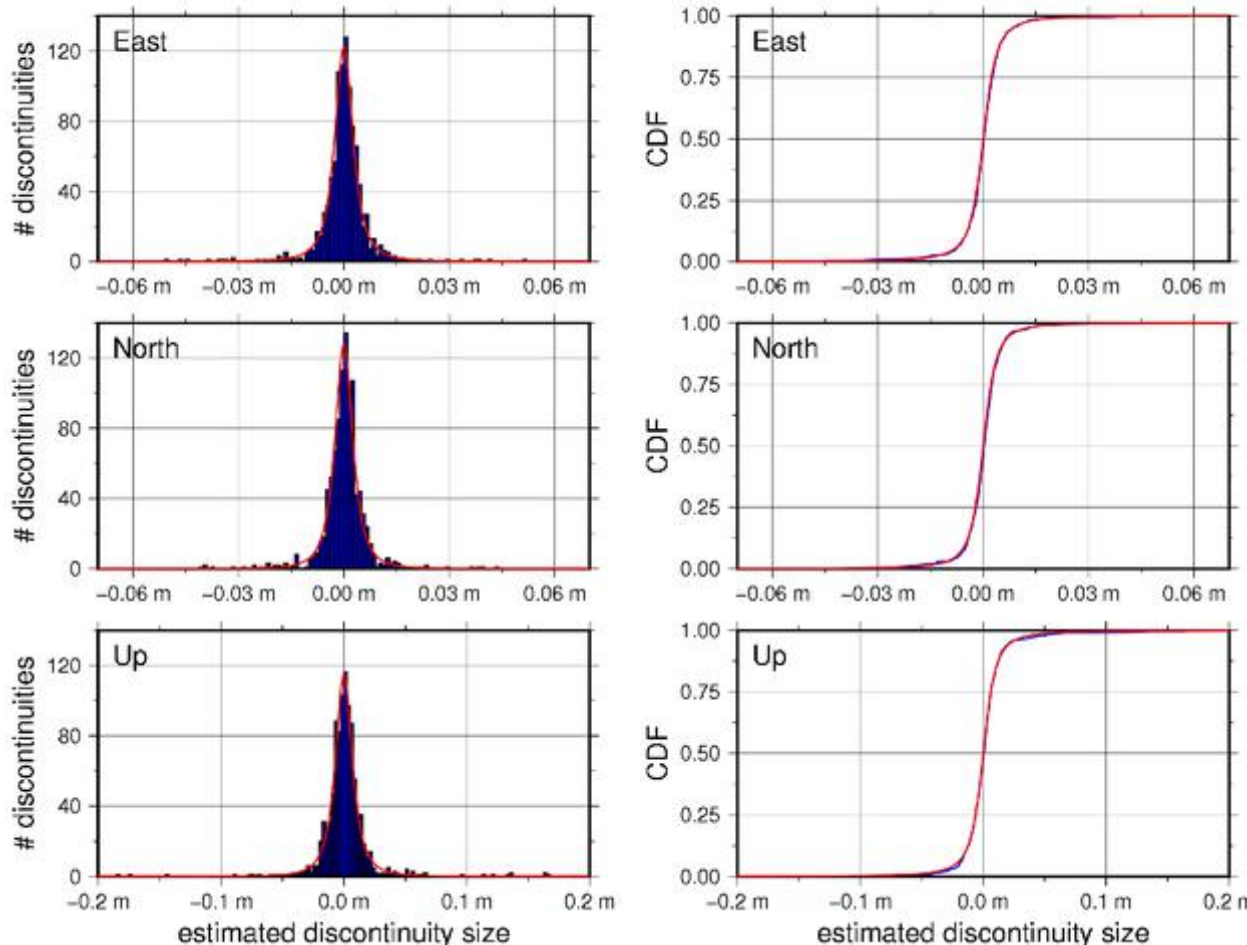# Accuracy of IGS station positions

- **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: $v = 2.02$; $\sigma = 2.85$ mm*
- *North: $v = 2.10$; $\sigma = 2.74$ mm*
- *Up: $v = 1.88$; $\sigma = 7.45$ 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.

19

Accuracy of IGS station positions

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

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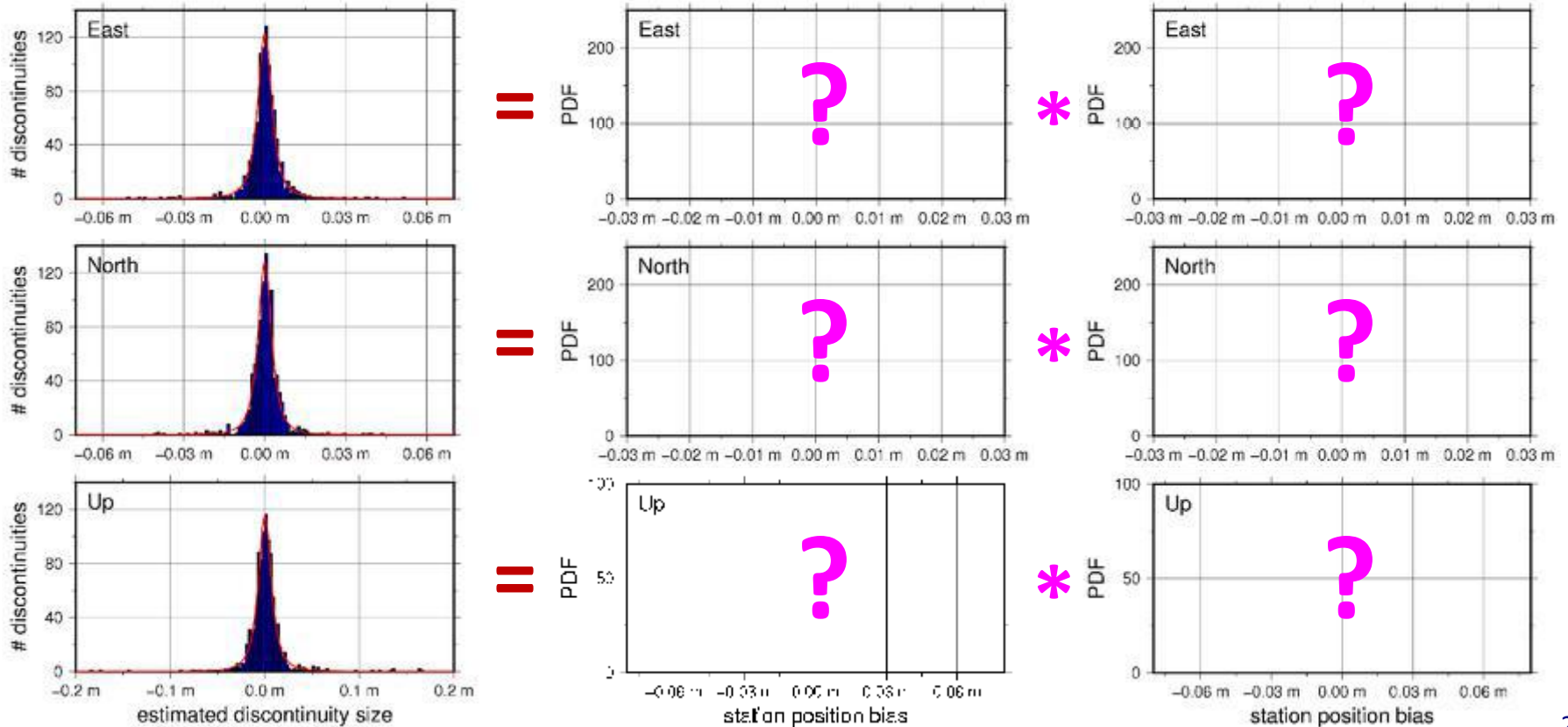
Accuracy of IGS station positions

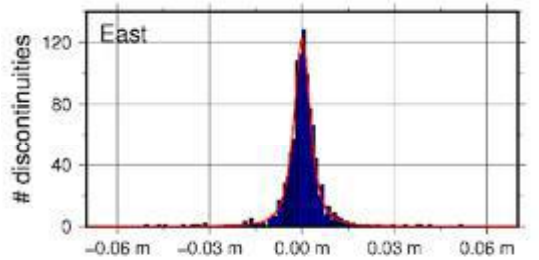- **What does it tell about the accuracy of IGS station positions?**
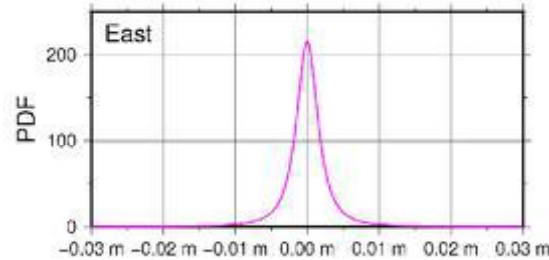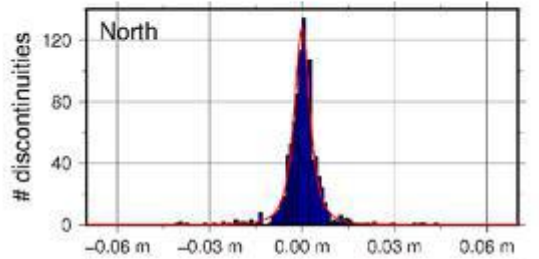
Student's *t* ≈ **Student's *t*** * **Student's *t***
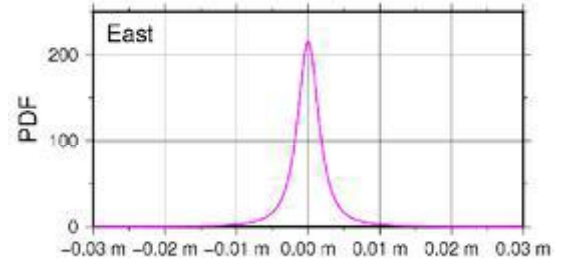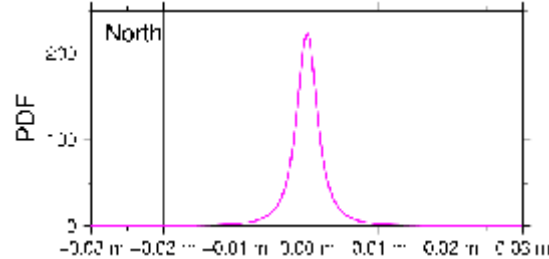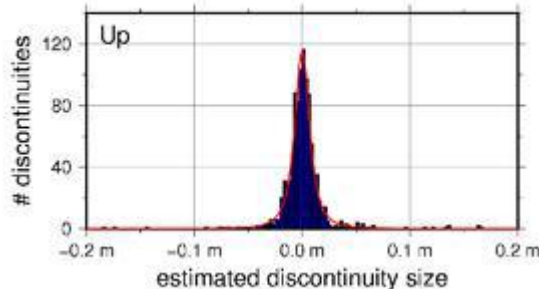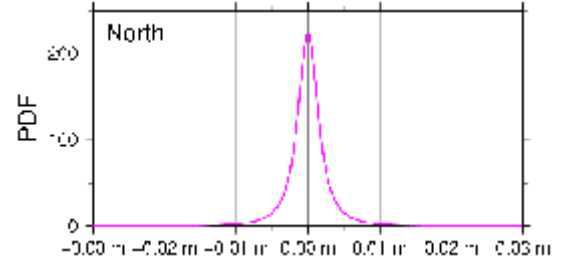
Accuracy of IGS station positions

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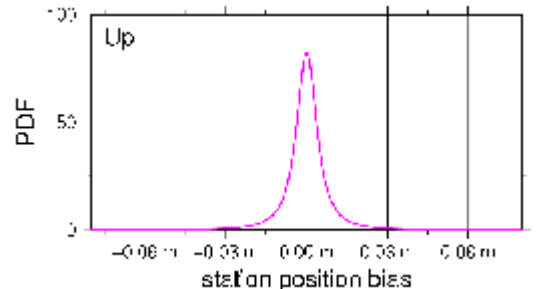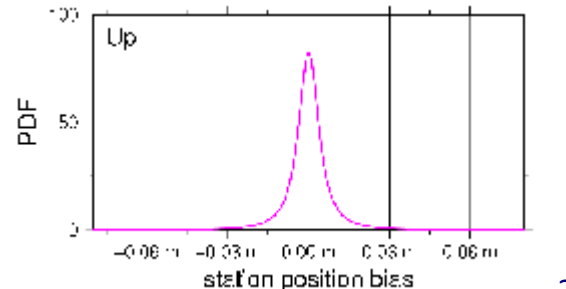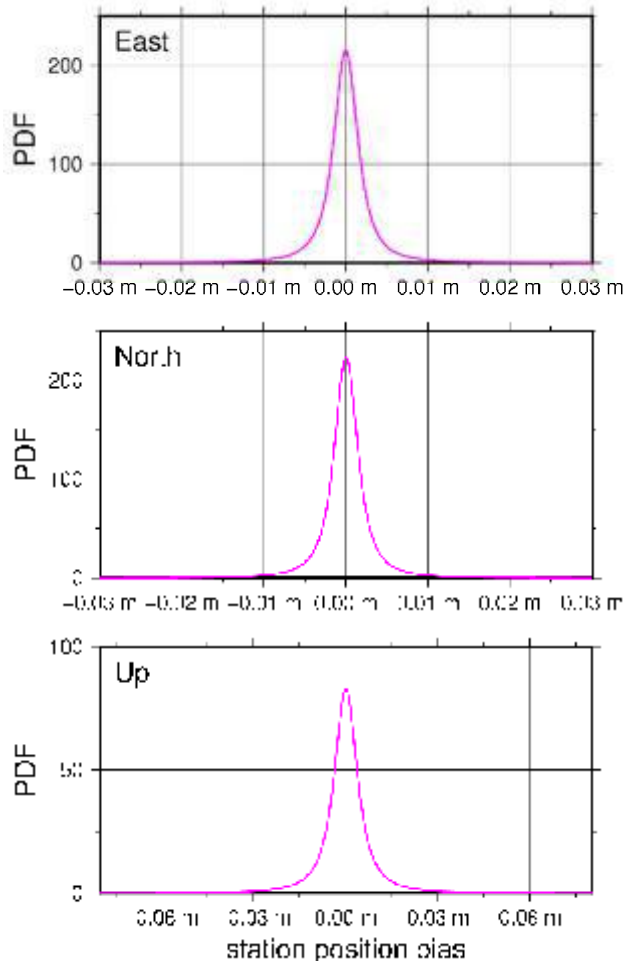

– **Equipment-related biases in IGS station positions follow heavy-tailed distributions (modelled here as Student's *t*-distributions).**

→ **Confidence intervals grow « fast » with confidence levels.**

	Student's *t* params		confidence intervals [mm]		
	ν	σ [mm]	90%	95%	99%
East	1.75	1.61	± 5.2	± 8.0	± 20.4
North	1.80	1.56	± 4.9	± 7.5	± 18.7
Up	1.66	4.17	± 14.1	± 22.0	± 59.0

Accuracy of IGS station positions

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

igs08.atx (before correction)

igs14.atx (after correction)
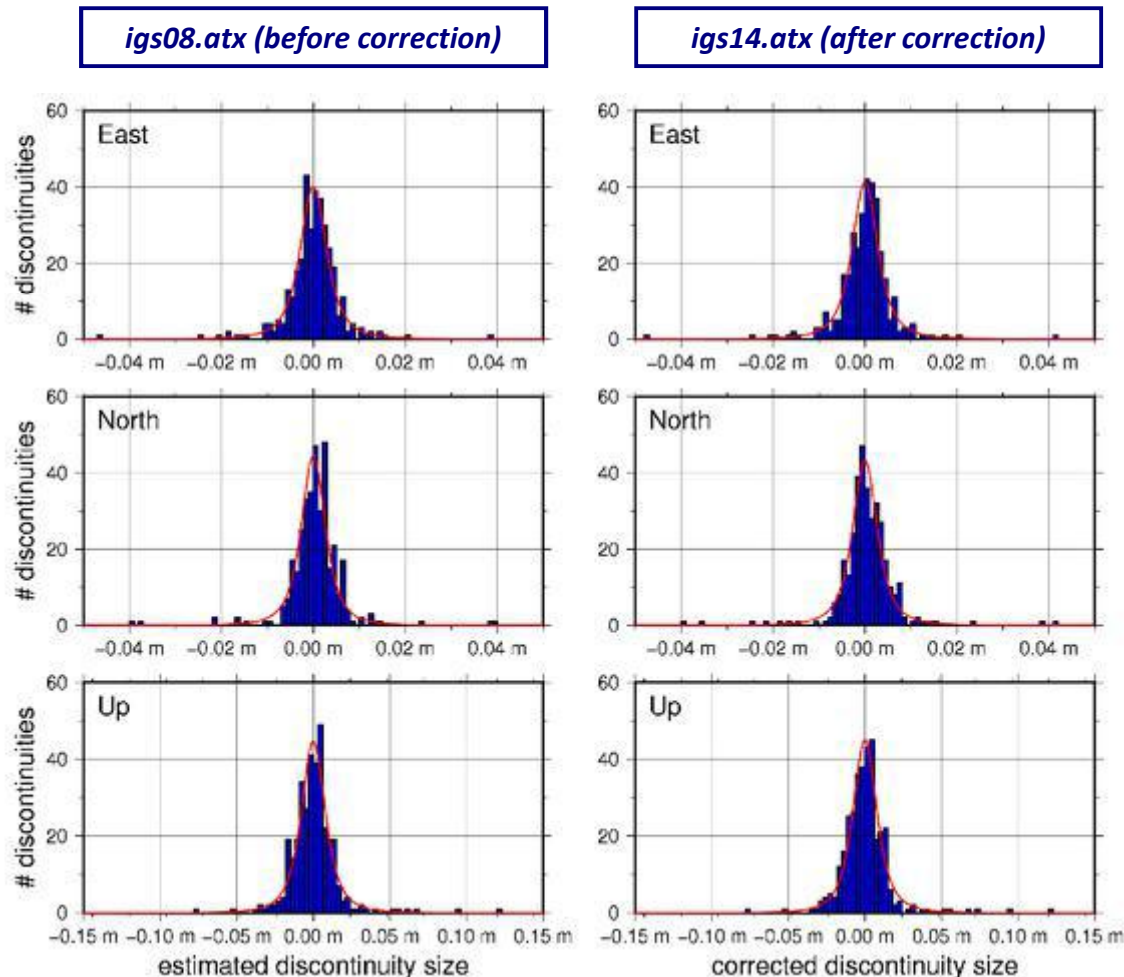
– **Subset of 346 antenna change discontinuities involving at least one antenna with updated calibration from igs08 to igs14.atx**

– **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
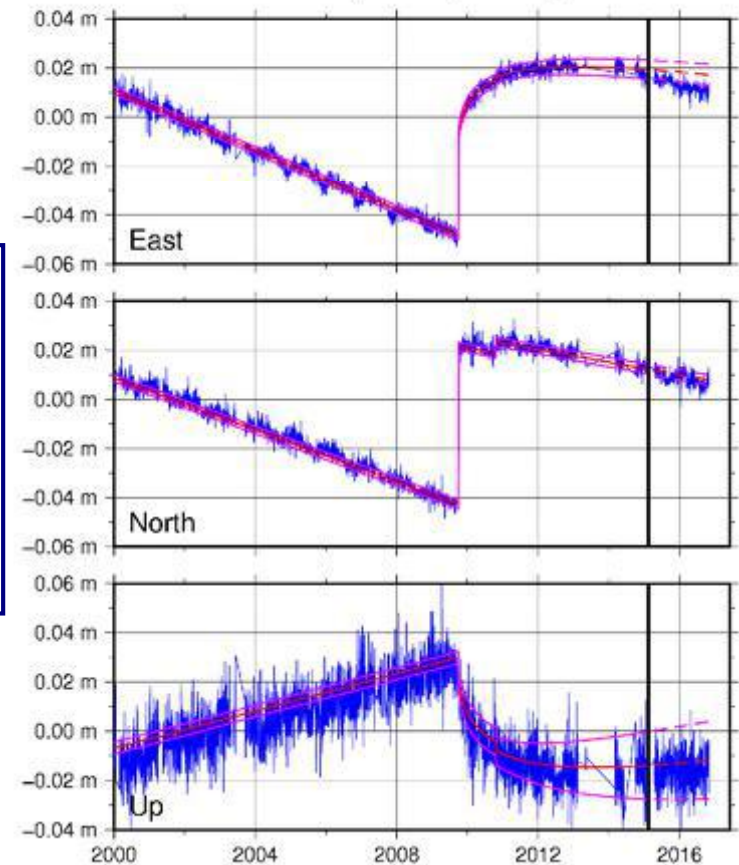
- **IGS daily station position time series vs. propagated ITRF2014 coordinates: two examples**
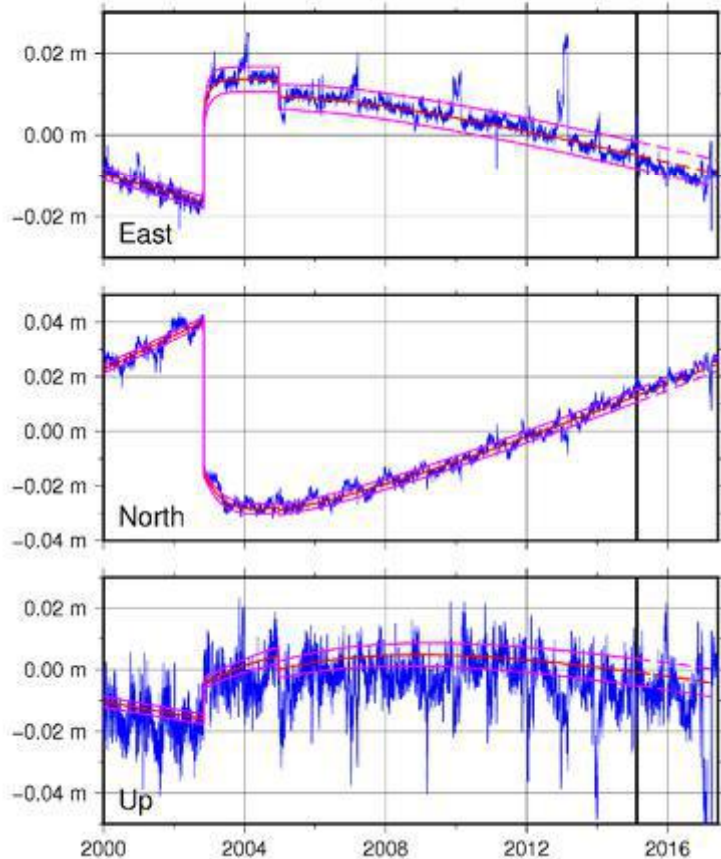
— *daily IGS station position time series*
— *propagated ITRF2014 coordinates*
— *± 3σ confidence intervals*

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*
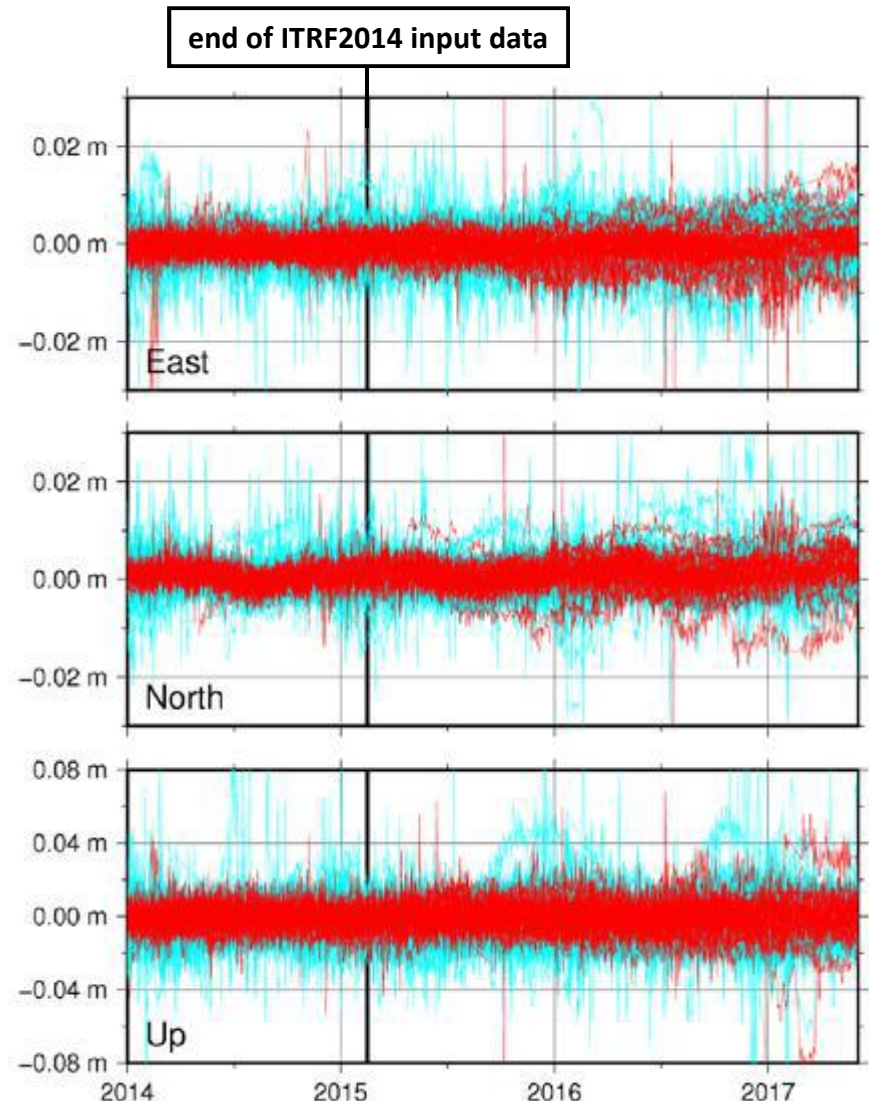 — *Stations with PSD model*

ITRF2014 PSD models: 2.5 years after

- **PSD model prediction errors**

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    - 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
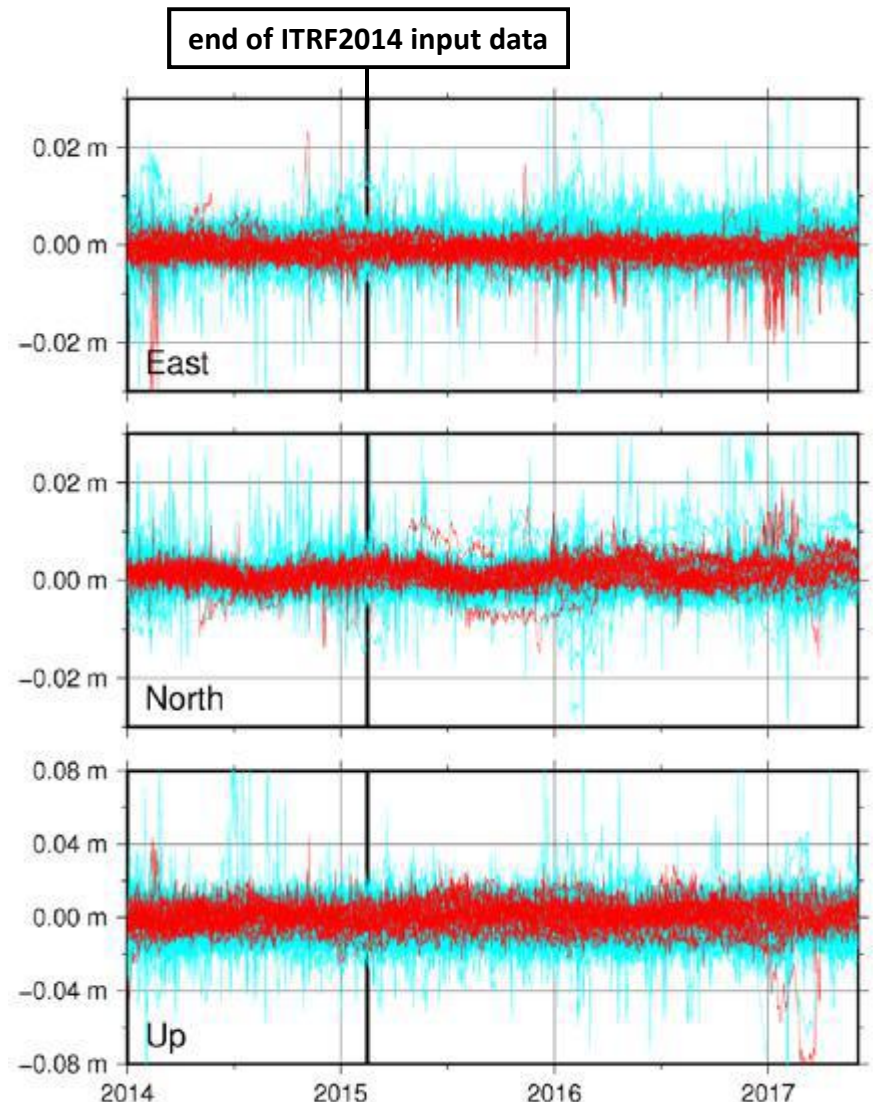 — *IGS14 stations without PSD model*
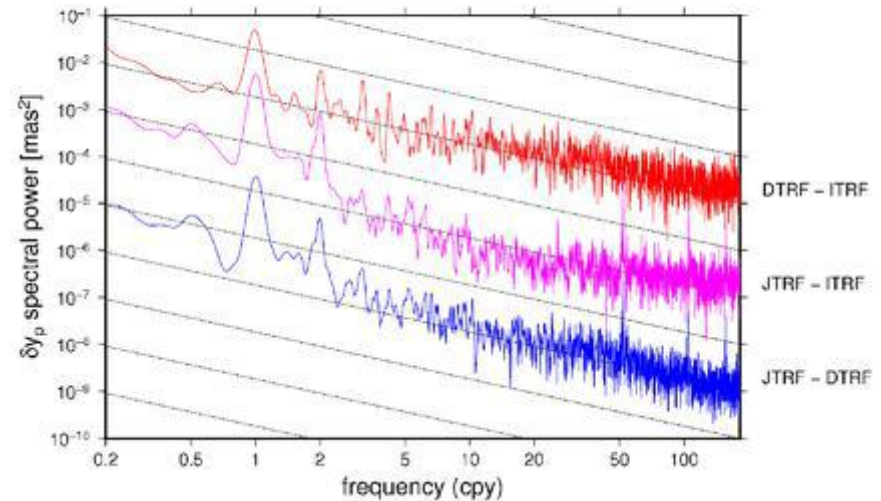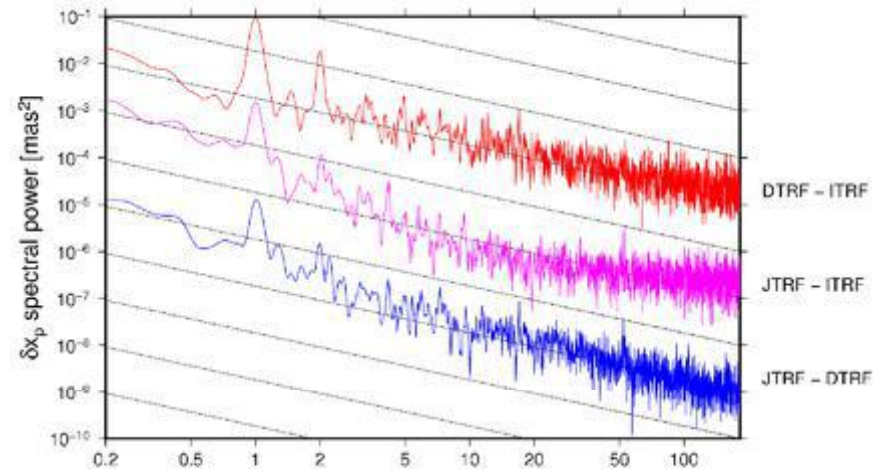 — *IGS14 stations with PSD model*

end of ITRF2014 input data

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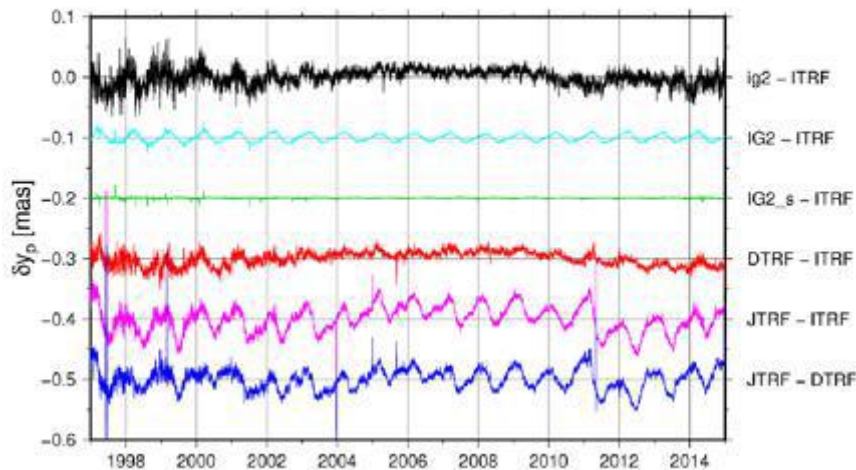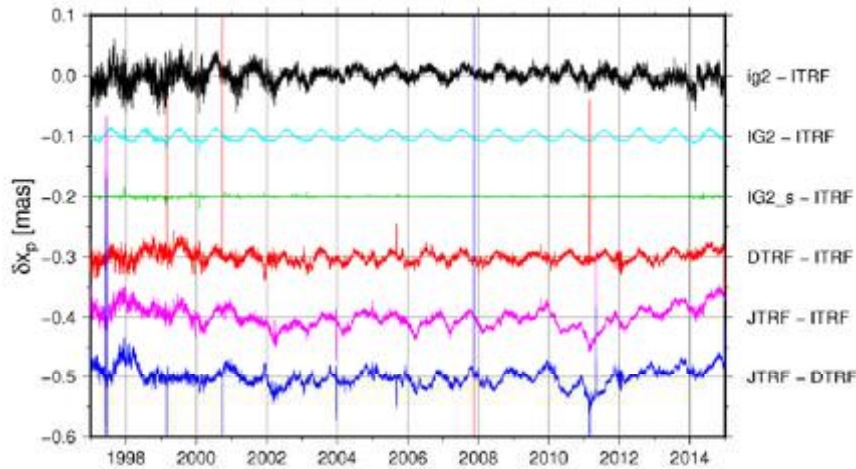
Detrended polar motion differences

Power spectra of polar motion differences

Inter-comparison of I/D/JTRF2014 polar motion series

[μas]	DTRF – ITRF		JTRF – ITRF		JTRF - DTRF	
	x_p	y_p	x_p	y_p	x_p	y_p
total RMS	9.904	11.791	16.839	21.676	15.262	17.252
365.250 d	5.637	3.959	7.074	14.031	6.238	11.330
182.625 d	2.390	1.399	1.535	5.366	2.183	4.056
7.00000 d	0.090	0.130	0.172	1.078	0.237	1.027
3.50000 d	0.122	0.056	0.159	0.599	0.088	0.551
2.33333 d	0.132	0.042	0.041	0.436	0.126	0.427
< 5 cpy	5.499	9.542	14.552	14.939	12.823	11.197
5-70 cpy	4.551	4.531	3.227	3.302	4.423	4.491
> 70 cpy	3.099	3.127	2.977	2.888	2.267	2.398

*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*

- 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)

I/D/JTRF2014 polar motion series vs. geophysical excitation data
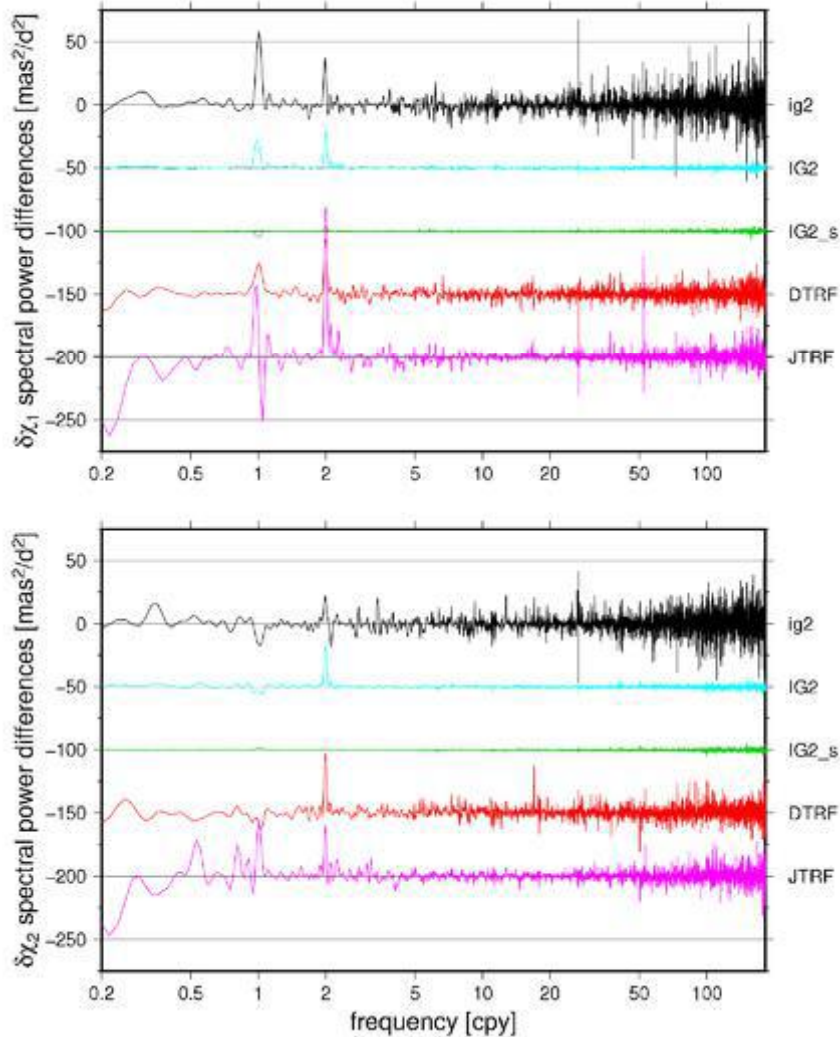
- Convert polar motion series into "geodetic excitation" series by the "gain adjustment" method of Chen et al. (2013)

- 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

[] [mas/d]	ig2 – LDC		IG2 – LDC		IG2_s – LDC		ITRF – LDC		DTRF – LDC		JTRF – LDC	
	χ_1	χ_2	χ_1	χ_2	χ_1	χ_2	χ_1	χ_2	χ_1	χ_2	χ_1	χ_2
corr coeff	0.971	0.984	0.971	0.984	0.971	0.984	0.971	0.984	0.971	0.984	0.971	0.984
total RMS	8.072	8.101	8.072	8.100	8.072	8.100	8.073	8.101	8.075	8.112	8.081	8.108
365.250 d	1.223	0.513	1.220	0.516	1.218	0.517	1.218	0.516	1.220	0.515	1.221	0.526
182.625 d	1.149	1.039	1.149	1.041	1.147	1.037	1.147	1.037	1.151	1.042	1.158	1.041
13.6600 d	1.408	1.046	1.404	1.043	1.404	1.043	1.404	1.043	1.401	1.043	1.401	1.042
7.00000 d	0.212	0.110	0.211	0.116	0.211	0.116	0.211	0.116	0.219	0.114	0.235	0.112
< 5 cpy	3.421	3.134	3.422	3.135	3.422	3.135	3.422	3.135	3.422	3.134	3.419	3.134
5-70 cpy	4.713	4.784	4.712	4.787	4.712	4.787	4.713	4.787	4.712	4.790	4.715	4.787
> 70 cpy	5.132	5.521	5.135	5.517	5.135	5.517	5.136	5.519	5.141	5.532	5.145	5.528

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 (χ_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!