The International Terrestrial Reference Frame (ITRF)
ITRF2014 and future plans

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Of the……..

Content

- ITRF general description
- ITRF2014 Input Data, Network
- ITRF2014: Innovations in modelling the nonlinear station motions:
  - Periodic signals: annual, semi-annual
  - Post-Seismic Deformation (PSD)
- ITRF2014 Key performance indicators
- Roadmap for future plan: ITRF2020

How the ITRF is constructed ?

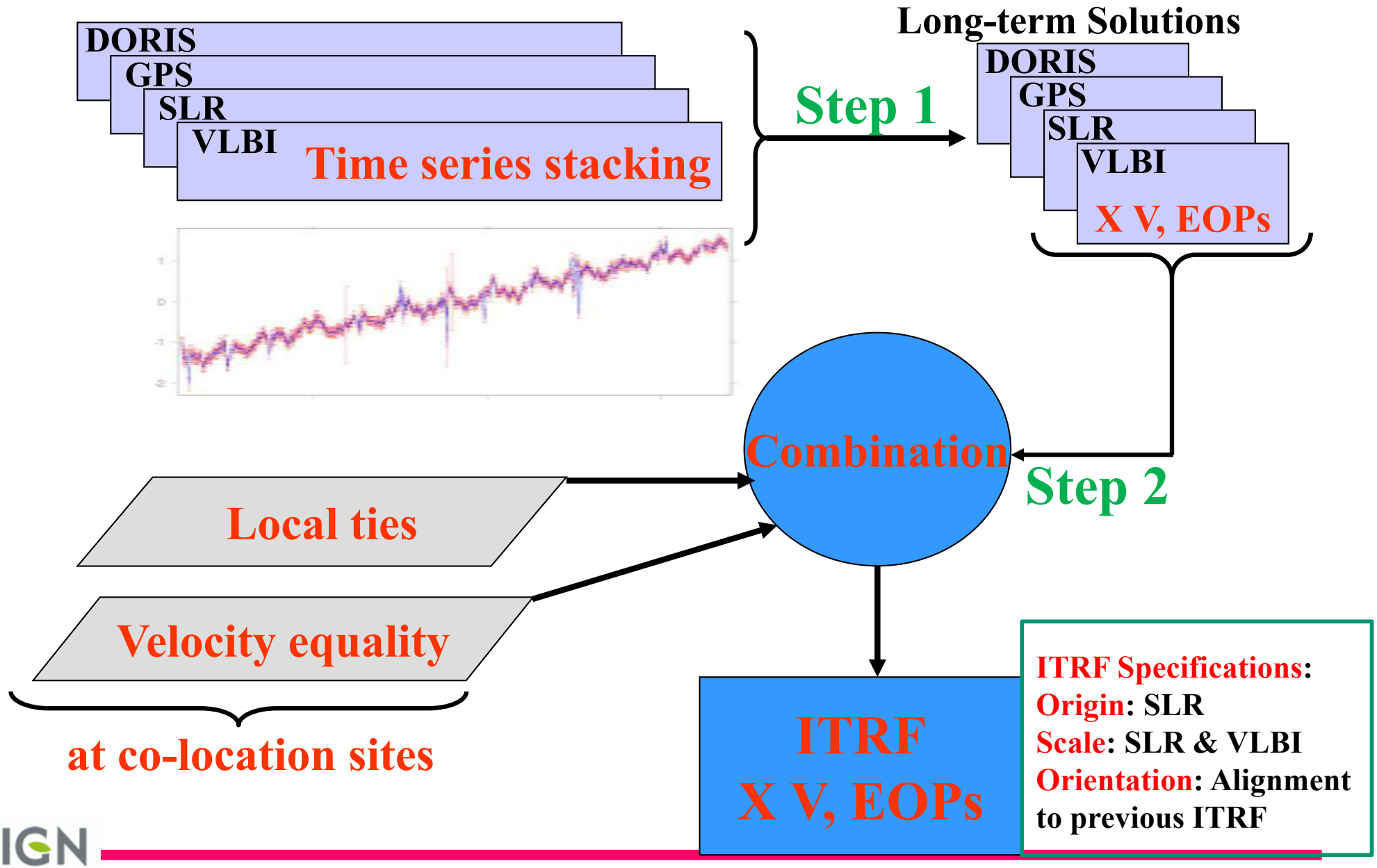
- **Input :**
  - Time series of mean station positions (at weekly or daily sampling) and daily EOPs from the 4 techniques
  - Local ties in co-location sites
- **Output :**
  - Station positions at a reference epoch and linear velocities
  - Earth Orientation Parameters

Combination model

$$\begin{cases} X_s^i = X_c^i + (t_s^i - t_0)\dot{X}_c^i \\ \quad + T_k + D_k X_c^i + R_k X_c^i \\ \quad + (t_s^i - t_k)\left[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i\right] \\ \\ \dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{cases}$$

$$\begin{cases} x_s^p & = x_c^p + R2_k \\ y_s^p & = y_c^p + R1_k \\ UT_s & = UT_c - \frac{1}{f} R3_k \\ \dot{x}_s^p & = \dot{x}_c^p \\ \dot{y}_s^p & = \dot{y}_c^p \\ LOD_s & = LOD_c \end{cases}$$

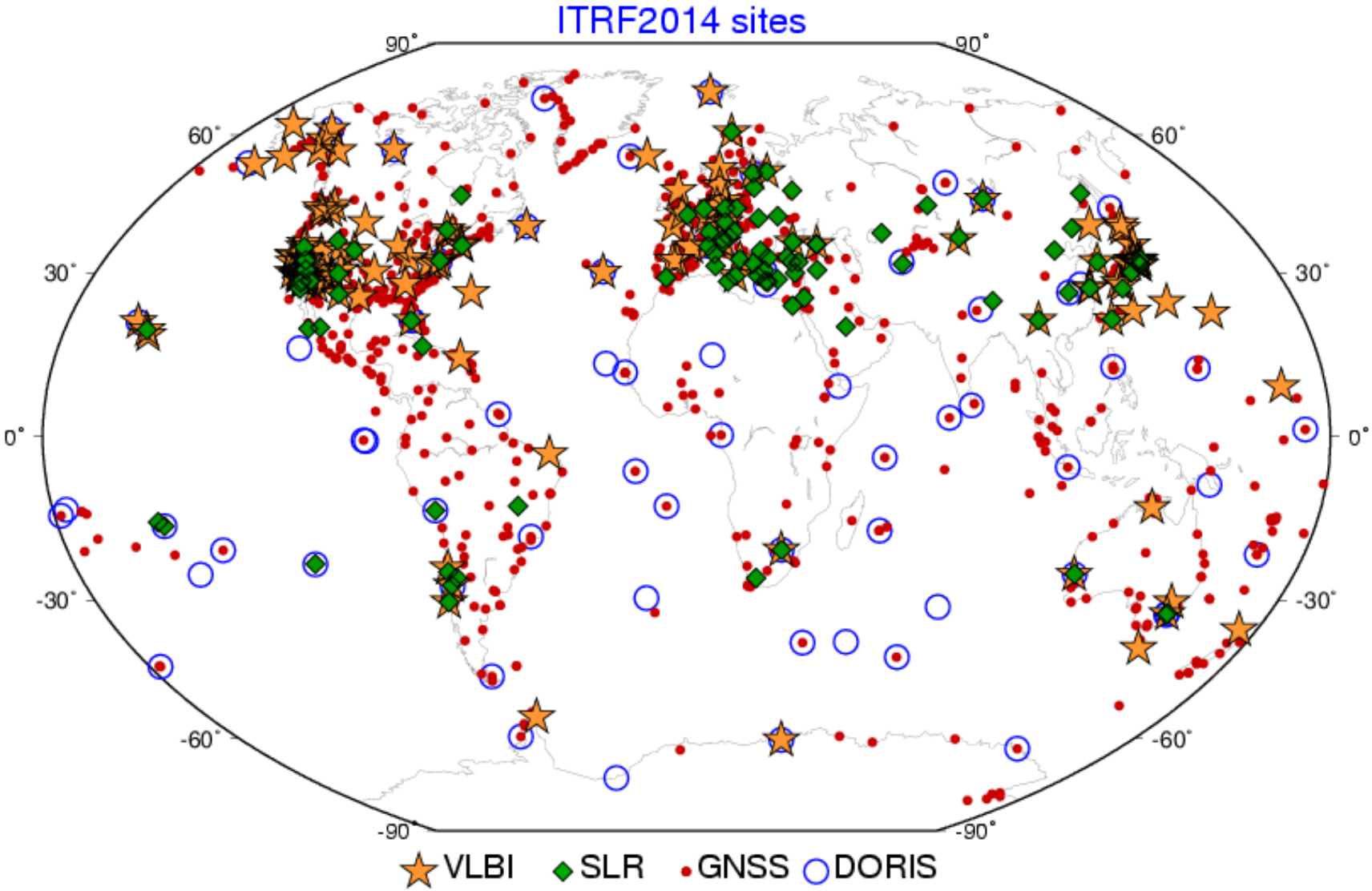
ITRF Construction



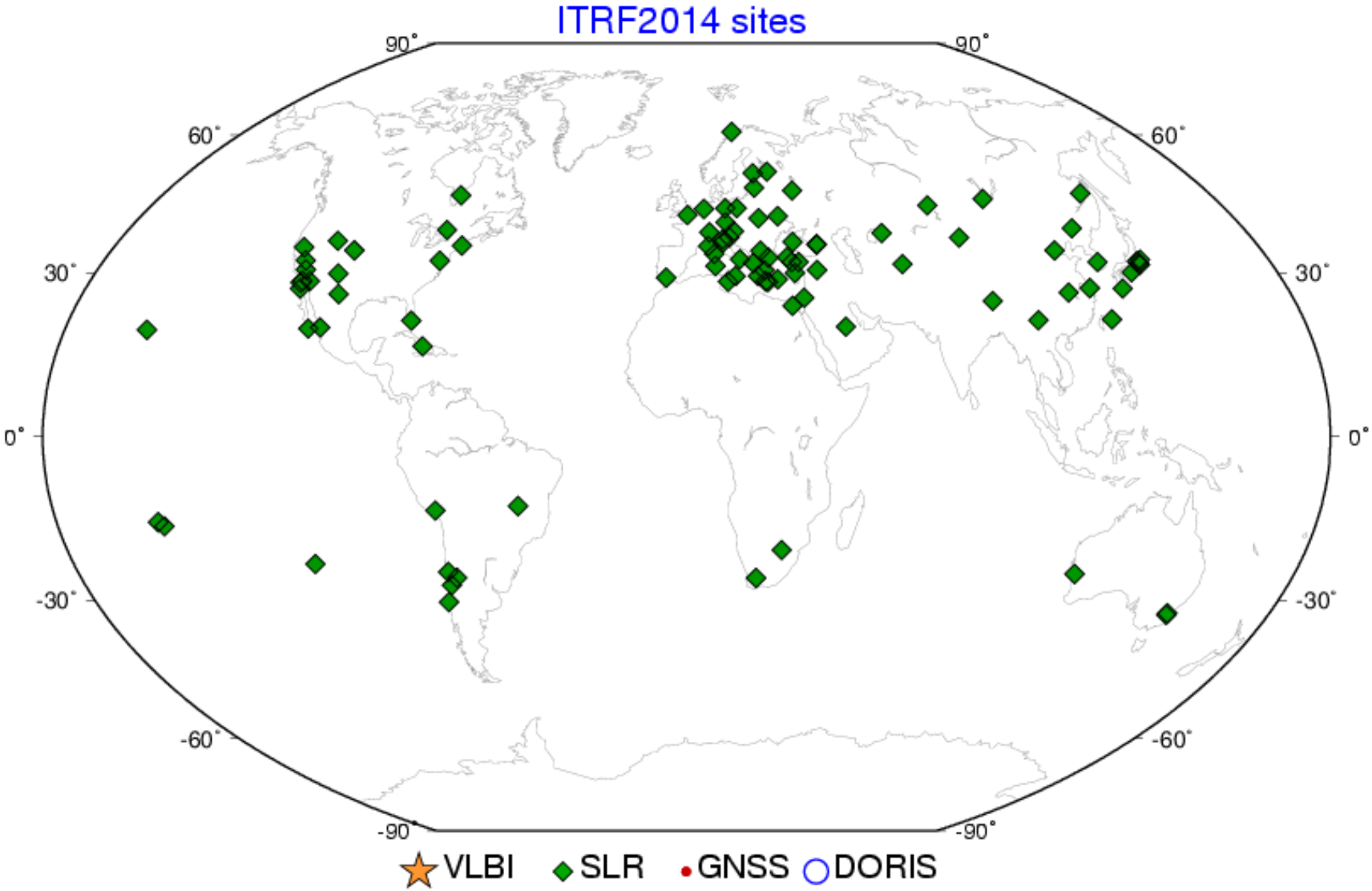
ITRF2014: Input data

Service/Technique	Number of Solutions	Time span	# of sites
IGS/GNSS/GPS	7714 daily	1994.0 – 2015.1 (21 yrs)	884
IVS/VLBI	5328 daily	1980.0 – 2015.0 (35 yrs)	124
ILRS/SLR	244 fortnightly 1147 weekly	1980.0 – 1993.0 1993.0 – 2015.0 (35 yrs)	96
IDS/DORIS	1140 weekly	1993.0 – 2015.0 (22 yrs)	71

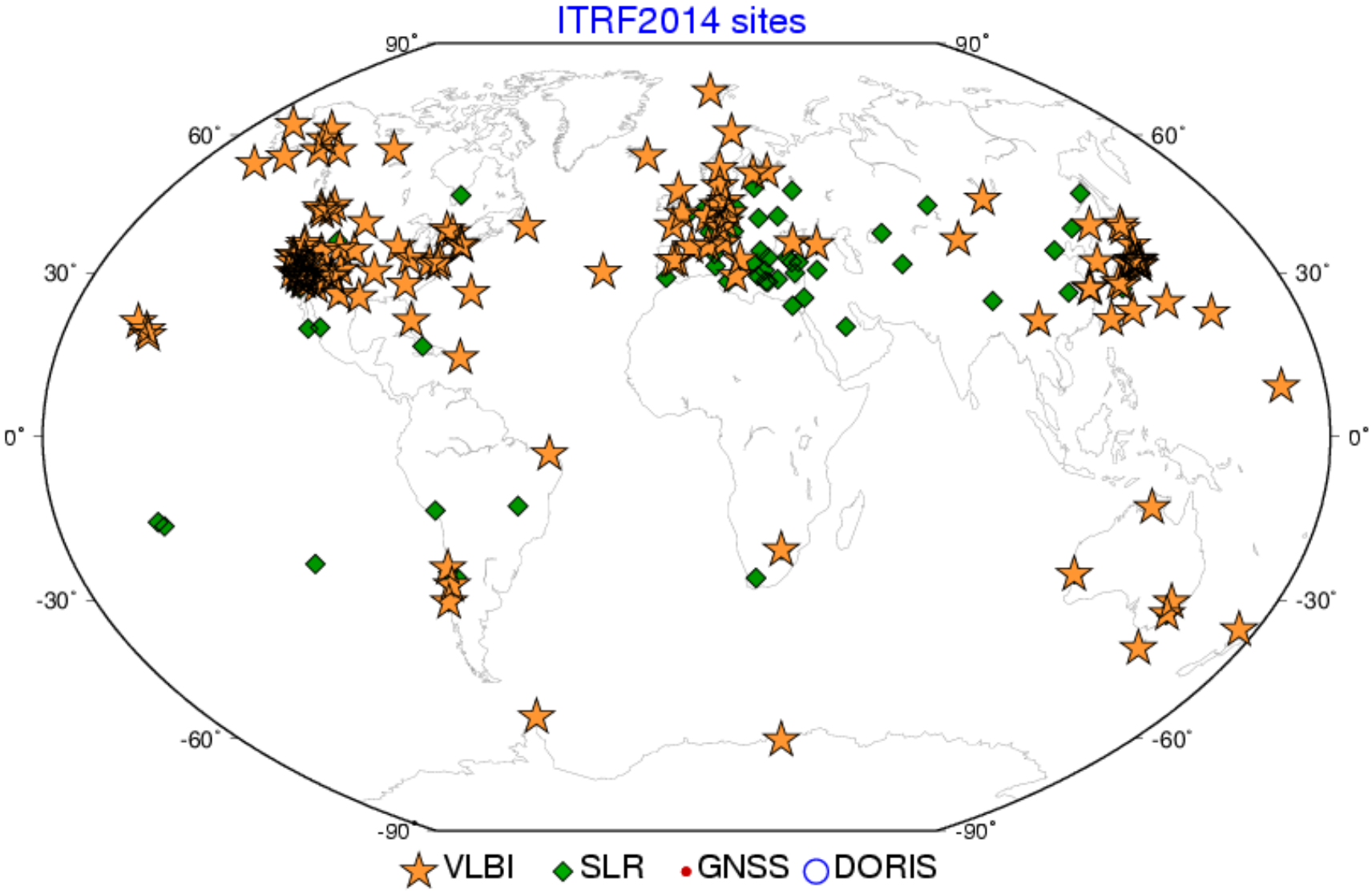
ITRF2014 Network



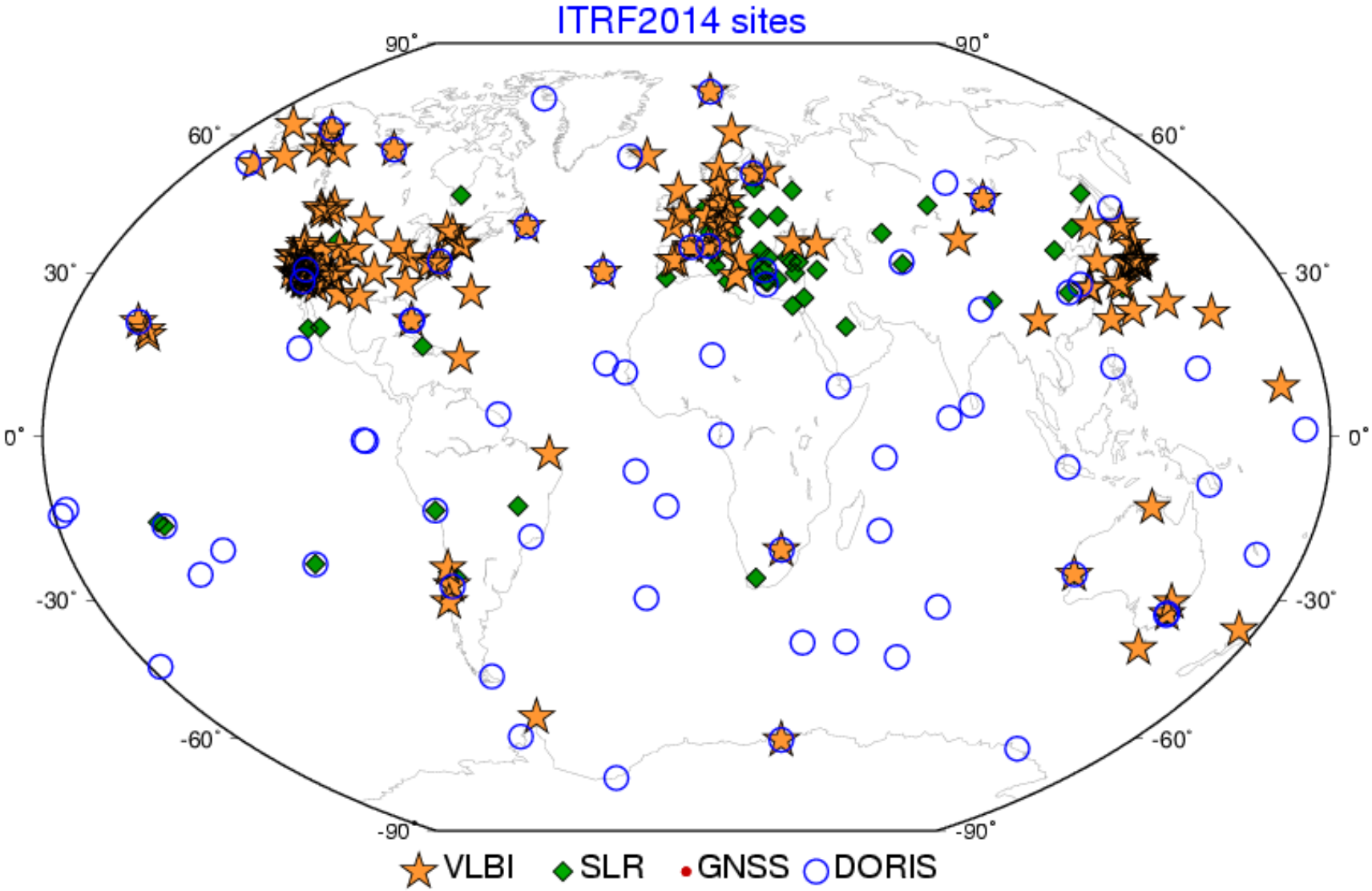
ITRF2014 Network : SLR



ITRF2014 Network: VLBI

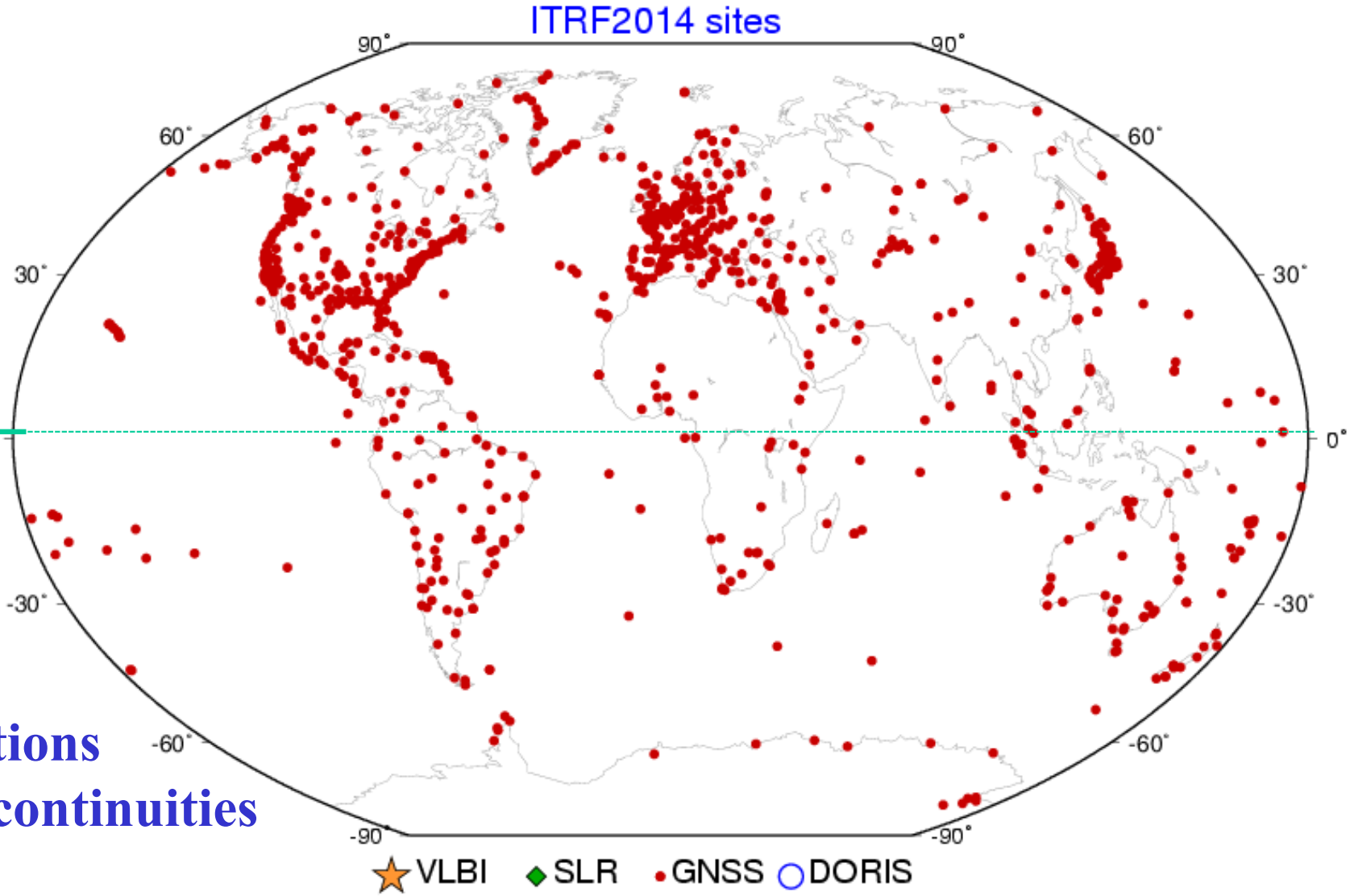


ITRF2014 Network: DORIS



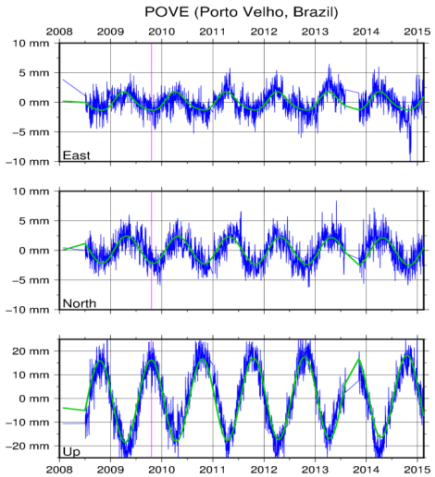
ITRF2014: GNSS

Site #
696
188



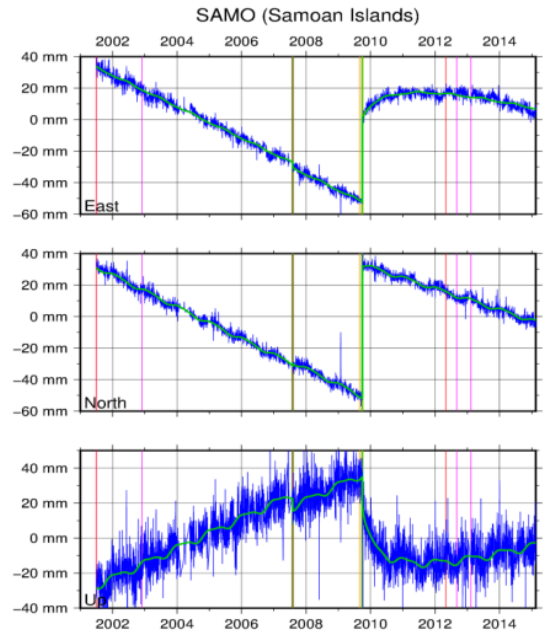
884 sites
1054 stations
1882 discontinuities

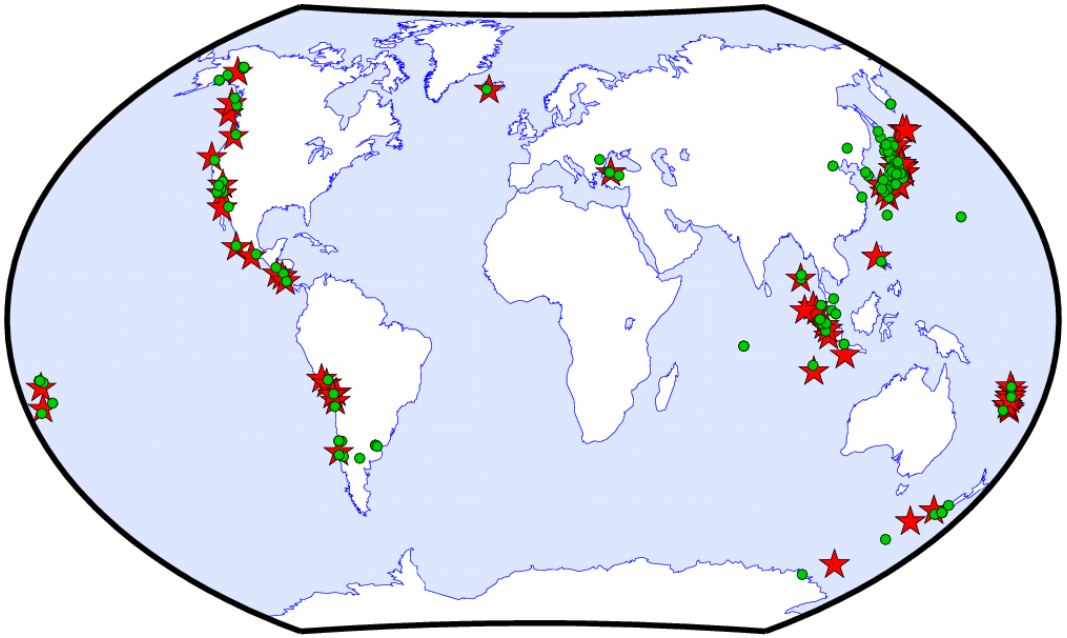
ITRF2014: Modelling nonlinear station motions



- **Position time series of all stations exhibit periodic signals**

- **More than 100 sites are subject to Post-Seismic Deformation due to major earthquakes**



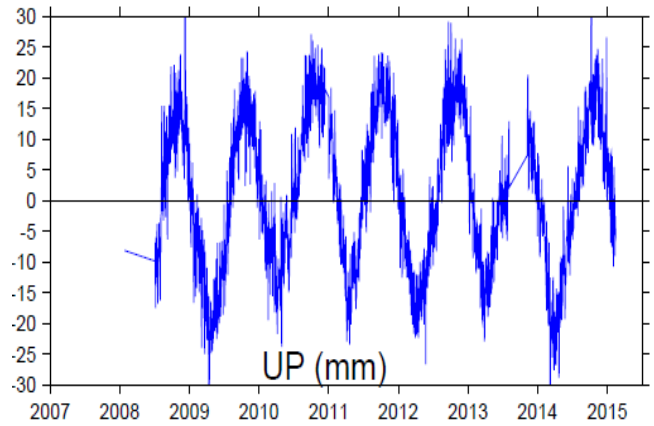


Red Stars: EQ Epicenters (58)

Green circles: ITRF2014 sites (117)

Precisely modeling the above leads to more robust secular frame and site velocities.

Periodic Signals



- **Loading effects:**
  - **Atmosphere**
  - **Terrestrial water (Hydrology)**
  - **Ocean circulation**

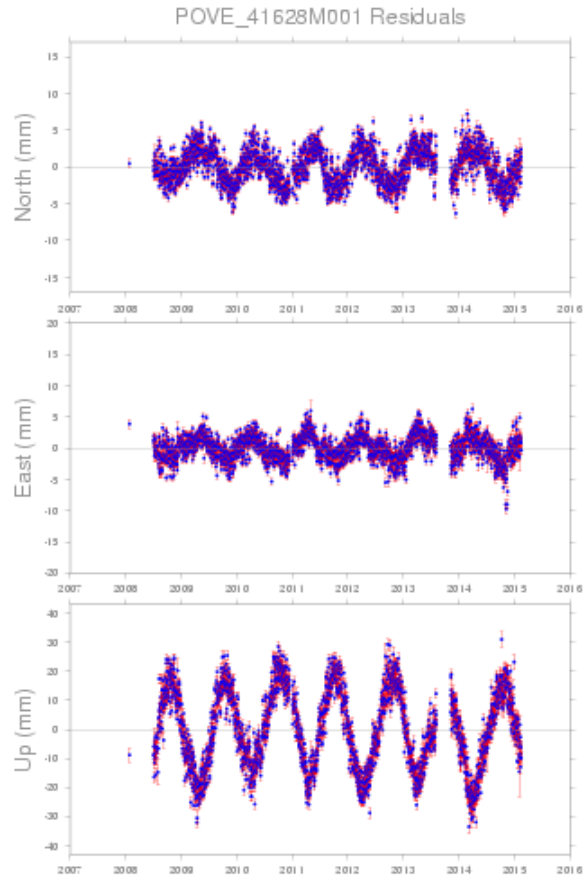
  ==> Annual, semi-annual, inter-annual, but also short periods (e.g. daily) variations

- **Technique systematic errors, e.g. GPS draconitic year (351.4 days) and its harmonics**

Periodic Signals

Annual & semi-annual terms estimated, using:

$$\Delta X_f = \sum_{i=1}^{n_f} a^i \cos(\omega_i t) + b^i \sin(\omega_i t)$$



ΔX_f **total sum of all frequencies**

n_f **number of frequencies**

$$\omega_i = \frac{2\pi}{\tau_i}$$

τ_i **period of the ith frequency**

==> 6 parameters per station & per frequency, i.e. a & b along each X, Y, Z axis.

Periodic Signals

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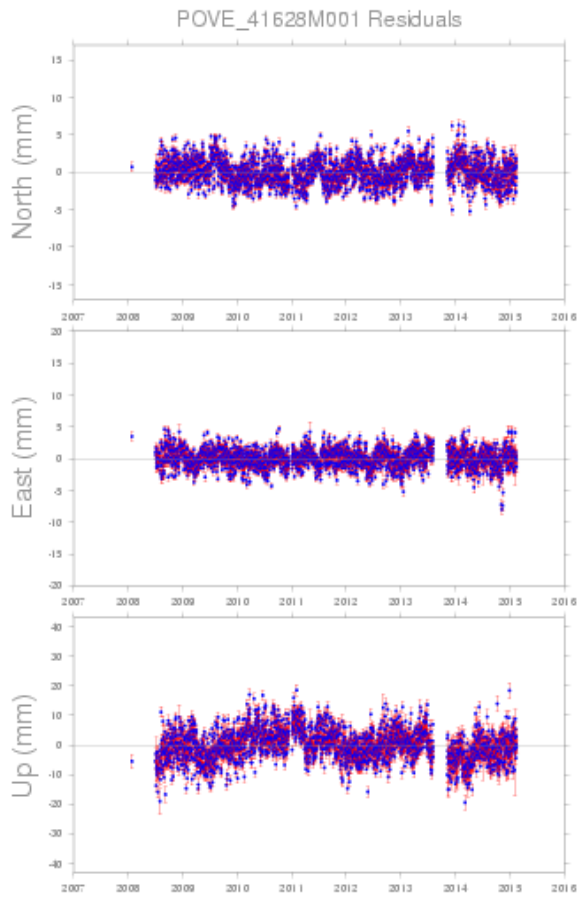

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Estimating seasonal signals vs applying non-tidal atmospheric loading (NTAL) model ?

Three IGS cumulative solutions:

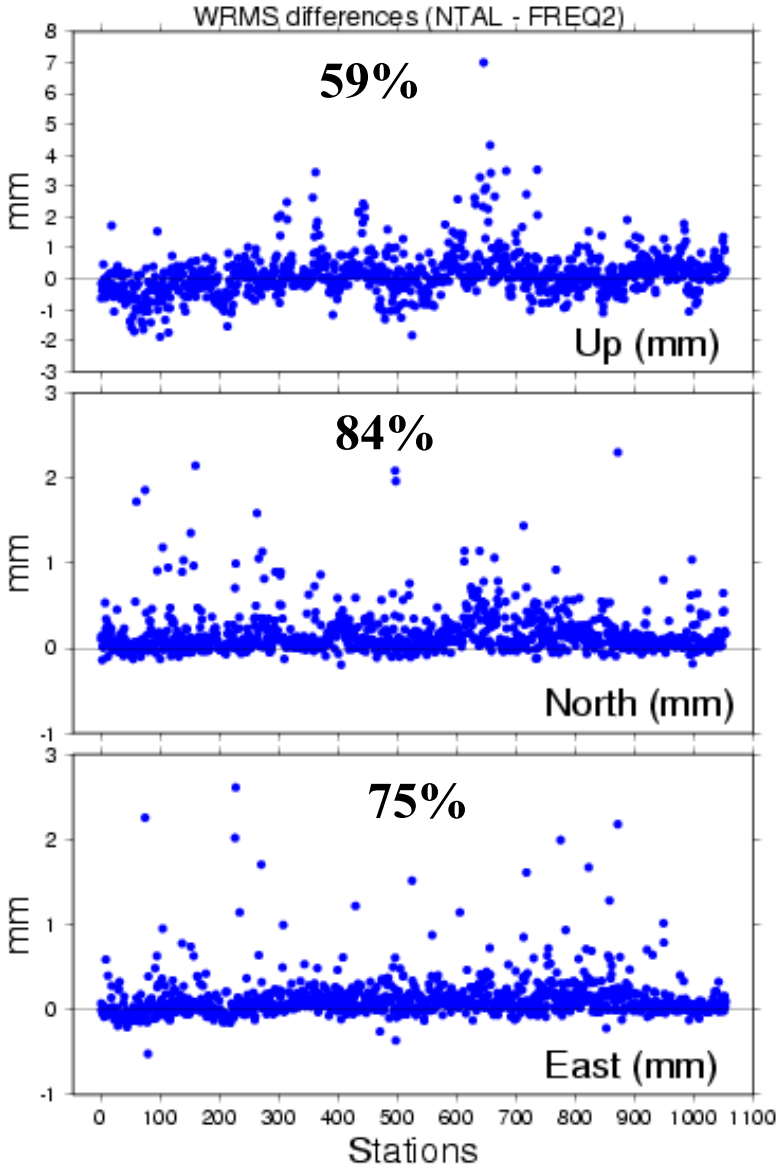
- **STD: Periodic signals NOT estimated, NTAL model NOT applied**
- **NTAL*: Non-tidal atmospheric loading model applied before stacking**
- **F2: Annual and semi-annual signals estimated**

*** NTAL model provided by Tonie van Dam**

Station WRMS Diffs (NTAL – F2)

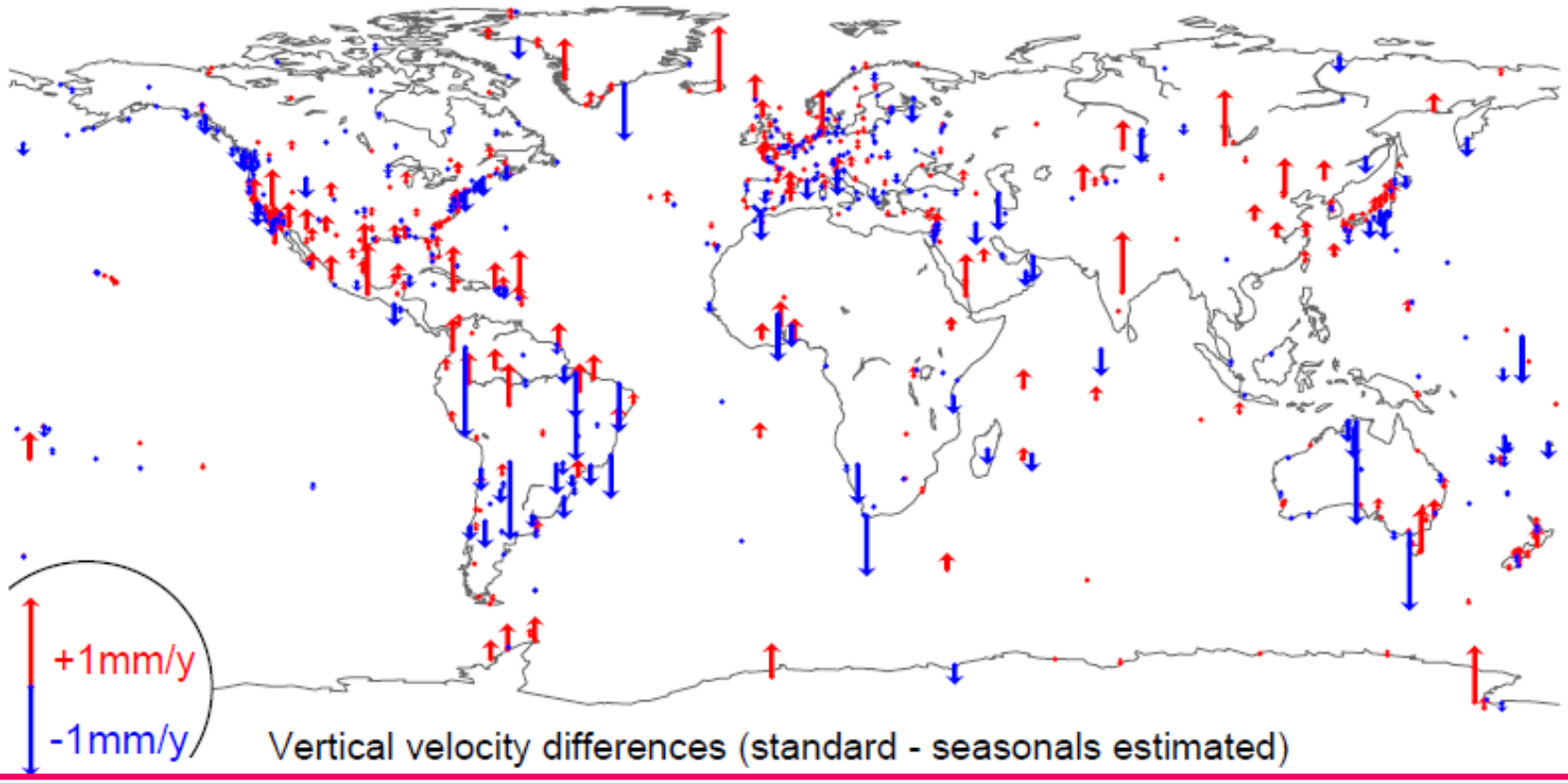
- **Positive values mean better performance for seasonal terms estimation**

- **Negative values mean better performance for NTAL**

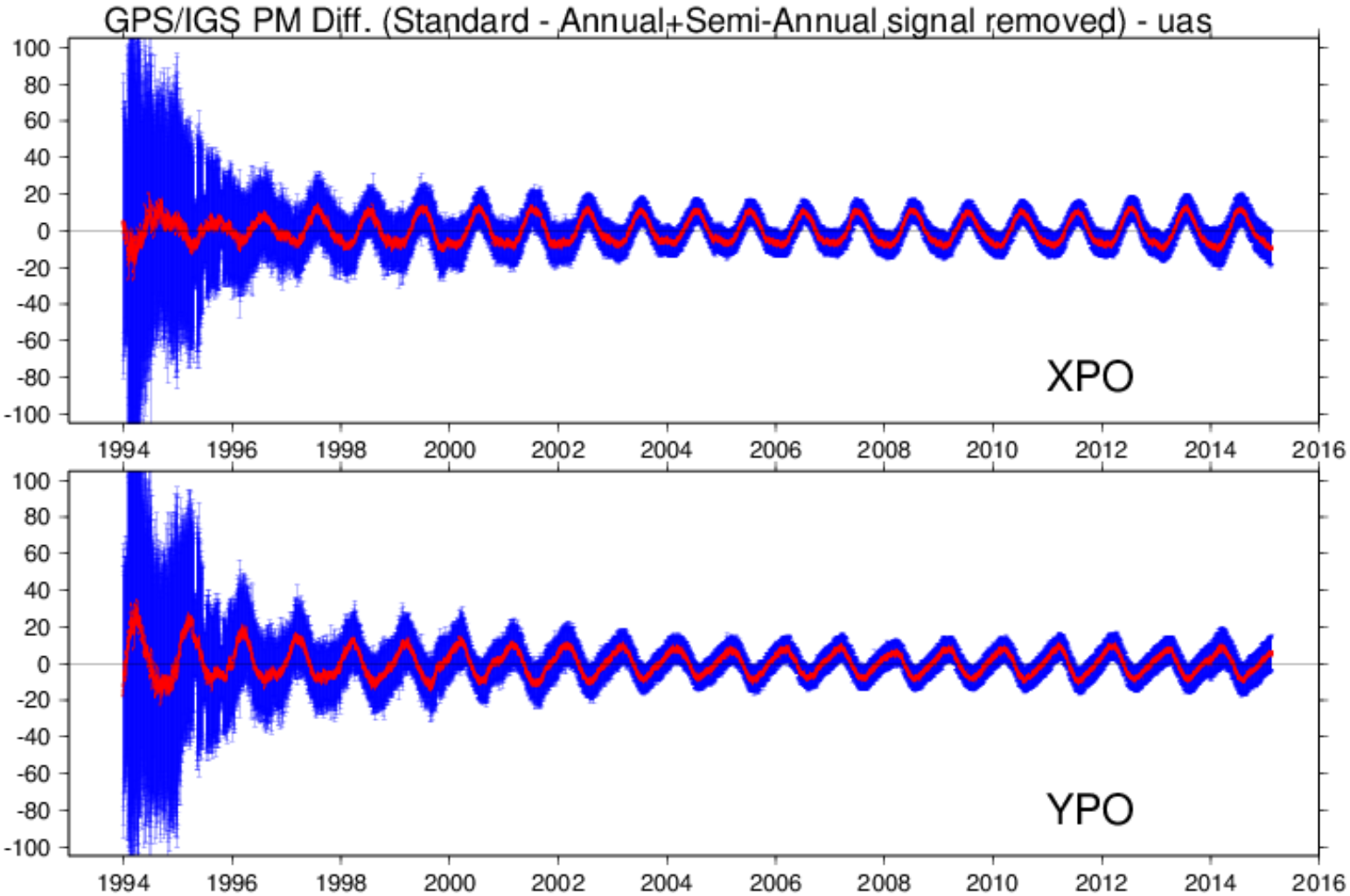


Impact of estimating seasonal signals on site velocities (STD – F2)

- **Negligible impact on horizontal velocities << 0.1 mm/yr**
- **Up to 1 mm/yr change in vertical velocities, for stations with large seasonal signals/number of discontinuities, or/and data gaps in time series**



Impact of estimating seasonal signals on Polar Motion

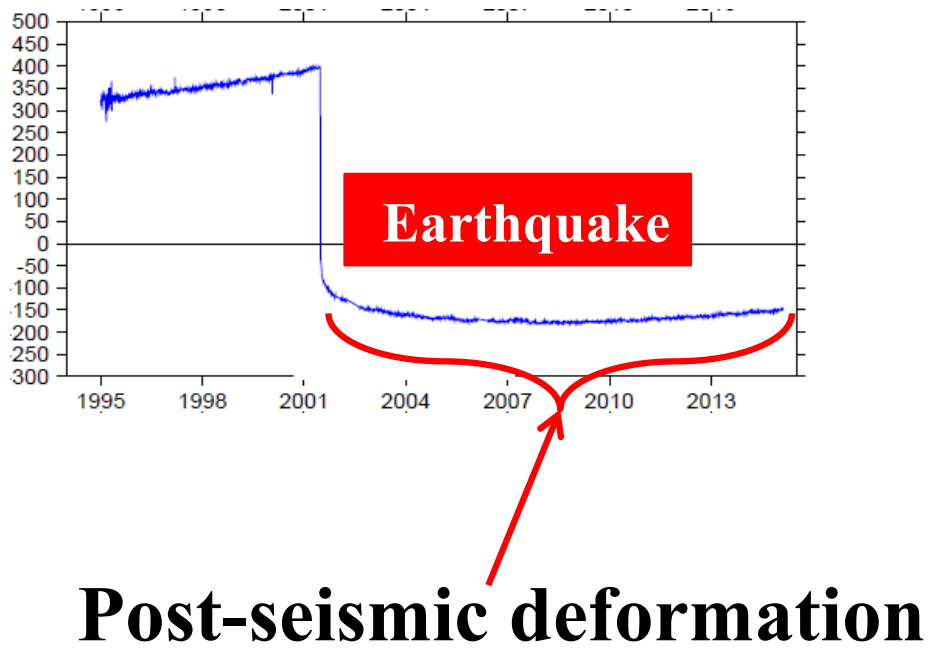


Post-Seismic Deformations

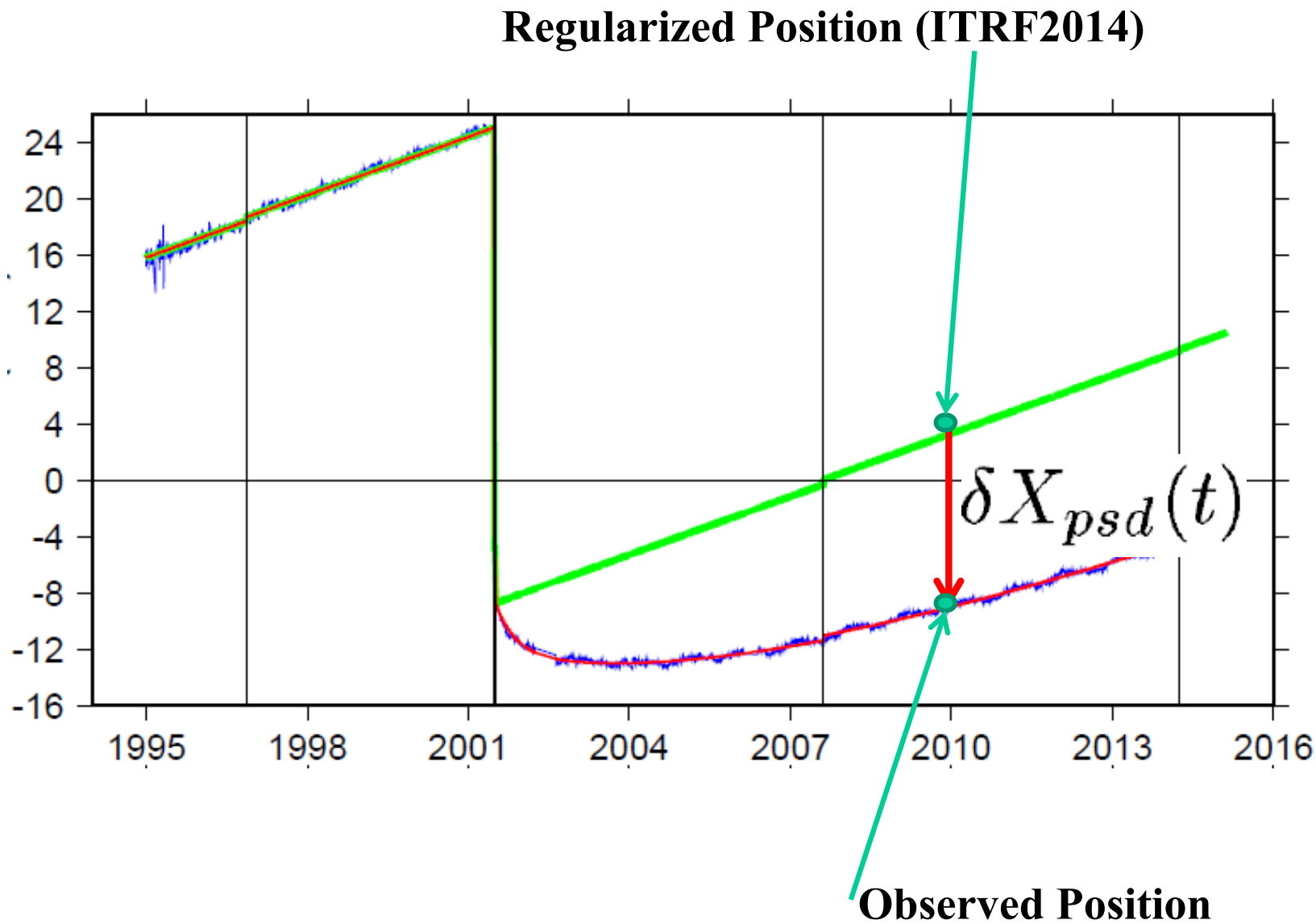
Post-Seismic Deformations

- **Fitting parametric models using GNSS/GPS data**
  - **at major GNSS/GPS Earthquake sites**
  - **Apply these models to the 3 other techniques at Co-location EQ sites**

- **Parametric models:**
  - **Logarithmic**
  - **Exponential**
  - **Log + Exp**
  - **Two Exp**



PSD Correction



How to use ITRF2014 PSD models ?

Regularized Position (ITRF2014)

$$X_{PSD}(t) = \boxed{X(t_0) + \dot{X}(t - t_0)} + \delta X_{PSD}(t)$$

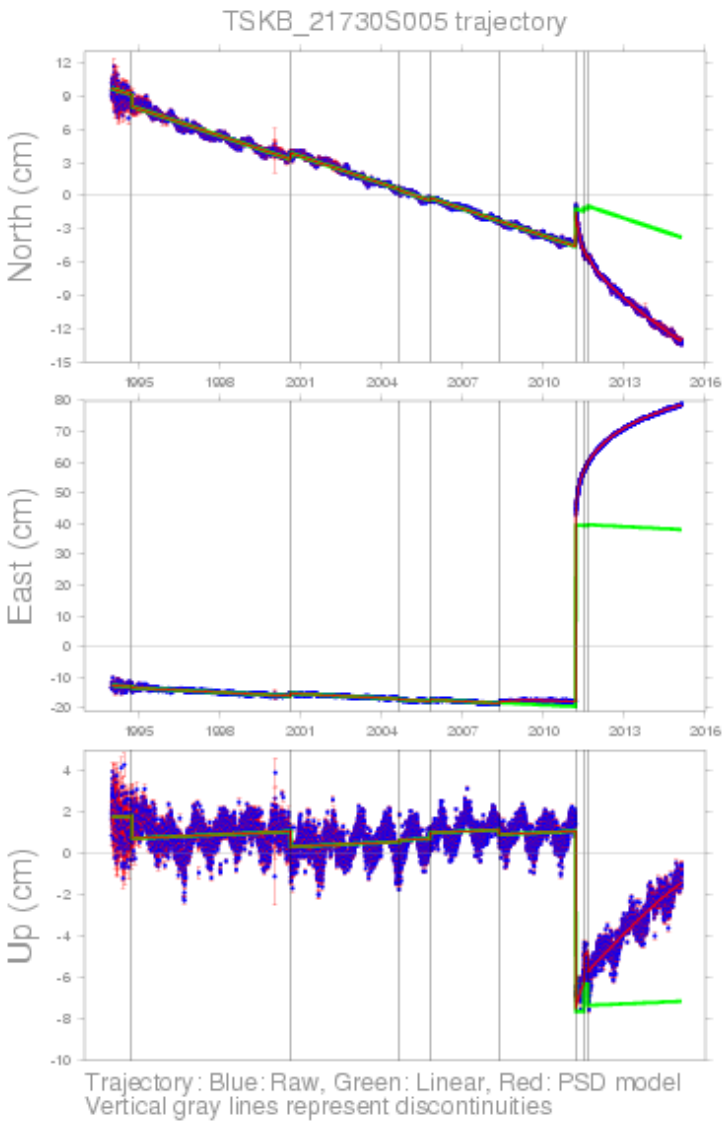
$$\delta L(t) = \sum_{i=1}^{n^l} A_i^l \log(1 + \frac{t - t_i^l}{\tau_i^l}) + \sum_{i=1}^{n^e} A_i^e (1 - \mathrm{e}^{-\frac{t - t_i^e}{\tau_i^e}})$$

Local Frame

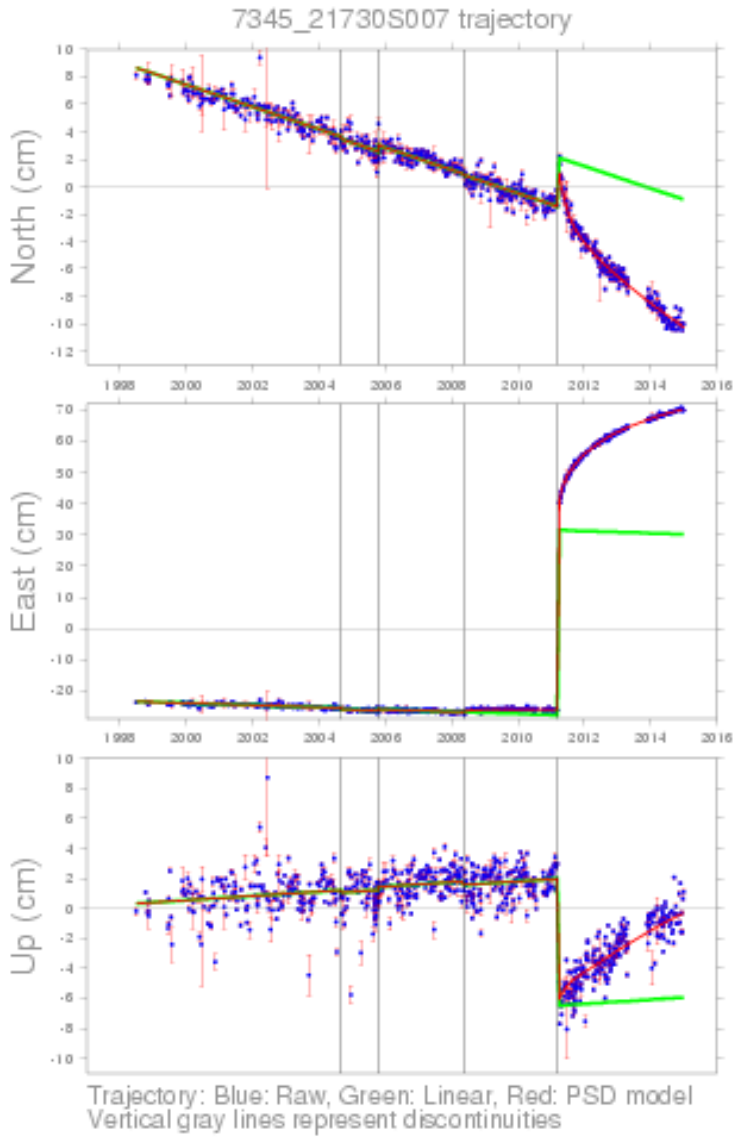
PSD Subroutines available at ITRF2014 Web site:
http://itrf.ign.fr/ITRF_solutions/2014/

Tsukuba Trajectory

GNSS

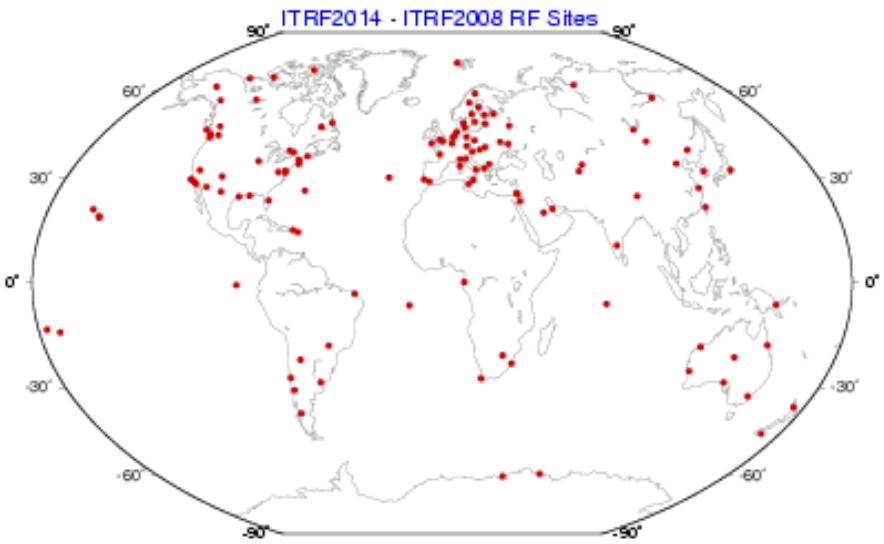


VLBI



ITRF2014 Frame Specification

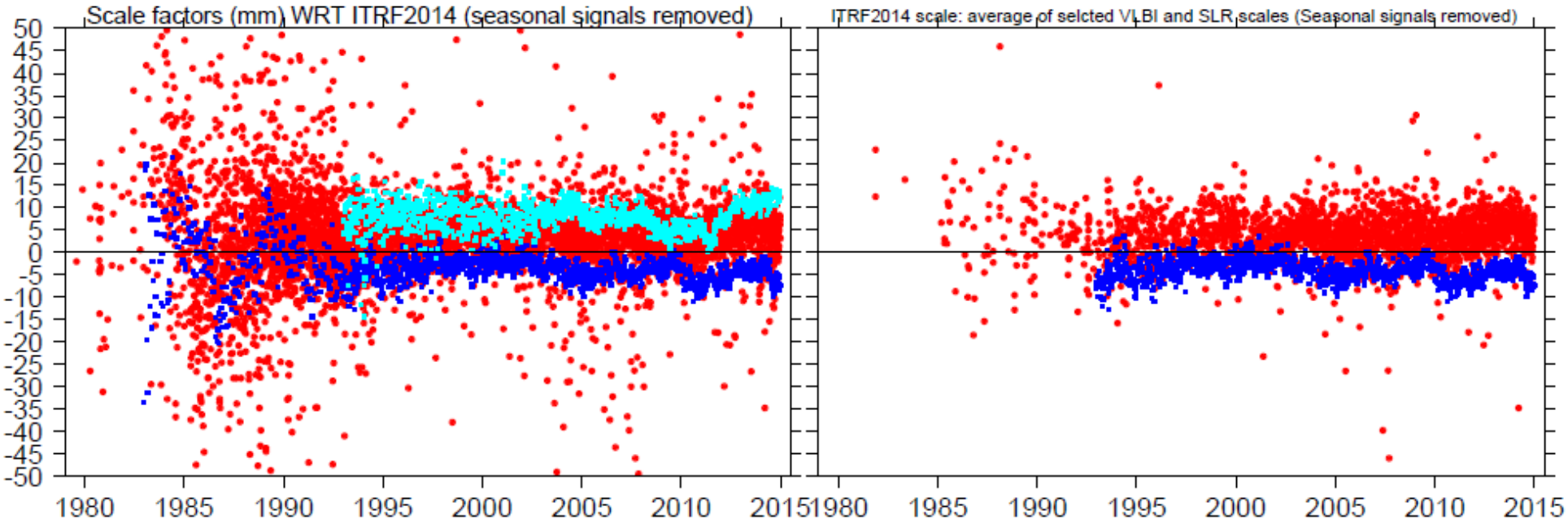
- **Origin: SLR: Zero translation or translation rate between ITRF2014 and SLR frame**
- **Scale: Arithmetic average of VLBI & SLR intrinsic scales: Zero scale or scale rate between ITRF2014 & the VLBI & SLR average**
- **Orientation : Zero rotation and rotation rate WRT ITRF2008, using 127 RF stations:**



DORIS, SLR & VLBI scales wrt ITRF2014

Full time series of scale factors

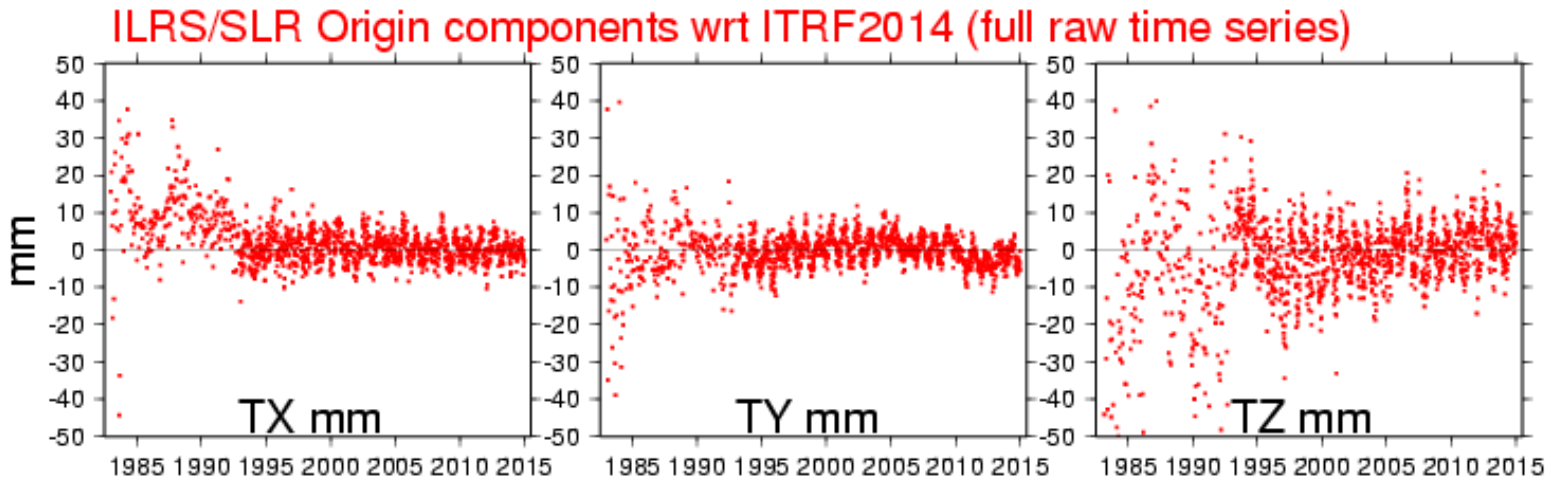
Scale factors of SLR and VLBI solutions selected to define ITRF2014 scale



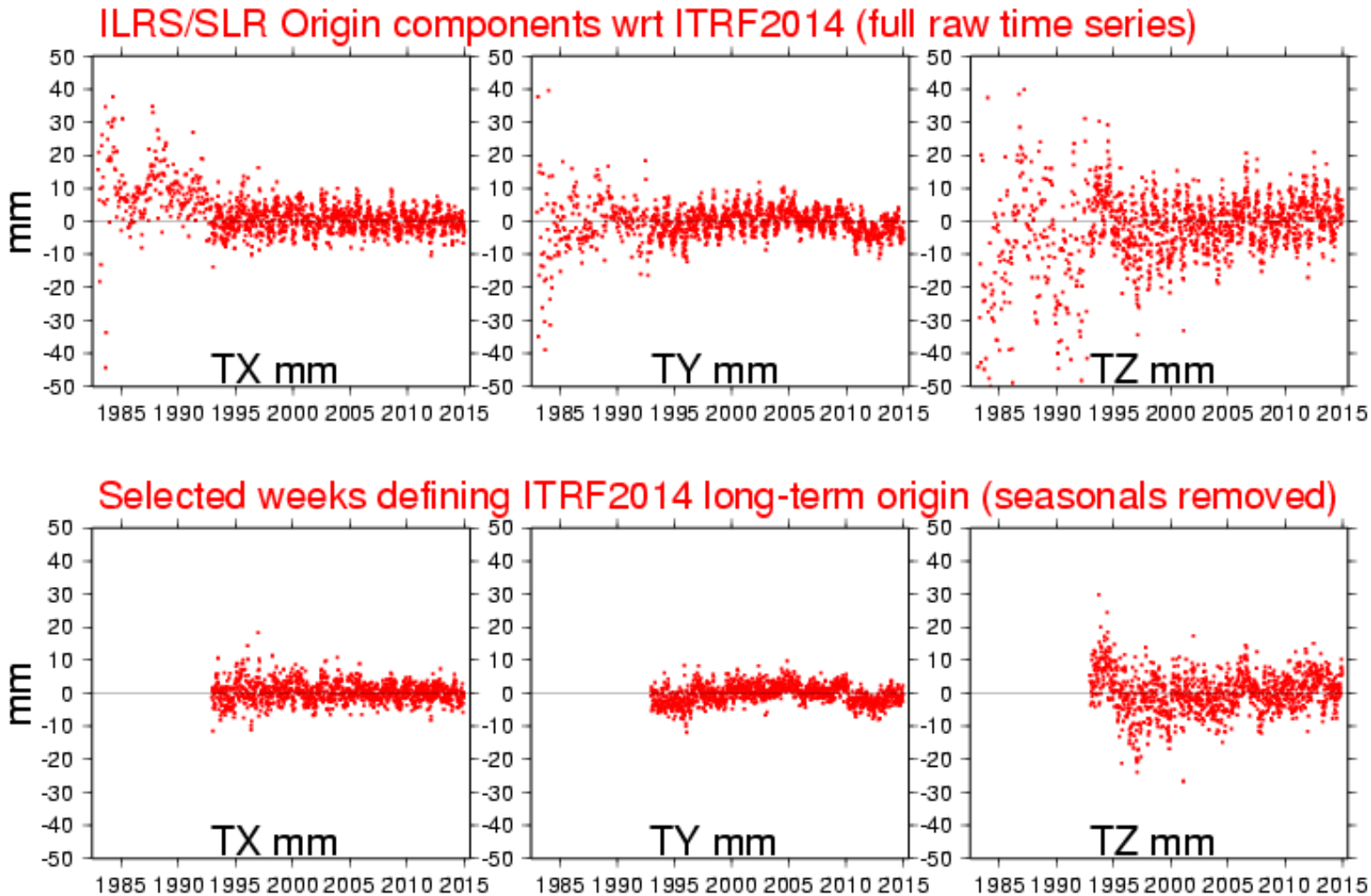
DORIS SLR VLBI

SLR to VLBI scale offset : 1.4 ppb = ~8 mm.

ILRS/SLR origin components wrt ITRF2014



ILRS/SLR origin components wrt ITRF2014

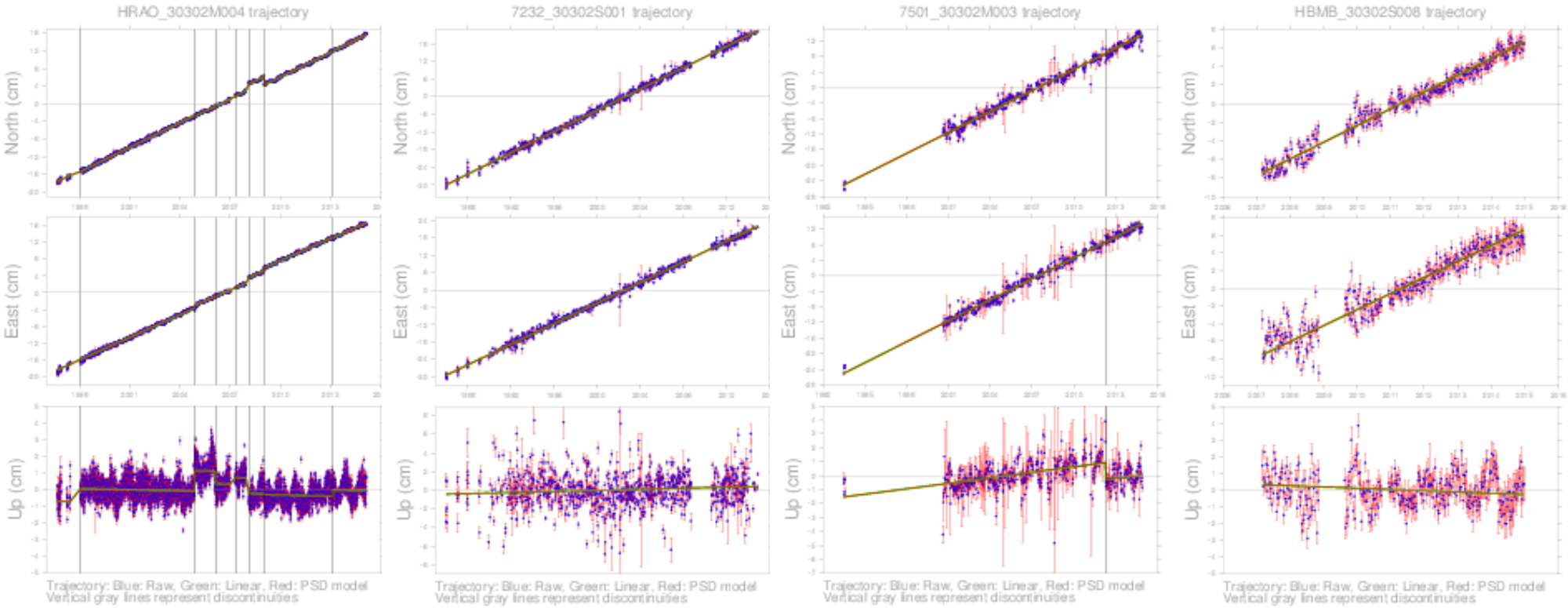


Preparation for ITRF2020 (1/2)

- **Why ITRF2020?** After consultation, the majority favors ITRF2020 for different reasons
- ITRF2020 ==> Toward improving the ITRF
- At the techniques level: a number of effects and model updates to be considered, e.g.:
  - SLR range biases
  - VLBI antenna deformation
  - DORIS SRP modelling
  - A number of model updates for GNSS
  - All techniques: Improve data processing to reduce the noise level (see illustration next)

Periodic signals, Discontinuities and Noise level

GPS **VLBI** **SLR** **DORIS**



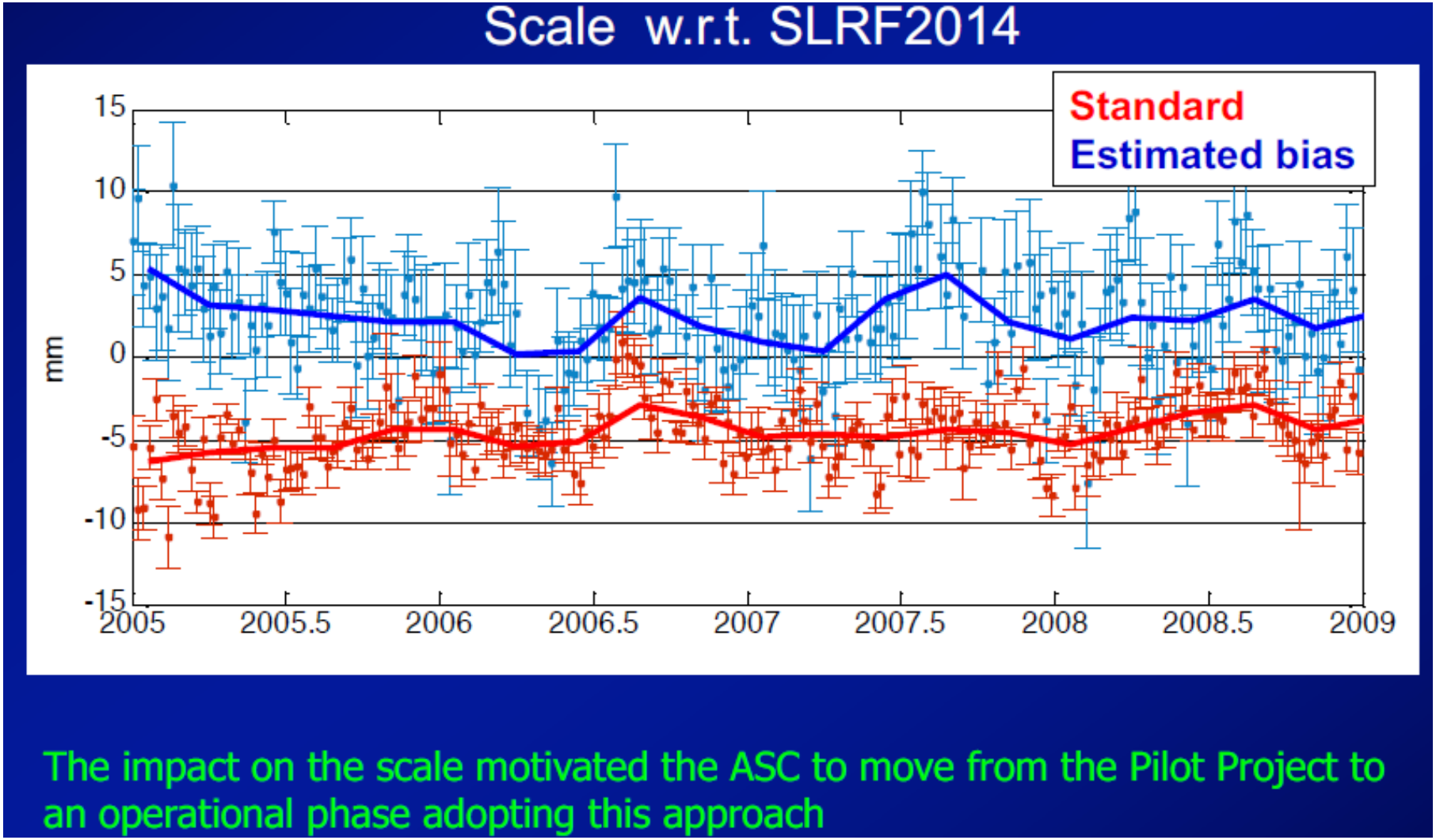
Hartebeesthoek : at an important co-location site

Preparation for ITRF2020 (2/2)

- **ITRF2020 ==> Toward improving the ITRF**

- **<u>At the combination level</u>:**
  - **Track down the VLBI & SLR scale discrepancy**
  - **Provide annual & semi annual signals for all techniques in the CM frame**
  - **Isolate/understand technique discrepancies in seasonal signals at co-location sites**
  - **Provide accurate annual and semi-annual geocenter motion models for specific applications, e.g. POD**

Impact of SLR Range Bias on the Scale



Courtesy Erricos Pavlis

"Instantaneous" position: linear & nonlinear parts

$$X(t) = \overbrace{X(t_0) + \dot{X}.(t - t_0)}^{\text{Regularized position}} + \delta X(t)_{PSD} + \delta X(t)_S + \delta X(t)_G$$

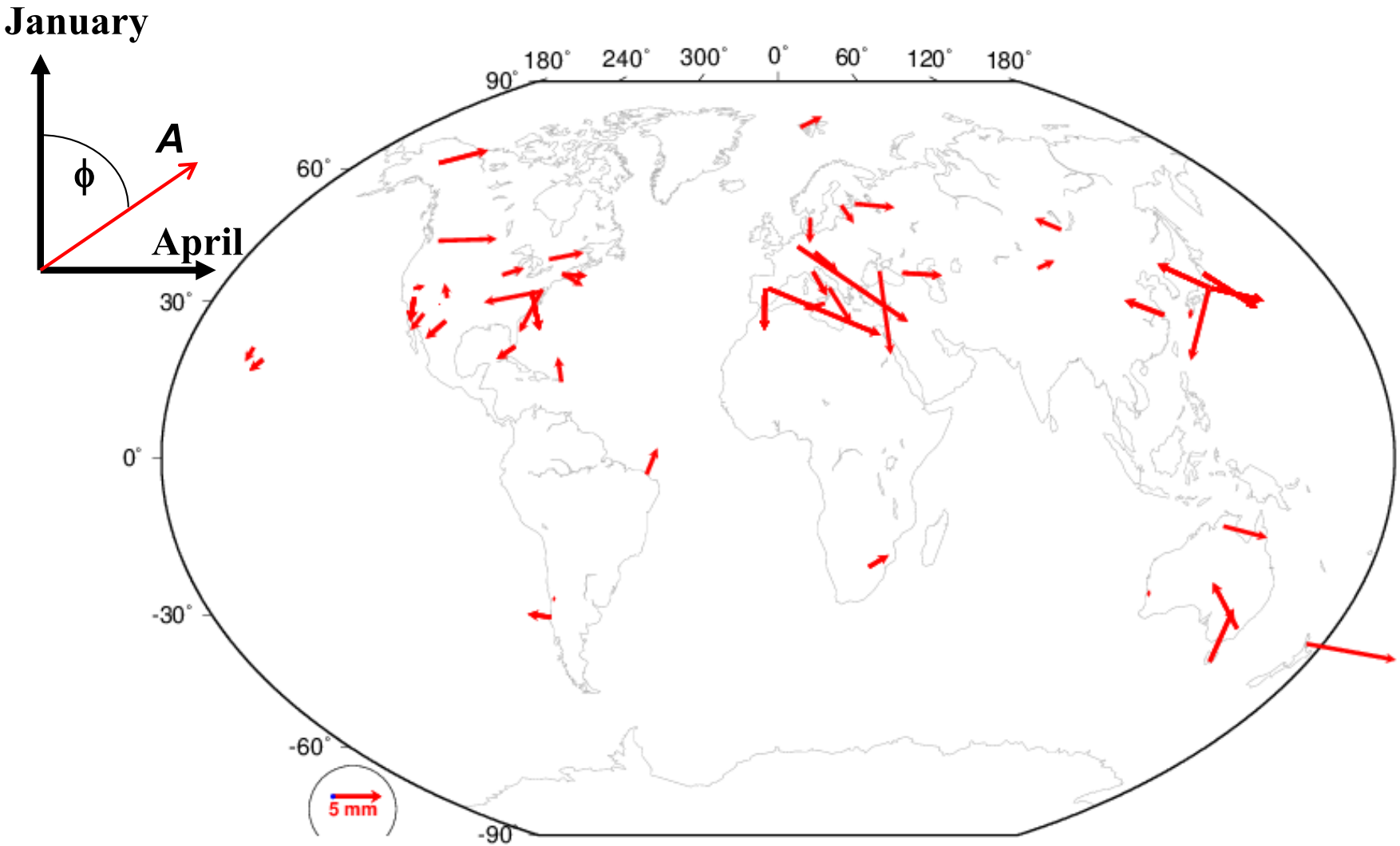
$\sum$ **Post-Seismic Deformations**

$\sum$ **Seasonal Signals of all frequencies**
Caution: significant discrepancies between techniques
Or a Loading model with ALL contributions (ATM, …)

If seasonal signals are in CF, add Geocenter Motion
Caution: different models exist, with significant differences

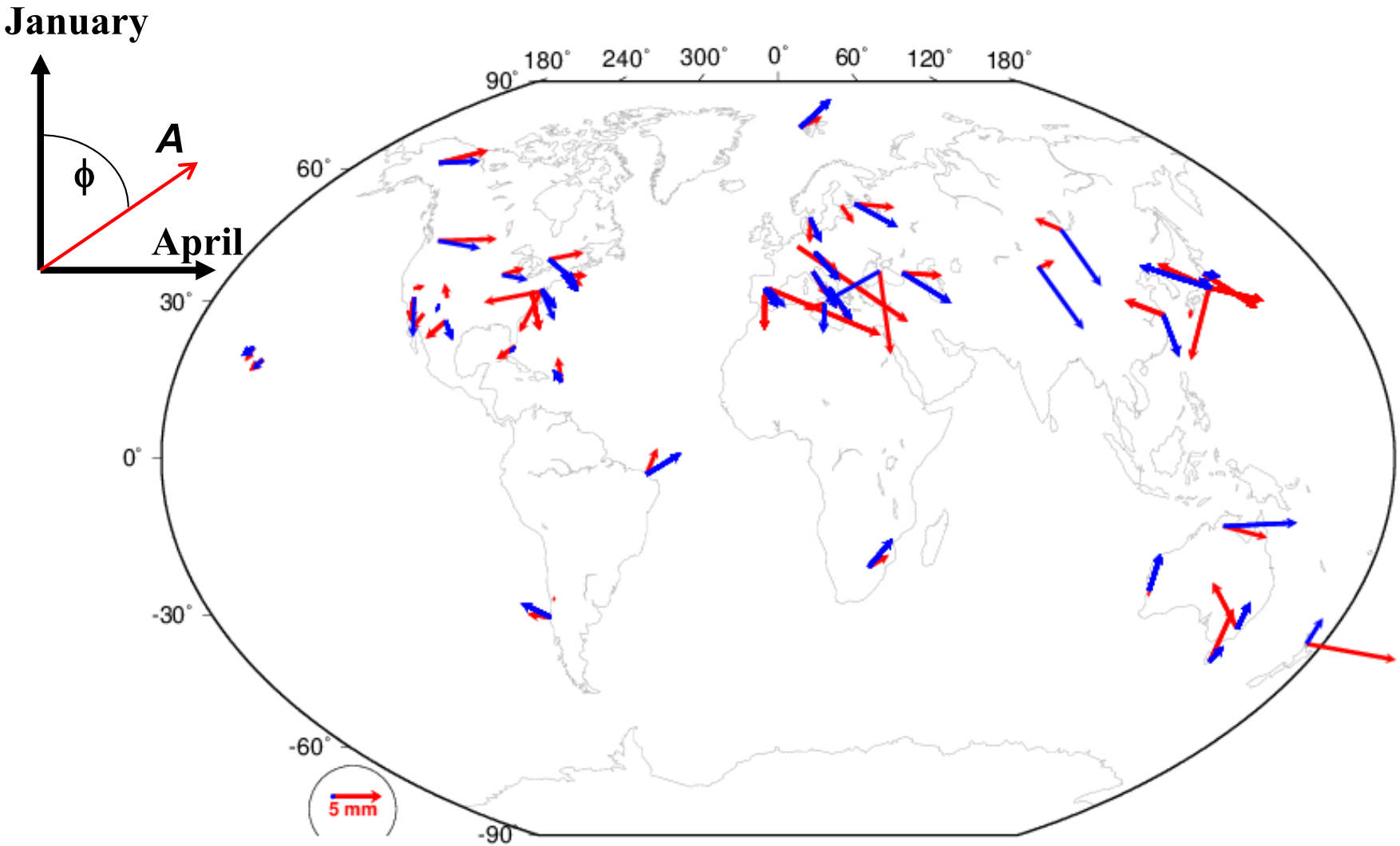
All the δX corrections could be part of future ITRF products

Up annual signals : VLBI (CN frame)



$$Dh = A.\cos(2\pi f(t - t_0) + \phi)$$

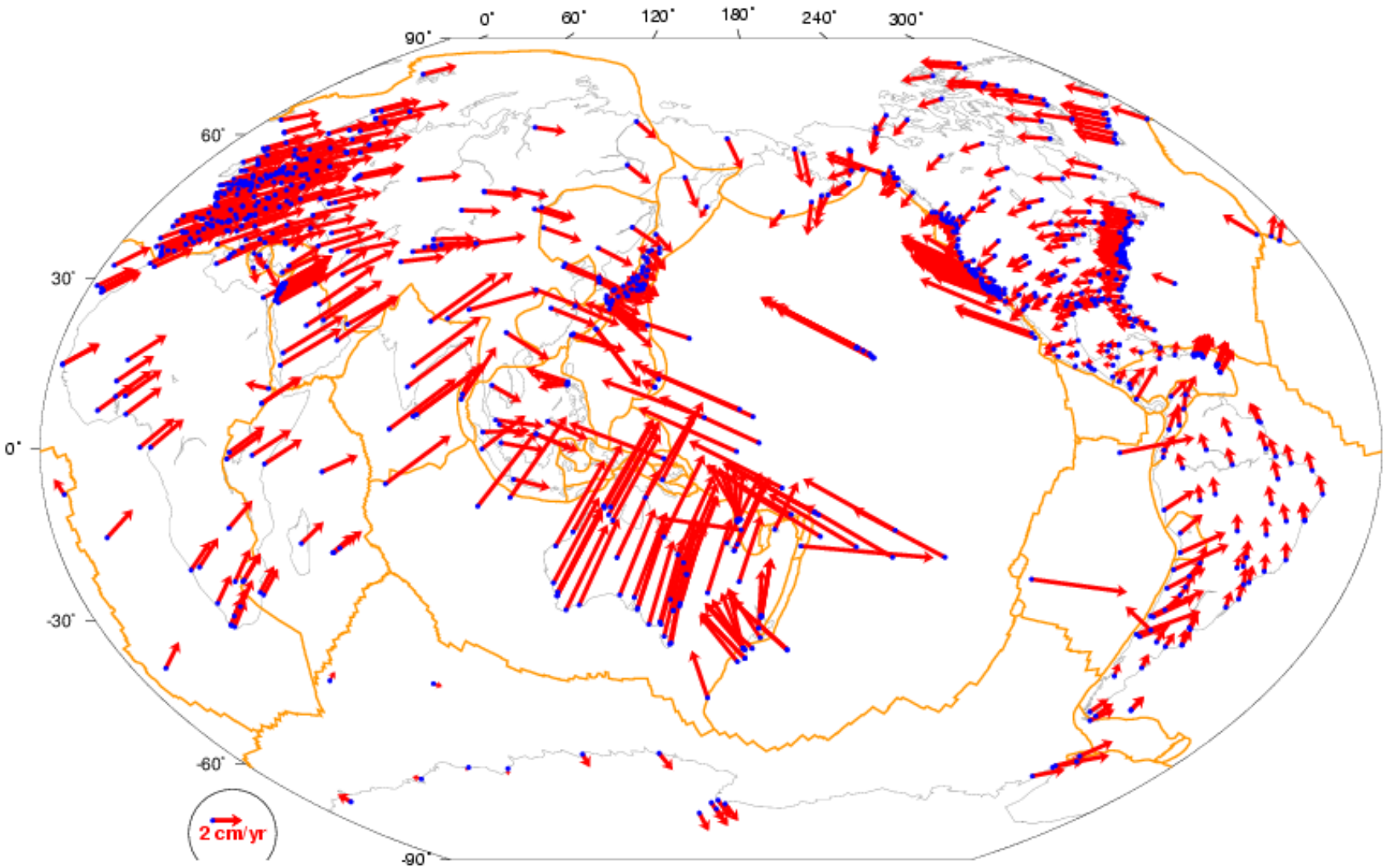
Up annual signals : VLBI + GNSS (CN Frame)



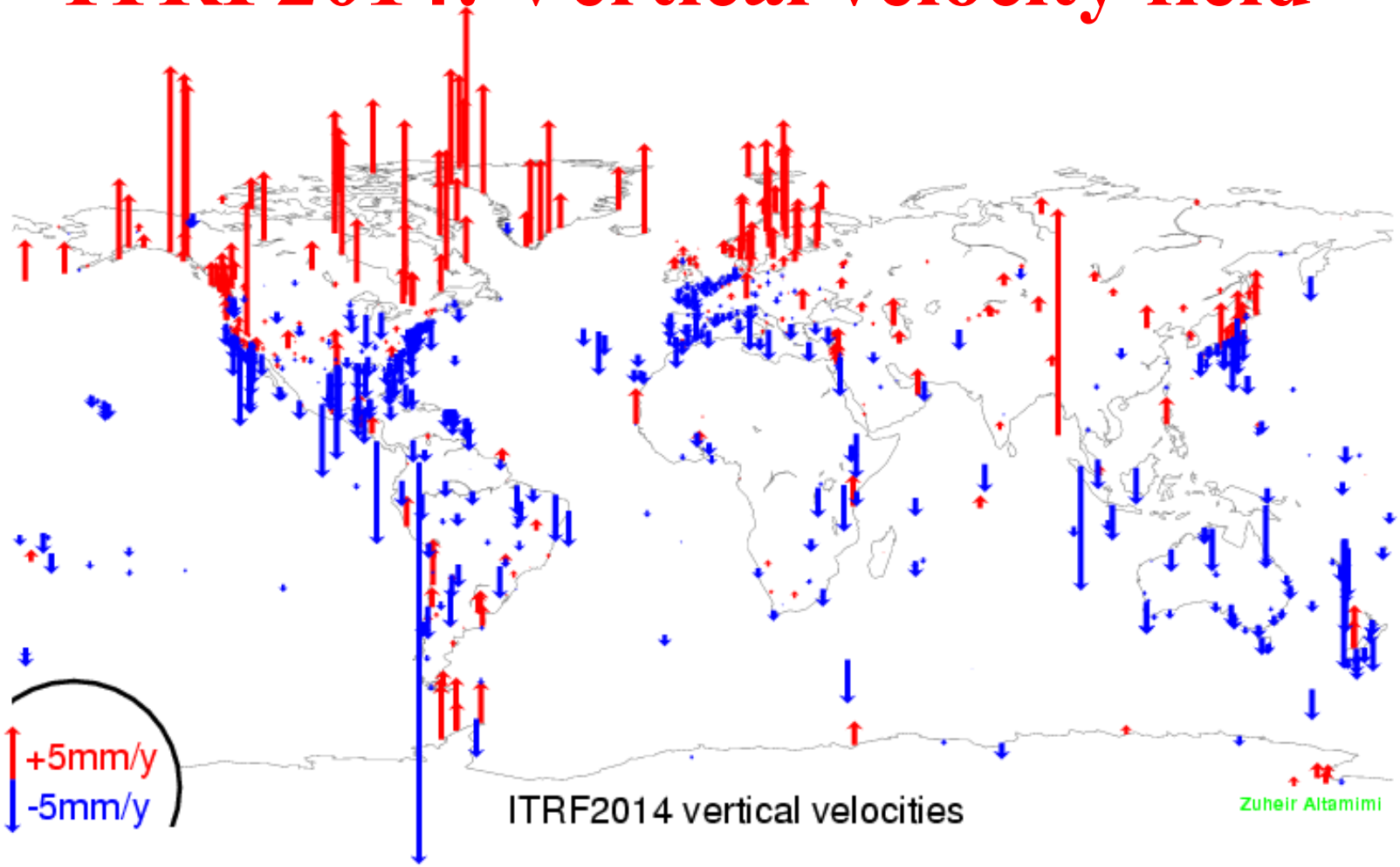
Annual Geocenter motion : different estimates

	Amp X (mm)	Phase X (deg)	Amp Y (mm)	Phase Y (deg)	Amp Z (mm)	Phase Z (deg)
SLR CN: Uneven Network	2.1	63.7	3.1	329.1	3.1	22.7
SLR CN: 8 stations	1.7	60.7	3.6	325.0	2.2	28.7
SLR Via Multi-technique	1.1	55.7	3.7	356.8	2.3	51.1
Via GPS Net	1.5	48.0	3.3	335.1	2.0	47.7
Via VLBI Net	1.7	53.7	3.1	327.1	2.9	55.8

ITRF2014: Horizontal velocity field

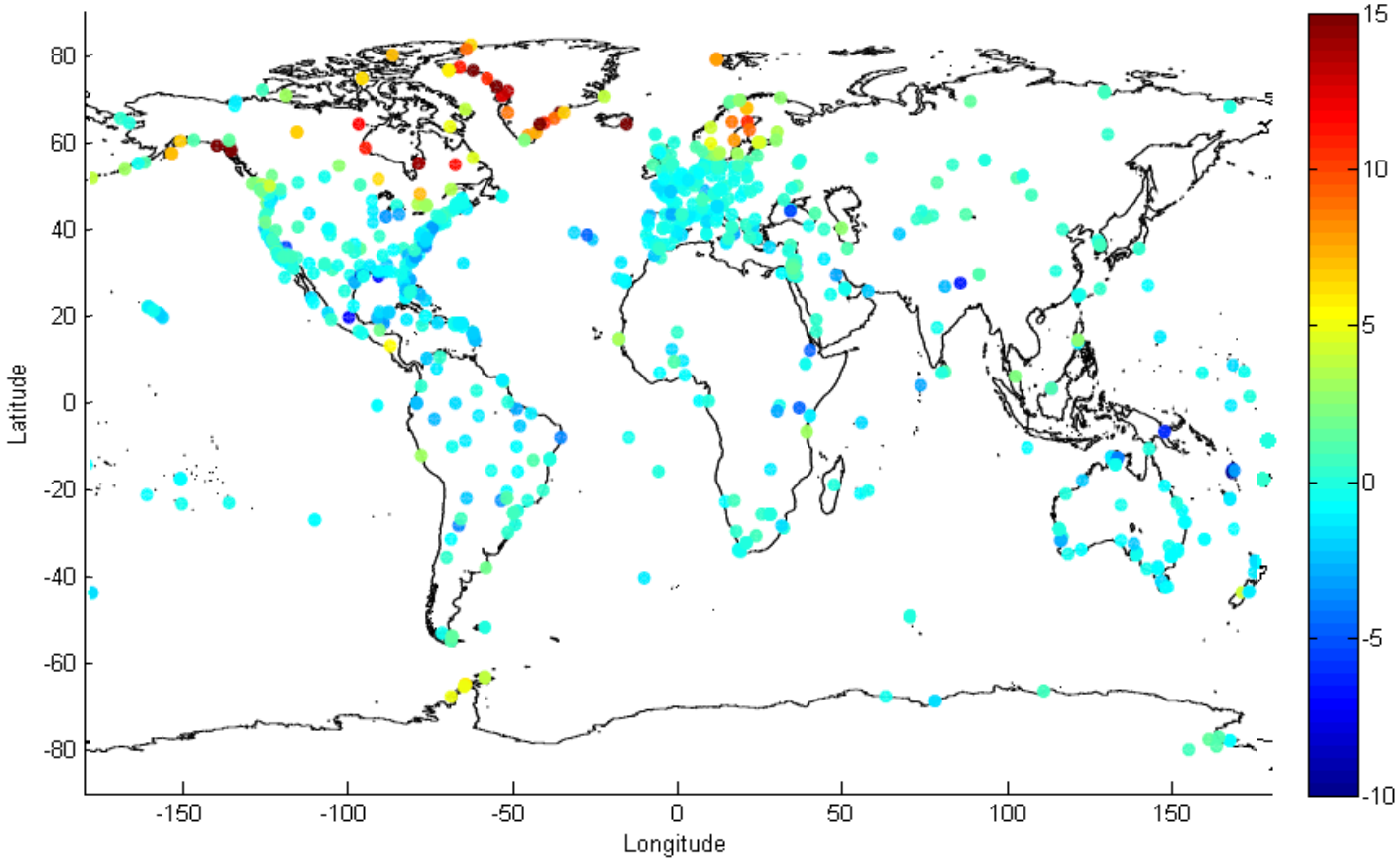


ITRF2014: Vertical velocity field



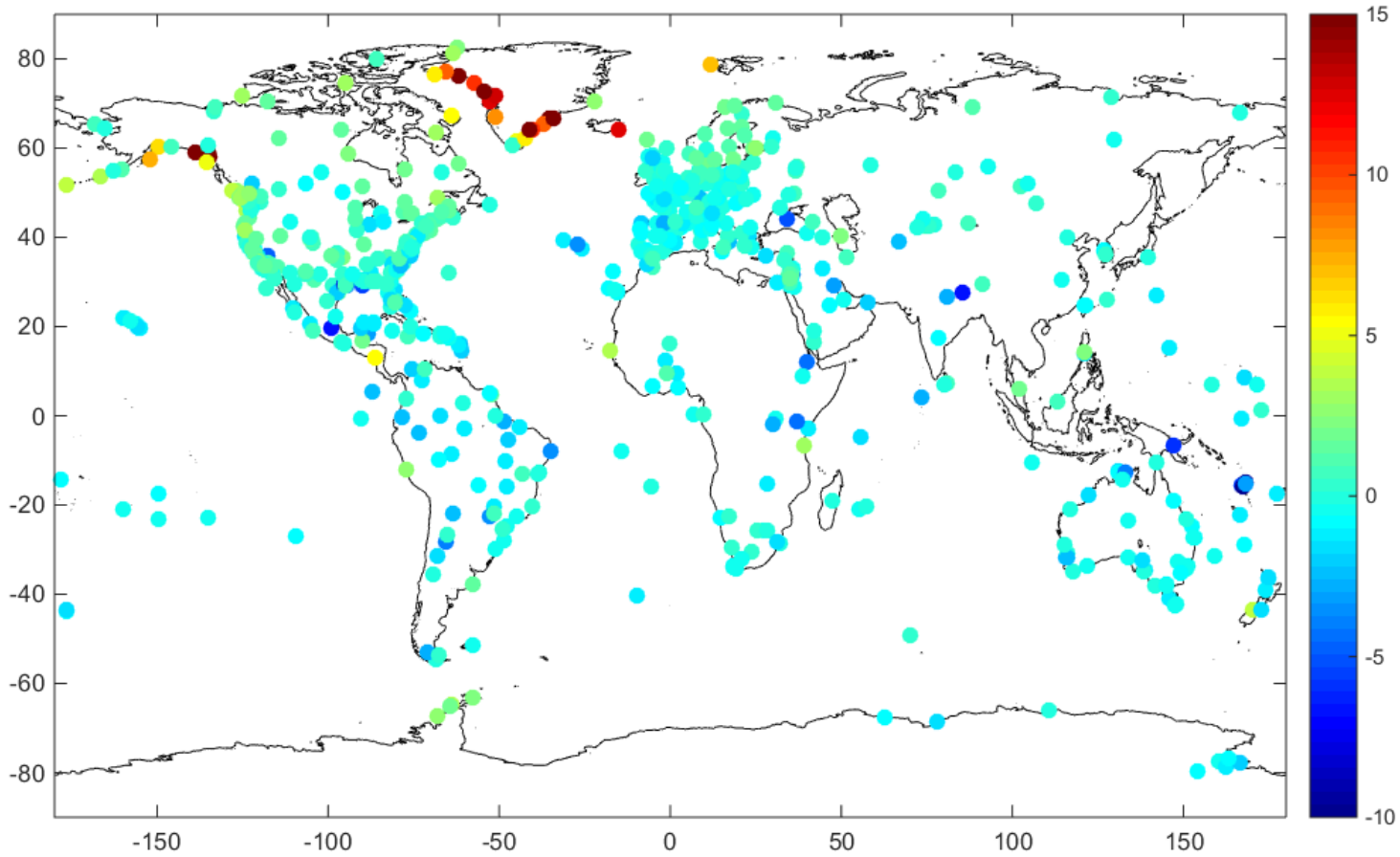
ITRF Accuracy/precision

Evolution of the spatial consistency of vertical velocities: ITRF2014



ITRF Accuracy/precision

Vertical velocity differences between ITRF2014 and ICE-6G/GIA model



Summary & Conclusion

- More than 3 decades of R&D to improve the ITRF
- The most precise/accurate reference frame available today
- Accessible everywhere & anywhere thanks to IGS products

- ITRF2014 published in 2016, and in JGR Open Access article
- ITRF2014 innovation: modelling of non-linear station motions
- Estimating seasonal signals
  - A more robust frame and site velocities
  - Performs better than applying a pressure loading model
  - No significant impact on horizontal velocities
- Precise modeling of post-seismic deformations

- Persistent scale offset between VLBI & SLR
- Need to mitigate technique systematic errors in preparation for ITRF2020