The International Terrestrial Reference Frame: Current status and future development

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Outline

- **Reference Frame representations for a deformable Earth:**
  - **Quasi-instantaneous RF**
  - **Long-term (Secular) RF - main focus here -**
- **ITRF and site non-linear motions:**
  - **Periodic signals**
  - **Co- & Post-Seismic deformation**
- **Impact of station non-linear motions on the ITRF ?**
- **Any impact on ITRF defining parameters ?**
- **Conclusion**

Defining a Reference System & Frame:

Three main conceptual levels :

- **Ideal Terrestrial Reference System (TRS):**
  Theoretical definition (Origin, Scale & Orientation)
- **Terrestrial Reference Frame (TRF):**
  Numerical realization of the TRS to which users have access
- **Coordinate System: Cartesian (X,Y,Z), geographic (λ, ϕ, h), ...**

– **As the TRS, the TRF has an origin, scale & orientation**

– **TRF is constructed using space geodesy observations, hence with uncertainties**

"Motions" at the surface of the deformable Earth

- **Nearly linear motion:**
  - Tectonic motion: horizontal
  - Post-Glacial Rebound: Vertical & Horizontal

- **Non-Linear motion:**
  - Periodic: Annual, Semi & Inter-Annual (caused by loading effects), draconitic
  - Rupture: Co-seismic, Volcano Eruptions, etc.
  - Transient or post-seismic deformation

Reference Frame Representations

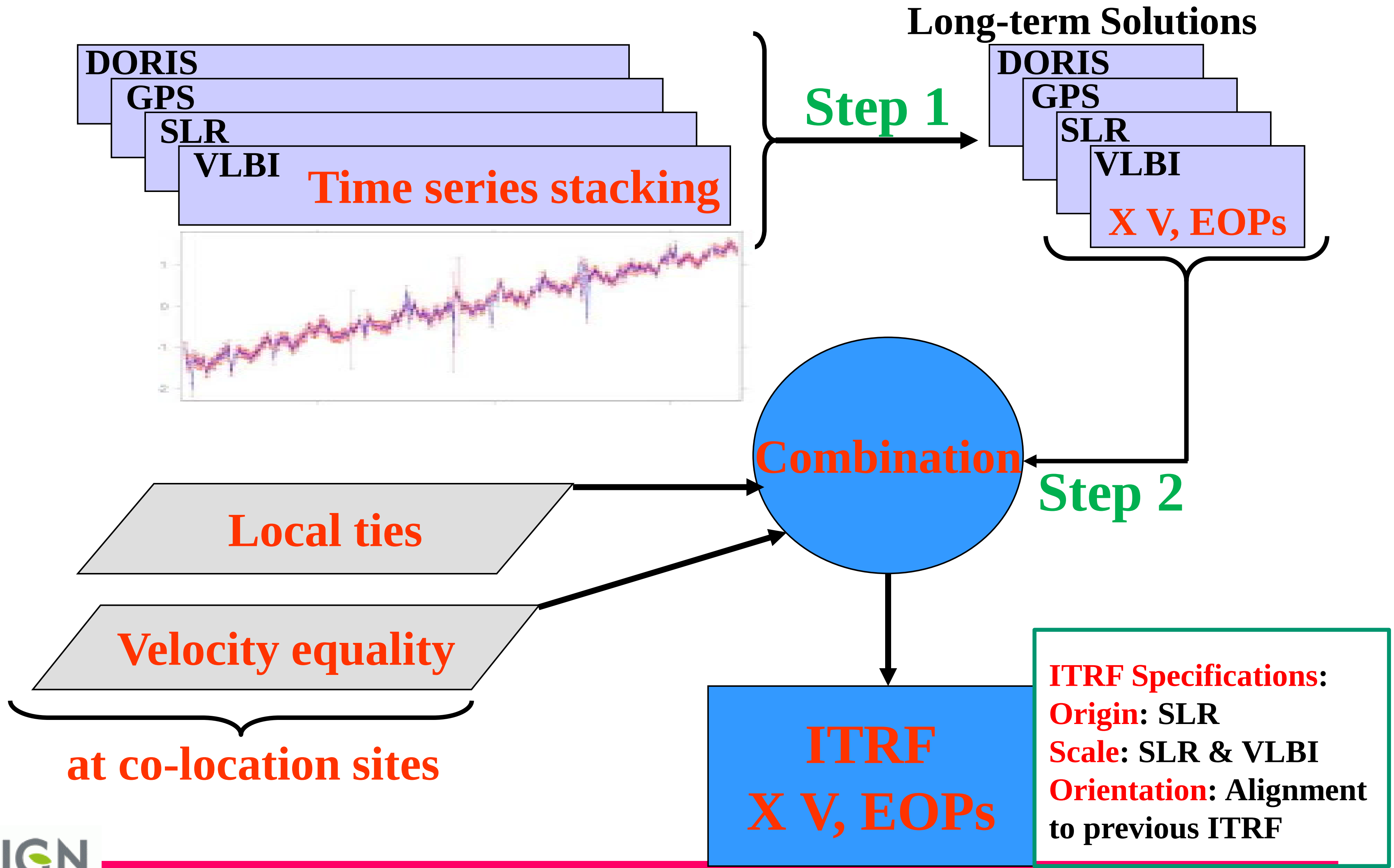
- "Quasi-Instantaneous" Frame: mean station positions at "short" interval: few hours, one day, one week

  ==> Non-linear motion embedded in time series of quasi-instantaneous frames

- Long-Term Secular Frame: mean station positions at a reference epoch (t_0) and station velocities: $X(t_c) = X(t_0) + \dot{X}(t_c - t_0)$ e.g.:
  - ITRF
  - Cumulative GNSS solution expressed in the ITRF

To define a TRF, 14 parameters need to be specified: Origin (6 components), scale (2), orientation (6)

ITRF Construction



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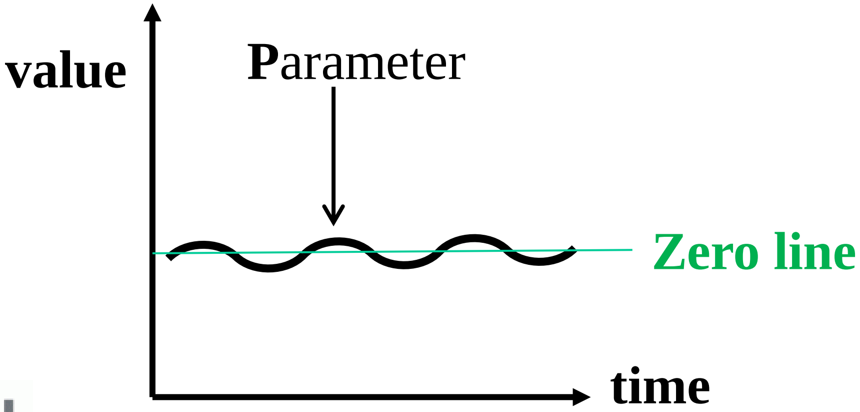
ITRF Combination: Step 1 (1/2)

- **Stacking/accumulating individual time series where the long-term**
  - **origin of SLR and DORIS**

  and
  - **scale of VLBI, SLR and DORIS**

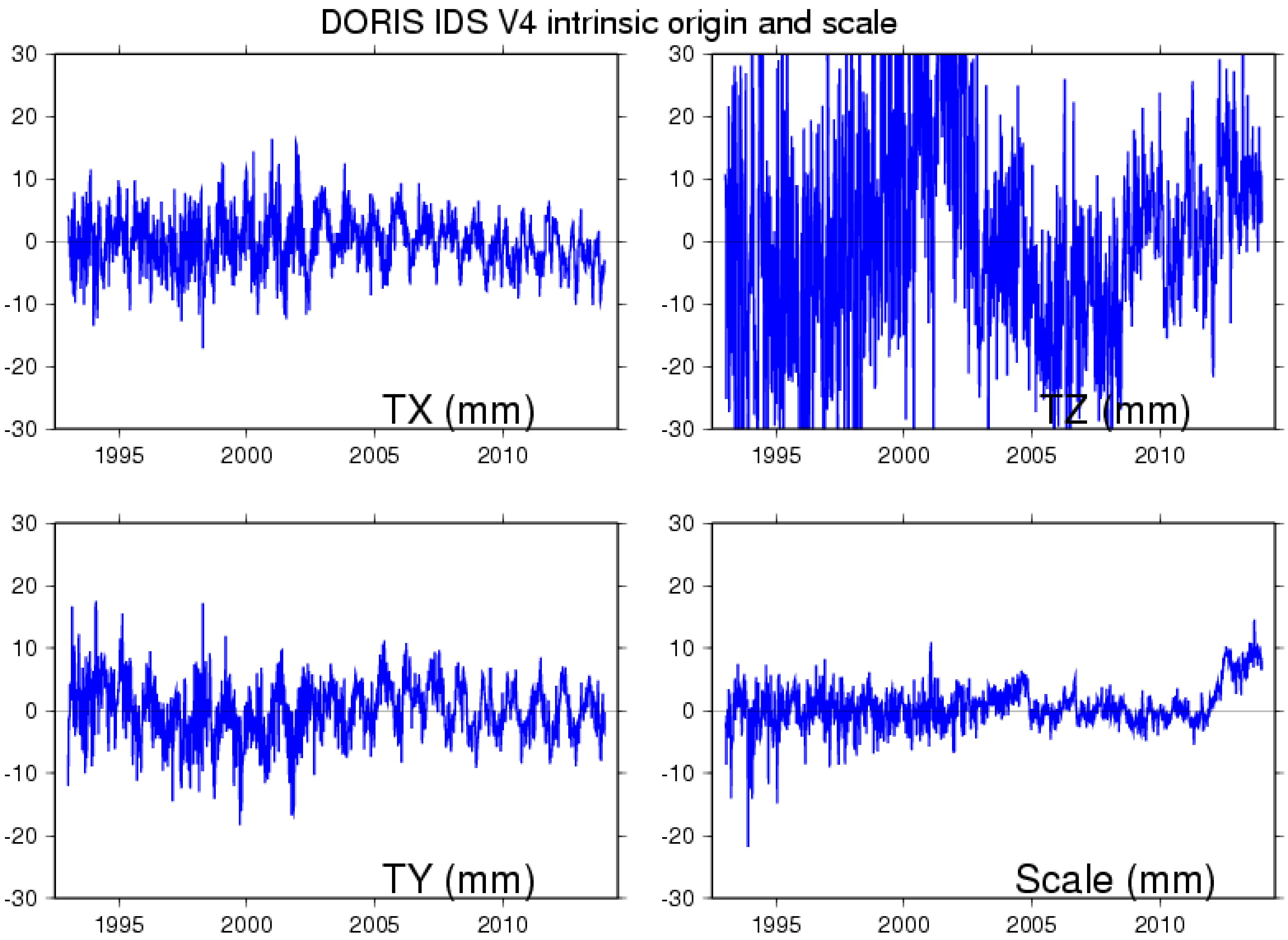
are defined via internal/intrinsic constraints:



$$\begin{cases} \sum_{k \in K} P_k = 0 \\ \sum_{k \in K} (t_k - t_0) P_k = 0 \end{cases}$$

(Altamimi et al., 2007)

DORIS – IDS V4 Intrinsic Origin & Scale

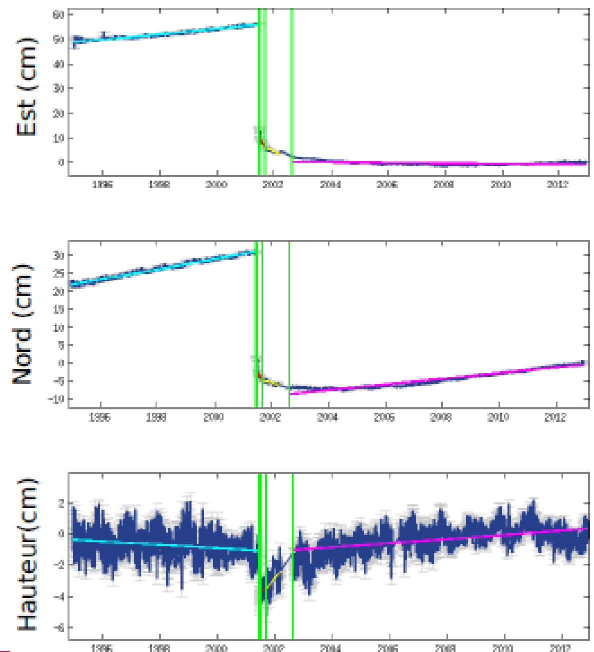


ITRF Combination: Step 1 (2/2)

- **Handling of non-linear station motions:**
  - **Periodic signals: using sinusoidal functions:**

$$\sum \boldsymbol{a} \cos \boldsymbol{\omega t} + \boldsymbol{b} \sin \boldsymbol{\omega t}$$

  - **Post-seismic deformation :**
    - **Piece-Wise Linear (PWL) function**
    - **Parametric models (logarithmic or and/exponential)**



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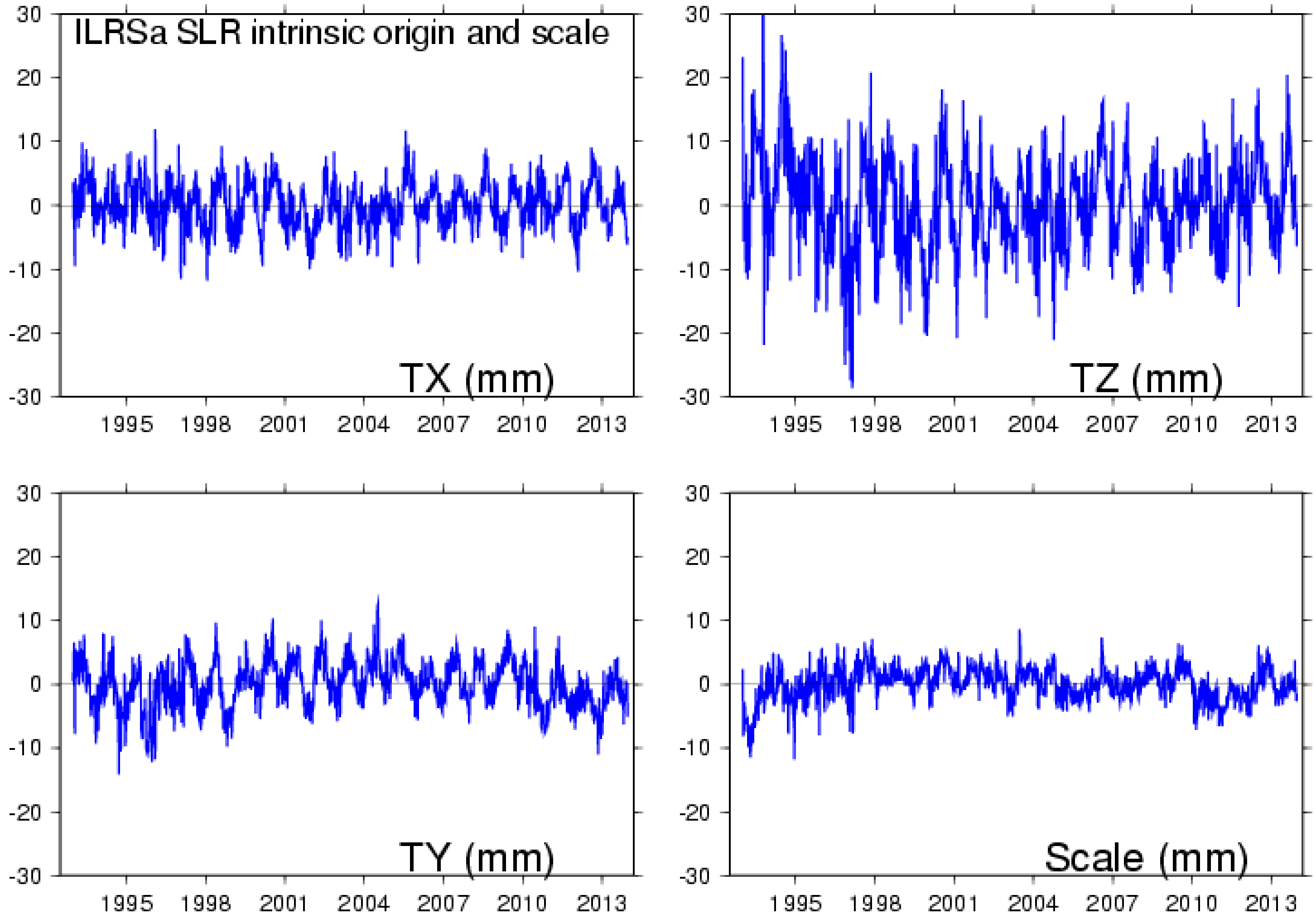
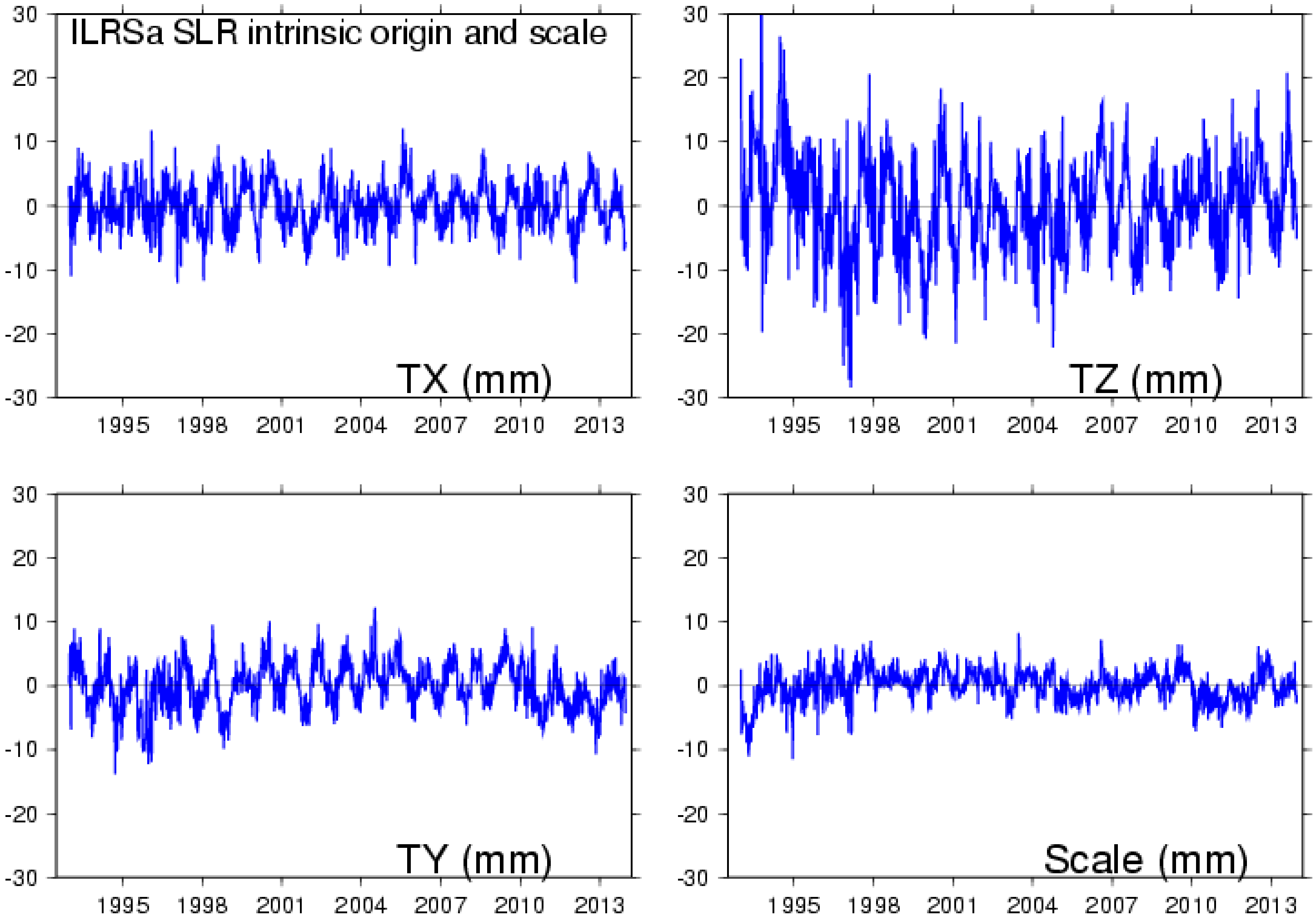
SLR Intrinsic Origin & Scale
PWL model for (Arequipa & Concepcion) EQ sites



SLR Intrinsic Origin & Scale

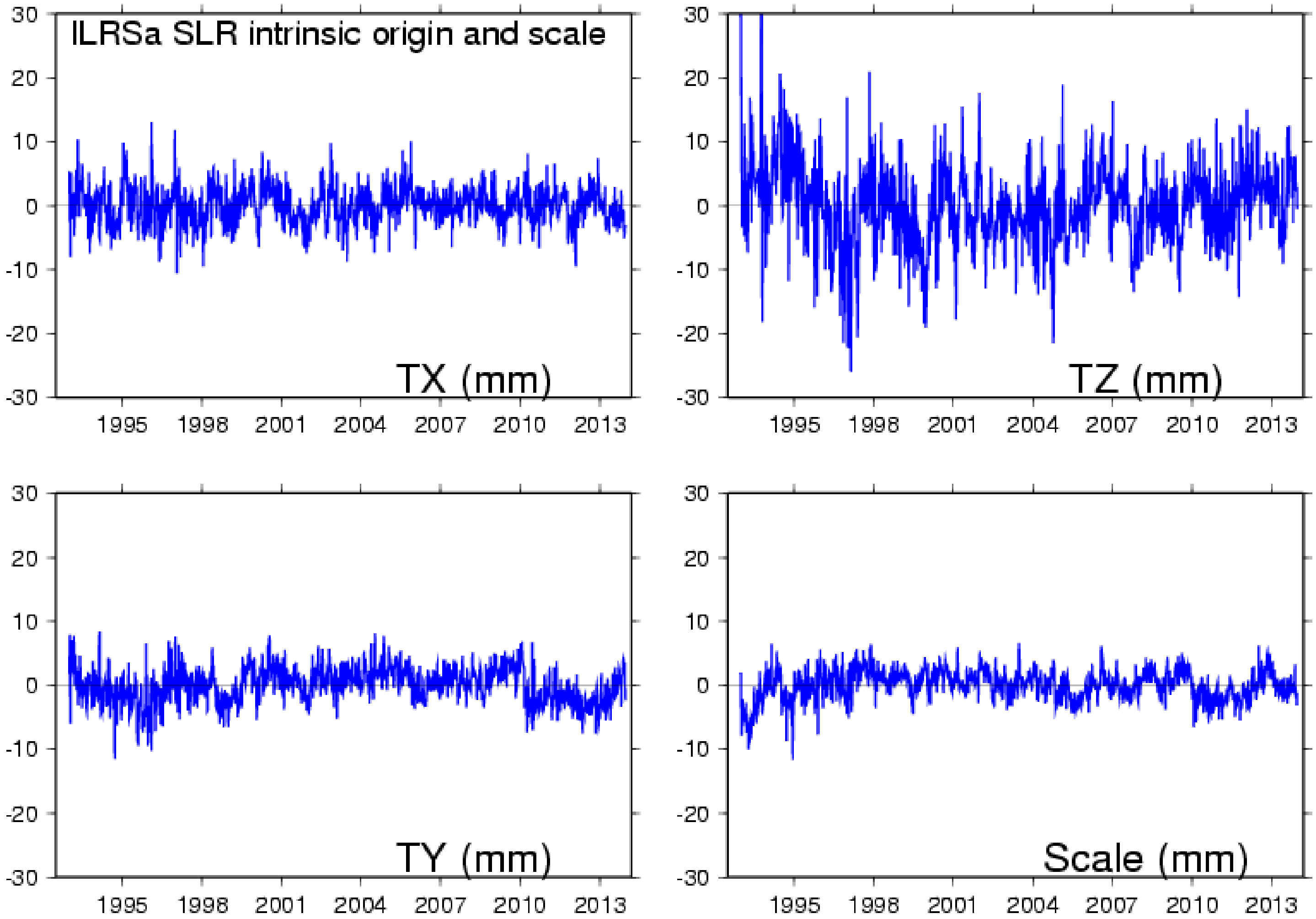
Parametric model applied for Arequipa and Concepcion



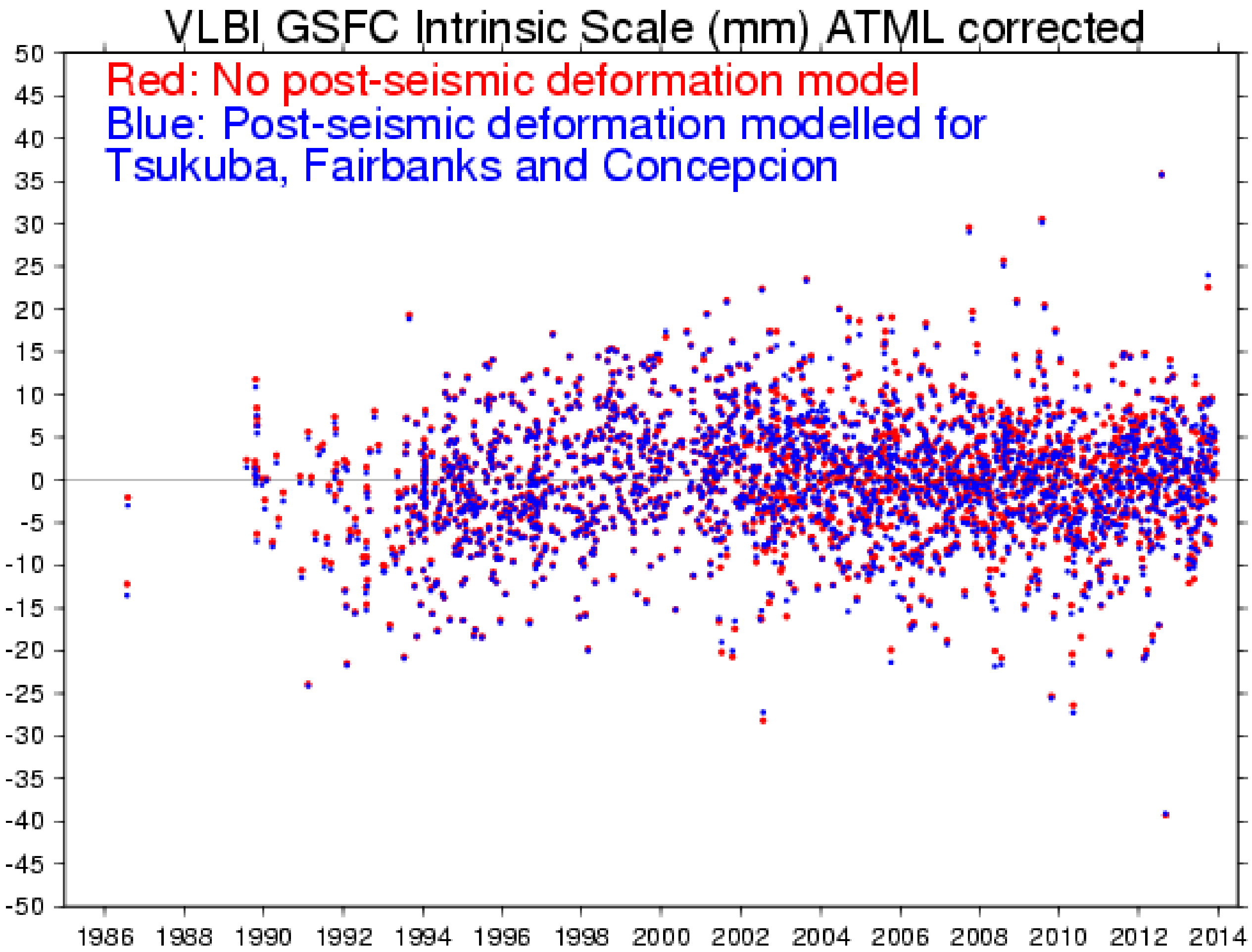
SLR Intrinsic Origin & Scale

Parametric model applied for Arequipa and Concepcion

Annual and semi-annual signals removed



VLBI/GSFC2011b Intrinsic Scale



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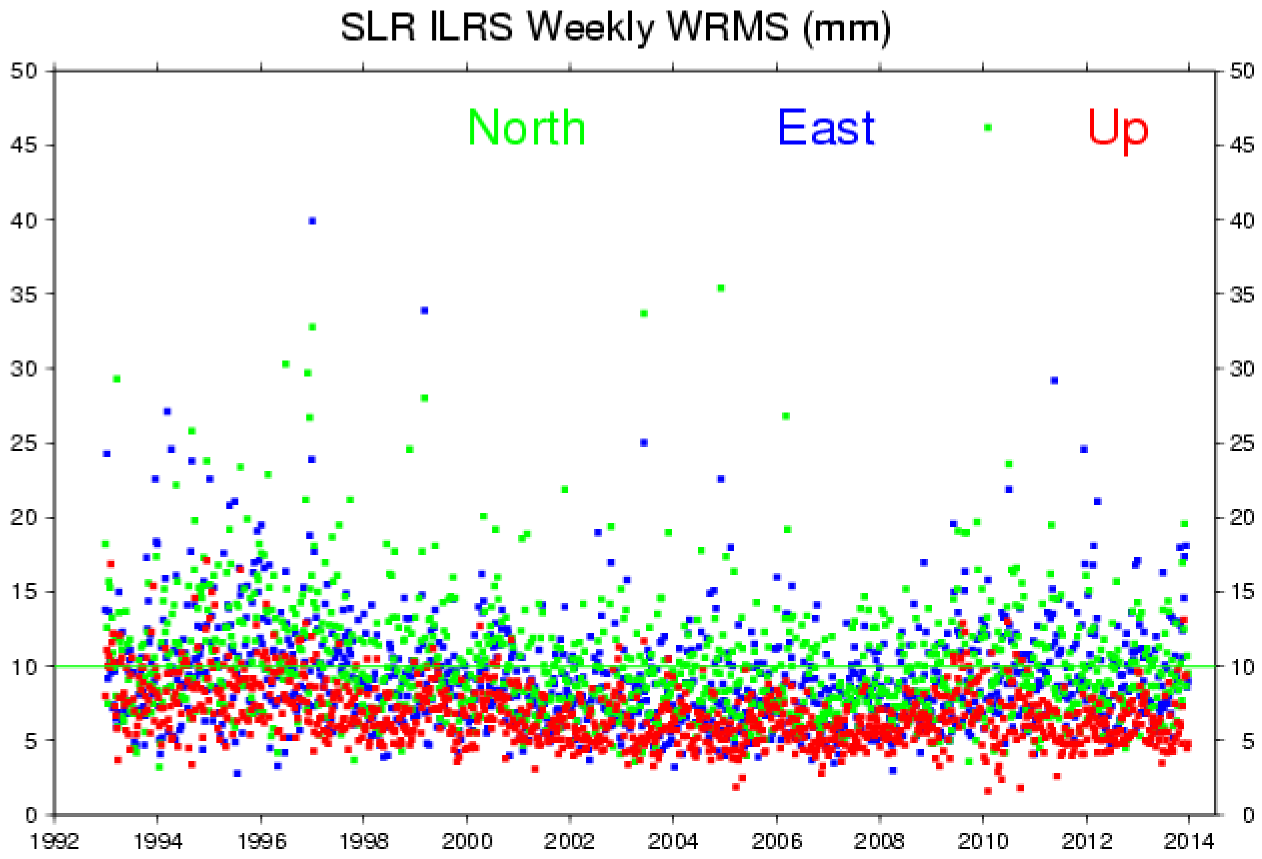
SLR WRMS
PWL model for (Arequipa & Concepcion) EQ sites



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SLR WRMS

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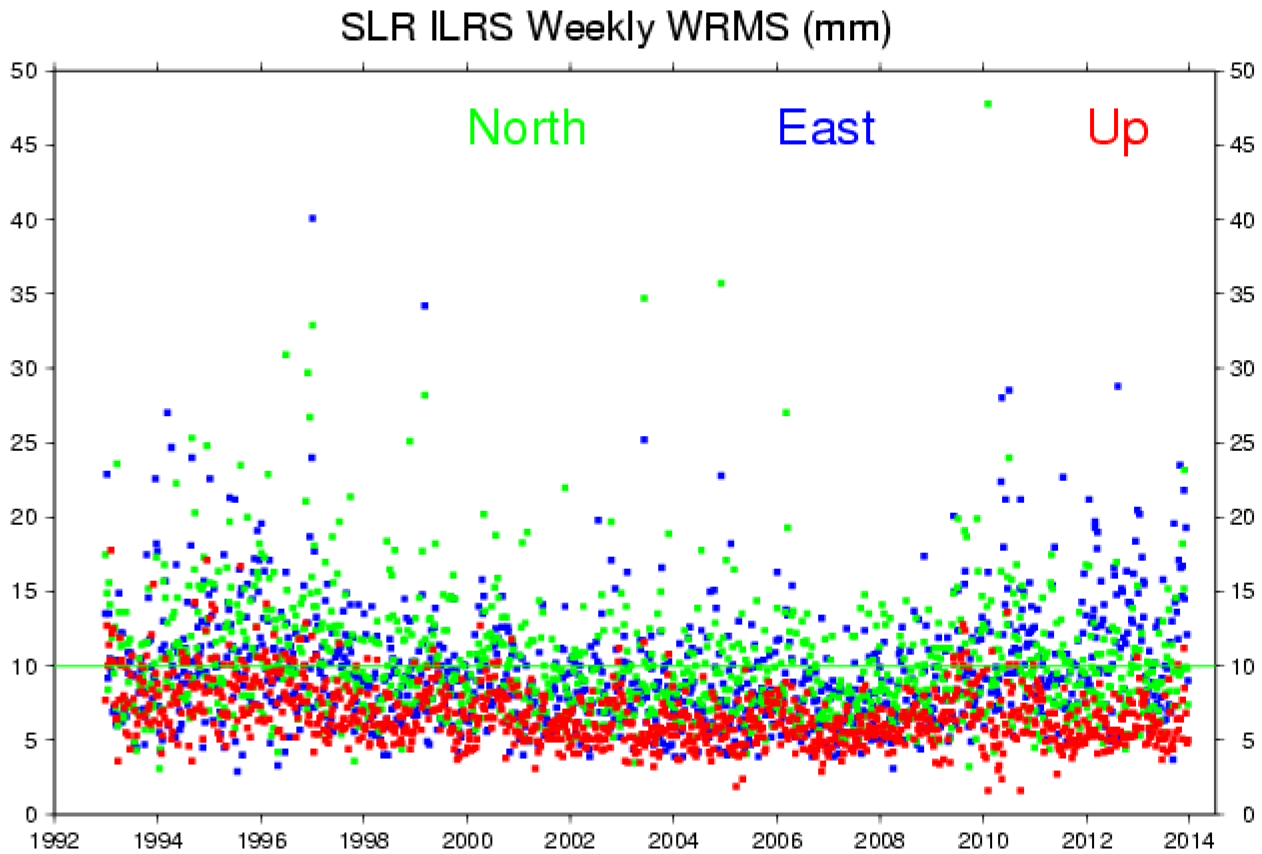
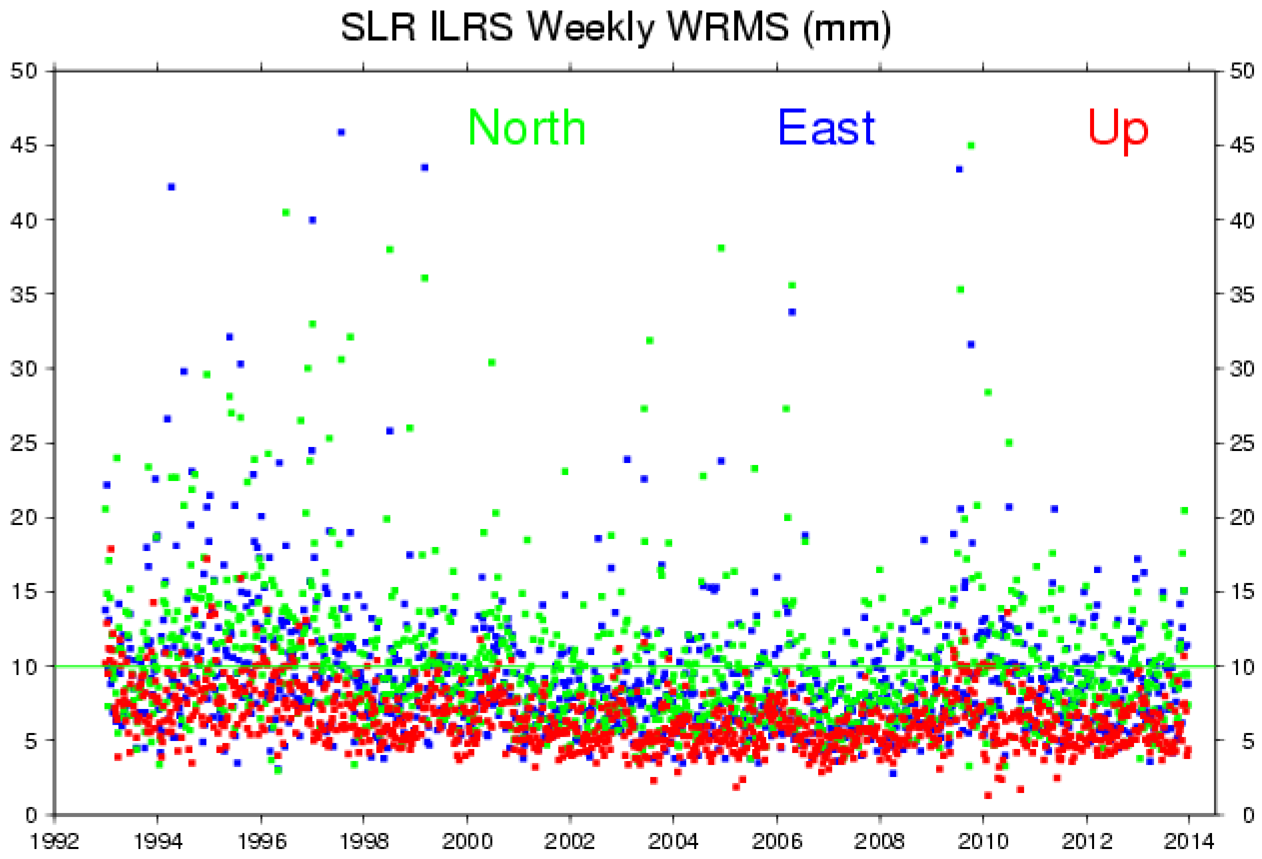


SLR WRMS

Parametric model applied for Arequipa and Concepcion
Annual and semi-annual signals removed



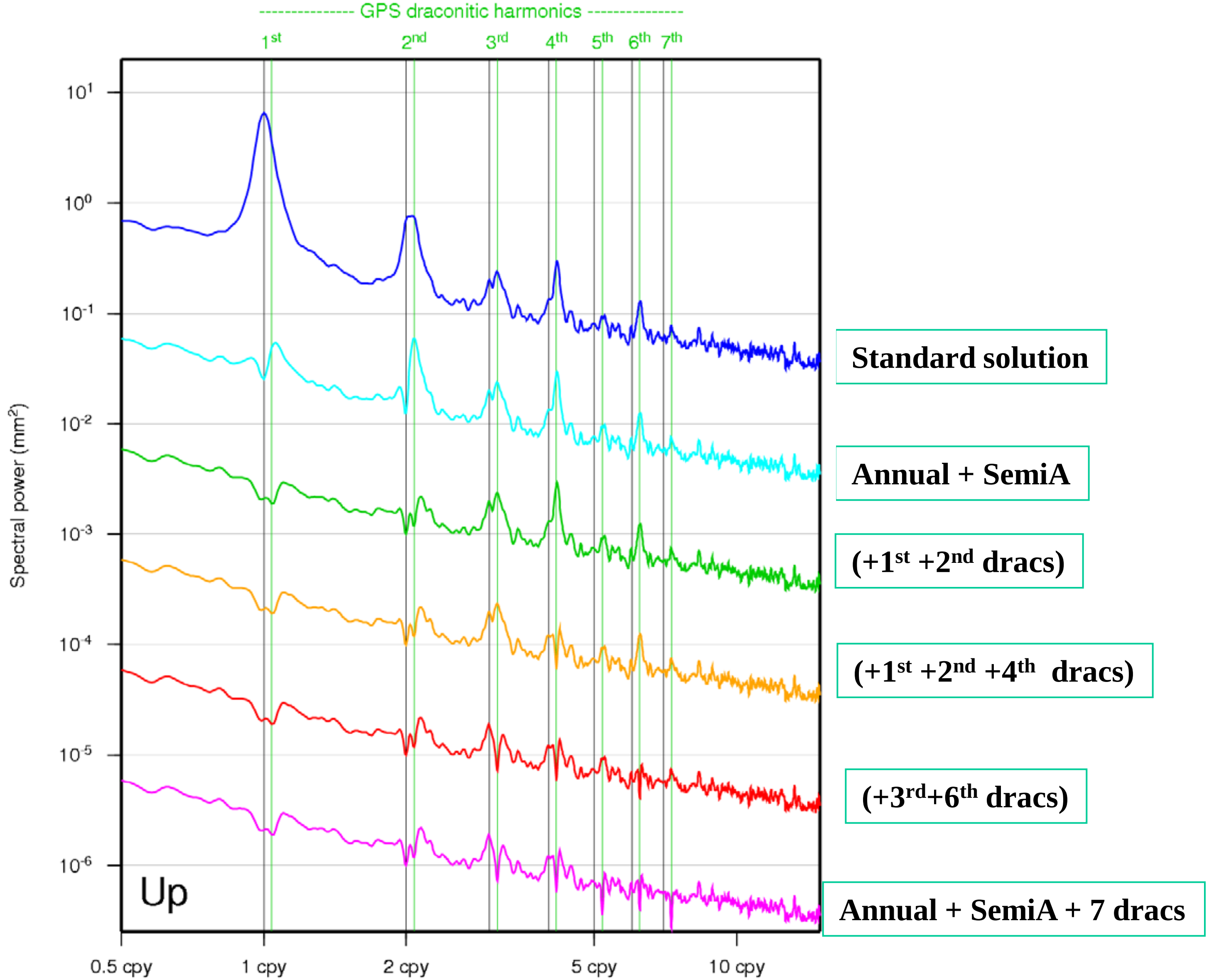
Preparation for ITRF2013

- **What's new ?**
  - Reprocessed solutions from the 4 techniques
  - Improving the process of detection of discontinuities in the time series

  - Applying NT-ATML (+) corrections to ITRF2013 input data

  - Periodic signals (at least annual & semi-annual):
  - Co- & Post-seismic deformation (parametric models will be applied)

IGS station position Up residuals: stacked periodogram



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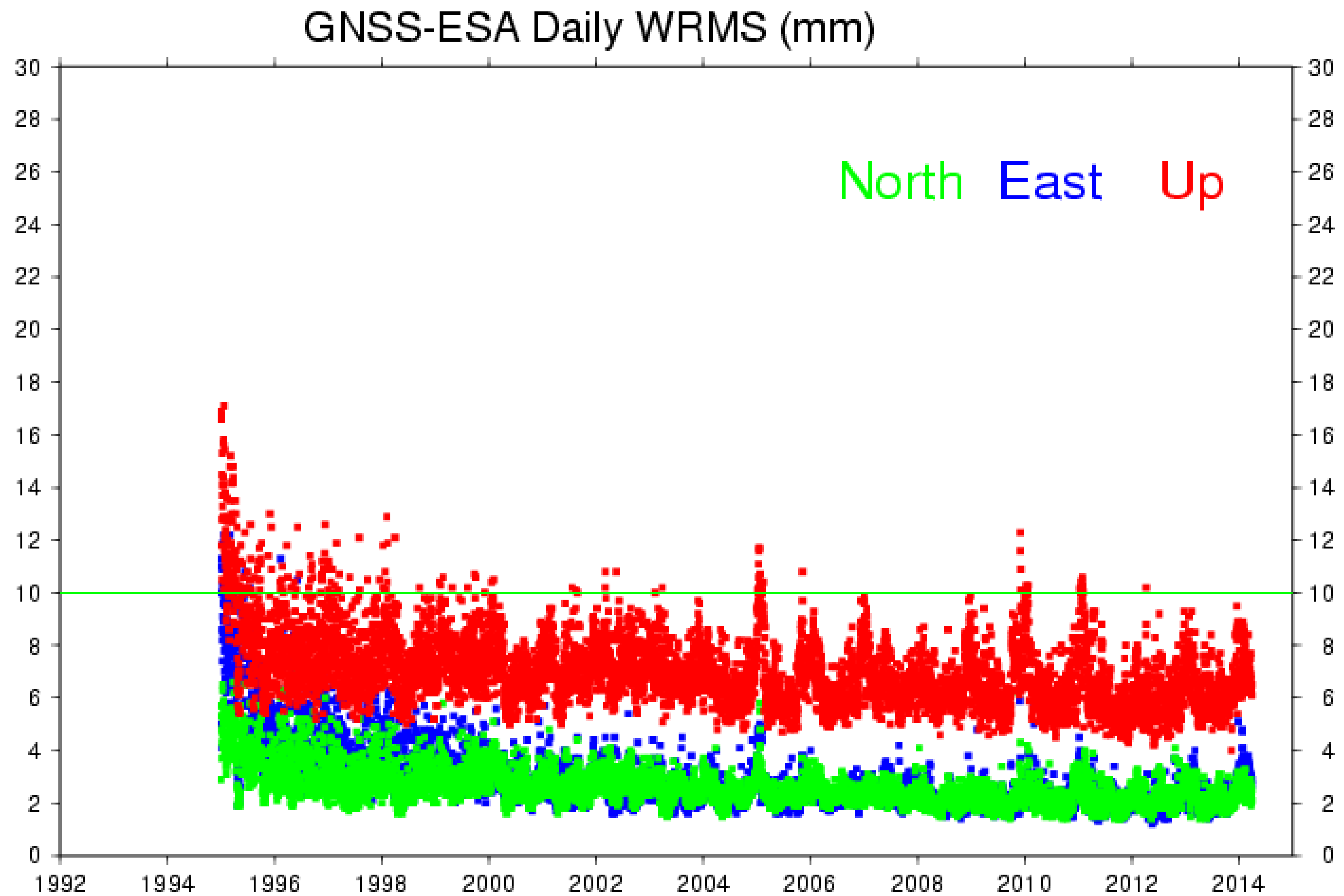
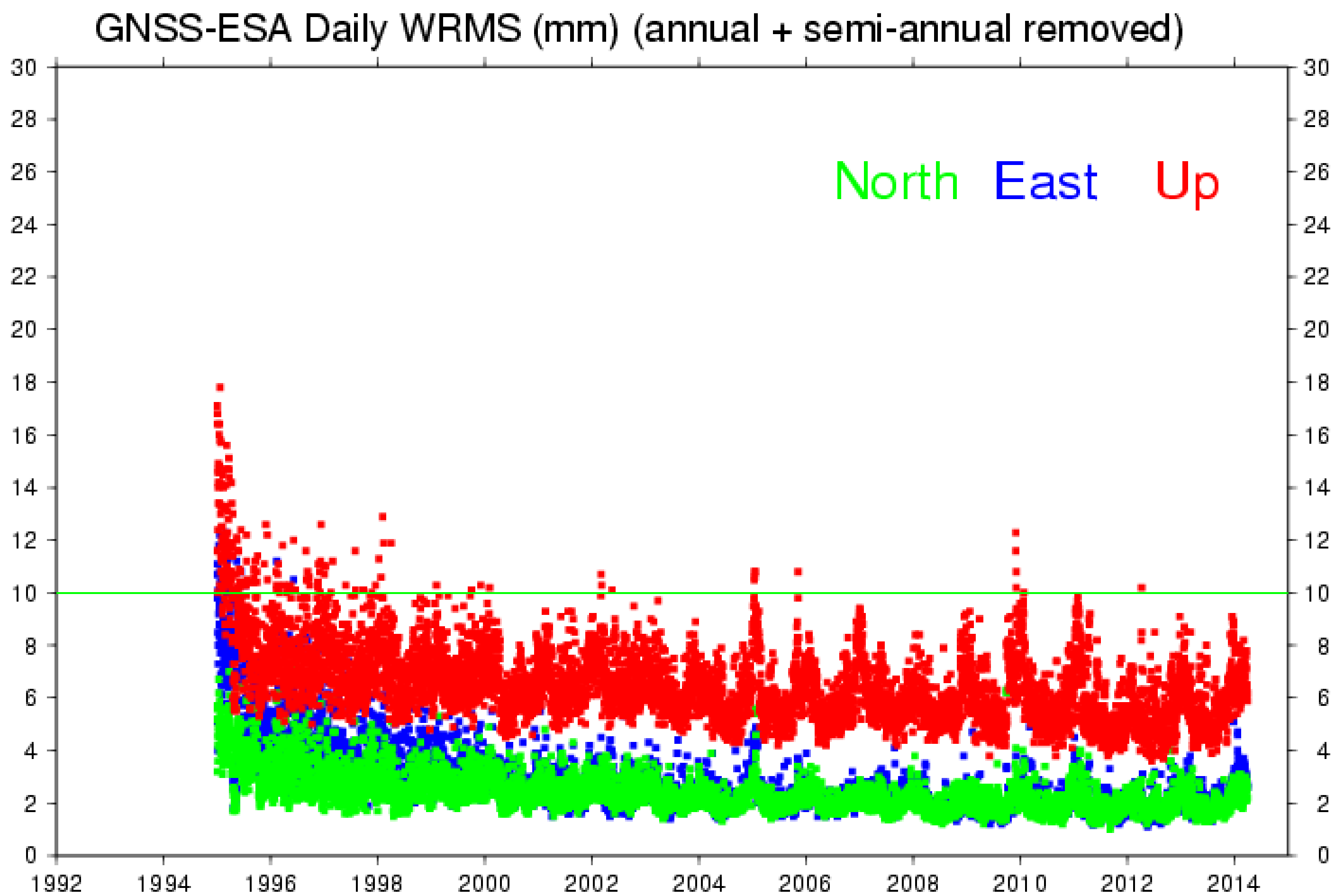
ESA Repro2 daily WRMS



ESA Repro2 daily WRMS (Ann+semi-Ann signals removed)



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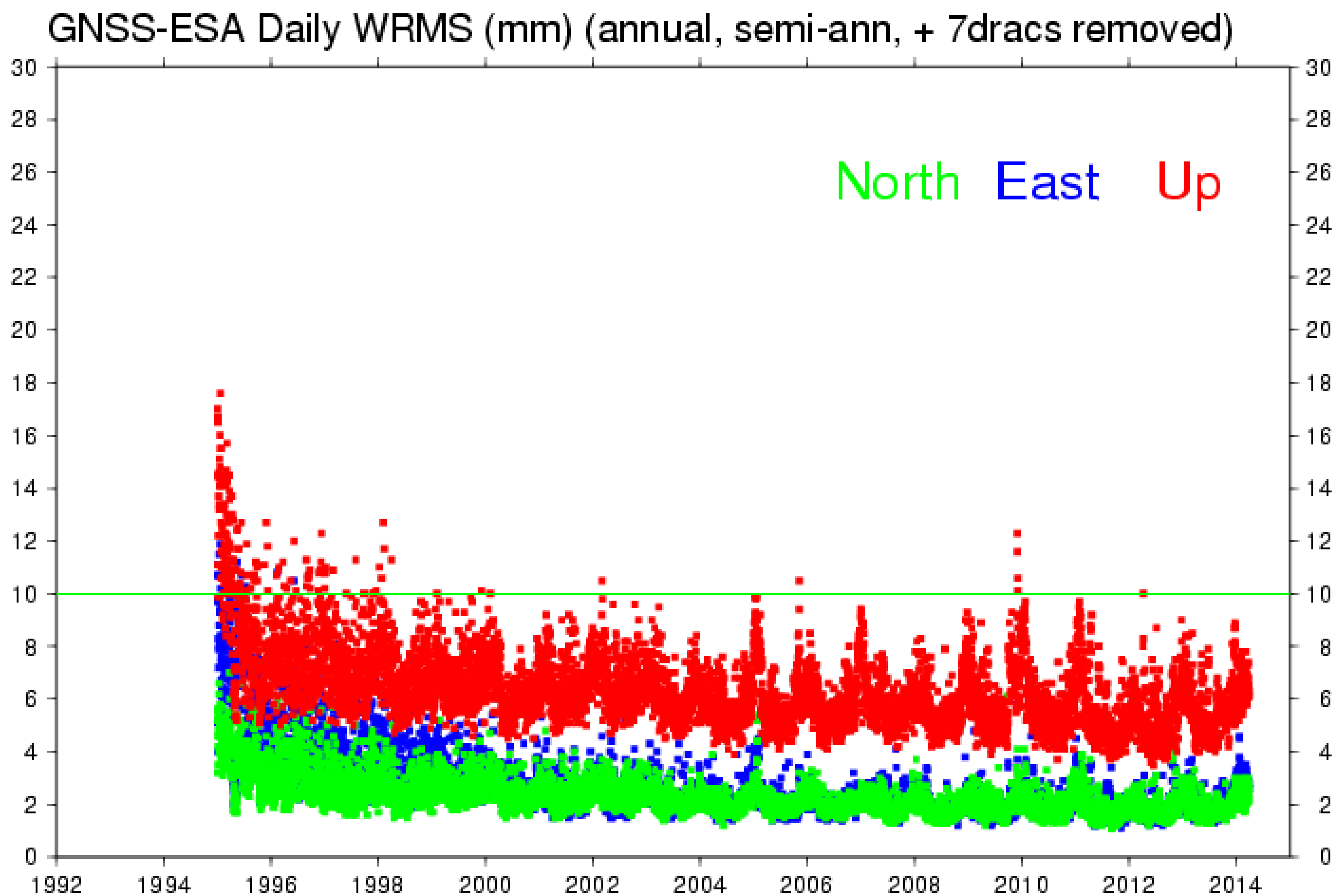
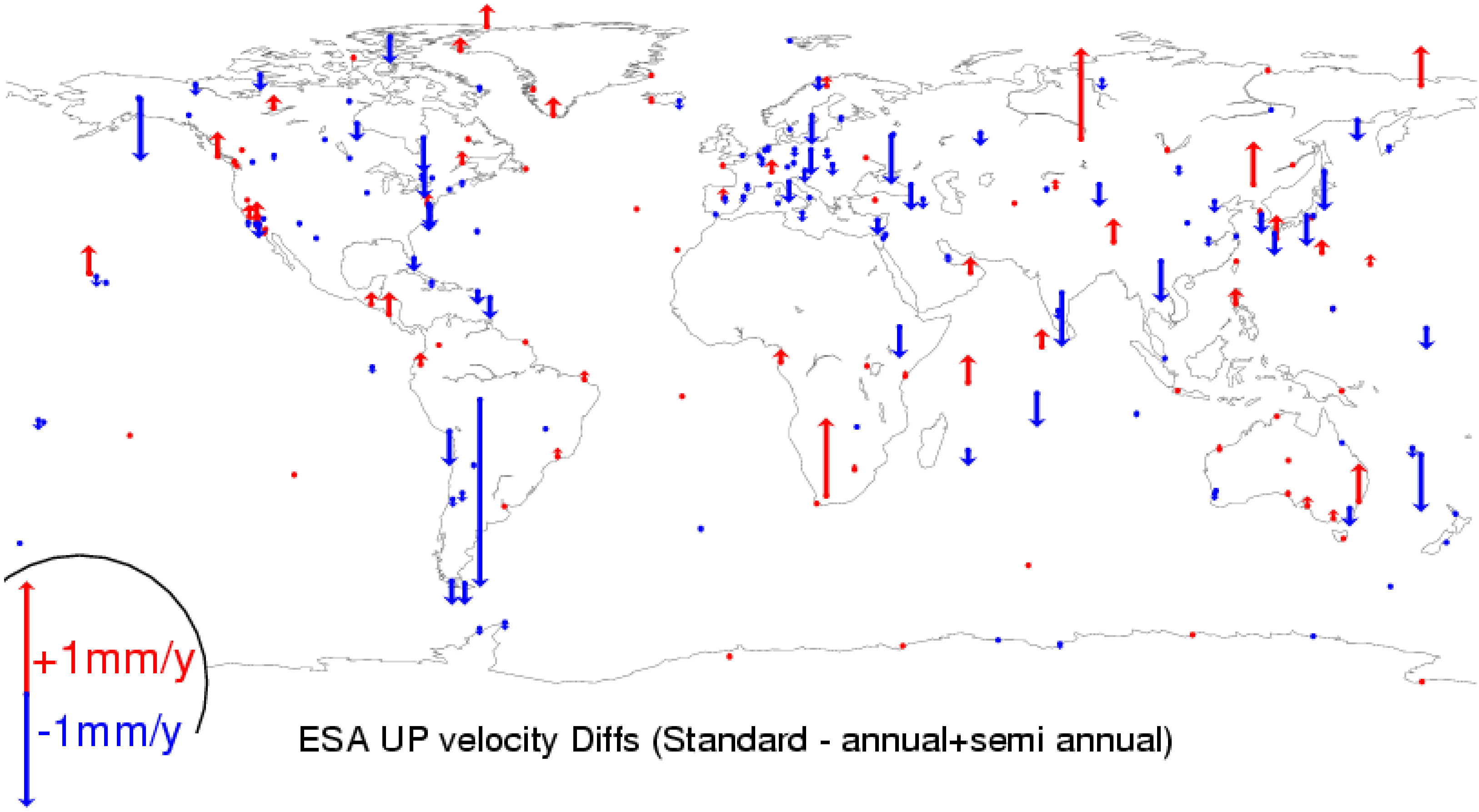
ESA Repro2 daily WRMS
(Ann+semi-Ann + 7 dracs removed)



ESA GNSS Repro 2 Vertical velocity differences (Standard – Annual+Semi-Annual)



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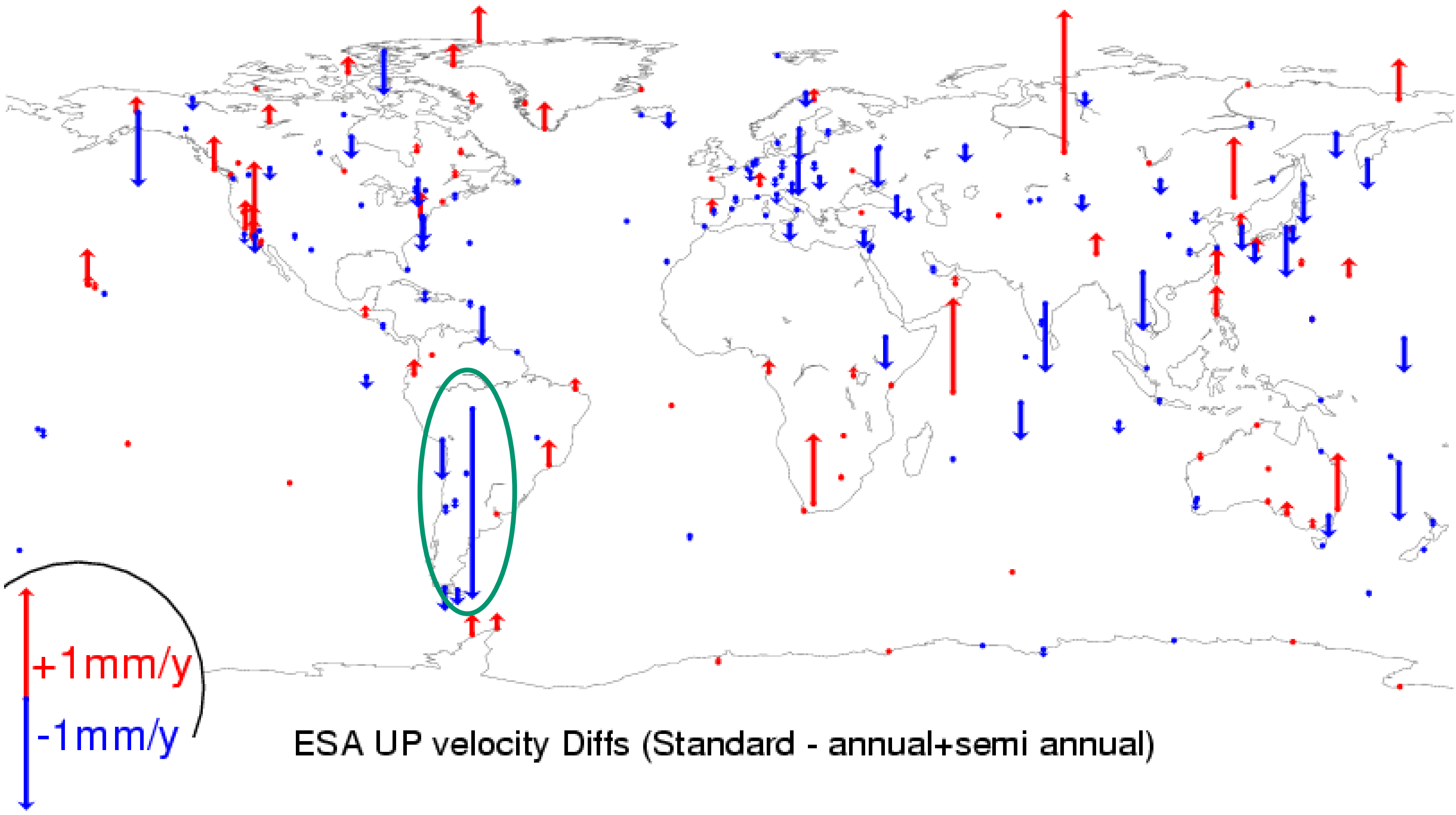
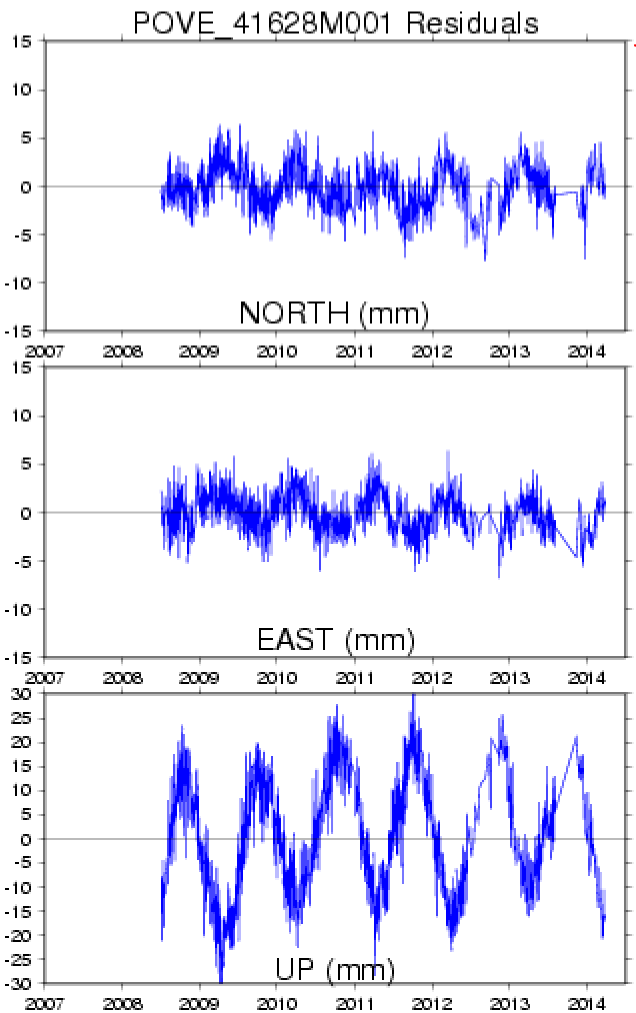
ESA GNSS Repro 2 Vertical velocity differences (Standard – Annual+Semi-Annual + 7 dracs)



Position Residuals of Porto Velho, Brazil

Standard Solution

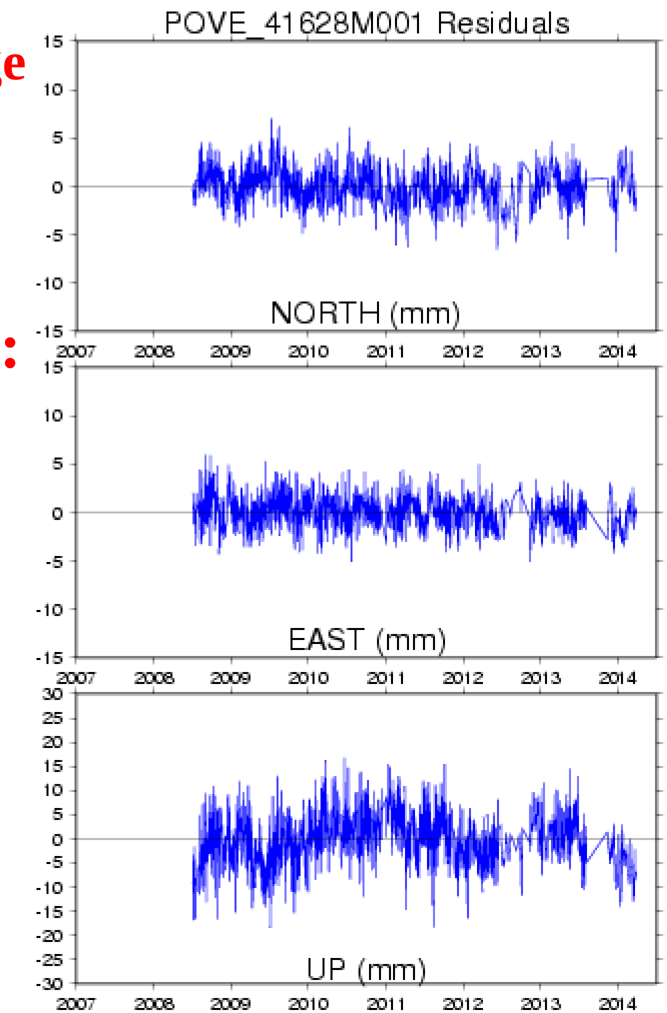


Velocity change

Horizontal: 0.2 mm/yr

Vertical: 1.7 (±0.15) mm/yr

Ann+semi-ann removed



Modeling post-seismic deformations

- **Up to ITRF2008:**
  - Piece-wise linear (PWL) function

- **For ITRF2013, parametric models:**
  - Logarithmic
  - Exponential
  - Logarithmic + Exponential
  - Two Exponential functions

Parametric post seismic models

Parametric models for postseismic displacements :

$\forall i \in \{E, N, U\}, X_i(t) =$

$$\begin{cases} X_1(t_0) + V_1 \times (t - t_0) & , \quad t < t_{eq} \\ X_2(t_{eq}) + V_2 \times (t - t_{eq}) + D(t - t_{eq}), & t > t_{eq} \end{cases}$$

Parametric postseismic models use logarithmic or exponential functions :

$D(t - t_{eqk})$ with

$$D(t - t_{eqk}) = A \; log(1 + \frac{t - t_{eqk}}{\tau}) \tag{1}$$

or

$$D(t - t_{eqk}) = A \; (1 - e^{-\frac{t - t_{eqk}}{\tau}}) \tag{2}$$

[e.g. : Kreemer et al., 2006]

or

$$D(t - t_{eqk}) = A_1 \; log(1 + \frac{t - t_{eqk}}{\tau_1}) + A_2 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_2}}) \tag{3}$$

or

$$D(t - t_{eqk}) = A_1 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_1}}) + A_2 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_2}}) \tag{4}$$

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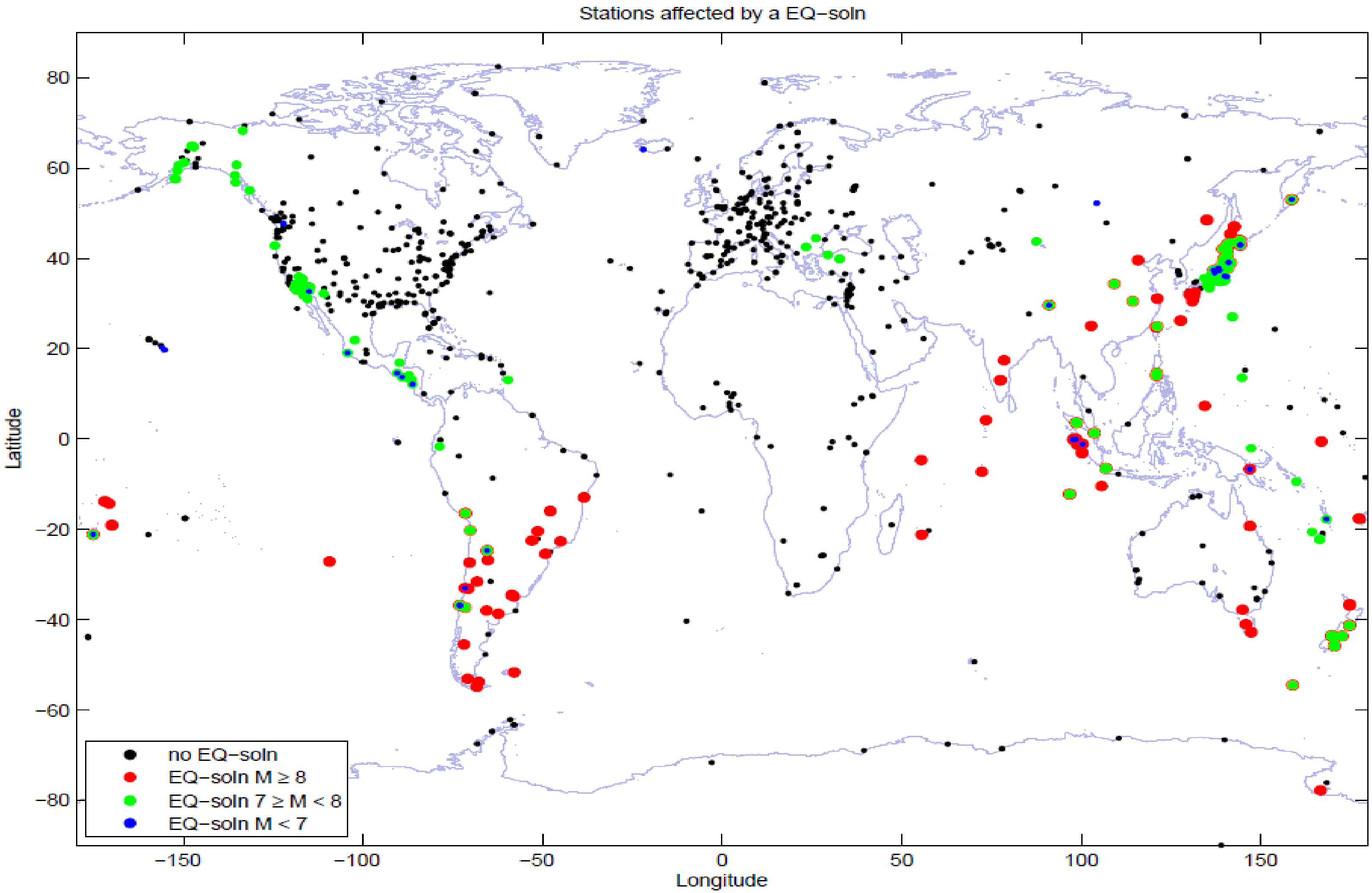
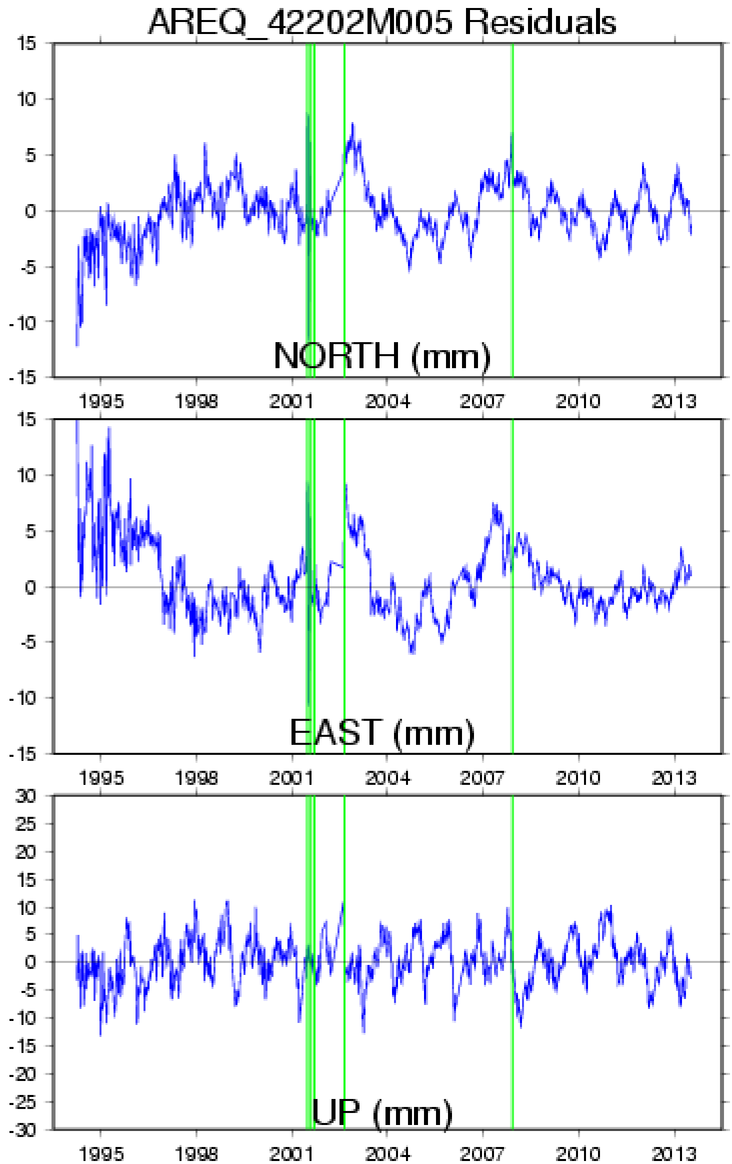
Sites affected by EQ discontinuities



(Métivier et al., 2014 under review)

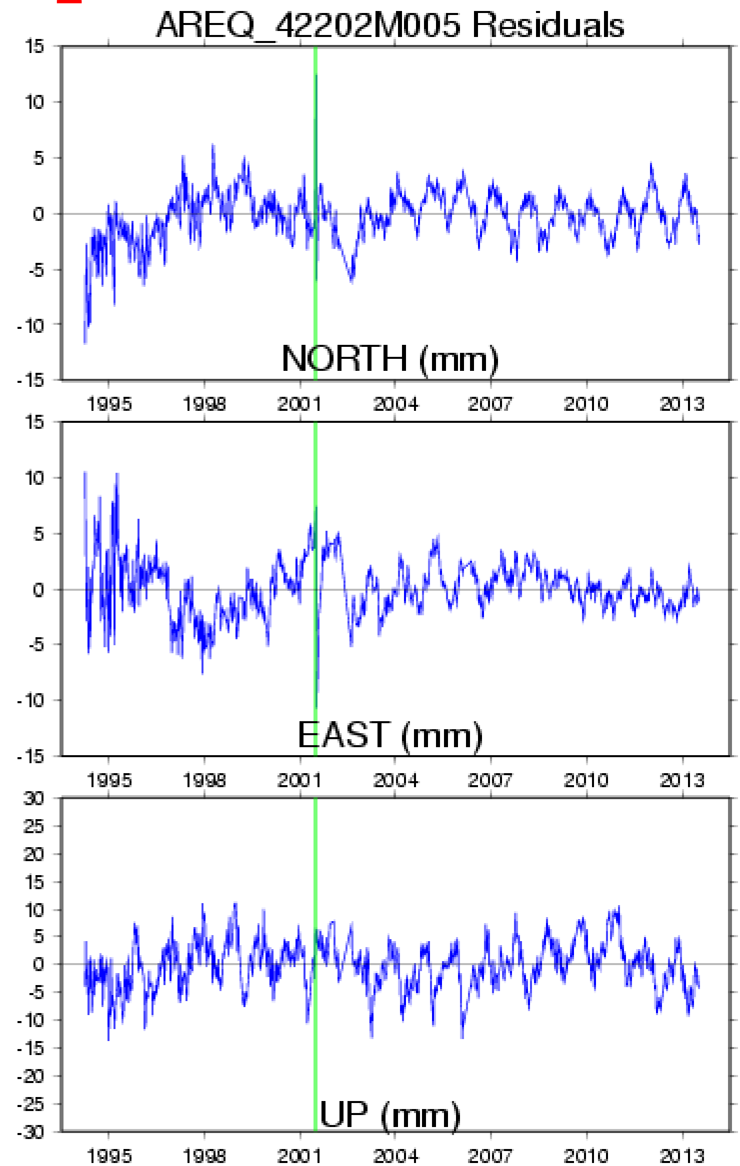
Arequipa

Linear Function



Multiple velocities estimated

Parametric Model



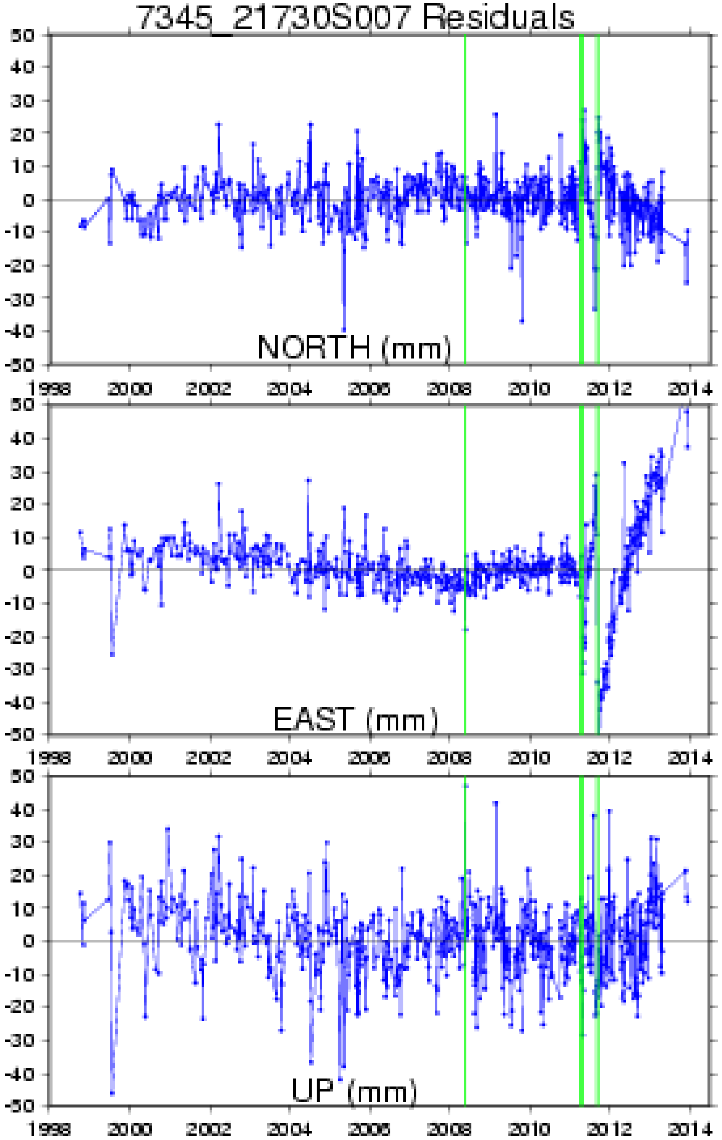
One velocity estimated

Post-fit residuals

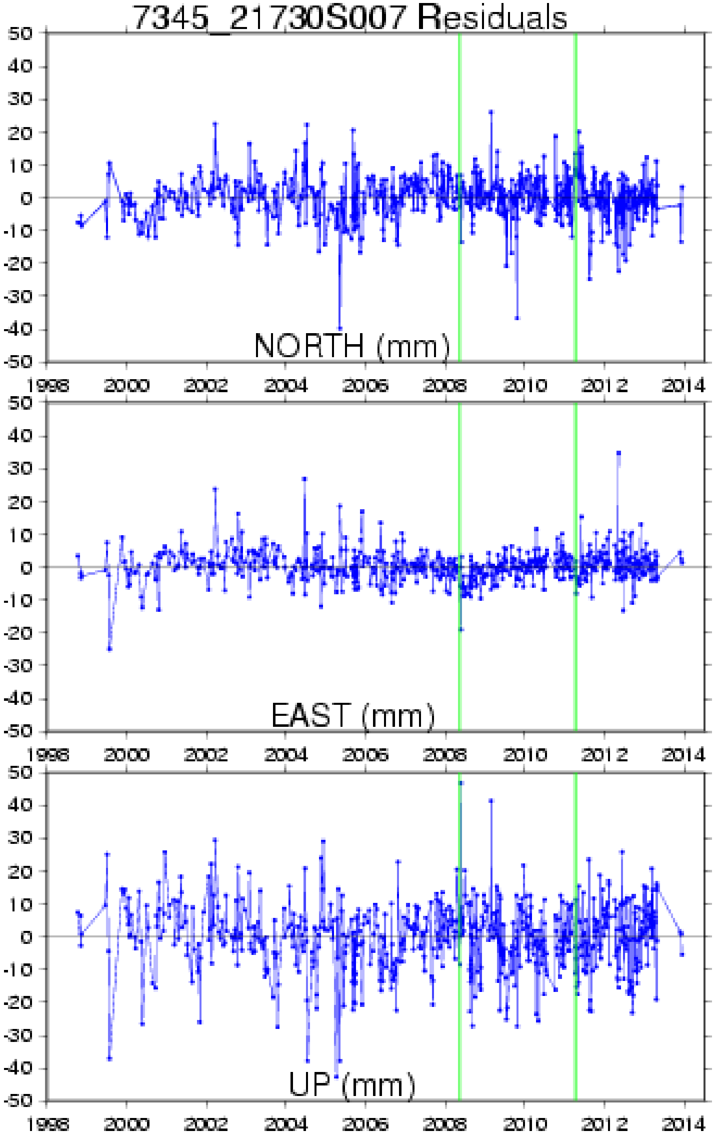
Lercier et al., 2014, submitted

Linear Function **Tsukuba VLBI** Parametric Model

Multiple velocities estimated



Post-fit residuals



One velocity estimated

Lercier et al., 2014, submitted

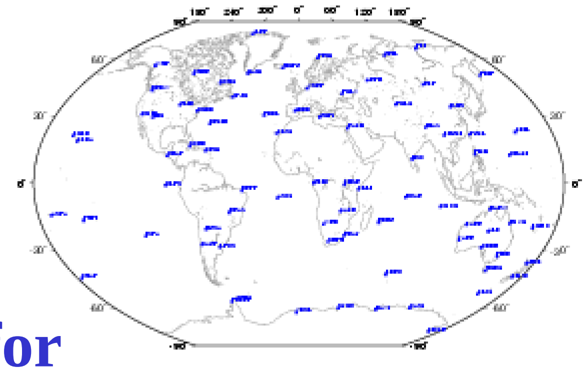
Example of GNSS cumulative solution

- **Data: IGS station position time series (1994-2013)**
- **Two cumulative solutions where EQ sites are modelled using:**
  - **PWL model**
  - **Parametric (Log or/and Exp) models for 11 EQ sites**
  - **Both cumulative solutions are expressed in ITRF2008 using minimum constraints over 80 reference sites**

$$(A^T A)^{-1} A^T (X_R - X_c) = 0$$

ITRF (X_R)

Cumulative Solution (X_c)

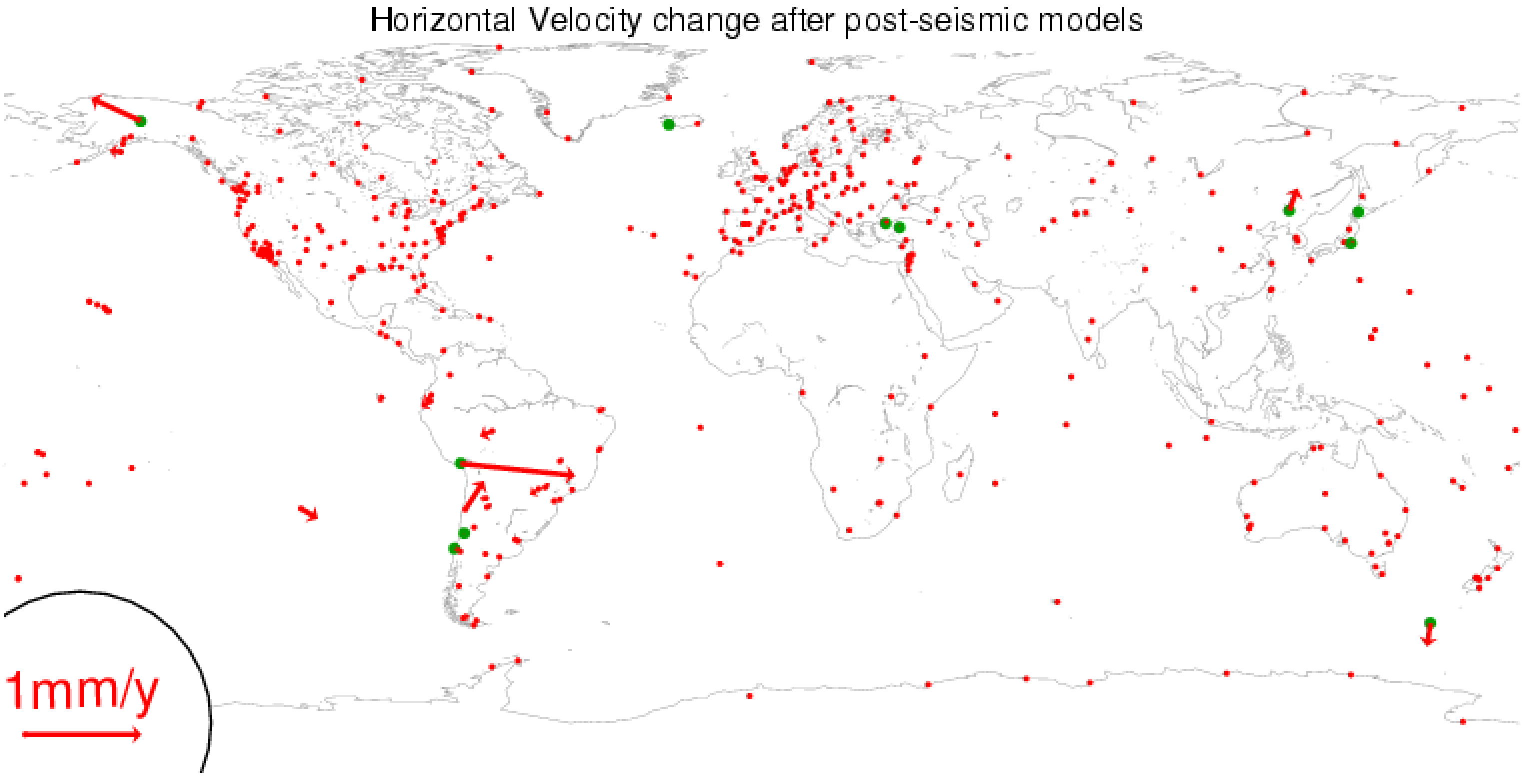


==> Same origin, scale & orientation for both cumulative solutions

Horizontal Velocity changes

After post-seismic models for (shown in green):

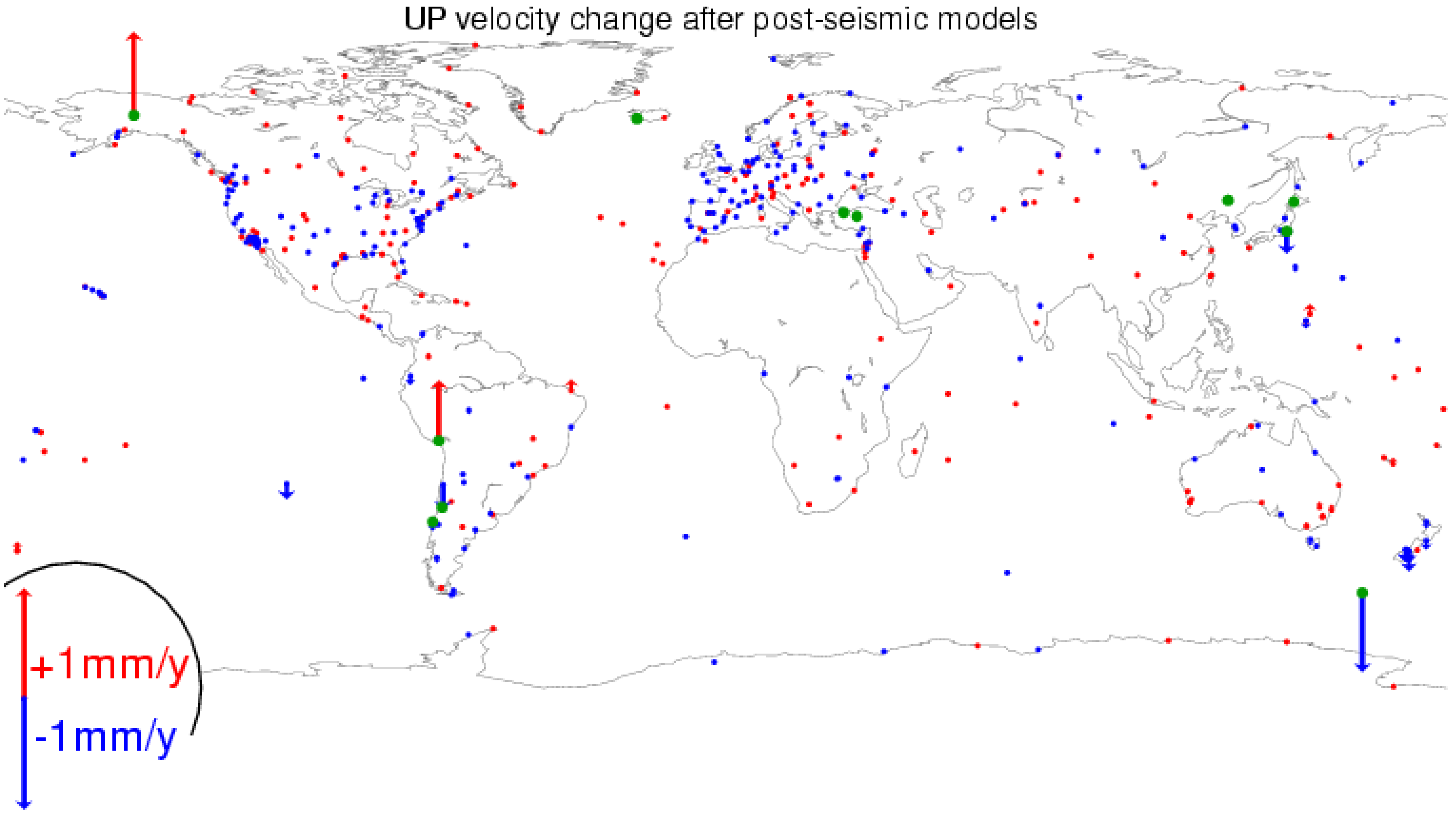
AREQ
TSKB
STK2
CHAN
FAIR
CONZ
SANT
ANKR
TUBI
RYEZ
MAC1



Vertical Velocity changes

After post-seismic models for (shown in green):

AREQ
TSKB
STK2
CHAN
FAIR
CONZ
SANT
ANKR
TUBI
RYEZ
MAC1



Conclusion

- Impact of station non-linear motions on the ITRF or a cumulative solution expressed in the ITRF:
  - No impact on the RF defining parameters (origin, scale & orientation)
  - Pos&Vel changes for EQ sites after the events
  - Velocity changes (up to 1 mm/yr) for some sites when removing periodic signals
  - We should be able to precisely define the frame in such a way that Earthquakes & periodic signals have little to no impact on its defining parameters

- ITRF2013: Estimation of
  - Periodic signals ==> more precise velocities
  - Post-seismic deformation using parametric models for major EQ sites.