Fondement des Conventions IERS

Systèmes de Référence Terrestres

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Of the……………..

Key Points

- Summary of Chapter 4 of the IERS Conventions: Terrestrial reference systems and frames
- Reference frame definition and the concept of minimum constraints
- ITRF/CATREF combination model & the rank deficiency problem
- Current status
  - ITRF2014: Modelling of nonlinear motions:
  - Annual and semi-annual signals
  - Post-seismic deformation (PSD)

- ITRF brief history in the context of the 30th anniversary of the IERS
- ITRF network and accuracy evolution
- Future plan: preparation for ITRF2020
  - Mitigation of technique systematic errors
  - Periodic signals: utility, impact and user need
  - Geocenter motion uncertainty?

Chapter 4 of the IERS Conventions

- Basic Concepts: Definition of TRS and TRF
- TRS: is a spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points attached to the solid surface of the Earth have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations)– See next two slides –
- TRF: is de defined as the realization of a TRS, through the realization of its origin, orientation axes and scale, and their time evolution. It is achieved by a set of physical points with precisely determined coordinates in a specificc coordinate system as a realization of a TRS.
- Concept of minimum constraints
- ITRS & ITRF definition/description

Defining a Reference System & Frame:

Three main conceptual levels :

- **Ideal Terrestrial Reference System (TRS):**
  Ideal, mathematical, theoretical system
- **Terrestrial Reference Frame (TRF):**
  Numerical realization of the TRS to which users have access
- **Coordinate System: cartesian (X,Y,Z), geographic (λ, ϕ, h), …**
  - **The TRF is a materialization of the TRS inheriting the mathematical properties of the TRS**
  - **As the TRS, the TRF has an origin, scale & orientation**
  - **TRF is constructed using space geodesy observations**

Terrestrial Reference System

A tridimensional reference frame (mathematical sense)
Defined in an Euclidian affine space of dimension 3:

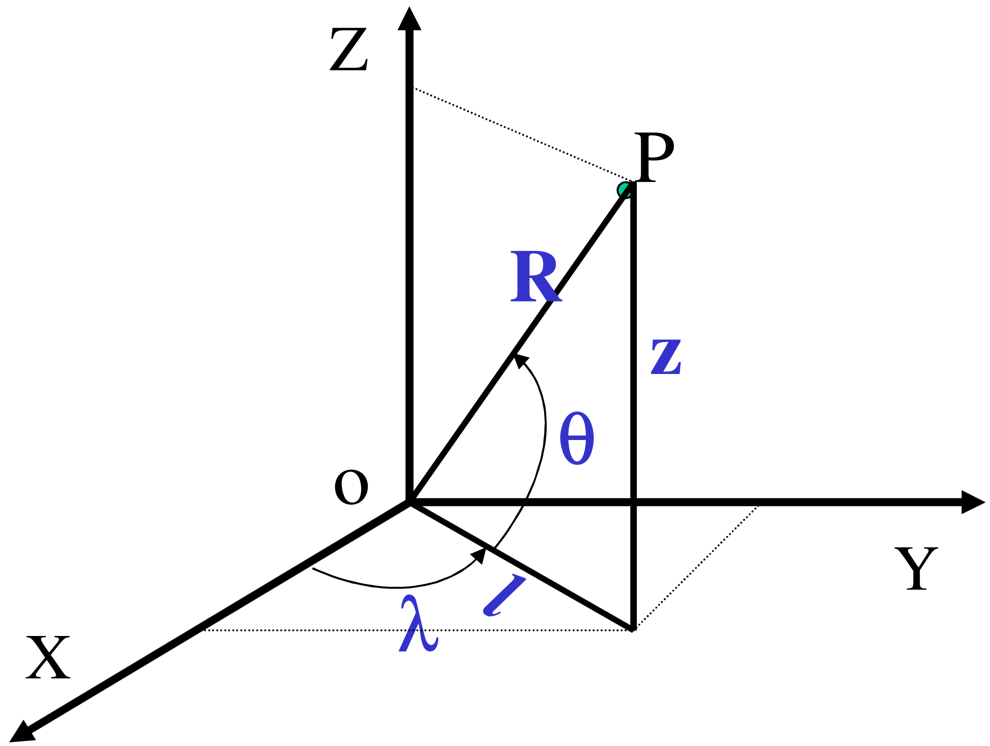
Affine Frame (O,E) where

O: point in space (**Origin**)
E: vector base: orthogonal with the same length:
- vectors co-linear to the base (**Orientation**)
- unit of length (**Scale**)

$$\lambda = \left\|\vec{E}\right\|_{i=1,2,3} \qquad \vec{E}_i . \vec{E}_j = \lambda^2 \delta_{ij} \qquad (\delta_{ij} = 1, \quad i = j)$$

Coordinate Systems

- Cartesian: X, Y, Z
- Ellipsoidal: λ, φ, h
- Mapping: E, N, h
- Spherical: R, θ, λ
- Cylindrical: l, λ, Z



$$OP \left| \begin{array}{l} l\cos\lambda \\ l\sin\lambda \\ z \end{array} \right.$$

Cylindrical

$$OP \left| \begin{array}{l} R\cos\theta\cos\lambda \\ R\cos\theta\sin\lambda \\ R\sin\theta \end{array} \right.$$

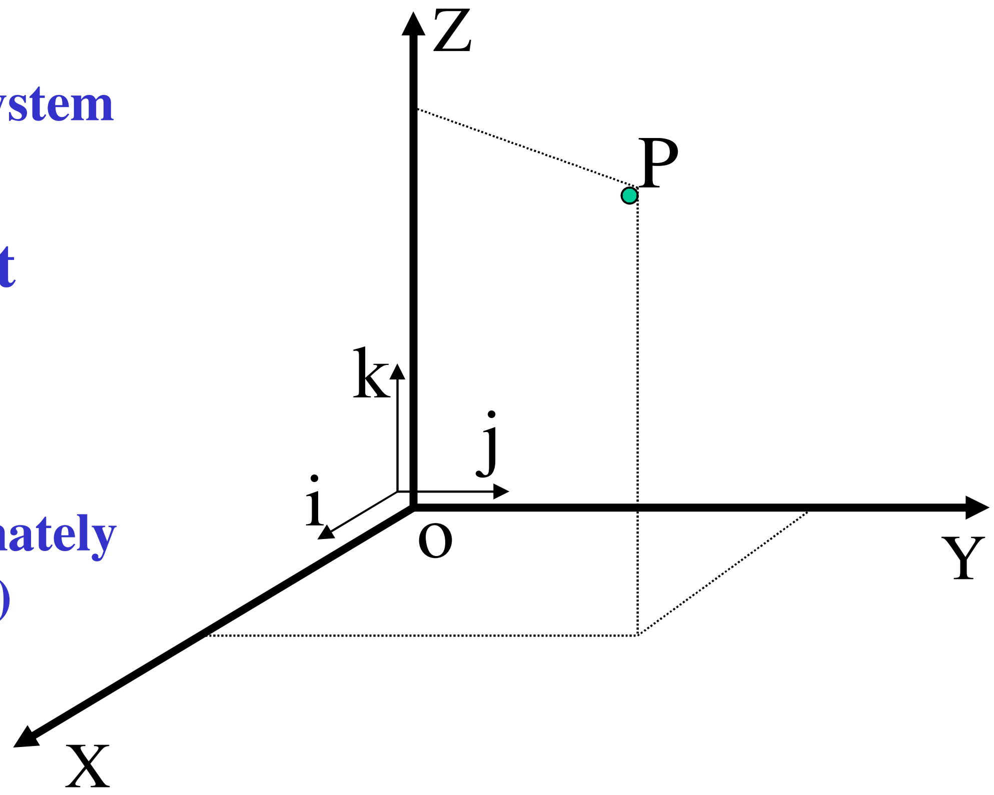
Spherical

Terrestrial Reference System in the context of space geodesy

- **Origin:**
  - Center of mass of the Earth System

- **Scale (unit of length): SI unit**

- **Orientation:**
  - Equatorial (Z axis is approximately the direction of the Earth pole)



Transformation between TRS (1/2)

7-parameter similarity :

$$\boxed{X_2 = T + \lambda.\mathfrak{R}.X_1}$$

Translation Vector $\quad T = (T_x, T_y, T_z)^T$

Scale Factor $\quad \lambda$

Rotation Matrix $\quad \mathfrak{R} = R_x.R_y.R_z$

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos R1 & \sin R1 \\ 0 & -\sin R1 & \cos R1 \end{pmatrix}$$

$$R_y = \begin{pmatrix} \cos R2 & 0 & -\sin R2 \\ 0 & 1 & 0 \\ \sin R2 & 0 & \cos R2 \end{pmatrix}$$

$$R_z = \begin{pmatrix} \cos R3 & \sin R3 & 0 \\ -\sin R3 & \cos R3 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Transformation between TRS (2/2)

In the context of space geodesy we use the linearized formula:

$$X_2 = X_1 + T + DX_1 + R.X_1 \tag{1}$$

with: $T = (T_x, T_y, T_z)^T$, $\lambda = (1 + D)$, and $\mathfrak{R} = (I + R)$

where $R = \begin{pmatrix} 0 & -R3 & R2 \\ R3 & 0 & -R1 \\ -R2 & R1 & 0 \end{pmatrix}$

T is less than one meter, D & R less than 10^{-8}

The 2nd ordre terms are neglected: less than $10^{-13} \approx 0.0006$ mm.

Differentiating equation 1 with respect to time, we have:

$\approx \mathbf{0}$

$$\dot{X}_2 = \dot{X}_1 + \dot{T} + D\dot{X}_1 + \dot{D}X_1 + R\dot{X}_1 + \dot{R}X_1 \tag{2}$$

$D\dot{X}_1$ and $R\dot{X}_1$ are negligible and therefore are omitted from the equation.

International Terrestrial Reference System (ITRS): Definition (IERS Conventions)

- **Origin:** Center of mass of the whole Earth, including oceans and atmosphere
- **Unit of length:** meter SI, consistent with TCG (Geocentric Coordinate Time)
- **Orientation:** consistent with BIH (Bureau International de l'Heure) orientation at 1984.0.
- **Orientation time evolution:** ensured by using a No-Net-Rotation-Condition w.r.t. horizontal tectonic motions over the whole Earth

$$\boxed{h = \int_C X \times V dm = 0}$$

Implementation of a TRF

- Definition at a chosen epoch, by selecting 7 parameters

- A law of time evolution, by selecting 7 rates of the 7 parameters

  assuming linear station motion!

- ==> 14 parameters are needed to define a TRF

How to define the 14 parameters ?
« Datum definition »

- Origin & rate: CoM (Dynamical Techniques)
- Scale & rate: depends on physical parameters
- Orientation: conventional
- Orient. Rate: conventional: Geophysical meaning (Tectonic Plate Motion)

- ==> Lack of information for some parameters:
  - Orientation & rate (all techniques)
  - Origin & rate in case of VLBI
  - ==> Rank Deficiency in terms of Normal Eq. System

Implmentation of a TRF in practice

The normal equation constructed upon observations of space techniques is written in the form of:

$$N.(\Delta X) = K \qquad (1)$$

where $\Delta X = X_{est} - X_{apr}$ are the linearized unknowns

Eq. (1) is a singular system: has a rank deficiency equal to the number of TRF parameters not given by the observations. Additional constraints are needed:

- Tight constraints ($\sigma \leq 10^{-10}$) m
- Removable constraints ($\sigma \cong 10^{-5}$) m
- Loose constraints ($\sigma \geq 1$) m

Applied over station coordinates

$$\boxed{(X_{est} - X_{apr}) = 0 \qquad (\sigma)}$$

- Minimum constraints (applied over the TRF parameters, see next)

TRF definition using minimum constraints (1/3)

The standard relation linking two TRFs: 1 and 2 is

$$\boxed{X_2 = X_1 + A\theta}$$

$$X_i = (x_i, y_i, z_i, \dot{x}_i, \dot{y}_i, \dot{z}_i)^T$$

$$\theta = (T1, T2, T3, D, R1, R2, R3, \dot{T}1, \dot{T}2, \dot{T}3, \dot{D}, \dot{R}1, \dot{R}2, \dot{R}3)^T$$

θ **is the vector of the 7 (14) transformation parameters**

Least squares adjustment gives for ***θ*** **:**

$$\boxed{\theta = \overbrace{(A^T A)^{-1} A^T}^{\mathbf{B}} (X_2 - X_1)}$$

A : **desigin matrix of partial derivatives given in the next slide**

The Design matrix A

$$A = \overbrace{\left(\begin{array}{cc}
\overbrace{\cdots \quad \cdots \quad \cdots}^{\text{7 parameters}} & \cdots \quad \cdots \quad \cdots \\
\begin{matrix} 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\ 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 \\ 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \end{matrix} & 0 \\
\approx 0 & \begin{matrix} 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\ 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 \\ 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \end{matrix} \\
\cdots \quad \cdots \quad \cdots & \cdots \quad \cdots \quad \cdots
\end{array}\right)}^{\text{14 parameters}}$$

Note: A (but rather B) can be reduced to specific parameters: e.g. if only rotations and rotation rates are needed, then the first 4 columns of the two parts are deleted.

TRF definition using minimum constraints (2/3)

- **The equation of minimum constraints is written as:**

$$\boxed{B(X_2 - X_1) = 0 \qquad\qquad (\Sigma_\theta)}$$

It nullifies the 7 (14) transformation parameters between TRF 1 and TRF 2 at the Σ_θ level

- **The normal equation form is written as:**

$$\boxed{B^T \Sigma_\theta^{-1} B(X_2 - X_1) = 0}$$

Σ_θ is a diagonal matrix containing small variances of the 7(14) parameters, usually at the level of 0.1 mm

TRF definition using minimum constraints (3/3)

Considering the normal equation of space geodesy:

$$N_{nc}(\Delta X) = K \qquad \textbf{(1)}$$

where $\Delta X = X_{est} - X_{apr}$ **are the linearized unknowns**

Selecting a reference solution $\boldsymbol{X_R}$,the equation of minimal constraints is given by:

$$B^T \Sigma_\theta^{-1} B(\Delta X) = B^T \Sigma_\theta^{-1} B(X_R - X_{apr}) \qquad \textbf{(2)}$$

Accumulating (1) and (2), we have:

$$\boxed{(N_{nc} + B^T \Sigma_\theta^{-1} B)(\Delta X) = K + B^T \Sigma_\theta^{-1} B(X_R - X_{apr})}$$

Note: if $X_R = X_{apr}$, the 2nd term of the right-hand side vanishes

Crust-based TRF

The instantaneous position of a point on the Earth surface at epoch t could be written as :

$$X(t) = X(t_0) + \dot{X}.(t - t_0) + \sum \Delta X_c(t) + \sum \Delta X_{nc}(t)$$

$\boldsymbol{X(t_0)}$: **position at a reference epoch t_0**

$\dot{\boldsymbol{X}}$: **linear velocity**

$\sum \Delta \boldsymbol{X_c(t)}$: **Class 1 Conventional models, e.g. :**

- **Solid Earth, Ocean & Pole tides (models, IERS Conv.)**

$\sum \Delta \boldsymbol{X_{nc}(t)}$: : **Class 2 models or estimated quantities:**

- **Loading deformation (seasonal and non-seasonal)**
- **Post-Seismic Deformation**
- **…**

Reference Frame Representations

- Long-Term linear Frame: mean station positions at a reference epoch (t_0) and station velocities:

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

<= Regularized Position
With piece-wise linear function

  - The indispensable basis for science and operational geodesy applications

Secular Frame + corrections (PSDs, Seasonals, Geocenter motion)
==> modeled "Quasi-Instantaneous" station positions

$$\boxed{X(t) = X(t_0) + \dot{X}.(t - t_0) + \delta X(t)_{PSD} + \delta X(t)_S + \delta X(t)_G}$$

- "Quasi-Instantaneous" RF: mean station positions at a "short" & "regular" interval:
  - Daily or weekly representations
  - Nonlinear motion embedded in their time series
  - Still rely on the ITRF for at least the orientation definition

Why ITRF ?
Strengths and weaknesses of space geodetic techniques

Parameter	VLBI	SLR	GNSS	DORIS
Origin	-	***	*	*
Scale	***	***	-	*
Orientation	-	-	-	-
Geographic density	*	*	***	*
Real Time access to the ITRF	*	-	***	-

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

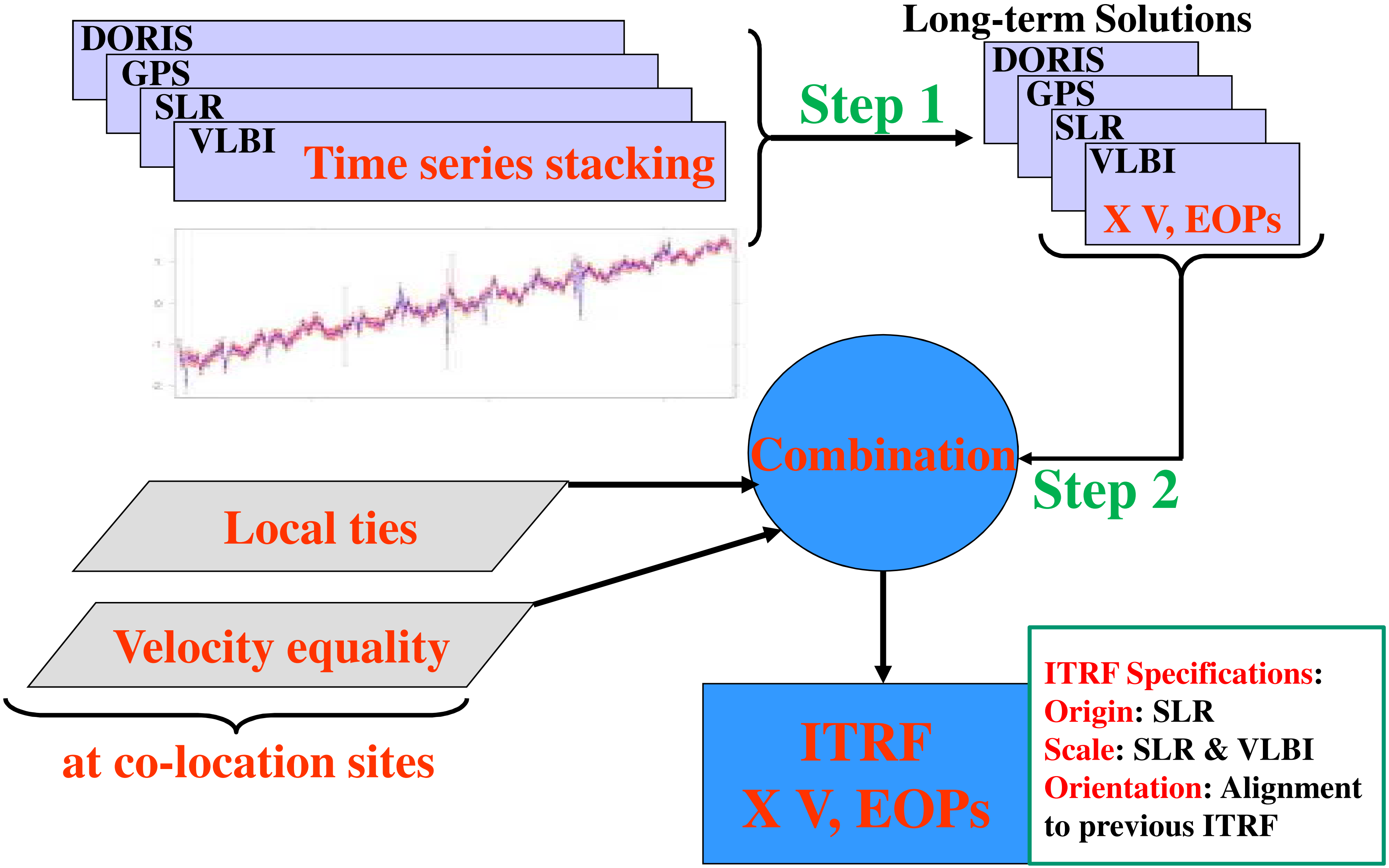
Combination model

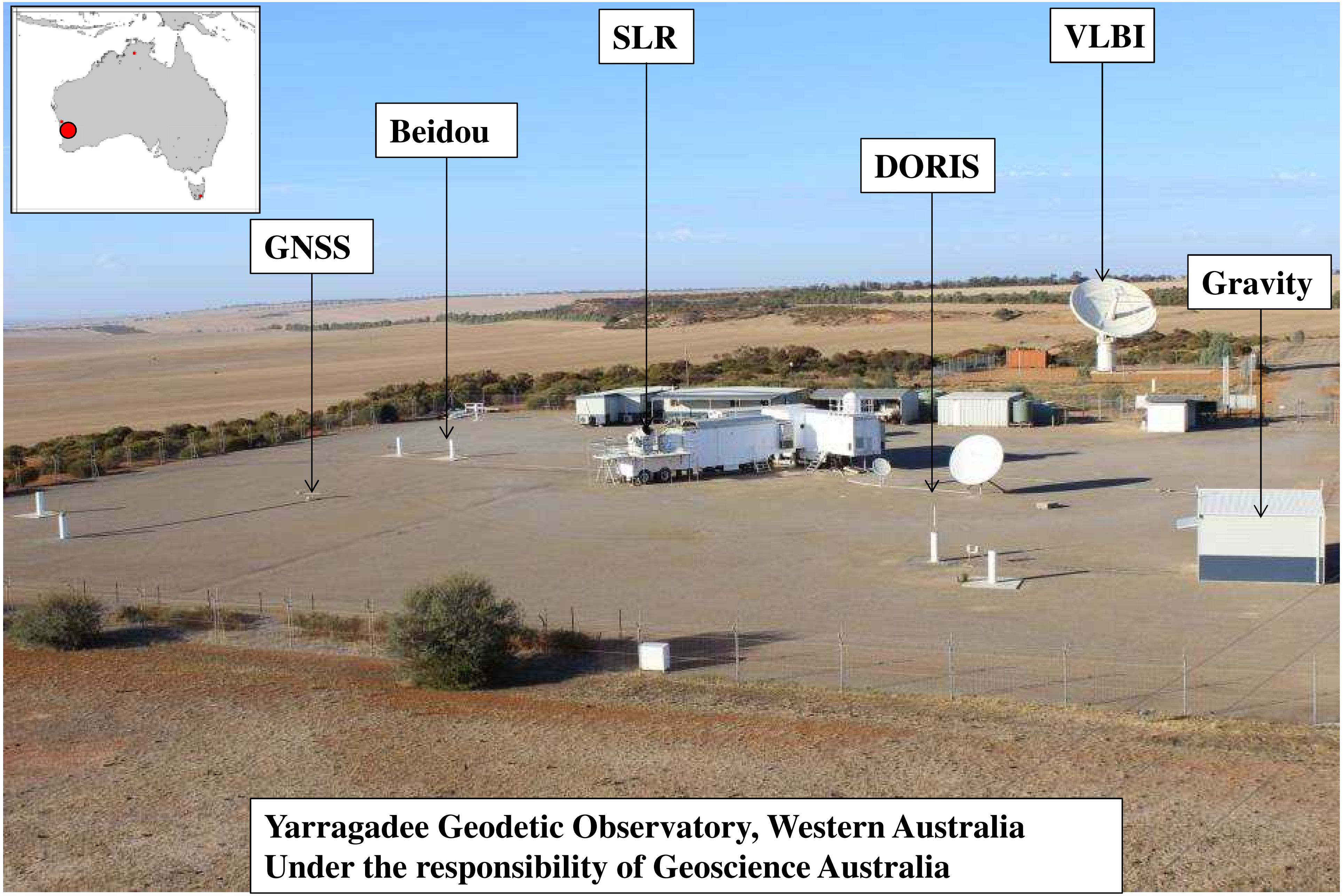
$$\begin{cases} X_s^i = X_c^i + (t_s^i - t_0)\dot{X}_c^i \\ \qquad + T_k + D_k X_c^i + R_k X_c^i \\ \qquad + (t_s^i - t_k)\left[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i\right] \\ \\ \dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{cases}$$

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

Local ties $DX_{(GPS,VLBI)} = X_{VLBI} - X_{GPS}$

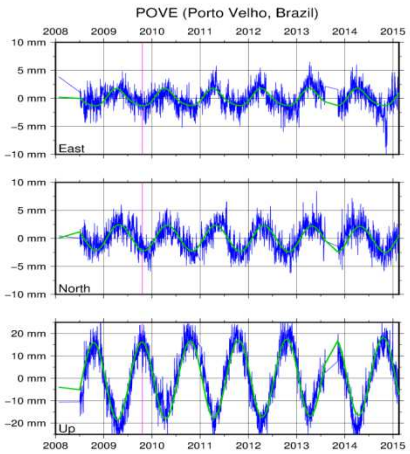
ITRF Construction





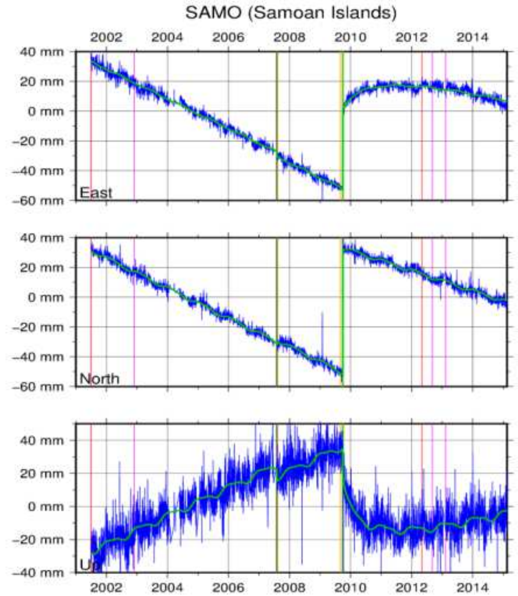
Yarragadee Geodetic Observatory, Western Australia
Under the responsibility of Geoscience Australia

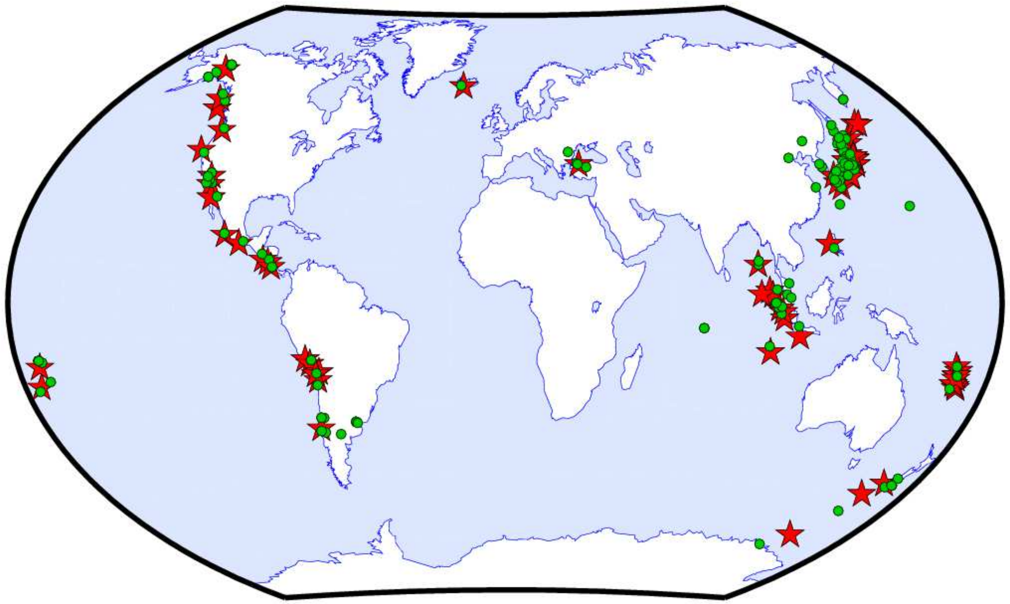
ITRF2014: Modelling nonlinear station motions



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

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



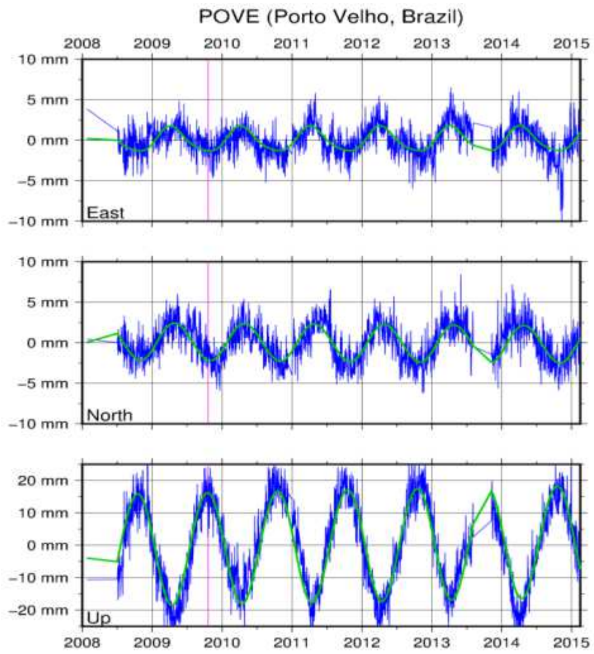


Red Stars: EQ Epicenters (58)
Green circles: ITRF2014 sites (117)

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

Periodic signals: reference frame definition

- **CM : Center of Mass Frame**
- **CF : Center of Figure Frame**
- **CN : Center of Network Frame**



IERS Conventions:

$$\boxed{\vec{X} = \vec{X}_{ITRF} - \vec{O}_G}$$

$\vec{O}_G$ **is the vector from the ITRF origin to the instantaneous CM**

How to add Periodic Signals?

Sine & Cosine Function

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

→ 6 parameters per station & per frequency: (a , b) following the three axis X, Y, Z.
→ With respect to a secular (ITRF) frame we can write:

$$X(t)_s - \delta X(t)_{PSD} = X(t_0)_{itrf} + \dot{X}_{itrf} \,.\, (t - t_0) + T(t) + \Delta X_f(t)$$

Estimating both $T(t)$ and $\Delta X_f(t)$ introduces a number of rank deficiencies to be dealt with…

Stacking of time series & rank deficiency

- CATREF combination model involves a 14-parameter similarity transformation (very efficient for reference frame definition)
- Need to specify the reference frames for both (1) station positions & velocities and (2) periodic signals: CM, CF or CN

- 14 Degrees of Freedom (DoF) to define the secular frame
- 14 DoF for each frequency, handled by:

  – Minimum Constraints (MC) : No net periodic Translation, Rotation, or/and Scale of a reference set of stations

  ==> Seasonal signals are expressed in:

  – the CN frame if the MC are applied to zero deformation

  – the CF frame if the MC are applied to a geophysical (or Grace) model

  – Internal Constraints (IC): Zero periodic signals in Translation, Scale & eventually Rotation time series

  ==> Seasonal signals are expressed in the CM frame

  (as sensed by, e.g., SLR or DORIS)

Reference Frame & the rank deficiency problem

- Use the concept of minimum constraints :

$$A^T.\Delta X = 0$$

$$A = \begin{pmatrix} . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i \\ 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i \\ 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 \\ . & . & . & . & . & . & . \end{pmatrix}$$

But in CATREF we use:

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

X_R & X_E: Reference & Estimated coordinates

- Or/and:
- Internal constraints, a minimum-type of constraints, applied to the frame parameters (Altamimi et al., 2007): For each time series of a parameter P_k

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

Internal constraints

Internal (intrinsic) constraints in case of time series stacking

For any transformation parameter P_k at any epoch t_k, we can write:

$$P_k = P_k(t_0) + (t_k - t_0).\dot{P}_k \tag{12}$$

We impose two conditions to define the frame at t_0 and its time evolution:

$$P_k(t_0) \;=\; 0 \qquad and \qquad \dot{P}_k \;=\; 0 \tag{13}$$

Eq. (12) describes a regression line solvable by least squares adjustment:

$$\begin{pmatrix} K & \sum_{k\in K}(t_k - t_0) \\ \sum_{k\in K}(t_k - t_0) & \sum_{k\in K}(t_k - t_0)^2 \end{pmatrix} \begin{pmatrix} P_k(t_0) \\ \dot{P}_k \end{pmatrix} = \begin{pmatrix} \sum_{k\in K} P_k \\ \sum_{k\in K}(t_k - t_0)P_k \end{pmatrix} \tag{14}$$

Satisfying Eq. (13) and considering Eq. (14) ==> $\boxed{\begin{cases} \sum_{k\in K} P_k = 0 \\ \sum_{k\in K}(t_k - t_0)P_k = 0 \end{cases}}$ (13-bis)

Periodic signals & the rank deficiency problem (1/2)

Sine & Cosine Function

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

- **6 parameters per station & per frequency: (a , b)**
- **Use the concept of minimum constraints**

- $(A^T A)^{-1} A^T \begin{pmatrix} a^i_{xR} - a^i_x \\ a^i_{yR} - a^i_y \\ a^i_{zR} - a^i_z \end{pmatrix} = 0$

- $(A^T A)^{-1} A^T \begin{pmatrix} b^i_{xR} - b^i_x \\ b^i_{yR} - b^i_y \\ b^i_{zR} - b^i_z \end{pmatrix} = 0$

$$A = \begin{pmatrix} . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i \\ 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i \\ 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 \\ . & . & . & . & . & . & . \end{pmatrix}$$

Periodic signals & the rank deficiency problem (2/2)

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

- **Or/and**
- **Use internal constraints upon the time series of the frame parameters P_k**

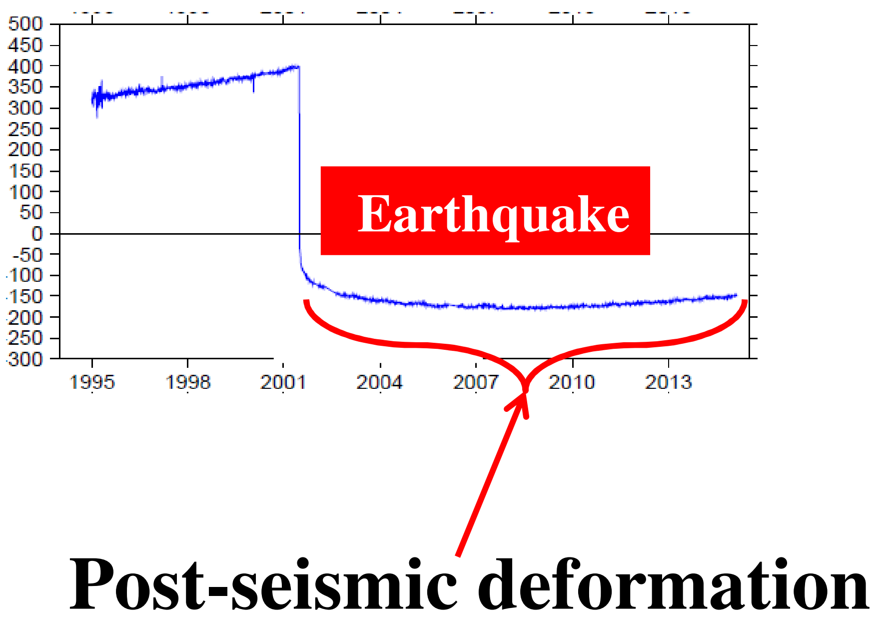
- $(B^T B)^{-1} B^T [P(t_1), \dots, P(t_k)]^T = 0$

where $$B = \begin{pmatrix} cos(\omega_i . t_1) & sin(\omega_i . t_1) \\ \vdots & \vdots \\ cos(\omega_i . t_k) & sin(\omega_i . t_k) \end{pmatrix}$$

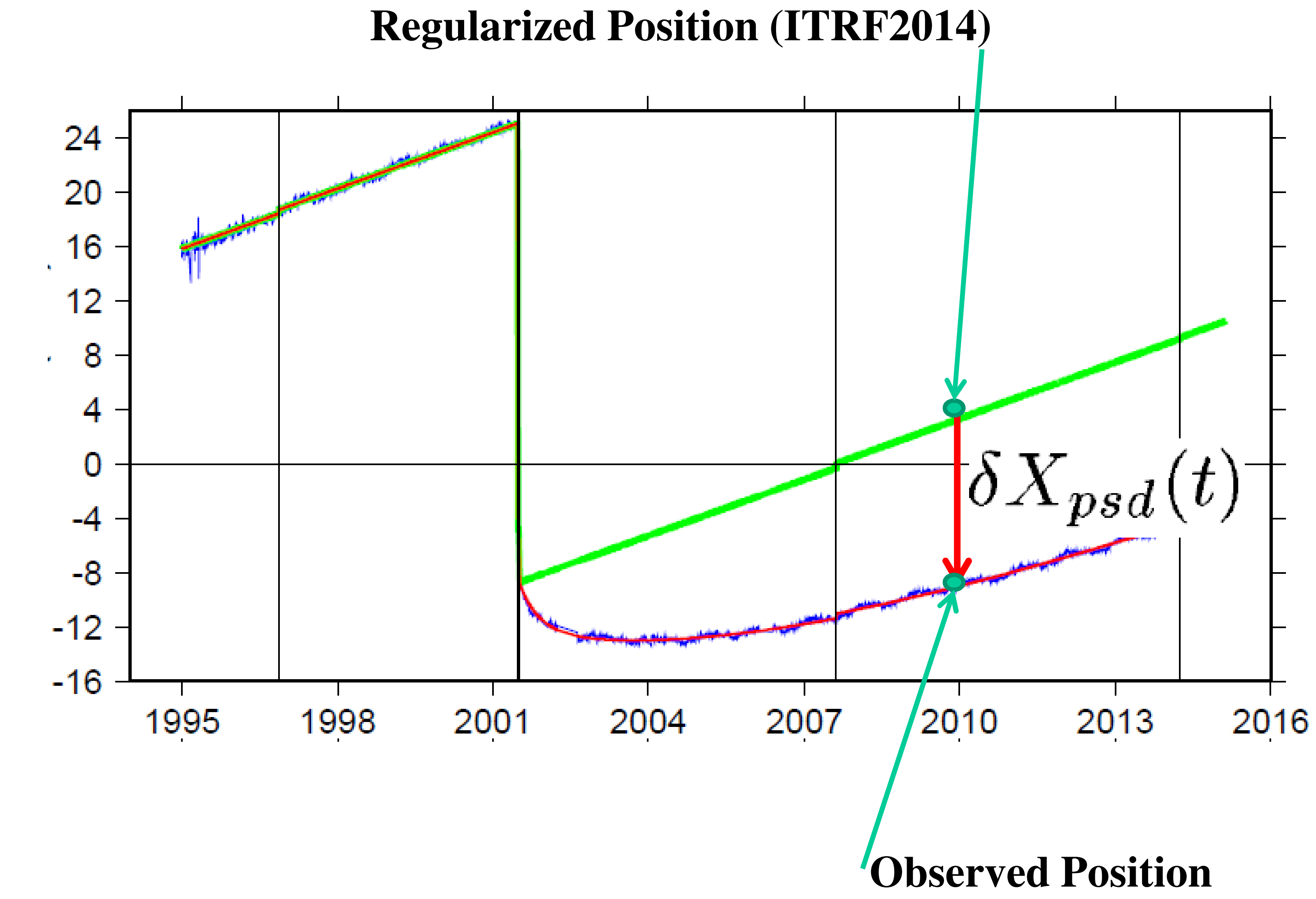
Post-Seismic Deformations

- Fitting parametric models using GNSS/GPS data
  - at all 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)

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

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

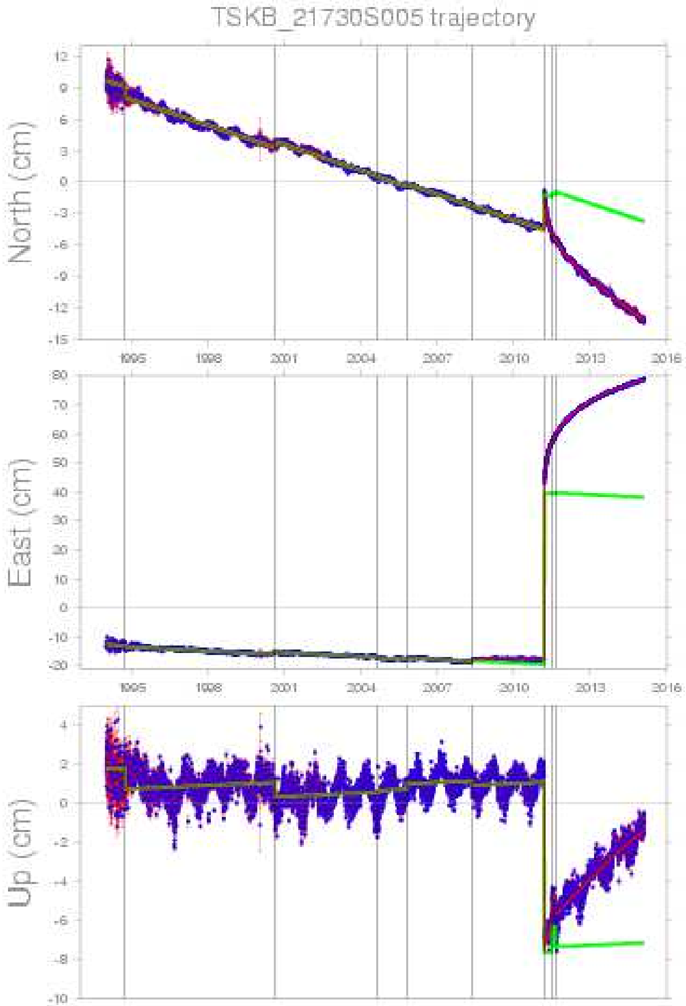
Local Frame

PSD Subroutines available at ITRF2014 Web site:

http://itrf.ign.fr/ITRF_solutions/2014/

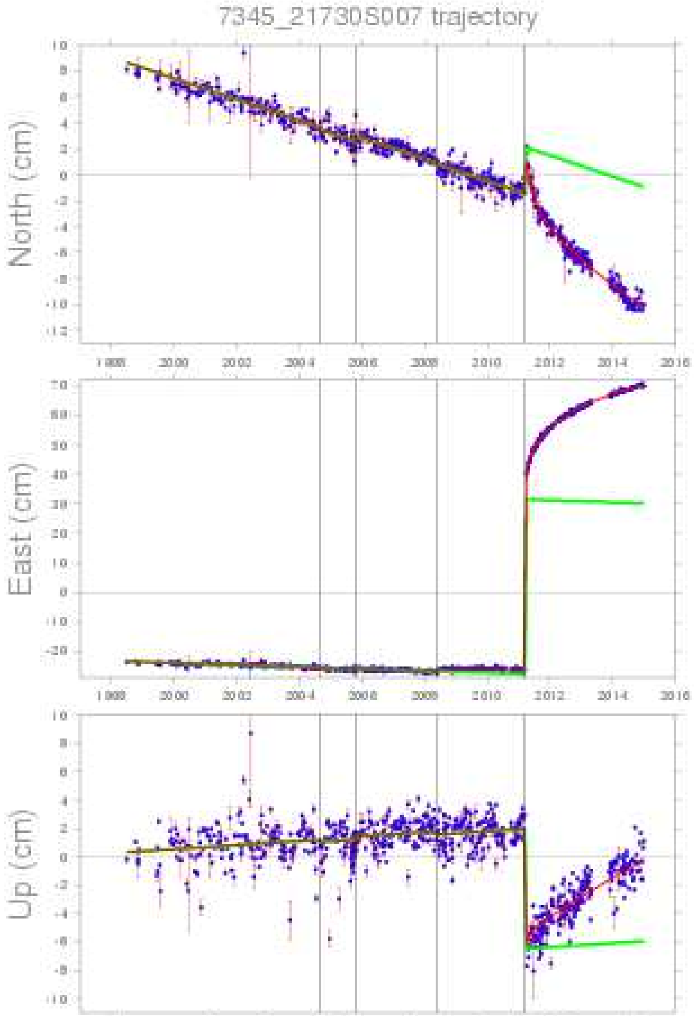
Tsukuba Trajectory

GNSS



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

VLBI



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

The ITRF adventure (1/2)

- Combination activities started at IGN in the early eighties
- First combined reference frame was BTS84, published in 1985 (Boucher & Altamimi, 1985):
  - VLBI, LLR, SLR & Doppler: MERIT campaign
  - ~20 co-location sites
  - Precision : decimeter
- 1988: Creation of the IERS ==> ITRF88
- 1992: GPS in the ITRF (ITRF91): 21 sites
- 1994 : Birth of IGS & SINEX format
- 1995: DORIS in the ITRF (ITRF94): 52 Sites
- 1998, 1999, 2003: creation of ILRS, IVS and IDS
- 2000: Reorganization of the IERS ==> Product Centers, including ITRS Center

History...(1/2)

STATUS OF THE REALIZATION OF THE BIH TERRESTRIAL SYSTEM

C. BOUCHER and Z. ALTAMIMI
Institut Géographique National
2, Avenue Pasteur
94160 Saint-Mandé
France

IAU 1988

History…(2/2)

TABLE I : Transformation parameters from BTS 84 to BTS 85
(the uncertainties are given in the second line)

T1 m	T2 m	T3 m	D 10^{-6}	R1 "	R2 "	R3 "
0.023	0.044	0.037	-0.0021	-0.0002	-0.0014	-0.0042
0.020	0.020	0.020	0.0029	0.0008	0.0007	0.0007

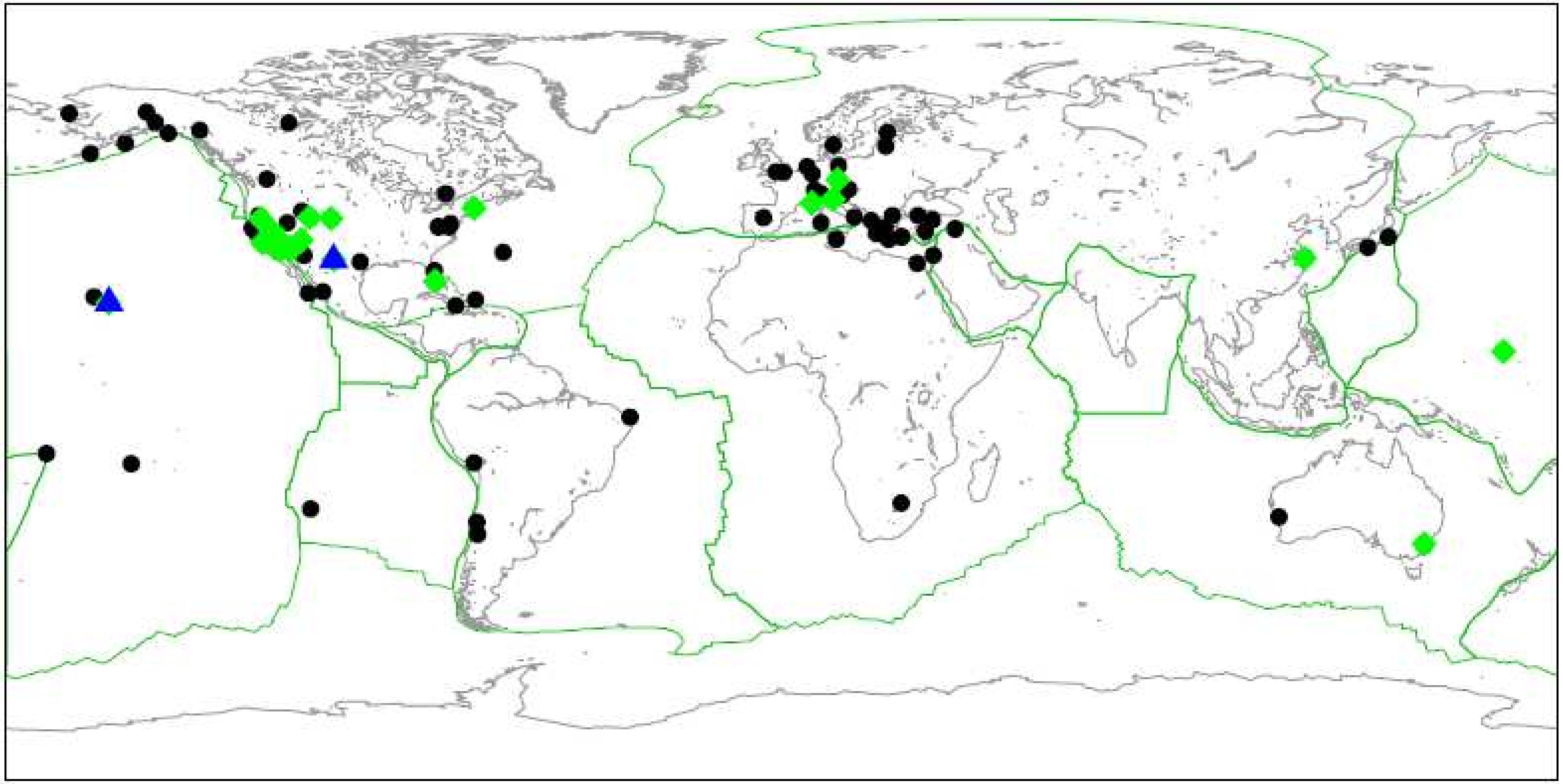
Table I shows the good level of consistency of the two BTS realizations : a few cm in the origin, 0.002 ppm in the scale and up to 4 mas in the orientation.

The ITRF adventure (2/2)

- 1980 – now: three generations of combination software packages
- CATREF software project started in Nov. 1995, using SINEX
  - Rigorous combination of station positions, velocities and EOPs
  - Analysis of station positions time series
  - Based on the 14-parameter similarity transformation
  - Various options for reference frame definition:
    minimum and internal constraints
- 13 ITRF versions: ITRF88 up to ITRF2014
- 1992: First combined velocity field in (ITRF91)
- 1995: Use of full variance-covariance information (ITRF94)
- 2006: ITRF and EOP rigorous combination (ITRF2005) using time series
- 2010: ITRF2008
- 2016: ITRF2014 published : modelling nonlinear variations
- Up to 2021: Preparation for ITRF2020

ITRF evolution:
Network, Precision & Accuracy

Network evolution: ITRF88



•1 ◆2 ▲3

Co-located techniques --> 20 2

Network evolution: ITRF2014

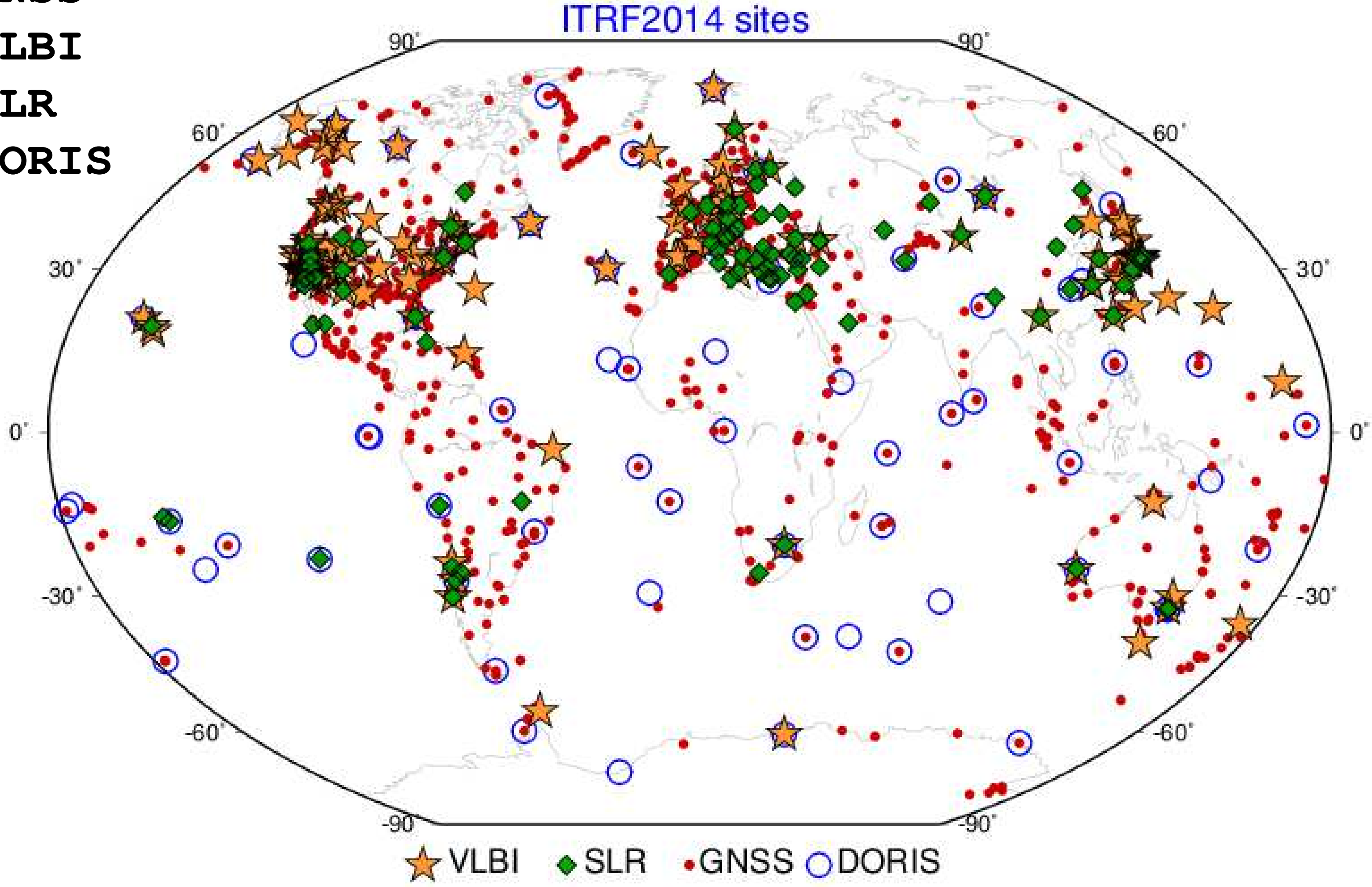
Sites per technique:

884 GNSS

124 VLBI

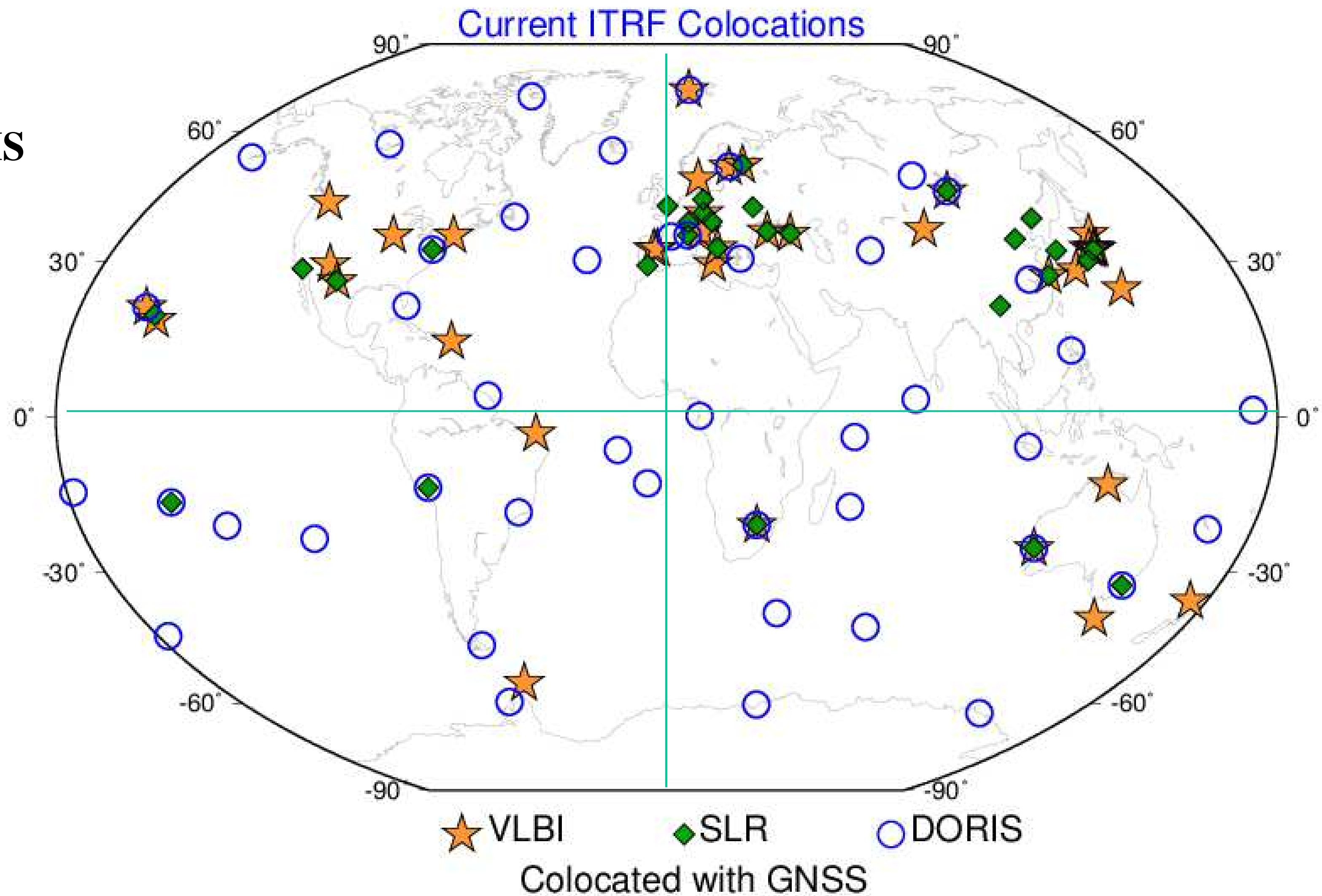
96 SLR

71 DORIS



Current colocations

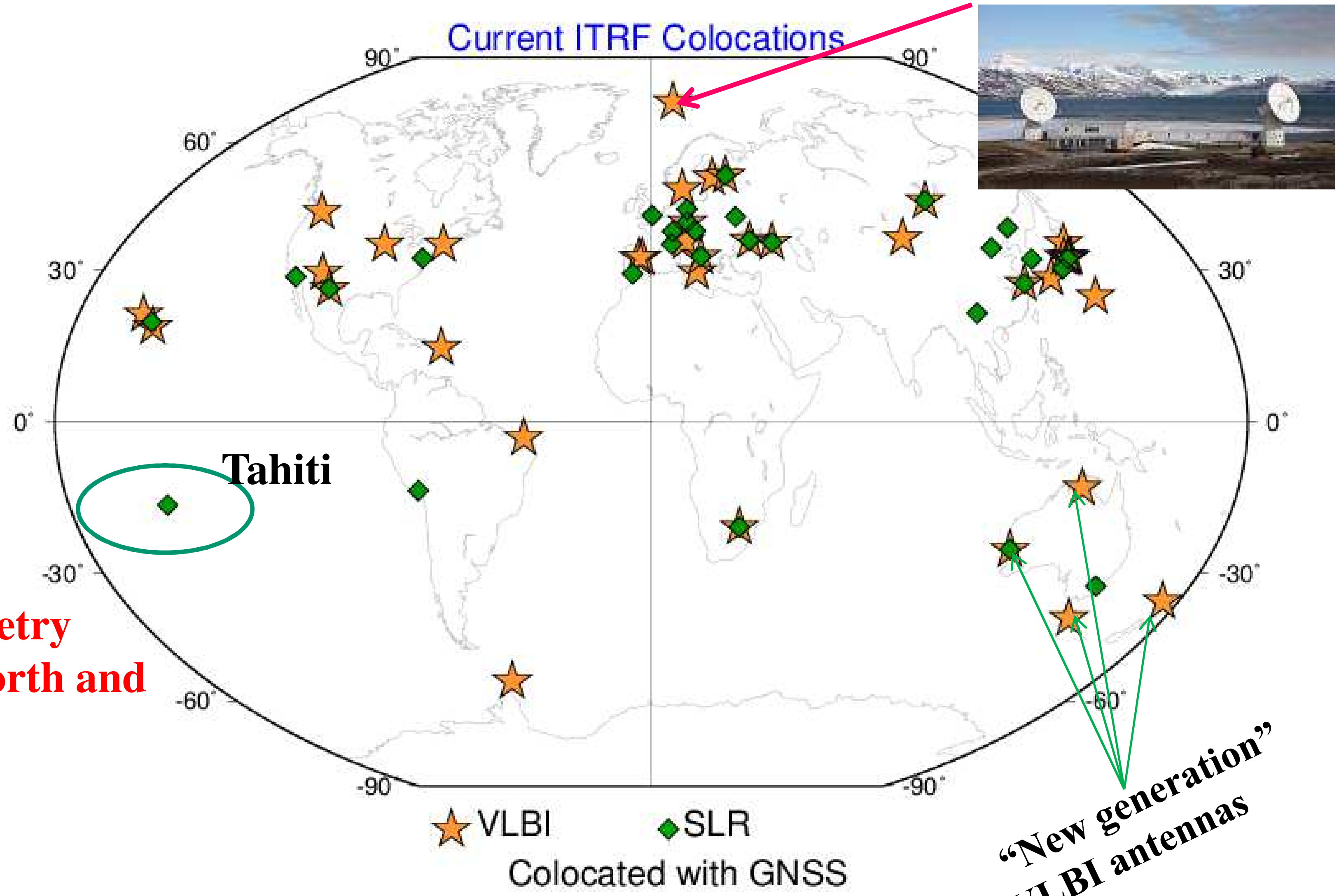
- ~ 44 VLBI
- ~ 30 SLR
- ~ 45 DORIS



Current colocations

New geodetic Observatory at Ny-Ålesund

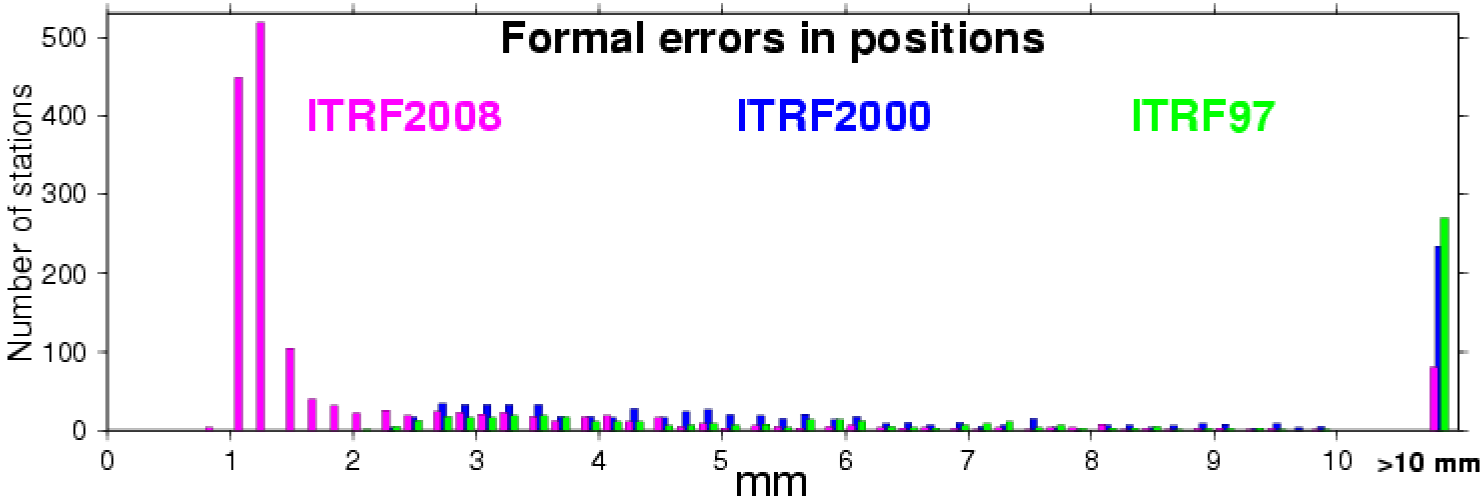
~ 44 VLBI
~ 30 SLR

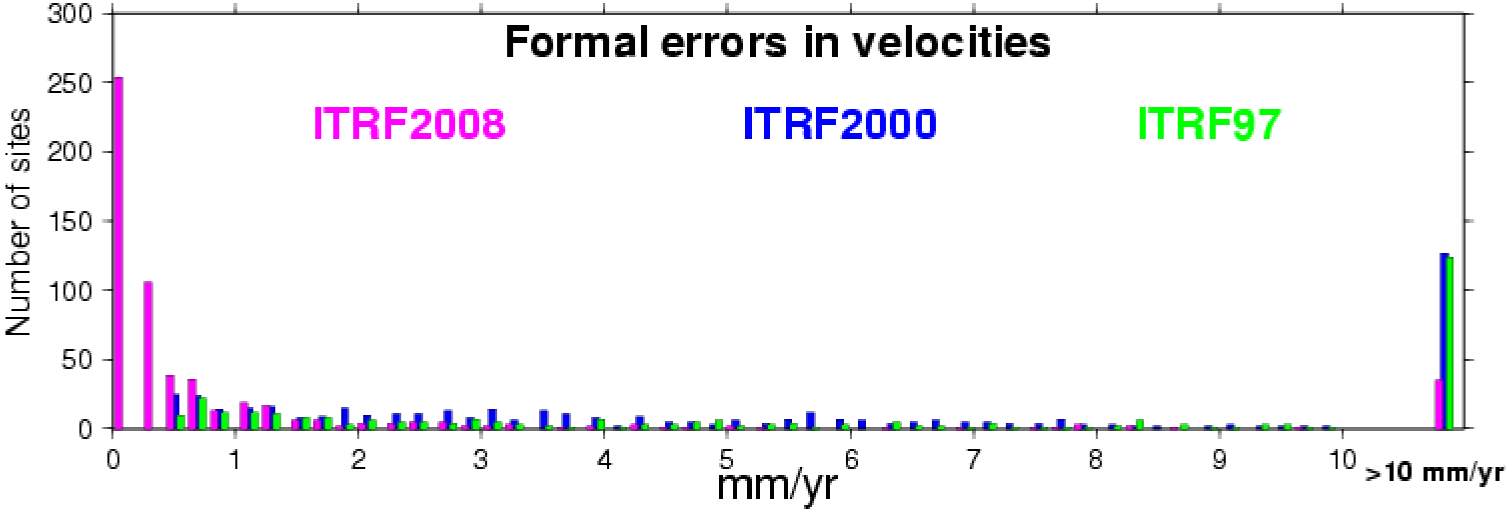


Poor geometry between north and south

"New generation" VLBI antennas

Precision evolution

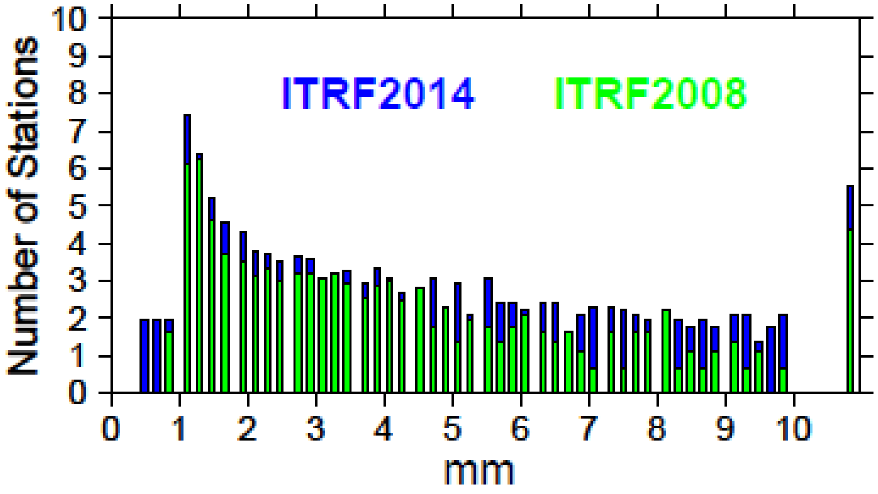




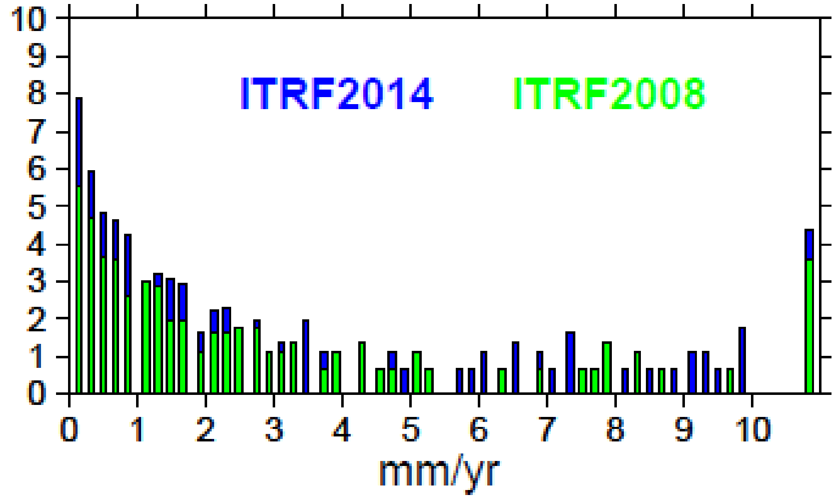
Precision evolution

Station Positions

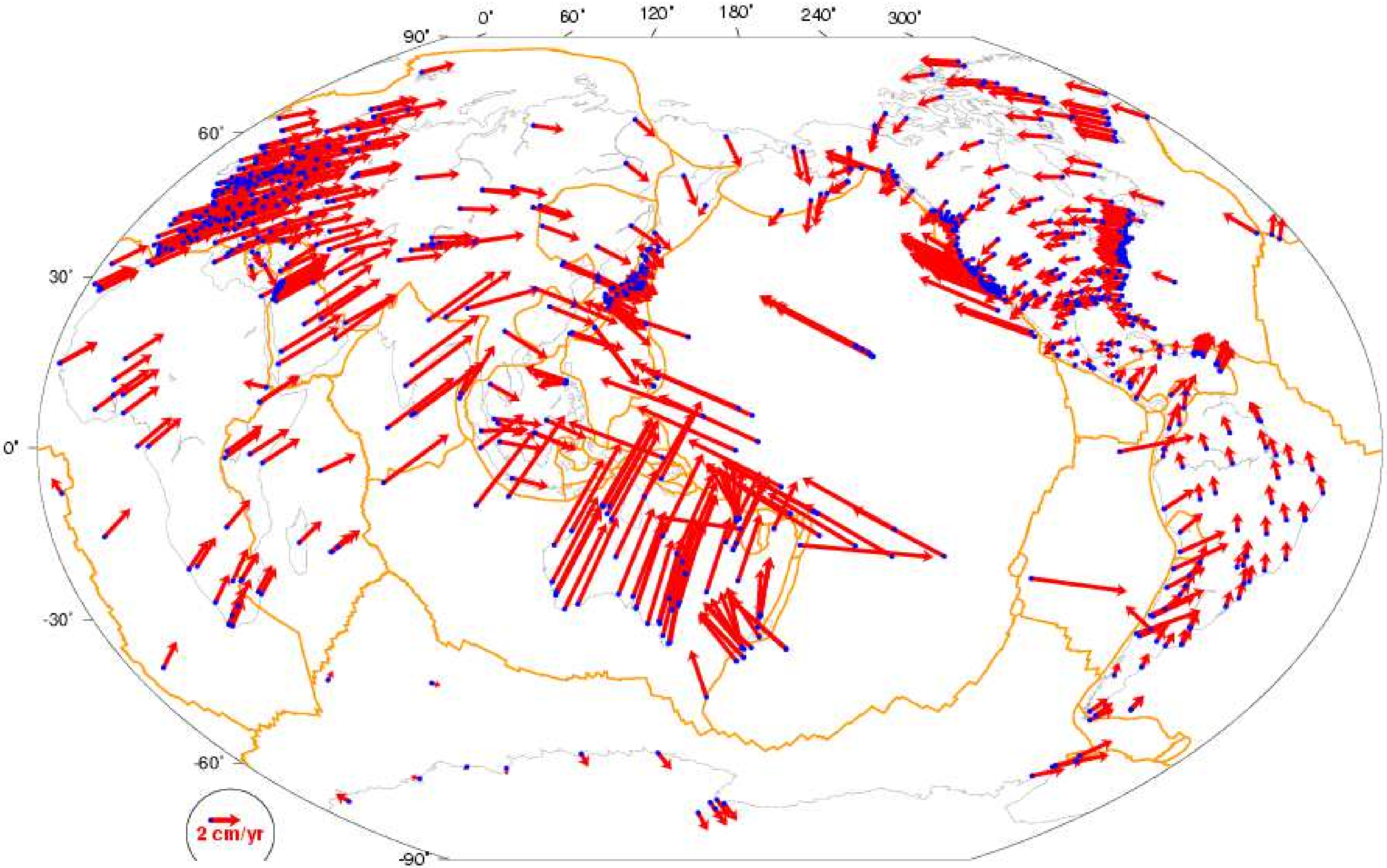
Log scale



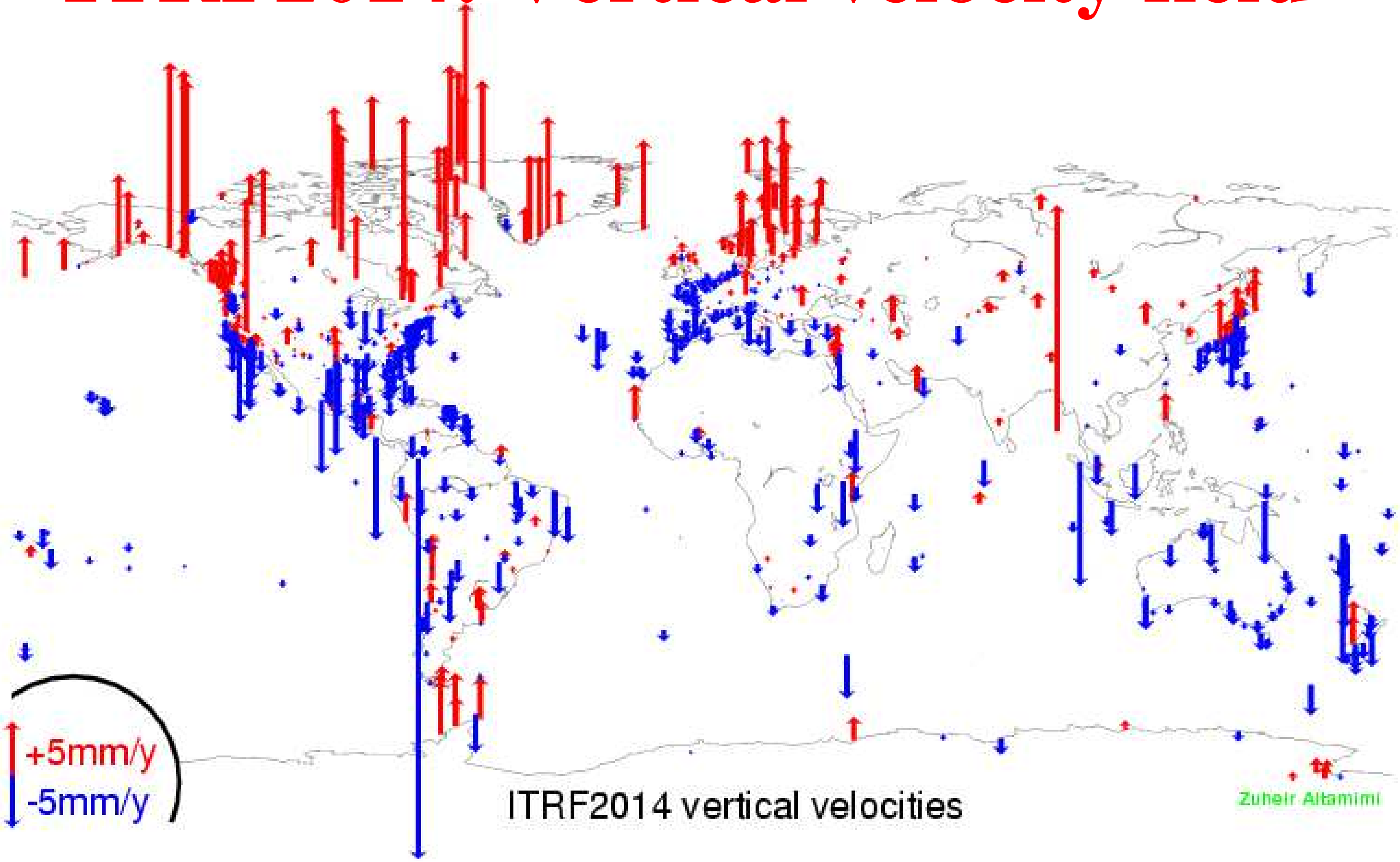
Station Velocities



ITRF2014 horizontal velocity field

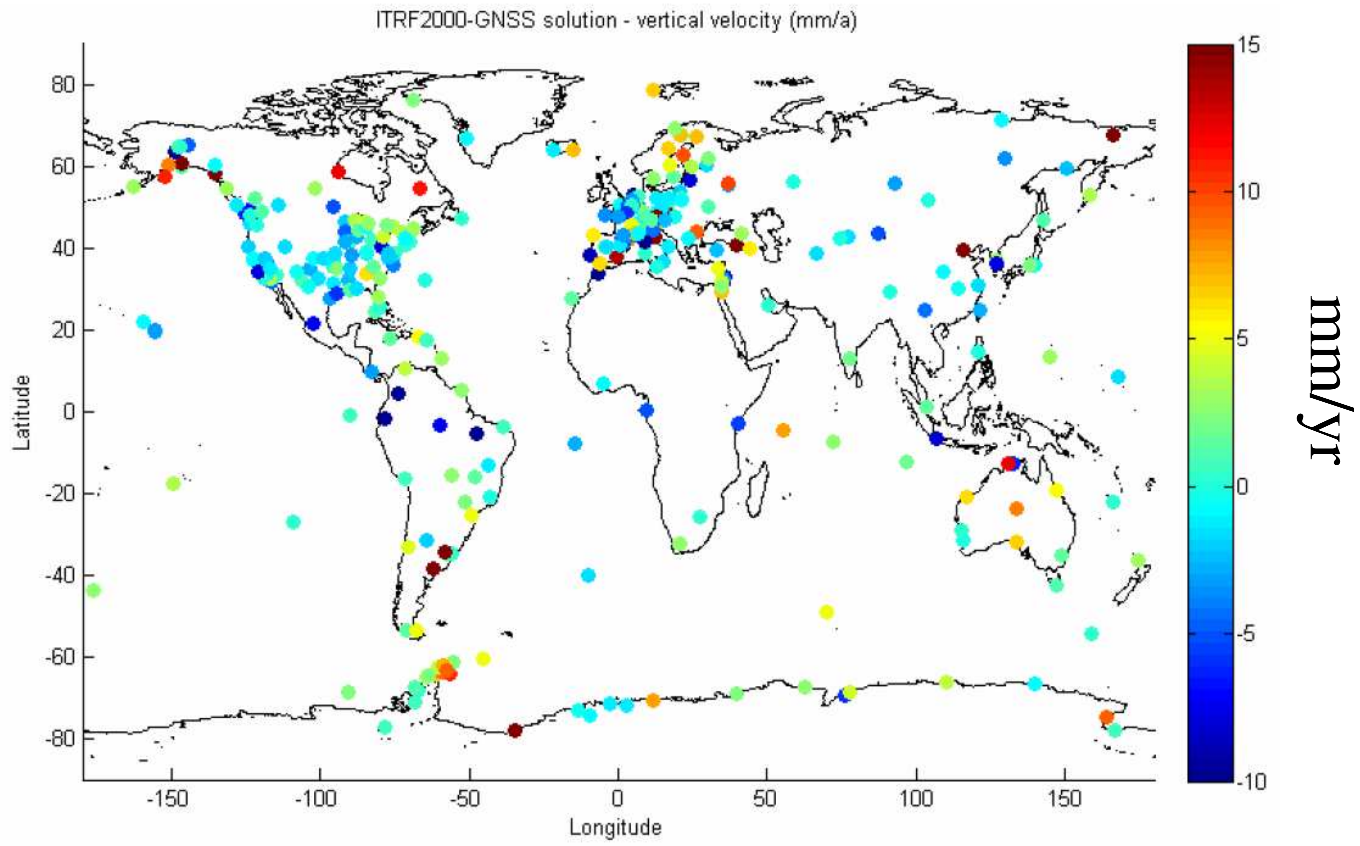


ITRF2014: Vertical velocity field



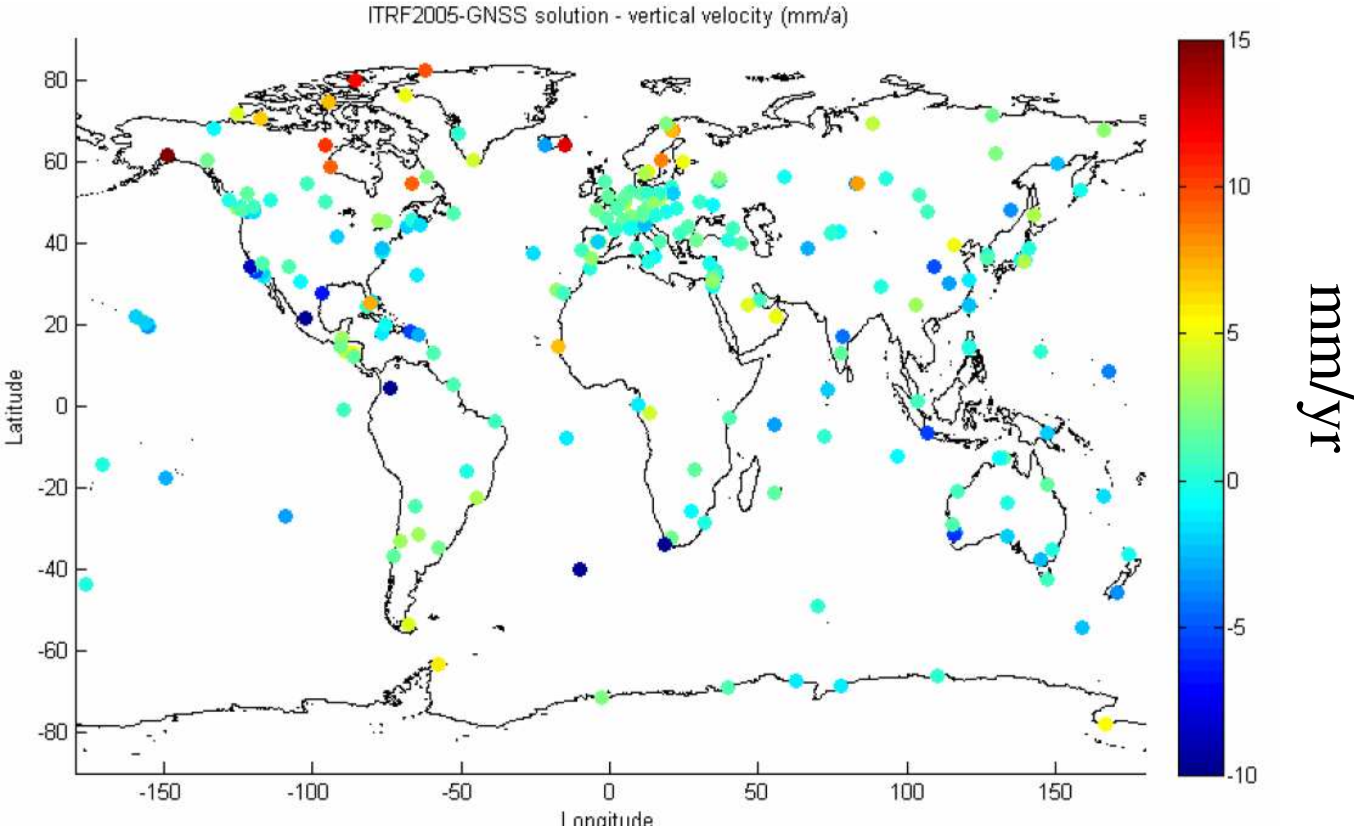
ITRF accuracy/precision

Evolution of the spatial consistency of vertical velocities: ITRF2000



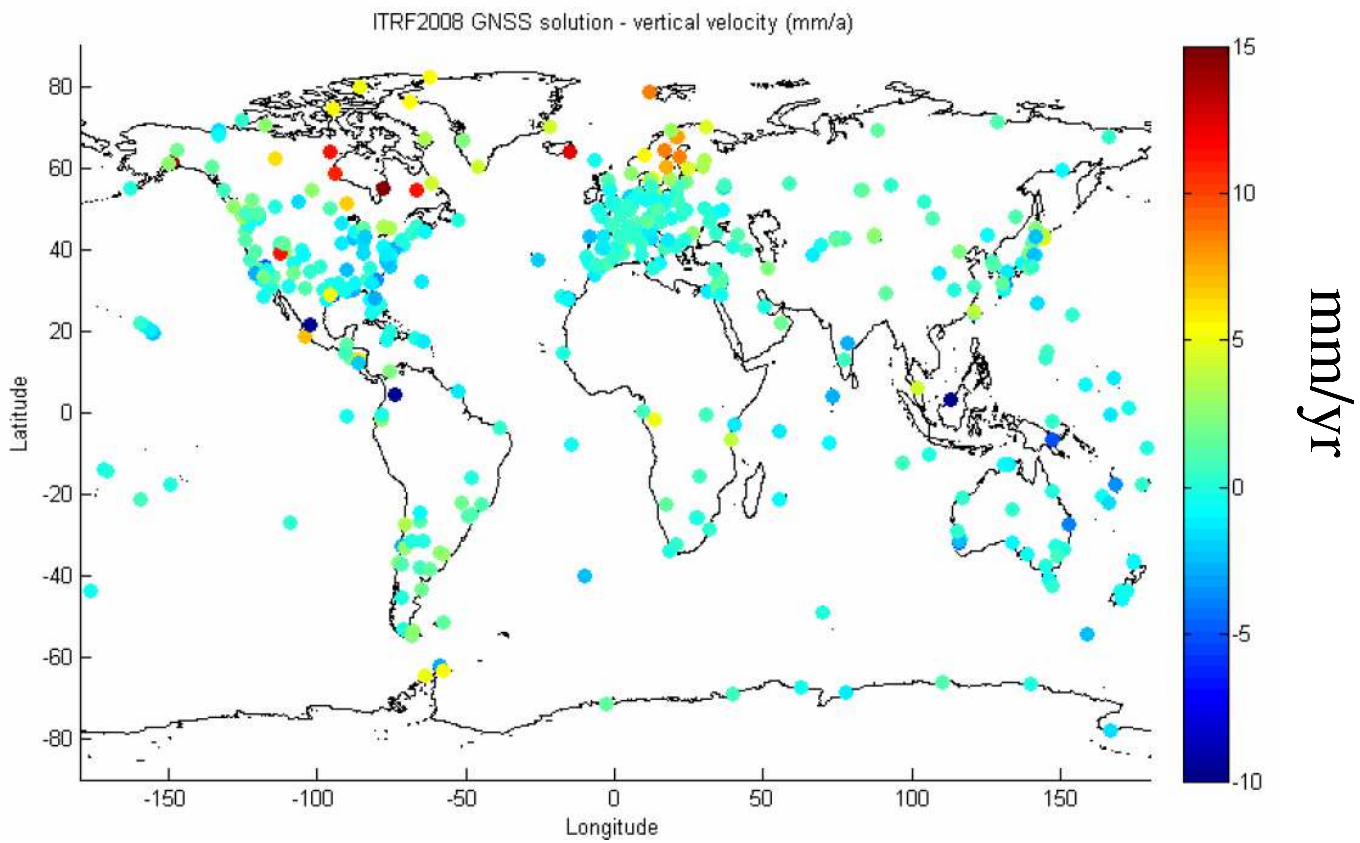
ITRF accuracy/precision

Evolution of the spatial consistency of vertical velocities: ITRF2005



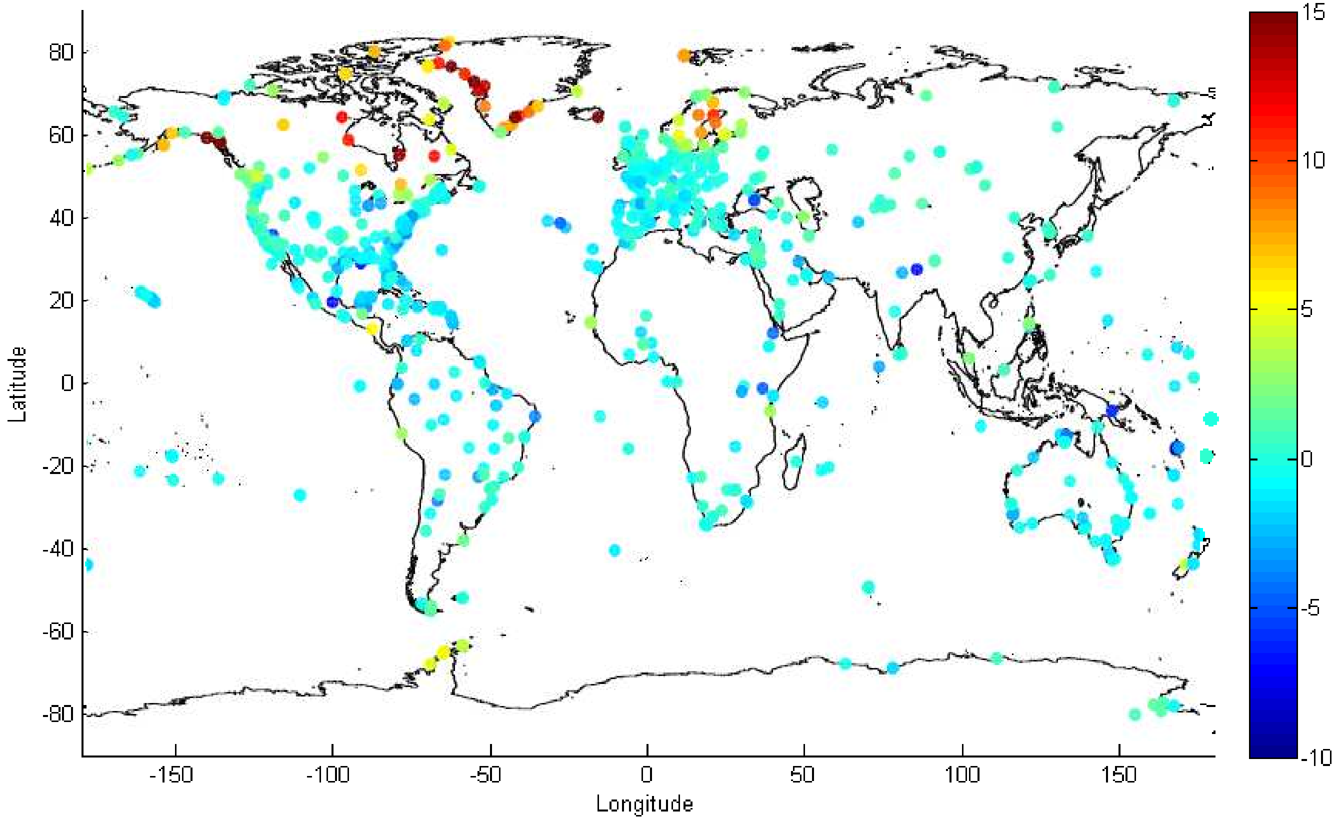
ITRF accuracy/precision

Evolution of the spatial consistency of vertical velocities: ITRF2008



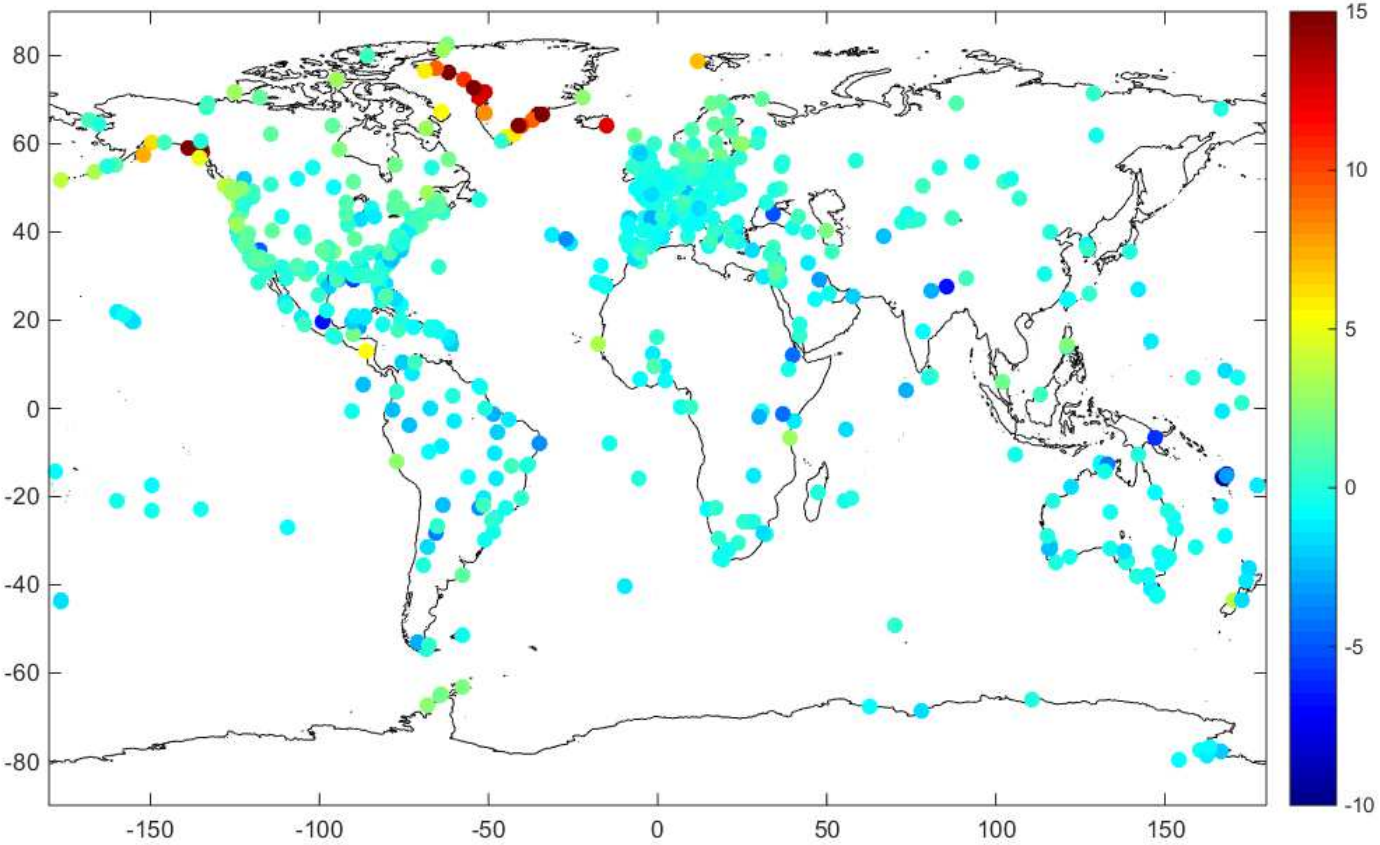
ITRF Accuracy/precision

Evolution of the spatial consistency of vertical velocities: ITRF2014



ITRF Accuracy/precision

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



Access to the ITRF using the IGS products (1/2)

- **How to express a GNSS network in the ITRF using IGS products (orbit, clocks, ERP: all expressed in the ITRF) ?**
- **Select a reference set of ITRF/IGS stations and collect RINEX data from IGS data centers;**
- **Process your stations together with ITRF/IGS ones:**
- **Fix IGS orbits, clocks and ERPs**
- **Eventually, add minimum constraints conditions in the processing:**

$$\boxed{X_R = X_c + A\theta} \xrightarrow{\theta = 0} \boxed{(A^T A)^{-1} A^T (X_R - X_c) = 0}$$

ITRF (X_R) **Your Solution** (X_c)

Access to the ITRF using the IGS products (2/2)

==> Your solution will be expressed in the ITRFyy consistent with IGS orbits

- **Propagate official ITRF station positions at the central epoch (t_c) of the observations:**

$$\boxed{X(t_c) = X(t_0) + \dot{X}(t_c - t_0)}$$

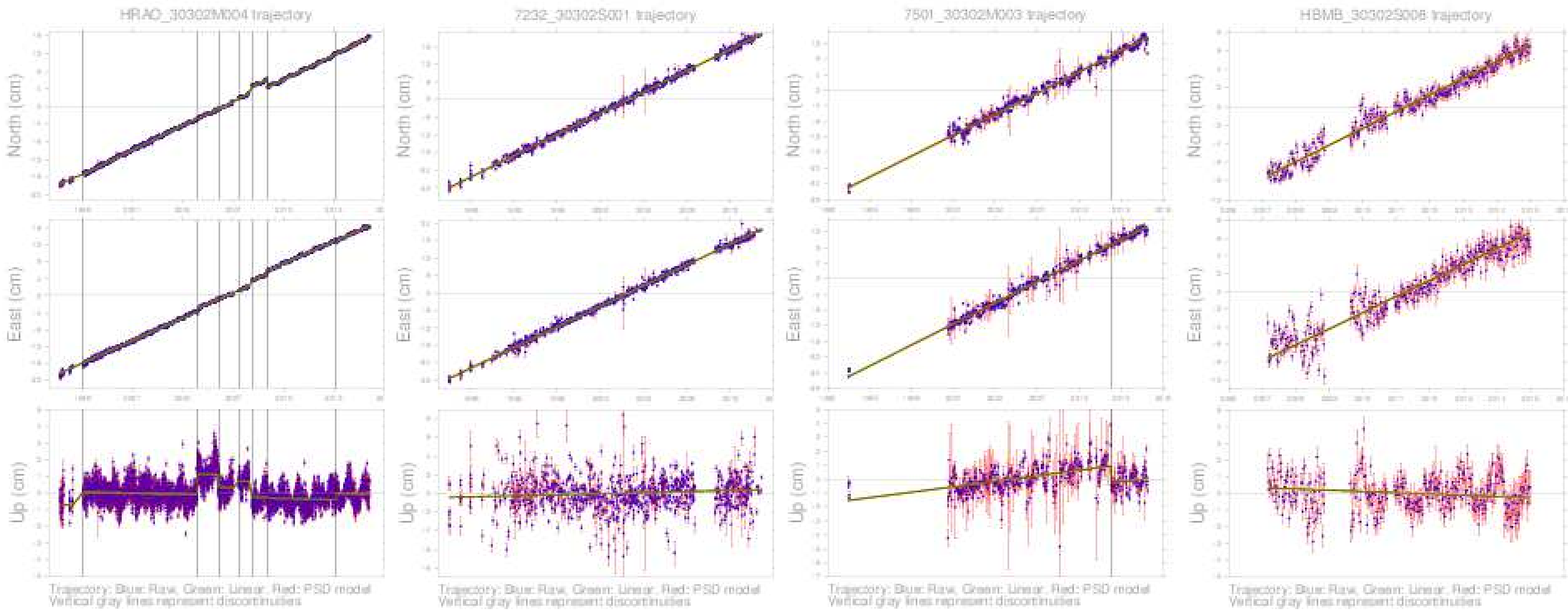
- **Compare your estimated ITRF station positions to official ITRF values and check for consistency:**
  - Transformation parameters should be zeros
  - No outliers: residuals smaller than a certain threshold.

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 : **an important co-location site**

Preparation for ITRF2020 (2/2)

- ITRF2020 ==> Toward improving the ITRF

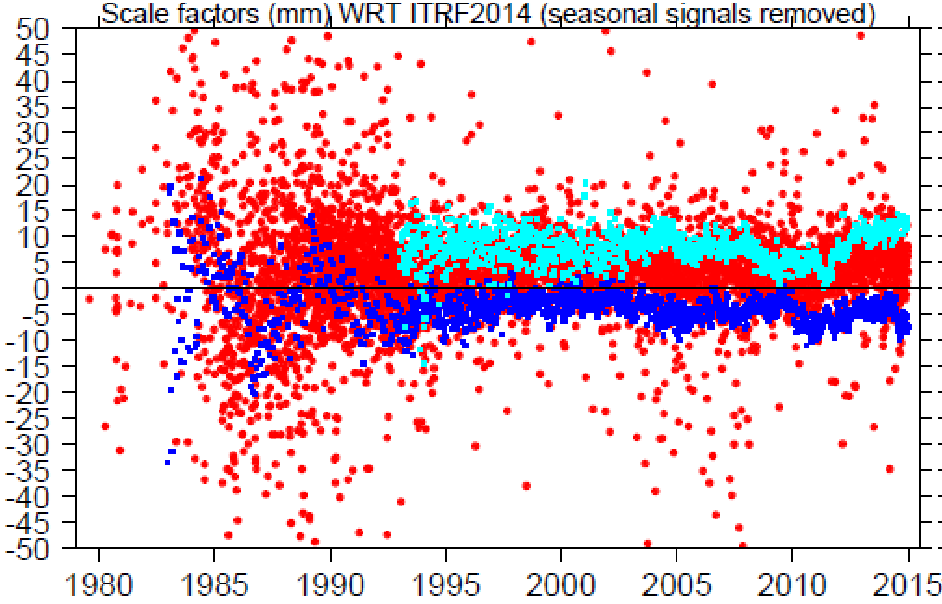
- <u>At the combination level</u>:
  - Track down the VLBI & SLR scale discrepancy
  - Provide annual & semi annual signals for all techniques in the CM frame
  - Isolate/understand technique discrepancies in seasonal signals at co-location sites
  - Provide accurate annual and semi-annual geocenter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

Evidences for VLBI/SLR Scale offset

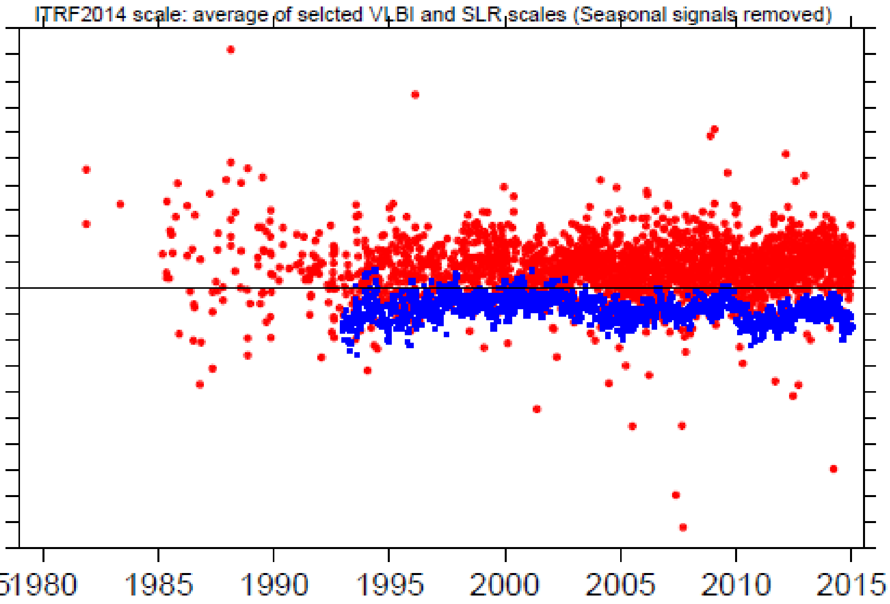
- **Demonstrated in ITRF2014, but also in past ITRF solutions**
- **SLR & VLBI solutions coexist with their own scales in DTRF and JTRF 2014:**
  - **scale offset: ~1.4 ppb**
- **SLR: Range Biases (ILRS work: in progress)**
- **VLBI: Antenna Gravitational Deformation**

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

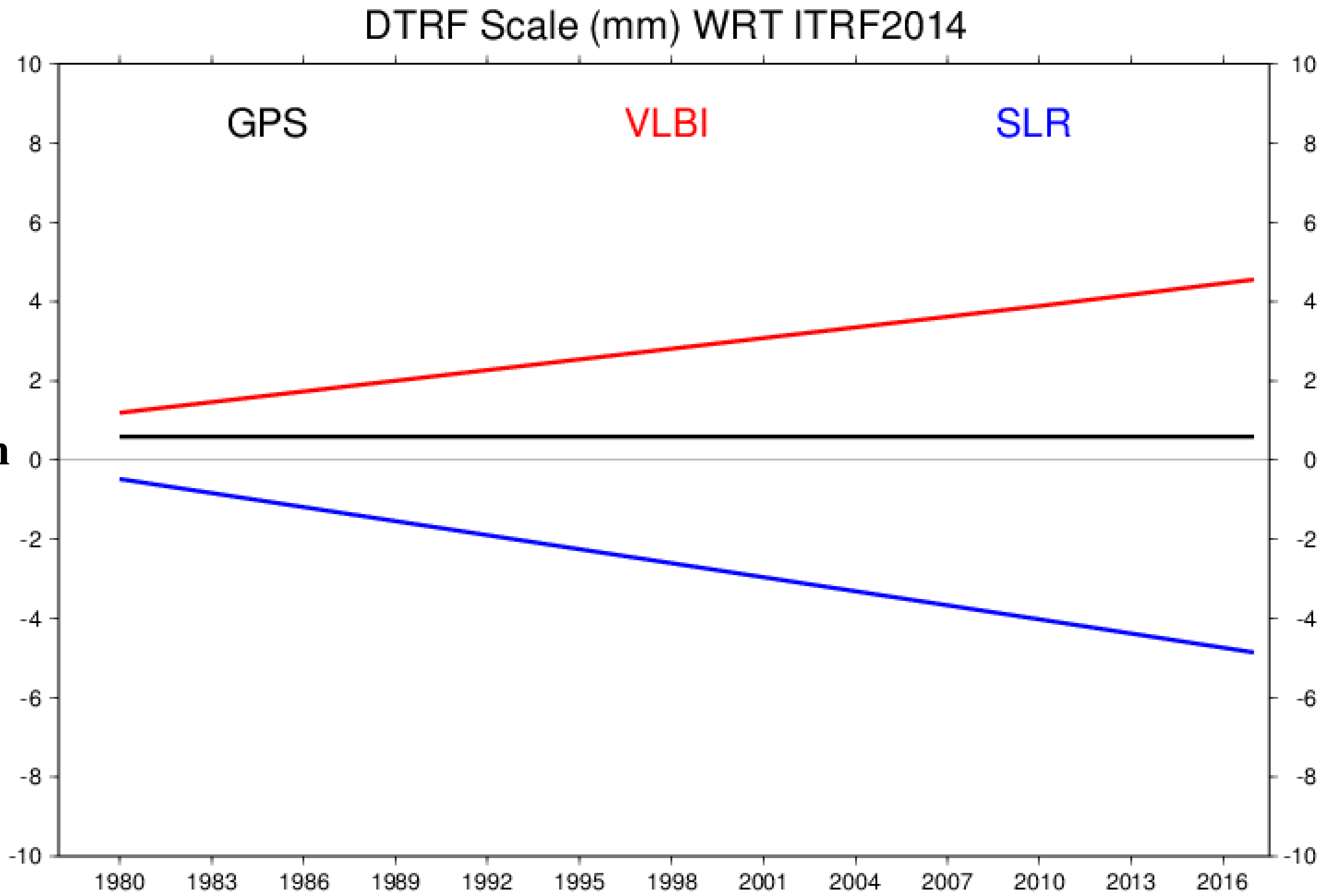
SLR to VLBI scale offset : 1.4 ppb = ~8 mm.

DTRF scales wrt ITRF2014

4.2 mm
at 2010.0

0.6 mm

-4.3 mm
at 2010.0



GPS, VLBI and SLR network solutions extracted from DTRF and ITRF 2014

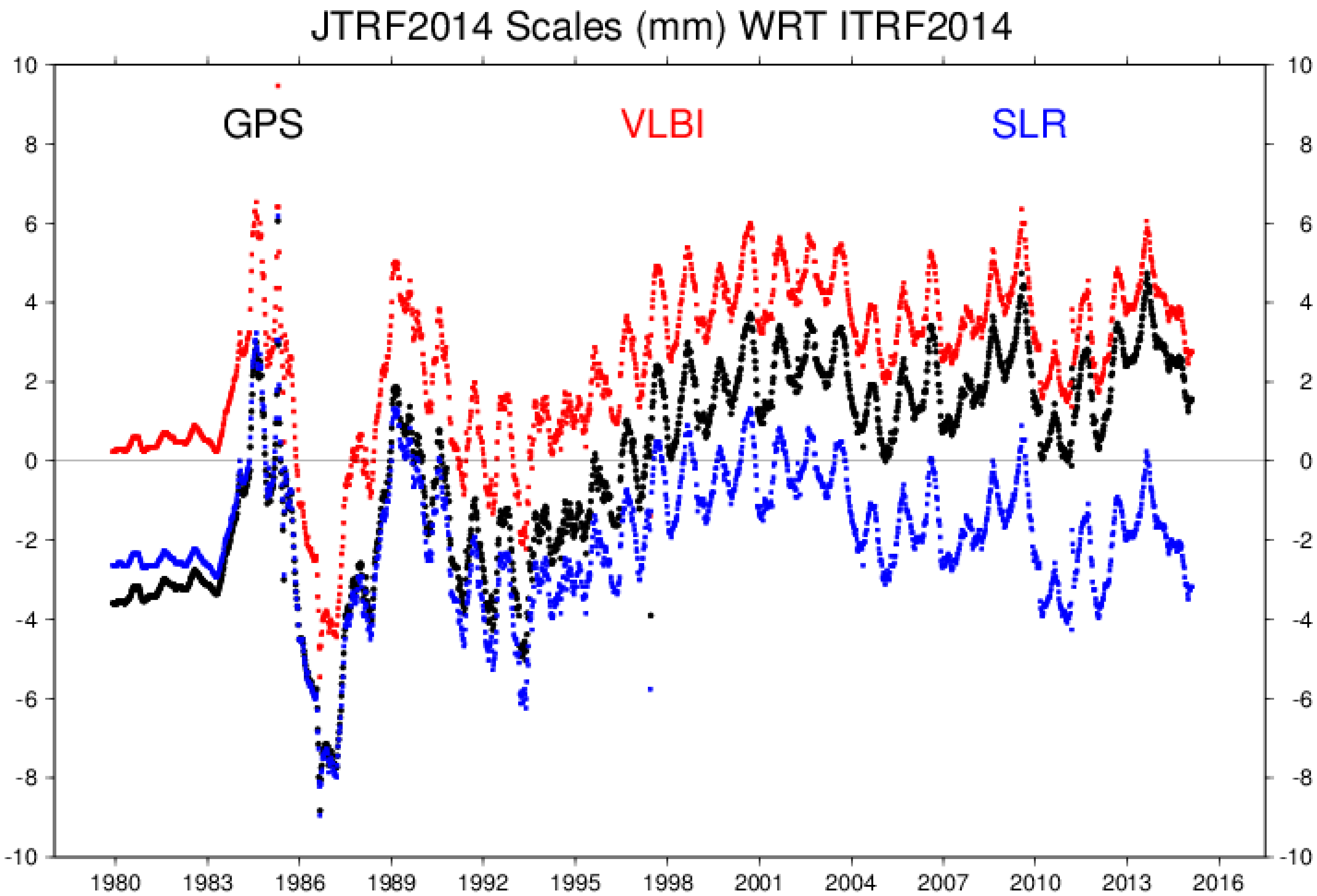
JTRF2014 scales wrt ITRF2014

At 2010.0

4.2 mm

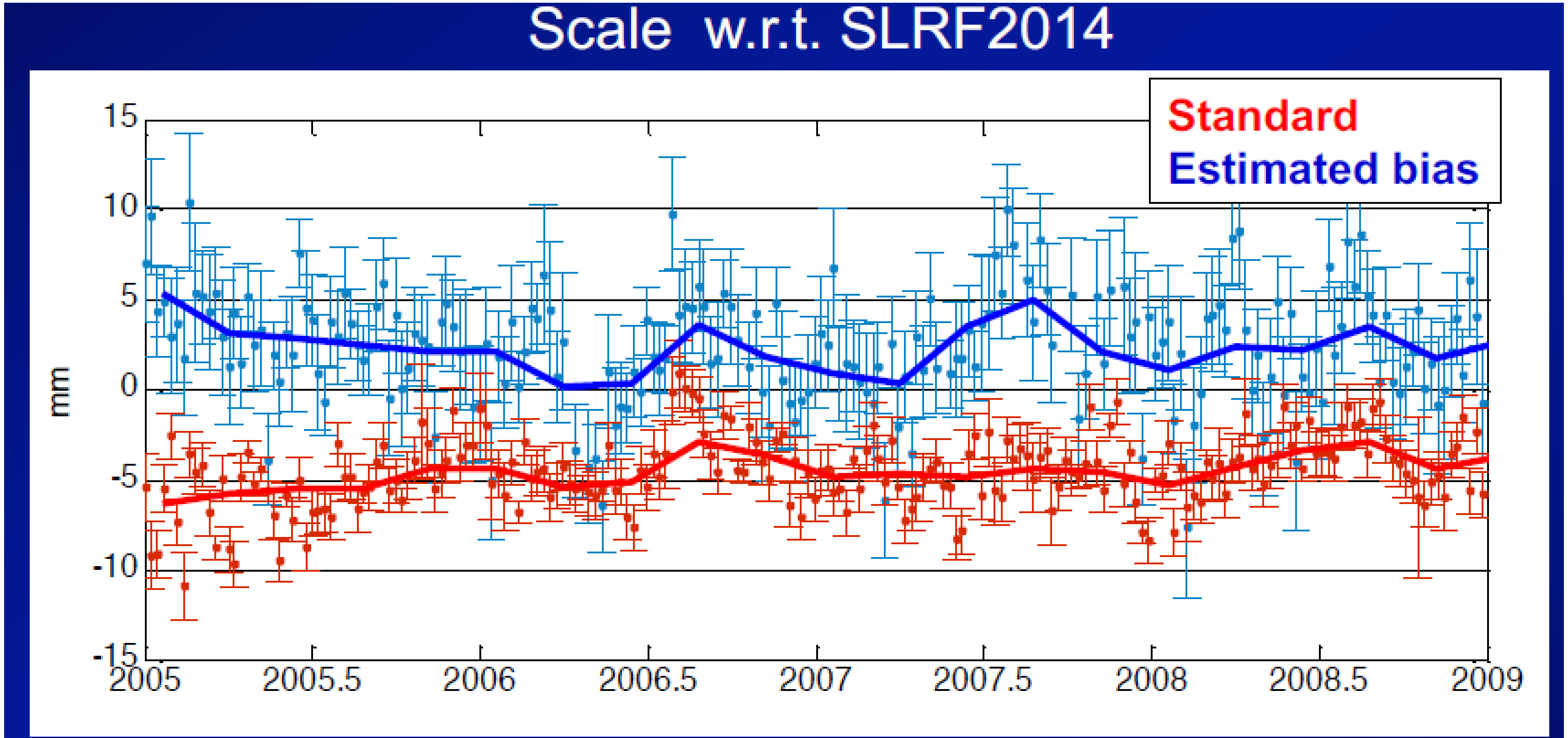
2.5 mm

-3.9 mm



GPS, VLBI and SLR network solutions extracted from JTRF and ITRF 2014

Impact of SLR Range Bias on the Scale

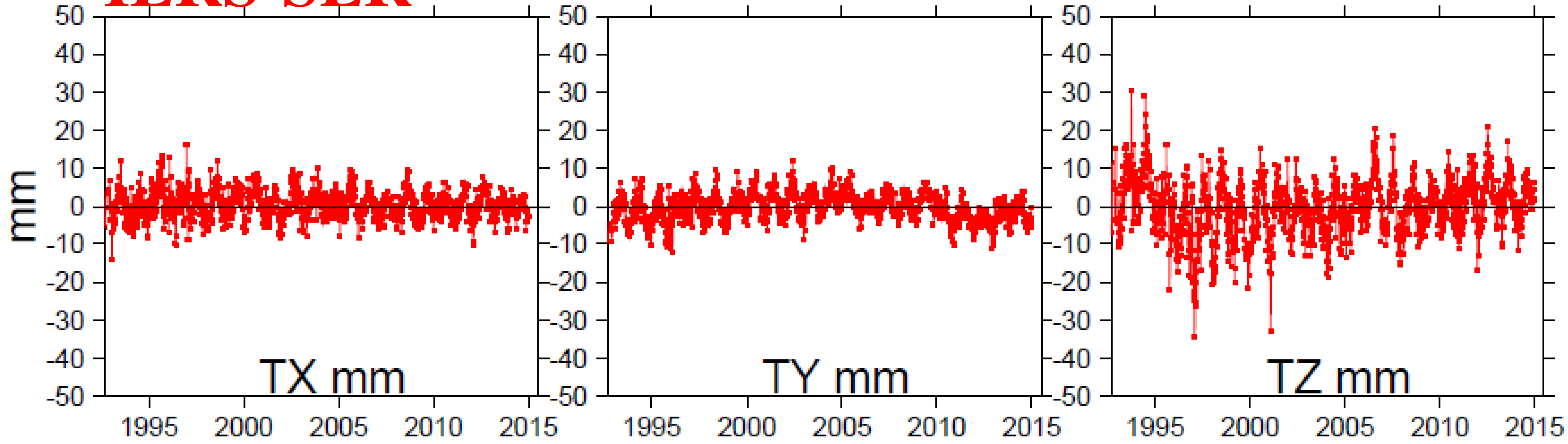


The impact on the scale motivated the ASC to move from the Pilot Project to an operational phase adopting this approach

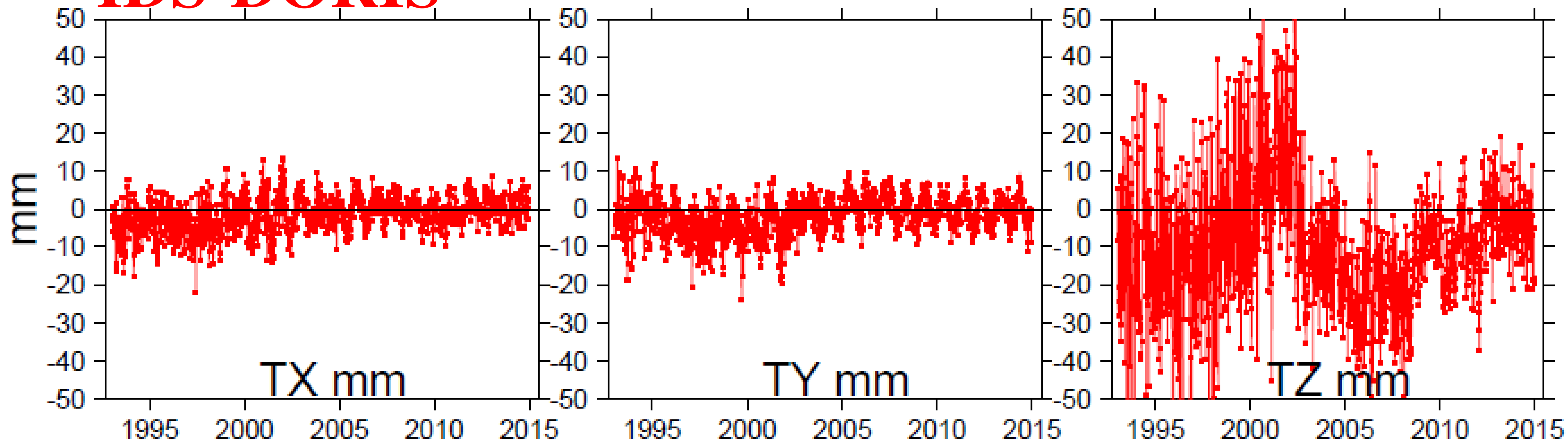
Courtesy Erricos Pavlis

ILRS-SLR & IDS-DORIS origin components wrt ITRF2014

ILRS-SLR



IDS-DORIS



"Instantaneous" position: linear & nonlinear parts

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

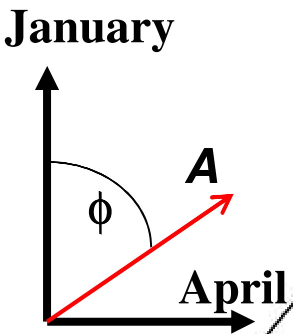
$\sum$ Post-Seismic Deformations

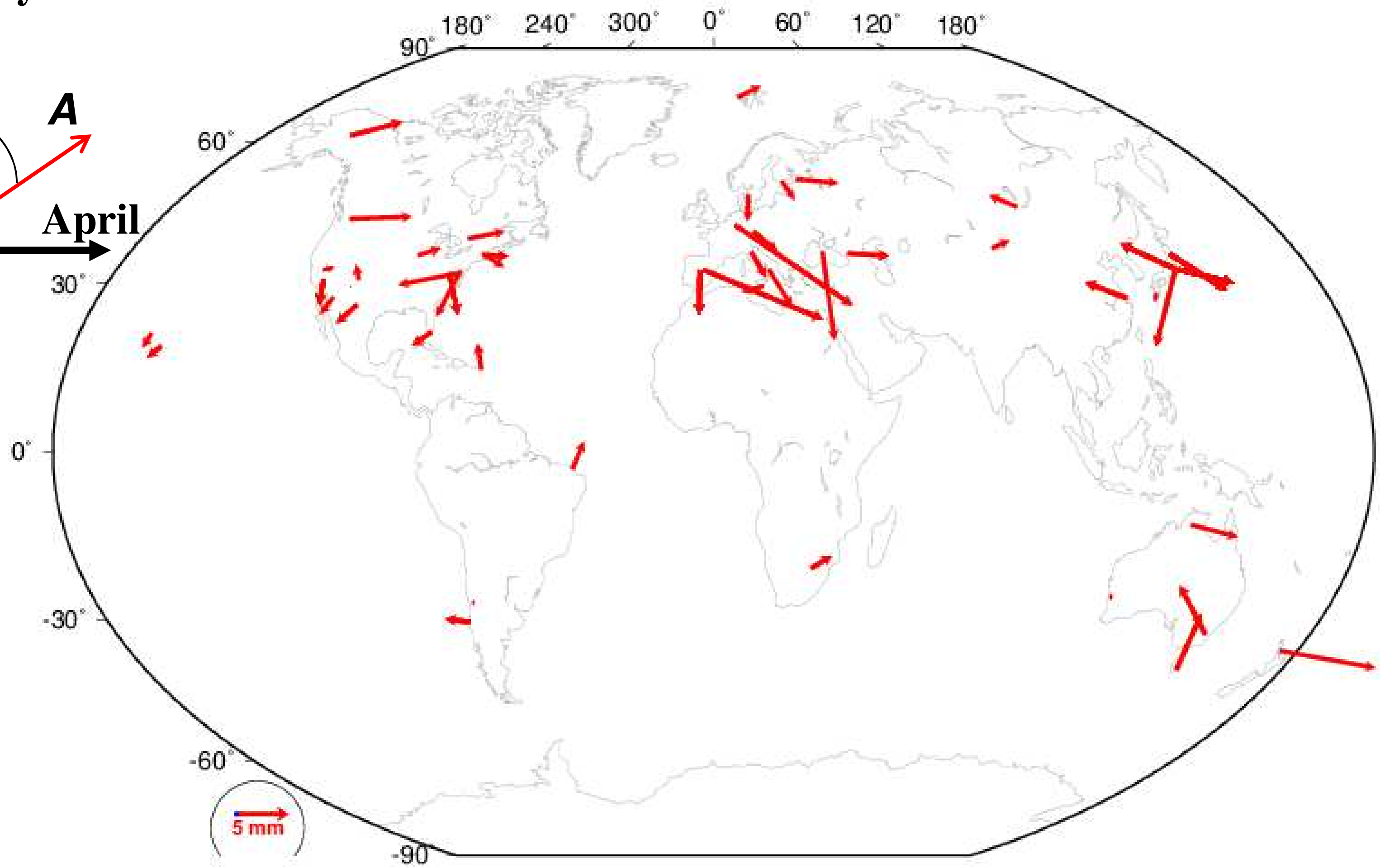
$\sum$ Seasonal Signals of all frequencies
Caution: significant discrepancies between techniques
Or a Loading model with ALL contributions (ATM, …)

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

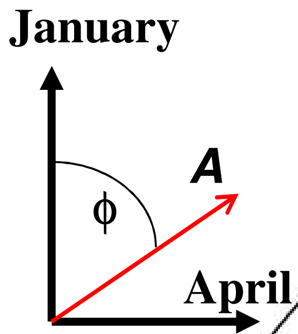
Up annual signals : VLBI (CN frame)

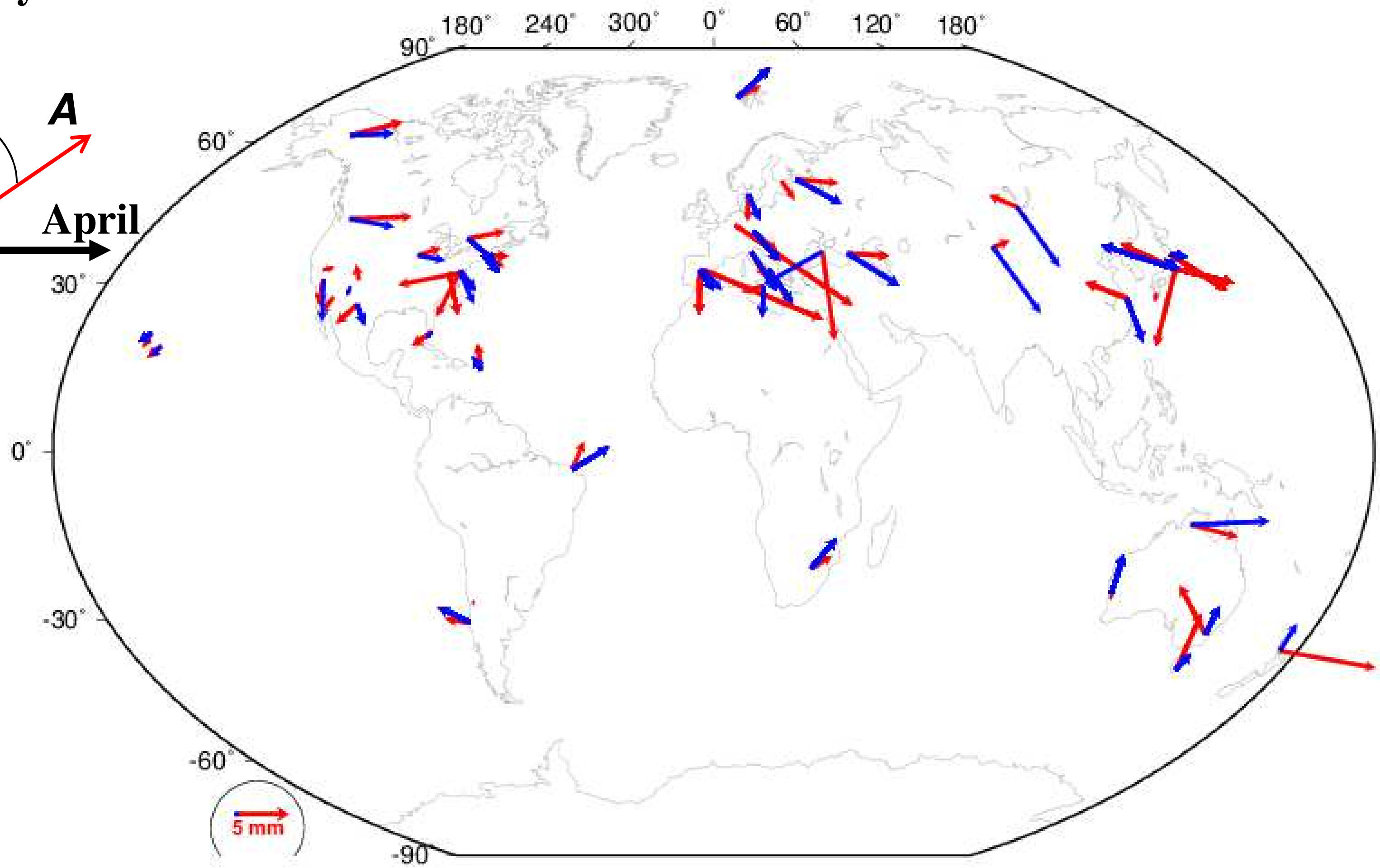




$$Dh = A.cos(\ 2\pi f\ (t - t_0) + \phi\ )$$

Up annual signals : VLBI + GNSS (CN Frame)

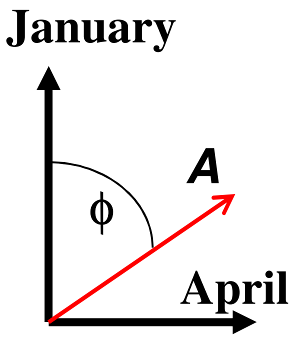




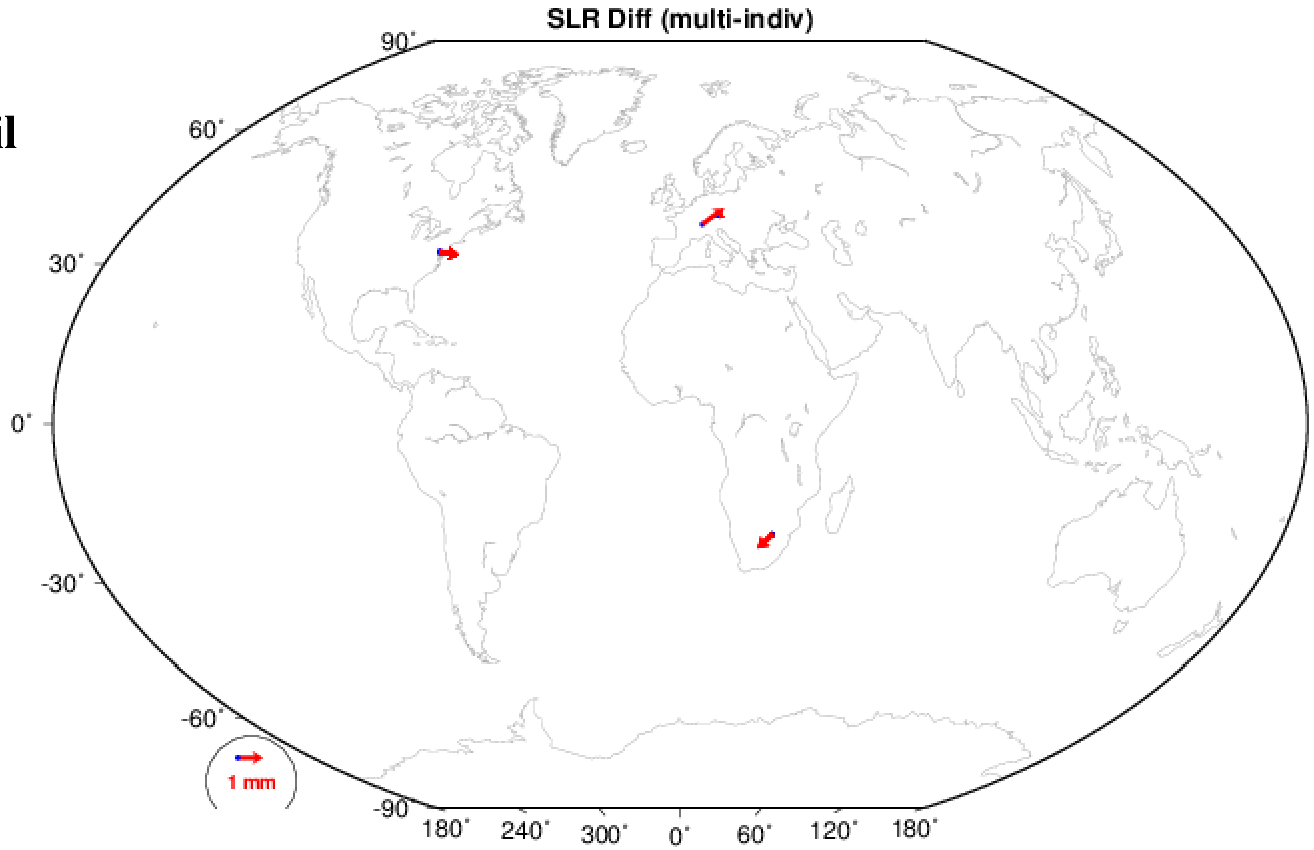
Annual Geocenter motion : different estimates

	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
Direct combination of seasonal signals(*)	1.1	36	3.3	337	2.9	36

Differences of Up annual signals in CM-SLR
Multi-technique *minus* SLR-only

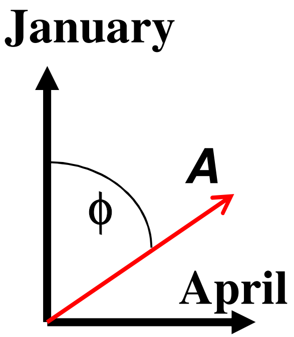


Agreement < 1 mm

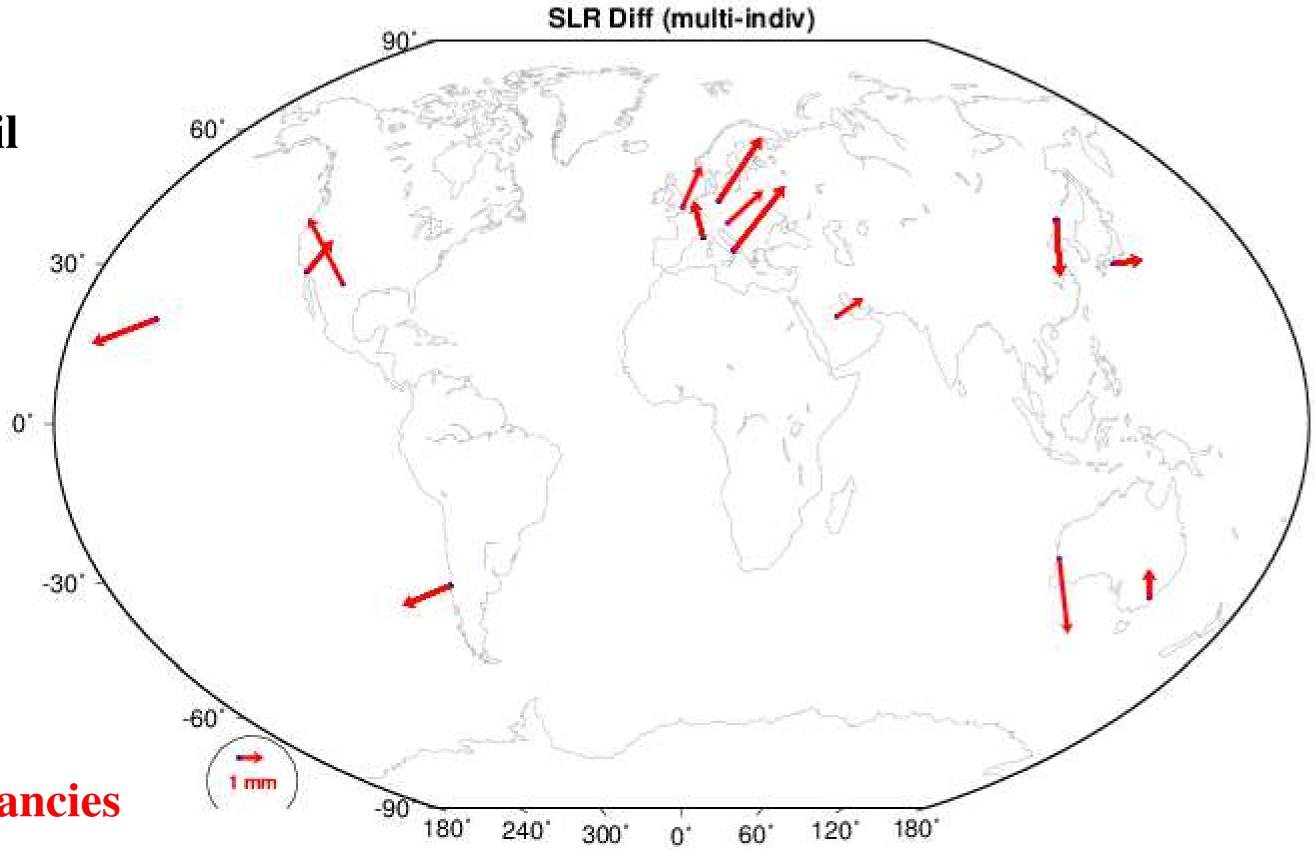


$$Dh = A.cos(\,2\pi f\,(t - t_0) - \phi\,)$$

Differences of Up annual signals in CM-SLR
Multi-technique *minus* SLR-only



Agreement > 1 mm



Large discrepancies caused by the co-motion constraints

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

Conclusion

- More than 3 decades of R&D to improve the ITRF
- The most precise/accurate reference frame available today
- Became essential with the increase of GPS/GNSS networks and their science applications
- Accessible everywhere & anywhere thanks to IGS products
- Several estimates of annual geocenter motion:
  - ± 1mm in amplitude and ± 30 deg in phase
- Evidences of a scale offset between SLR and VLBI:
  - VLBI & SLR co-exist with their discrepant scales in DTRF and JTRF
- Tie discrepancies > 5 mm for ~60% of co-location sites
- Most of current VLBI and SLR systems are old generation
- Need to mitigate technique systematic errors in preparation for ITRF2020
- Update of Chapter 4 of the IERS Conventions in progress