Global Terrestrial Reference Systems and Frames: Application to the International Terrestrial Reference System/Frame

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OUTLINE

- What is a Terrestrial Reference System (TRS), why is it needed and how is it realized ?
- Concept and Definition
- TRS Realization by a Frame (TRF)
- International Terrestrial Reference System (ITRS) and its realization: the International Terrestrial Reference Frame (ITRF)
- ITRF2008 Geodetic & Geophysical Results
- How to access the ITRF ?
- GNSS associated reference systems and their relationship to ITRF:
  - World Geodetic System (WGS84)
  - Galileo Terrestrial Reference Frame (GTRF)

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**

Ideal Terrestrial Reference System

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

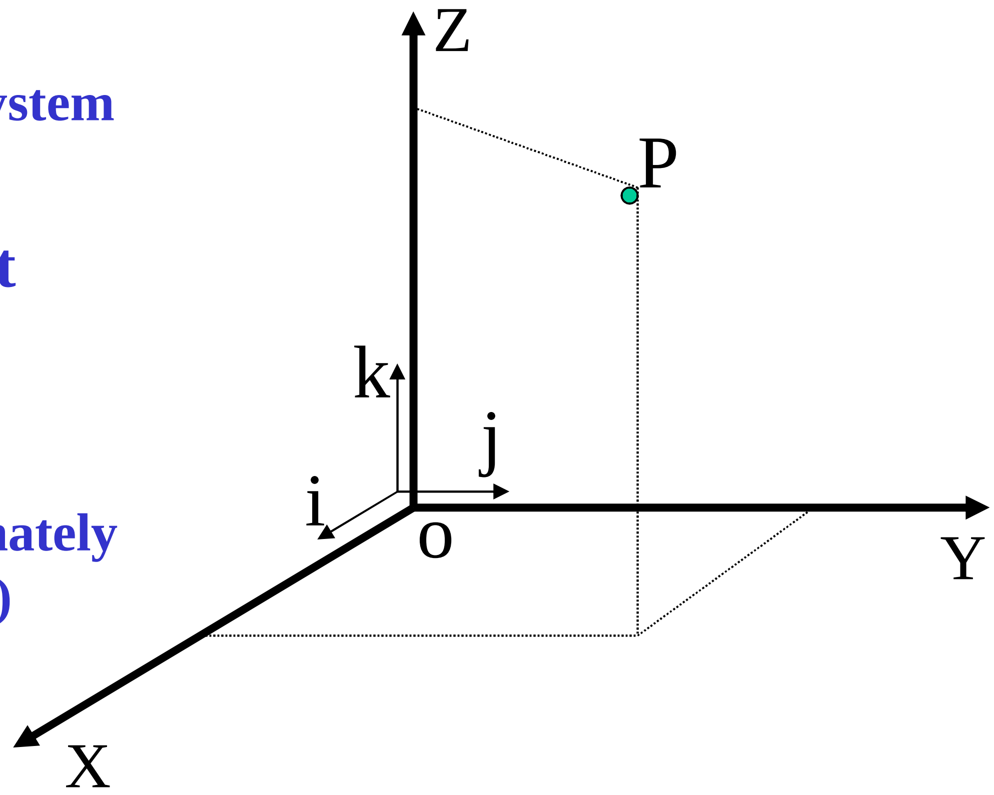
Affine Frame (O,E) where:

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

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

Terrestrial Reference Frame 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 $T = (T_x, T_y, T_z)^T$

Scale Factor λ

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

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

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

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

Transformation between TRS (2/2)

In space geodesy we use the linearized formula:

$$X_2 = X_1 + T + DX_1 + R.X_1 \qquad (1)$$

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

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

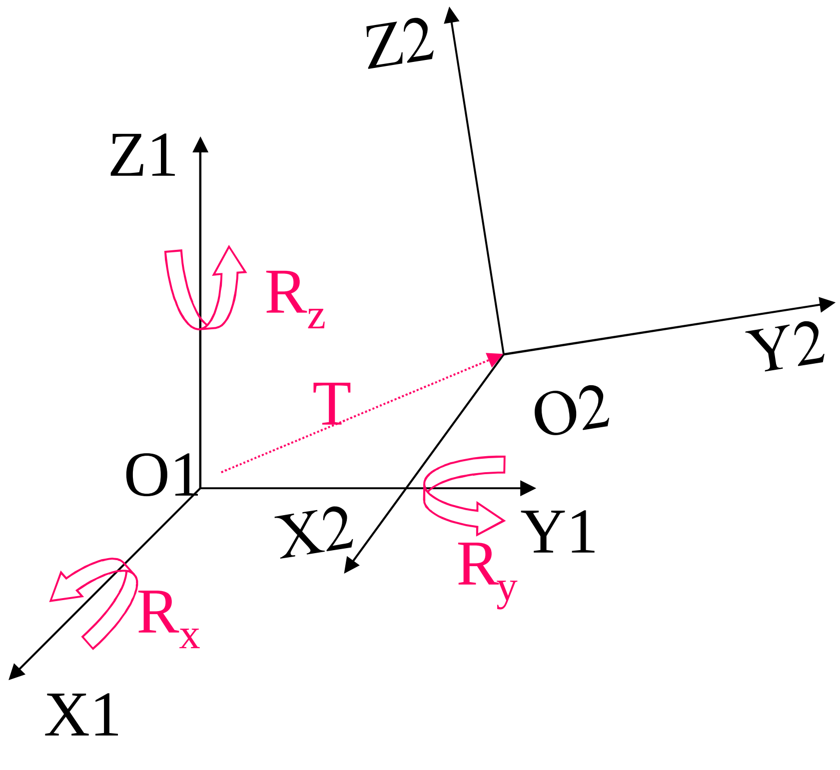
since T is less than 100 meters, D & R less than 10^{-5}

The terms of 2nd ordre are neglected: less than $10^{-10} \approx 0.6$ mm.

Differentiating equation 1 with respect to time, we have:

$$\dot{X}_2 = \dot{X}_1 + \dot{T} + \overbrace{D\dot{X}_1}^{\approx 0} + \dot{D}X_1 + \overbrace{R\dot{X}_1}^{\approx 0} + \dot{R}X_1$$

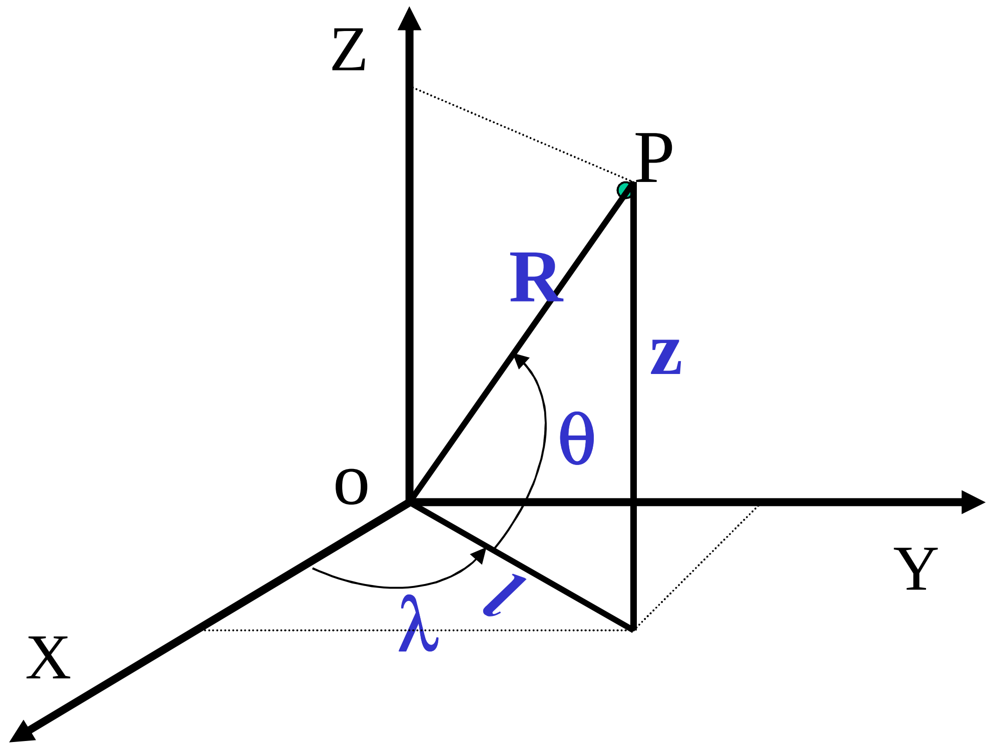
From one RF to another ?



$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_2 = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1 + \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} + \begin{pmatrix} D & -R_z & R_y \\ R_z & D & -R_x \\ -R_y & R_x & D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1$$

Coordinate Systems

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



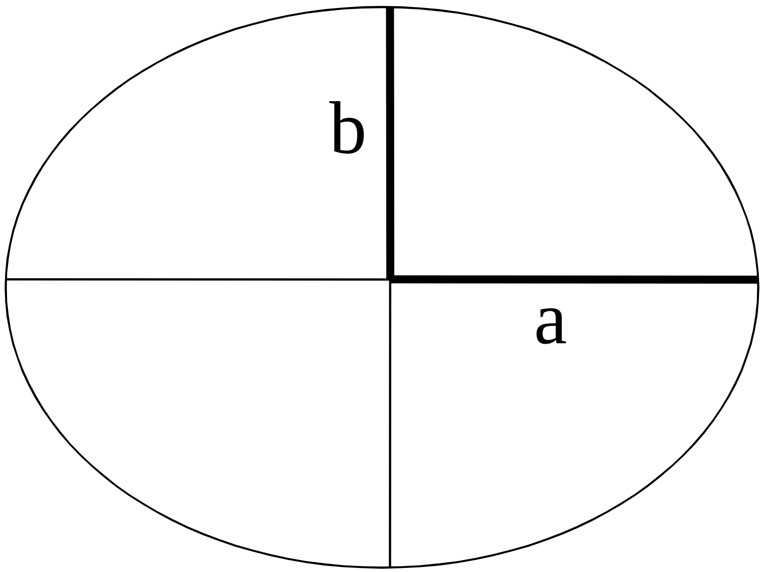
$$OP \left| \begin{array}{l} l\cos\lambda \\ l\sin\lambda \\ z \end{array} \right.$$

Cylindrical

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

Spherical

Ellipsoidal and Cartesian Coordinates: Ellipsoid definition



a: semi major axis

b: semi minor axis

f: flattening

e: eccentricity

$$e^2 = \frac{a^2 - b^2}{a^2}, \quad f = \frac{a - b}{a}$$

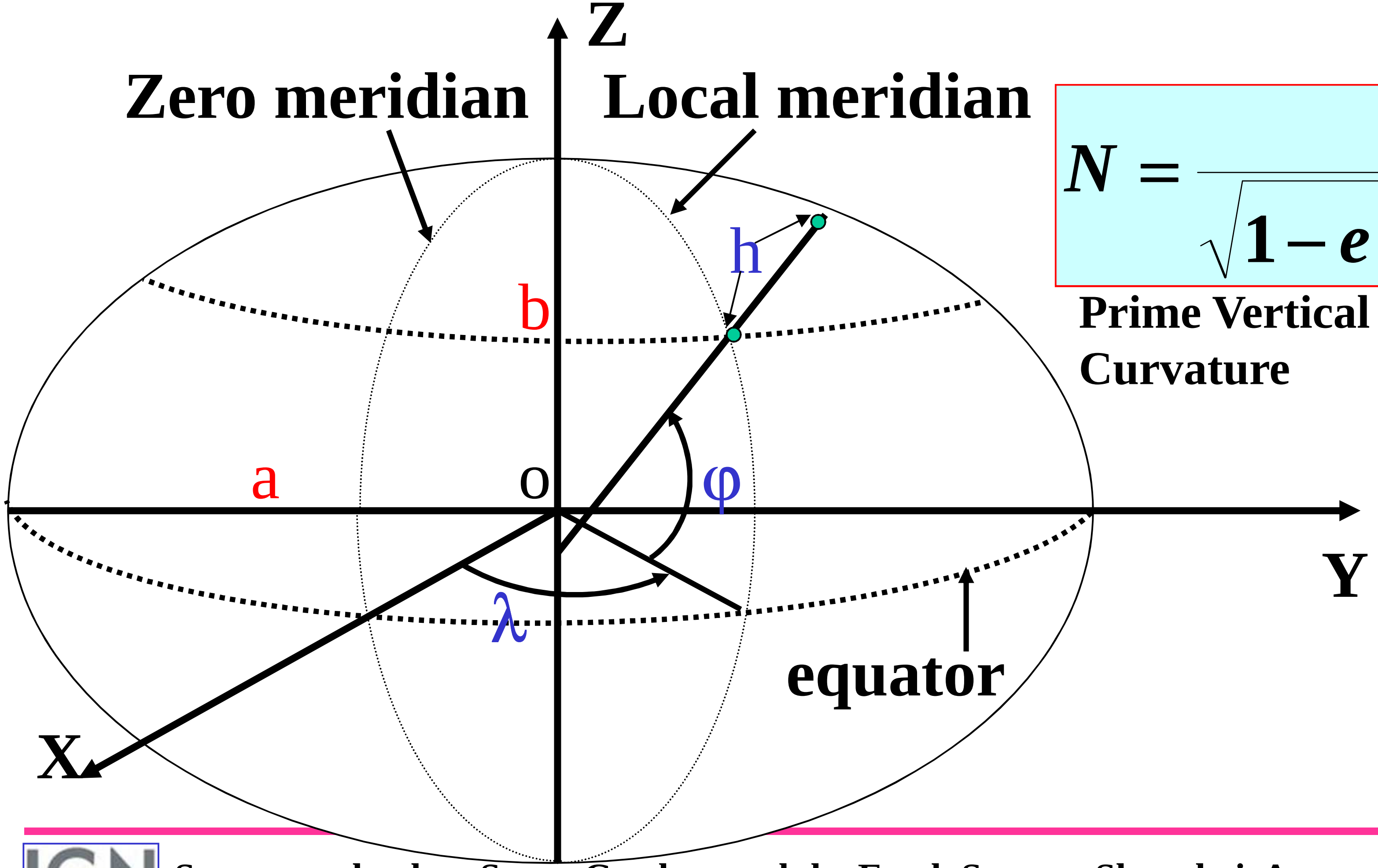
(a,b), (a,f), or (a,e^2) define entirely and geometrically the ellipsoid

Ellipsoidal and Cartesian Coordinates

$$X = (N + h)\cos\lambda\cos\varphi$$

$$Y = (N + h)\sin\lambda\cos\varphi$$

$$Z = [N(1 - e^2) + h]\sin\varphi$$



$$N = \frac{a}{\sqrt{1 - e^2\sin^2\varphi}}$$

Prime Vertical Radius of Curvature

$(X, Y, Z) \Longrightarrow (\lambda, \varphi, h)$

$$f = 1 - \sqrt{1 - e^2}$$

$$R = \sqrt{X^2 + Y^2 + Z^2}$$

$$\lambda = arctg\left(\frac{Y}{X}\right)$$

$$\mu = arctg\left[\frac{Z}{\sqrt{X^2 + Y^2}}\left((1 - f) + \left(\frac{e^2 a}{R}\right)\right)\right]$$

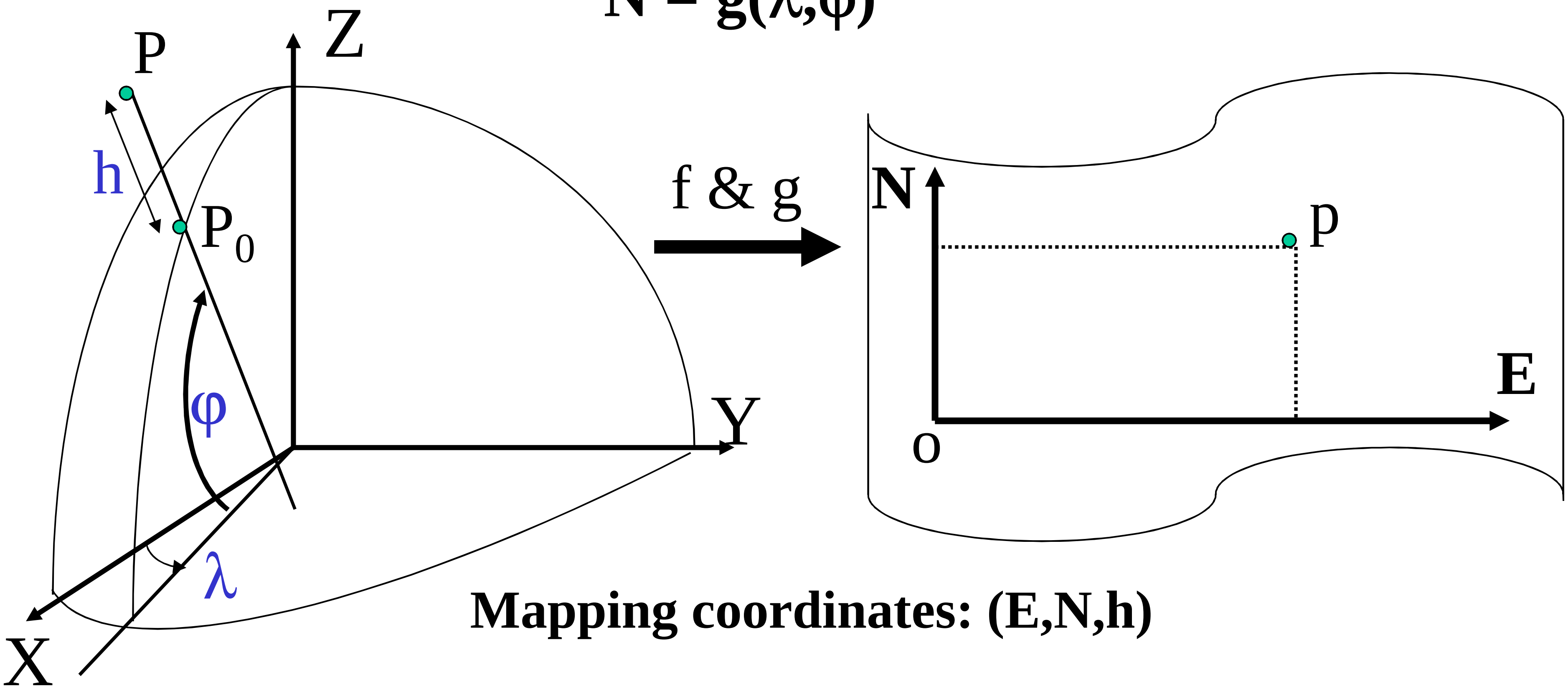
$$\varphi = arctg\left[\frac{Z(1 - f) + e^2 a \sin^3 \mu}{(1 - f)[X^2 + Y^2 - e^2 a \cos^3 \mu]}\right]$$

$$h = \sqrt{X^2 + Y^2}[\cos\varphi + Z\sin\varphi] - a\sqrt{1 - e^2 \sin^2 \varphi}$$

Map Projection

Mathematical function from an ellipsoid to a plane (map)

$$\mathbf{E = f(\lambda,\varphi)}$$
$$\mathbf{N = g(\lambda,\varphi)}$$



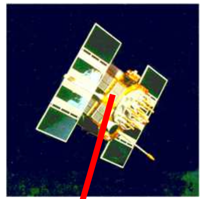
Mapping coordinates: (E,N,h)

Why a Reference System/Frame is needed?

- **Precise Orbit Determination for:**
  - **GNSS: Global Navigation Satellite Systems**
  - **Other satellite missions: Altimetry, Oceanography, Gravity**
- **Earth Sciences Applications**
  - **Tectonic motion and crustal deformation**
  - **Mean sea level variations**
  - **Earth rotation**
  - **…**
- **Geo-referencing applications**
  - **Navigation: Aviation, Terrestrial, Maritime**
  - **National geodetic systems**
  - **Cartography & Positioning**

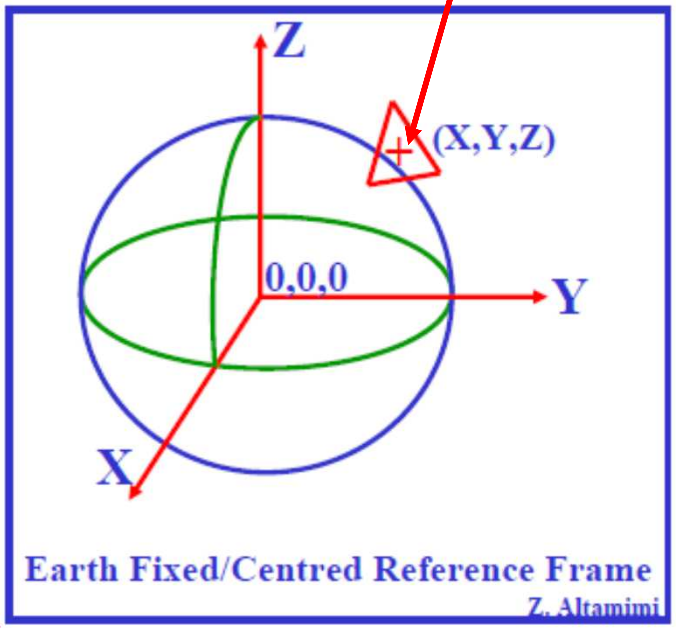
What is a Reference Frame in practice?

- **Earth fixed/centred RF: allows determination of station location/position as a function of time**



- **It seems so simple, but … we have to deal with:**
  - Relativity theory
  - Forces acting on the satellite
  - The atmosphere
  - Earth rotation
  - Solid Earth and ocean tides
  - Tectonic motion
  - …

Origin, Scale & Orientation



- **Station positions and velocities are now determined with mm and mm/yr precision**

"Motions" of the deformable Earth

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

- **Non-Linear motion:**
  - **Seasonal: Annual, Semi & Inter-Annual caused by loading effects**
  - **Rupture, transient: uneven motion caused by Earthquakes, Volcano Eruptions, etc.**

Crust-based TRF

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

$$X(t) = X_0 + \dot{X}.(t - t_0) + \sum_i \Delta X_i(t)$$

- X_0 : **point position at a reference epoch t_0**
- $\dot{X}$: **point linear velocity**
- $\Delta X_i(t)$: **high frequency time variations:**
  - **Solid Earth, Ocean & Pole tides**
  - **Loading effects: atmosphere, ocean, hydrology, Post-glacial-Rebound**
  - **... Earthquakes**

Reference Frame Representations

- "Quasi-Instanteneous" Frame: mean station positions at "short" interval:
  - One hour, 6-h, 12-h, one day, one week

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

- Long-Term Secular Frame: mean station positions at a reference epoch (t_0) and station velocities: $X(t) = X_0 + V*(t - t_0)$

Implementation of a TRF

- Definition at a given epoch, by selecting 7 parameters, tending to satisfy the theoretical definition of the corresponding TRS
- 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 ?
« TRF definition »

- **Origin & rate:** CoM (Satellite 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

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

- **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:

$$X_2 = X_1 + A\theta$$

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

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

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

Least squares adjustment gives for θ :

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

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

The Design matrix A

14 parameters

7 parameters

$$A = \begin{pmatrix}
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 & & & & & & & \\
0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 & & & & 0 & & & \\
0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 & & & & & & & \\
 & & & & & & & 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\
 & & & \approx 0 & & & & 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 \\
 & & & & & & & 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot
\end{pmatrix}$$

Note: ***A*** could be reduced to specific parameters. E.g. if only rotations and rotation rates are needed, then the first 4 columns of the two parts of ***A*** are deleted

TRF definition using minimum constraints (2/3)

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

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

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:

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

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

Selecting a reference solution X_R ,the equation of minimal constraints is given by:

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

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

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

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

Combination of daily or weekly TRF solutions (1/3)

The basic combination model is written as:

$$X_s^i = X_c^i + T_s + D_s X_c^i + R_s X_c^i$$

Inputs: X_s^i, coordinates of point i of individual solution s.
Outputs (unknowns): combined coordinates X_c^i and transformation parameters T_s, D_s, R_s from TRF s to TRF c.
Note that the translation vector T_s and the rotation matrix R_s have each three components around the three axes X, Y, Z.

The unknown parameters are linearized around their approximate values: x_0^i, y_0^i, z_0^i, so that $x_c^i = x_0^i + \delta x^i$ (respectively y_c^i, z_c^i).

Note: this combination model is valid at a give epoch, t_s, for both the input and output station coordinates

Combination of daily or weekly TRF solutions (2/3)

The observation equation system is written as:

$$\begin{pmatrix} I & A_s \end{pmatrix} \begin{pmatrix} \delta\chi_s \\ \delta T_s \end{pmatrix} + B_s = V_s$$

and the normal equation is:

$$\begin{pmatrix} P_s & P_s A_s \\ A_s^T P_s & A_s^T P_s A_s \end{pmatrix} \begin{pmatrix} \delta\chi_s \\ \delta T_s \end{pmatrix} + \begin{pmatrix} P_s B_s \\ A_s^T P_s B_s \end{pmatrix} = 0$$

where I is the identity matrix, As is the design matrix related to solution s, $\delta\chi_s$ and δT_s are the linearized unknowns of station coordinates and transformation parameters, respectively. B_s are the (observed - computed) values and V_s are the residuals. P_s: weight matrix = Σ_s^{-1}: inverse of variance-covariance matrix.

Combination of daily or weekly TRF solutions (3/3)

The design matrixs A_s has the following form:

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

Definition of the combined TRF

- **The normal equation system described in the previous slides is singular and has a rank diffciency of 7 parameters.**
- **The 7 parameters are the defining parameters of the combind TRF *c*: origin (3 components), scale (1 component) and orientation (3 components).**
- **The combined TRF *c*, could be defined by, e.g.:**
  - **Fixing to given values 7 parameters among those to be estimated**
  - **Using minimum constraint equation over a selected set of stations of a reference TRF solution X_R.**
    Refer to slide 24 for more details…

Combination of long-term TRF solutions

The basic combination model is extended to include station velocities and is written as:

$$\begin{cases} X_s^i = X_c^i + T_s + D_s X_c^i + R_s X_c^i \\ \dot{X}_s^i = \dot{X}_c^i + \dot{T}_s + \dot{D}_s X_c^i + \dot{R}_s X_c^i \end{cases}$$

where the dotted parameters are their time derivatives.

Inputs: X_s^i, position of point i, at epoch t_s and velocities, $\dot{X}_s^i$, of individual solution s.

Outputs: combined positions X_c^i, at epoch t_s, velocities and transformation parameters T_s, D_s, R_s, at epoch t_s, from TRF s to TRF c.

In the same way as for daily or weekly TRF combination, observation and normal equations could easily be derived.

Note: this combination model is only valid at a give epoch, both for the input and output station coordinates

Stacking of TRF time series

The basic combination model is written as:

$$X_s^i = X_c^i(t_0) + (t_s - t_0)\dot{X} + T_s + D_s X_c^i + R_s X_c^i$$

Inputs: Time series of station positions, X_s^i, at different epochs t_s.
Outputs: combined positions X_c^i at epoch t_0, velocities and transformation parameters T_s, D_s, R_s from TRF s to TRF c.

Here also, observation and normal equations are construted and solved by least squares adjustment.

Space Geodesy Techniques

- **Very Long Baseline Interferometry (VLBI)**
- **Lunar Laser Ranging (LLR)**
- **Satellite Laser Ranging (SLR)**
- **DORIS**
- **GNSS: GPS, GLONASS, GALILEO, COMPASS, …**

- **Local tie vectors at co-location sites**

Complex of Space Geodesy instruments

SLR/LLR

VLBI

GPS

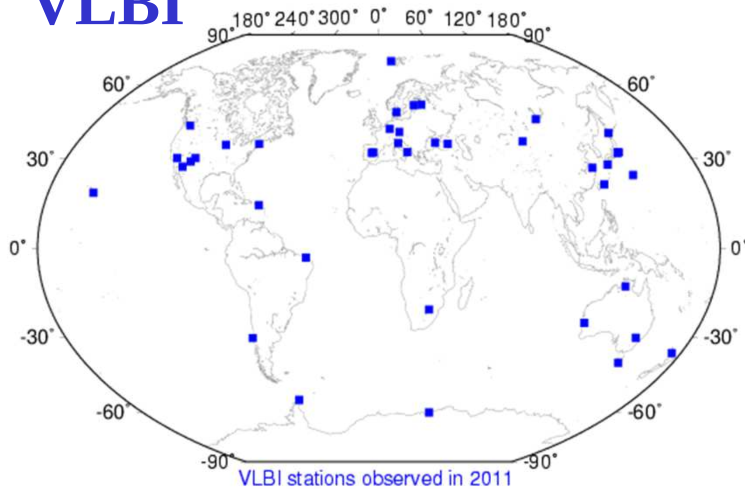
DORIS

Reference frame definition by individual techniques

	Satellite Techniques	VLBI
Origin	Center of Mass	-
Scale	GM, c & Relativistic corrections	c Relativistic corrections
Orientation	Conventional	Conventional

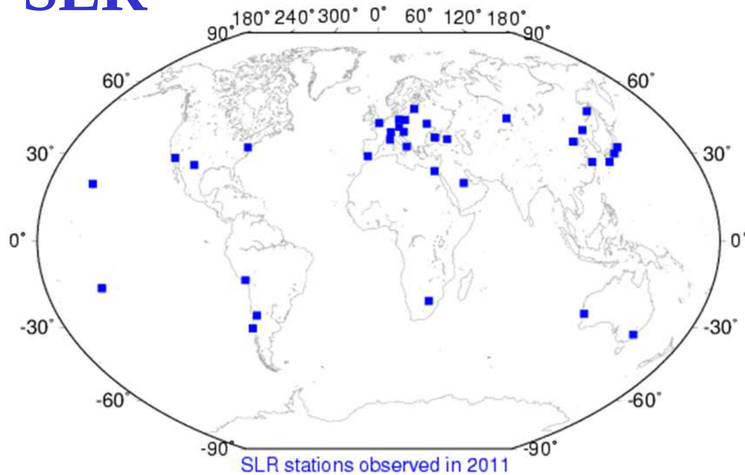
Current networks: stations observed in 2011

VLBI



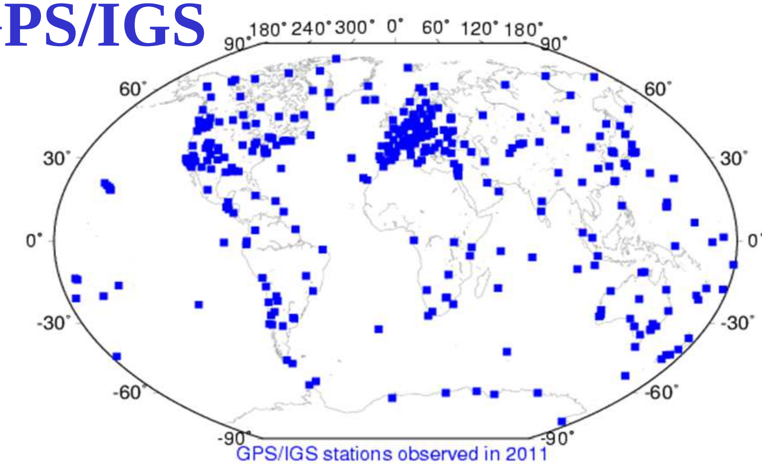
VLBI stations observed in 2011

SLR



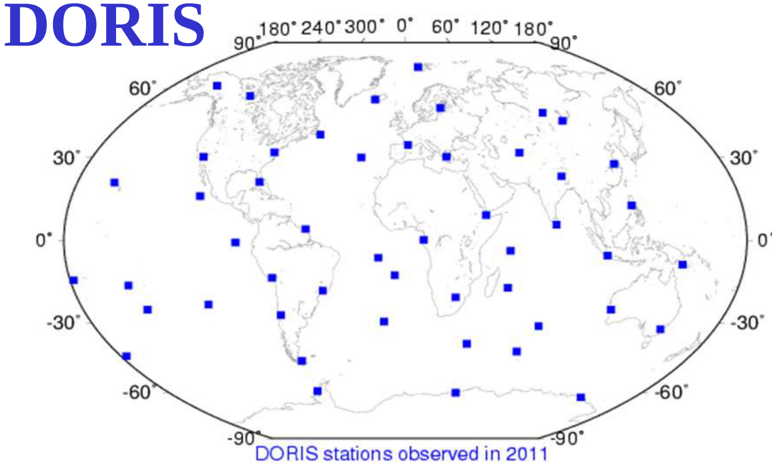
SLR stations observed in 2011

GPS/IGS



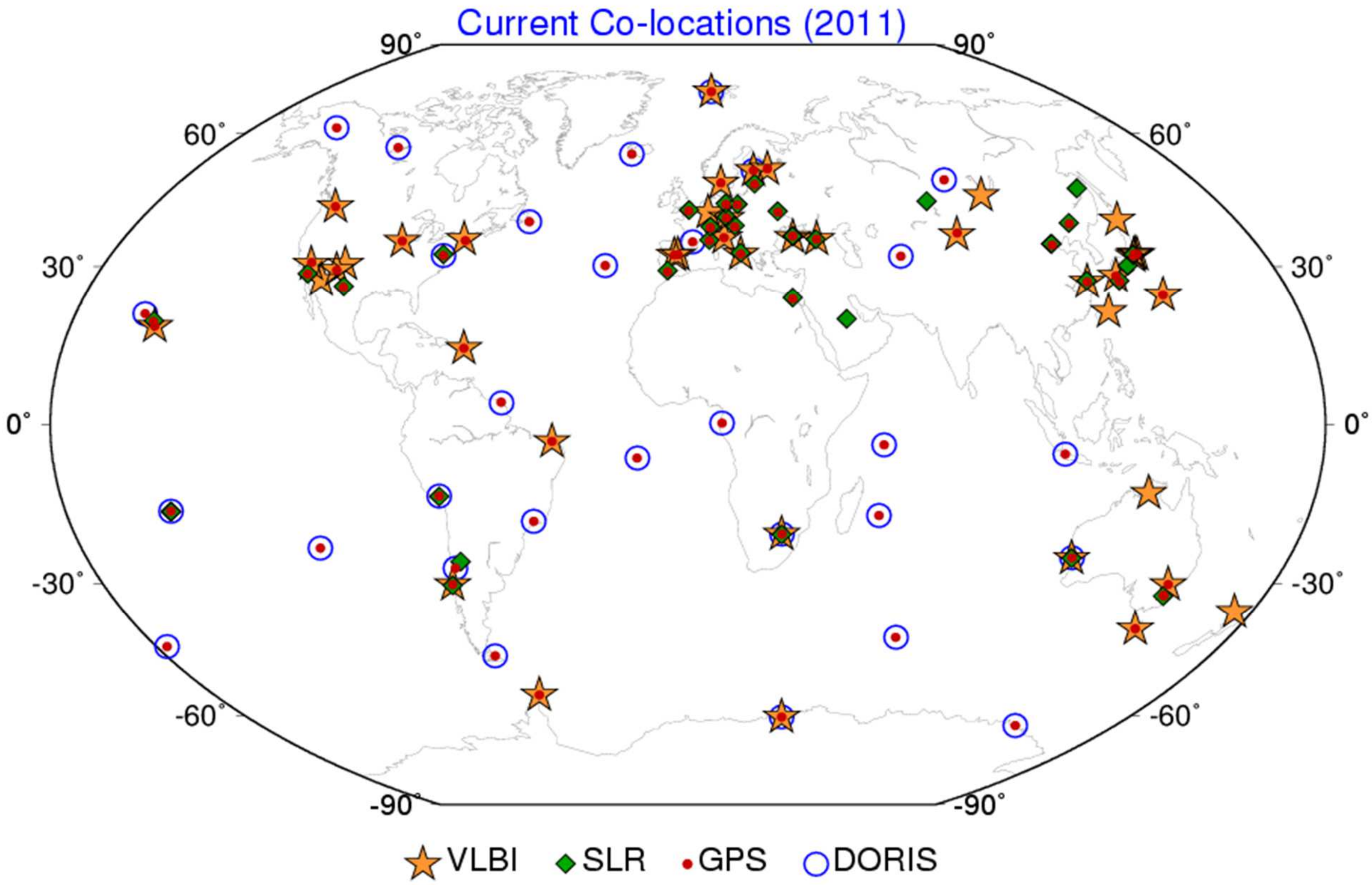
GPS/IGS stations observed in 2011

DORIS



DORIS stations observed in 2011

Current Co-locations (2011)



International Association of Geodesy
International Services

- International Earth Rotation and Reference Systems Service (IERS) (1988)

- Intern. GNSS Service (IGS) (1994)
- Intern. Laser Ranging Service (ILRS) (1998)
- Intern. VLBI Service (IVS) (1999)
- Intern. DORIS Service (IDS) (2003)

http://www.iag-aig.org/

International Terrestrial Reference System (ITRS)

Realized and maintained by the IERS

International Earth Rotation and Reference Systems Service (IERS)

Established in 1987 (started Jan. 1, 1988) by IAU and IUGG to realize/maintain/provide:

- **The International Celestial Reference System (ICRS)**
- **The International Terrestrial Reference System (ITRS)**
- **Earth Orientation Parameters (EOP)**
- **Geophysical data to interpret time/space variations in the ICRF, ITRF & EOP**
- **Standards, constants and models (i.e., conventions)**

http://www.iers.org/

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

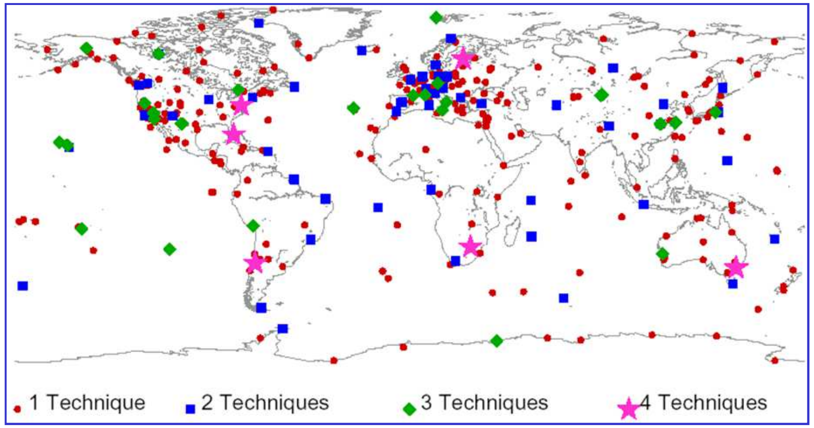
- **Origin**: Center of mass of the whole Earth, including oceans and atmosphere
- **Unit of length**: meter SI, consistent with TCG (Geocentric Coordinate Time)
- **Orientation**: consistent with BIH (Bureau International de l'Heure) orientation at 1984.0.
- **Orientation time evolution**: ensured by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

$$h = \int_C X \times V dm = 0$$

International Terrestrial Reference System (ITRS)

- Realized and maintained by ITRS Product Center of the IERS
- Its Realization is called International Terrestrial Reference Frame (ITRF)
- Set of station positions and velocities, estimated by combination of VLBI, SLR, GPS and DORIS individual TRF solutions
- Based on Co-location sites

Adopted by IUGG in 1991 for all Earth Science Applications



More than 800 stations located on more than 500 sites

Available: ITRF88,…,2000, 2005

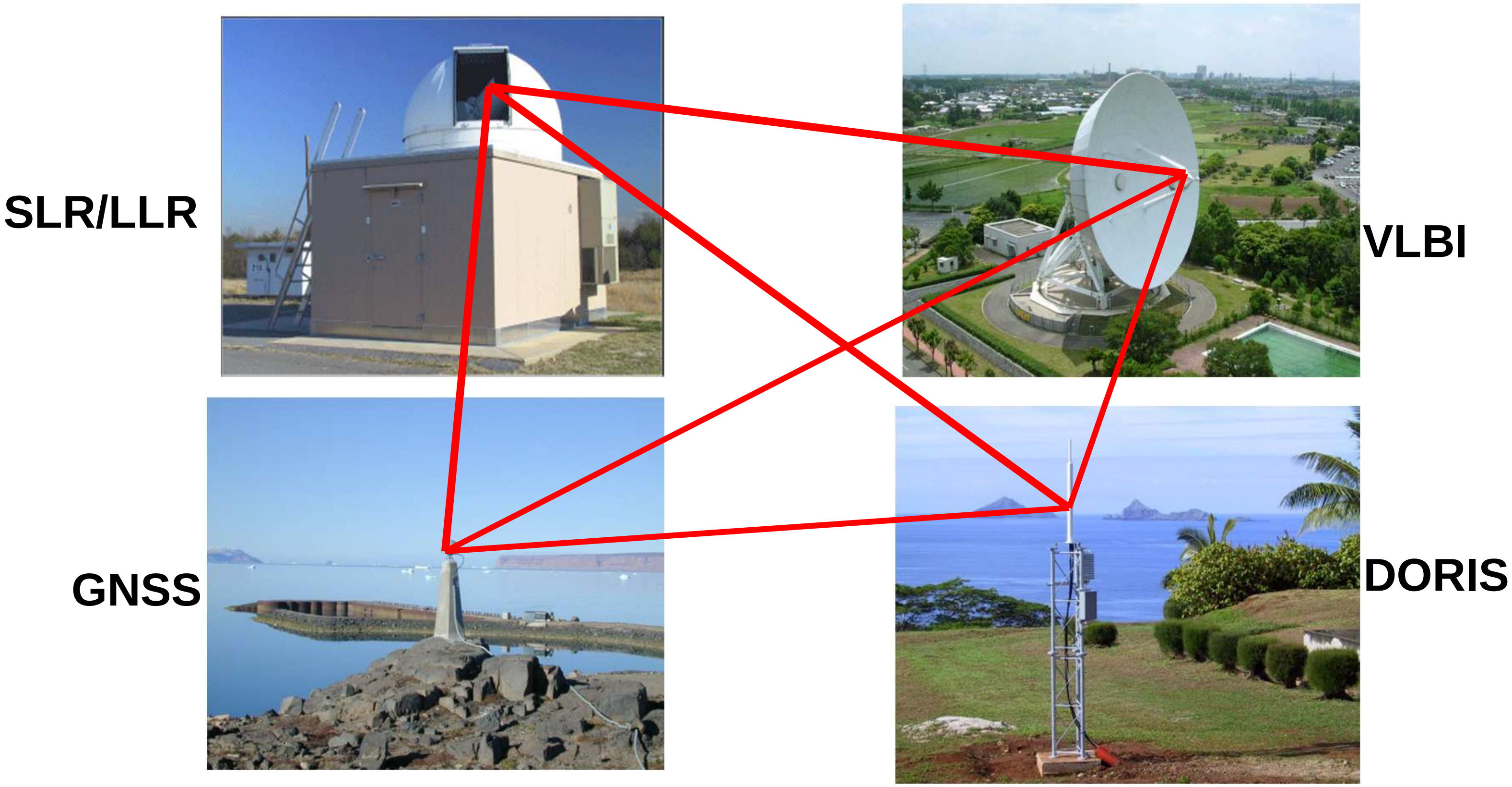
Latest : ITRF2008

http://itrf.ign.fr

Co-location site

- **Site where two or more instruments are operating**
- **Surveyed in three dimensions, using classical or GPS geodesy**
- **Differential coordinates (DX, DY, DZ) are available**

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



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Strenghts :
Contribution of Geodetic Techniques to the ITRF

Mix of techniques is fundamental to realize a frame that is stable in origin, scale, and with sufficient coverage

Technique Signal Source Obs. Type	**VLBI** Microwave Quasars Time difference	**SLR** Optical Satellite Two-way absolute range	**GPS** Microwave Satellites Range change	**DORIS**
Celestial Frame & UT1	**Yes**	No	No	**No**
Polar Motion	**Yes**	**Yes**	**Yes**	Yes
Scale	**Yes**	**Yes**	No (but maybe in the future!)	**Yes**
Geocenter ITRF Origin	No	**Yes**	Future	**Future**
Geographic Density	No	No	**Yes**	**Yes**
Real-time & ITRF access	Yes	Yes	**Yes**	Yes
Decadal Stability	**Yes**	**Yes**	Yes	Yes

How the ITRF is constructed ?

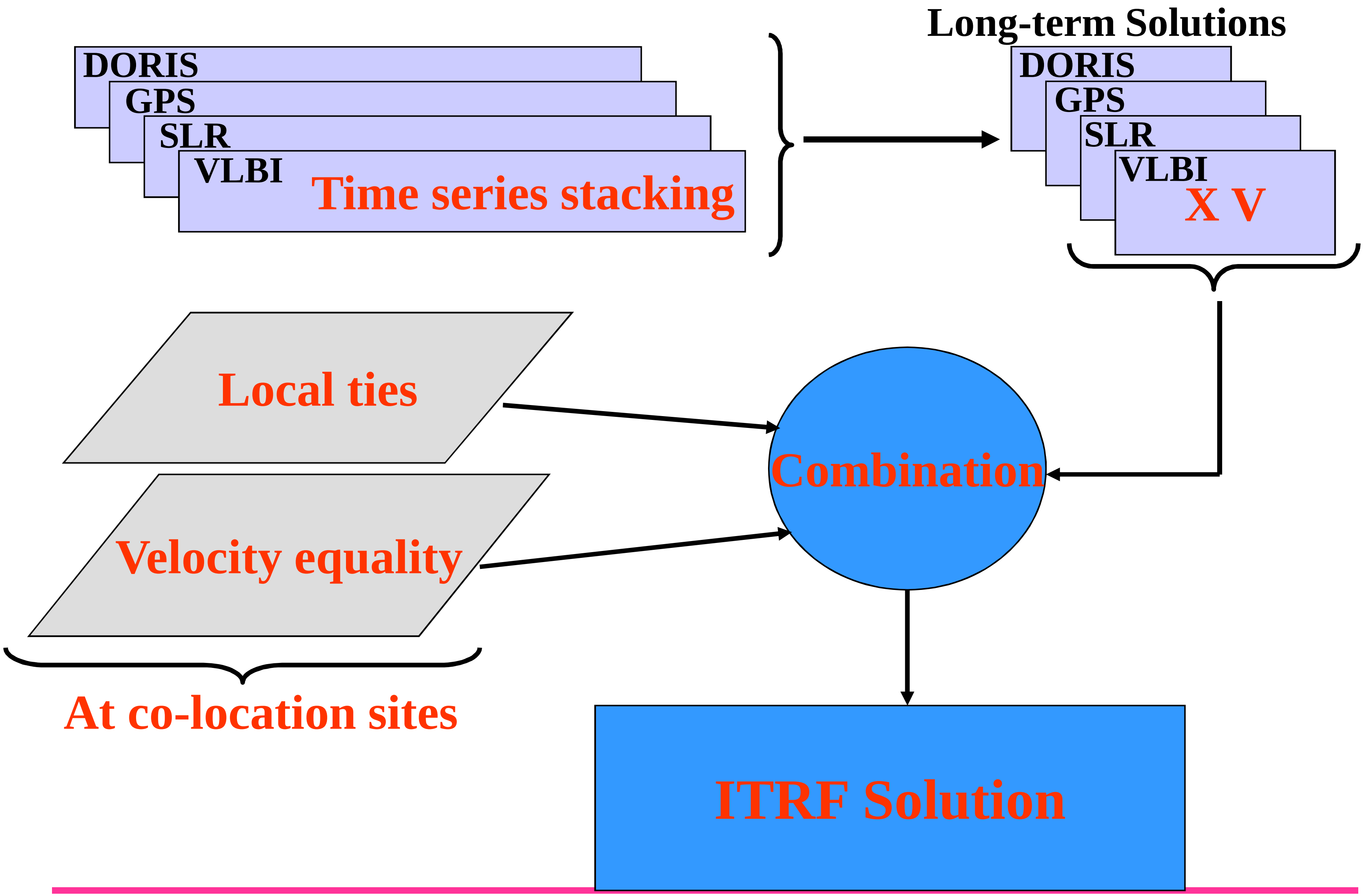
- **Input :**
  - Time series of mean station positions (at weekly or daily sampling) and daily EOPs from the 4 techniques
  - Local ties in co-location sites
- **Output :**
  - Station positions at a reference epoch and linear velocities
  - Earth Orientation Parameters

CATREF 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

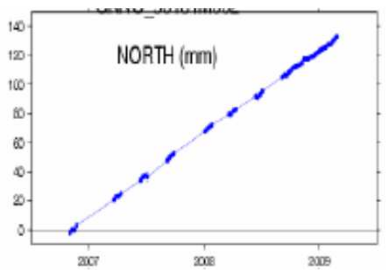


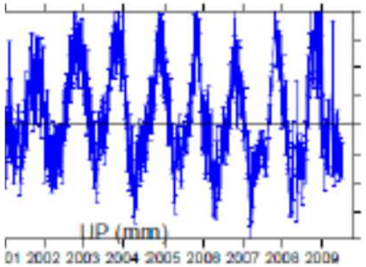
SINEX Format

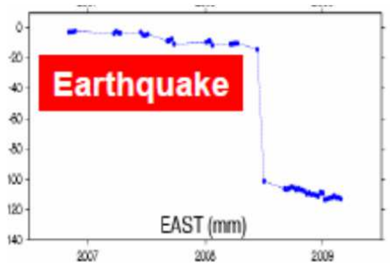
```
%=SNX 2.01 IGN 10:157:00000 IGN 04:003:00000 09:005:00000 C 01308 2 X V
*-------------------------------------------------------------------------------
+SITE/ID
*CODE PT __DOMES__ T _STATION DESCRIPTION__ APPROX_LON_ APPROX_LAT_ _APP_H_
 ANKR  A 20805M002   Ankara, Turkey          32 45 30.4  39 53 14.5   976.0
...
+SOLUTION/EPOCHS
*Code PT SOLN T Data_start__ Data_end____ Mean_epoch__
 ANKR  A    5 C 04:003:00000 08:133:00000 06:067:43200

...
+SOLUTION/ESTIMATE
*INDEX TYPE__ CODE PT SOLN _REF_EPOCH__ UNIT S __ESTIMATED VALUE____ _STD_DEV___

..................
    19 STAX   ANKR  A    5 06:183:00000 m    2 0.412194852609284E+07 0.17234E-03
    20 STAY   ANKR  A    5 06:183:00000 m    2 0.265218790321918E+07 0.12249E-03
    21 STAZ   ANKR  A    5 06:183:00000 m    2 0.406902377621100E+07 0.16467E-03
    22 VELX   ANKR  A    5 06:183:00000 m/y  2 -.668839830148651E-02 0.14215E-03
    23 VELY   ANKR  A    5 06:183:00000 m/y  2 -.270320979559104E-02 0.10069E-03
    24 VELZ   ANKR  A    5 06:183:00000 m/y  2 0.971313341105308E-02 0.13542E-03

..................
+SOLUTION/MATRIX_ESTIMATE L COVA
*PARA1 PARA2 ____PARA2+0__________ ____PARA2+1__________ ____PARA2+2__________
     1     1 0.150471439320574E-06
     2     1 -.140657602040892E-06 0.176947767515801E-06
     3     1 -.115071650206259E-06 0.127287839143953E-06 0.122184056413112E-06
..................
```

Power of station position time series

- **Monitor station behavior**
  - Linear, non-linear (seasonal), and discontinuities







- **Monitor time evolution of the frame physical parameter (origin and scale)**

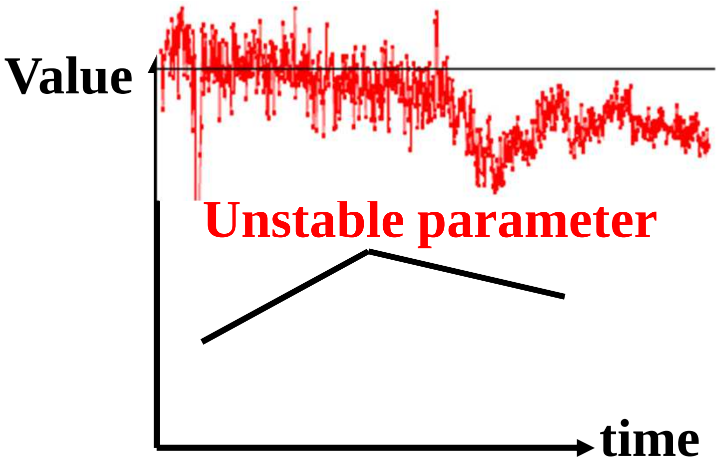
- **Estimate a robust long-term secular frame**

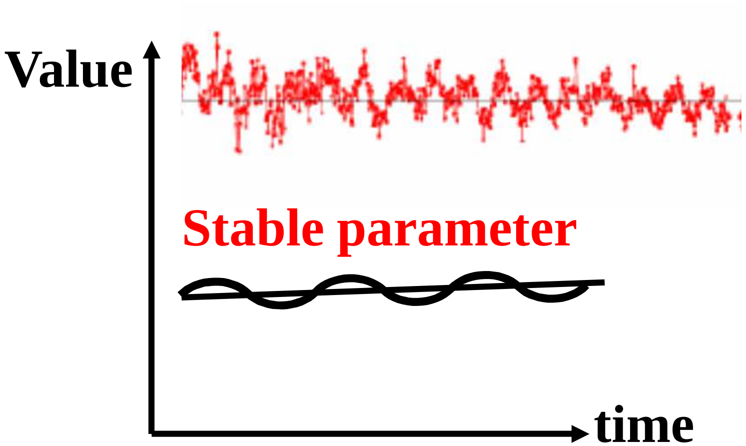
ITRF and Science Requirement

- **Long-term stable ITRF: 0.1 mm/yr**

==> Stable: linear behaviour of the TRF parameters, i.e. with no discontinuity :

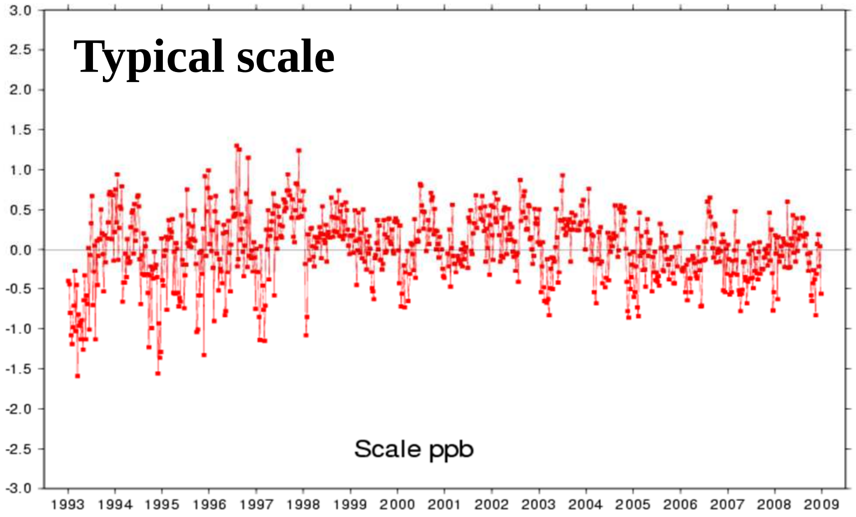
- **Origin Components: 0.1 mm/yr**
- **Scale 0.01 ppb/yr (0.06 mm/yr)**

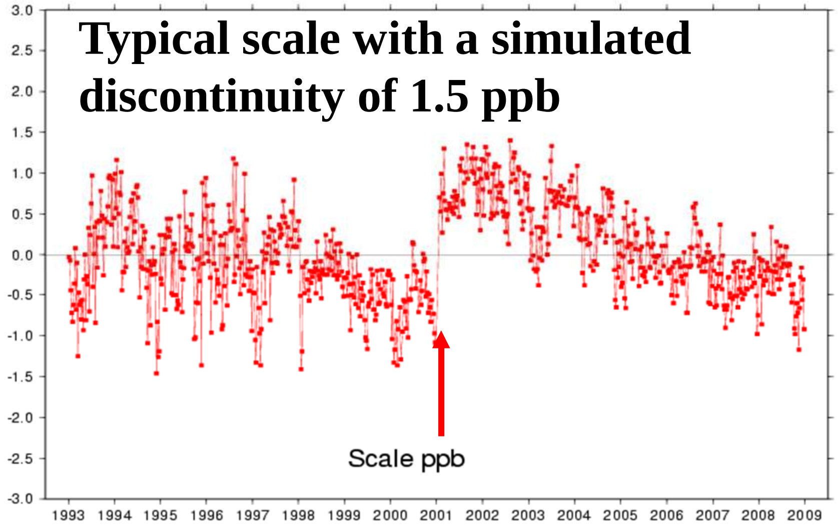




But stability also means TRF site position predictabilty

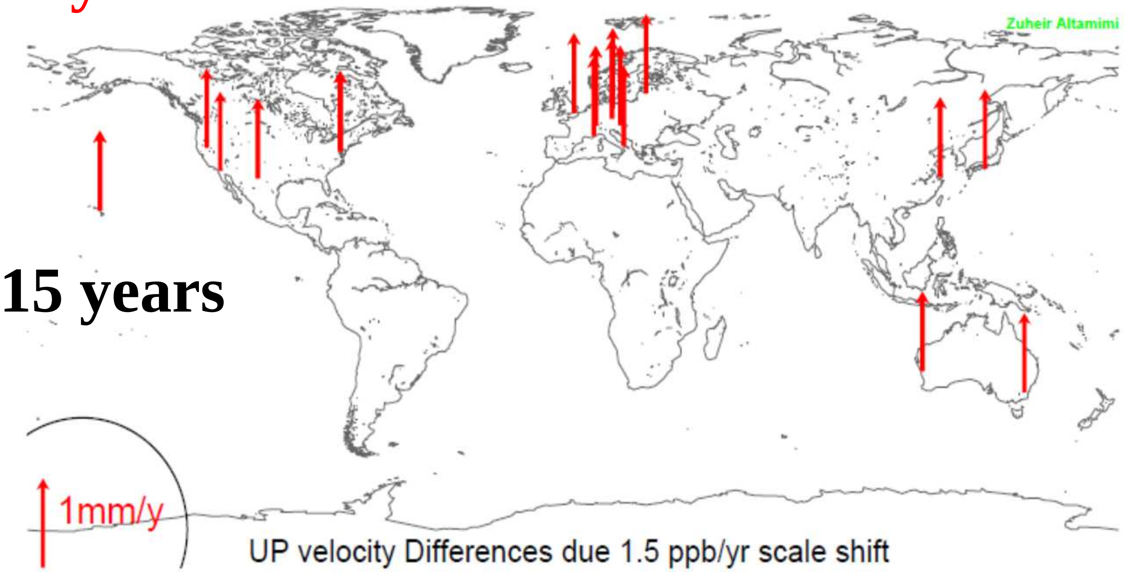
Impact of 1.5 ppb scale discontinuity



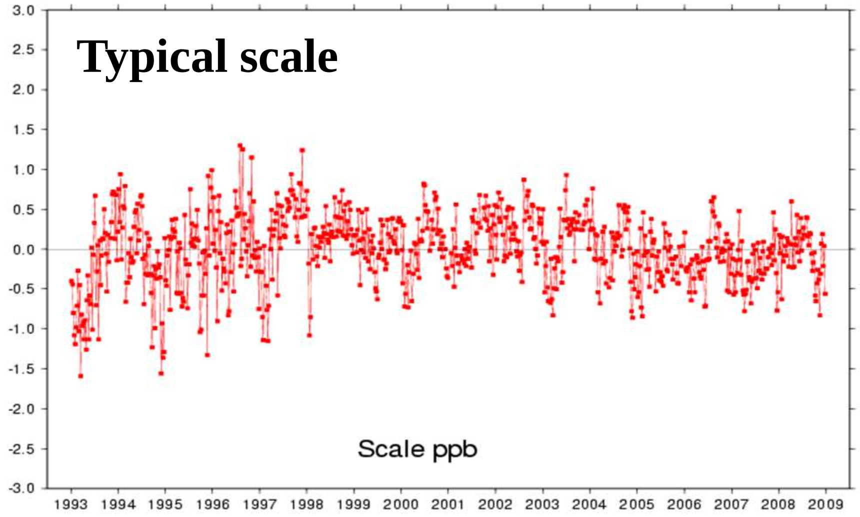


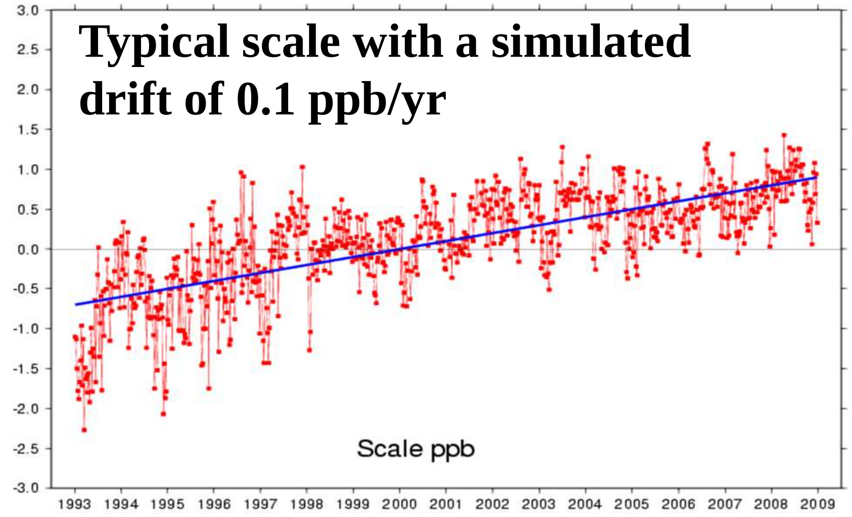
Vertical velocity Diffs

Data-span: 15 years



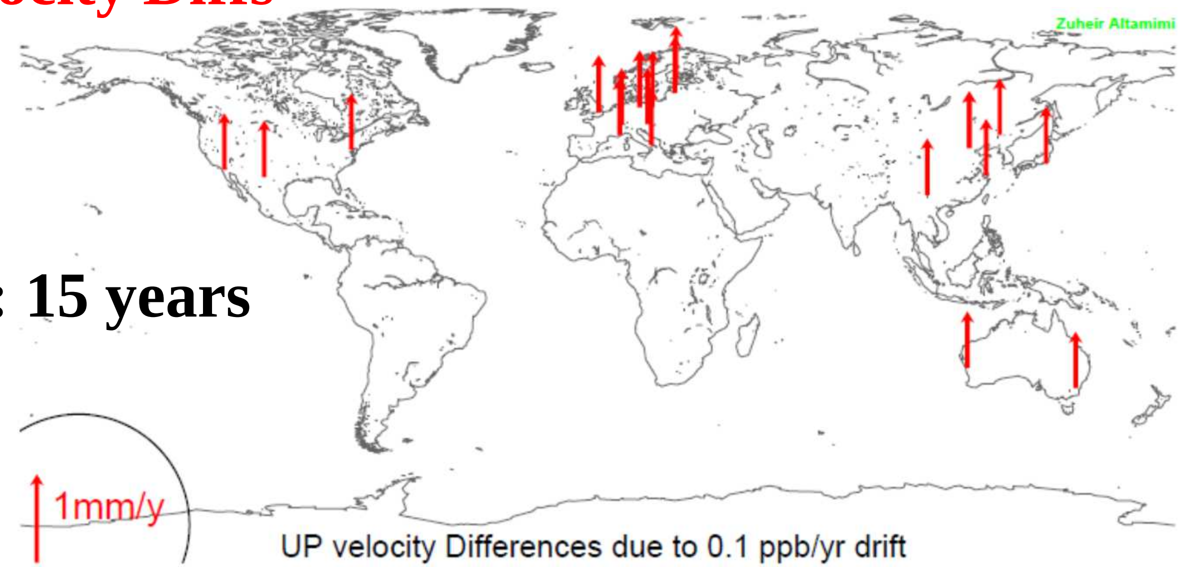
Impact of 0.1 ppb/yr scale drift





Vertical velocity Diffs

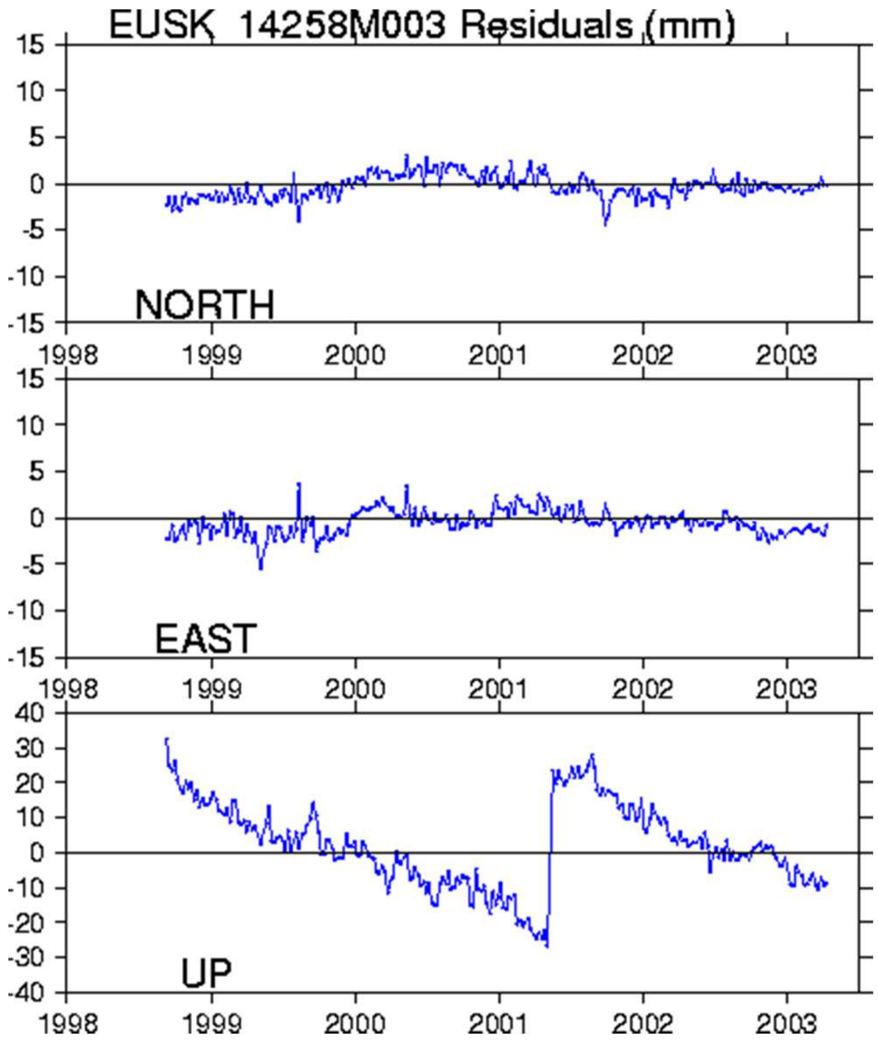
Data-span: 15 years



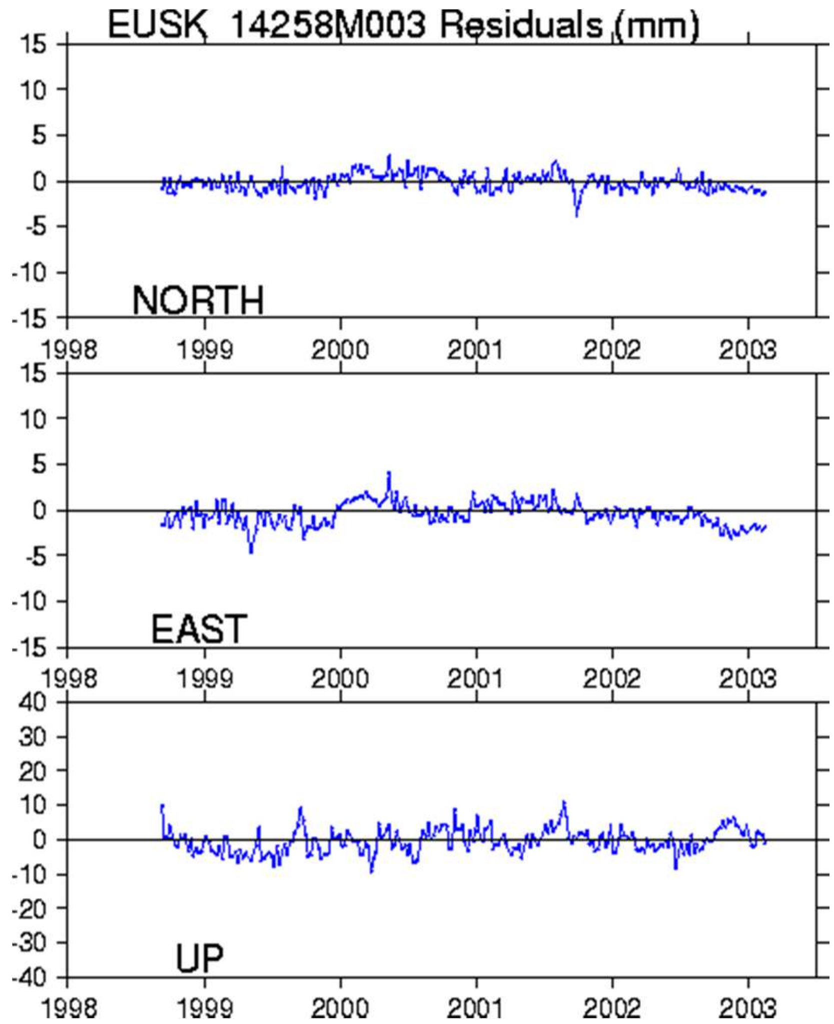
Some examples of discontinuities and seasonal variations

Dicontinuity due to equipment change

Before

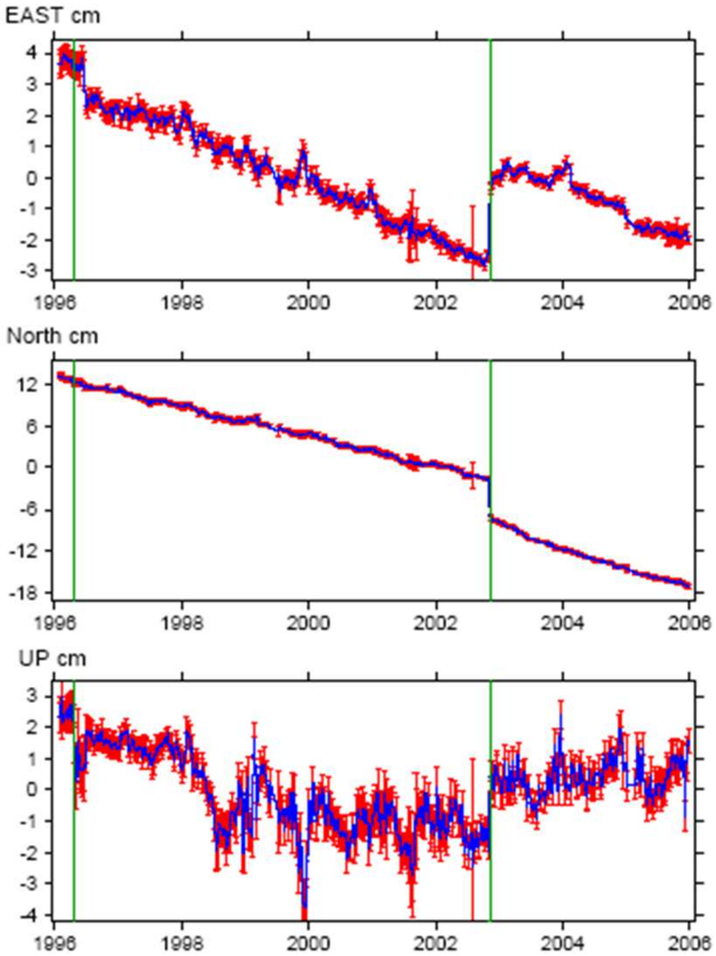


After

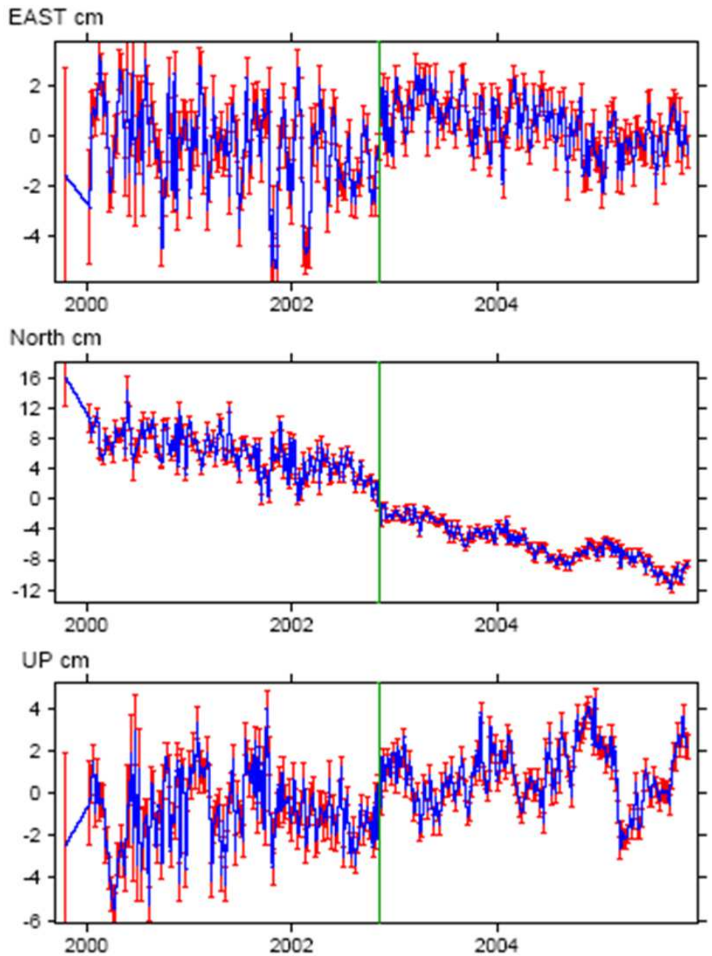


Denaly Earthquake (Alaska)

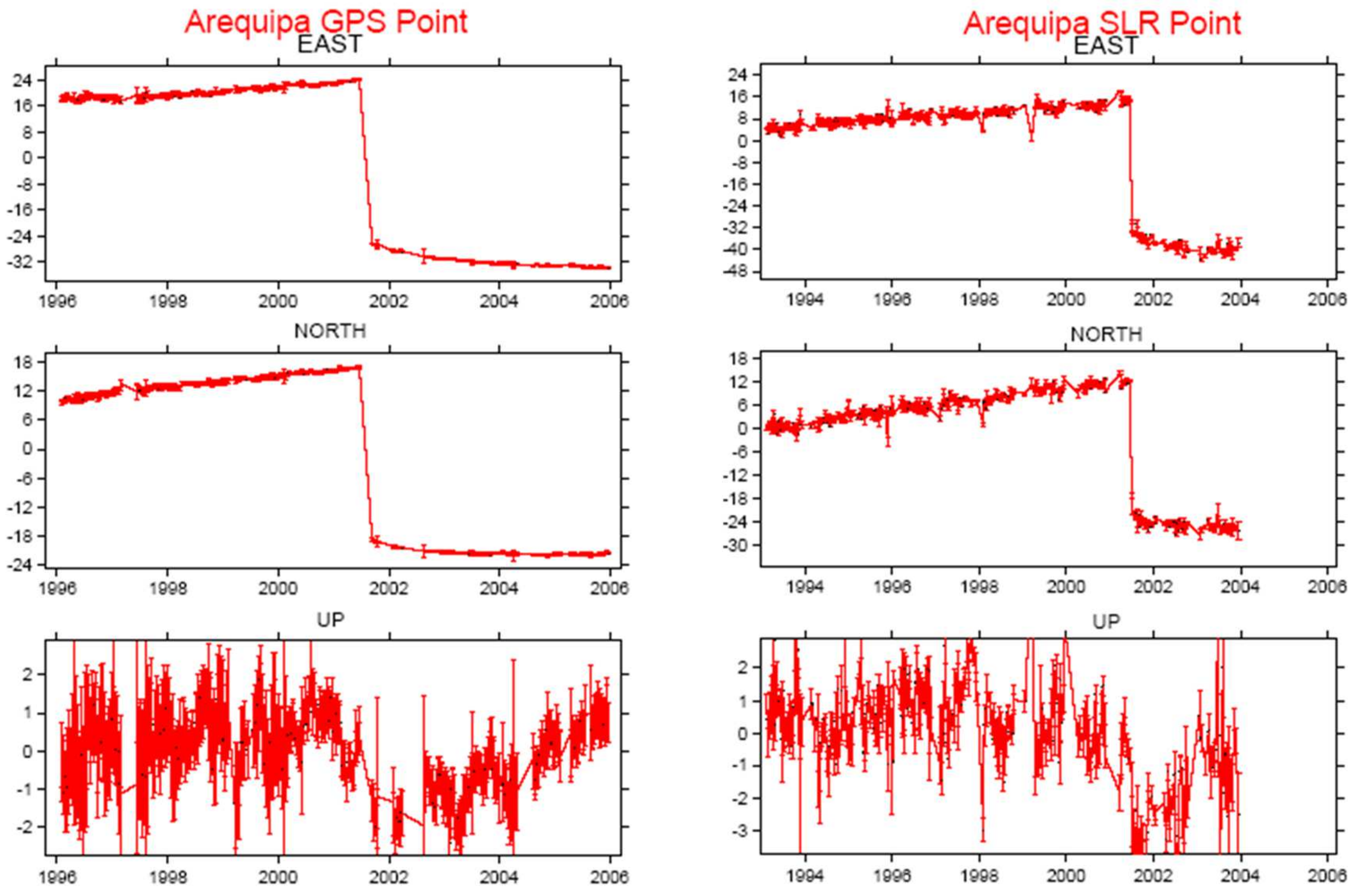
GPS



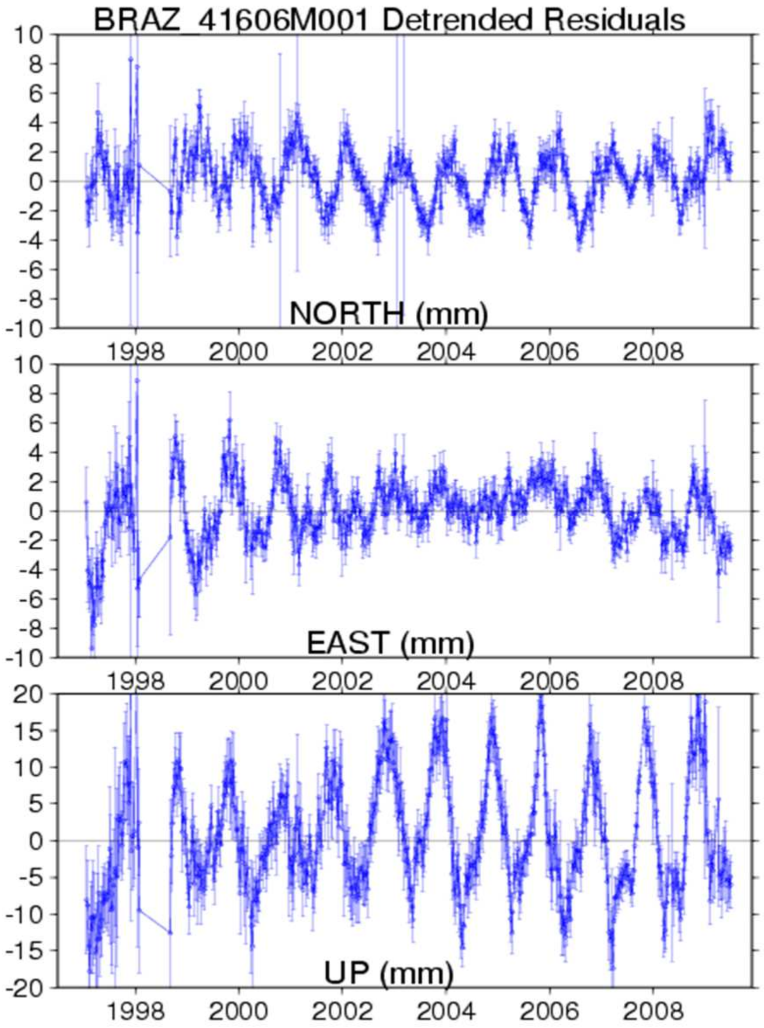
DORIS



Arequipa Earthquake



Example of seasonal variations BRAZ GPS antenna



ITRF2008

- **Time Series of Station Positions :**
  - **Daily (VLBI)**
  - **Weekly (GPS, SLR & DORIS)**
- **and Earth Orientation Parameters:**

  Polar Motion (x_p, y_p)

  Universal Time (UT1) (Only from VLBI)

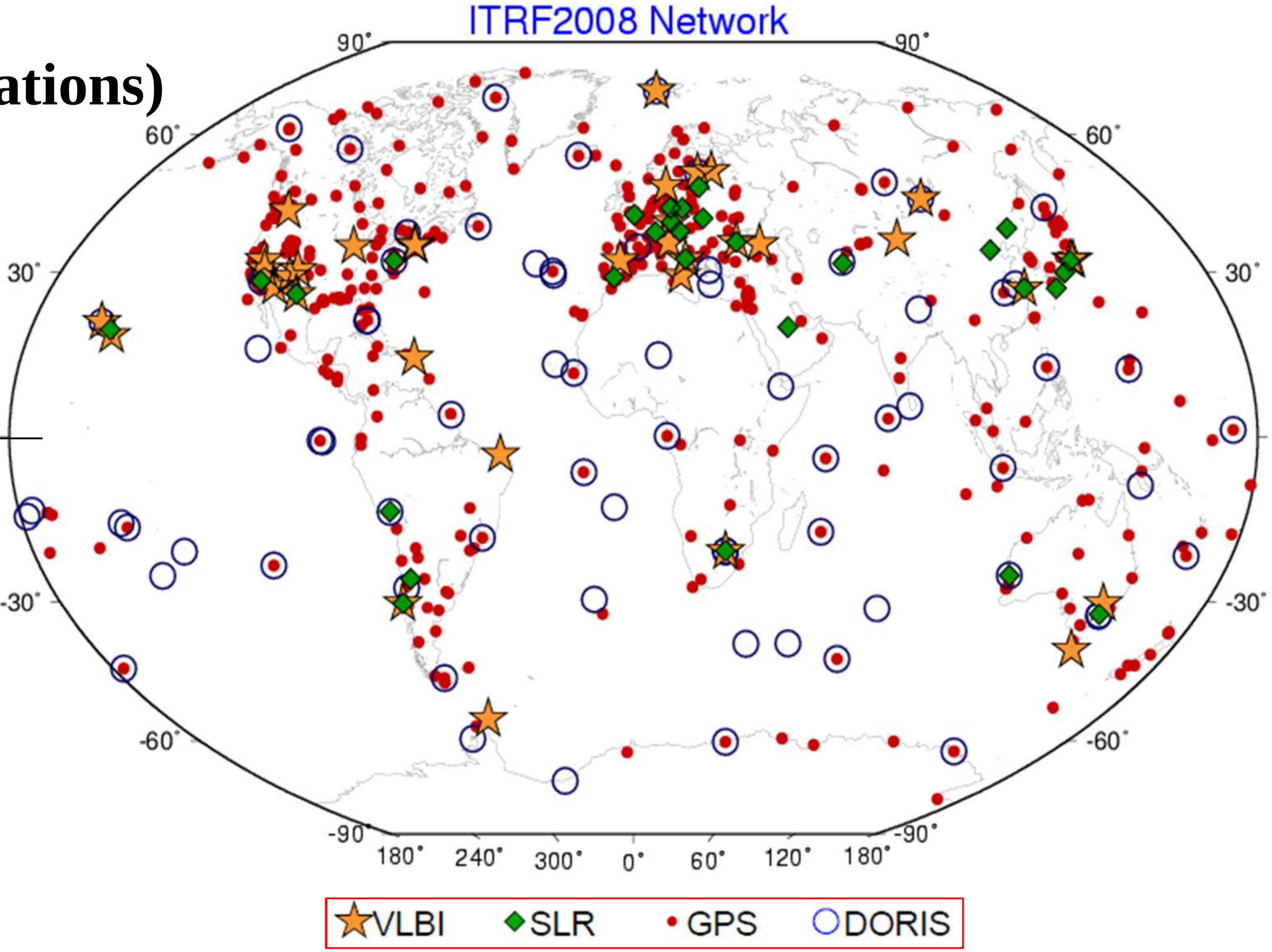
  Length of Day (LOD) (Only from VLBI)

ITRF2008 Network

580 sites (920 stations)

461 Sites North

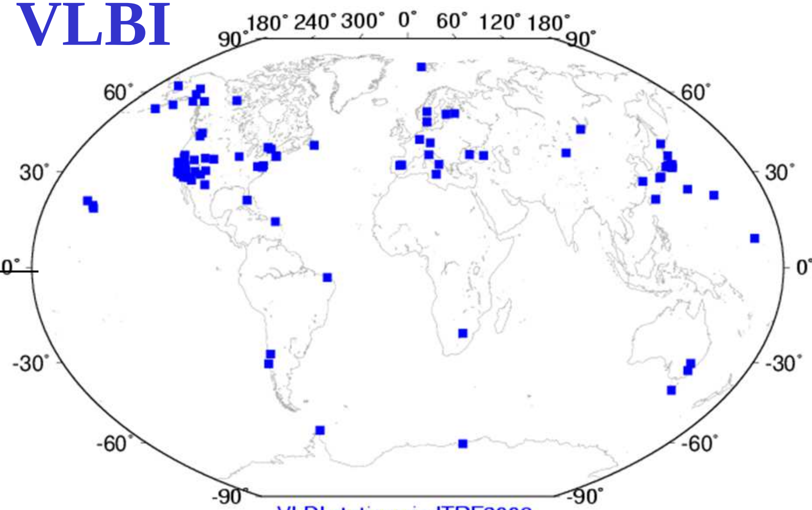
118 Sites South



ITRF2008: Site distribution per technique

VLBI

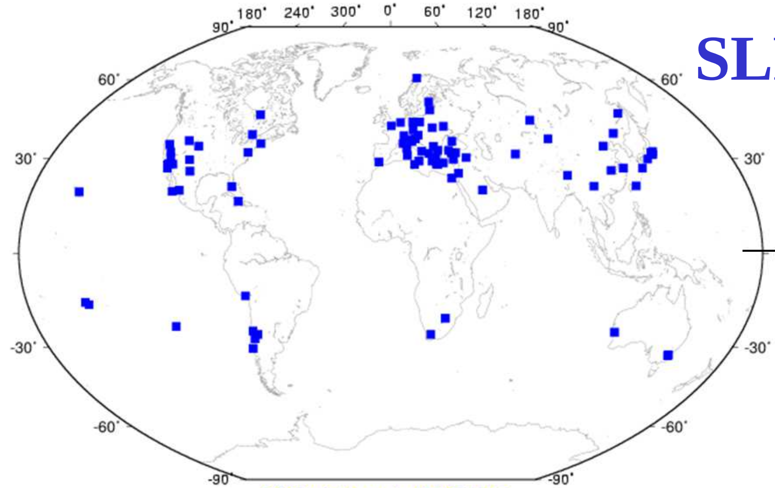
84
9



VLBI stations in ITRF2008

SLR

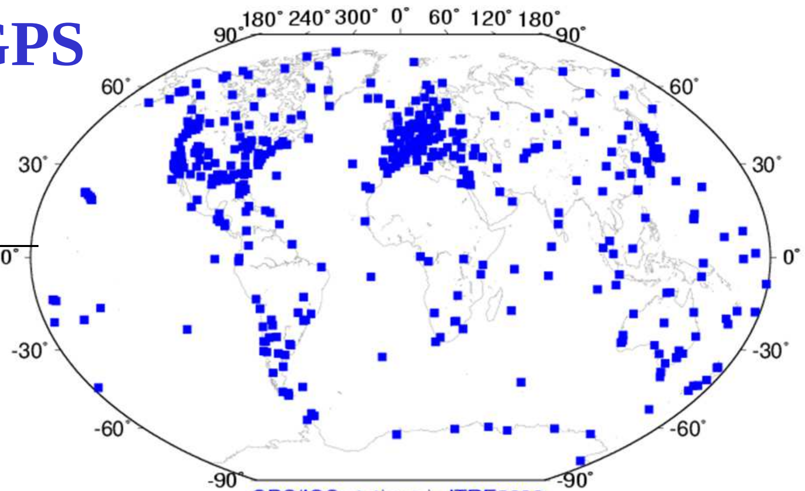
76
13



SLR stations in ITRF2008

GPS

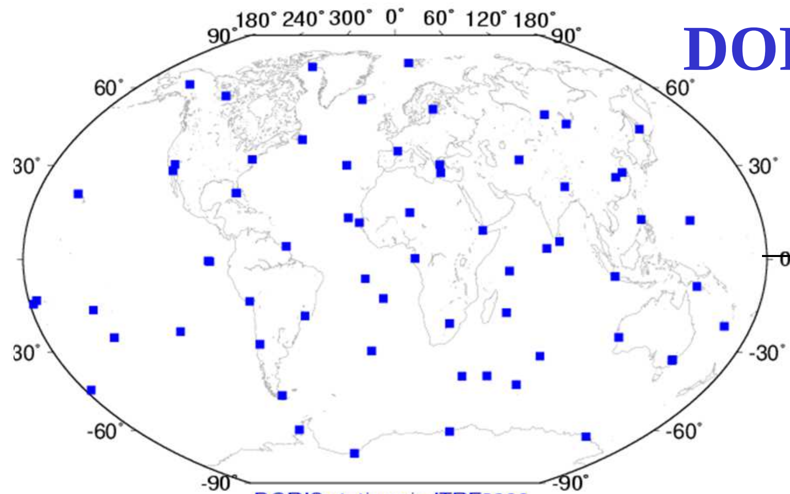
390
102



GPS/IGS stations in ITRF2008

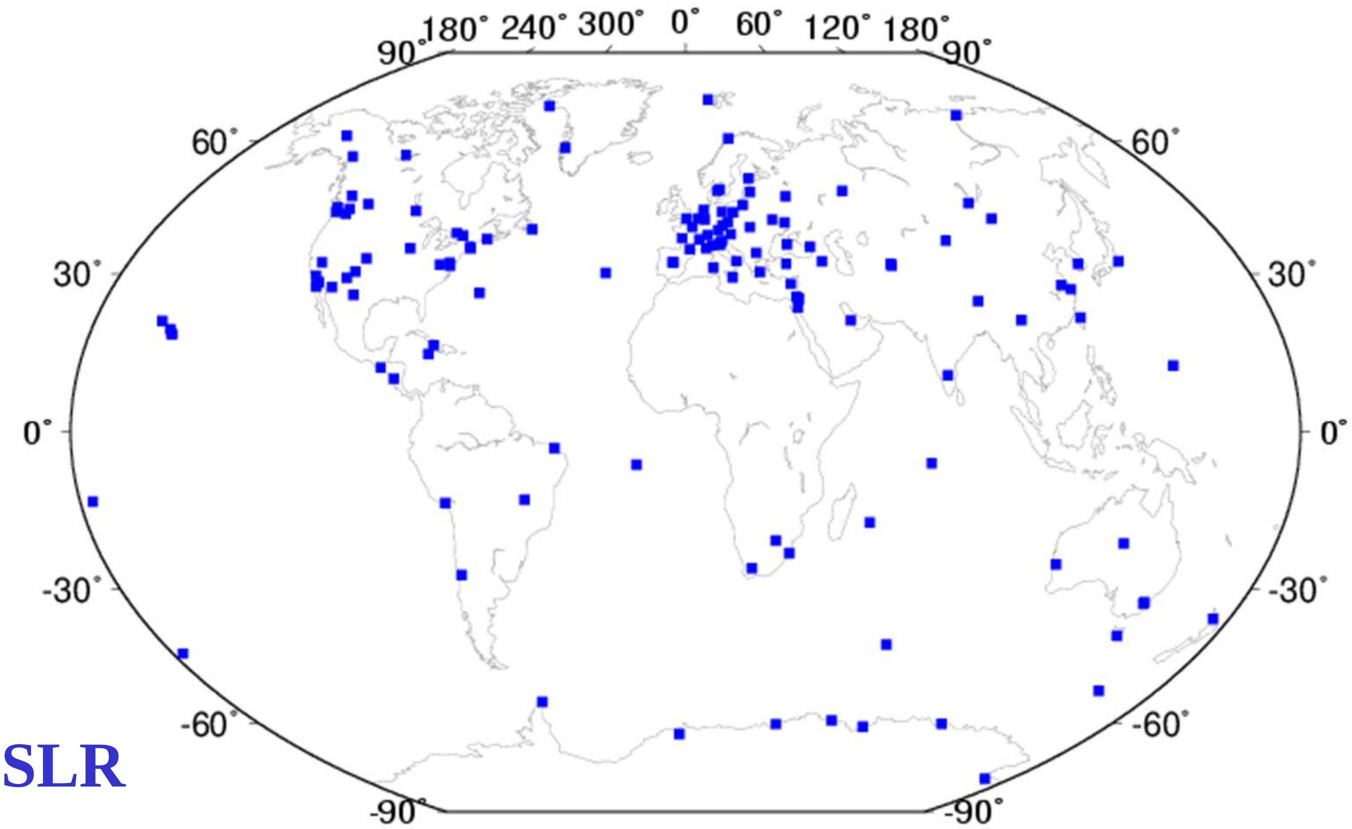
DORIS

34
32



DORIS stations in ITRF2008

ITRF2008 Datum Specification



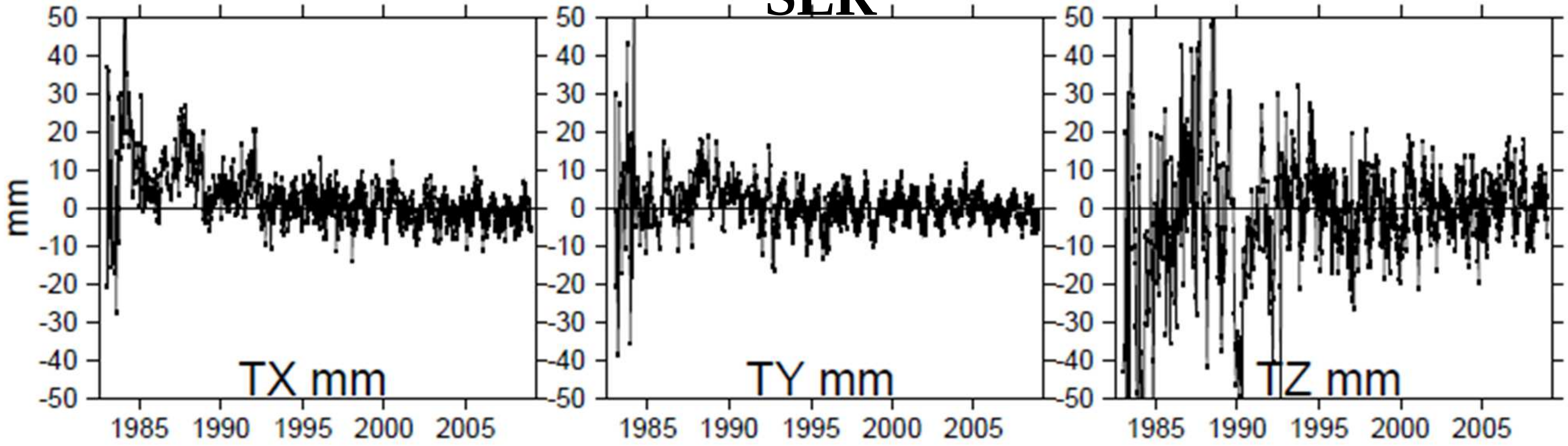
- **Origin: SLR**
- **Scale : Mean of SLR &VLBI**
- **Orientation: Aligned to ITRF2005**

  using 179 stations located at 131 sites:

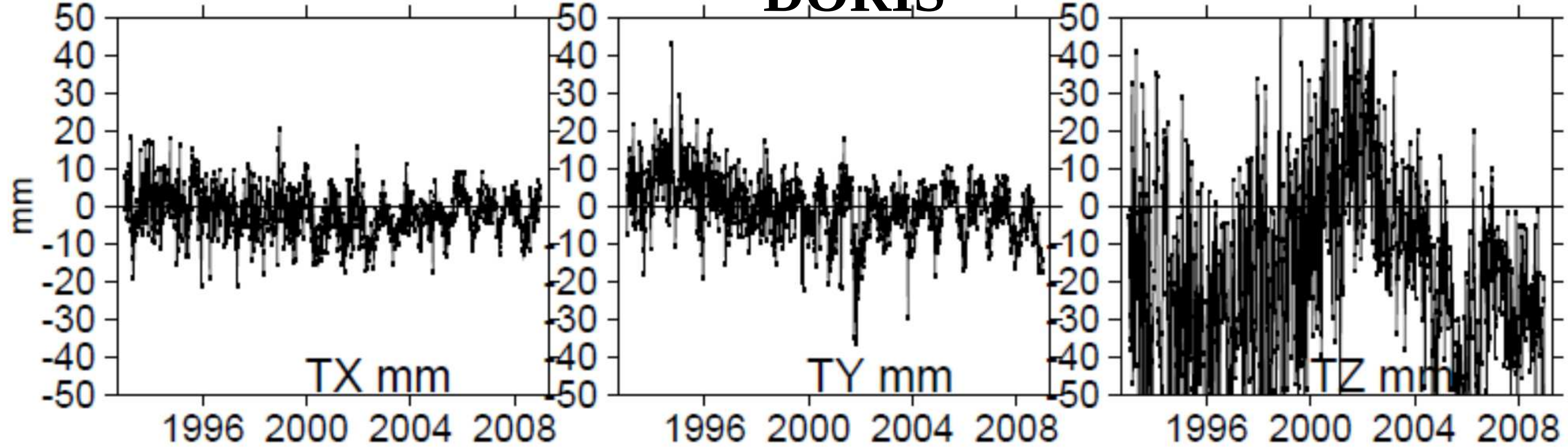
104 at northern hemisphere and 27 at southern hemisphere

SLR & DORIS origin components wrt ITRF2008

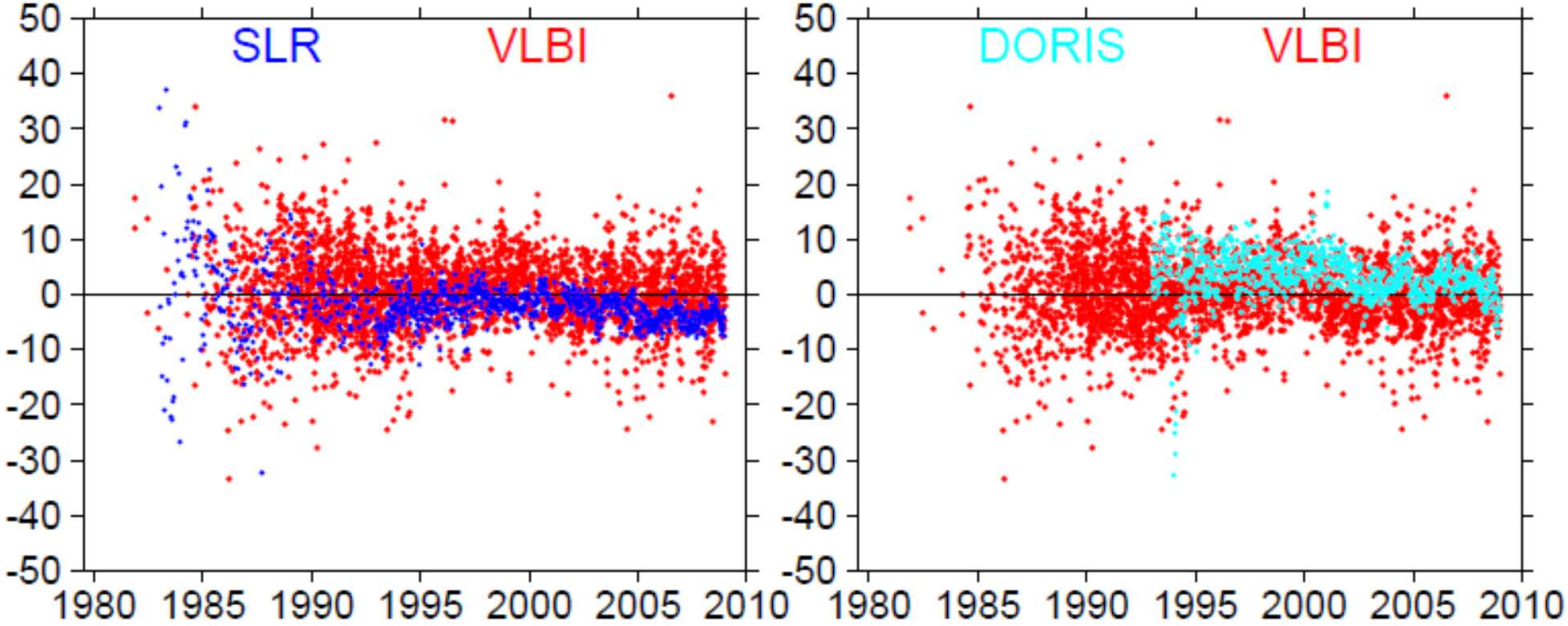
SLR



DORIS



Scales wrt ITRF2008



Transformation Param Fm ITRF2008 To ITRF2005

Tx mm	Ty mm	Tz mm	Scale ppb
-0.5 ± 0.2	-0.9 ± 0.2	-4.7 ± 0.2	0.94 ± 0.03

At epoch 2005.0

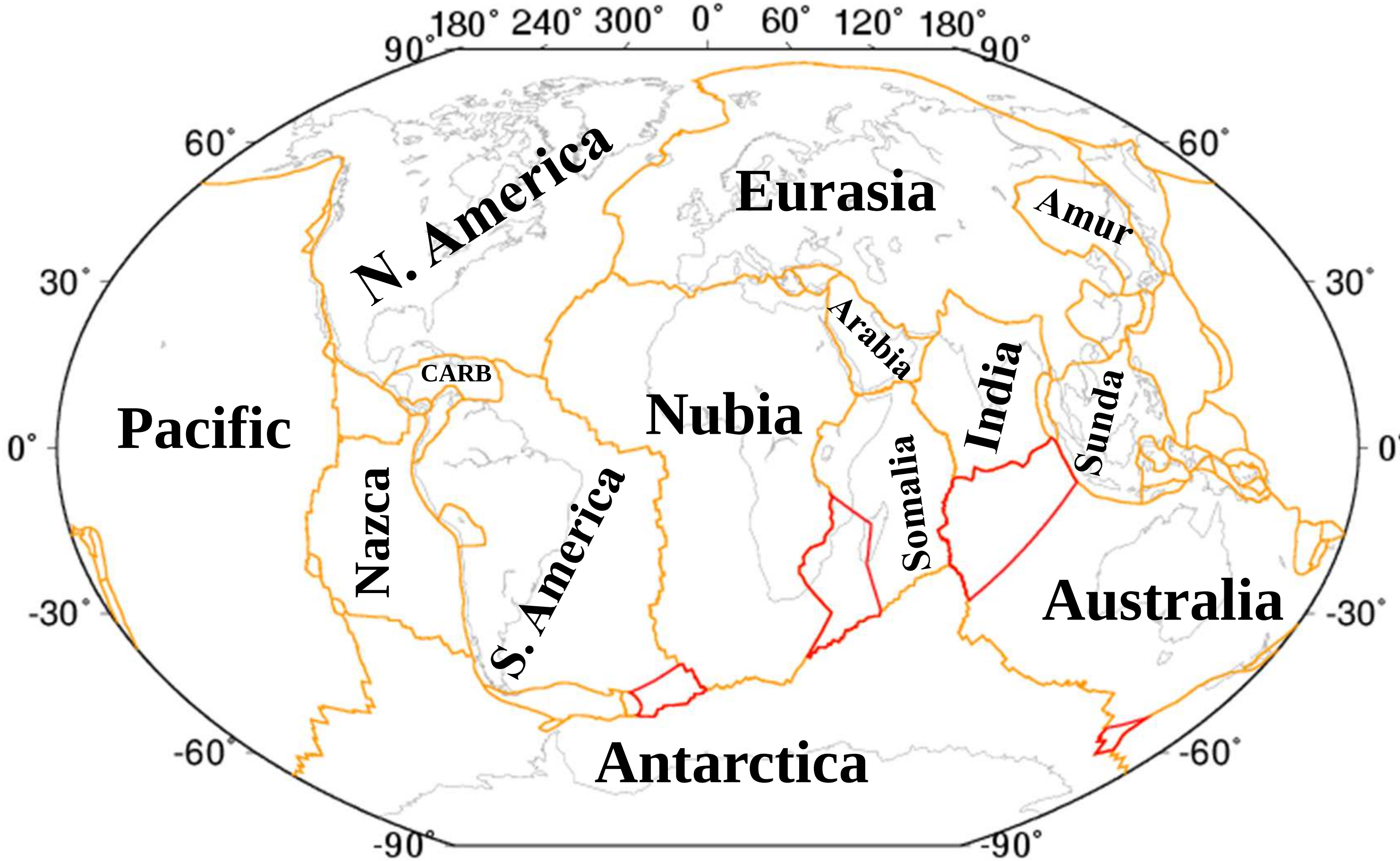
Tx rate mm/yr	Ty rate mm/yr	Tz rate mm/yr	Scale rate ppb/yr
0.3 ± 0.2	0.0 ± 0.2	0.0 ± 0.2	0.00 ± 0.03

How to estimate an absolute plate rotation pole ?

$$\dot{X} = \omega_{\boldsymbol{p}} \times X$$

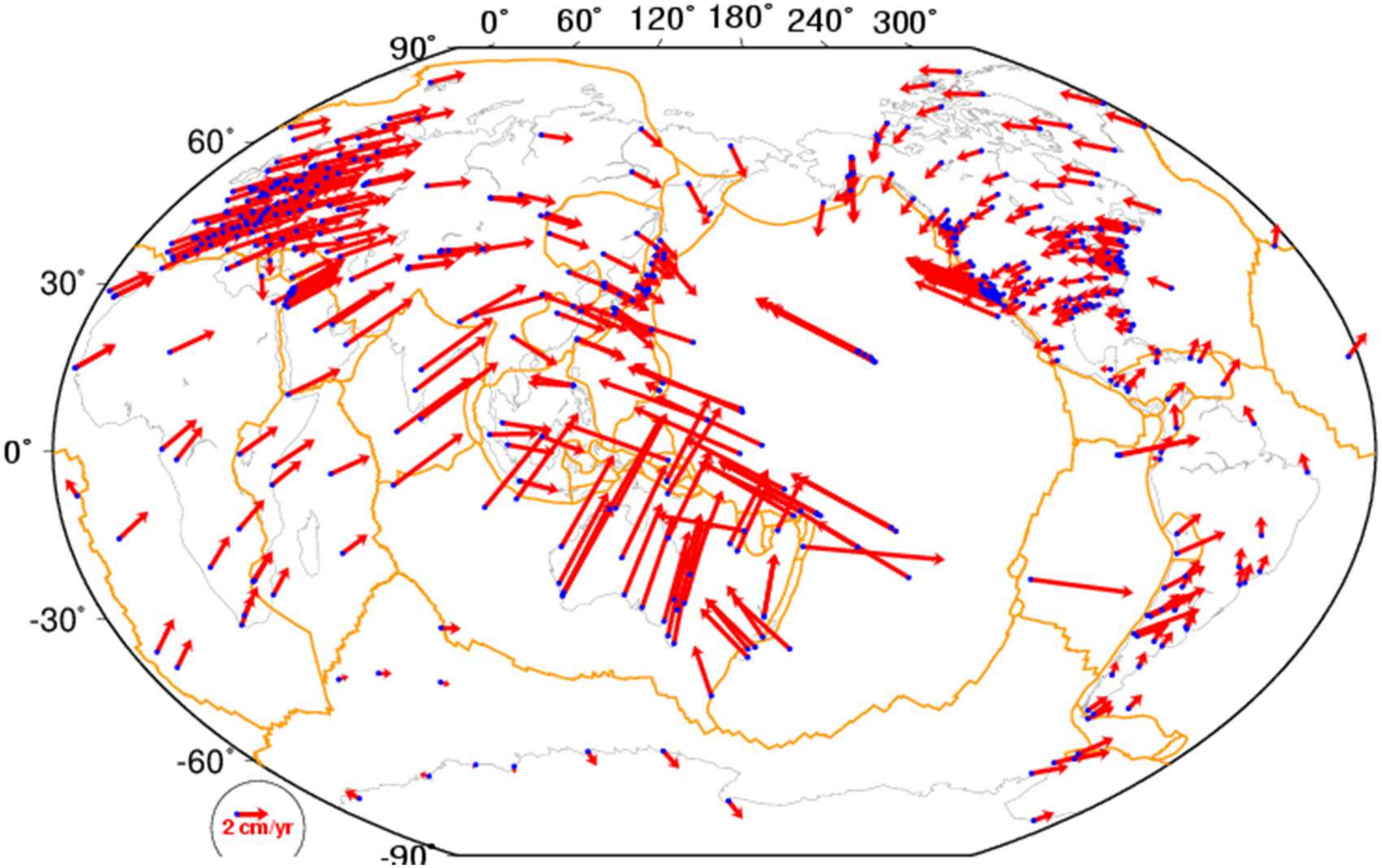
- **TRF definition**
- **Number and distribution over sites over the plate**
- **Quality of the implied velocities**
- **Level of rigidity of the plate**

Plate boundaries: Bird (2003) and MORVEL, DeMets et al. (2010)



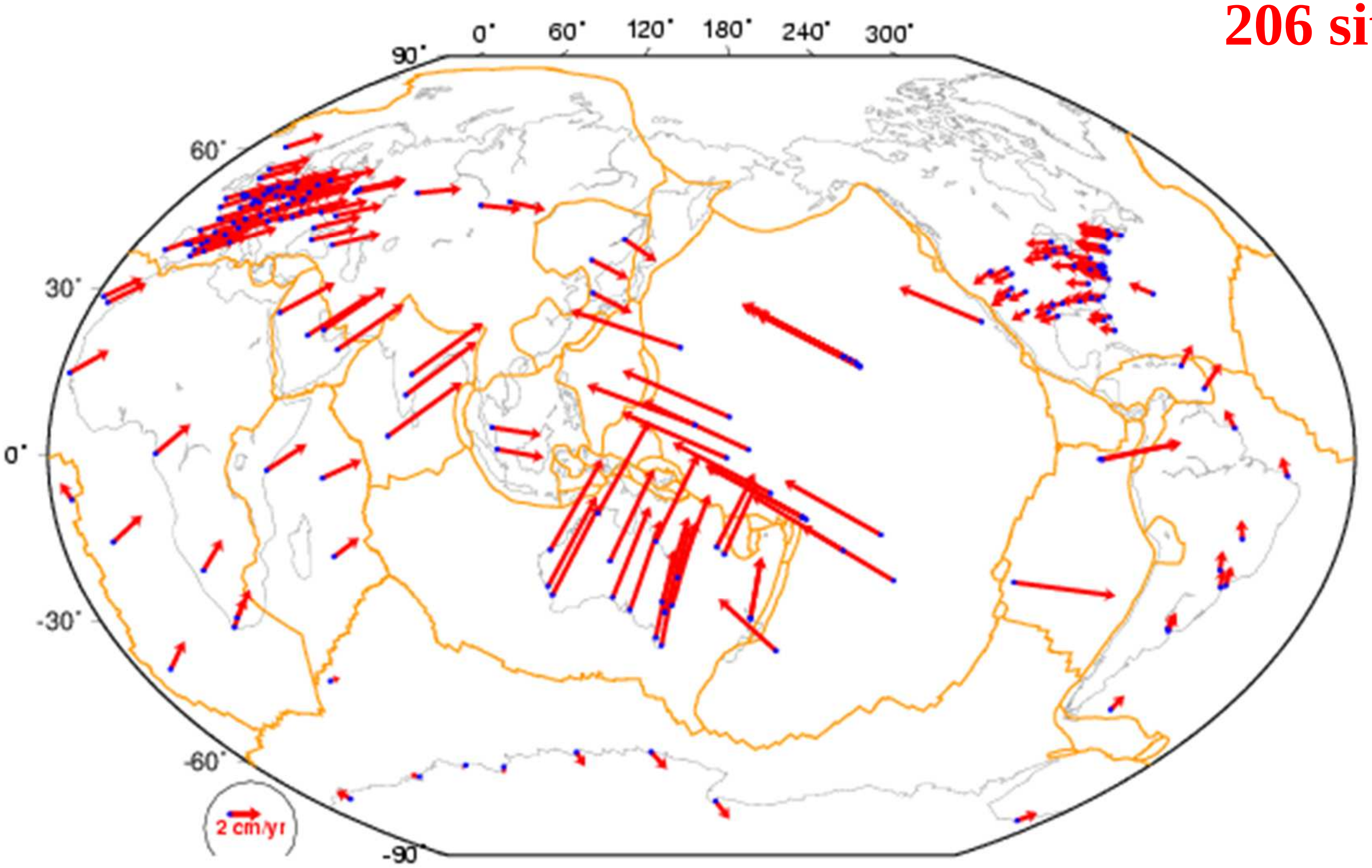
ALL ITRF2008 Site Velocities:
time-span > 3 yrs

509 sites



ITRF2008-PMM: Selected Site Velocities

206 sites



ITRF2008 Plate Motion Model

Inversion model: $\dot{X}_i = \omega_p \times X_i + \dot{T}$

Results:

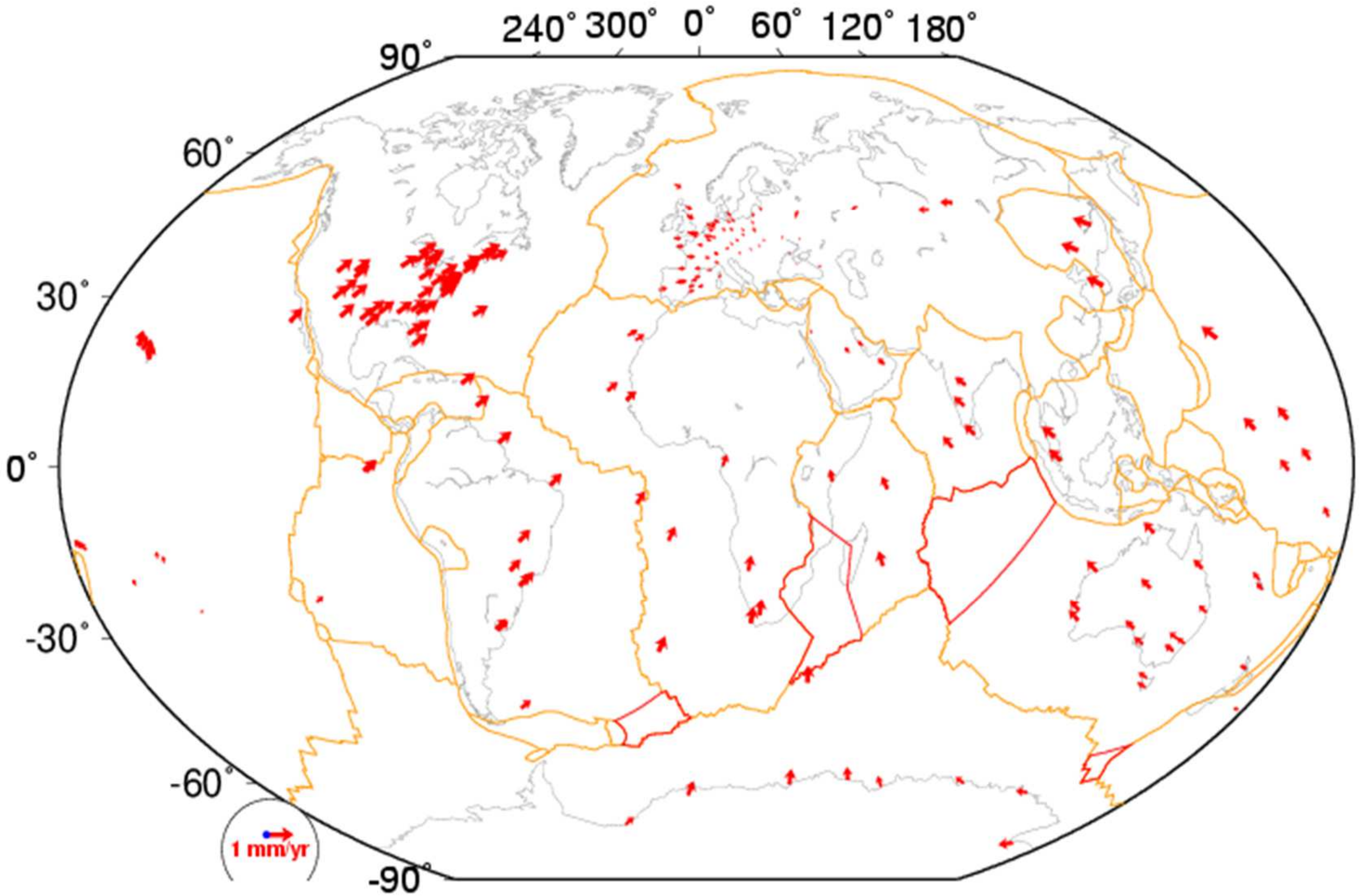
- **Angular velocities for 14 plates**
- **Translation rate components**

Table 2. Translation rate components

Number of sites			$\dot{T}_x$	$\dot{T}_y$	$\dot{T}_z$
Total	EURA	NOAM	mm/a		
206	69	44	0.41 ±0.27	0.22 ±0.32	0.41 ±0.30

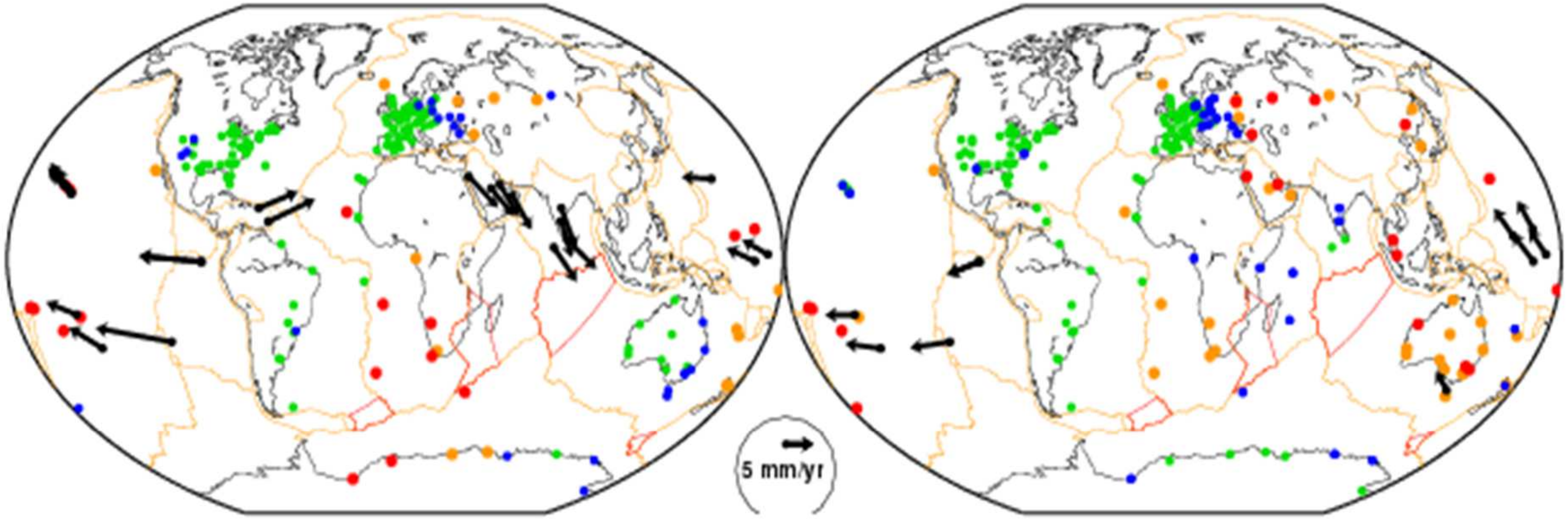
- **More details in JGR paper by Altamimi et al. (2012)**

Impcat of the translation rate



Comparison between ITRF2008 & NNR-NUVEL-1 & NNR-MORVEL56

After rotation rate transformation



NNR-NUVEL-1A
RMS:
East : 2.5 mm/yr
North: 2.1 mm/yr

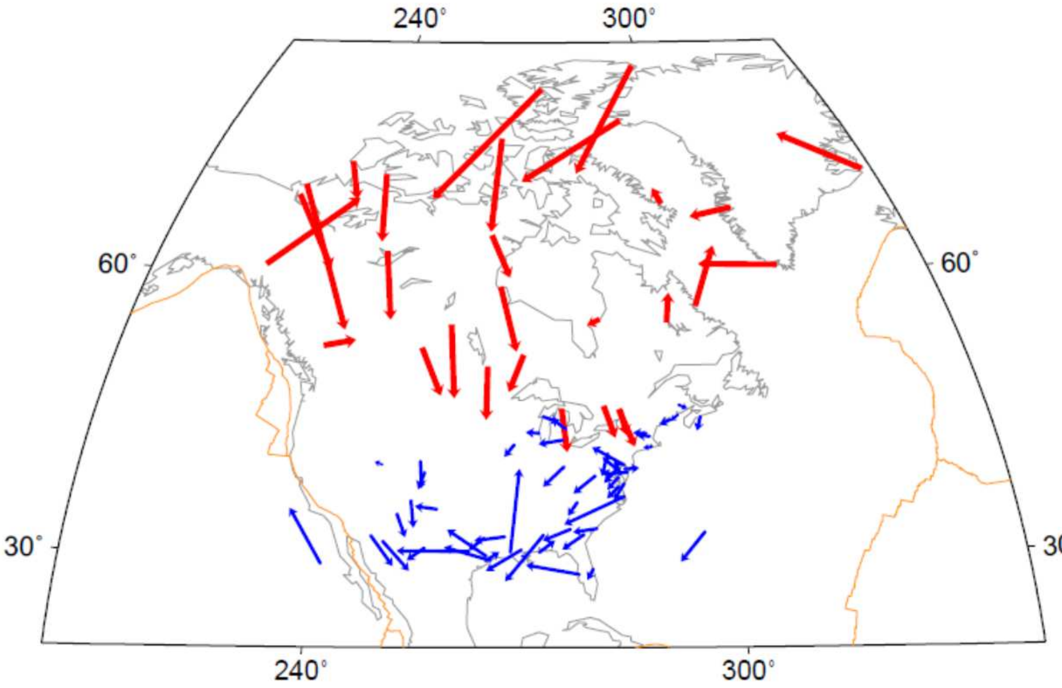
● Green:	< 2 mm/yr
● Blue :	2-3 mm/yr
● Orange:	3-4 mm/yr
● Red :	4-5 mm/yr
←• Black :	> 5 mm/yr

NNR-MORVEL56
RMS:
East : 1.8 mm/yr
North: 1.9 mm/yr

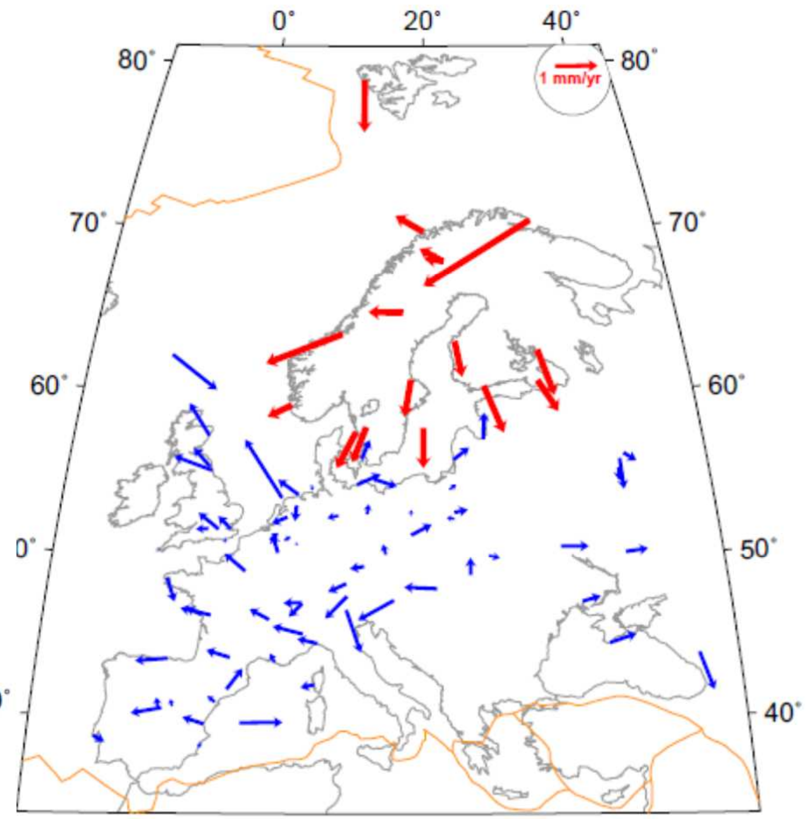
Plate motion and Glacial Isostatic Adjustment

Blue : points used

Red : points rejected



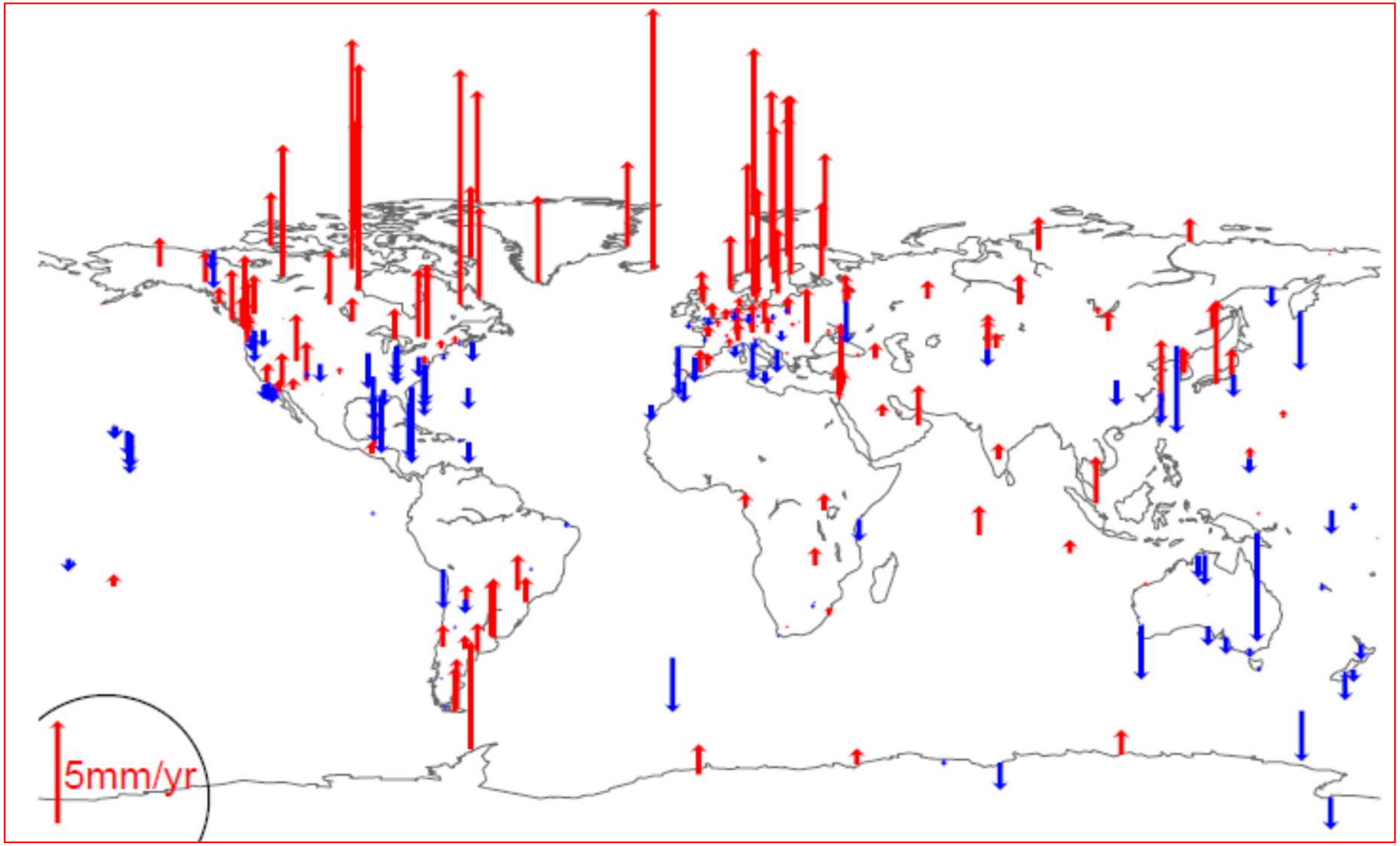
NOAM



EURA

Residual velocities after removing NOAM & EURA rotation poles

ITRF2008 Vertical velocity field



ITRF transformation parameters

Table 4.1: Transformation parameters from ITRF2008 to past ITRFs. "ppb" refers to parts per billion (or 10^{-9}). The units for rates are understood to be "per year."

ITRF Solution	$T1$ (mm)	$T2$ (mm)	$T3$ (mm)	D (ppb)	$R1$ (mas)	$R2$ (mas)	$R3$ (mas)	Epoch
ITRF2005	-2.0	-0.9	-4.7	0.94	0.00	0.00	0.00	2000.0
rates	0.3	0.0	0.0	0.00	0.00	0.00	0.00	
ITRF2000	-1.9	-1.7	-10.5	1.34	0.00	0.00	0.00	2000.0
rates	0.1	0.1	-1.8	0.08	0.00	0.00	0.00	
ITRF97	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF96	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF94	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF93	-24.0	2.4	-38.6	3.41	-1.71	-1.48	-0.30	2000.0
rates	-2.8	-0.1	-2.4	0.09	-0.11	-0.19	0.07	
ITRF92	12.8	4.6	-41.2	2.21	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF91	24.8	18.6	-47.2	3.61	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF90	22.8	14.6	-63.2	3.91	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF89	27.8	38.6	-101.2	7.31	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF88	22.8	2.6	-125.2	10.41	0.10	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	

Access & alignment to ITRF

- **Direct use of ITRF coordinates**
- **Use of IGS Products (Orbits, Clocks): all expressed in ITRF**
- **Alternatively:**
  - **Process GNSS data together with IGS/ITRF global stations in free mode**
  - **Align to ITRF by**
    - **Constraining station coordinates to ITRF values at the central epoch of the observations**
    - **Using minimum constraints approach**

Transformation from an ITRF to another at epoch t_c

- **Input :** X (ITRFxx, epoch t_c)
- **Output:** X (ITRFyy, epoch t_c)
- **Procedure:**
  - Propagate ITRF transformation parameters from their epoch (2000.0, slide 72) to epoch t_c, for both ITRFxx and ITRFyy:

$$P(t_c) = P(2000.0) + \dot{P}(t_c - 2000.0)$$

  - Compute the transformation parameters between ITRFxx and ITRFyy, by subtraction;
  - Transform using the general transformation formula given at slide 8:

    X(ITRFyy) = X(ITRFxx) + T + D.X(ITRFxx) + R.X(ITRFxx)

How to express a GPS network in the ITRF ?

- **Select a reference set of ITRF/IGS stations and collect RINEX data from IGS data centers;**
- **Process your stations together with the selected ITRF/IGS ones:**
  - **Fix IGS orbits, clocks and EOPs**
  - **Eventually, add minimum constraints conditions in the processing**

  ==> 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:**

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

  - **Compare your estimated ITRF station positions to official ITRF values and check for consistency!**

From the ITRF to Regional Reference Frames

- **Purpose: geo-referencing applications (σ ~ cm)**
- **There are mainly two cases/options to materialize a regional reference frame:**
  1. **Station positions at a given epoch, eventually updated frequently. Ex.: North & South Americas**
  2. **Station positions & minimized velocities or station positions & deformation model. Ex.: Europe (ETRS89) New Zealand, Greece (?)**
  - **Case 1 is easy to implement (see previous slide)**
  - **Case 2 is more sophisticated & needs application of:**
    - **Transformation formula (ETRS89)**
    - **Deformation model**

GNSS and their associated reference systems

GNSS	Ref. System/Frame
• GPS (broadcast orbits)	WGS84
• GPS (precise IGS orbits)	ITRS/ITRF
• GLONASS	PZ-90
• GALILEO	ITRS/ITRF/GTRF
• COMPASS	CGCS 2000
• QZSS	JGS

- All are ‘’aligned’’ to the ITRF
- WGS84 ≈ ITRF at the decimeter level
- GTRF ≈ ITRF at the mm level
- σ-Position using broadcast ephemerides = 150 cm

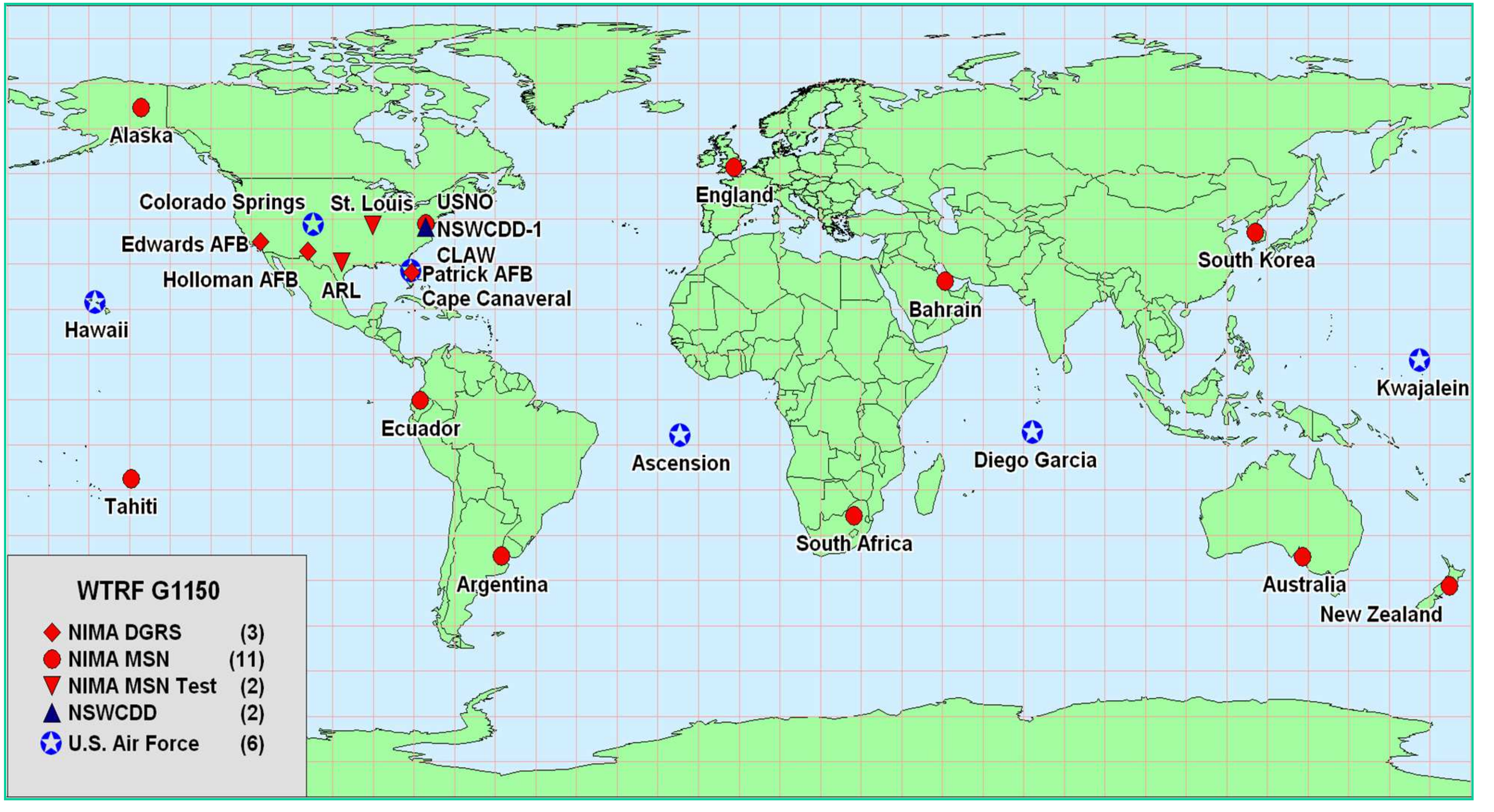
The World Geodetic System 84 (WGS 84)

- **Collection of models including Earth Gravitational model, geoid, transformation formulae and set of coordinates of permanent DoD GPS monitor stations**
- **WGS 60…66…72…84**
- **Originally based on TRANSIT satellite DOPPLER data**

The World Geodetic System 84 (WGS 84)

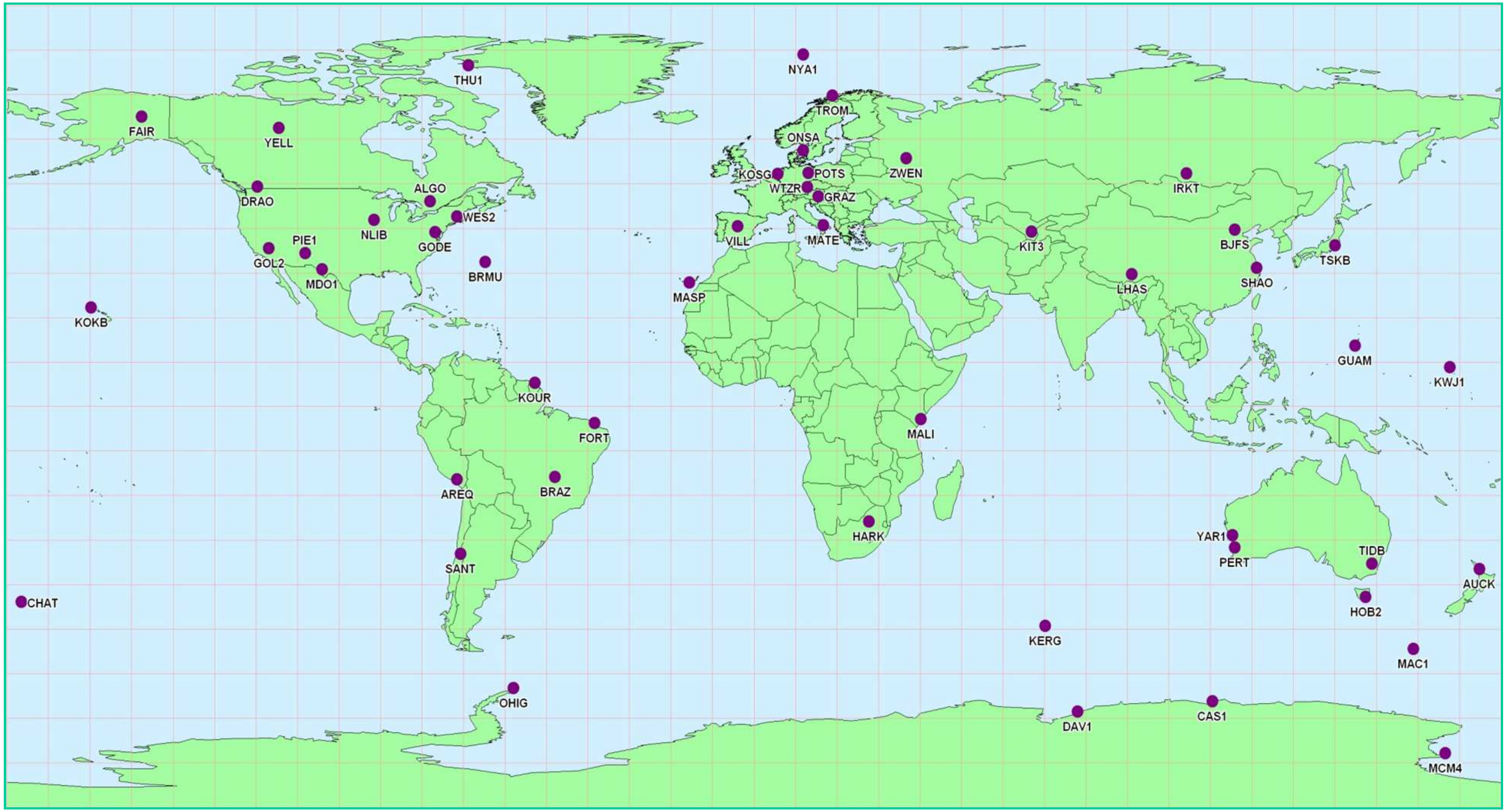
- Recent WGS 84 realizations based on GPS data:
  - G730 in 1994
  - G873 in 1997
  - G1150 in 2002
  - G1674 in 2012 (aligned to ITRF2008)
- Coincides with any ITRF at 10 cm level
- No official Transf. Param. With ITRF

WGS 84-(G1150)



Alaska
Colorado Springs
St. Louis
USNO
NSWCDD-1
Edwards AFB
CLAW
Patrick AFB
Holloman AFB
ARL
Cape Canaveral
Hawaii
England
South Korea
Bahrain
Kwajalein
Ecuador
Ascension
Diego Garcia
Tahiti
South Africa
Argentina
Australia
New Zealand
WTRF G1150
NIMA DGRS (3)
NIMA MSN (11)
NIMA MSN Test (2)
NSWCDD (2)
U.S. Air Force (6)

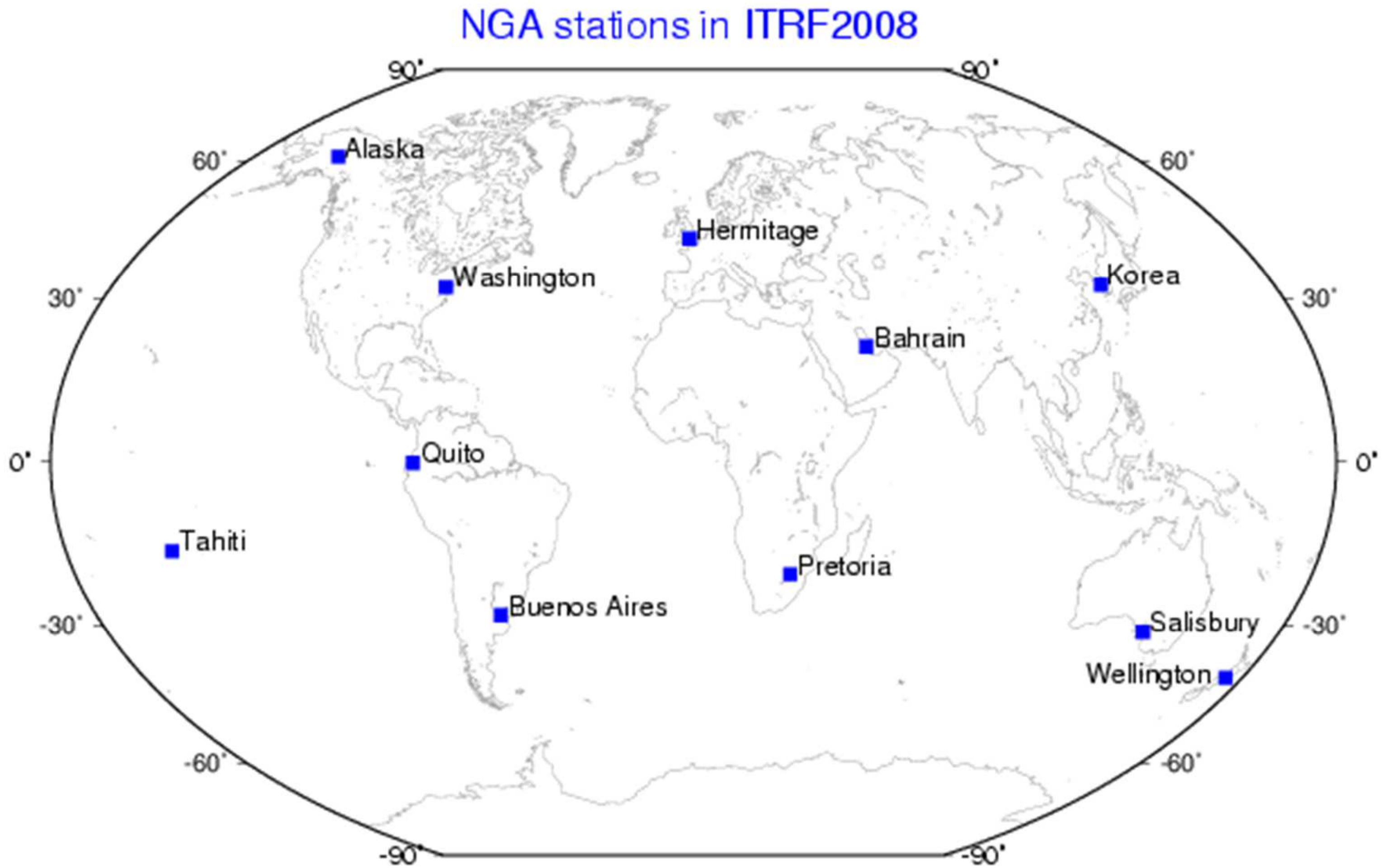
WGS 84-(G1150)



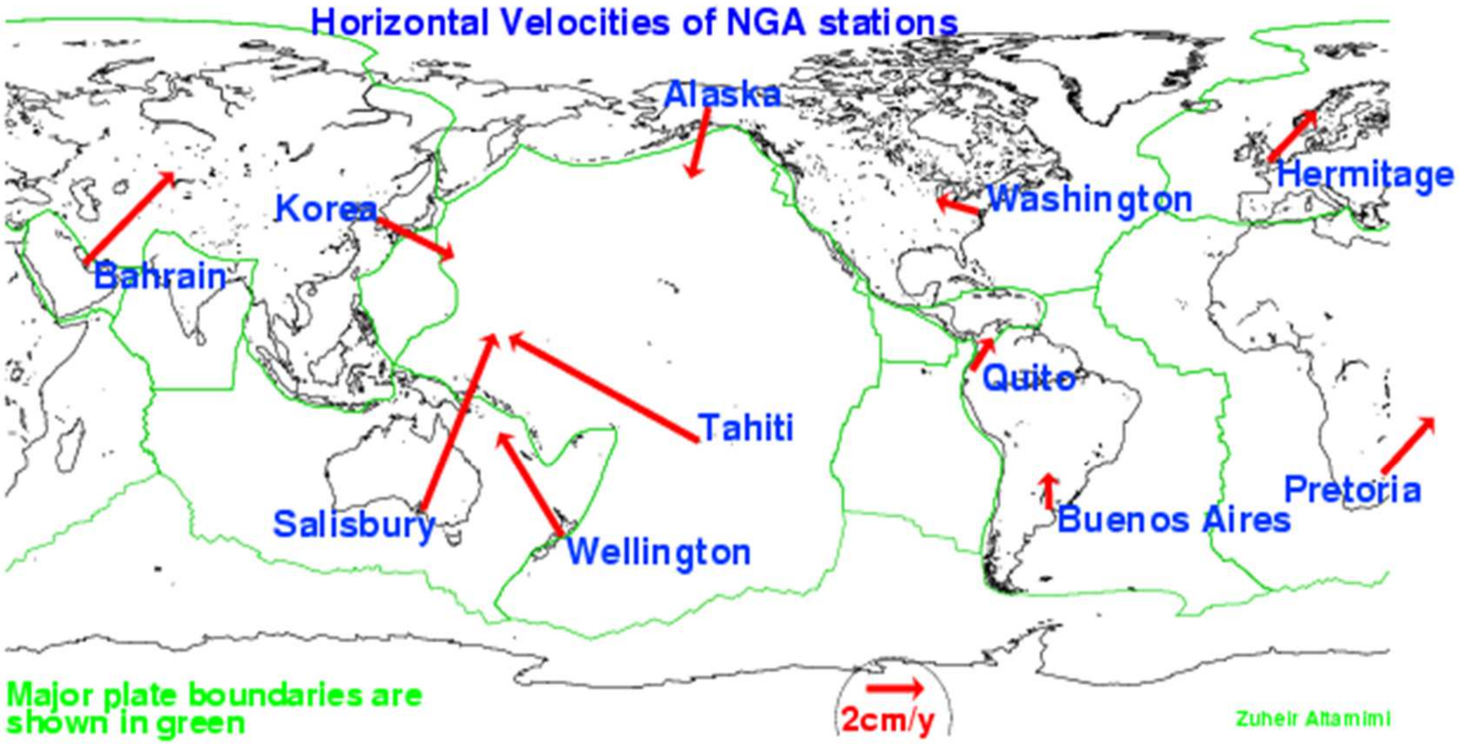
- Coordinates of ~20 stations fixed to ITRF2000
- No station velocities

WGS84 - NGA Stations in ITRF2008

NGA: National Geospatial-Intelligence Agency



WGS84 - NGA Stations in ITRF2008



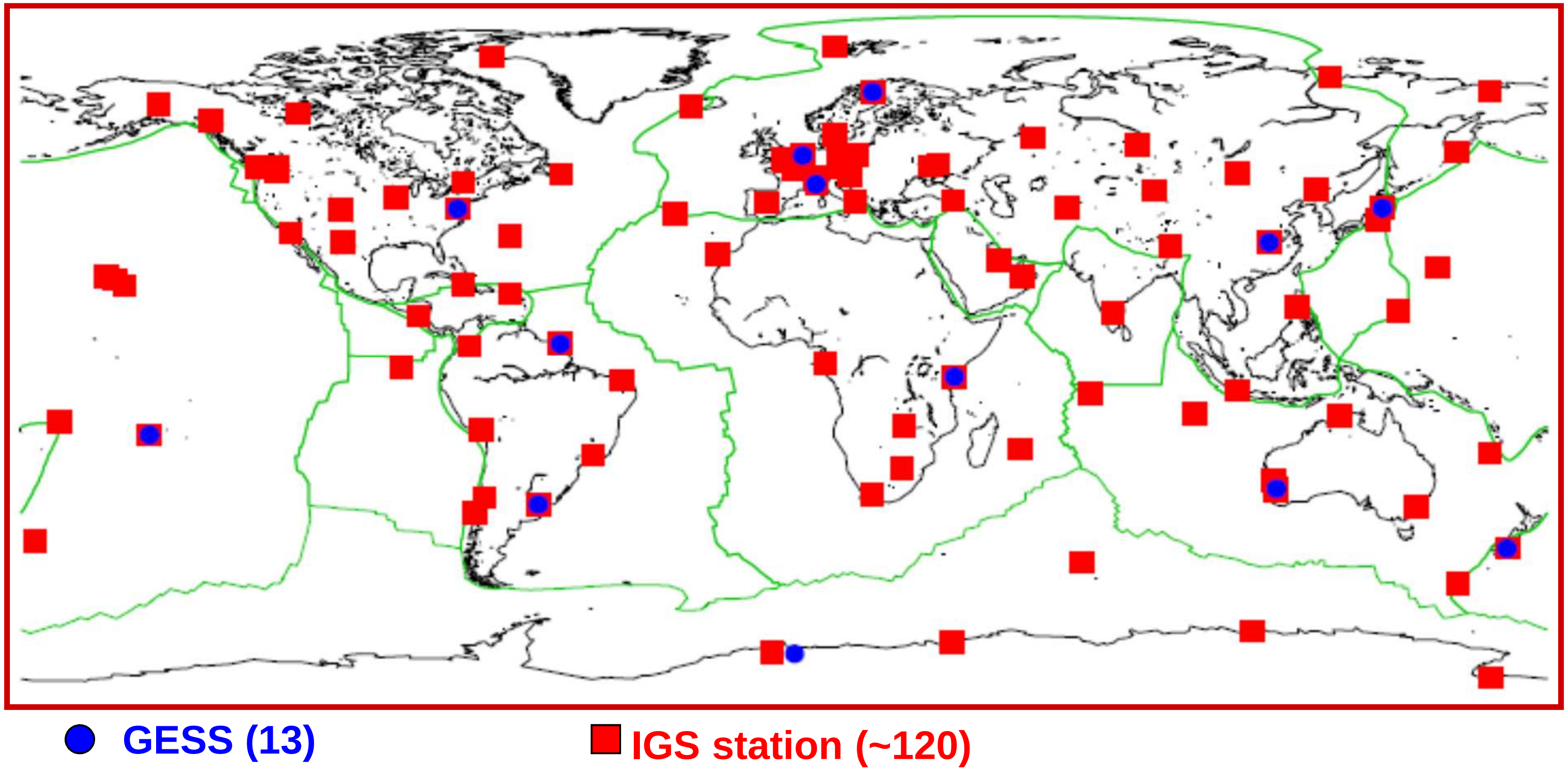
Galileo Terrestrial Reference Frame (GTRF)

- **Galileo Geodesy Service Provider (GGSP)**

- **GGSP Consortium (GFZ, AIUB, ESOC, BKG, IGN)**
  - **Define, realize & maintain the GTRF**
  - **GTRF should be "compatible" with the ITRF at 3 cm level**
  - **Liaison with IERS, IGS, ILRS**

- **GTRF is a realization of the ITRS**

The GTRF Experience



- Initial GSS positions&velocities are determined using GPS observations
- Subsequent GTRF versions using GPS & Galileo observations
- Ultimately Galileo Observations only

Combination Strategy

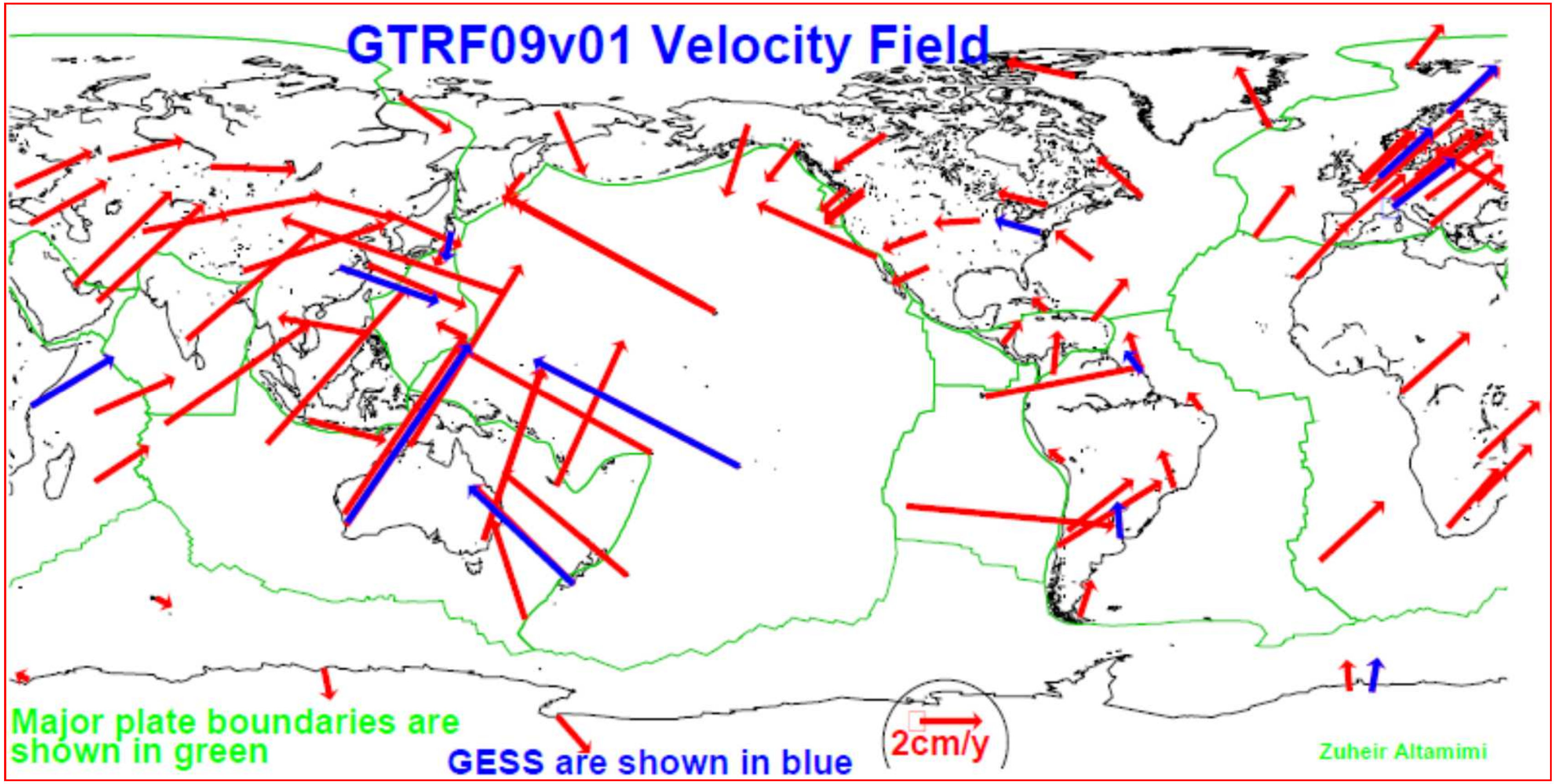
- Use Normal Equations from the 3 ACs
- Adequate for weigthing
- Weekly and cumulative solutions are transformed into the ITRF using Minimum Constraints

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

ITRF (X_R)

Combined Solution (GTRF) (X_c)

GTRF09v01 horizontal velocities



Comparison of GTRF09v01 to ITRF2005

- Transformation parameters

	T1	T2	T3	D	R1	R2	R3	Epoch
	mm	mm	mm	10-9	mas	mas	mas	y
ITRF2005	0.3	-0.3	-0.2	-0.02	-0.003	-0.007	-0.006	7:360
±	0.2	0.2	0.2	0.03	0.007	0.008	0.008	
Rates	0.0	-0.1	-0.1	0.01	-0.001	-0.002	-0.001	
±	0.2	0.2	0.2	0.03	0.007	0.008	0.008	

==> Perfect GTRF alignment to the ITRF at the sub-mm level

- RMS difference between stations coordinates and velocities

	N	WRMS-Pos.			Epoch	WRMS-Vel.		
		E	N	U		E	N	U
			mm		y		mm/y	
ITRF2005	89	1.0	1.2	2.6	7:360	0.3	0.3	0.6

Conclusion (1/2)

- **The ITRF**
  - **is the most optimal global RF available today**
  - **gathers the strenghs of space geodesy techniques**
  - **more precise and accurate than any individual RF**
- **Using the ITRF as a common GNSS RF will facilitate the interoperability**
- **Well established procedure available to ensure optimal alignment of GNSS RFs to ITRF**
- **To my knowledge: most (if not all) GNSS RFs are already ''aligned'' to ITRF**
- **GNSS RFs should take into account station velocities**

Conclusion (2/2)

WGS84, PZ90, GTRF

Are all connected to (compatible with)

a Unique System

The ITRS