The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

World Year of PHYSICS 2005

H4.SMR/1642-4

"IAG-IASPEI Joint Capacity Building Workshop on
Deformation Measurements and Understanding Natural
Hazards in Developing Countries"

17 - 23 January 2005

Reference Systems: Definition and Realization
Associated IAG Services
IAG Reference Frame Sub-commission for Europe (EUREF)

Zuheir Altamimi

Laboratiore de Recherche en Géodésie
Institut Géographique National
France

Reference Systems: Definition and Realization

Associated IAG Services

IAG Reference Frame Sub-commission for Europe (EUREF)

Zuheir ALTAMIMI

Laboratoire de Recherche en Géodésie

Institut Géographique National

France

IAG, IASPEI Workshop, ICTP, Trieste, Italy, January 17-22, 2005

OUTLINE

- Very Brief Introduction to Space Geodesy Techniques
- Why is a Terrestrial Reference System (TRS) needed and how is it realized ?
- Concept and Definition
- TRS Realization by a Frame (TRF)
- Associated IAG Services
- International Terrestrial Reference System (ITRS) and its realization the International Terrestrial Reference Frame (ITRF)
- ITRF Geodetic & Geophysical Results
- EUREF
- Future perspectives

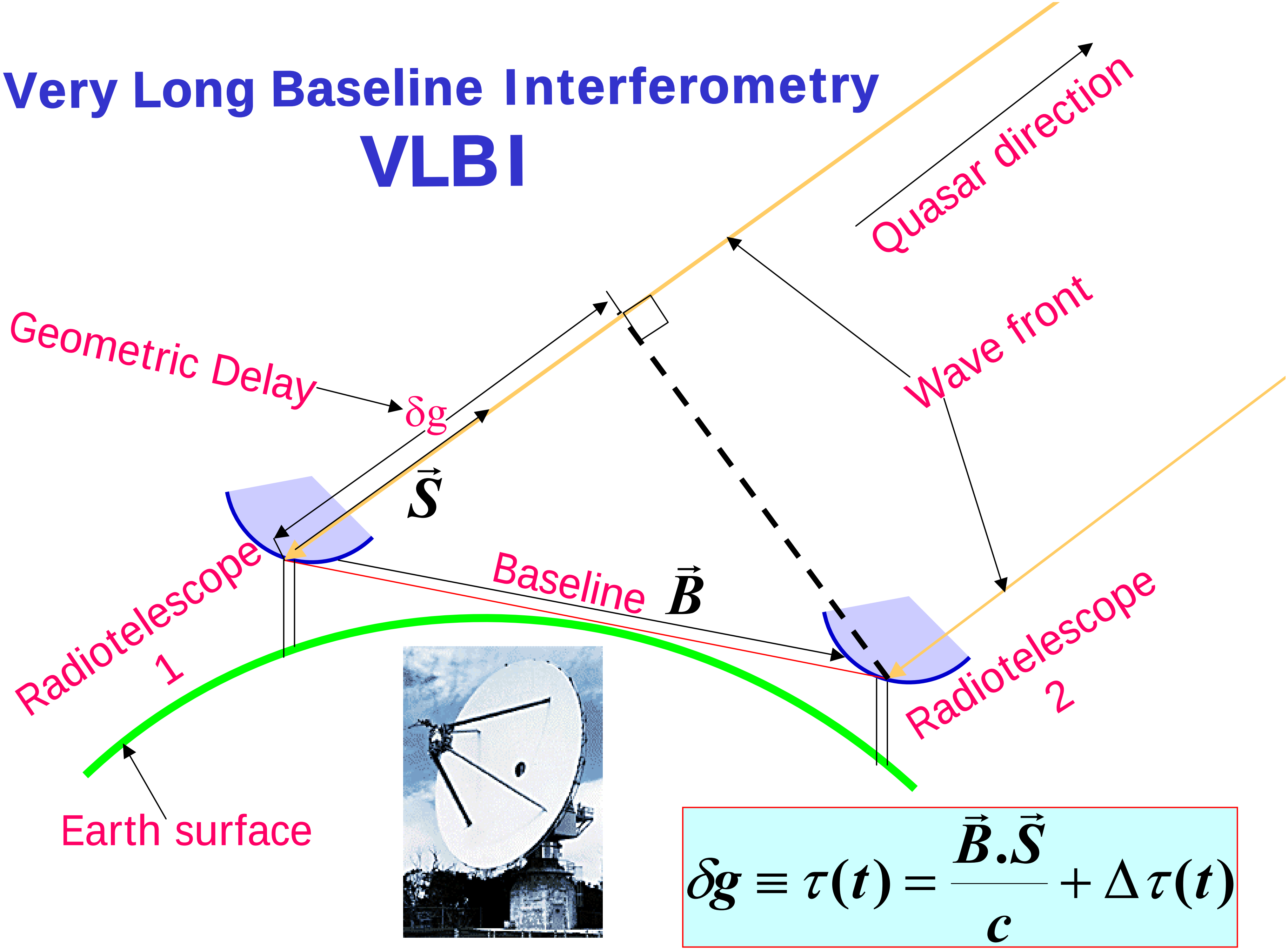
Geodesy

- Etymologically comes from Greek: « geôdaisia »: « dividing the Earth »
- Study of the form, dimensions, rotation and gravity field of the Earth
- Main geodesy activity: determination of point/object positions over the Earth surface or near-by space
- There is a need for a Terrestrial Reference System and a Coordinate System

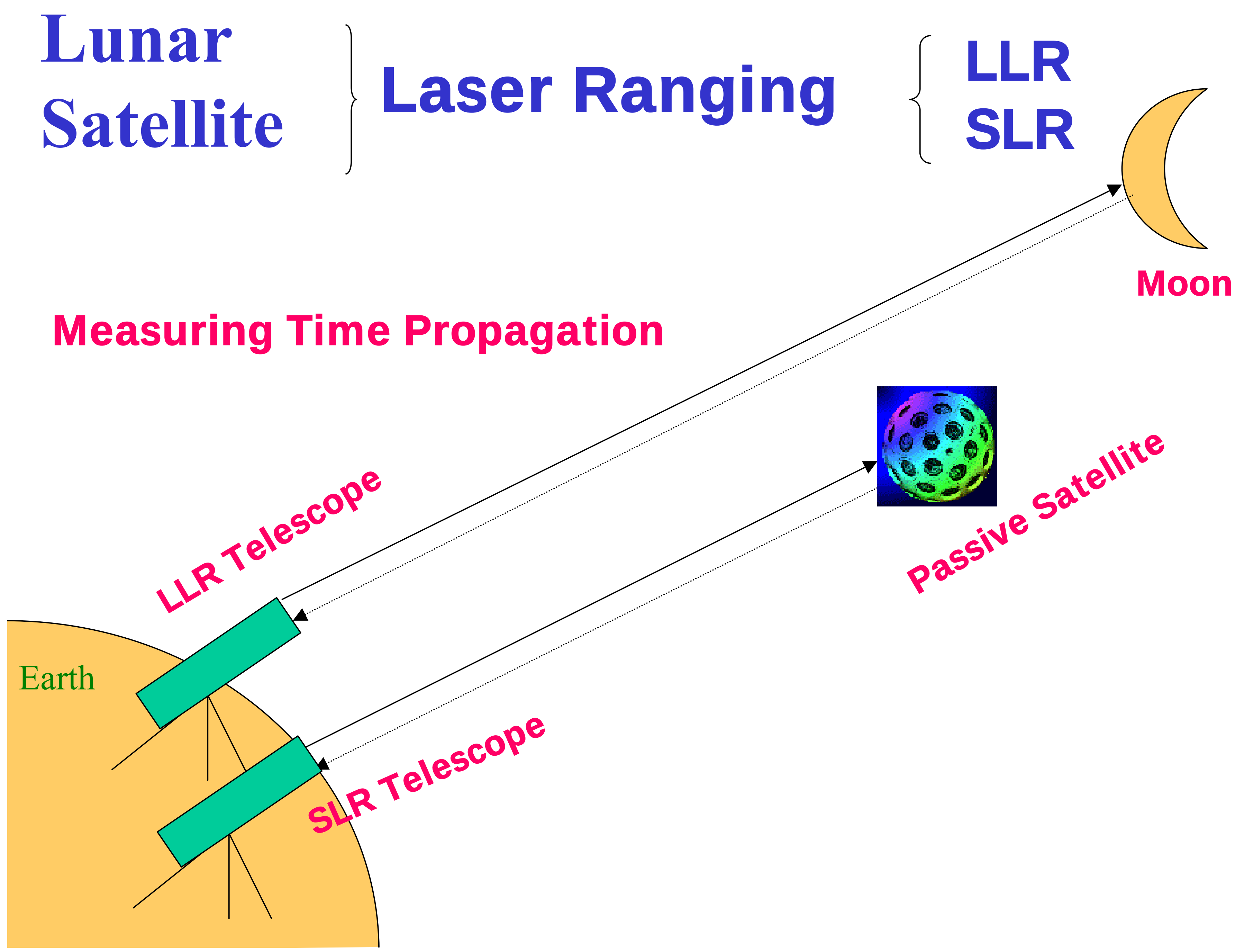
Space Geodesy Techniques

- Very Long Baseline Interferometry (VLBI)
- Lunar Laser Ranging (LLR)
- Satellite Laser Ranging (SLR)
- DORIS
- Global Positioning System (GPS)
- Others (PRARE, GLONASS, GALILEO)

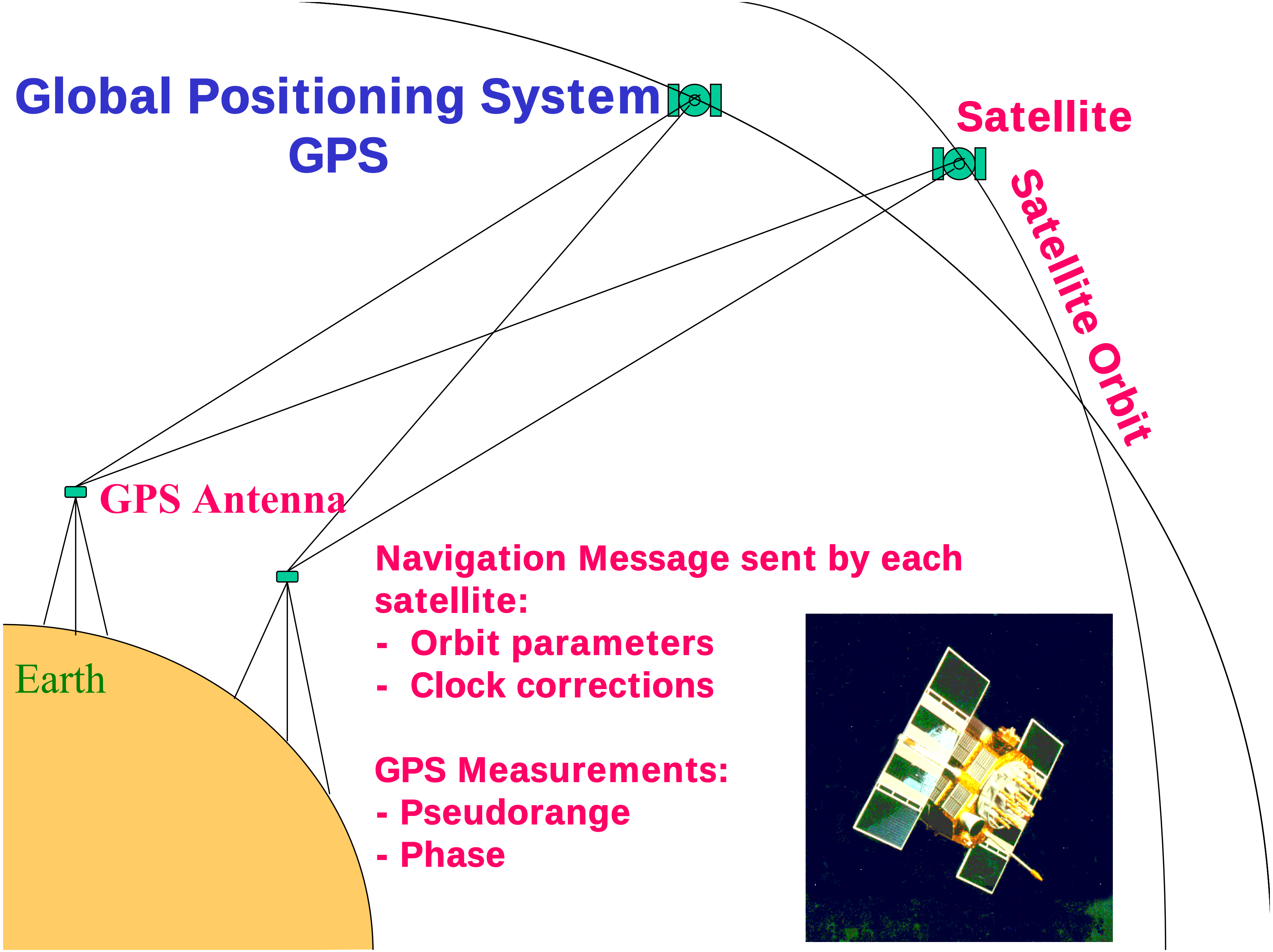
Very Long Baseline Interferometry
VLBI



$$\delta g \equiv \tau(t) = \frac{\vec{B}.\vec{S}}{c} + \Delta\tau(t)$$


Lunar
Satellite
Laser Ranging
LLR
SLR
Moon
Measuring Time Propagation
LLR Telescope
Passive Satellite
Earth
SLR Telescope

Global Positioning System
GPS



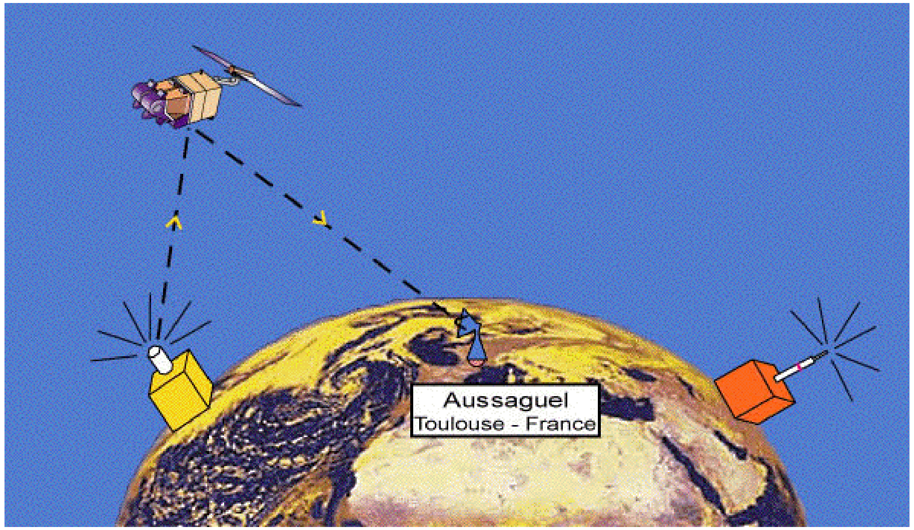
Navigation Message sent by each satellite:
- Orbit parameters
- Clock corrections

GPS Measurements:
- Pseudorange
- Phase

DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

- **French Technique developed by CNES, IGN and GRGS**
- **Uplink System: on-board receiver measures the doppler shift on the signal emitted by the ground beacon**



Why is a Terrestrial Reference System (TRS) Needed ?

- **One of the goals of Space Geodesy is to estimate point positions over the Earth surface**
- **Stations positions are neither observable nor absolute quantities. They have to be referred to some reference**
- **TRS: Mathematical model for a physical Earth in which point positions are expressed and have small variations due to geophysical effects. (Ideal definition)**
- **It is a spatial reference system co-rotating with the Earth in its diurnal motion in space.**

How to realize a TRS?

- Access to point positions requires measurements (observations) allowing their link to the mathematical object
- **TRF**: Set of physical points with determined coordinates
- The TRF a realization of the TRS, making use of Space Geodesy observations
- Each technique and data analysis realizes its own TRS
- Multitude of TRF exist.

Reference Systems: Terminology

- **Ideal Reference System** : **theoretical definition (not accessible)**
- **Conventional Reference System**: **set of conventions, algorithms, constants used to determine object positions in an IRS**
- **Conventional Reference Frame**:

  - Set of physical objects with their coordinates

  - Realization of an Ideal Reference System
- **Coordinate System**: **cartesian (X,Y,Z), geographic** (λ, ϕ, h),...

Ideal Terrestrial Reference System

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

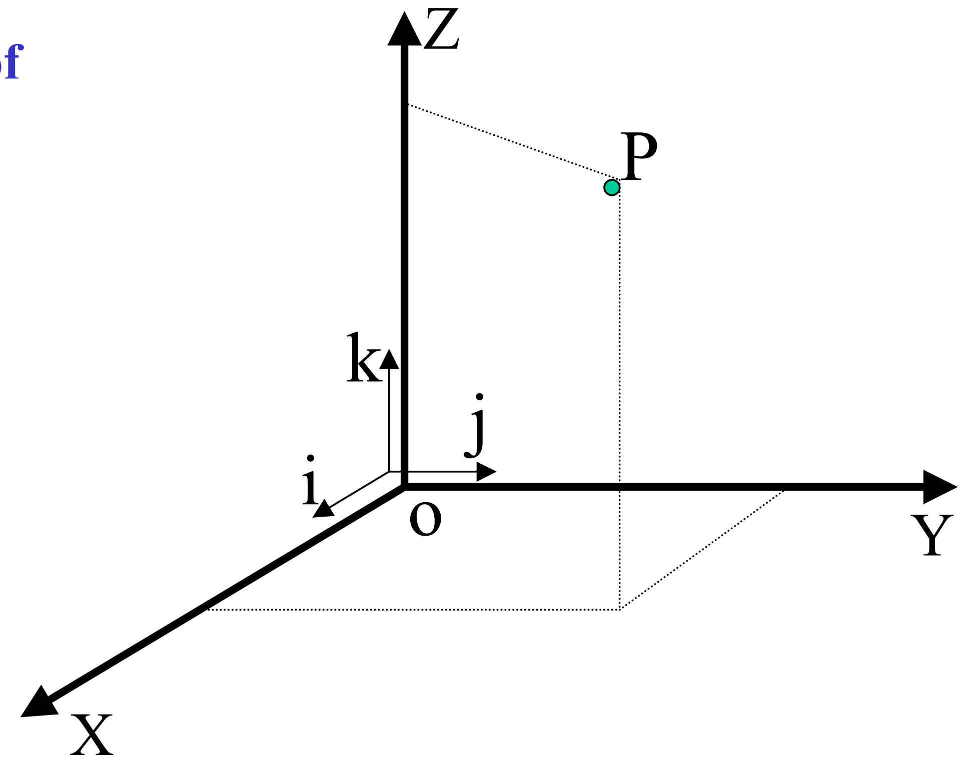
Affine Frame (O,E) where:

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

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

Affine Frame

- **Origin**:
  - Barycentric (Center of Mass of the solar system)
  - Geocentric: CoM of the Earth
- **Orientation**:
  - Ecliptic
  - Equatorial
- **Unit of length (Scale)**: Same norm for the 3 vectors



Ideal Terrestrial Reference System in the Context of Space Geodesy

- **Origin**: **Geocentric: Earth Center of Mass**
- **Scale**: **SI Unit**
- **Orientation**: **Equatorial (Z axis is the direction of the Earth pole)**

Transformation between TRS (1/2)

7-parameter similarity :

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

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

Scale Factor λ

Rotation Matrix $\Re = R_x.R_y.R_z$

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

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

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

Transformation between TRS (2/2)

In space geodesy we use the linearized formula:

$$X_2 = X_1 + T + DX_1 + R.X_1$$

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}

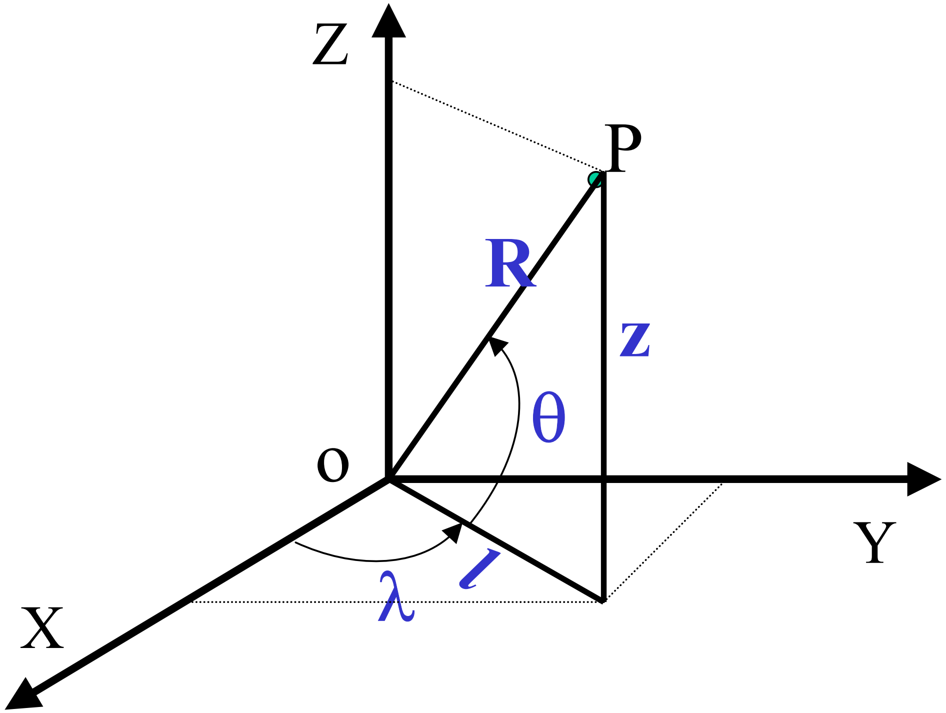
The terms of 2nd ordre are neglected: less than $10^{-10} \approx 0.6$ mm.

Differentiating equation 1 with respect to time, we have:

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

Coordinate Systems

- **3D**:
  - Cartesian: X, Y, Z
  - Ellipsoidal: λ, φ, h
  - Mapping: E, N, h
  - Spherical: R, θ, λ
  - Cylindrical: *l*, λ, Z
- **2D**:
  - Geographic: λ, φ
  - Mapping: E, N
- **1D** : Height system: H



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

Cylindrical

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

Spherical

Crust-based TRF

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

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

X_0 : **point position at a reference epoch t_0**

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

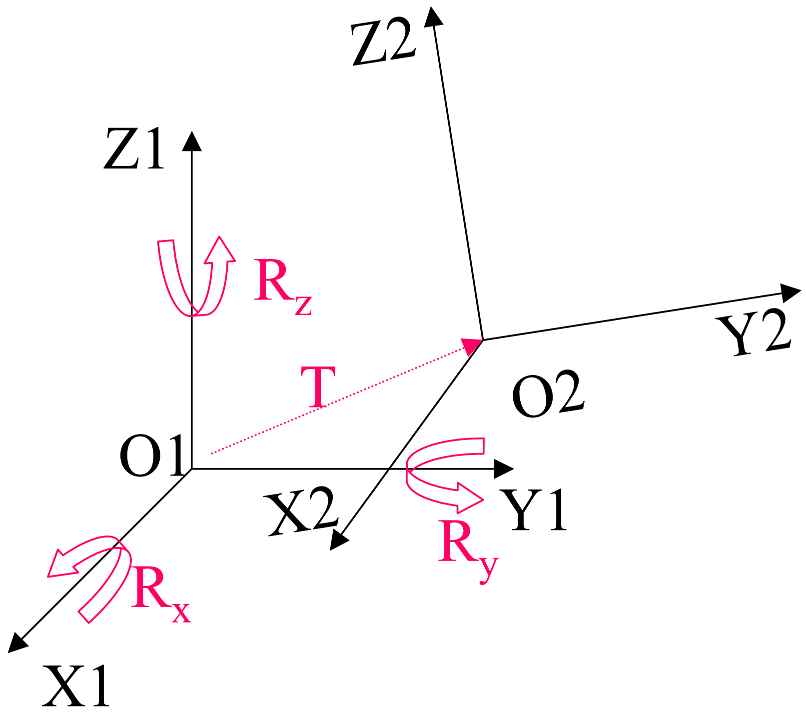
$\Delta X_i(t)$: **high frequency time variations:**

- **solid Earth tide**
- **ocean loading**
- **atmosphere loading**
- **geocenter motion**

TRS Realizations by Space Geodesy

- **Using data from:**
  - **one technique**
  - **Two or more techniques**

- **Using combination of station coordinates provided by several techniques**



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

Comparison of Two TRFs

Estimation of the Transformation parameters between the Two

$$\boldsymbol{X_2 = X_1 + T + DX_1 + RX_1}$$ or $$\boldsymbol{X_2 = X_1 + A\theta}$$

$$\theta = \begin{pmatrix} T1 \\ T2 \\ T3 \\ D \\ R1 \\ R2 \\ R3 \end{pmatrix}$$

$$A = \begin{pmatrix} 1 & 0 & 0 & x & 0 & z & -y \\ 0 & 1 & 0 & y & -z & 0 & x \\ 0 & 0 & 1 & z & y & -x & 0 \end{pmatrix}$$

θ **is solved for using Least Squares adjustment**

$$\theta = (A^T PA)^{-1} A^T P(X_2 - X_1)$$

And in case of velocities

$$\dot{\theta} = (A^T PA)^{-1} A^T P(\dot{X}_2 - \dot{X}_1)$$

Combination of TRF's

Based on the Transformation Formula of 7 parameters:
For each individual TRF s, we have:

$$\boxed{X_s = X_c + T + DX_c + RX_c}$$

The unknowns are:

- X_c **: station positions (& velocities)**
- **transformation parameters (& rates) from TRF *c* to TRF *s***

Solved for using least Squares adjustment

Implementation of a TRF

- Definition at a chosen epoch, by selecting 7 transformation parameters, tending to satisfy the theoretical definition of the corresponding TRS
- A law of time evolution, by selecting 7 rates of the 7 transformation 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

Geocenter Motion

Translational motion of the tracking network due to variation of the CoM position induced by mass redistribution

- Likely involves periodic and secular components
- Satellite techniques have limited abilities to accurately measure this motion
- TRF origin from satellite techniques coincides with the CoM averaged over the period of the used observations

TRF Scale

- GM adopted (or estimated) value in case of satellite techniques
- Relativistic corrections
- Troposphere modelling
- Technique-specific effects
  - VLBI, GPS and DORIS antenna-related effects
  - SLR ranging bias
- Station vertical motions

TRF implementation in practice

The initial NEQ system of space geodesy observations could be written as:

$$N_{unc}(\Delta X) = K$$

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

N_{unc} **Normal matrix is singular having a rank deficiency Equal to the number of TRF parameters not reduced by the observations. Some constraints are needed:**

- **Tight constraints ($\sigma \leq 10^{-10}$) m**
- **Removable constraints ($\sigma \cong 10^{-5}$) m**
- **Loose constraints ($\sigma \geq 1$) m**
- **Minimum constraints (applied over the TRF parameters and not over station coordinates)**

Datum Definition: Minimum Constraints (1/3)

Application of Minimum Constraints (MC) approach based on

theoretical works by many authors, since the 70's on, e.g.:

- Free Network Adjustment

- S-transformation

- Minimum/Inner Constraints

Main Goals:

- "Best" TRF datum definition
- TRF internal consistency: no distortion
- Preserve actual quality of space geodesy observations

Datum Definition : Minimum Constraints (2/3)

The starting point is the standard relation between two TRF's:

$$X_2 = X_1 + A\theta$$

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

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

Datum Definition : Minimum Constraints (3/3)

L.S. yields for θ: $\theta = \overbrace{(A^TA)^{-1}A^T}^{\mathbf{B}}(X_2 - X_1)$

To have X_1 and X_2 be expressed in the same frame (i.e. $\theta = 0$), a "datum definition" equation at Σ_θ level could be written as

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

and in terms of normal equation:

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

Adding the above equation to the initial NEQ system, we have:

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

Σ_θ is a diagonal matrix of small variances over the 14 transformation parameters.

International Association of Geodesy
(1/3) Associated Space Geodesy Services

- International Earth Rotation and Reference Systems Service (IERS) (1988)
- Intern. GPS 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 Association of Geodesy
(2/3) Other Associated Services

- International Gravimetric Service
- International Geoid Service
- International Center for Earth Tide
- Permanent Service for Mean Sea Level
- Time Section of the International Bureau of Weights and Measures
- IAG Bibliographic Service

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

International Association of Geodesy
(3/3) Commissions

4 Commissons

- 1: Reference frames
- 2: Gravity field
- 3: Earth rotation and geodynamics
- 4: Positioning and Applications

IAG Commission 1: Reference Frames

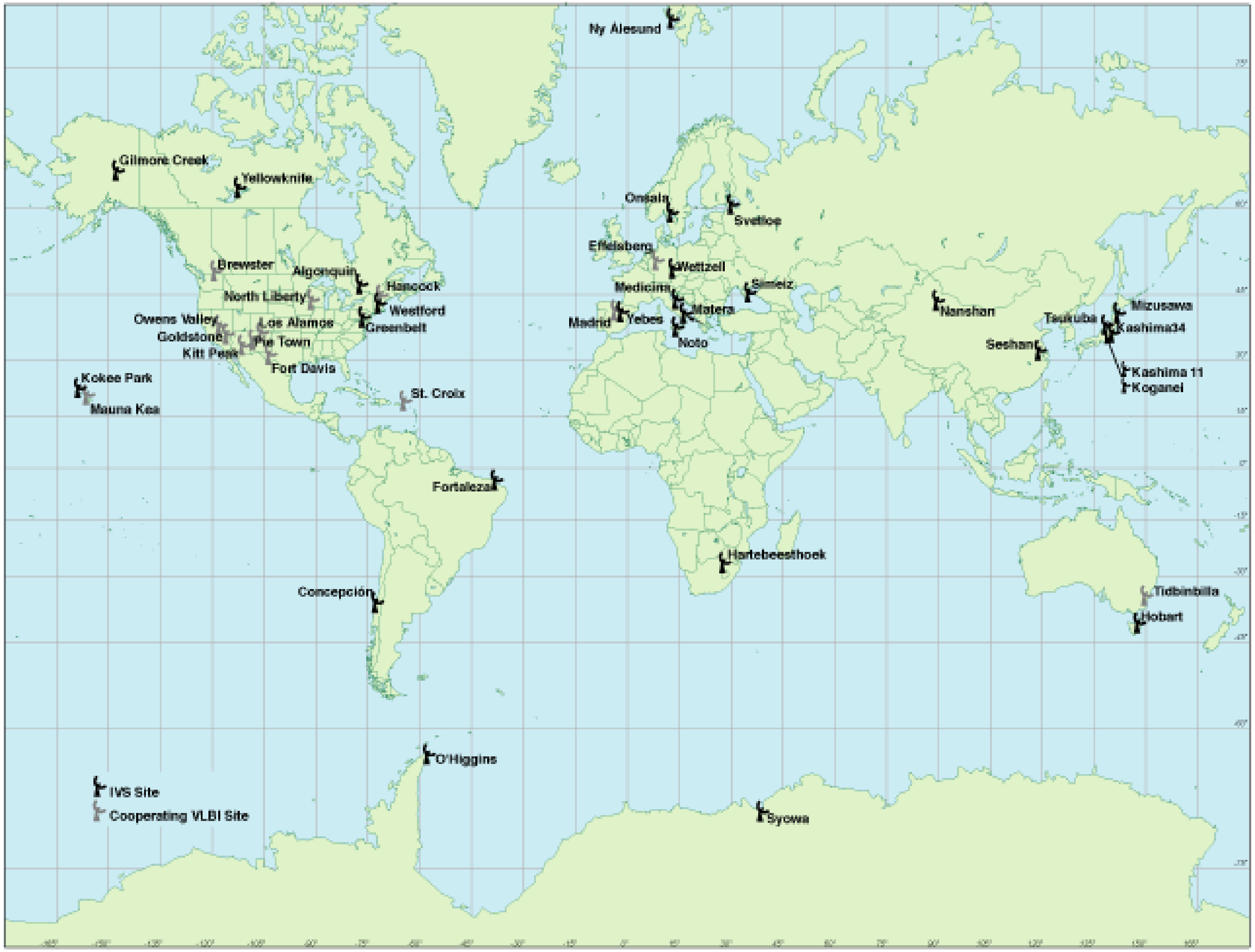
- …
- Sub-Commission Global Reference Frames
- Sub-Commission Regional Reference Frames
- …

Sub-Commission 1.3: Regional Reference Frames

Regional Sub-commissions

- SC1.3a Europe (EUREF)
- SC1.3b South and Central America (SIRGAS)
- SC1.3c North America (NAREF)
- SC1.3d Africa (AFREF)
- SC1.3e South-East Asia and Pacific
- SC1.3f Antarctica (SCAR)

IVS Current Network

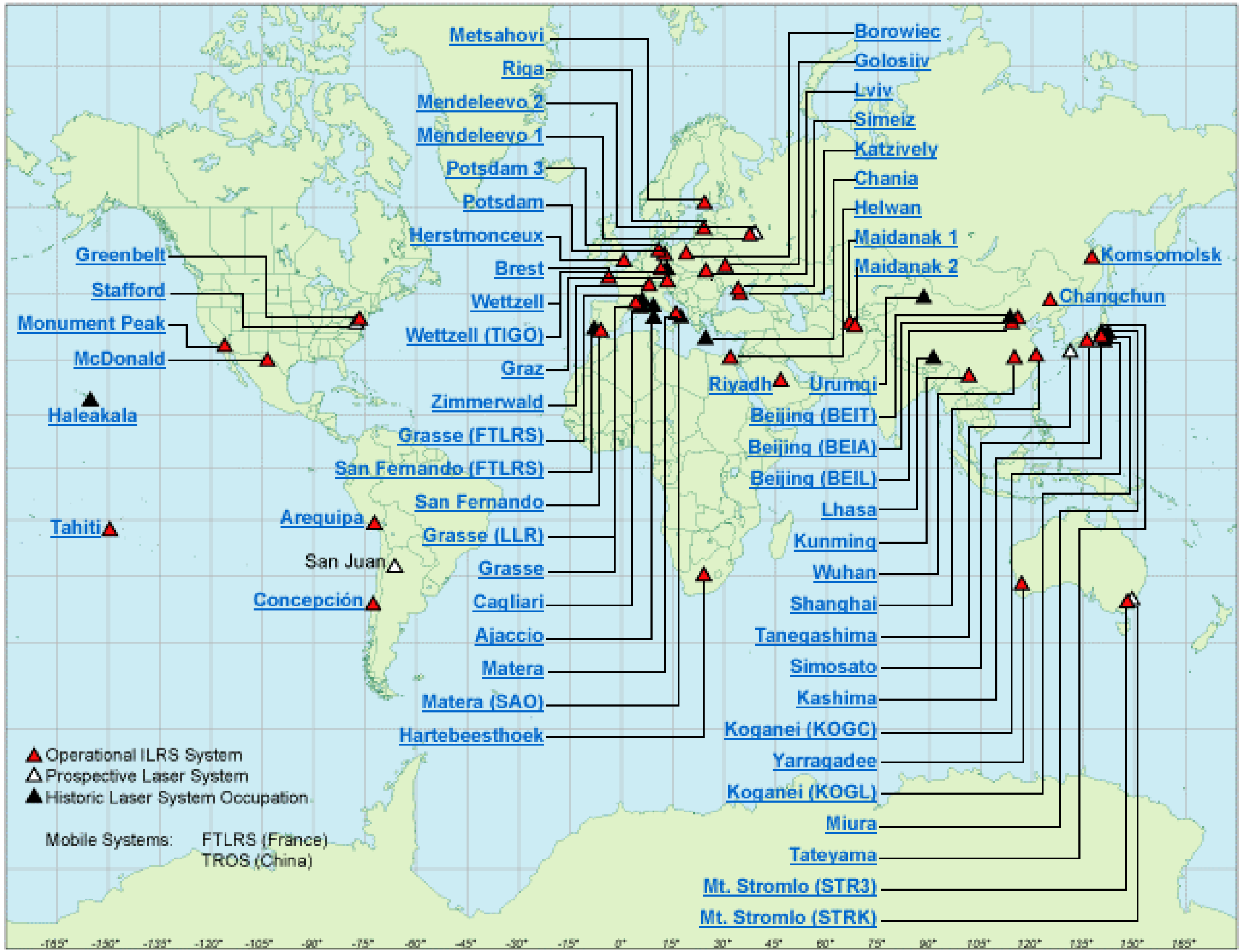


IVS Main Products

- a terrestrial reference frame (TRF),
- the international celestial reference frame (ICRF),
- Earth orientation parameters (EOP).

http://ivscc.gsfc.nasa.gov/

ILRS Current Network

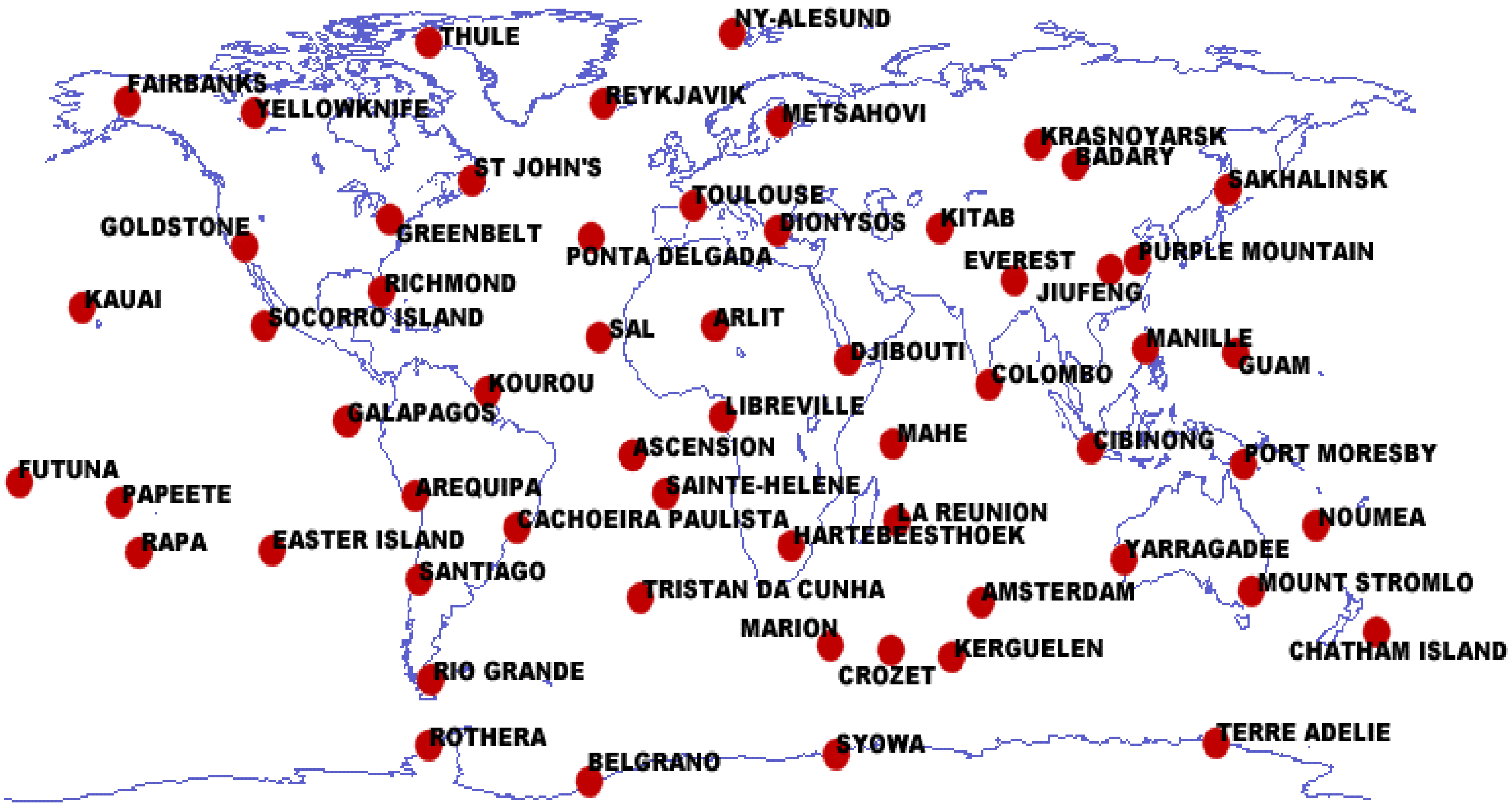


ILRS Main Products

- Earth orientation parameters (polar motion and length of day)
- Station coordinates and velocities of the ILRS tracking systems
- Time-varying geocenter coordinates
- Static and time-varying coefficients of the Earth's gravity field
- Centimeter accuracy satellite ephemerides
- Fundamental physical constants
- Lunar ephemerides and librations
- Lunar orientation parameters

http://ilrs.gsfc.nasa.gov/

IDS Current Network

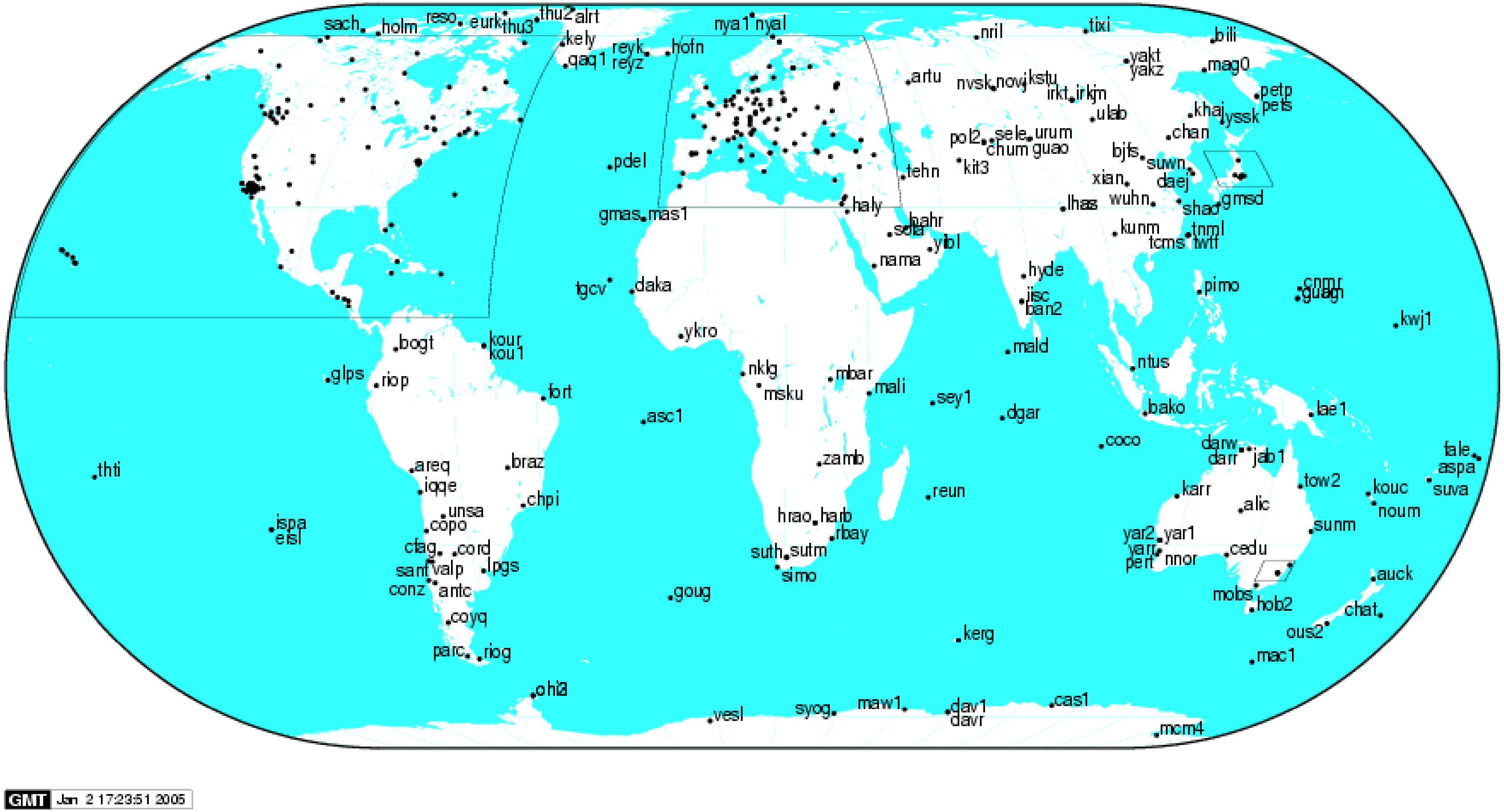


IDS Main Products

- **DORIS satellite ephemerides**
- **Satellit Orbits for altimetric/Oceanography mission (Topex/Poseidon)**
- **DORIS tracking station positions and velocities**

http://lareg.ensg.ign.fr/IDS/

IGS Current Network



IGS Main Products

- GPS satellite ephemerides
- GLONASS satellite ephemerides
- Earth rotation parameters
- IGS tracking station coordinates and velocities
- GPS satellite and IGS tracking station clock information
- Zenith tropospheric path delay estimates
- Global ionospheric maps

http://igscb.jpl.nasa.gov

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/

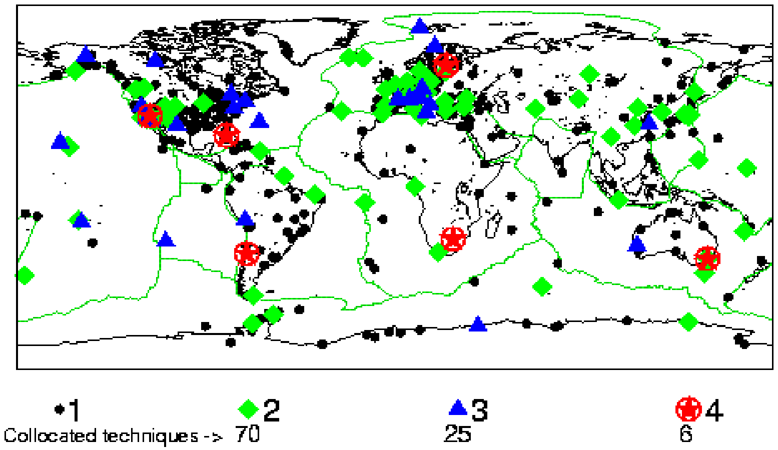
International Terrestrial Reference System (ITRS): Definition

- **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

International Terrestrial Reference System (ITRS)

- **Realized and maintained by the International Earth Rotation and Reference Systems Service (IERS)**
- **Its Realization is called International Terrestrial Reference Frame (ITRF)**
- **Set of station positions and velocities, estimated by combination of VLBI, LLR, SLR, GPS and DORIS individual TRF solutions**

Adopted by IUGG in 1991 for all Earth Science Applications



More than 800 stations located on more than 500 sites

Available: ITRF88, 89,…,97

Latest: ITRF2000

http://www.ensg.ign.fr/ITRF/

International Terrestrial Reference Frame (ITRF)
Datum Definition (ITRF2000)

- Origin: defined by an average of SLR solutions

- Scale: defined by an average of SLR + VLBI solutions

- Orientation: aligned to ITRF97 at epoch 1997.0

- Orientation time evolution: No-Net-Rotation Condition: aligned to NNR-NUVEL-1A

ITRF Orientation Time Evolution: No-Net-Rotation Condition

The NNRC is the null angular momentum h, defined in Tisserand mean Frame and given by:

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

If applied to rigid tectonic plates gives: $\boxed{h = \sum_{p \in P} Q_p \omega_p = 0}$

NNR-NUVEL-1A used: $\boxed{\omega_{PACIFIC} = -3/8\pi \sum_{p \in P} Q_p \Omega_p}$

ITRF2000 orientation & rate definition

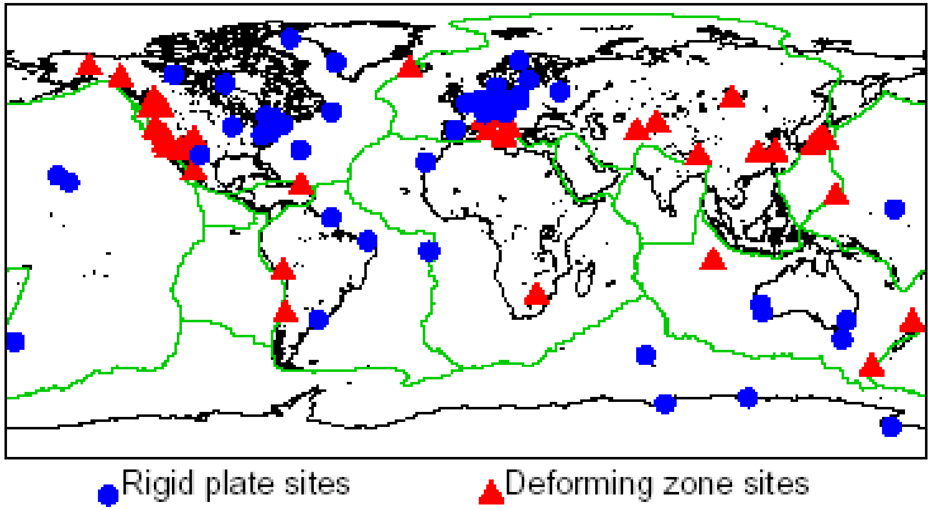
- Orientation: ITRF97 at 1997.0 (1 mm)
- Rate: NNR-NUVEL-1A (1 mm/y)

Using a Datum Eq.:

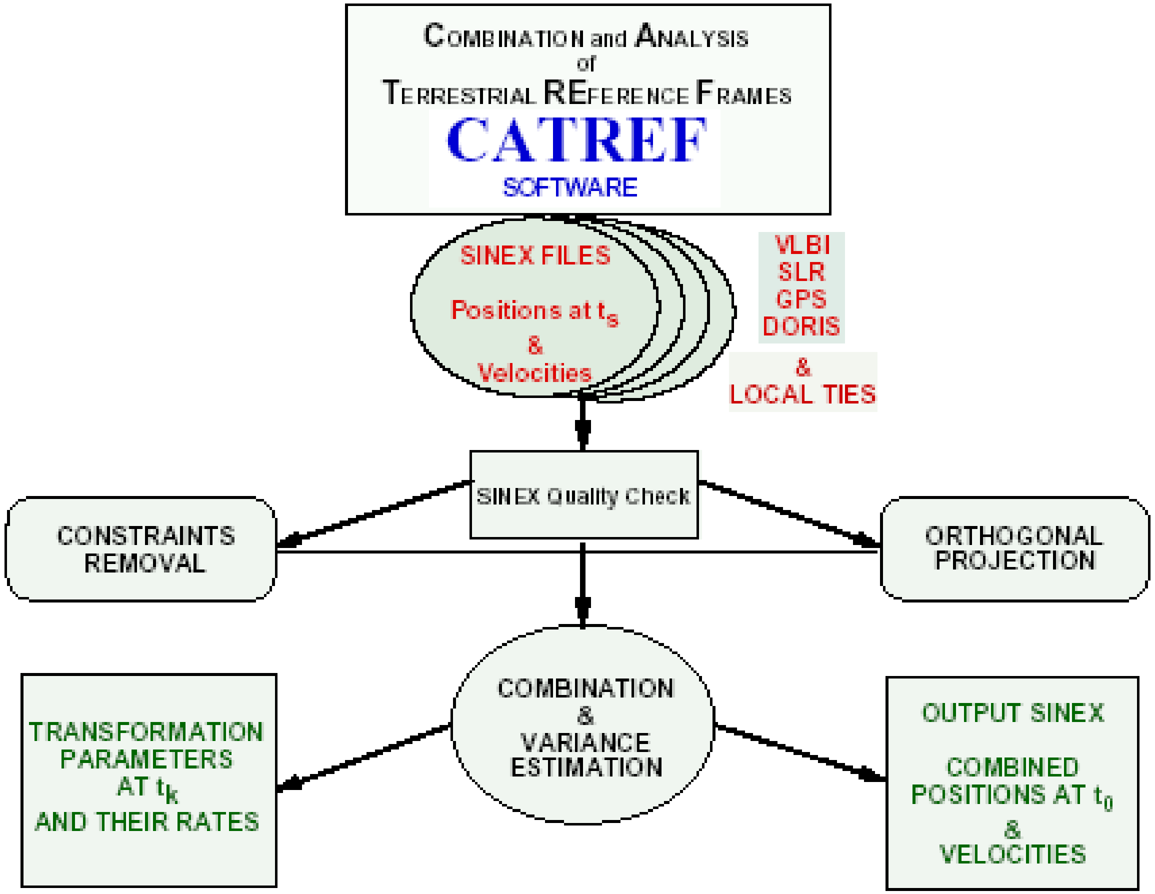
$$\boxed{B(X - X_0) = 0}$$

$$B = (A^T A)^{-1} A^T$$

$$A = \begin{pmatrix} . & . & . \\ 0 & z_a^i & -y_a^i \\ -z_a^i & 0 & x_a^i \\ y_a^i & -x_a^i & 0 \\ . & . & . \end{pmatrix}$$



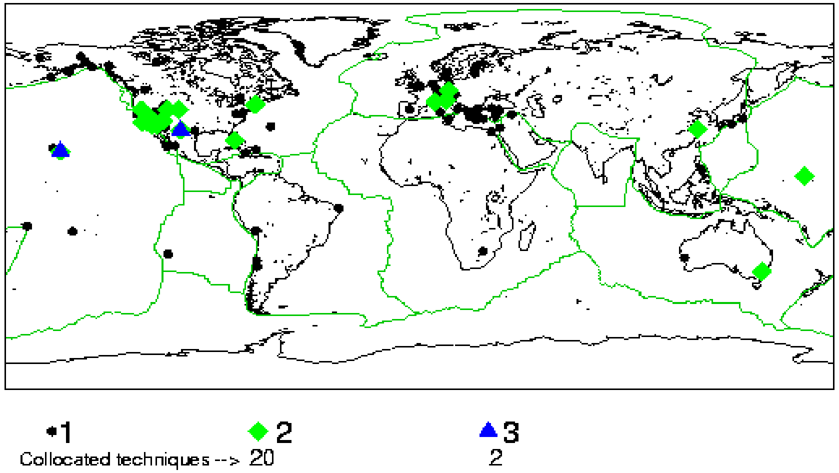
- X_0: Positions (ITRF97) or Velocities (NNR-NUVEL-1A)
- X: Estimated Positions/Velocities



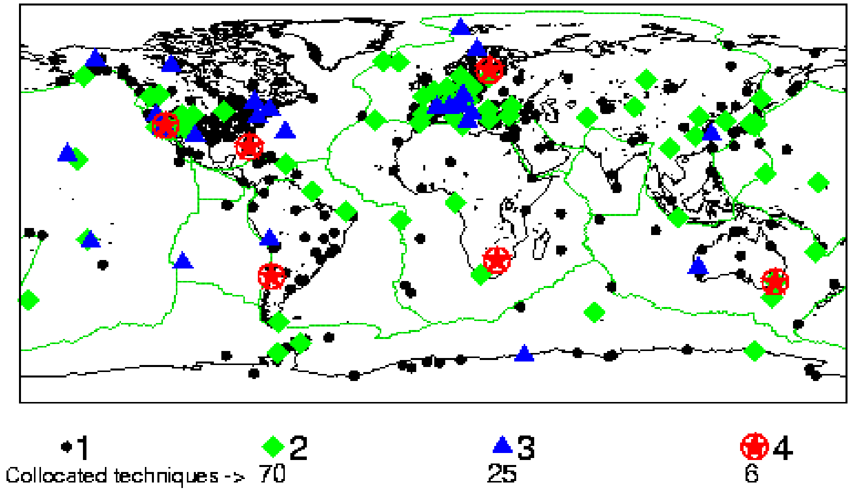
$$\left\{\begin{array}{rcl} X_s^i & = & X_{itrf}^i + (t_s^i - t_0)\dot{X}_{itrf}^i + T_k + D_k X_{itrf}^i + R_k X_{itrf}^i \\ & + & (t_s^i - t_k)\left[\dot{T}_k + \dot{D}_k X_{itrf}^i + \dot{R}_k X_{itrf}^i\right] \\ \dot{X}_s^i & = & \dot{X}_{itrf}^i + \dot{T}_k + \dot{D}_k X_{itrf}^i + \dot{R}_k X_{itrf}^i \end{array}\right.$$

ITRF Network Evolution

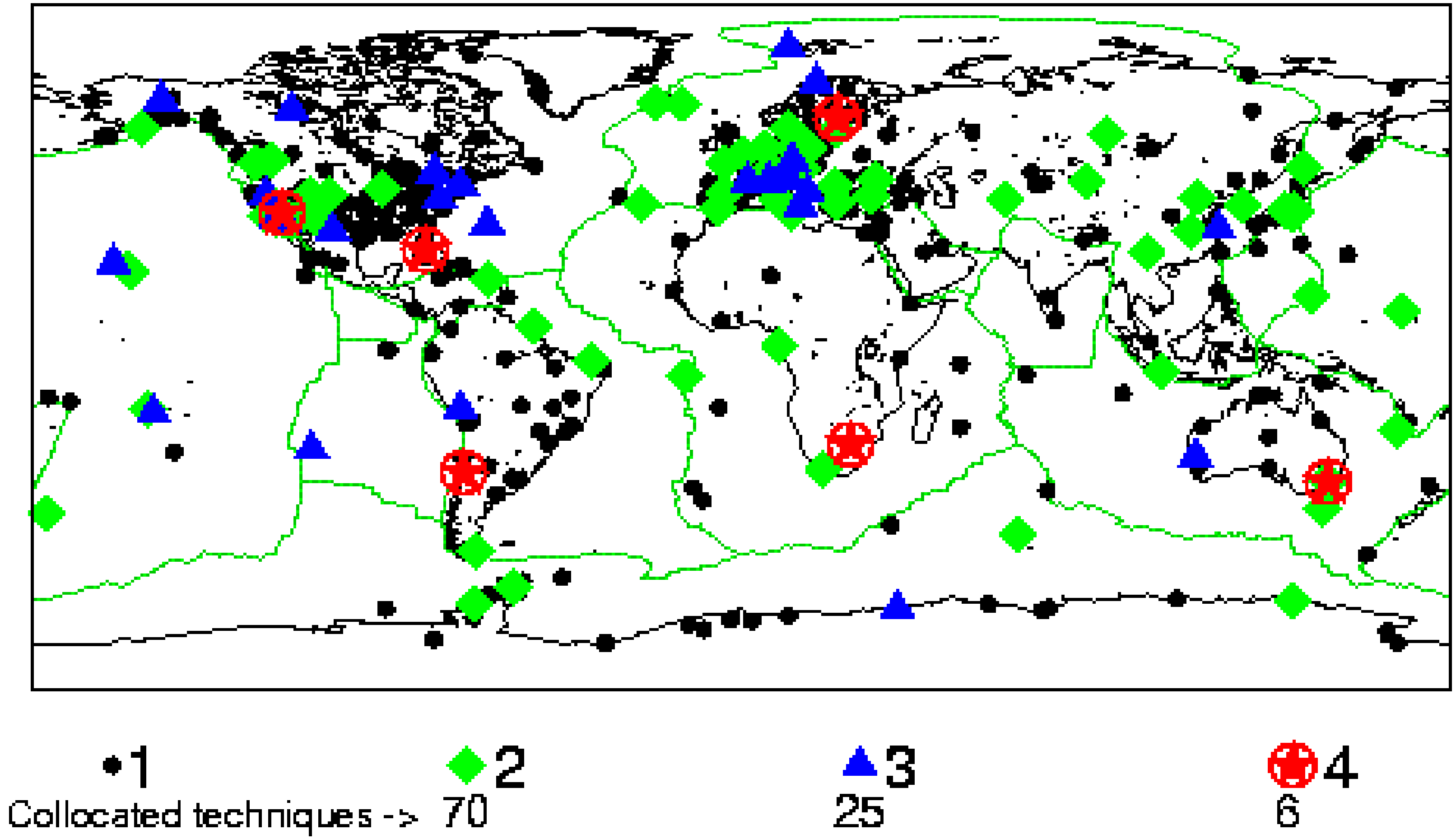
ITRF88



ITRF2000



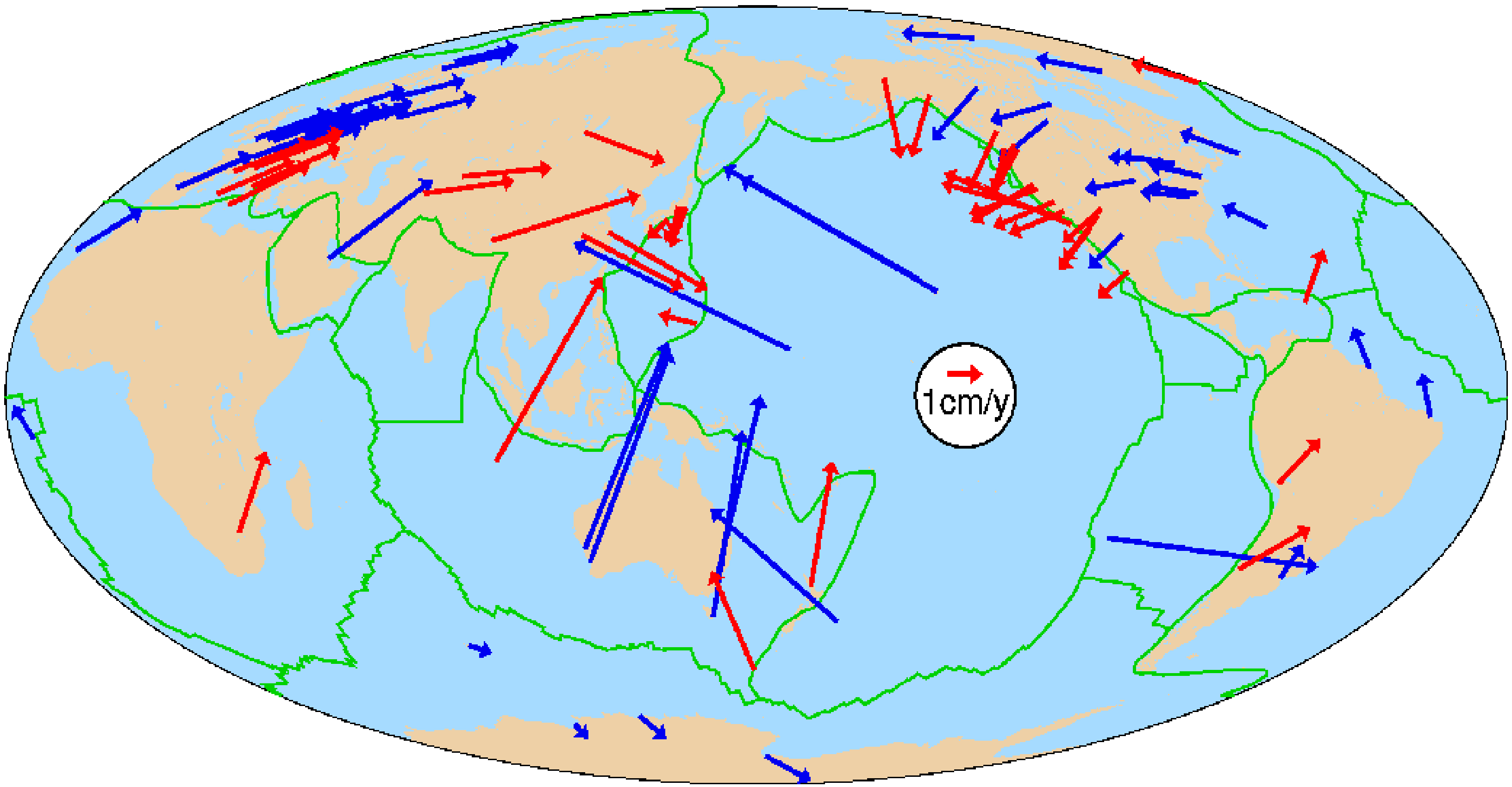
ITRF2000 Network



ITRF2000 Horizontal Velocities

Uncertainties < 1 mm/y

Blue: stable part of tectonic plates **Red: deforming zones**



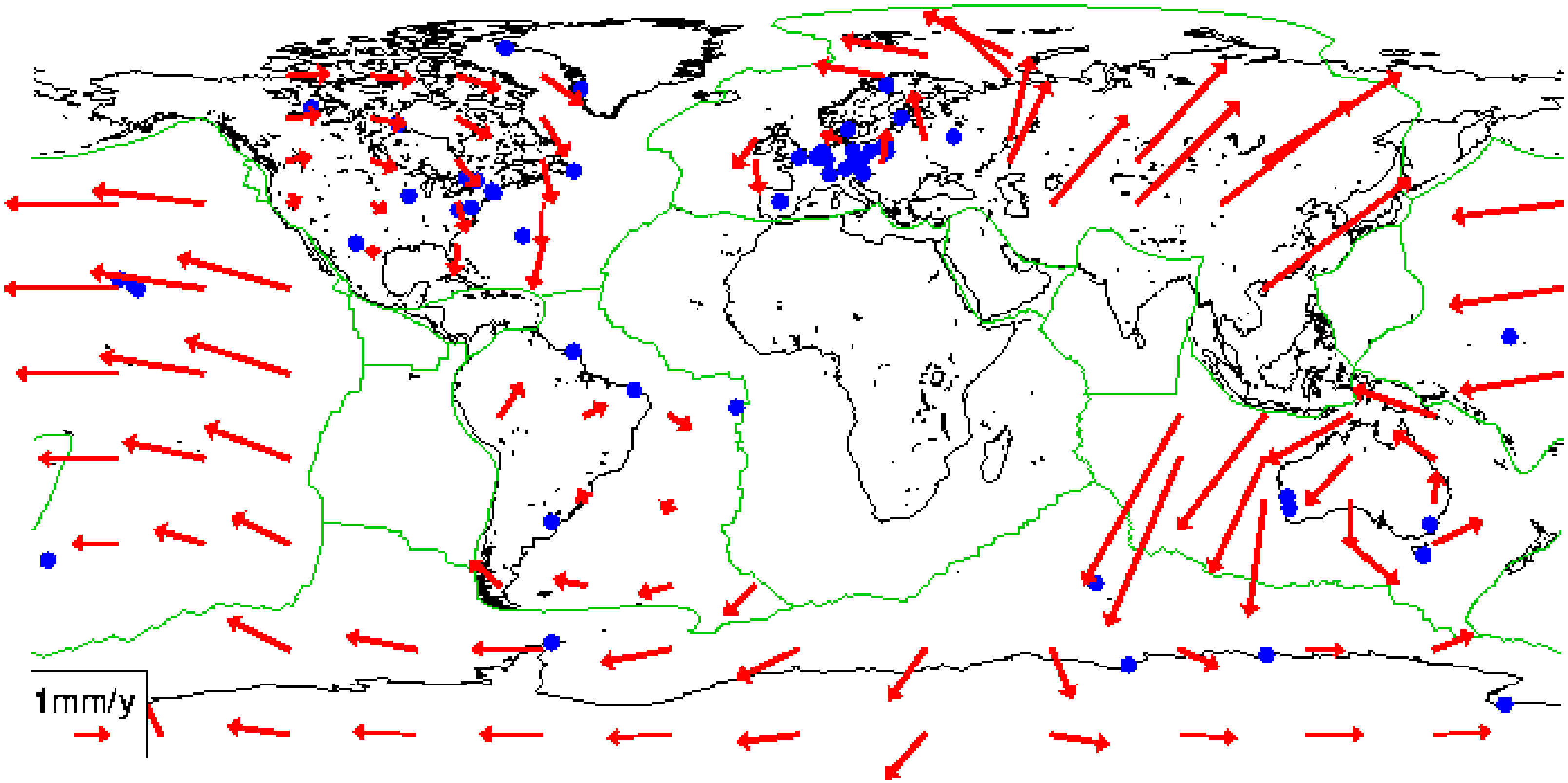
How to estimate an absolute plate rotation pole ?

$$\boxed{\dot{X} = \omega_p \times X}$$

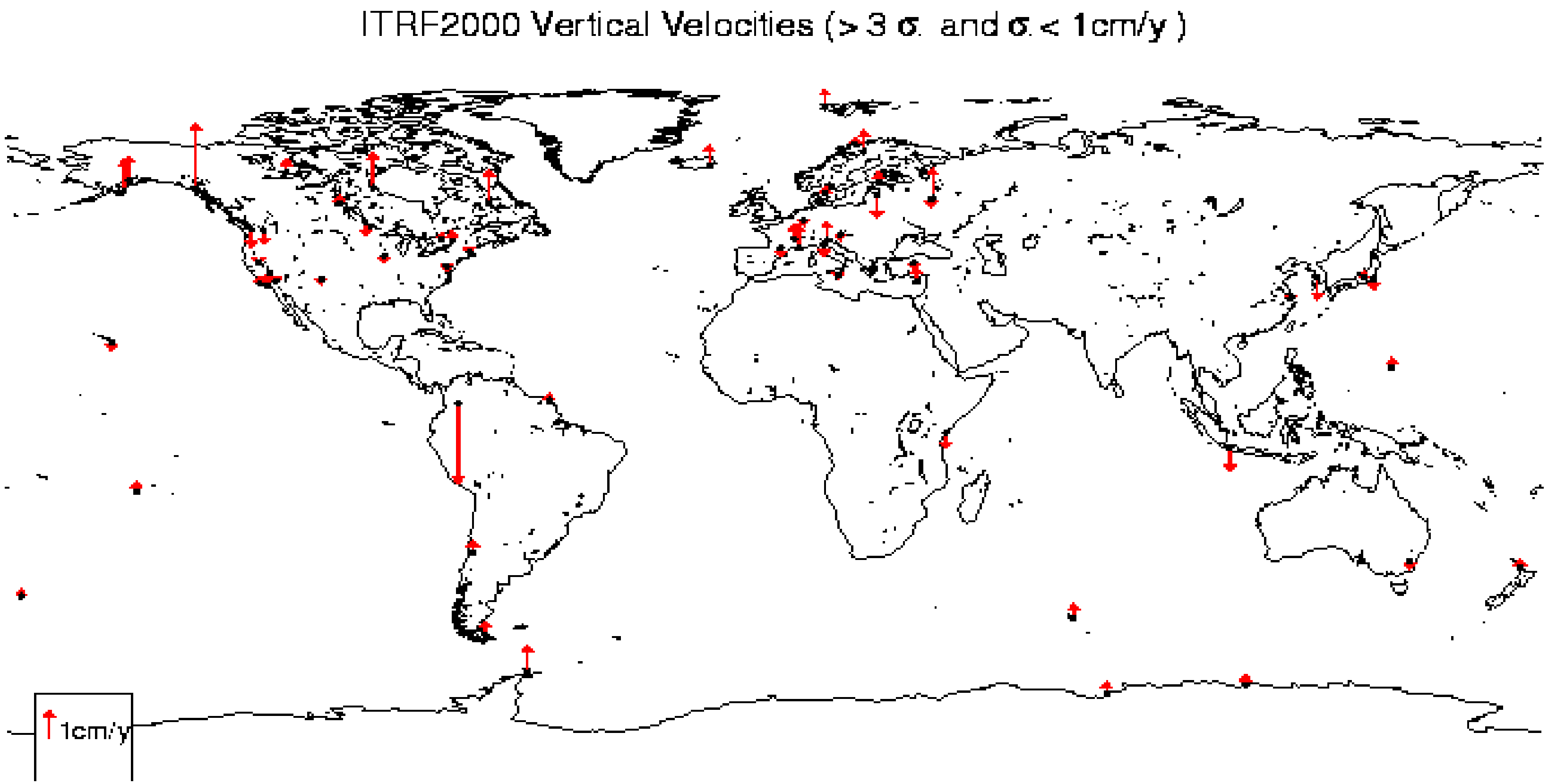
- Datum definition
- Point number and their distribution over the plate
- Quality of the implied velocities
- Level of rigidity of the plate

Tectonic Plate Motion from ITRF2000

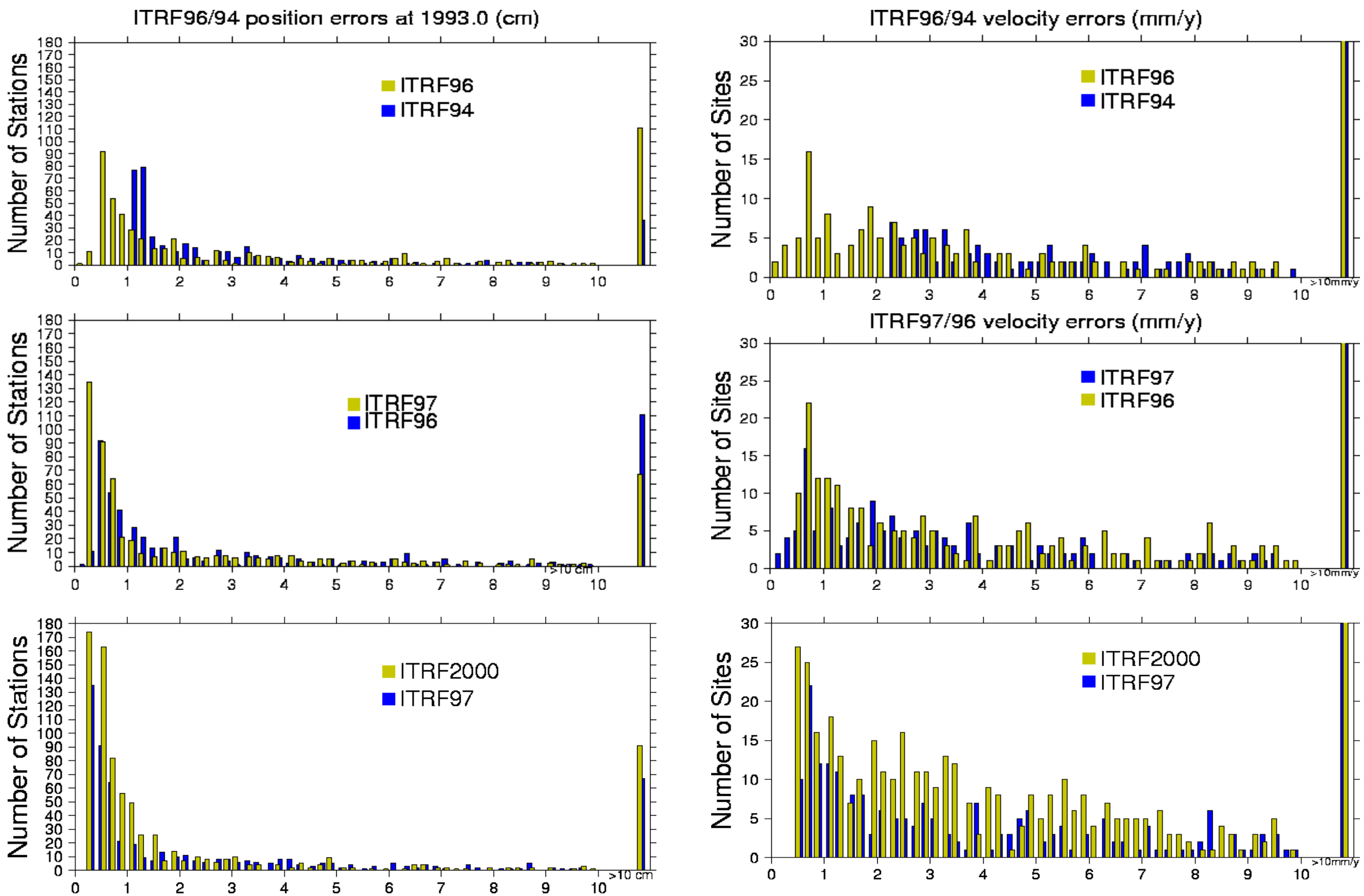
ITRF2000 versus NNR-NUVEL-1A



ITRF2000 Vertical Velocities



ITRF: Quality



ITRF: Quality

WRMS from ITRF2000

Technique	Positions (mm)	Velocities (mm/y)
VLBI	2-3	1
SLR	2-10	1-5
GPS	2-5	1-2
DORIS	25-30	5

Future ITRF solutions

Based on Time Series of Station Positions :

- **Daily (VLBI)**
- **Weekly (GPS, SLR & DORIS)**

and Earth Orientation Parameters:

Polar Motion (x_p, y_p)

Universal Time (UT1)

Length of Day (LOD)

- **Next Version: ITRF2004 to be released 2005**

Other IERS Combination Activities
Combination Pilot Project

- **Analysis & combination at weekly basis**
- **TRF, EOPs, + other parameters**
- **Participation of several Combination Centers**

Combination in the era of times series

- **Daily/Weekly/Monthly solutions of Station positions allow to detect:**
  - **station non-linear and seasonal motions, discontinuities and other problems**
  - **geocenter motion**
  - **loading effects (common mode)**
  - **Ensure TRF & EOP consistency in the combination**

- **But : how to ensure the TRF long-term stability (well defined time evolution) in presence of non-linear variations ?**
- **Basic question: real non-linear variations vs real geophysical motions ?**

TRF & EOP time series Combination

CATREF Software

INPUT: $X(t)$, **EOP(t) in daily/weekly/monthly SINEX files**

OUTPUT: $X(t_0)$, $\dot{X}$, **EOP(t)**, $(\underbrace{T_x, T_y, T_z}_{\text{Geocenter}}, D, R_x, R_y, R_z)$

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

Datum Definition with Minimum Constraints Over a Reference Set of stations

$$\boxed{(A^T A)^{-1} A^T (X_{RS} - X_c) = 0}$$

$$\begin{cases} x_s^p &= x^p + R2_k \\ y_s^p &= y^p + R1_k \\ UT_s &= UT - \frac{1}{f} R3_k \\ \dot{x}_s^p &= \dot{x}^p + \dot{R}2_k \\ \dot{y}_s^p &= \dot{y}^p + \dot{R}1_k \\ LOD_s &= LOD + \frac{\Lambda_0}{f} \dot{R}3_k \end{cases}$$

- **Matching common EOP parameters at UT noon**
- **Propagate at UT noon if rates are available**

Terrestrial Reference System Realization
Current debate

Secular (linear) time evolution

vs

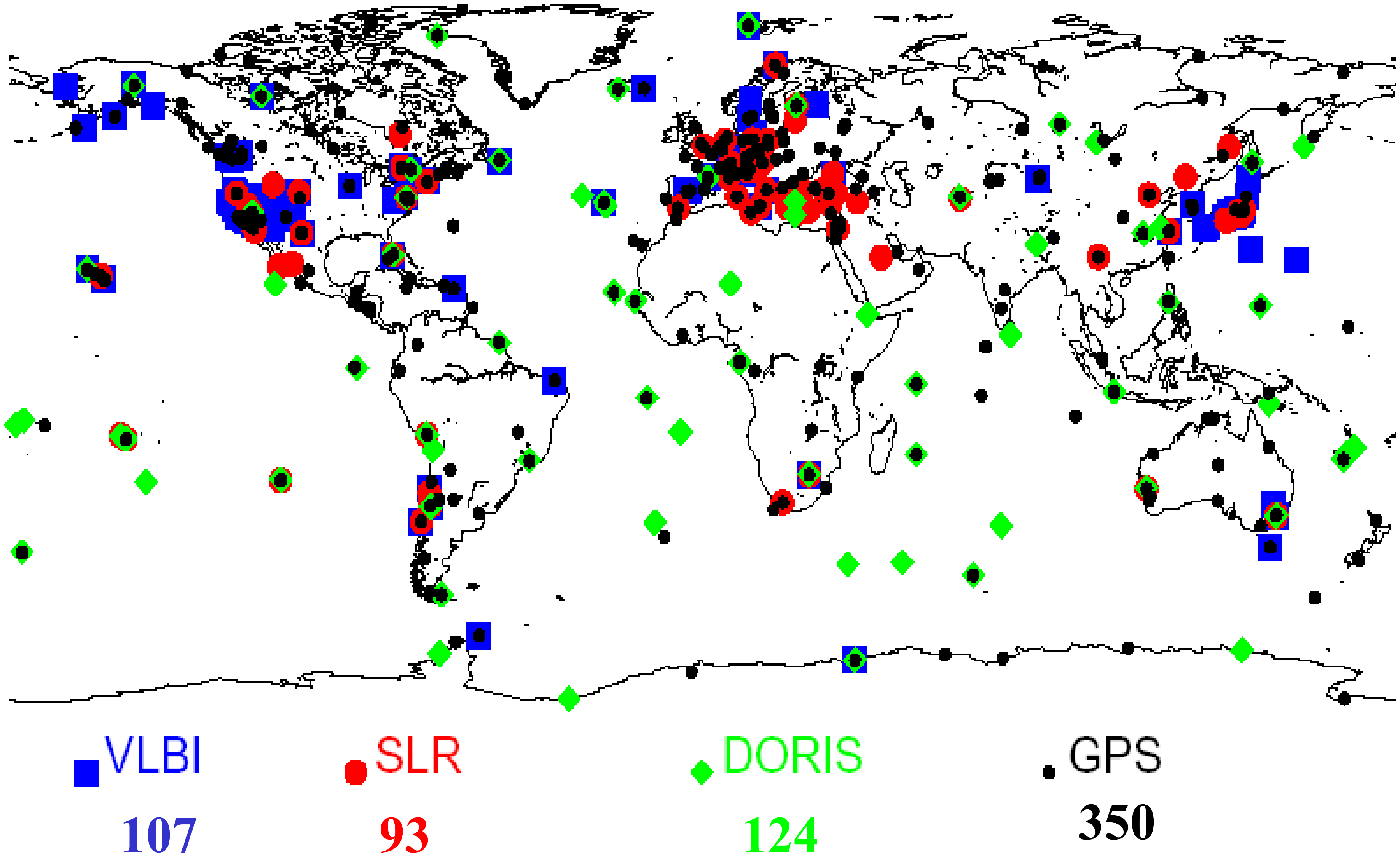
Other approaches taking into account non-linear variations due to, mainly, loading effects

Recent Multi-technique combination

- **Data:**
  - VLBI: GSFC/IVS daily : 1980 – 2004 (24 years)
  - SLR : ASI weekly : 1984 – 2004 (20 years)
  - GPS: IGS combined weekly: 1999 – 2004 (4.5 years)
  - DORIS: IGN-JPL-D05 weekly: 1993 – 2004 (10.5 years)
- **Strategy:**
  - Per technique combination ➔ Pos. Vel. & EOP
  - Combination of the per-tech. combinations + Ties

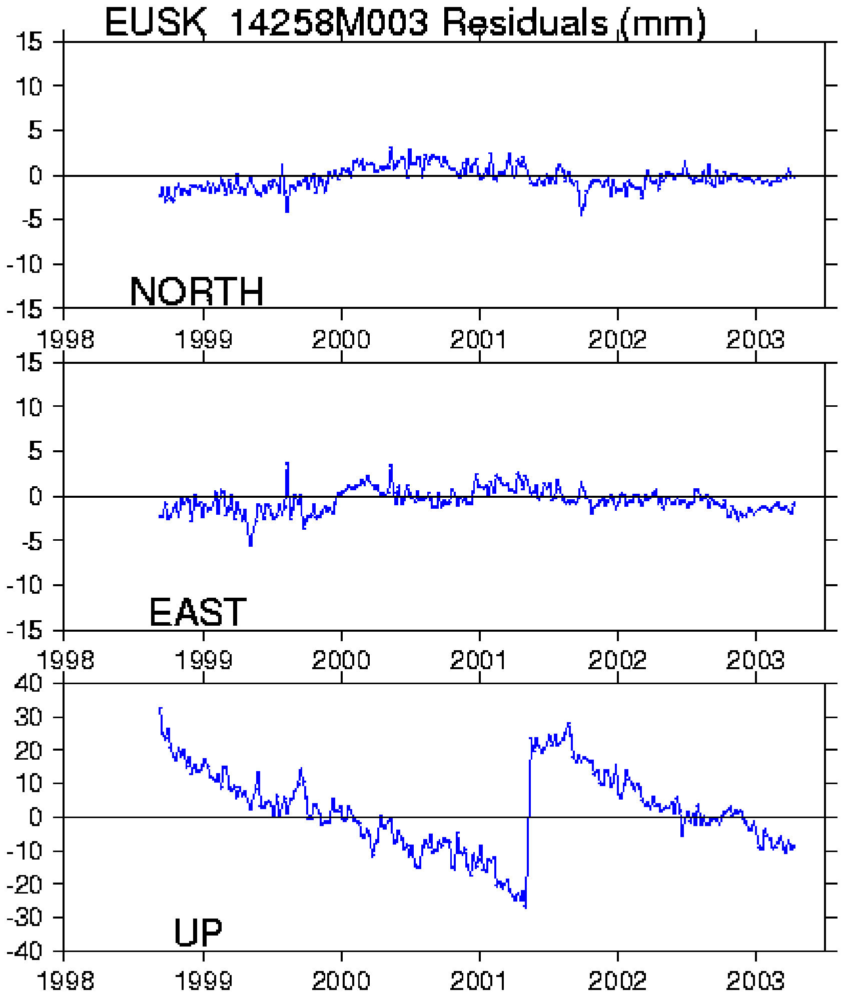
    ➔ Pos. Vel. & EOP

Colocations

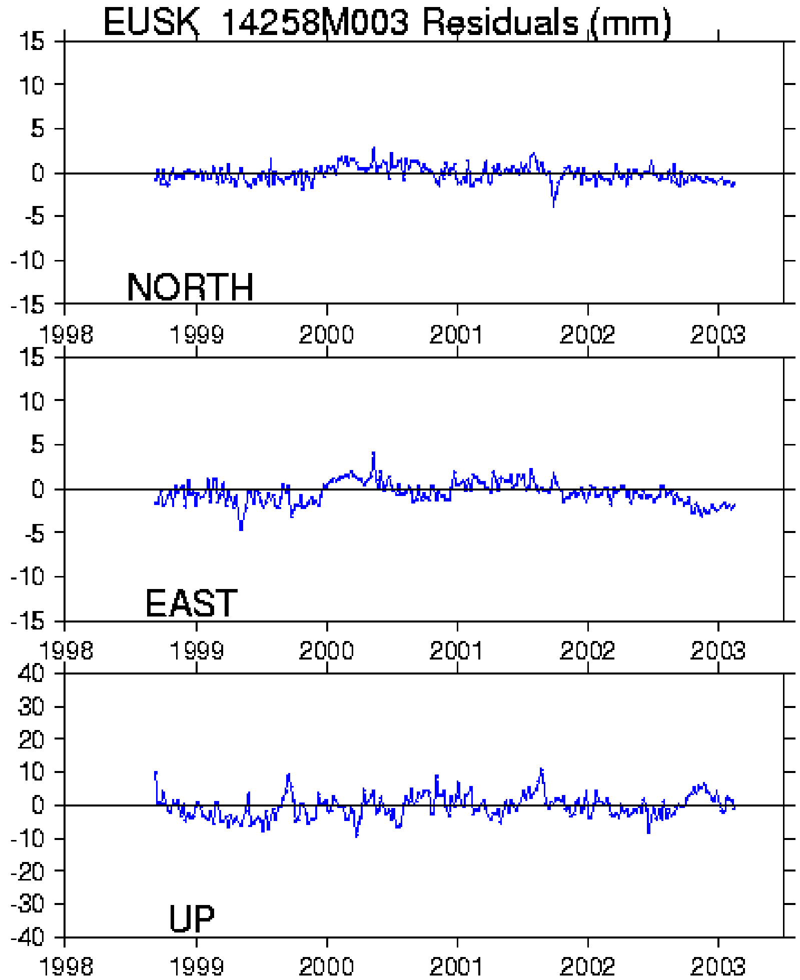


Dicontinuity Monitoring

Before

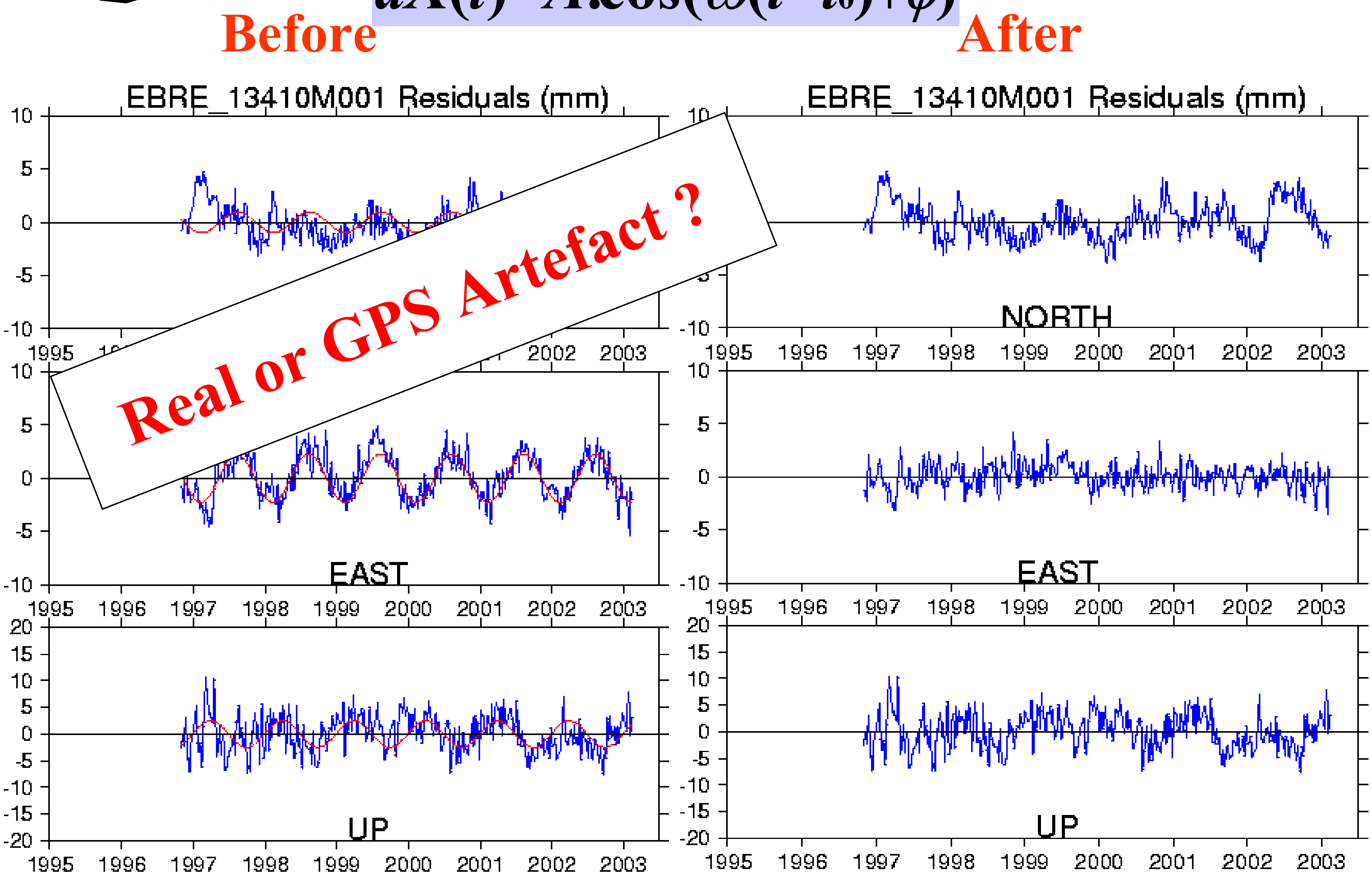


After

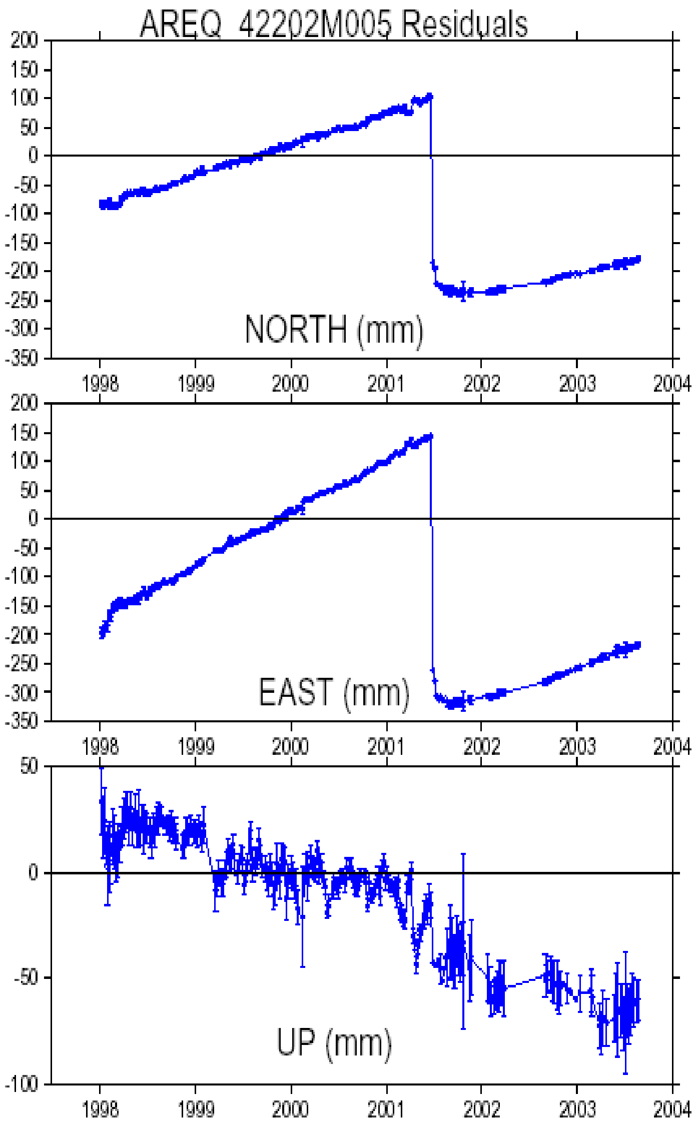


Seasonal Variations

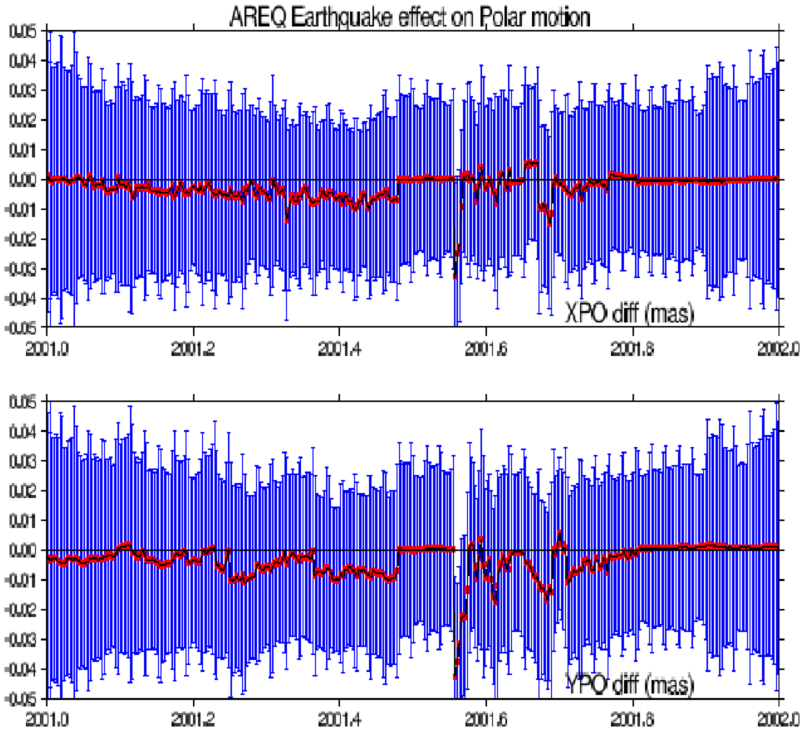
$$dX(t)=A.\cos(\omega(t-t_0)+\phi)$$



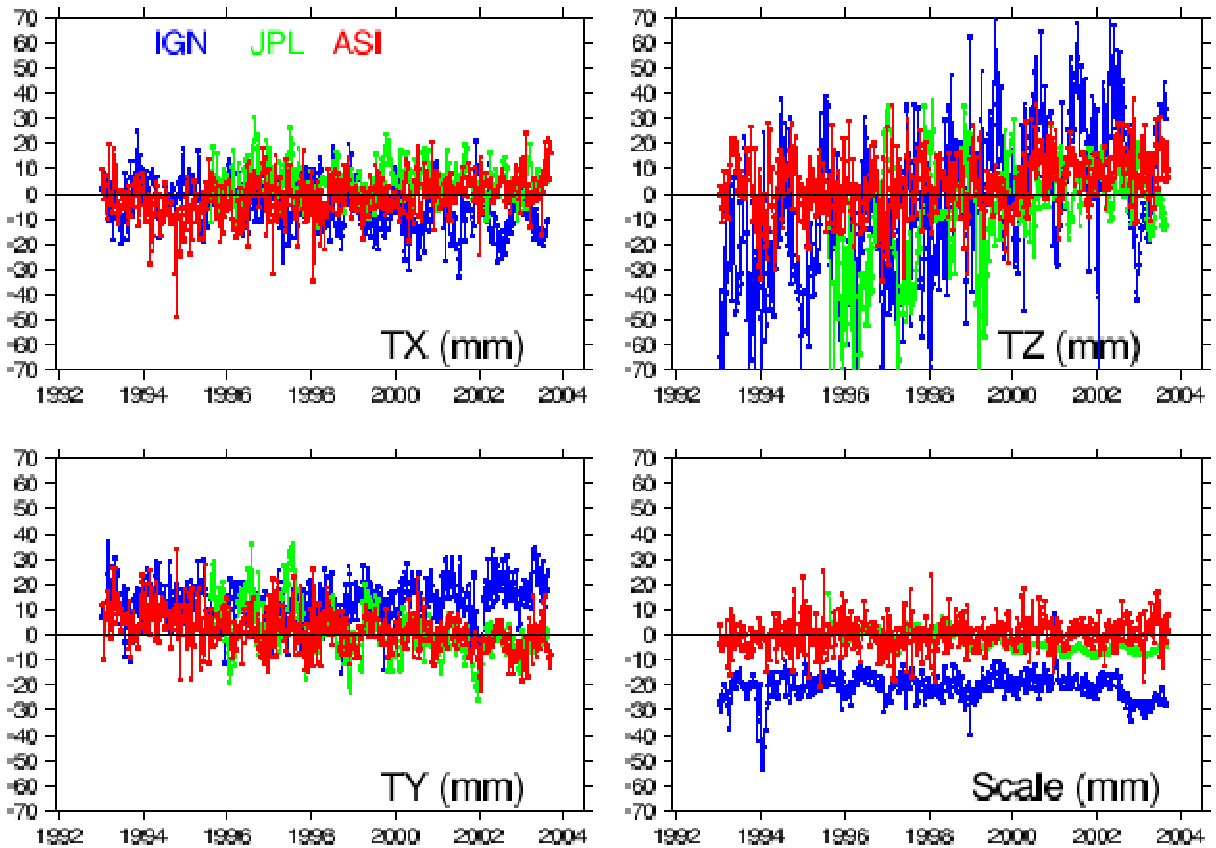
Arequipa Earthquake



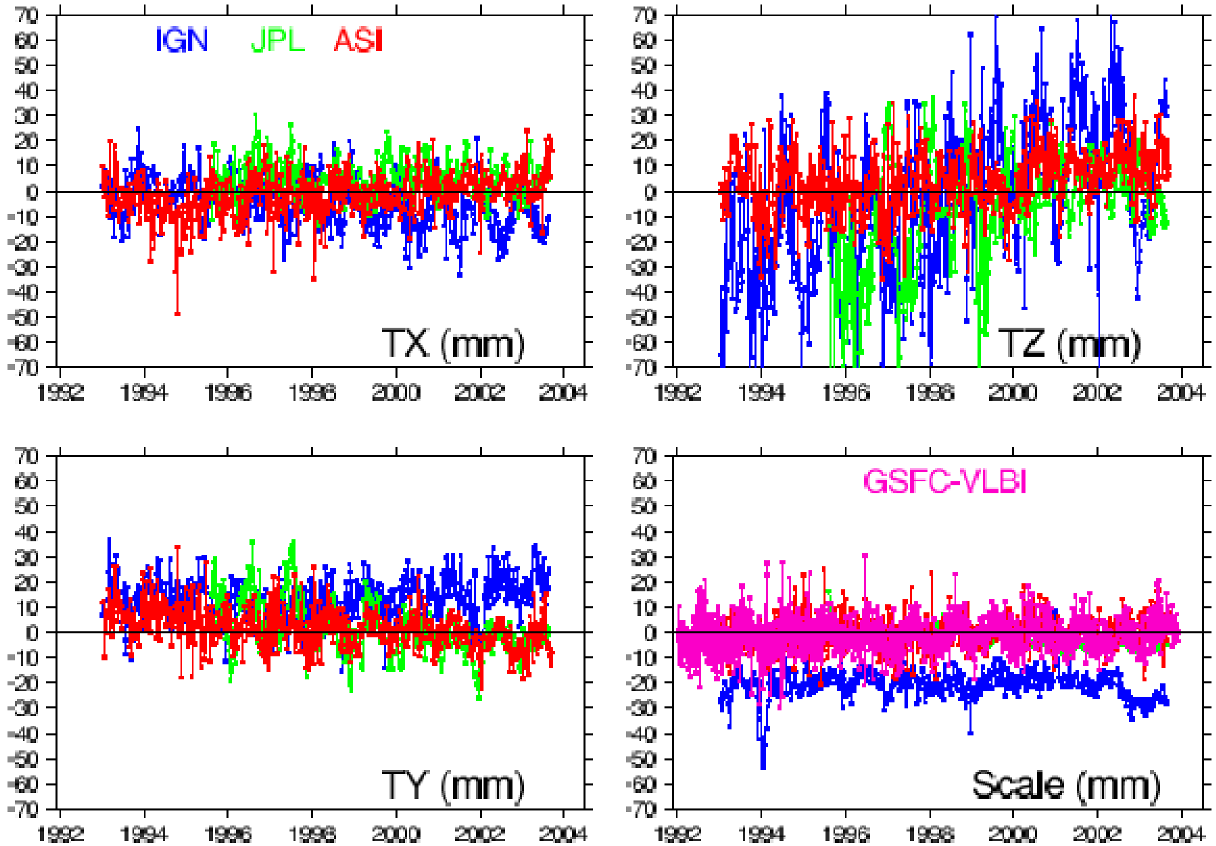
Impact of AREQ Earthquake on Polar Motion
If pre & post station velocity is constrained to be the same



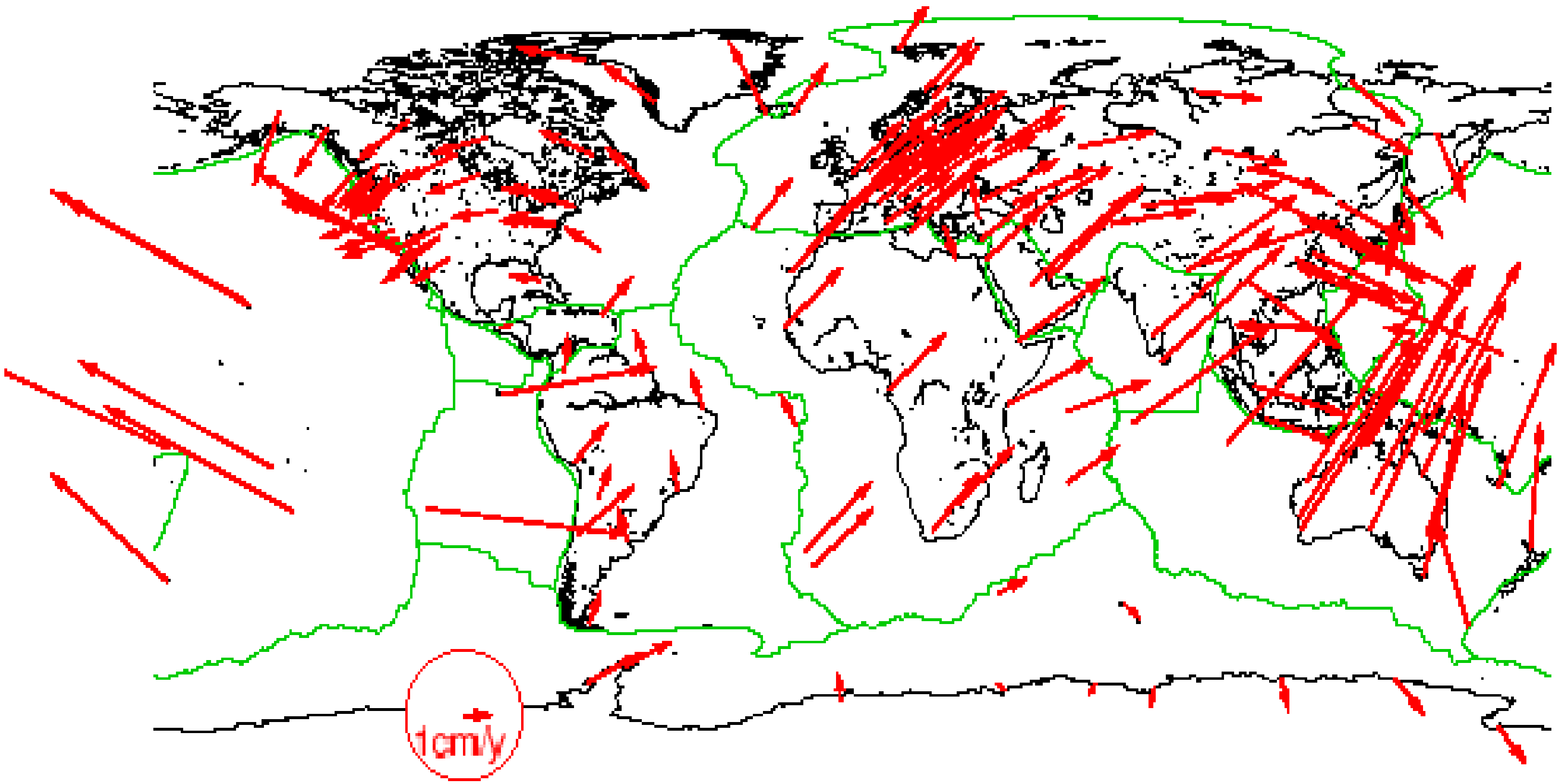
Origin & Scale Variation



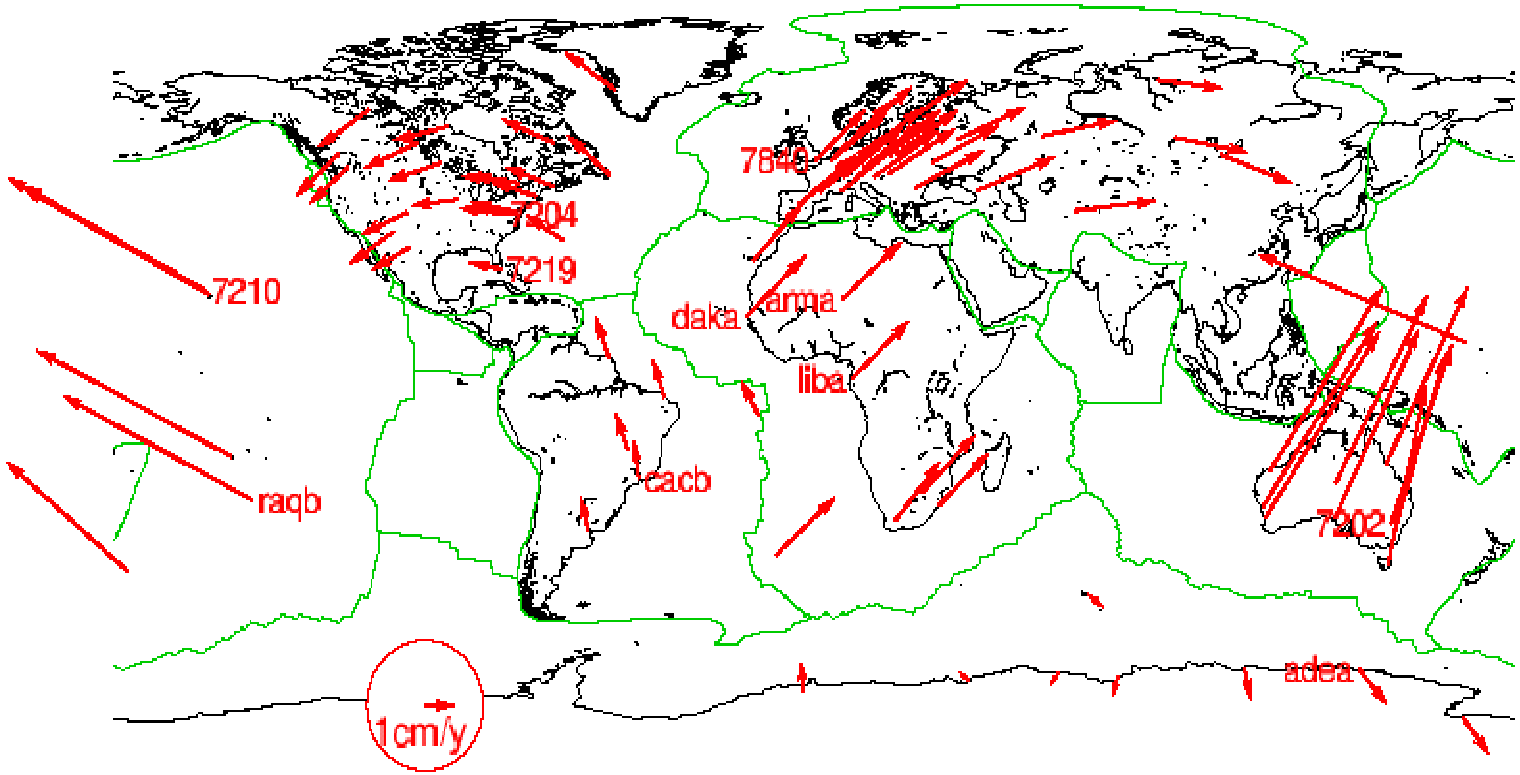
Origin & Scale Variation



Site velocities with σ < 3mm/y



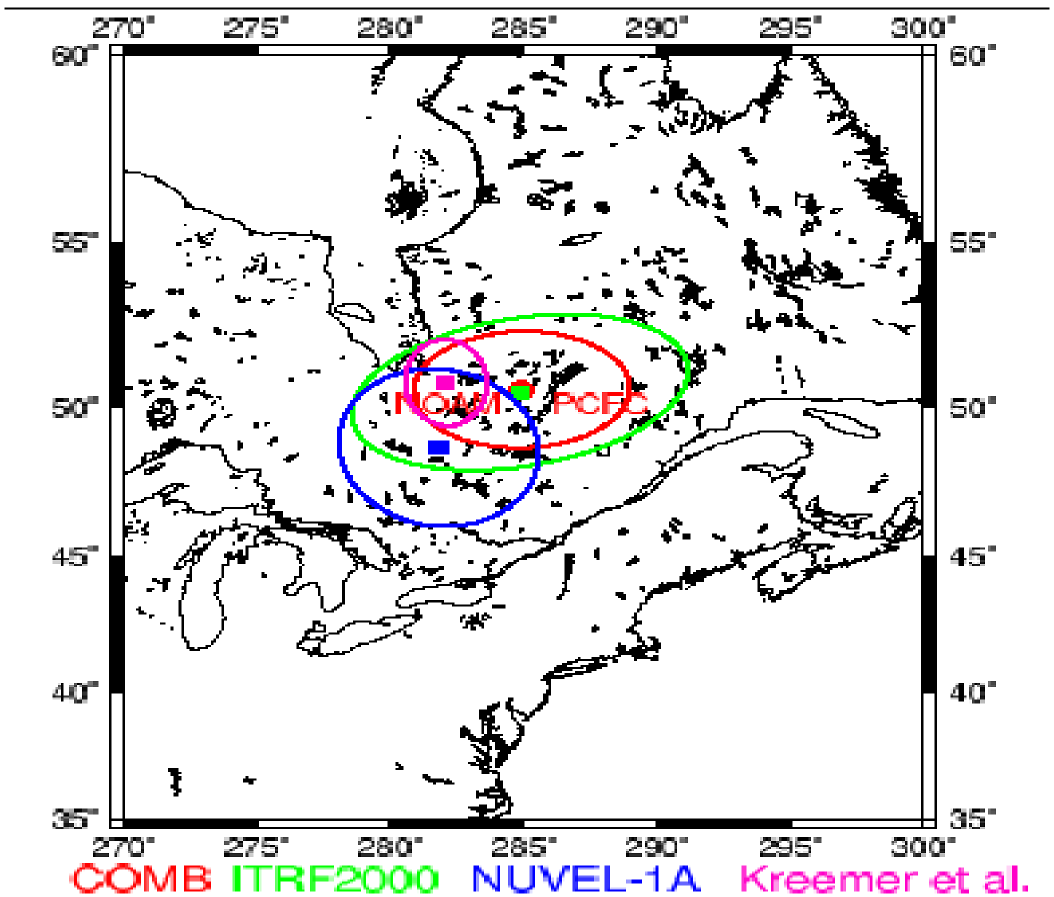
Site velocities used in rotation poles estimation



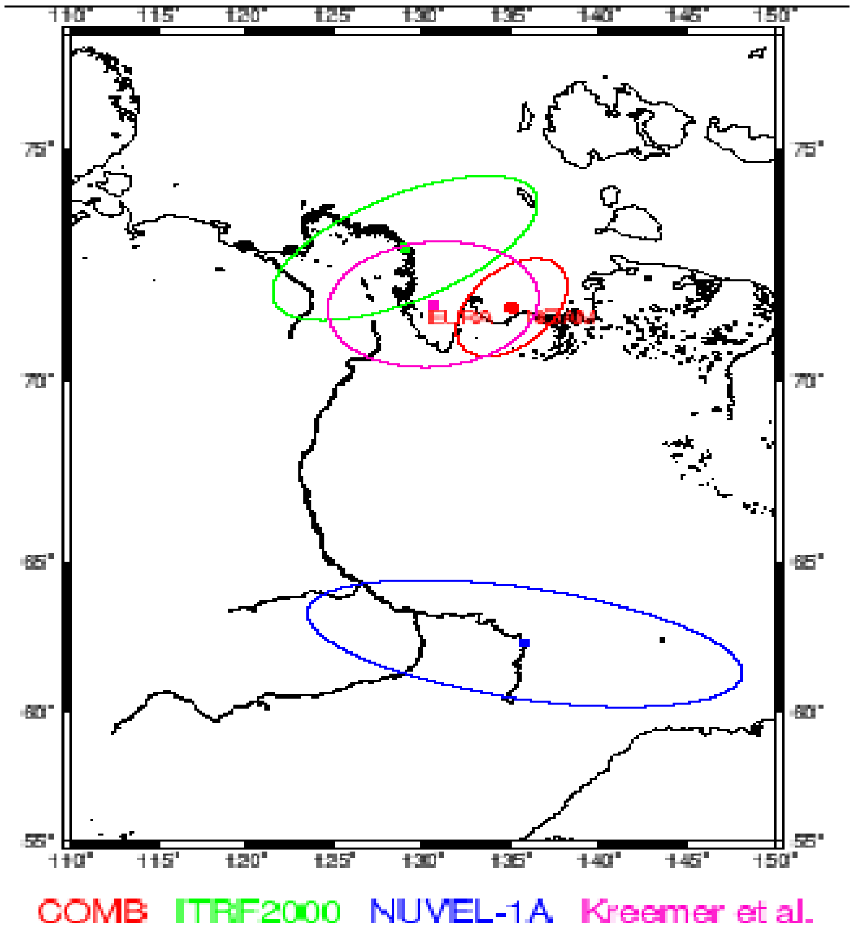
Differences between Multi-technique combination and NUVEL-1A

Pairs of plates	Ω	$><$	Ω_N (deg./My)	$\|\Omega - \Omega_N\|$	$\approx$ mm/y	GPS seul mm/y	ITRF2000 mm/y
PCFC-AFRC	0.933	$>$	0.927	0.020	2.2	2.7	
PCFC-ANTA	0.871	$>$	0.870	0.020	0.5	0.6	0.7
PCFC-AUST	1.074	$=$	1.074	0.036	3.3	2.7	4.9
PCFC-EURA	0.919	$>>$	0.859	0.077	6.4	6.6	6.9
PCFC-NOAM	0.764	$>$	0.749	0.039	2.4	2.8	2.2
PCFC-SOAM	0.672	$>$	0.637	0.052	4.9	5.8	3.9
EURA-NOAM	0.238	$>>$	0.214	0.044	3.6	3.5	4.6
EURA-AFRC	0.065	$<<$	0.123	0.070	7.6	8.1	

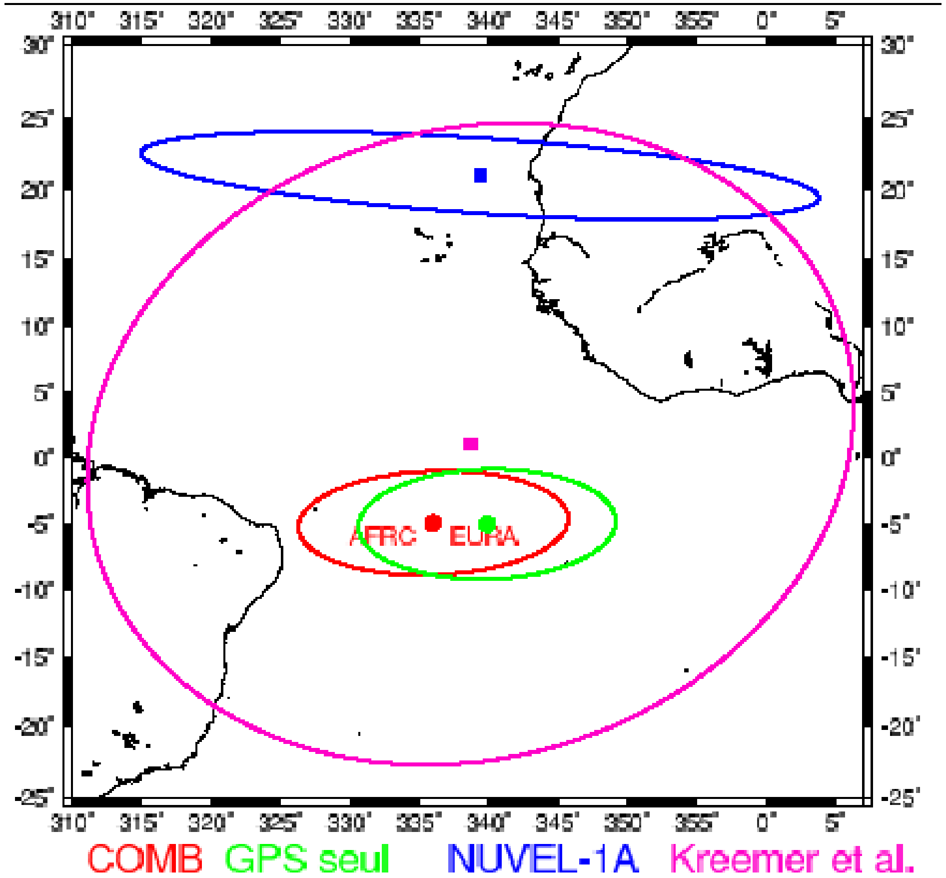
PCFC NOAM Rotation Pole Location



EURA – NOAM Rotation Pole Location

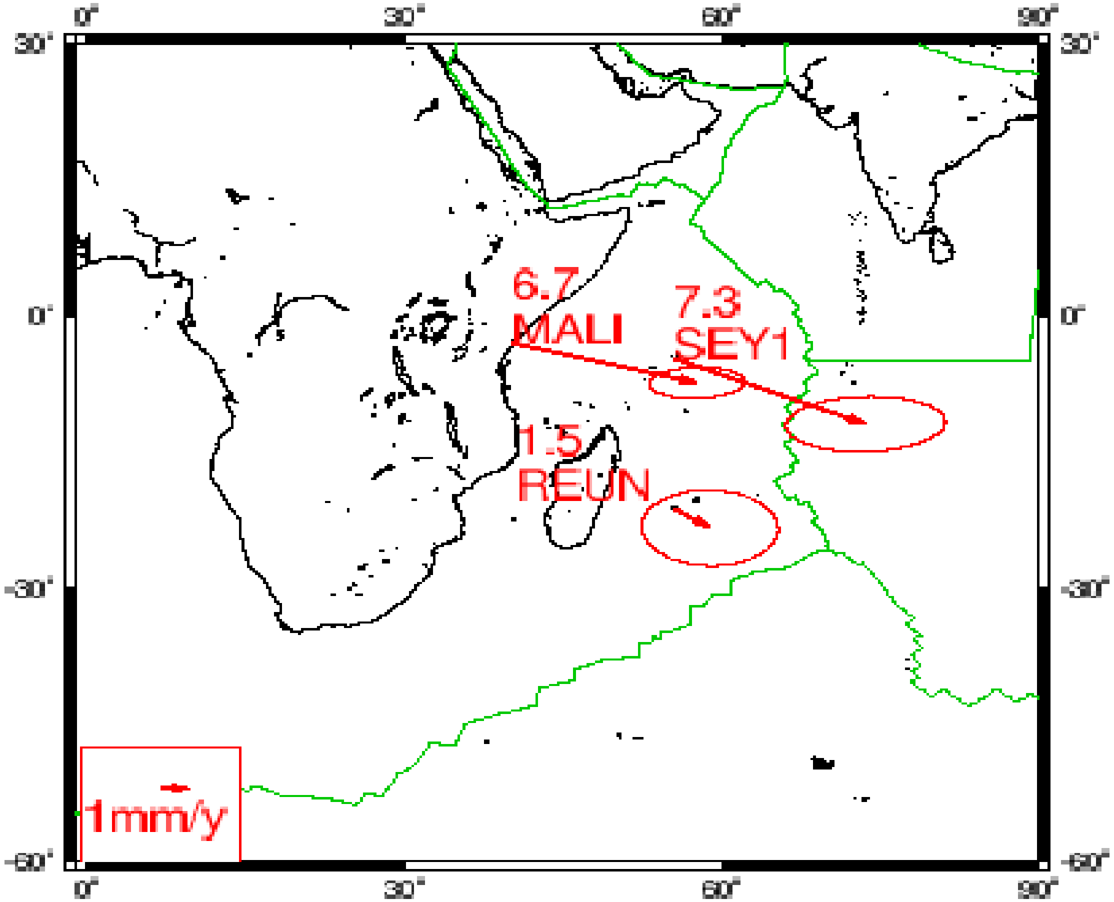


EURA – AFRC (NUBI) Rotation Pole Location

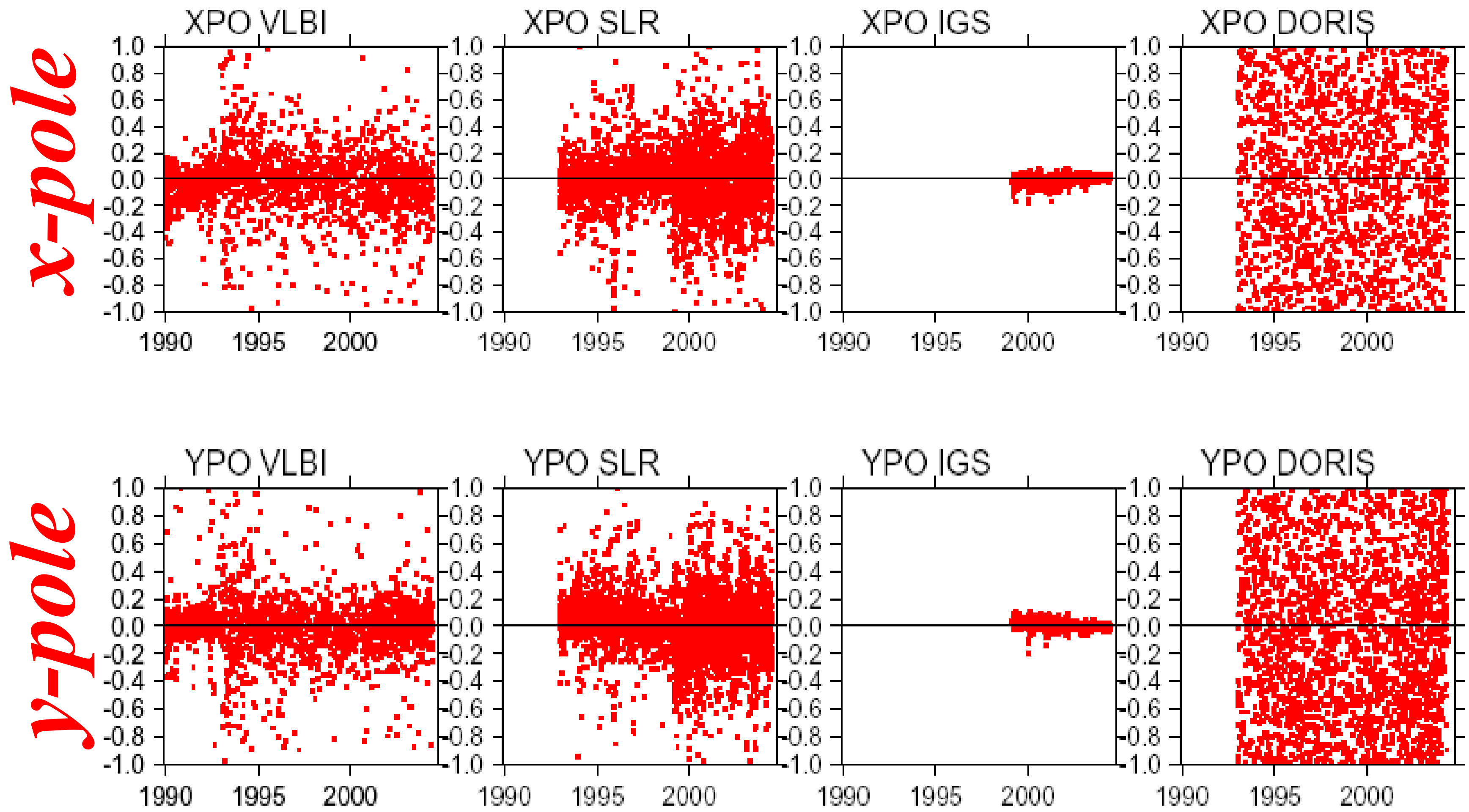


Nubia-Eurasia velocity ~50% slower than NUVEL1-A prediction

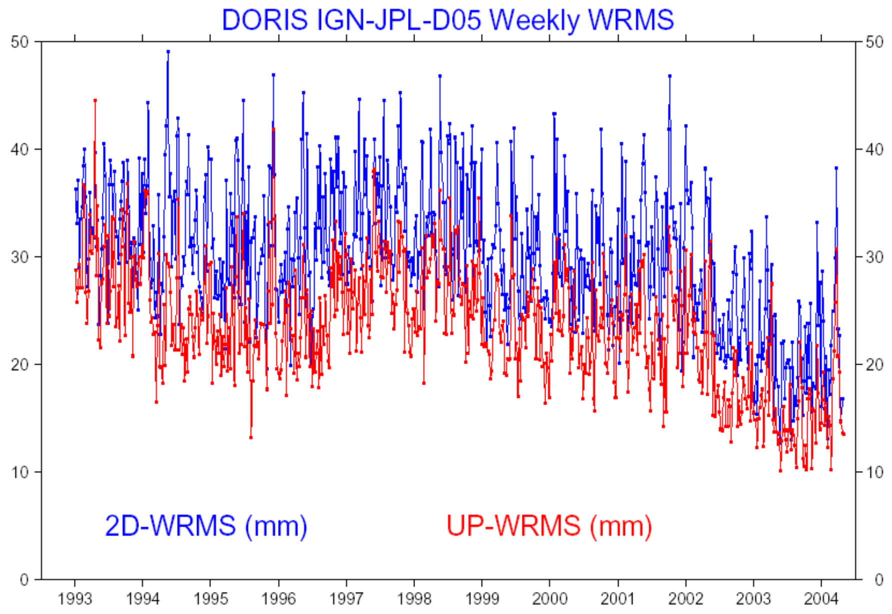
Nubia – Somalia ???

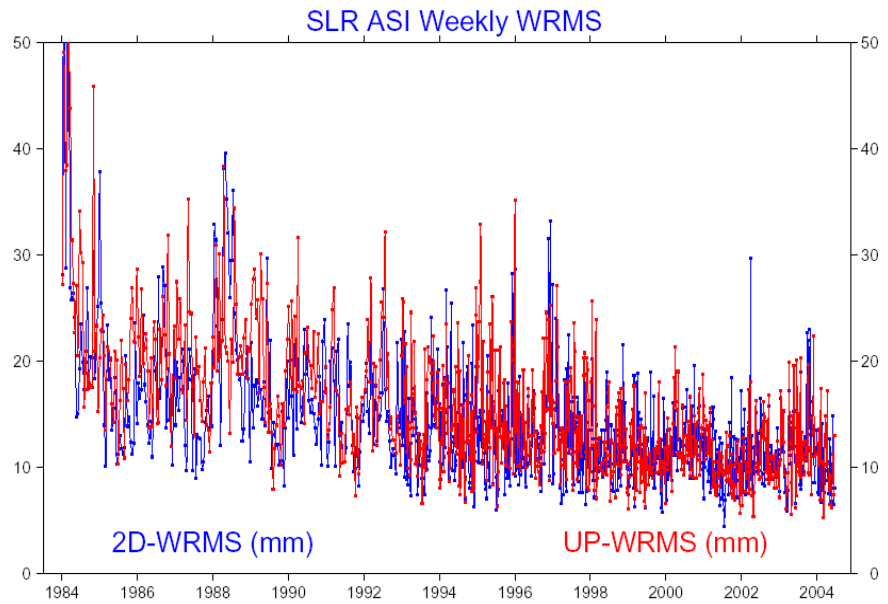


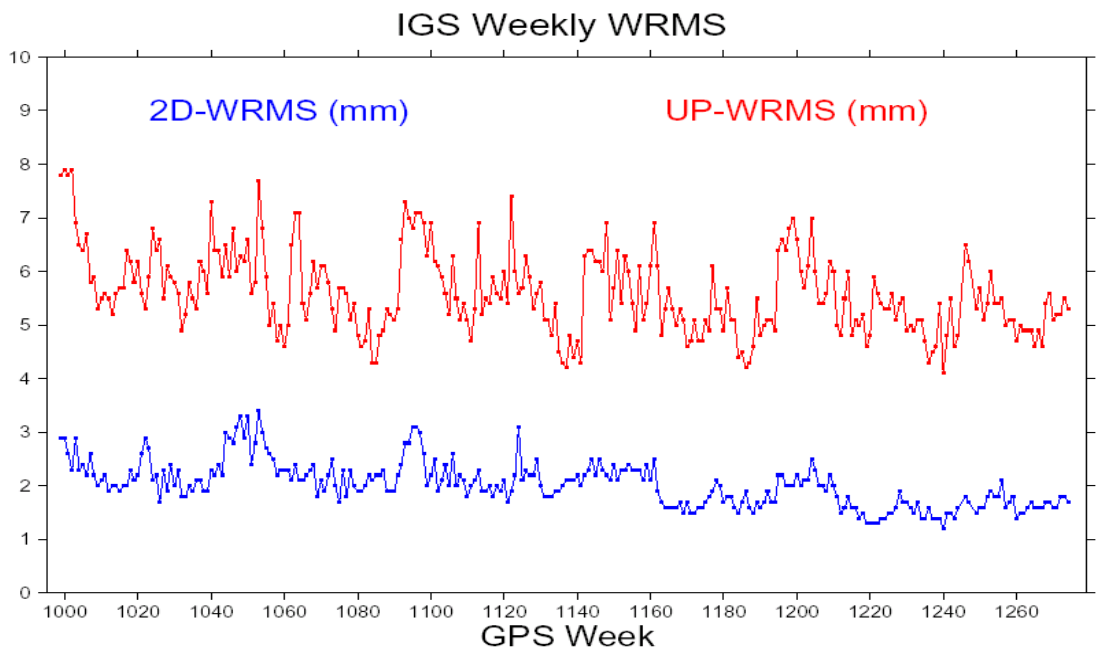
Mult-technique Combination over 14 years
Polar Motion Residuals (Zoom ± 1 *mas*)



DORIS, SLR and IGS Weekly WRMS







Indicative WRMS

Solution	Position 2-D	mm Up	Velocity 2-D	mm/y Up	Polar Motion Xpole	μas Ypole
VLBI/GSFC	2	3	1	2	160	130
SLR/ASI	3	5	1	2	210	200
GPS/IGS	2	5	1	2	25	25
DORIS/IGN-JPL	10	12	2.2	2.6	1800	1300

Access to ITRS

- Direct use of ITRF coordinates
- Use of IGS Products (e.g.Orbits): all related to ITRF
- Fixing or constraining some ITRF station coordinates in the analysis of GPS measurements
- Use of transformation formulae

Future Galileo System

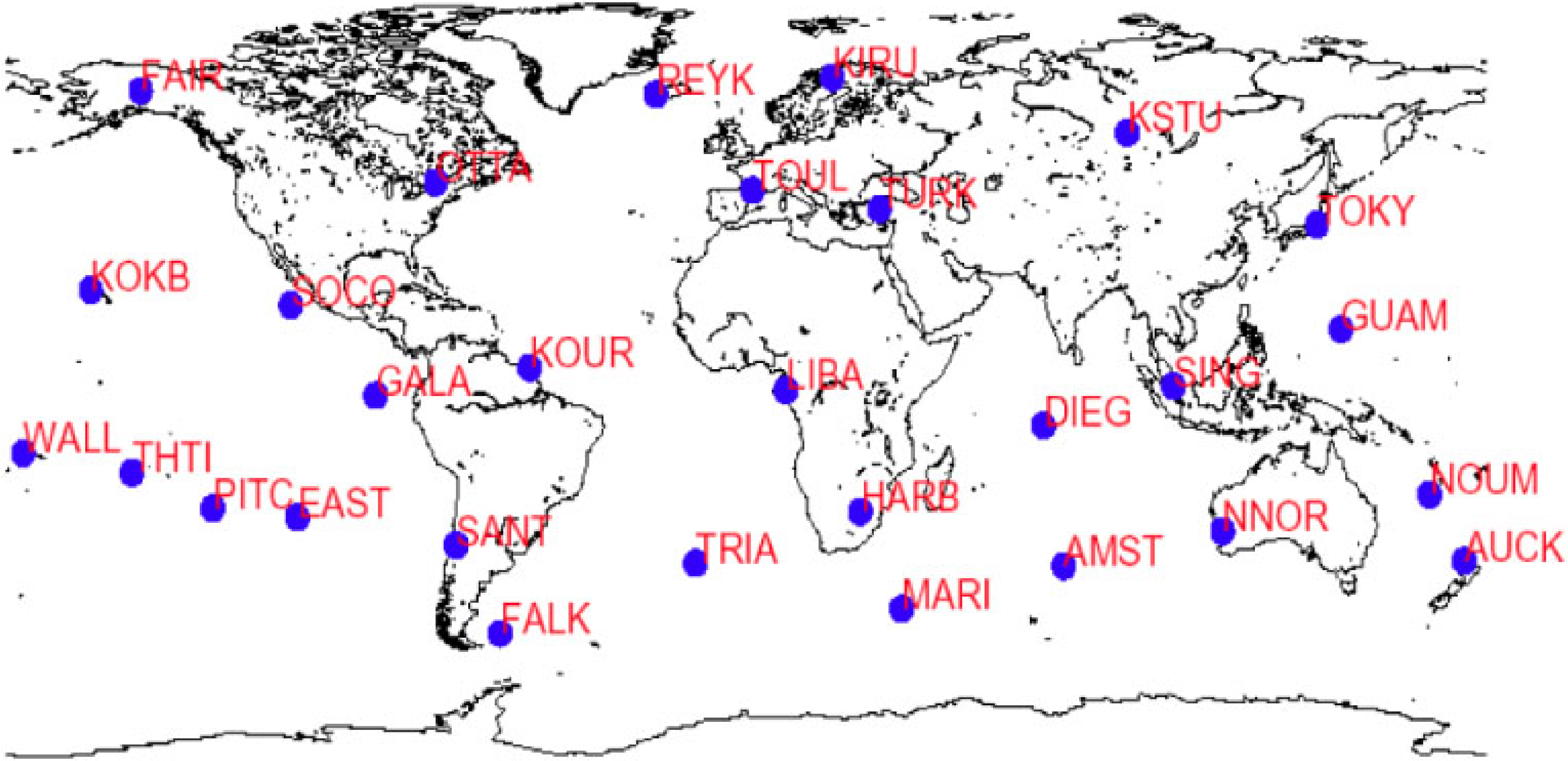
- Will be based on ITRS/ITRF

- Simillar to IGS/GPS: Orbits, Clocks

Will be expressed in ITRF

- Proposals for Galileo Geodesy Service Provider: Under Review
  - Define, realize & maintain the GTRF
  - Compatible with the ITRF
  - Liaison with IERS, IGS, ILRS

Provisional Locations of Galileo Sensor Stations



~20 GSS for IOV ~ 30 GSS for FOC

EUREF: IAG Regional Sub-commission for Europe

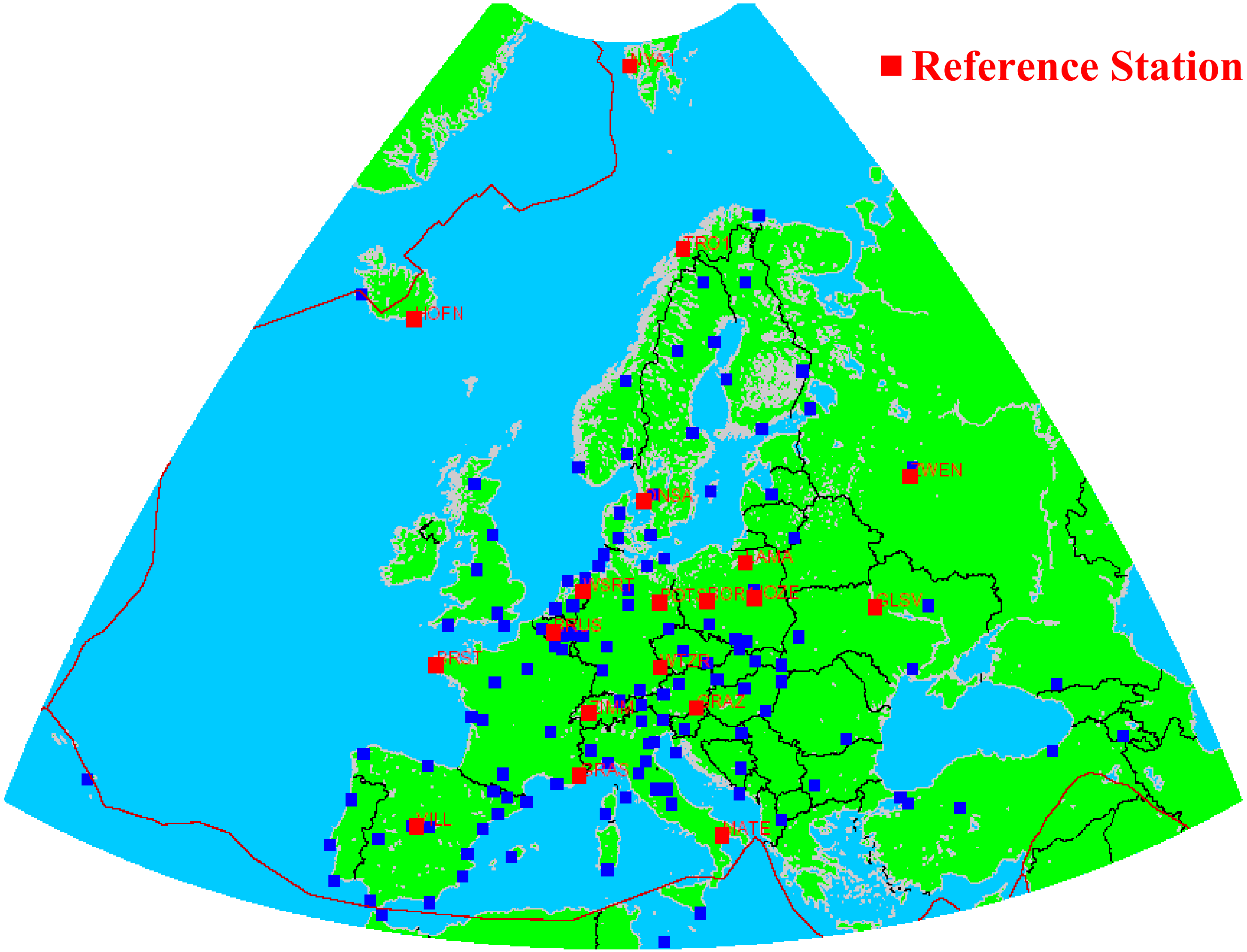
- **Definition, realization and maintenance of the ETRS89 and EVRS**
- **ETRS89 definition:**
  - Coincides with ITRS at epoch 1989.0
  - Fixed to the stable part of the Eurasian plate (co-moving with the palte)
- **EUREF Permanent Network**
  - ~ 160 GPS permanent stations
  - ~ 15 Analysis Centers
  - EPN Central Bureau

http://www.euref-iag.net/

Dense European Velocity Field

- **EUREF Project**
- **Long term maintenance of the ETRS89**
  - **Go from "static" to kinematic realization**
  - **Properly take into account 3D-PGR modelling**
  - **Carefully study local deformation and seasonal variations**
- **A grid or/and formula allowing high accuracy positioning in the ETRS89**
- **Precise ETRS89 station positions & velocities of the EPN (Basis of the Velocity Model)**
- **Accurate frame definition using minimum constraints approach**

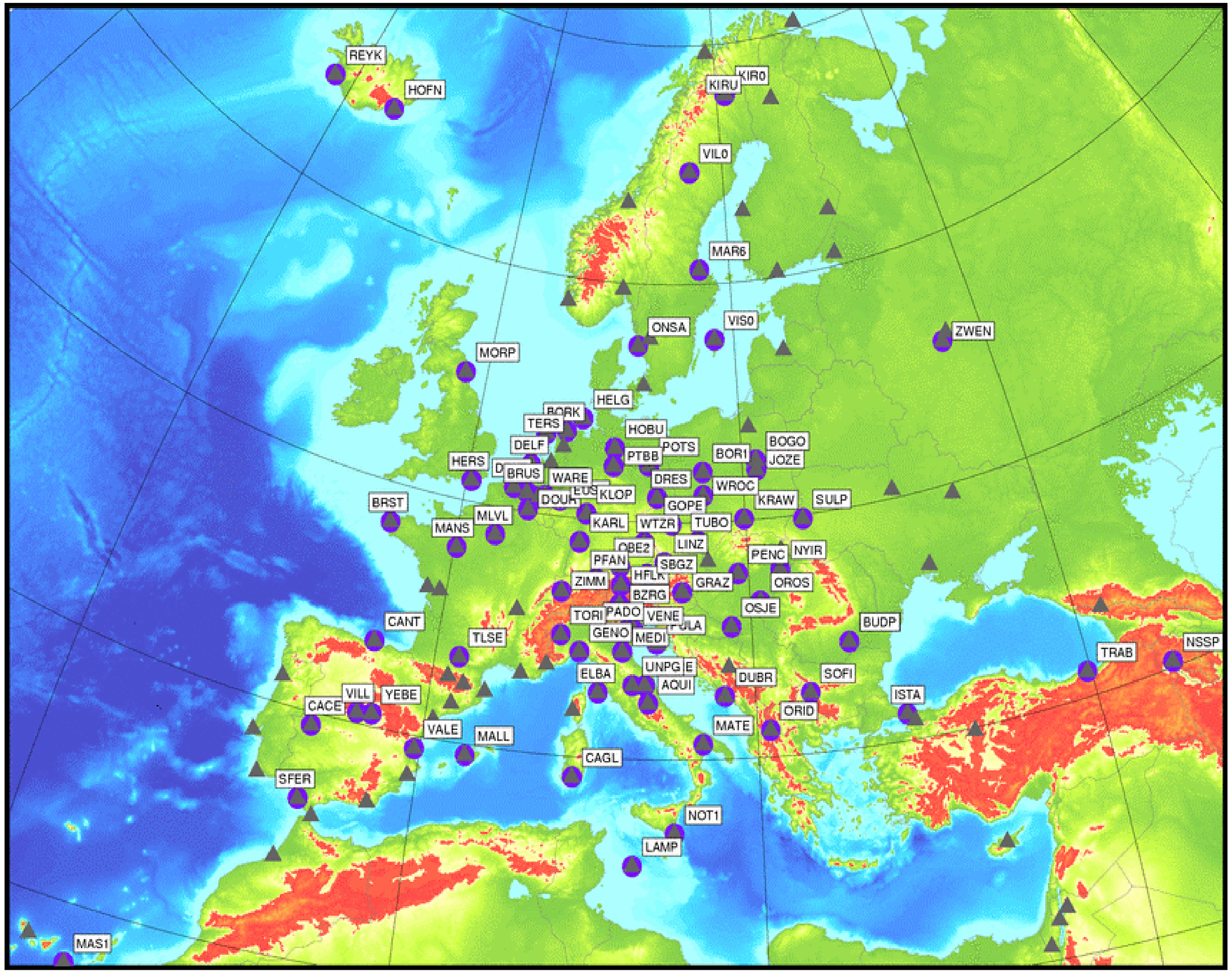
EUREF Permanent Network



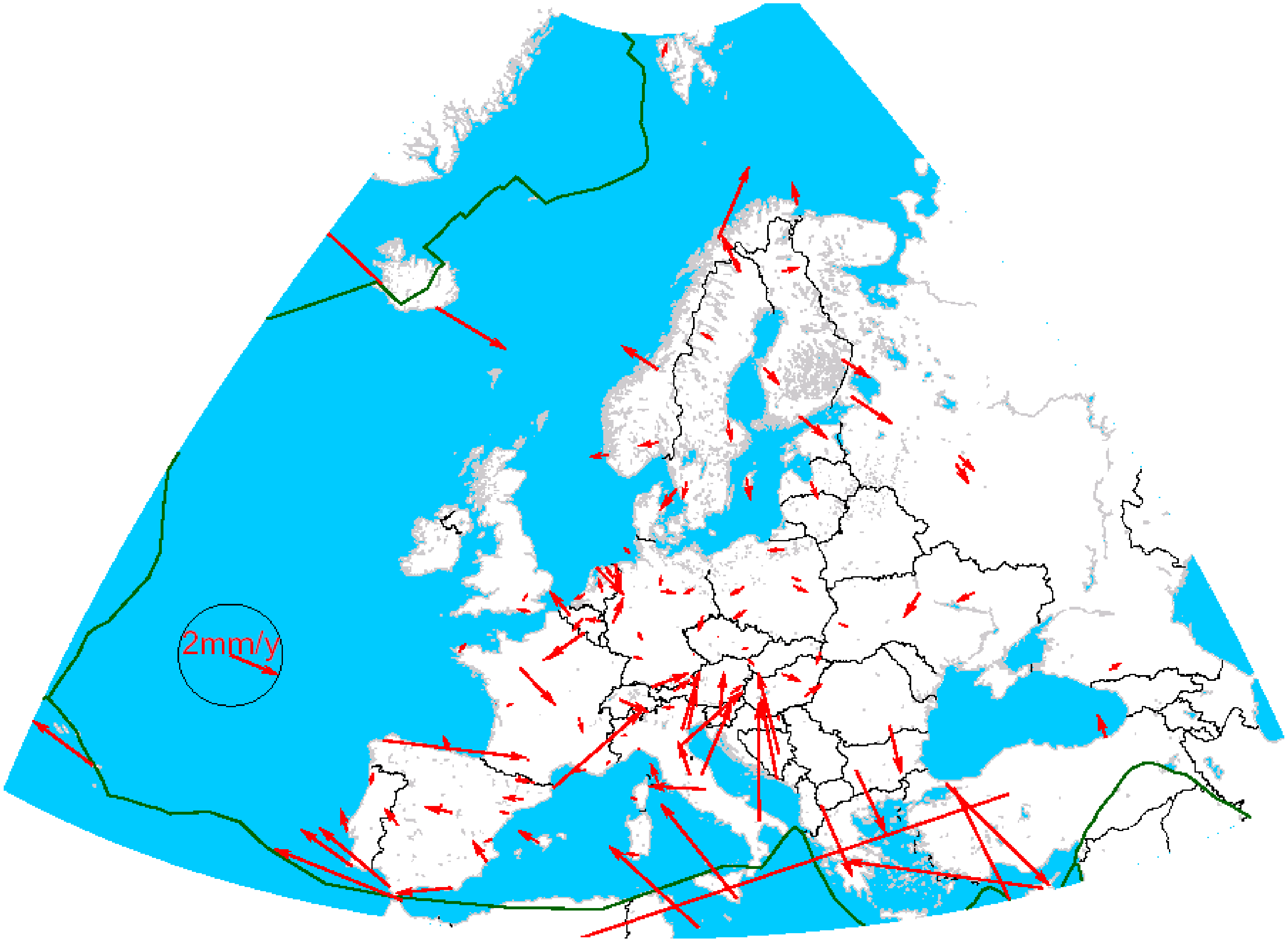
EPN HOURLY TRACKING NETWORK

(C. Bruyninx, G. Carpentier and F. Roosbeek, 2003)

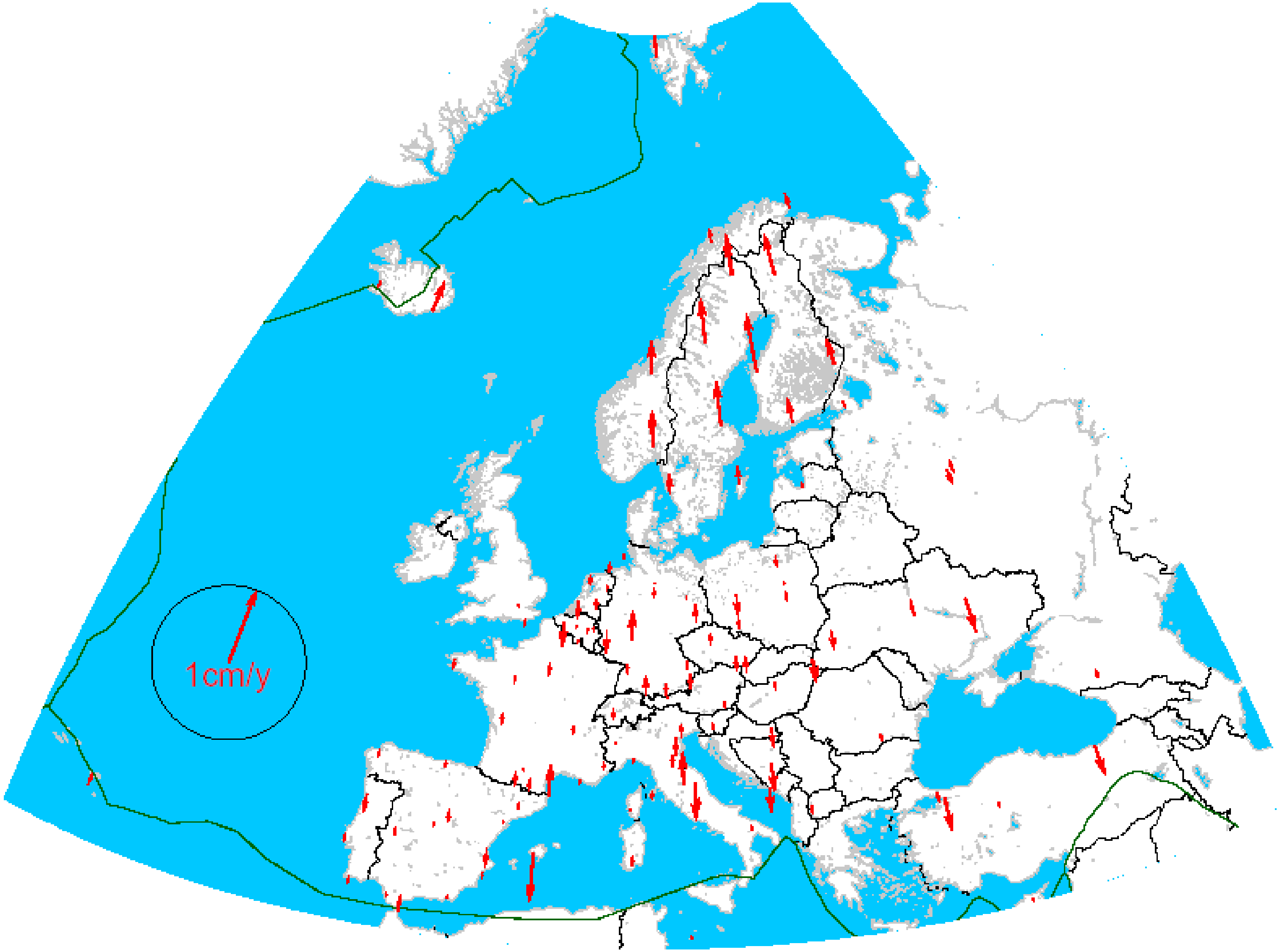
38% (06/2000) → 45 % (06/2001) → 55 % (06/2002) → 58% (06/2003)



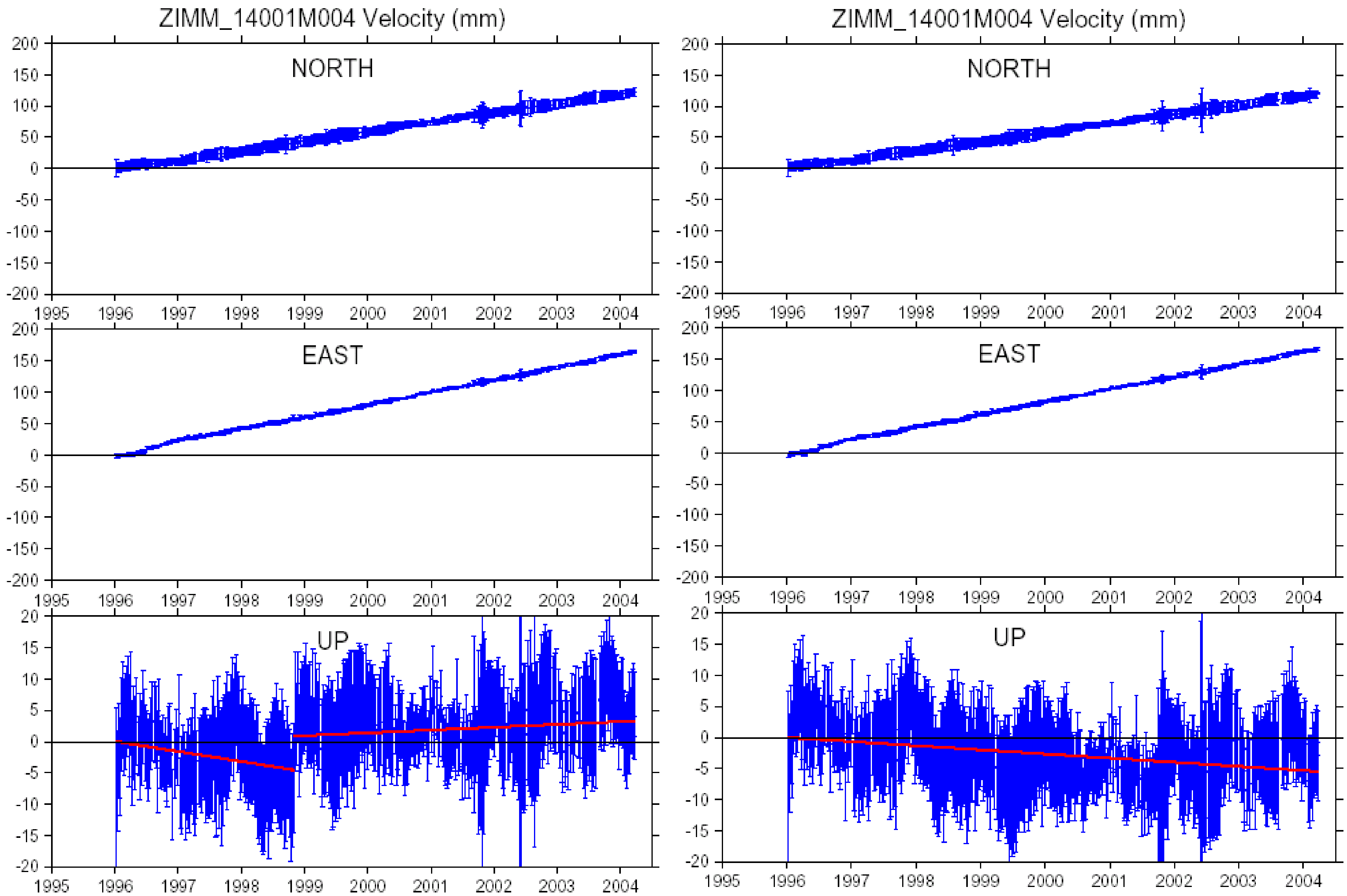
EPN ETRS89 Horizontal Velocities



EPN ETRS89 Vertical Velocities



Vertical Velocities (?)



Concluding Remarks

- IAG Services play a major role providing geodetic products
- IAG integrates the services/products in GGOS
- Era of Time series of geodetic products: TRF, EOP, geocenter motion, etc.
- Geodetic signals for geodynamic applications
- Next ITRF solutions will based on time series
- IERS Combination Pilot Project (weekly basis)
- Well defined and accurate ITRF is always needed for the expression of the geodetic results
- Leave « non-periodic geophysical effects » in geodetic data for a posteriori analysis through residuals of time series
- Reffinement of the ITRF datum definition will continue as appropriate