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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
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Associated IAG Services
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Zuheir ALTAMIMI
Laboratoire de Recherche en Géodésie
Institut Géographique National
France

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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 \} \}

Measuring Time Propagation

SLR Telescope

Earth

Moon

Passive Satellite
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)

\[ \lambda = \| \vec{E}_i \|_{i=1,2,3} \quad \vec{E}_i \cdot \vec{E}_j = \lambda^2 \delta_{ij} \quad (\delta_{ij} = 1, \ i = j) \]
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:

\[
X_2 = T + \lambda R X_1
\]

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

Scale Factor \( \lambda \)

Rotation Matrix \( R = R_x R_y R_z \)

\[
R_x = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos R_1 & \sin R_1 \\
0 & -\sin R_1 & \cos R_1
\end{pmatrix}
\]

\[
R_y = \begin{pmatrix}
\cos R_2 & 0 & -\sin R_2 \\
0 & 1 & 0 \\
\sin R_2 & 0 & \cos R_2
\end{pmatrix}
\]

\[
R_z = \begin{pmatrix}
\cos R_3 & \sin R_3 & 0 \\
-\sin R_3 & \cos R_3 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
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 \( R = (I + R) \)

where
\[
R = \begin{pmatrix}
0 & -R_3 & R_2 \\
R_3 & 0 & -R_1 \\
-R_2 & R_1 & 0
\end{pmatrix}
\]

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

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

Differentiating equation 1 with respect to time, we have:

\[ \dot{X}_2 = \dot{X}_1 + \dot{T} + \dot{D}X_1 + \ddot{D}X_1 + \dot{R}X_1 + \ddot{R}X_1 \]
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

\[
\begin{align*}
\text{Cylindrical: } & \begin{bmatrix} l \cos \lambda \\ l \sin \lambda \\ z \end{bmatrix} \\
\text{Spherical: } & \begin{bmatrix} R \cos \theta \cos \lambda \\ R \cos \theta \sin \lambda \\ R \sin \theta \end{bmatrix}
\end{align*}
\]
Crust-based TRF

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

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

$X_0$ : 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

\[
\begin{align*}
(X) &= (X) + (T_x) + \begin{pmatrix}
D - R_z & R_y \\
R_z & D - R_x \\
-R_y & -R_x & D
\end{pmatrix}
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} \\
(Y)_2 &= (Y)_1 + (T_y) + \begin{pmatrix}
D - R_z & R_y \\
R_z & D - R_x \\
-R_y & -R_x & D
\end{pmatrix}
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} \\
(Z)_2 &= (Z)_1 + (T_z) + \begin{pmatrix}
D - R_z & R_y \\
R_z & D - R_x \\
-R_y & -R_x & D
\end{pmatrix}
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
\end{align*}
\]
Comparison of Two TRFs

Estimation of the Transformation parameters between the Two

\[ X_2 = X_1 + T + DX_1 + RX_1 \]

or

\[ X_2 = X_1 + A \theta \]

\[ \theta = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ D \\ R_1 \\ R_2 \\ R_3 \end{bmatrix} \]

\[ A = \begin{bmatrix} 1 & 0 & 0 & x & 0 & z & -y \\ 0 & 1 & 0 & y & -z & 0 & x \\ 0 & 0 & 1 & z & y & -x & 0 \end{bmatrix} \]

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

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

\( \theta \) is solved for using Least Squares adjustment

And in case of velocities
Combination of TRF’s

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

\[ X_s = X_c + T + DX_c + RX_c \]

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 (\( \sigma \approx 10^{-5} \)) 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:

\[ X_2 = X_1 + A\theta \]

\[ \theta = (T_1, T_2, T_3, D, R_1, R_2, R_3, \dot{T}_1, \dot{T}_2, \dot{T}_3, \dot{D}, \dot{R}_1, \dot{R}_2, \dot{R}_3)^T \]

\[ A = \begin{pmatrix}
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 & \approx 0 & 1 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\
0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 & 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \\
0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots
\end{pmatrix} \]
Datum Definition: Minimum Constraints (3/3)

L.S. yields for $\theta$:

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

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

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

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:

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

$\Sigma_\theta$ 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 Commissions

• 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 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:

$$h = \sum_{p \in P} Q_p \omega_p = 0$$

NNR-NUVEL-1A used:

$$\omega_{PACIFIC} = -\frac{3}{8\pi} \sum_{p \in P} Q_p \Omega_p$$
**ITRF2000 orientation & rate definition**

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

Using a Datum Eq.:

\[ B(X - X_0) = 0 \]

\[
B = (A^T A)^{-1} A^T
\]

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

- \( X_0 \): Positions (ITRF97) or Velocities (NNR-NUVEL-1A)
- \( X \): Estimated Positions/Velocities
\[
\begin{align*}
X_s^i &= X_{itr}^i + (t_s^i - t_0) \dot{X}_{itr}^i + T_k + D_k X_{itr}^i + R_k X_{itr}^i \\
&+ (t_s^i - t_k) \left[ \dot{T}_k + \dot{D}_k X_{itr}^i + \dot{R}_k X_{itr}^i \right] \\
\dot{X}_s^i &= \dot{X}_{itr}^i + T_k + \dot{D}_k X_{itr}^i + \dot{R}_k X_{itr}^i
\end{align*}
\]
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?

\[ \dot{X} = \omega_p \times X \]

- 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

ITRF2000 Vertical Velocities (> 3σ and σ < 1 cm/y)
ITRF: Quality

ITRF96/94 position errors at 1993.0 (cm)

ITRF96/94 velocity errors (mm/y)

ITRF97/96 velocity errors (mm/y)

ITRF2000 and ITRF97
## ITRF: Quality

### WRMS from ITRF2000

<table>
<thead>
<tr>
<th>Technique</th>
<th>Positions (mm)</th>
<th>Velocities (mm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLBI</td>
<td>2-3</td>
<td>1</td>
</tr>
<tr>
<td>SLR</td>
<td>2-10</td>
<td>1-5</td>
</tr>
<tr>
<td>GPS</td>
<td>2-5</td>
<td>1-2</td>
</tr>
<tr>
<td>DORIS</td>
<td>25-30</td>
<td>5</td>
</tr>
</tbody>
</table>
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), $(T_x, T_y, T_z, D, R_x, R_y, R_z)$

Datum Definition with Minimum Constraints Over a Reference Set of stations

\[
\begin{align*}
X_i^s &= X_{itr}^i + (t_s^i - t_0) \dot{X}_{itr}^i + T_k + D_k X_{itr}^i + R_k X_{itr}^i \\
&+ (t_s^i - t_k) \left[ \dot{T}_k + \dot{D}_k X_{itr}^i + \dot{R}_k X_{itr}^i \right] \\
\dot{X}_i^s &= \dot{X}_{itr}^i + \ddot{T}_k + \ddot{D}_k X_{itr}^i + \ddot{R}_k X_{itr}^i
\end{align*}
\]

\[
\begin{align*}
x_s^p &= x^p + R_{2_k} \\
y_s^p &= y^p + R_{1_k} \\
UT_s &= UT - \frac{1}{f} R_{3_k} \\
\dot{x}_s^p &= \dot{x}^p + \ddot{R}_{2_k} \\
\dot{y}_s^p &= \dot{y}^p + \ddot{R}_{1_k} \\
LOD_s &= LOD + \frac{\dot{a}}{f} R_{3_k}
\end{align*}
\]

- 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
Dicontinuity Monitoring

Before

EUSK 14258M003 Residuals (mm)

NORTH

1998 1999 2000 2001 2002 2003

EAST

1998 1999 2000 2001 2002 2003

UP

1998 1999 2000 2001 2002 2003

After

EUSK 14258M003 Residuals (mm)

NORTH

1998 1999 2000 2001 2002 2003

EAST

1998 1999 2000 2001 2002 2003

UP

1998 1999 2000 2001 2002 2003
Seasonal Variations

\[ dX(t) = A \cos(\omega(t-t_0) + \phi) \]

Before

After

Real or GPS Artefact?
Arequipa Earthquake

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

[Graphs showing variation in IGN, JPL, ASI, TX (mm), TZ (mm), TY (mm), and Scale (mm) over the years 1992 to 2004]
Origin & Scale Variation

[Images of four graphs showing data over time]
Site velocities with $\sigma < 3\text{mm/y}$
Site velocities used in rotation poles estimation
Differences between Multi-technique combination and NUVEL-1A

| Pairs of plates | $\Omega$ (deg./My) | $\Omega_N$ (deg./My) | $|\Omega - \Omega_N|$ | $\approx \gamma$ (mm/y) | GPS seul (mm/y) | ITRF2000 (mm/y) |
|----------------|-------------------|----------------------|-----------------------|----------------------|----------------|----------------|
| PCFC-AFRC      | 0.933             | 0.927                | 0.020                 | 2.2                  | 2.7            | 0.7            |
| 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            |                |
EURA – NOAM Rotation Pole Location
Nubia-Eurasia velocity ~50% slower than NUVEL1-A prediction
Nubia – Somalia ???
Mult-technique Combination over 14 years
Polar Motion Residuals (Zoom $\pm 1\ mas$)
## Indicative WRMS

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

• Similar 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 plate)

- **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

Reference Station
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