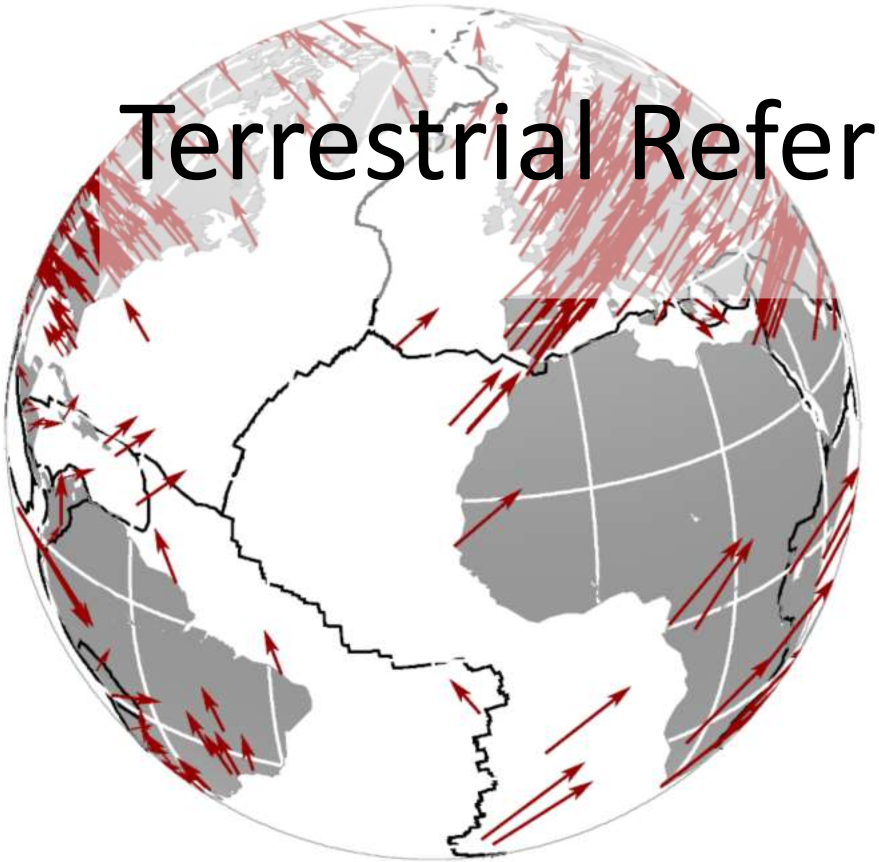
Terrestrial Reference Frames



EGU campfire - Geodesy 101

December 1st 2022

EGU Division Geodesy

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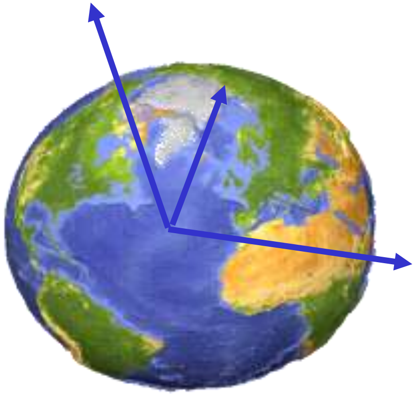
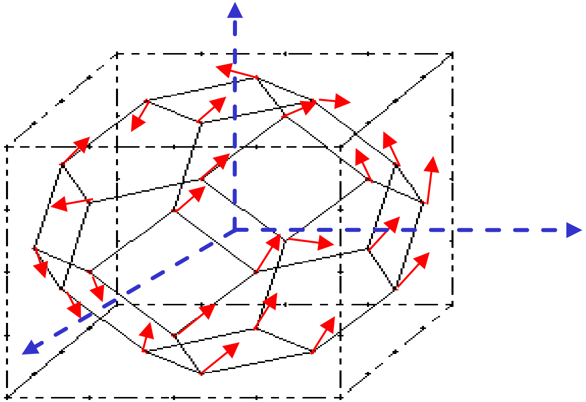
Ackowledgment:
Z. Altamimi, J. Legrand, P. Rebischung,
R. Rietbroek, L. Métivier



Concept:
(=Terrestrial Reference System)

- Mathematical concept



Real world: Terrestrial Reference Frame (TRF)

- Table of coordinates of materialized points (=reference points).
  May include velocities (=dynamic TRF) + other terms + statistical information

- Axes can be accessed by positioning objects with respect to reference points

Why so many terrestrial reference frames?

Example of Terrestrial Reference Frames:
NAD 83, OSGB 1970, RGF93
ED 50, ETRF2014, ETRF2000, …
WGS84(2139), GTRF16v01, GTRF, PZ-90.11, CGCS2000
ITRF2020, ITRF2014, ITRF2008, ITRF2005, …

- Network coverage, new permanent instruments
- Earth’s non predictable deformations (Earthquake)
- Measurement technique improvement (infrastructure, processing), computation strategy
- Limited Coordinate precision (see later)

How to determine coordinates?

Space geodetic techniques. VLBI : Very Long Baseline Interferometry

Principle:

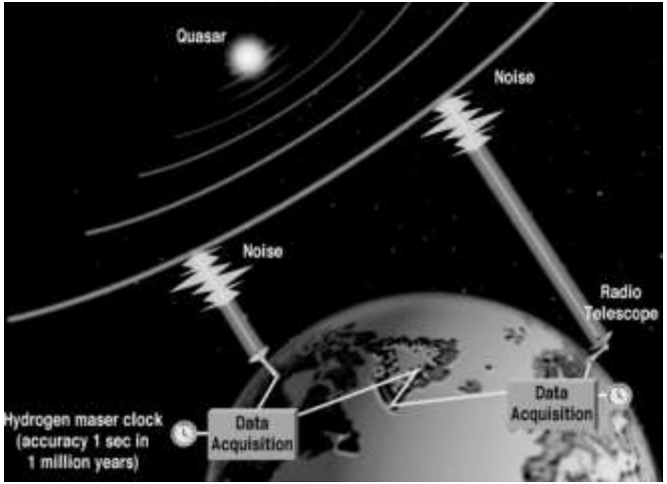


Image source: IVS web site, https://ivscc.gsfc.nasa.gov/about/vlbi/whatis.html

➕ Contribution

- Link to the celestial frame: Earth rotation
- Long history

Structure:

Activity coordinated by the International VLBI Service (IVS):

- Scheduling
- Data centers
- Analysis Centers etc…
- Station operations
- Correlation Centers

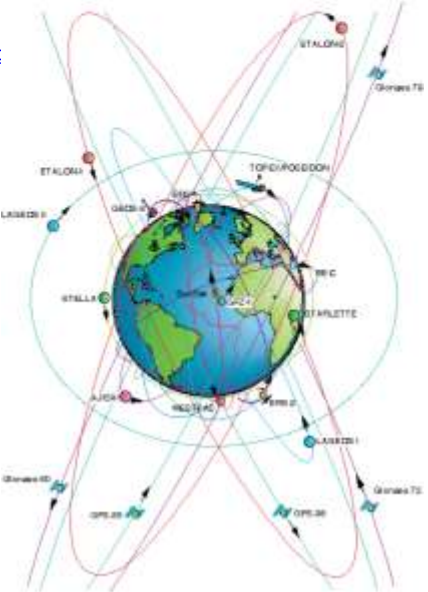
Nothnagel A., T. Artz, D. Behrend, Z. Malkin (2017), "International VLBI Service for Geodesy and Astrometry – Delivering high-quality products and embarking on observations of the next generation", Journal of Geodesy, 91(7):711–721, DOI:10.1007/s00190-016-0950-5

How to determine coordinates?

Space geodetic techniques. Satellite Laser Ranging (SLR)

Herstmonceux SLR station
Source: http://sgf.rgo.ac.uk/work.html

Lageos satellite
Source : https://lageos.gsfc.nasa.gc



Satellite mission with SLR reflectors.
Source:
https://ilrs.gsfc.nasa.gov/missions/satellite_missions/index.html

Contribution

- Origin of the Frame (CM)
- Long history
- POD/orbit evaluation

Structure:
Activity coordinated by the International SLR Service (ILRS)

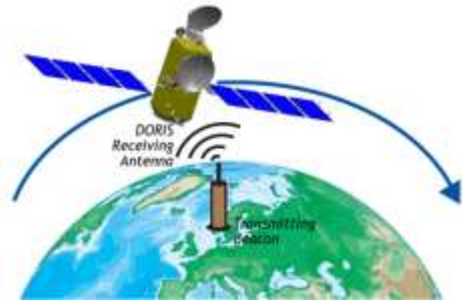
Pearlman, M.R., Noll, C.E., Pavlis, E.C. et al. (2019) The ILRS: approaching 20 years and planning for the future. J Geod 93:2161–2180. DOI: https://doi.org/10.1007/s00190-019-01241-1

How to determine coordinates?

Space geodetic techniques. DORIS = Doppler & Radiopositioning Integrated by Satellite

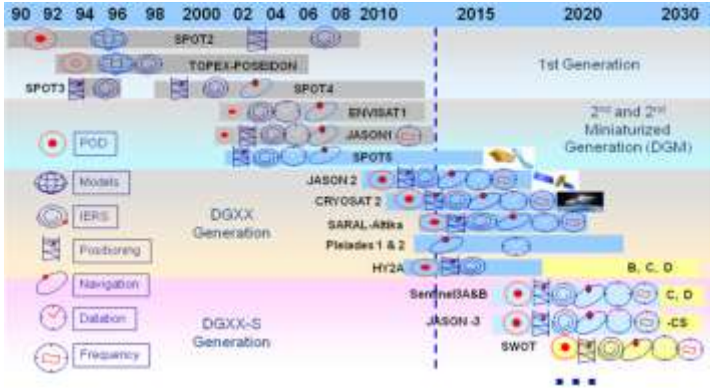
Contribution

- Spatial coverage over its full history
- POD, ITRF dissemination



Source: https://space-geodesy.nasa.gov/techniques/DORIS.html

Source: https://doris-mission.cnes.fr/en/DORIS/GP_applications.htm



Structure:

Activity coordinated by the International DORIS Service (IDS)

Willis, P.; Lemoine, F.G.; Moreaux, G. et al. (2016), The International DORIS Service (IDS), recent developments in preparation for ITRF2013, IAG SYMPOSIA SERIES, 143, 631-639, DOI: 10.1007/1345_2015_164

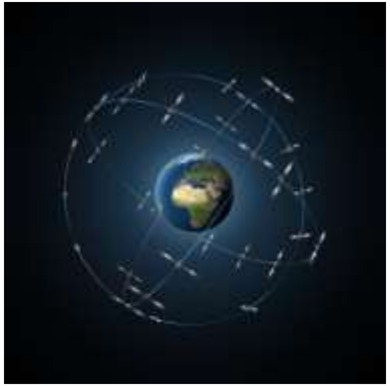
Source: https://ids-doris.org/network/sitelogs/station.html?code=KERGUELEN

IDS

How to determine coordinates?

Space geodetic techniques. GNSS

GPS, Glonass, Beidou, Galileo,
QZSS, IRNSS



Credit: ESA-P. Carril
https://www.esa.int/ESA_Multimedia/Images/2014/07/Galileo_constellation

Noto GNSS station. Source:
https://epncb.oma.be/_networkdata/siteinfo4onestation.php?station=NOT100ITA

➕

Contribution

- Temporal resolution
- Network
- ITRF dissemination

Structure:

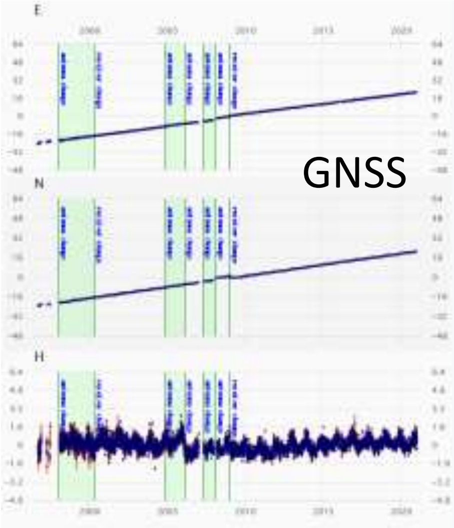
Activity coordinated by the International GNSS Service (IGS)

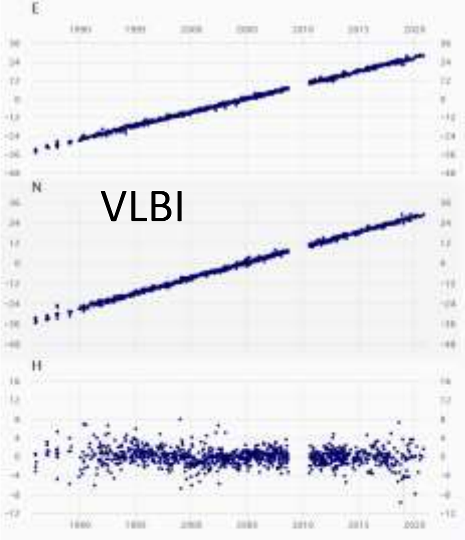
Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. Teunissen, Peter J.G., & Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967-982). Cham, Switzerland: Springer International Publishing. DOI: 10.1007/978-3-319-42928-1.

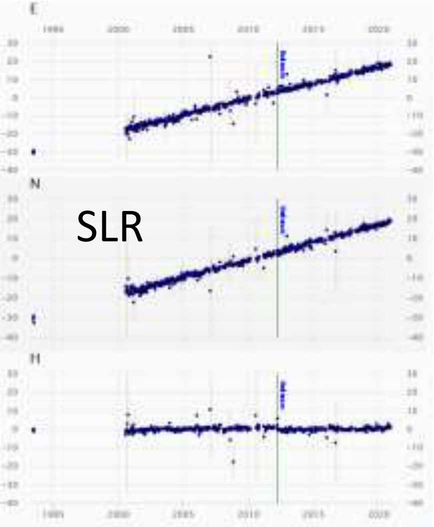
How to determine coordinates?

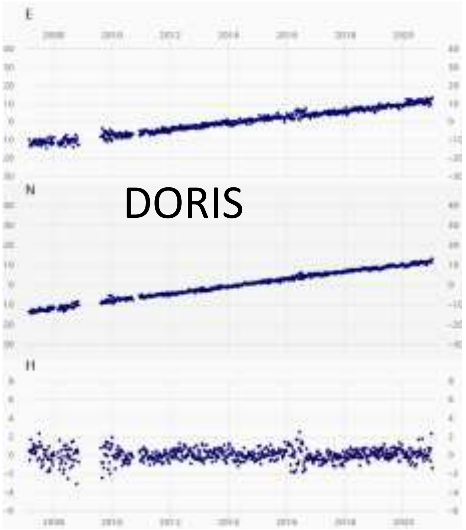
Example of position time series

Image source: Muller J-M, J-C. Poyard (2014), Hartebeesthoek local tie survey, RT/G 199









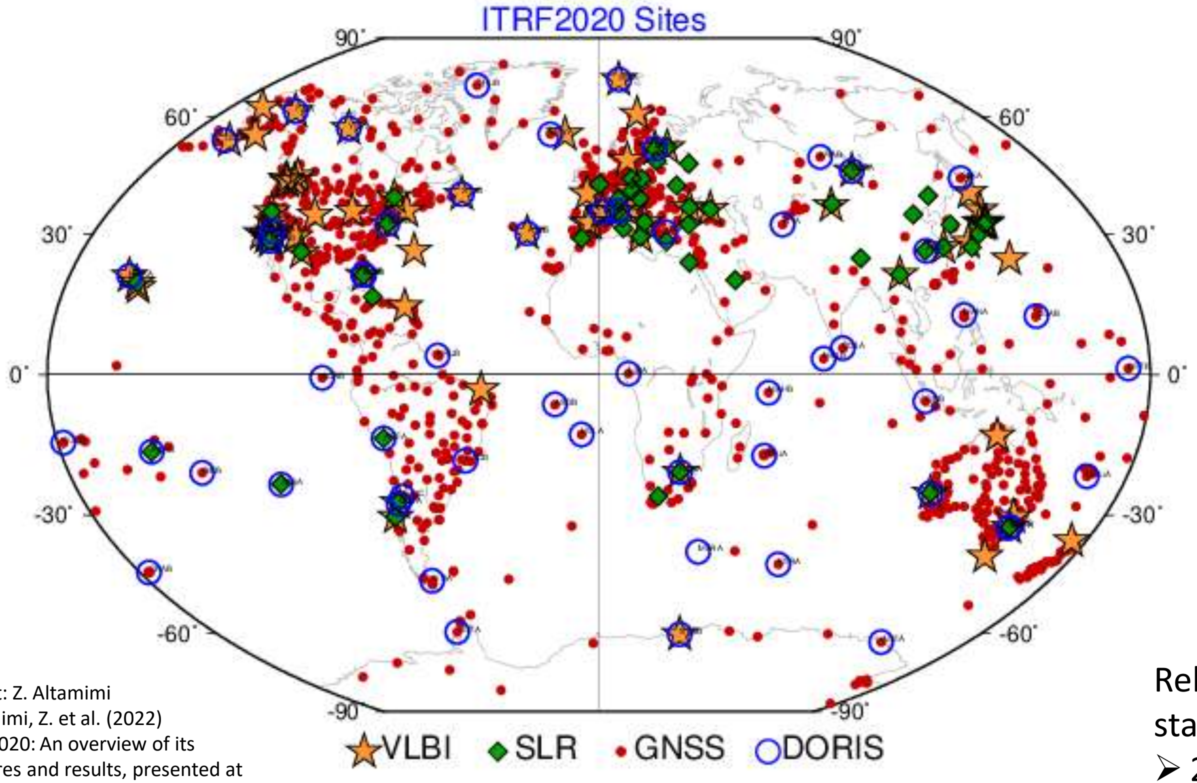
Plots available at: https://itrf.ign.fr/en/timeseries

Data source: IAG technique services and ITRF2020 analysis (Altamimi et al., 2022)

- Hellmers H., Modiri S., Thaller D., Gipson J., Blossfeld M., Seitz M., Bachmann, S. (2022) The IVS contribution to ITRF2020, technical report, itrf.ign.fr
- Moreaux G., P. Štěpánek, H. Capdeville, F. Lemoine, M. Otten (2022), The DORIS contribution to ITRF2020, technical report, itrf.ign.fr
- Pavlis E., Luceri V. (2022), The ILRS contribution to ITRF2020, technical report, itrf.ign.fr
- Rebishcung P. (2022) IGS contribution to ITRF2020, technical report, itrf.ign.fr

How to determine coordinates?

Whole network processed by the International Association of Geodesy (IAG) technique services for ITRF2020

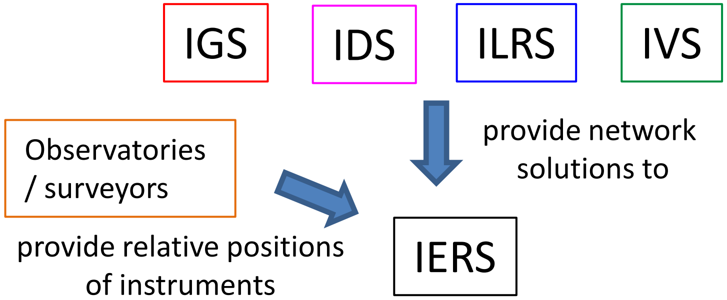


Credit: Z. Altamimi
Altamimi, Z. et al. (2022)
ITRF2020: An overview of its features and results, presented at REFAG 2022, oct 2022


Credit : D. Pesce 2013

Relative positions determined by standard surveying at co-location sites.

- ➢ 253 such vectors in ITRF2020



IGS

IDS

ILRS

IVS

provide network solutions to

Observatories / surveyors

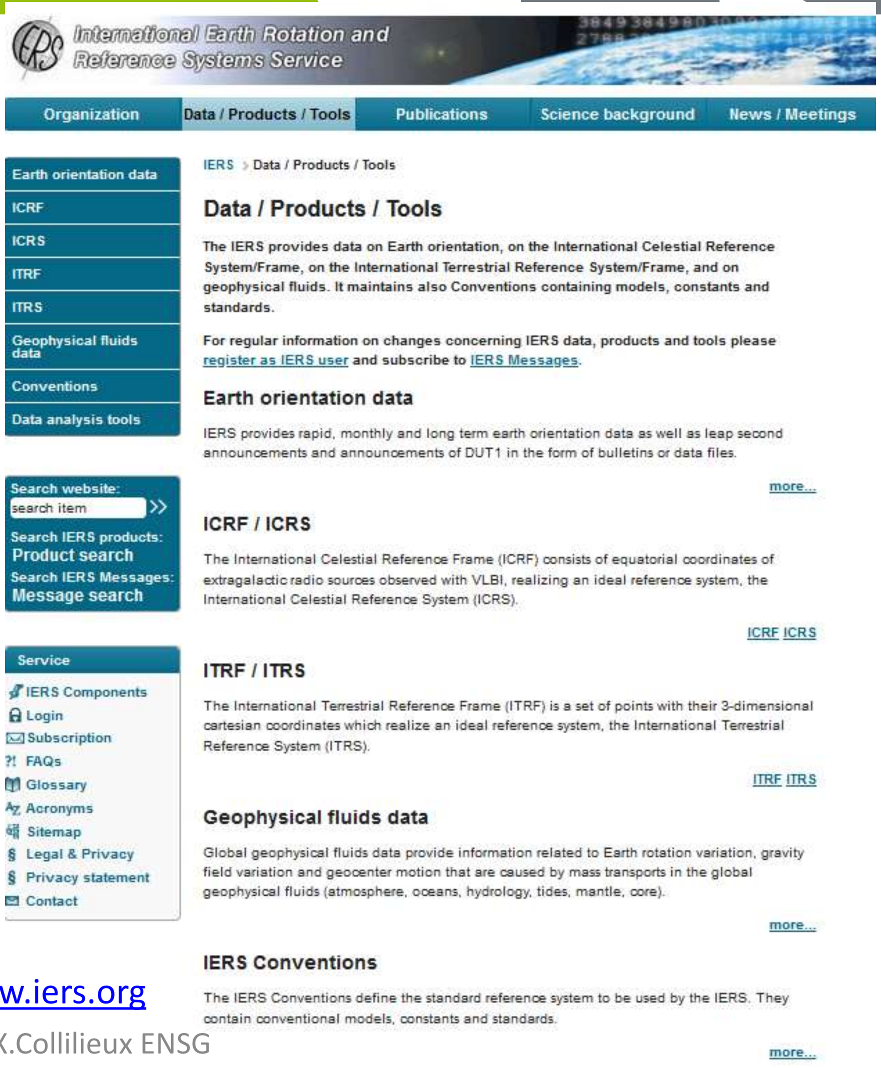
provide relative positions of instruments

IERS

The **International Earth Rotation and Reference Systems Service** (IERS) :
in charge of processing the
International Terrestrial Reference Frame (ITRF) which gives a physical access to the Internation Terrestrial Reference System (ITRS).

IERS functions as one of the International Association of Geodesy (IAG) Scientific Services.

https://www.iers.org



Data / Products / Tools

The IERS provides data on Earth orientation, on the International Celestial Reference System/Frame, on the International Terrestrial Reference System/Frame, and on geophysical fluids. It maintains also Conventions containing models, constants and standards.

For regular information on changes concerning IERS data, products and tools please register as IERS user and subscribe to IERS Messages.

Earth orientation data

IERS provides rapid, monthly and long term earth orientation data as well as leap second announcements and announcements of DUT1 in the form of bulletins or data files.

more...

ICRF / ICRS

The International Celestial Reference Frame (ICRF) consists of equatorial coordinates of extragalactic radio sources observed with VLBI, realizing an ideal reference system, the International Celestial Reference System (ICRS).

ICRF ICRS

ITRF / ITRS

The International Terrestrial Reference Frame (ITRF) is a set of points with their 3-dimensional cartesian coordinates which realize an ideal reference system, the International Terrestrial Reference System (ITRS).

ITRF ITRS

Geophysical fluids data

Global geophysical fluids data provide information related to Earth rotation variation, gravity field variation and geocenter motion that are caused by mass transports in the global geophysical fluids (atmosphere, oceans, hydrology, tides, mantle, core).

more...

IERS Conventions

The IERS Conventions define the standard reference system to be used by the IERS. They contain conventional models, constants and standards.

more...

Frame definition. What needs?

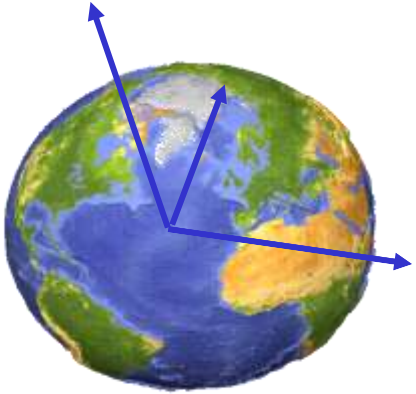
- Various needs:
  - Mapping, civil engineering
  - Navigation
  - National reference frame
  - Earth sciences: Earthquakes, volcanology, deformation monitoring
  - Astronomy : Observatory position, Earth's rotation in space
  - Precise Orbit Determination (POD): altimetry satellite, GNSS satellites

  Etc…

- Requirements (GGOS = Global Geodetic Observing System):
  1 mm and 0.1 mm/yr in TRF frame parameters

Plag, H. P., & Pearlman, M. (2007). The **Global Geodetic Observing System**: Meeting the Requirements of a Global Society on a Changing Planet in 2020 The Reference Document. *Int. Assoc. Geod*.

Frame definition. ITRS



- Origin :
  Earth center of mass (CM) (solid Earth + fluid layers)
- Scale:
  - SI units
  - Consistent with TCG (Geocentric Coordinate Time) trough relativistic modeling
- Orientation
  - At reference epoch : conventional
  - Time evolution: no-net-rotation of horizontal tectonic motions over the whole Earth which could be written as

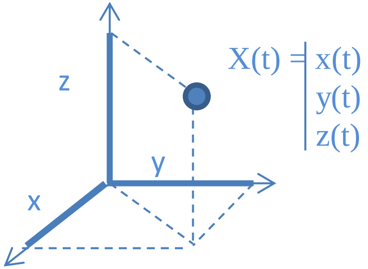
$$\vec{h}_C = \iint_C \vec{r} \wedge \left[\frac{d}{dt}\vec{r}\right]_{ITRS} dM = \vec{0}$$

Earth's crust

Boucher, C., Current Intercomparisons Between CTS's, in Reference Frames in Astronomy and Geophysics, edited by J. Kovalevsky, I. I. Mueller, and B. Kolaczek, Kluwer Academic Publisher, Dordrecht, pp.327 – 343, 1989.

ITRF coordinates

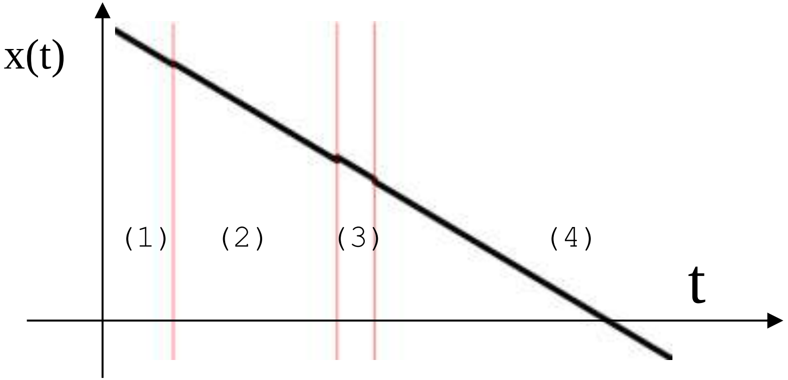
ITRF = table of coordinates



Example: coordinate of one point

Reference epoch
Ex: the reference epoch of ITRF2014 is 2010.0

t(year)	x(m)	y(m)	z(m)	vx(m/y)	vy(m/y)	vz(m/y)	tmin	tmax	id
2010.0	4202777.3053	171368.0862	4778660.2517	-.01305	0.01758	0.01031		96:277	(1)
2010.0	4202777.3058	171368.0882	4778660.2528	-.01305	0.01758	0.01031	96:277	03:113	(2)
2010.0	4202777.3056	171368.0882	4778660.2528	-.01312	0.01760	0.01074	03:113	04:295	(3)
	Etc . . .								



Example: What is the x coordinate at epoch 2002.5?

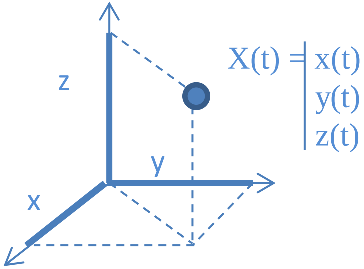
$$x(2002.5) = \boxed{x(2010.0)} + (2002.5-\boxed{2010.0}) \cdot \boxed{vx(2002.5)}$$

$$= 4202777.3058 - 7.5 \cdot (-.01305)$$

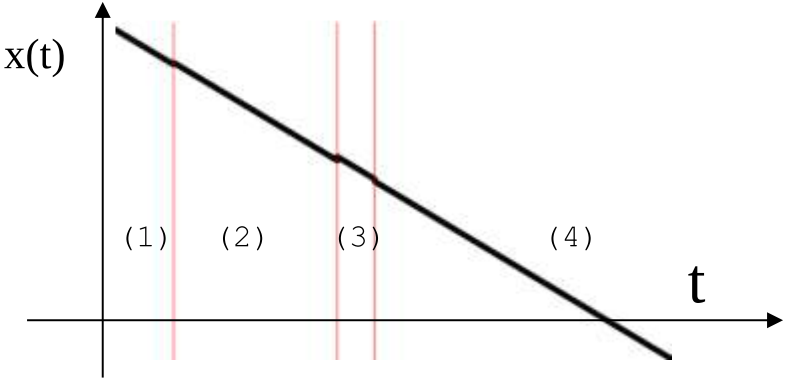
$$= 4202777.4037$$

ITRF coordinates

ITRF = table of coordinates



What kind of deformation does this kinematic model account for?

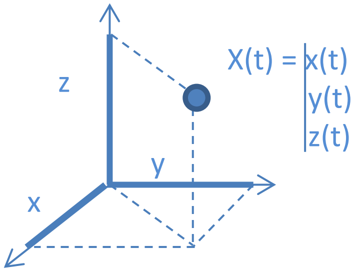


- Tectonic motion in stable part of the tectonic plates
- Post-Glacial Rebound
- Earthquake Co-seismic motion
- Post-seismic motion in Earthquake (far-field areas)

+ Instrument related discontinuities !

This description is valid up to ITRF2008: ITRF94, …, ITRF96, … ITRF2008

Relationship between frame coordinates and « instantaneous coordinates »

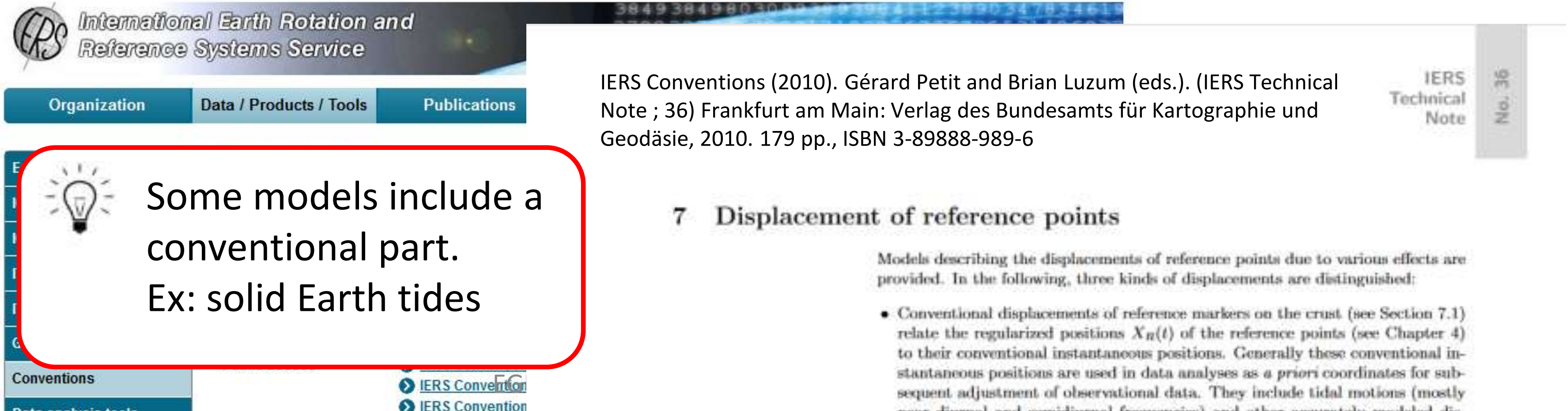


$$X(t) = X_{ITRF}(t) + \boxed{\Delta X(t)}$$

Well modeled crust deformation:

- Solid Earth tides
- Pole tides
- Tidal Ocean tide loading
- Atmospheric tide loading

https://www.iers.org/IERS/EN/DataProducts/Conventions/conventions.html



IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6

7 Displacement of reference points

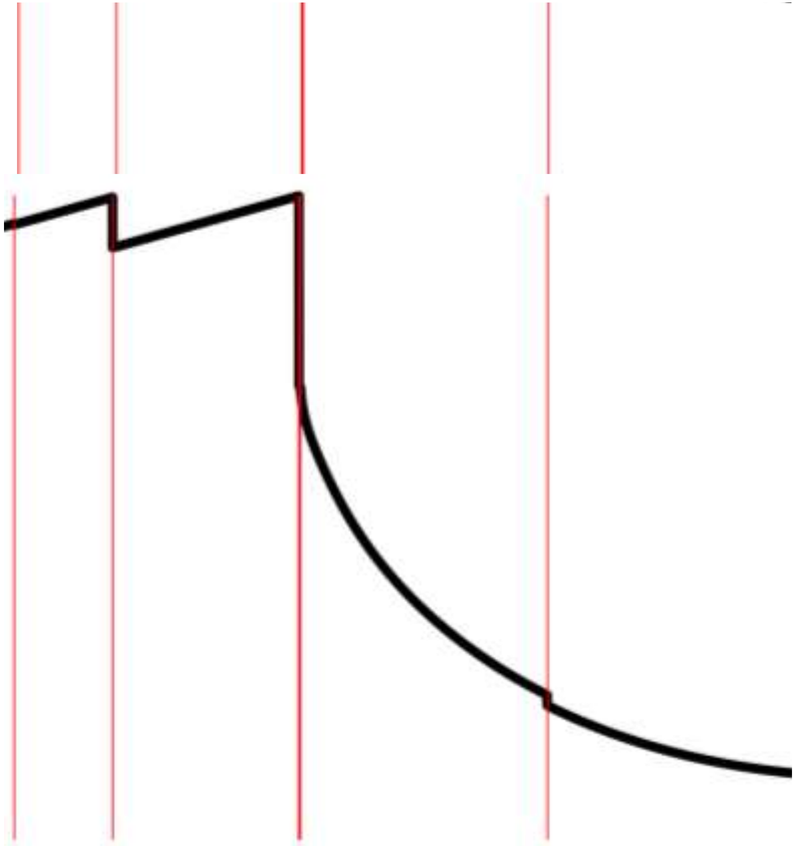
Models describing the displacements of reference points due to various effects are provided. In the following, three kinds of displacements are distinguished:

- Conventional displacements of reference markers on the crust (see Section 7.1) relate the regularized positions $X_R(t)$ of the reference points (see Chapter 4) to their conventional instantaneous positions. Generally these conventional instantaneous positions are used in data analyses as *a priori* coordinates for subsequent adjustment of observational data. They include tidal motions (mostly

Some models include a conventional part.
Ex: solid Earth tides

ITRF coordinates

Kinematic model in ITRF2014



Position discontinuities at t_i

Velocity changes at t_j

$$X_{ITRF}(t) = X(t_0) + V(t-t_0)$$

$$+ \Sigma_i \, dX_i \cdot H(t-t_i) + \Sigma_j \, dV_j \cdot H(t-t_j)$$

$$+ d_{PSD}(t)$$

Post-seismic deformation modelat t_i

ITRF coordinates

Post-seismic displacements

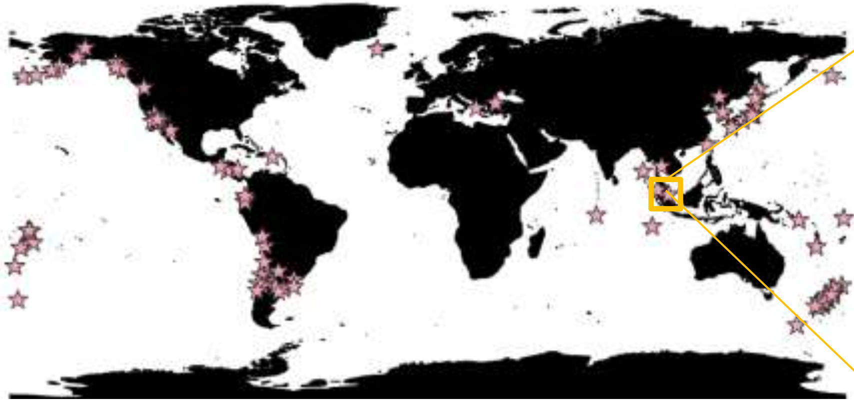
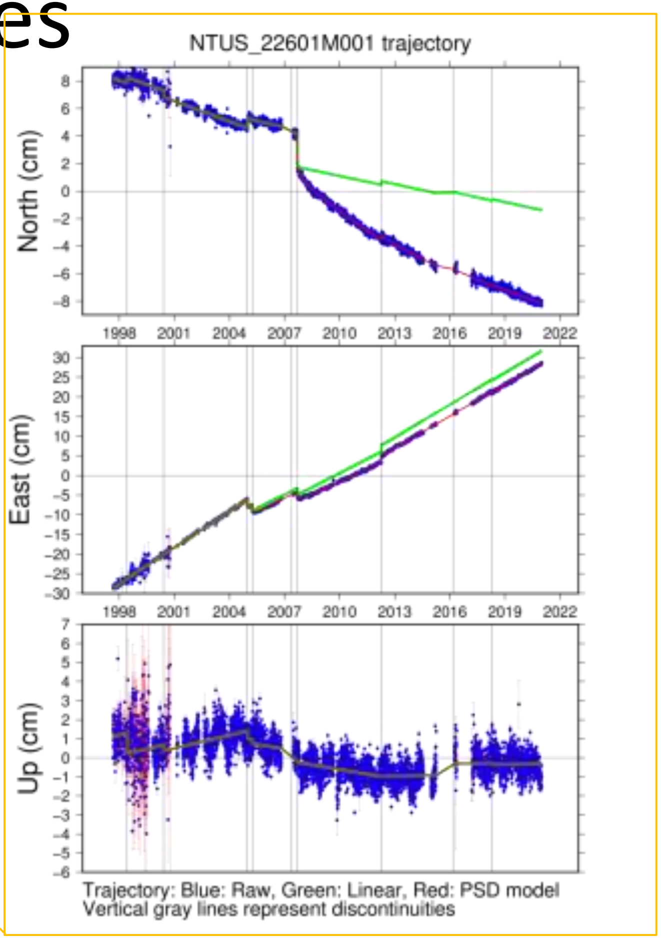


Fig. Stations with post-seismic motion modelling in ITRF2020



NTUS_22601M001 trajectory

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

Post-seismic displacements

How to compute the post-seismic displacement? $d_{PSD}(t) = ?$

- Models provided for East, North and Height separately
- Composed of up to two functions

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

- Coefficients $A_i^l \; A_i^e \; t_i^l \; t_i^e \; \tau_i^l \; \tau_i^e$ are provided
- Displacements need to be converted in Cartesian x,y,z using a rotation matrix (which depends on point longitude λ and latitude φ)

$$R(\lambda, \phi) = \begin{pmatrix} -\sin(\lambda) & \cos(\lambda) & 0 \\ -\sin(\phi)\cos\lambda & -\sin(\phi)\sin\lambda & \cos\phi \\ \cos\phi\cos\lambda & \cos\phi\sin\lambda & \sin\phi \end{pmatrix}$$

More info at *http://itrf.ign.fr*

ITRF2020P: Equations of post-seismic deformation models

After an Earthquake, the position of a station during the post-seismic trajectory, X_{PSD}, at an epoch t could be written as:

$$X_{PSD}(t) = X(t_0) + \dot{X}(t - t_0) + \delta X_{PSD}(t) \quad (1)$$

where $\dot{X}$ is the station linear velocity vector, and $\delta X_{PSD}(t)$ is the total sum of the post-seismic deformation (PSD) corrections at epoch t. For each component $L \in$ {E,N,U}, we note δL the total sum of PSD corrections expressed in the local frame at epoch t:

$$\delta L(t) = \sum_{i=1}^{n^l} A_i^l \log(1 + \frac{t - t_i^l}{\tau_i^l}) + \sum_{i=1}^{n^e} A_i^e (1 - e^{-\frac{t - t_i^e}{\tau_i^e}}) \quad (2)$$

where:

n^l : Number of logarithmic terms of the parametric model
n^e : Number of exponential terms of the parametric model
A_i^l : Amplitude of the i^{th} logarithmic term
A_i^e : Amplitude of the i^{th} exponential term
τ_i^l: Relaxation time of the i^{th} logarithmic term
τ_i^e: Relaxation time of the i^{th} exponential term
t_i^l: Earthquake time(date) corresponding to i^{th} logarithmic term
t_i^e: Earthquake time(date) corresponding to the i^{th} exponential term
The variance of $\delta L(t)$ is given by:

$$var(\delta L) = C.var(\theta).C^T \quad (3)$$

where θ is the vector of parameters of the post-seismic deformation model:

$$\theta = [A_1^l, \tau_1^l, \ldots A_{n^l}^l, \tau_{n^l}^l, A_1^e, \tau_1^e, \ldots A_{n^e}^e, \tau_{n^e}^e]$$

The elements of the matrix C are computed by the following formulas:

$$\frac{\partial \delta L}{\partial A_i^l} = \log(1 + \frac{t - t_i^l}{\tau_i^l}) \quad (4)$$

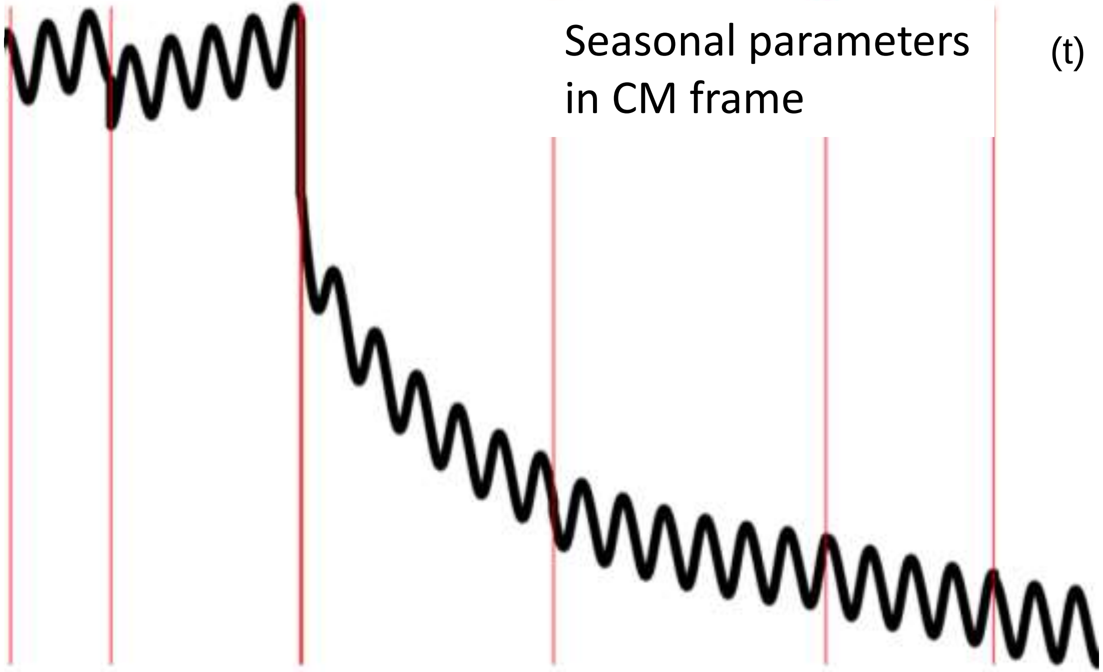
$$\frac{\partial \delta L}{\partial \tau_i^l} = -\frac{A_i^l (t - t_i^l)}{(\tau_i^l)^2 (1 + \frac{t - t_i^l}{\tau_i^l})} \quad (5)$$

$$\frac{\partial \delta L}{\partial A_i^e} = 1 - e^{-\frac{(t - t_i^e)}{\tau_i^e}} \quad (6)$$

$$\frac{\partial \delta L}{\partial \tau_i^e} = -\frac{A_i^e (t - t_i^e) e^{-\frac{(t - t_i^e)}{\tau_i^e}}}{(\tau_i^e)^2} \quad (7)$$

ITRF coordinates

Kinematic model in ITRF2020



Seasonal parameters in CM frame

Position discontinuities at t_i

Velocity discontinuities at t_j

$$(t) \quad = X(t_0) + V\,(t-t_0)$$

$$+ \Sigma_i\, dX_i \cdot H(t-t_i) + \Sigma_j\, dV_j \cdot H(t-t_j)$$

$$+ d_{PSD}(t)$$

Post-seismic deformation modelat t_i

$$+ d_{seasonal\ CM}(t)$$

Periodic displacements

$$\begin{aligned} d_{\text{seasonal CM}}(t) = \quad & a_i \cos(2\pi\, t) + b_i \sin(2\pi\, t) \longleftarrow \text{annual} \\ & + c_i \cos(4\pi\, t) + d_i \sin(4\pi\, t) \longleftarrow \text{Semi-annual} \end{aligned}$$

with t in decimal year

$$d_{\text{seasonal CM}}(t) = d_{\text{seasonal CF}}(t) - \underbrace{T_{\text{seasonal}}(t)}_{\text{geocenter motion : CM w.r.t CF}}$$

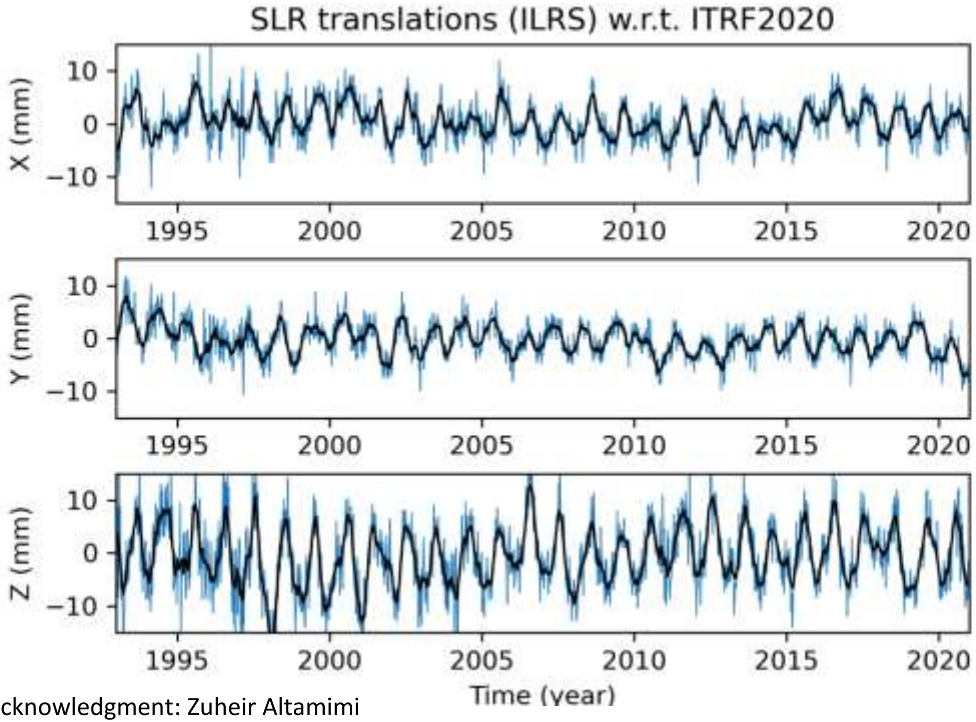
By definition, in the center of figure frame (CF), the averaged displacement over the whole Earth’s surface is zero.

Blewitt, G. (2003). Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth. *Journal of geophysical research: solid earth*, *108*(B2).

Figure by Roelof Rietbroek. See the post: https://wobbly.earth/post/geocenter/

ITRF2020

Magnitude of the geocenter motion: Net-translation of SLR network over time



Acknowledgment: Zuheir Altamimi

A specific seasonal geocenter motion model has been computed from ITRF2020 analysis.

➡ This model is in good agreement with recent geocenter motion estimates in particular Wu et al. (2020).

Rebischung, P., Z. Altamimi, X. Collilieux, L. Métivier and K. Chanard (2022) ITRF2020 seasonal geocenter motion model , REFAG 2022, oct 2022

Wu, X., Haines, B. J., Heflin, M. B., & Landerer, F. W. (2020). Improved global nonlinear surface mass variation estimates from geodetic displacements and reconciliation with GRACE data. *Journal of Geophysical Research: Solid Earth*, *125*(2), e2019JB018355.

ITRF2020

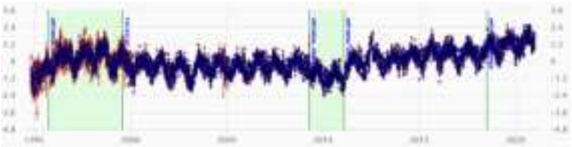


Fig: height displacement at Potsdam observed by GNSS

IGS data submitted for ITRF2020 (source: itrf.ign.fr)

Why and when using seasonal displacements?

CAUTION! ITRF2020 seasonal parameters contains seasonal non-tidal loading deformations

- To determine satellite orbits (Precise Orbit Determination). Need geocenter motion so displacement in CM frame
- Alignment of space geodetic solutions to preserve seasonal signals in the aligned solution

So which frame for seasonal?

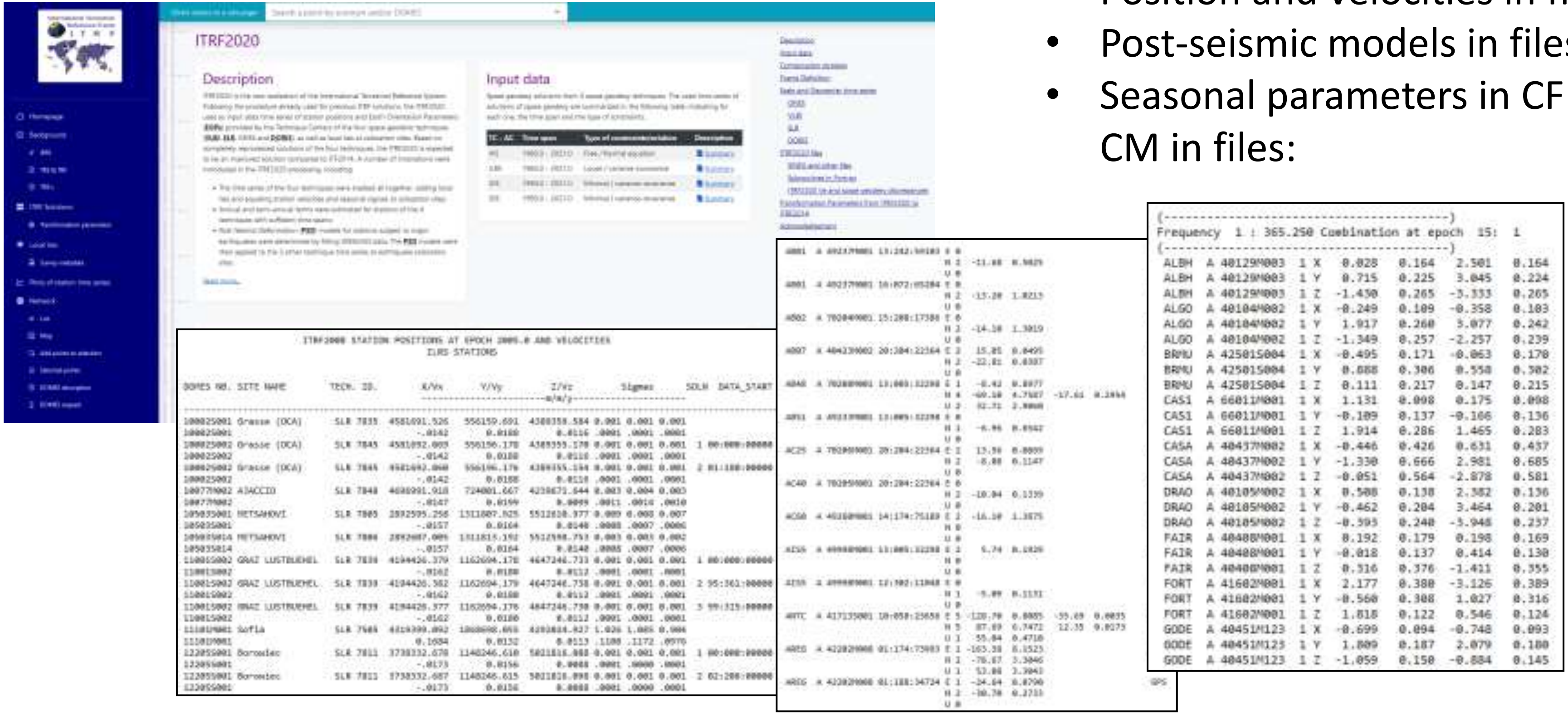
- if CM: the aligned solution will contain a net translational motion (=ITRF2020 geocenter motion model)

- if CF : no-net translational motion

ITRF2020

https://itrf.ign.fr/en/solutions/itrf2020

- Position and velocities in files :
- Post-seismic models in files:
- Seasonal parameters in CF or CM in files:



ITRF2020

Description

Input data

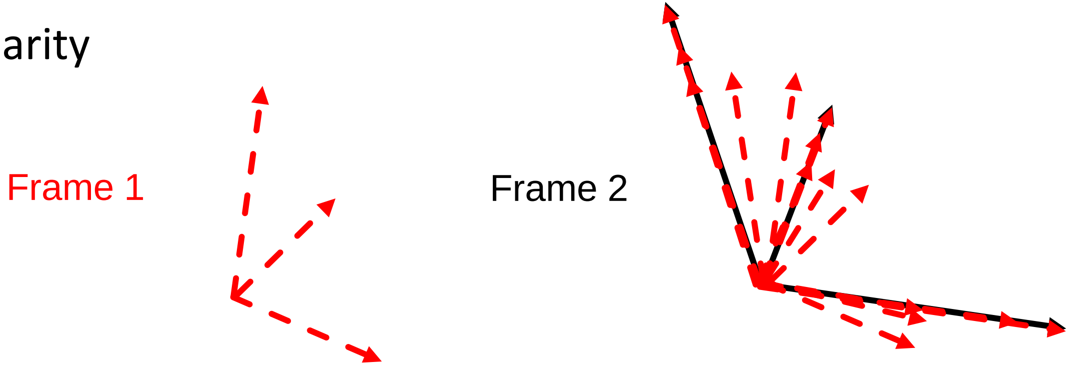
```
ITRF2008 STATION POSITIONS AT EPOCH 2005.0 AND VELOCITIES
                      ILRS STATIONS

DOMES NB. SITE NAME        TECH. ID.       X/Vx        Y/Vy          Z/Vz          Sigmas       SOLN  DATA_START
```

```
(----------------------------------------)
Frequency  1 : 365.250 Combination at epoch  15:  1
(----------------------------------------)
 ALBH  A 40129M003  1 X   0.028   0.164   2.501   0.164
 ALBH  A 40129M003  1 Y   0.715   0.225   3.045   0.224
 ALBH  A 40129M003  1 Z  -1.430   0.265  -3.333   0.265
 ALGO  A 40104M002  1 X  -0.249   0.109  -0.358   0.103
 ALGO  A 40104M002  1 Y   1.917   0.260   3.077   0.242
 ALGO  A 40104M002  1 Z  -1.349   0.257  -2.257   0.239
 BRMU  A 42501S004  1 X  -0.495   0.171  -0.063   0.170
 BRMU  A 42501S004  1 Y   0.088   0.306   0.550   0.302
 BRMU  A 42501S004  1 Z   0.111   0.217   0.147   0.215
 CAS1  A 66011M001  1 X   1.131   0.098   0.175   0.098
 CAS1  A 66011M001  1 Y  -0.109   0.137  -0.106   0.136
 CAS1  A 66011M001  1 Z   1.914   0.286   1.465   0.283
 CASA  A 40437M002  1 X  -0.446   0.426   0.631   0.437
 CASA  A 40437M002  1 Y  -1.330   0.666   2.981   0.685
 CASA  A 40437M002  1 Z  -0.051   0.564  -2.878   0.581
 DRAO  A 40105M002  1 X   0.508   0.138   2.382   0.136
 DRAO  A 40105M002  1 Y  -0.462   0.204   3.464   0.201
 DRAO  A 40105M002  1 Z  -0.393   0.240  -3.948   0.237
 FAIR  A 40408M001  1 X   0.192   0.179   0.198   0.169
 FAIR  A 40408M001  1 Y  -0.018   0.137   0.414   0.130
 FAIR  A 40408M001  1 Z   0.316   0.376  -1.411   0.355
 FORT  A 41602M001  1 X   2.177   0.388  -3.126   0.389
 FORT  A 41602M001  1 Y  -0.560   0.308   1.027   0.316
 FORT  A 41602M001  1 Z   1.818   0.122   0.546   0.124
 GODE  A 40451M123  1 X  -0.699   0.094  -0.748   0.093
 GODE  A 40451M123  1 Y   1.809   0.187   2.079   0.180
 GODE  A 40451M123  1 Z  -1.059   0.150  -0.884   0.145
```

Frame transformation

- You have all your results in ITRF2014 and want to tranform them to ITRF2020?

3D similarity



- *Translation*
- *Rotation*
- *scale factor*

7 parameters

$$X_1 = [x_1, y_1, z_1]^T \qquad X_2 = [x_2, y_2, z_2]^T$$

$$X_2 = T + \lambda \mathcal{R} X_1$$

$$X_2 = T + (I_3 + d \cdot I_3 + R) X_1$$

Small rotations

14 parameter transformations

Relationship between dynamic TRF

14-parameter transformation
Velocities are frame-dependent!

$$\begin{pmatrix} x_2(t)\\ y_2(t)\\ z_2(t)\end{pmatrix} = \begin{pmatrix} t_x(t)\\ t_y(t)\\ t_z(t)\end{pmatrix} + \begin{pmatrix} x_1(t)\\ y_1(t)\\ z_1(t)\end{pmatrix} + d(t)\cdot\begin{pmatrix} x_1(t)\\ y_1(t)\\ z_1(t)\end{pmatrix} + \begin{pmatrix} 0 & -\epsilon_z(t) & \epsilon_y(t)\\ \epsilon_z(t) & 0 & -\epsilon_x(t)\\ -\epsilon_y(t) & \epsilon_x(t) & 0\end{pmatrix}\begin{pmatrix} x_1(t)\\ y_1(t)\\ z_1(t)\end{pmatrix}$$

$$\begin{pmatrix} \dot{x}_2(t)\\ \dot{y}_2(t)\\ \dot{z}_2(t)\end{pmatrix} = \begin{pmatrix} \dot{t}_x\\ \dot{t}_y\\ \dot{t}_z\end{pmatrix} + \begin{pmatrix} \dot{x}_1(t)\\ \dot{y}_1(t)\\ \dot{z}_1(t)\end{pmatrix} + \dot{d}\cdot\begin{pmatrix} x_1(t)\\ y_1(t)\\ z_1(t)\end{pmatrix} + \begin{pmatrix} 0 & -\dot{\epsilon}_z & \dot{\epsilon}_y\\ \dot{\epsilon}_z & 0 & -\dot{\epsilon}_x\\ -\dot{\epsilon}_y & \dot{\epsilon}_x & 0\end{pmatrix}\begin{pmatrix} x_1(t)\\ y_1(t)\\ z_1(t)\end{pmatrix}$$

With $t_x(t) \quad t_y(t) \quad t_z(t) \quad d(t) \quad \epsilon_x(t) \quad \epsilon_y(t) \quad \epsilon_z(t)$ *at* $t=t_0$
$\dot{t}_x \quad \dot{t}_y \quad \dot{t}_z \quad \dot{d} \quad \dot{\epsilon}_x \quad \dot{\epsilon}_y \quad \dot{\epsilon}_z$

= the 14 parameters

* Rotation sign convention from the International Earth Rotation and Reference System Service (IERS).

14 parameter transformations

Example: transformation parameters from ITRF2014 to ETRF2014

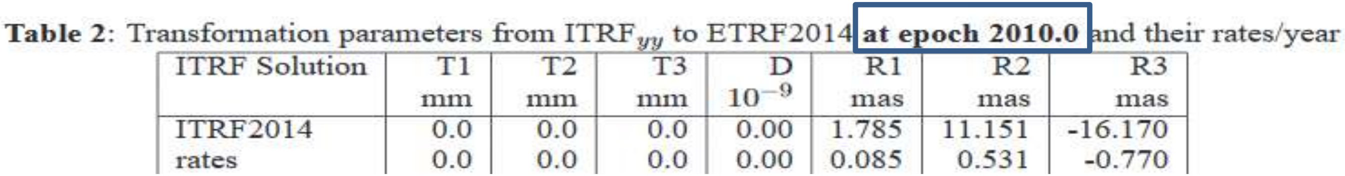


Table 2: Transformation parameters from ITRF$_{yy}$ to ETRF2014 **at epoch 2010.0** and their rates/year

ITRF Solution	T1 mm	T2 mm	T3 mm	D 10^{-9}	R1 mas	R2 mas	R3 mas
ITRF2014	0.0	0.0	0.0	0.00	1.785	11.151	-16.170
rates	0.0	0.0	0.0	0.00	0.085	0.531	-0.770

Source: Altamimi, 2018, EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems

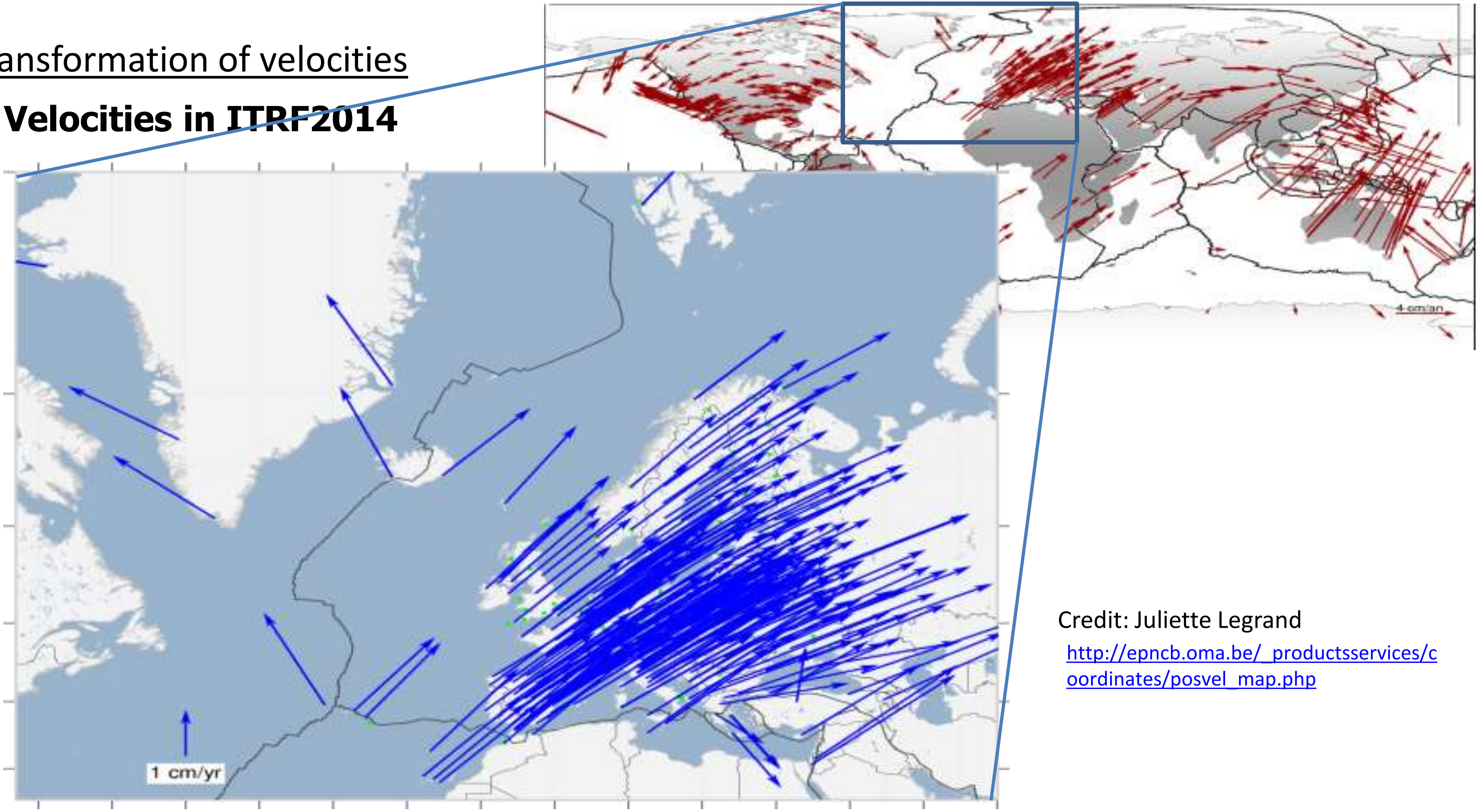
Transformation parameter rates need to be used to compute the 7-parameter values at any epoch

Application: what are the rotations values in 1989.0 ?

$$\varepsilon_x\,(t) = R1(t) = R1(2010.0) + \dot{R1}\ .\ (1989.0 - 2010.0) = 0$$

Transformation of velocities

Velocities in ITRF2014



Credit: Juliette Legrand

http://epncb.oma.be/_productsservices/coordinates/posvel_map.php

Transformation of velocities

Velocities in ETRF2014 after transforming velocities

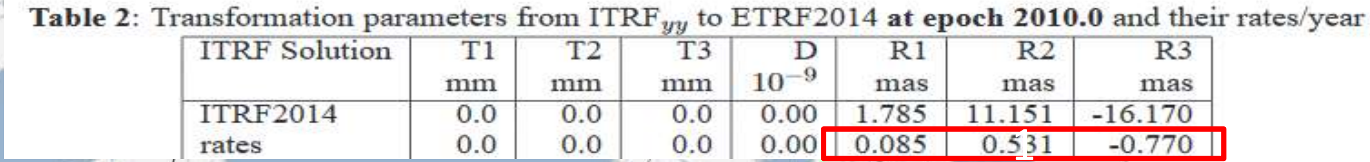


Table 2: Transformation parameters from ITRF$_{yy}$ to ETRF2014 **at epoch 2010.0** and their rates/year

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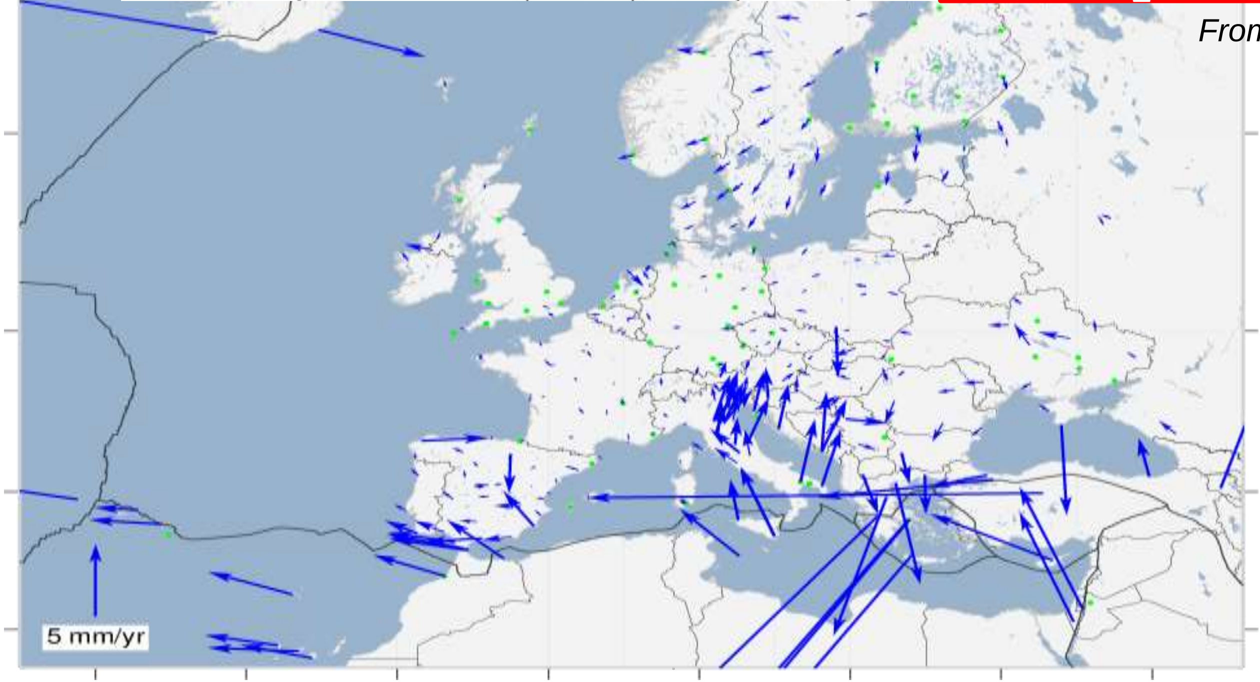
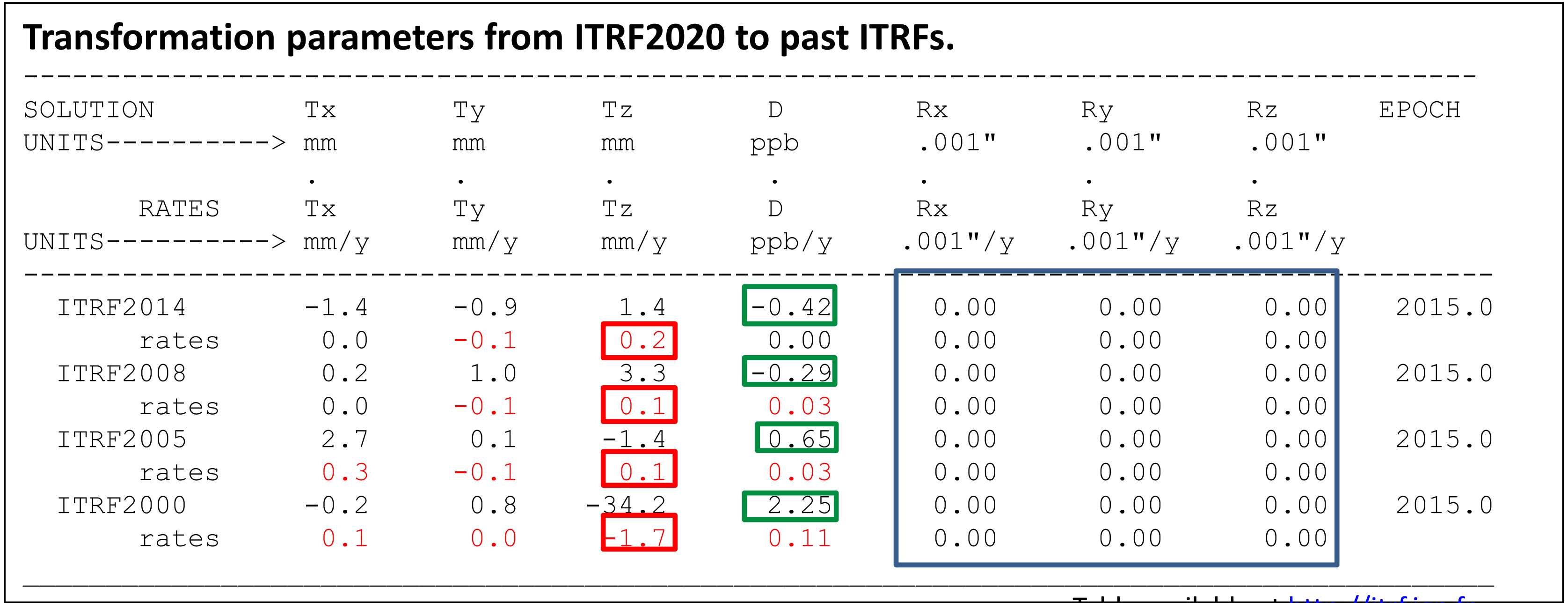
From Altamimi, (2018)



Credit: Juliette Legrand

http://epncb.oma.be/_productsservices/coordinates/posvel_map.php

14 parameter transformations



Transformation parameters from ITRF2020 to past ITRFs.

```
----------------------------------------------------------------------------------------------
SOLUTION         Tx       Ty       Tz        D        Rx        Ry        Rz       EPOCH
UNITS---------->  mm       mm       mm       ppb      .001"     .001"     .001"
                  .        .        .         .        .         .         .
       RATES     Tx       Ty       Tz        D        Rx        Ry        Rz
UNITS---------->  mm/y     mm/y     mm/y     ppb/y   .001"/y   .001"/y   .001"/y
----------------------------------------------------------------------------------------------
  ITRF2014       -1.4     -0.9      1.4     -0.42      0.00      0.00      0.00     2015.0
       rates      0.0     -0.1      0.2      0.00      0.00      0.00      0.00
  ITRF2008        0.2      1.0      3.3     -0.29      0.00      0.00      0.00     2015.0
       rates      0.0     -0.1      0.1      0.03      0.00      0.00      0.00
  ITRF2005        2.7      0.1     -1.4      0.65      0.00      0.00      0.00     2015.0
       rates      0.3     -0.1      0.1      0.03      0.00      0.00      0.00
  ITRF2000       -0.2      0.8    -34.2      2.25      0.00      0.00      0.00     2015.0
       rates      0.1      0.0     -1.7      0.11      0.00      0.00      0.00
______________________________________________________________________________________________
```

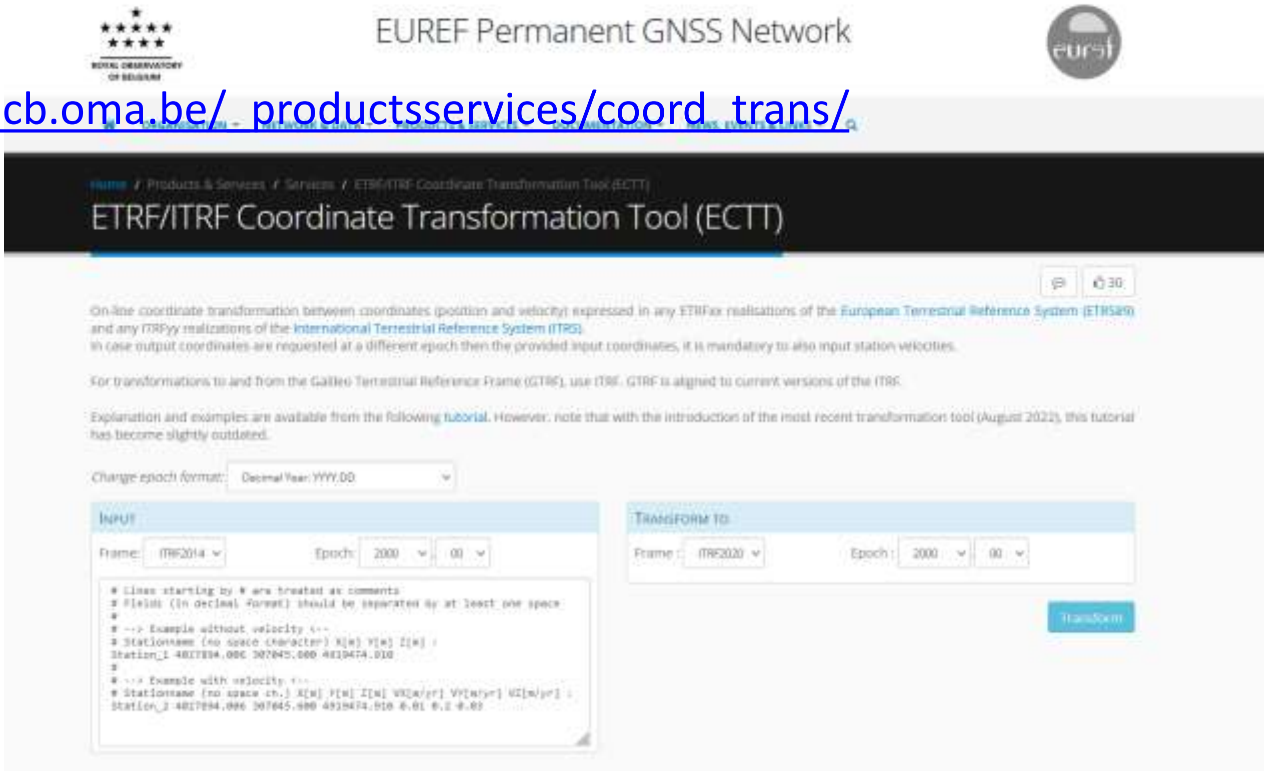
Table available at http://itrf.ign.fr

- Successive Frame alignment in orientation
- Different scale definition strategy and modeling
- Translation rates get smaller, especially in TZ

14 parameter transformations

Online software to perform 14-parameter transformations between ITRF solutions and more:

http://epncb.oma.be/_productsservices/coord_trans/



ETRF/ITRF Coordinate Transformation Tool (ECTT)

On-line coordinate transformation between coordinates (position and velocity) expressed in any ETRFxx realisations of the European Terrestrial Reference System (ETRS89) and any ITRFyy realizations of the International Terrestrial Reference System (ITRS).
In case output coordinates are requested at a different epoch then the provided input coordinates, it is mandatory to also input station velocities.

For transformations to and from the Galileo Terrestrial Reference Frame (GTRF), use ITRF. GTRF is aligned to current versions of the ITRF.

Explanation and examples are available from the following tutorial. However, note that with the introduction of the most recent transformation tool (August 2022), this tutorial has become slightly outdated.

Change epoch format: Decimal Year: YYYY.DD

INPUT

Frame: ITRF2014 Epoch: 2000 . 00

```
# Lines starting by # are treated as comments
# Fields (in decimal format) should be separated by at least one space
#
# --> Example without velocity <--
# Stationname (no space character) X[m] Y[m] Z[m] :
Station_1 4027894.006 307045.600 4919474.910
#
# --> Example with velocity <--
# Stationname (no space ch.) X[m] Y[m] Z[m] VX[m/yr] VY[m/yr] VZ[m/yr] :
Station_2 4027894.006 307045.600 4919474.910 0.01 0.2 0.03
```

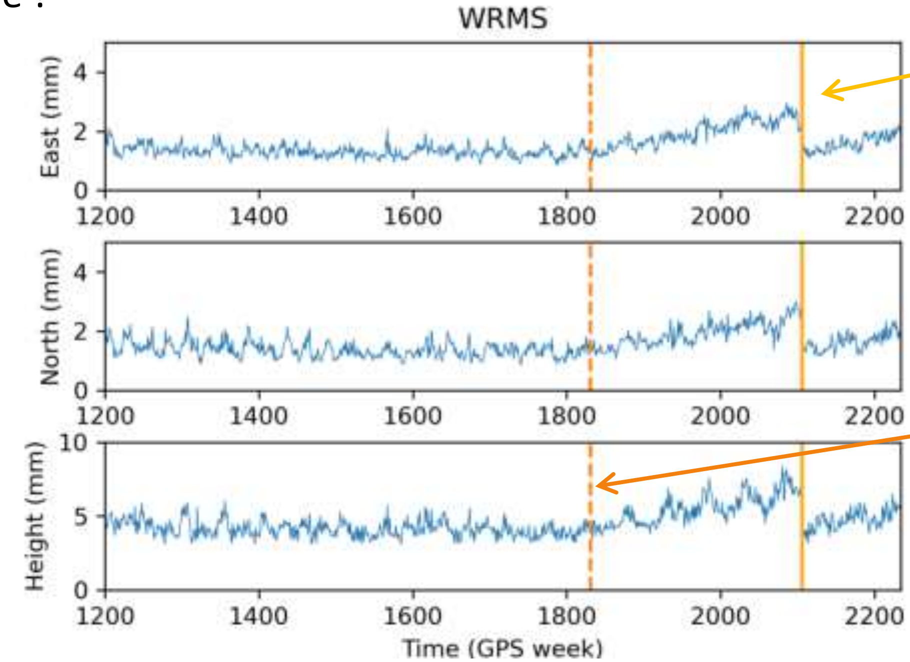
TRANSFORM TO

Frame : ITRF2020 Epoch : 2000 . 00

Why choosing the most recent frame?

Effect of coordinate limited precision on Frame alignement?

- Note: $X_{ITRF}(t)$ becomes less precise with increasing t.
- Consequence: the « mean difference » between observed coordinates X(t) and $X_{ITRF}(t)$ gets bigger with time !



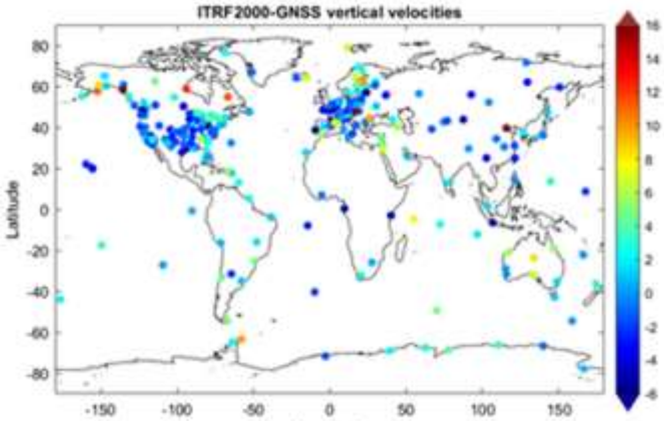
Update to IGS14b

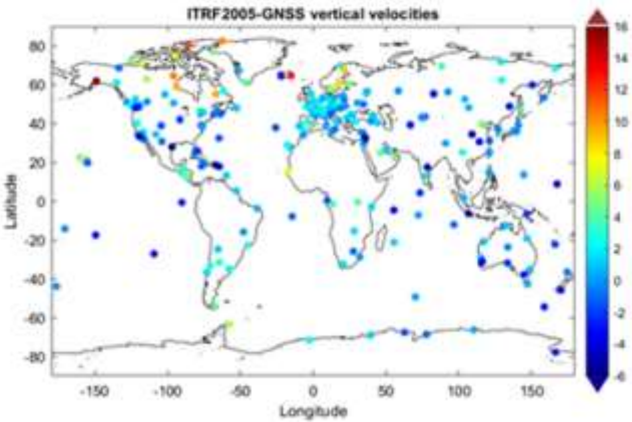
Start of ITRF2014 data extrapolation

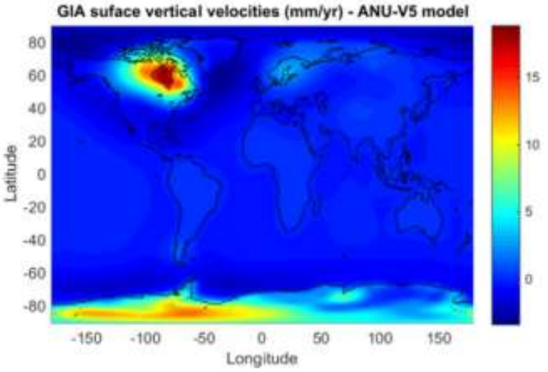
Fig. WRMS of 7-parameter estimation between GNSS weekly coordinate time series (IGS) and ITRF2014 (more precisely IGS14 and IGS14b frames)

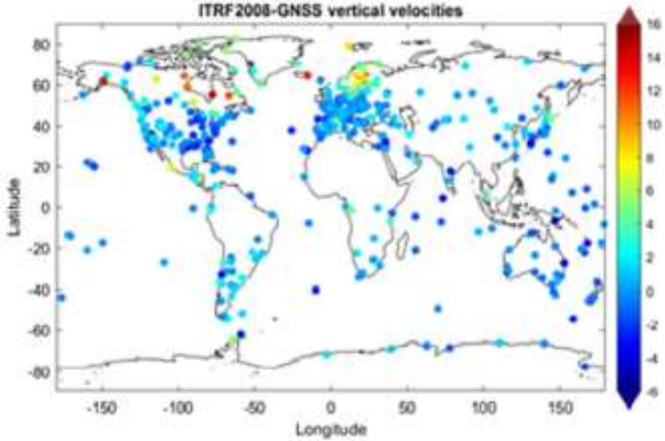
Acknowledgment: Paul Rebischung

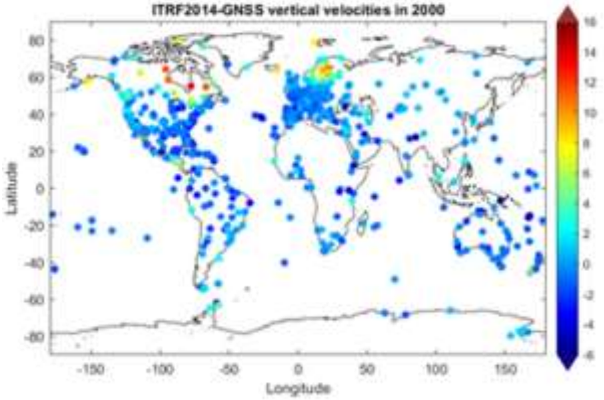
Why choosing the most recent frame?


ITRF2000-GNSS vertical velocities


ITRF2005-GNSS vertical velocities


GIA suface vertical velocities (mm/yr) - ANU-V5 model


ITRF2008-GNSS vertical velocities


ITRF2014-GNSS vertical velocities in 2000

Métivier, L., Altamimi, Z., & Rouby, H. (2020). Past and present ITRF solutions from geophysical perspectives. *Advances in space research*, *65*(12), 2711-2722.

Frame accuracy

Frame accuracy:

- Frame datum accuracy
- individual station coordinate !

What accuracy for individual station coordinate?

- ➢ Agreement at ITRF2020 co-location sites

GNSS to	Tie vector discrepancies < 5 mm
VLBI	50% (=38 vectors)
SLR	36% (19 vectors)
DORIS	32% (39 vectors)

Altamimi Z, Rebischung P., Collilieux X., Métivier, L., Chanard, K., ITRF2020: An augmented reference frame refining the modeling of nonlinear station motions, J. Geodesy, submitted

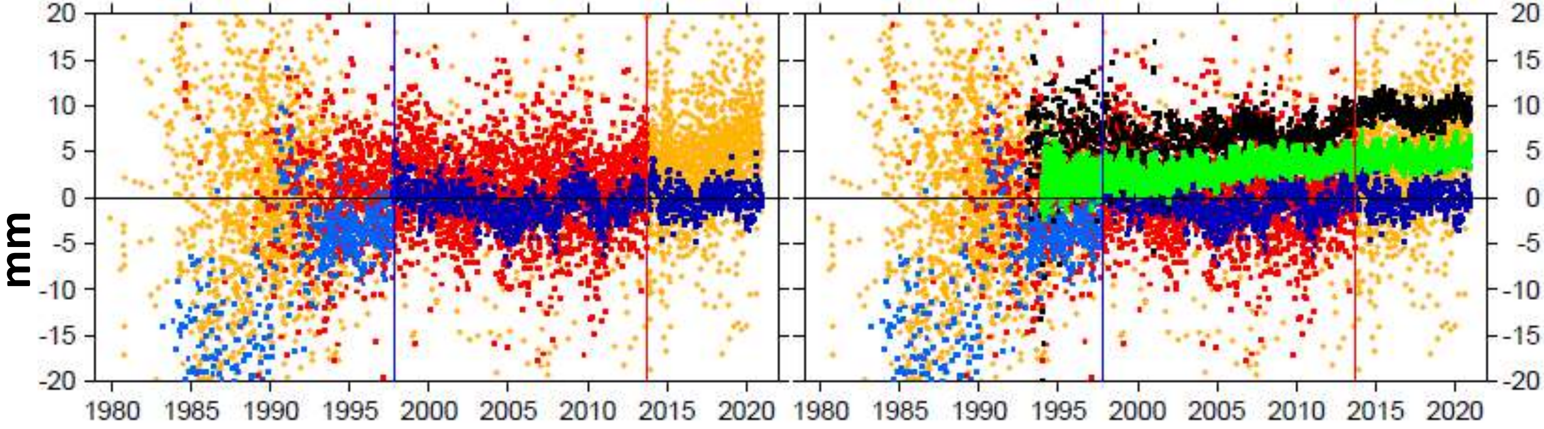
Credit : D. Pesce 2013

Frame accuracy

Frame datum accuracy

Internal = frame space geodesy results

Height positioning agreement between space geodetic techniques from ITRF2020 analysis



- Orange and Red: VLBI scale
- Light blue and Dark blue: SLR scale
- Green: GNSS scale
- Black: DORIS scale

Credit: Z. Altamimi
Altamimi, Z., P. Rebischung, X. Collilieux, L. Métivier and K. Chanard (2022)
ITRF2020: An overview of its features and results, REFAG 2022, oct 2022

Frame accuracy

Frame datum accuracy

External evaluation. Example of evaluation made on ITRF2008 origin time evolution

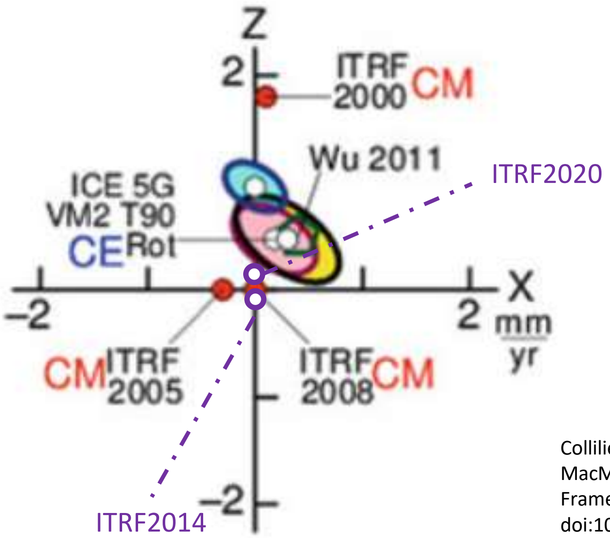


Fig. Evaluation of ITRF2008 origin drift along X and Z directions based on post-glacial rebound models and global inversion

Collilieux, X., Z. Altamimi, D.F. Argus, C. Boucher, A. Dermanis, B.J. Haines, T.A. Herring, C. Kreemer, F.G. Lemoine, C. Ma, D.S. MacMillan, J. Makinen, L. Métivier, J.C. Ries, F.N. Teferle and X. Wu (2014) External evaluation of the Terrestrial Reference Frame: report of the task force of the IAG sub-commission 1.2 , International Association of Geodesy Symposia 139, pp. 197-202, doi:10.1007/978-3-642-37222-3_25

Thank you