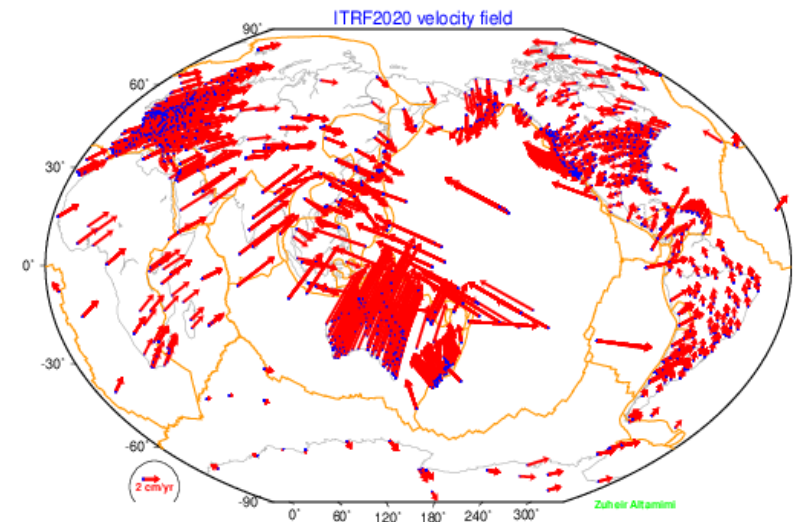
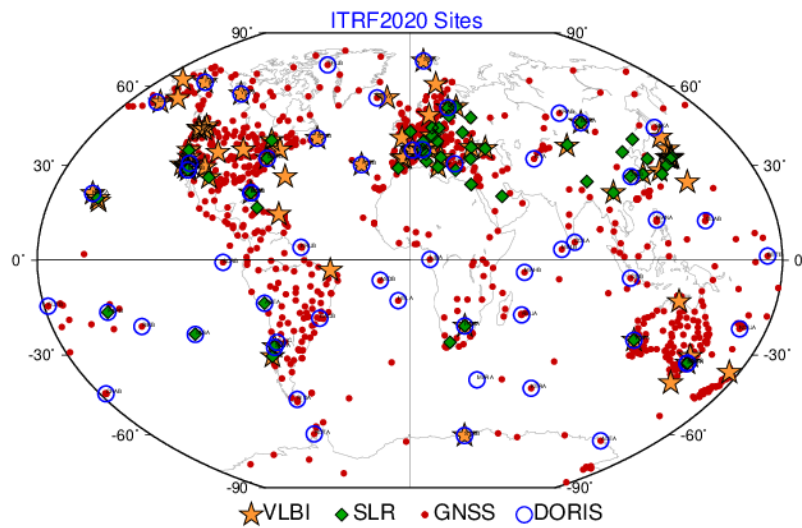


The International Terrestrial Reference Frame Past, Present and Future

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Paul Rebischung
Xavier Collilieux
IGN-IPGP, France



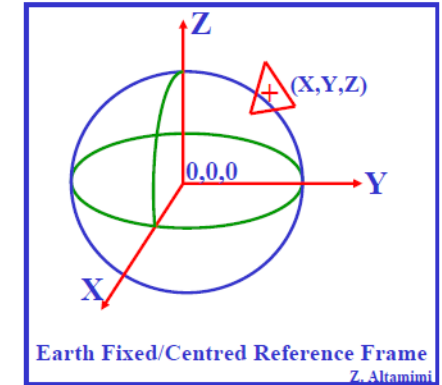
Outline

- Introduction : Recall of some concepts
- Reference frame representations and:
 - The reality of a deformable Earth
 - Technique systematic errors
 - User needs
- The ITRF: Its genesis: Past, Present and Future: continuous development & improvement
- ITRF2020 and its updates : modeling of nonlinear station motions : seasonal signals & post-seismic deformation
 - Analysis strategy & weighting of the input data
 - Some results of ITRF2020 updates
- Sustainability of the geodetic infrastructure (?)

Defining a Reference System, Reference Frame & Coordinate System:

Three main conceptual levels :

- Terrestrial Reference System (TRS):
Theoretical system: Trihedron co-rotating with the Earth, with an origin, scale & orientation
- Terrestrial Reference Frame (TRF):
Numerical realization of the TRS to which users have access
- Coordinate System: cartesian (X,Y,Z) , geographic (λ, ϕ, h) , ...

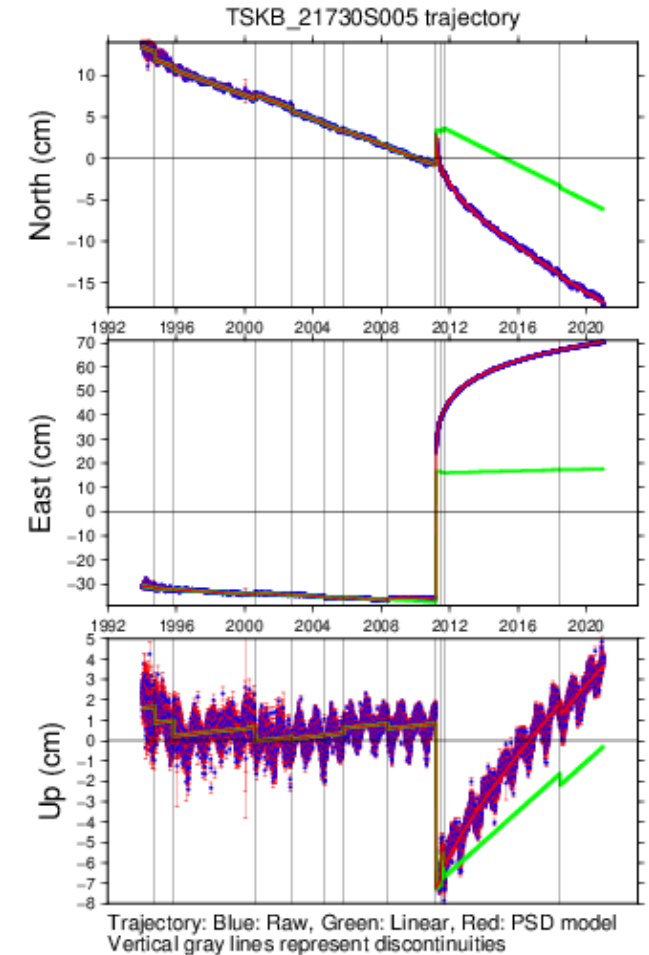


Notes:

- As the TRS, the TRF has an **origin, scale & orientation**
- TRF is constructed using space geodesy observations

“Motions” of the deformable Earth & technique systematic errors

- **Nearly linear motions:**
 - Tectonic motion
 - Post-Glacial Rebound
 - **Nonlinear displacements:**
 - Loading deformation, due to atmospheric pressure, hydrology and ocean circulation
 - Co- & Post-seismic deformations,
 - Transient deformations, Volcano Eruptions, local events...
-
- **Technique systematic errors:**
 - DORIS: mis-modelling of the solar radiation pressure ==> inaccurate determination of the geocenter components
 - GNSS geocenter affected by large draconitic errors. GNSS scale (based on satellite antenna calibrations) biased with respect to SLR/VLBI.
 - SLR range biases have significant impact on the TRF scale
 - VLBI antenna gravitational deformation ==> impact on the TRF scale



Reference Frame Representations

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

$$X(t) = X(t_0) + \dot{X}(t - t_0) \quad \begin{array}{l} \leq \text{Regularized Position} \\ \text{With piece-wise linear function} \end{array}$$

- The indispensable basis for science and operational geodesy applications

- **Nonlinear Reference Frames**:

- **Augmented Parametric RF**: Long-Term Frame + nonlinear parametric functions ($\Rightarrow$ ITRF2020):

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

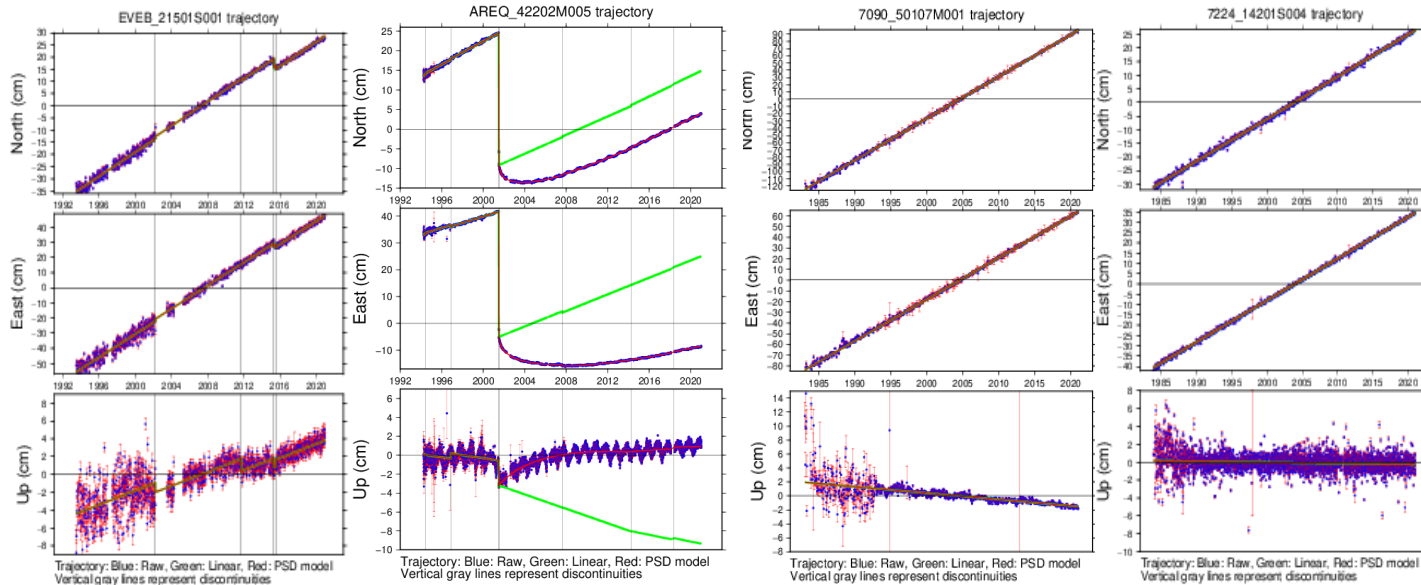
- **Non-parametric RF**: Time series of "Quasi-Instantaneous" reference frames
 - Daily or weekly representations
 - Nonlinear motion embedded in their time series
 - Still rely on the ITRF for at least the orientation definition

The International Terrestrial Reference Frame (ITRF):

- Realized and maintained by the **ITRF Center** hosted by IGN
- By combination of DORIS, GNSS, SLR and VLBI station position time series

Input

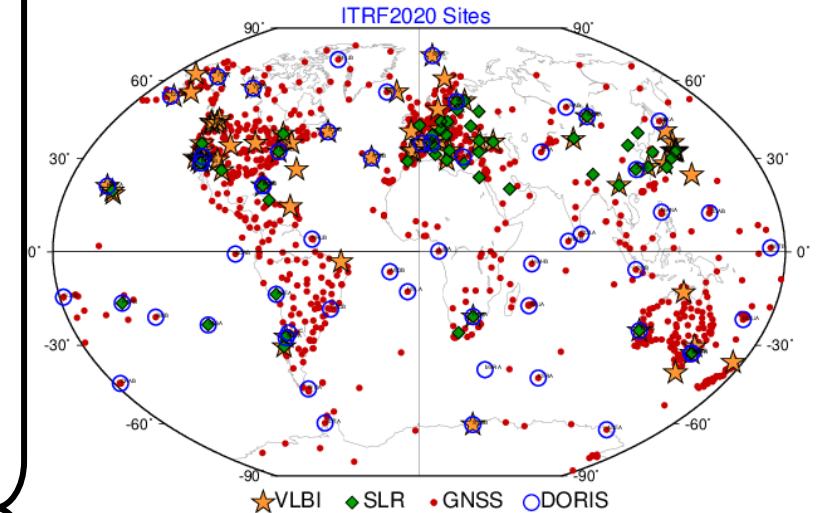
DORIS Weekly
GNSS Daily
SLR Weekly
VLBI Session-wise



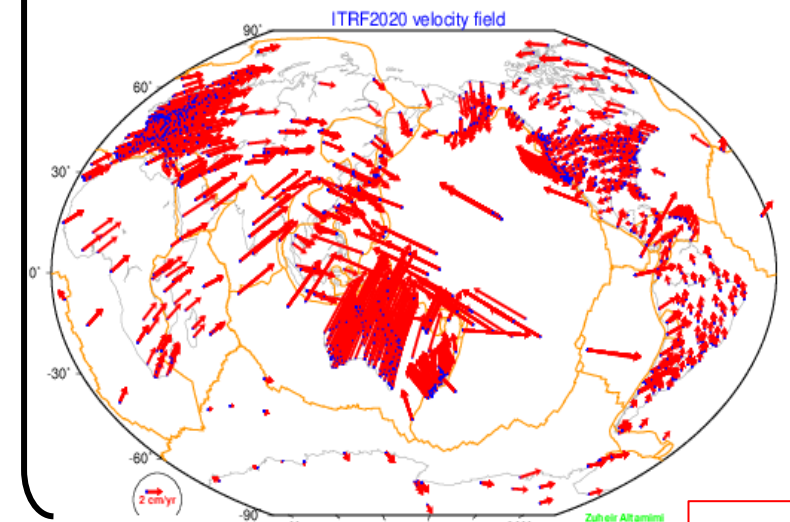
**Fundamentally based on
Co-location Sites**

Time series analysis & stacking

Output



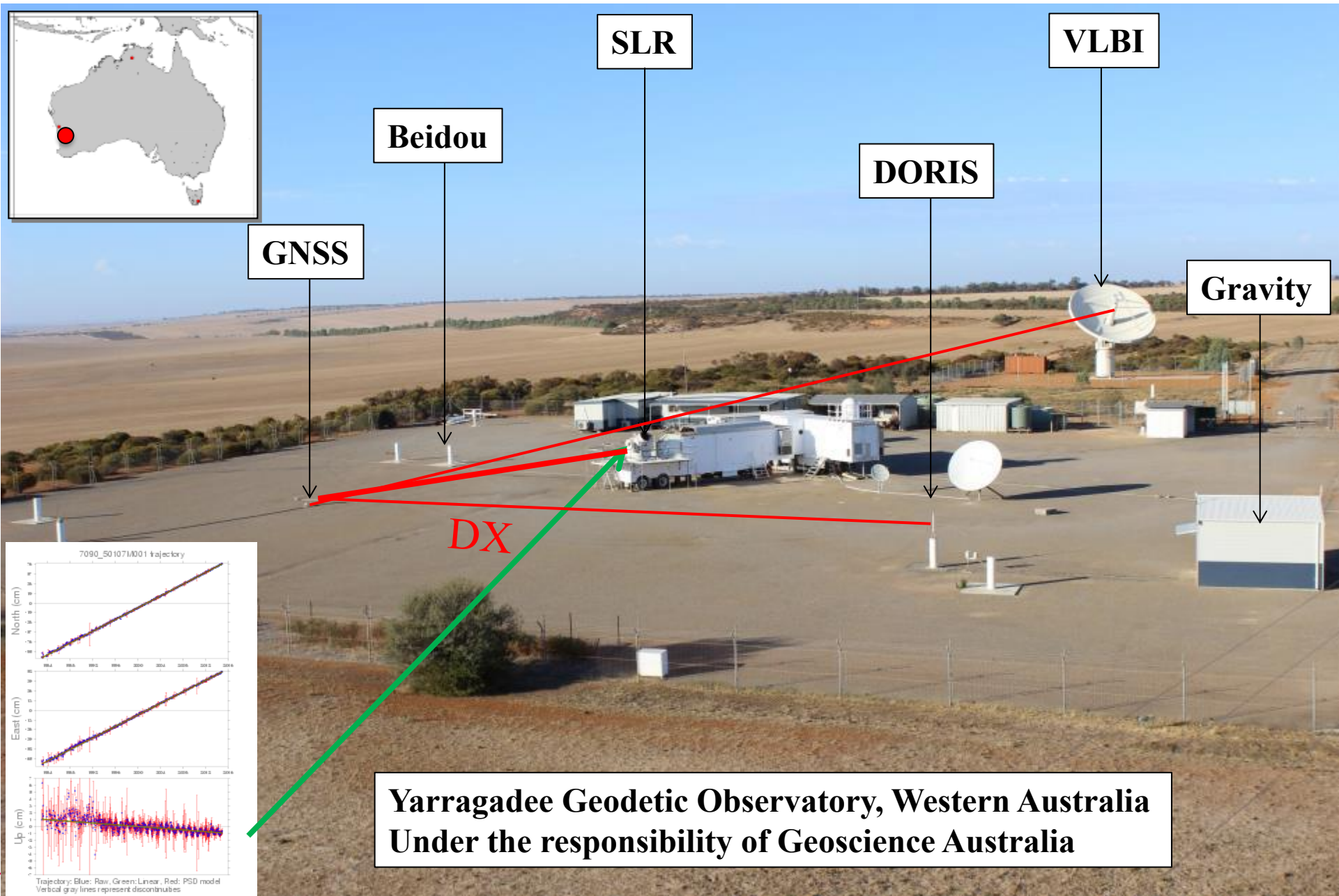
Station coordinates



Station velocities

+++ ...

Colocation site



ITRF Combination model: basic equations

Station positions, velocities, transformation parameters & periodic terms

$$\left\{ \begin{aligned} \begin{pmatrix} x_s^i \\ y_s^i \\ z_s^i \end{pmatrix} &= \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} + (t_s^i - t_0) \begin{pmatrix} \dot{x}^i \\ \dot{y}^i \\ \dot{z}^i \end{pmatrix} + T_k + D_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} + R_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} \\ &+ (t_s^i - t_k) \left[\dot{T}_k + \dot{D}_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} + \dot{R}_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} \right] \\ &+ \sum_{j=1}^{n_f} \left[\begin{pmatrix} a_x^i \\ a_y^i \\ a_z^i \end{pmatrix} \cos[\omega_j(t_s^i - t_0)] + \begin{pmatrix} b_x^i \\ b_y^i \\ b_z^i \end{pmatrix} \sin[\omega_j(t_s^i - t_0)] \right] \\ \begin{pmatrix} \dot{x}_s^i \\ \dot{y}_s^i \\ \dot{z}_s^i \end{pmatrix} &= \begin{pmatrix} \dot{x}^i \\ \dot{y}^i \\ \dot{z}^i \end{pmatrix} + \dot{T}_k + \dot{D}_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} + \dot{R}_k \begin{pmatrix} x^i \\ y^i \\ z^i \end{pmatrix} \end{aligned} \right.$$

Earth Orientation Parameters

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

PSD: applied as a correction model before stacking

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

Why is the ITRF needed?

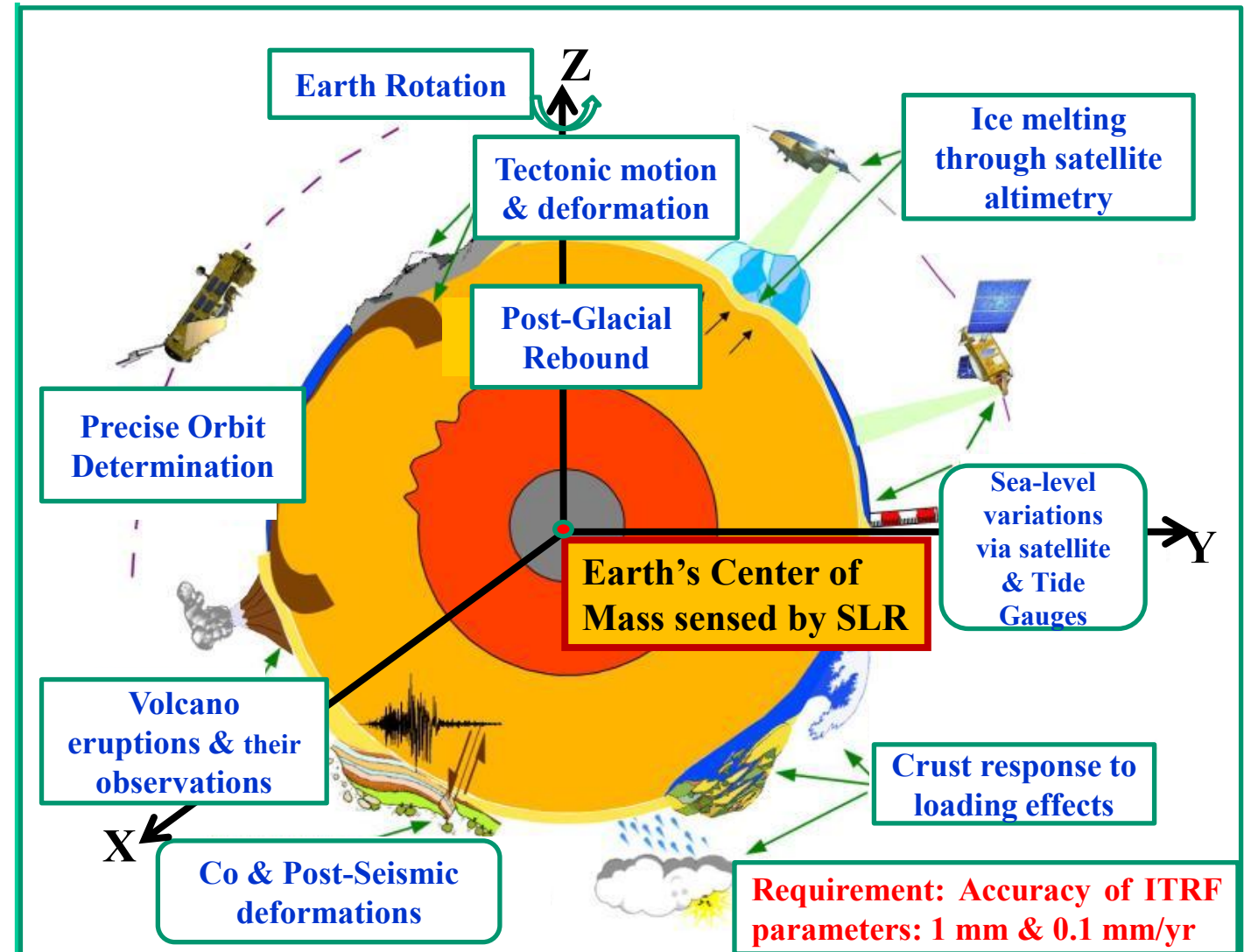
Operational geodesy applications:

- Positioning : Real Time or a posteriori
- Navigation: Aviation, Terrestrial, Maritime
- National geodetic systems/frames
- **Today: via GNSS only!**
- **Require the availability of the orbits and the reference frame (ITRF)**
- **Many, many users...**

GNSS-specific reference frames:

- GTRF/Galileo, WGS84/GPS, PZ-90/GLONASS, CGCS2000/Beidou, JGS/QZSS
- All are aligned to the ITRF

Scientific Applications:



Continuous observations are fundamental

The ITRF adventure

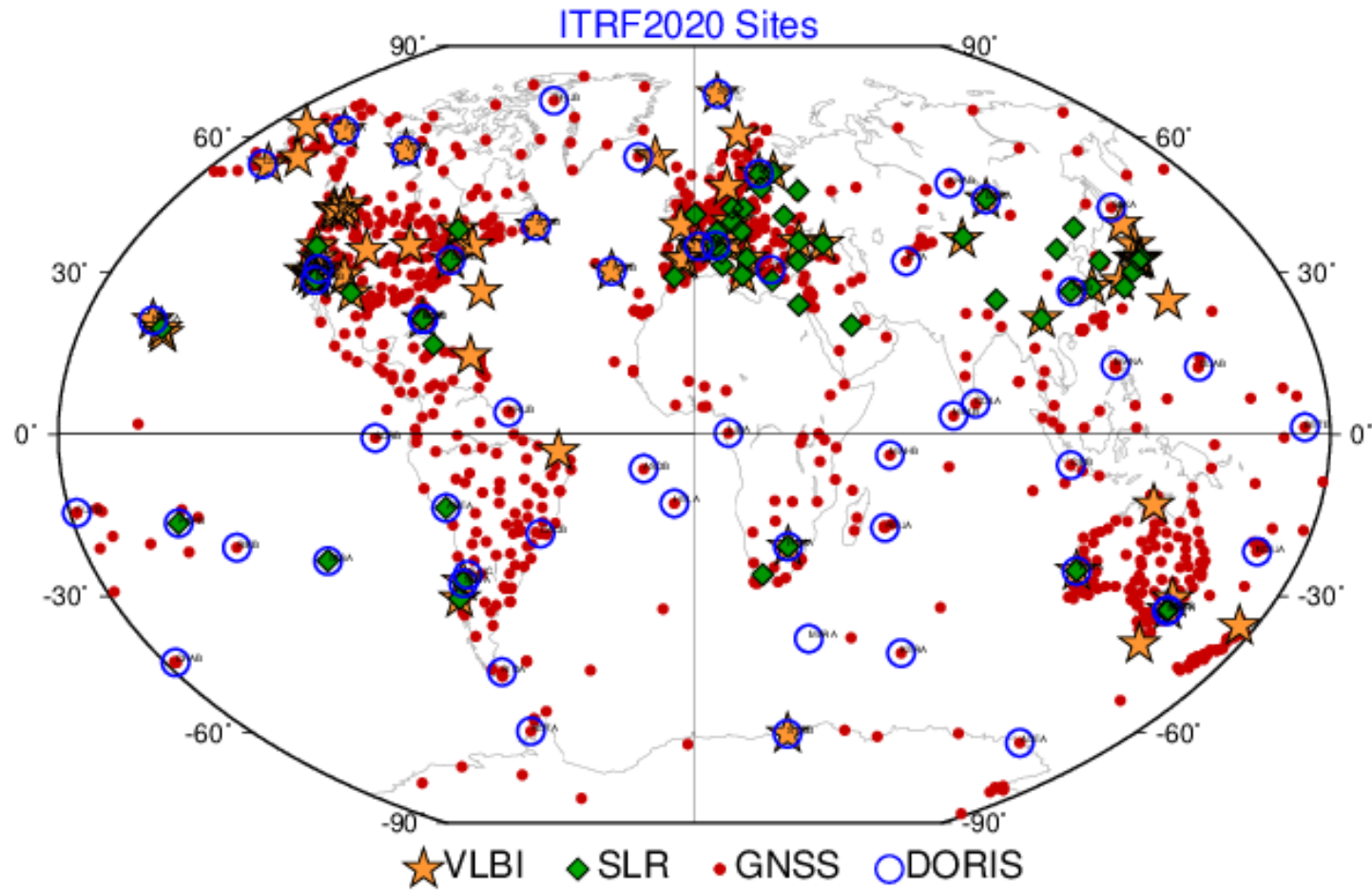
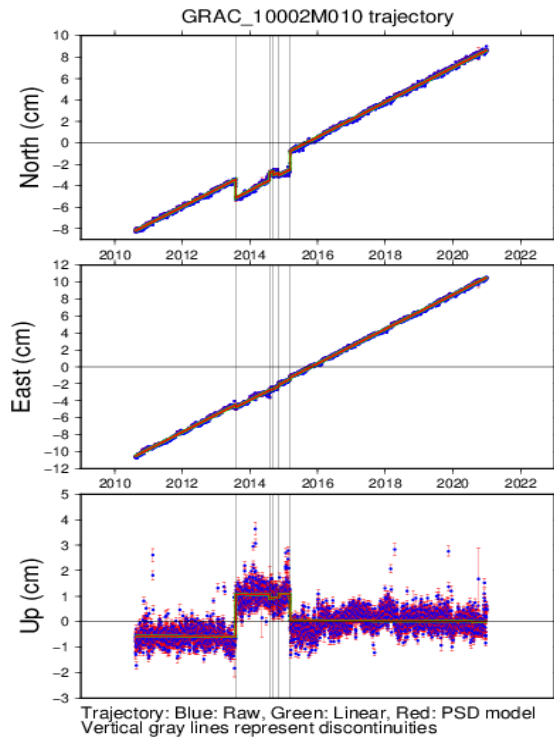
- **1985: BTS84:** 1st combined TRF from space geodesy: (Boucher & Altamimi, 1985), followed by BTS85, BTS86 & BTS87
- **1988:** Creation of the IERS ==> ITRF88
- 1992: ITRF91 velocity field estimated from space geodesy data (VLBI & SLR)
- 1992: GPS in the ITRF (ITRF91): 21 sites
- 1994: Birth of IGS & SINEX format
- 1995: DORIS in the ITRF (ITRF94): 52 Sites
- 1998, 1999, 2003: creation of ILRS, IVS and IDS
- **2000:** Reorganization of the IERS ==> ITRS Center, including ITRS CCs (DGFI, followed lately by JPL)
- 1980 – now: 3 generations of combination software packages
- 1995: start of CATREF software
- 13 ITRF versions: ITRF88 up to ITRF2014
- 2016: ITRF2014 published: modelling nonlinear variations
- **2022: ITRF2020 published**
- **2024 – 2025 : ITRF2020 updates (u2023, u2024) published**

Resolutions on ITRS & ITRF

- **IUGG2007**: adopted the **ITRS** as the preferred Geocentric Terrestrial Reference System (GTRS) for scientific and technical applications
- **CGPM2011**: recommends that the **ITRS**, as defined by the IUGG and realized by IERS, be adopted as the unique international reference system for terrestrial reference frames for all metrological applications
- **ICG2012**: recommendation to align GNSS-specific reference frames (WGS84, PZ90, GTRF, CGCS2000, JGS) to the ITRF
- **IUGG2019**: recommend to the user community that the **ITRF** be the standard for positioning, satellite navigation and Earth Science applications, ...
- **UN-GGIM-2019**: adoption of the **ITRS** and the **ITRF** as the standard for scientific, geospatial and operational geodetic applications
- **ISO Standard on ITRS/ITRF**

ITRF2020 Network

- 1223 sites
 - 878 Northern hemisphere
 - 355 Southern hemisphere
- 1800 stations
- **3106 discontinuities**
- ~1159 GNSS sites
 - 1344 stations
 - **2938 discontinuities**



DORIS



GNSS



SLR



VLBI



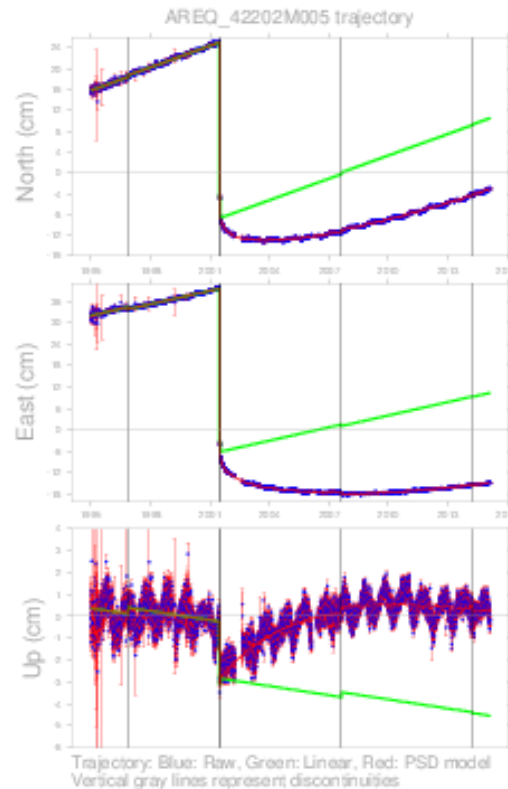
Analysis Strategy of ITRF2020 & its updates

Input data: **Time series:**

- DORIS/IDS weekly
- GNSS/IGS daily
- SLR/ILRS weekly
- VLBI/IVS: Session-wise
- Local ties

Additional constraints **at colocation sites:** Equality constraints for

- Station velocities
- Station seasonal signals



Time series analysis & stacking of the 4 technique time series **all together +**
Modeling of nonlinear station motions:

- Periodic signals
- Post-Seismic Deformation

ITRF2020 Specifications:

Origin: SLR

Scale: SLR & VLBI

Orientation: Alignment to ITRF2014

ITRF2020 updates: Alignment to ITRF2020

ITRF2020

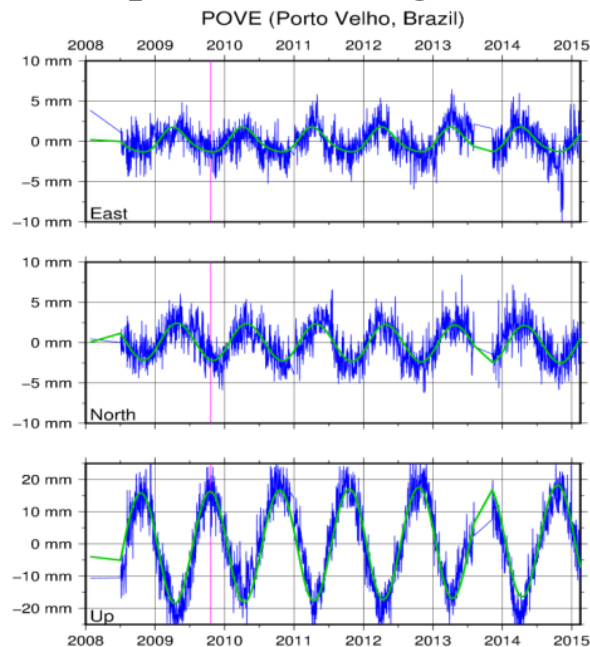
$X, \dot{X}, \delta X_{PSD}$, Seasonal Signals and EOPs

Weighting of input solutions in the ITRF2020 combination

- CATREF stacking model assumes (variable) white noise.
- But geodetic (especially GNSS) station position time series also contain **colored noise**.
- To avoid an overdominance of GNSS and an overly optimistic output covariance matrix, technique-specific corrective variance factors were applied in the ITRF2020 combinations:
 - Trajectory models were adjusted to individual station position time series with:
 - a) white noise only
 - b) white + power-law noise
 - Ratios were computed between the formal variances of station velocities obtained in both cases.
 - Technique-specific corrective variance factor = Median ratio over all stations of the technique
 - These factors multiply the white-noise-based variance factors from the individual technique stackings.
- Local tie uncertainties are re-evaluated with a lower bound uncertainty of 2mm in any of the three components (East, North and Vertical)

ITRF2020 Innovation: Precisely Modeling nonlinear station motions

Impact of loading effects

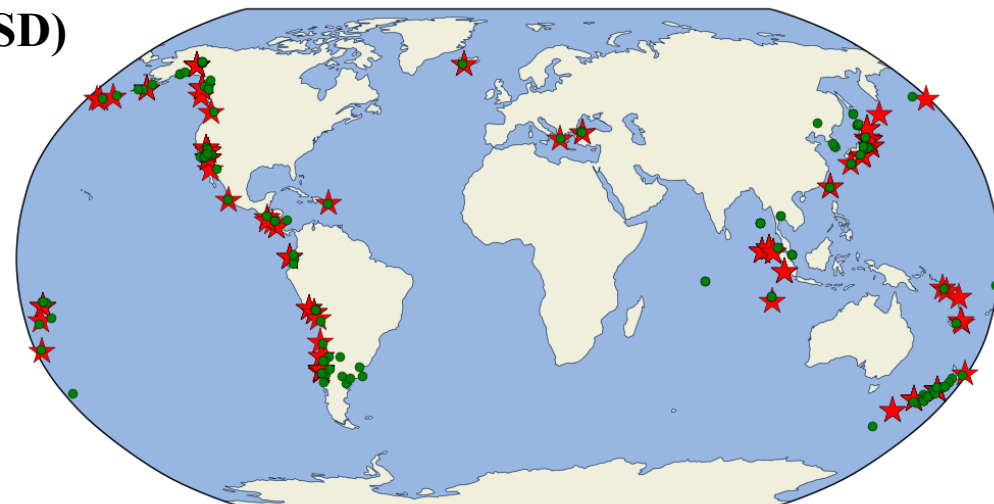
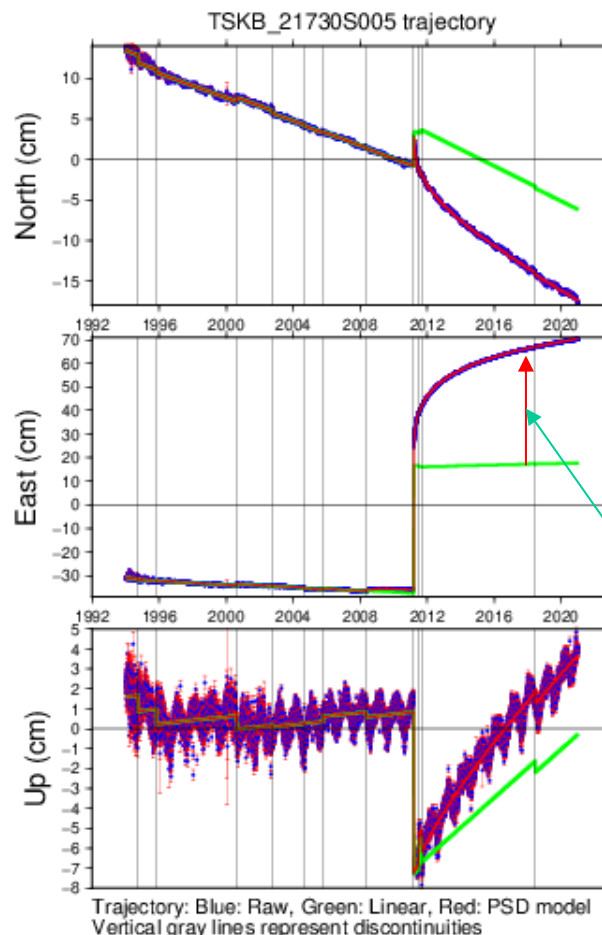


Sine wave function

$$\Delta X_f(t) = \sum_{j=1}^{n_f} a_j^i \cos(\omega_j t) + b_j^i \sin(\omega_j t)$$

Post-Seismic Deformation (PSD)

Impact of major earthquakes



Red Stars: EQ Epicenters (65)

Green circles: ITRF2020 sites (118)

Refined PSD Parametric models:

1. Logarithmic Function
2. Exponential Function
3. Logarithmic + Exponential
4. Two Exponential Functions
5. Two Logarithmic Functions

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

Motivations for regular (yearly) updates of ITRF2020

- The stability of the ITRF long-term origin, evaluated to be at the level of or better than 5 mm and 0.5 mm/yr for its time evolution,
- The agreement in scale between VLBI and SLR, at the level of 1-2 mm, with no drift,
- The growth of extrapolation errors of the ITRF2020 coordinates beyond the end of the ITRF2020 input data,
- Changes in the positions of certain ITRF2020 stations (due to, e.g., earthquakes and equipment changes) that occurred after the end of the ITRF2020 input data.

Specifications of ITRF2020 updates

- Include 3 years (2021.0 – 2024.0) for the first update, and 4 years (2021.0 – 2025.0) for the second update
- Same analysis strategy as for ITRF2020: Accumulate the full 4 technique time series all together, adding local ties and co-motion constraints
- Align each ITRF2020 update to ITRF2020 for both the long-term frame and seasonal signal (CM Frame) defining parameters (origin, scale, and orientation)
- Adding new post 2021.0 discontinuities when necessary
- Updating PSD parametric models
- IAG TCs used the same models and strategy as for their contributions to the ITRF2020
- ITRF2020 updates are delivered using the same types of files as ITRF2020

Alignment of ITRF2020 updates to ITRF2020: 42 degrees of freedom

- 14 parameters for the TRF definition (origin, scale, orientation):

$$(A^T A)^{-1} A (X_{ITRF2020} - X_{update}) = 0$$

$$(A^T A)^{-1} A (\dot{X}_{ITRF2020} - \dot{X}_{update}) = 0$$

- 28 parameters for the annual and semi-annual signals:

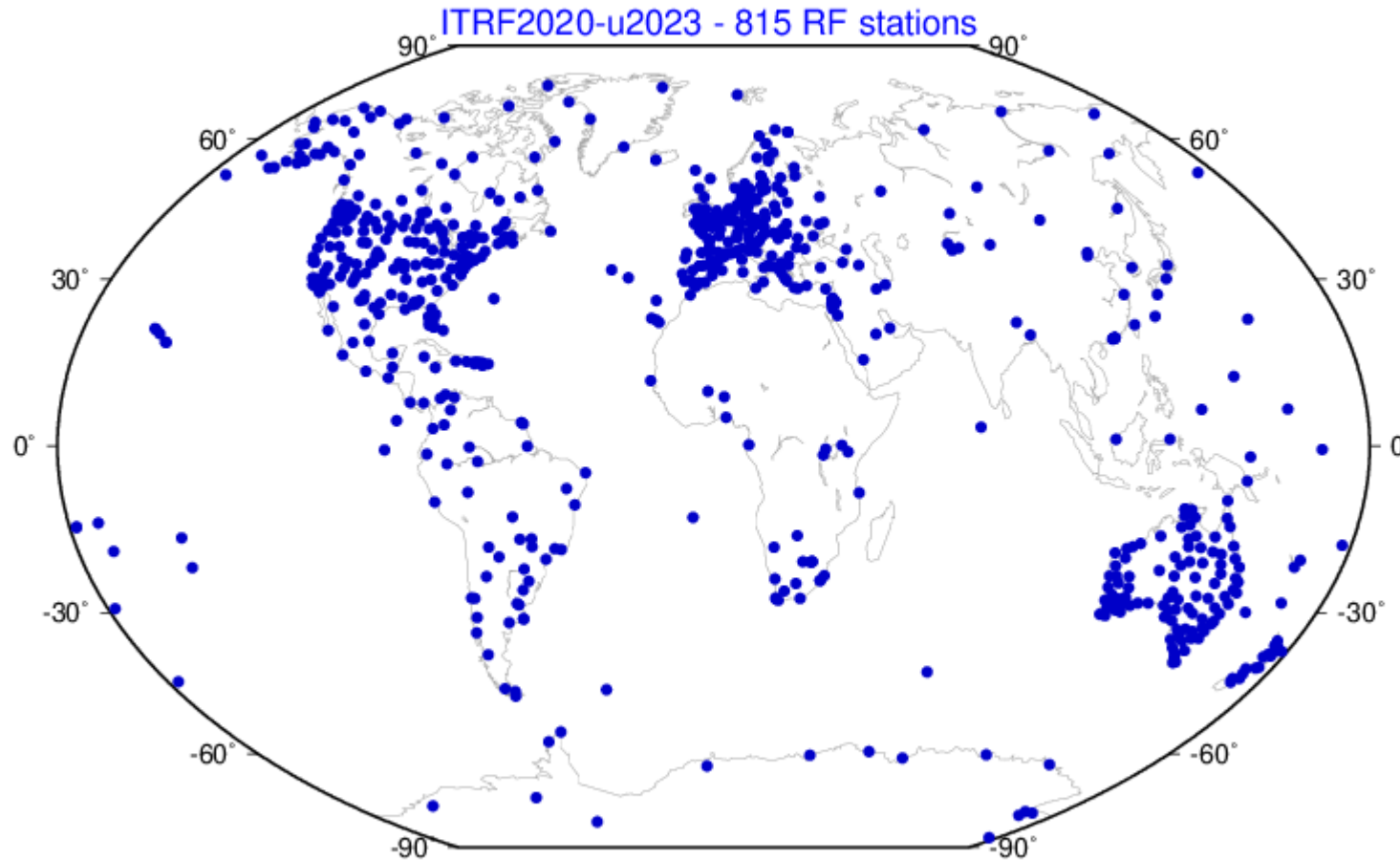
$$(A^T A)^{-1} A \begin{pmatrix} a_{x_ITRF2020_CM}^i - a_{x_update}^i \\ a_{y_ITRF2020_CM}^i - a_{y_update}^i \\ a_{z_ITRF2020_CM}^i - a_{z_update}^i \end{pmatrix} = 0$$

$$(A^T A)^{-1} A \begin{pmatrix} b_{x_ITRF2020_CM}^i - b_{x_update}^i \\ b_{y_ITRF2020_CM}^i - b_{y_update}^i \\ b_{z_ITRF2020_CM}^i - b_{z_update}^i \end{pmatrix} = 0$$

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

In short : No net translation, no net scale and no net rotation between ITRF2020 and its updates

815 RF stations used in the alignment of ITRF2020-u2023 to ITRF2020



~838 RF stations used in the alignment of ITRF2020-u2024 to ITRF2020

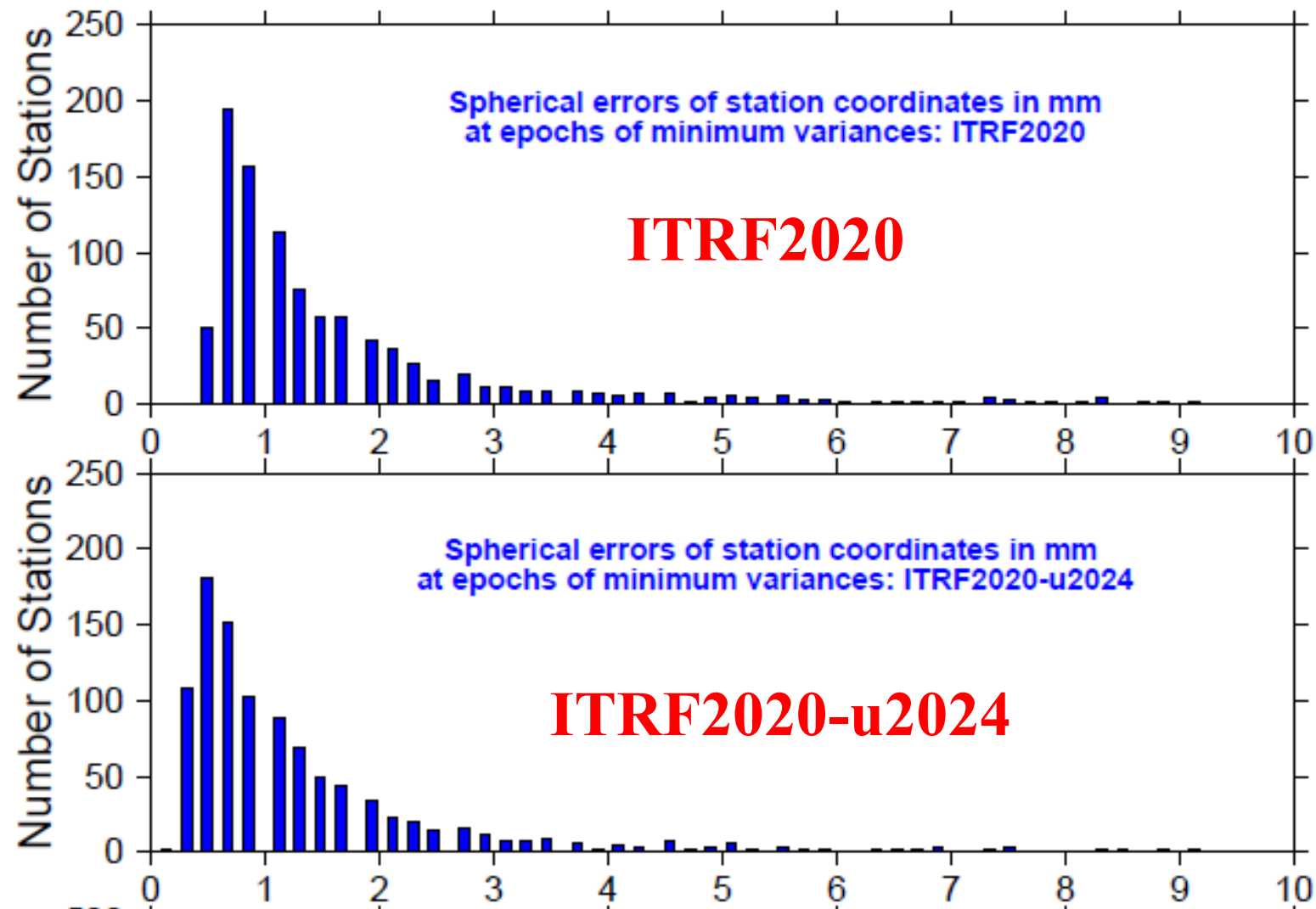
WRMS of the alignment

ITRF2020-u2023

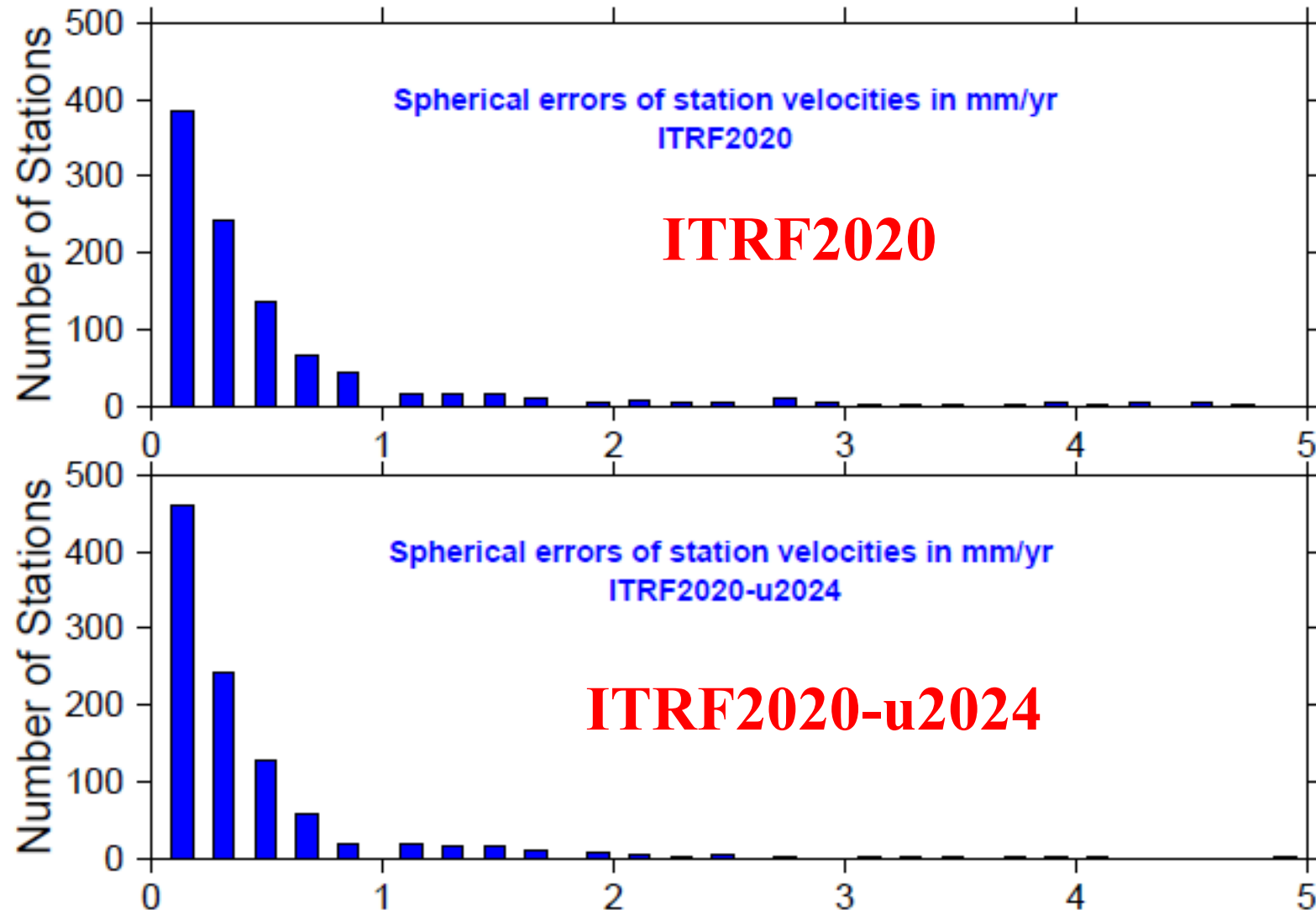
	East	North	Up
positions @ 2015.0	0.11 mm	0.10 mm	0.28 mm
velocities	0.02 mm/yr	0.02 mm/yr	0.05 mm/yr
annual signals	0.05 mm	0.05 mm	0.15 mm
semi-annual signals	0.03 mm	0.02 mm	0.06 mm

Similar numbers for ITRF2020-u2024

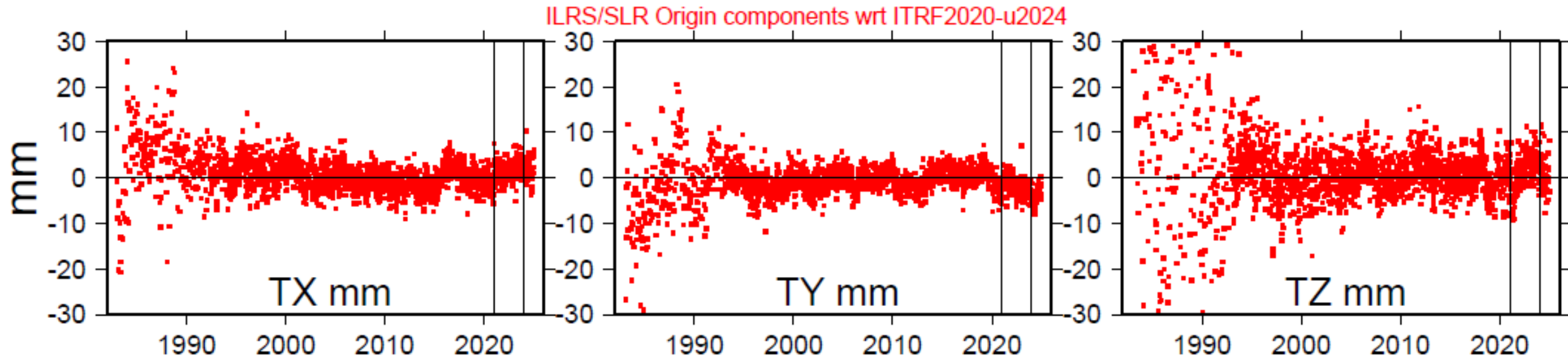
Precision gain in station coordinates



Precision gain in station velocities



ILRS/SLR Origin components wrt ITRF2020-u2024



Offset (mm) at 2015.0	0.23	-0.78	0.87
Drift (mm/yr)	-0.03	-0.01	-0.01

- Origin alignment uncertainty at the level of 1 mm at 2015.0 and better than 0.1 mm/yr

Scale uncertainties (in ppb): **ITRF2020**



Scale uncertainties (in ppb): ITRF2020 - u2024

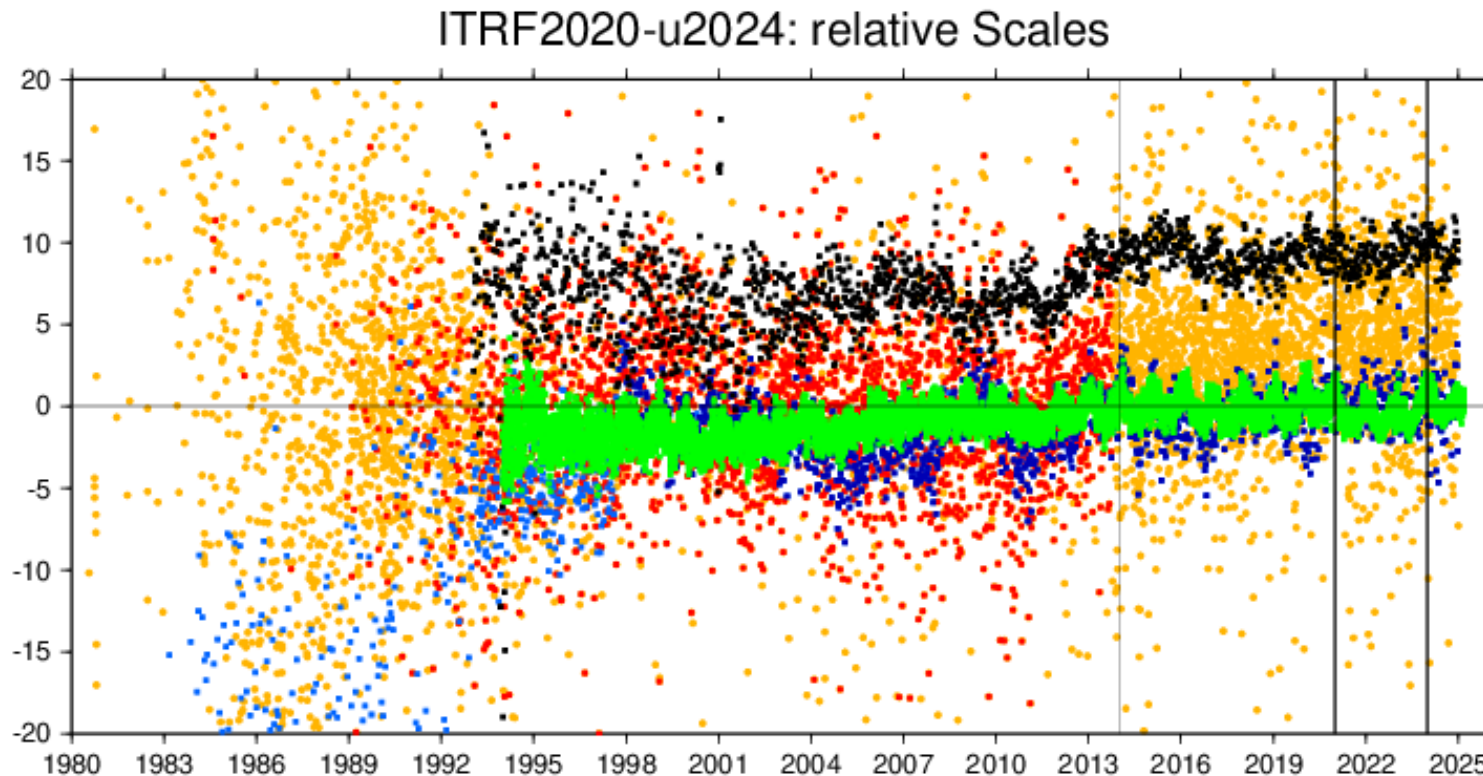


VLBI scale change: ~ -0.10 ppb

SLR scale change : ~ -0.06 ppb

Rough ITRF2020-u2024 scale alignment uncertainty: ~ 0.1 ppb (~ 0.6 mm)

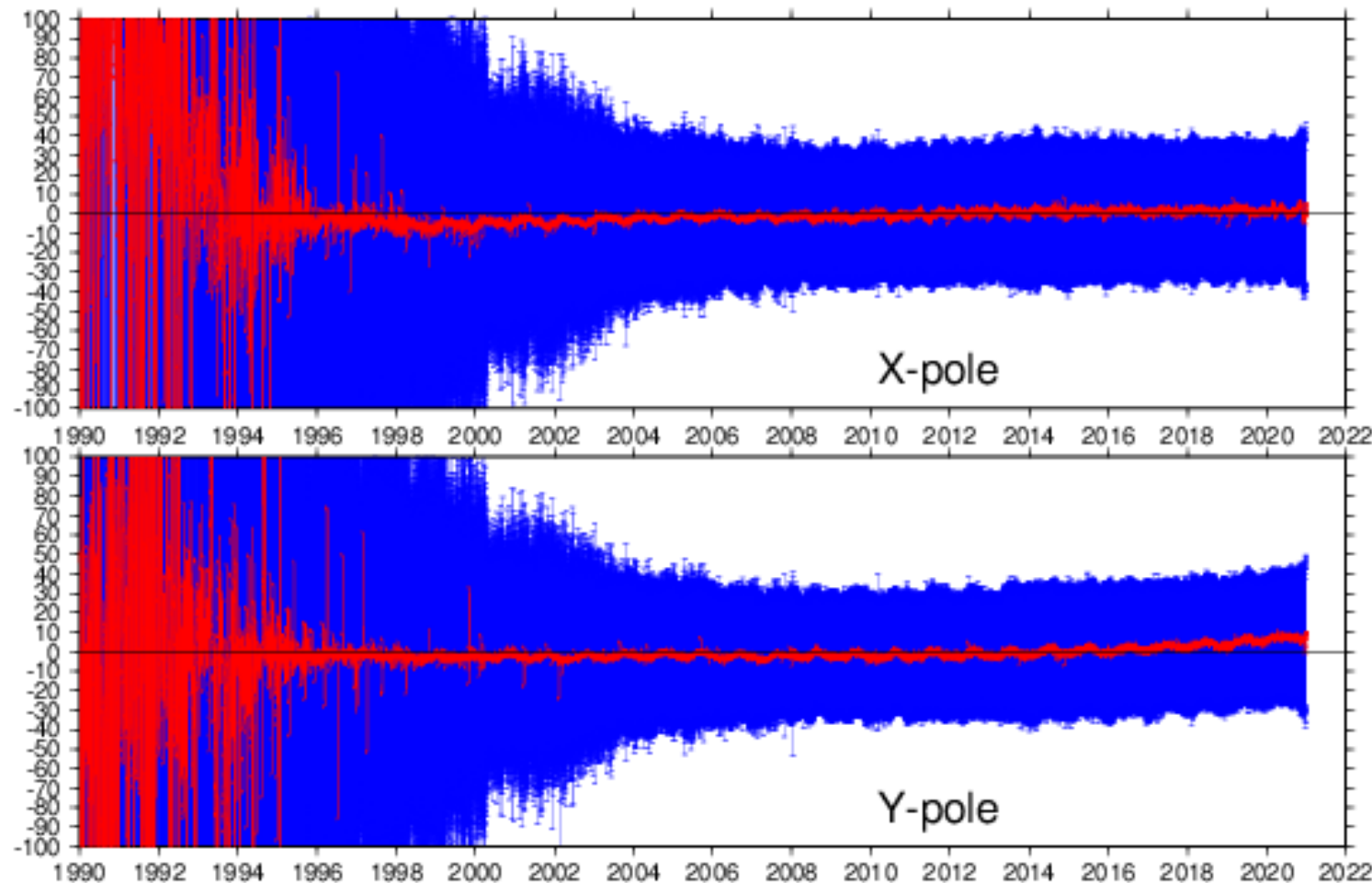
Relative scales Scale : ITRF2020-u2024



- **Orange:** all VLBI Sessions
- **Red:** Selected VLBI Sessions (Solid Volume $\geq 10^{19} \text{ m}^3$)
- **Light blue:** all SLR time series
- **Dark blue:** Selected SLR time series
- **Green:** IGS/Repro3/Operational (compatible with igs20.atx)
- **Black:** DORIS

Ny-Alesund VLBI Velocity changes were introduced at epochs 2004:186 and 2016:233 as for the co-located GNSS stations NYAL and NYA1
==> substantial attenuation of the VLBI scale drift after around 2014.0

Polar motion diffs ITRF2020 - ITRF2020-u2024 (in μas)



Uncertainty of Polar Motion alignment to ITRF2020 $\sim 1 \mu\text{as}$ and $0.5 \mu\text{as/yr}$

Risk of degradation and gaps : current SLR & VLBI networks

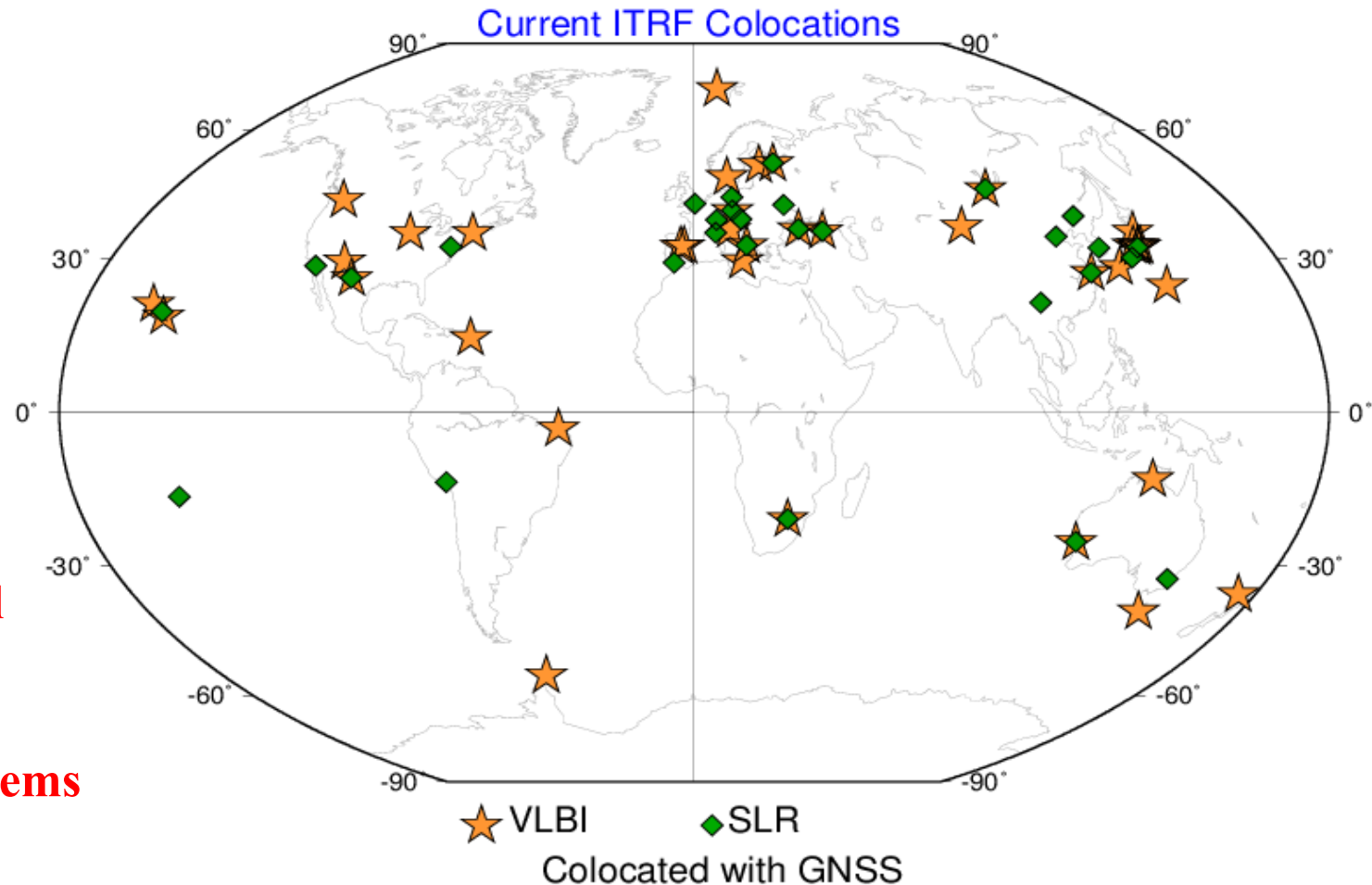
SLR 30 sites



VLBI 34



- **SLR & VLBI are fundamental to the ITRF**
- **Poor geometry**
- **> 50 % are old generation systems**
- **BUT some significant progress with VGOS network**





ITRF: Some considerations for the future

- Long-term solutions (station positions & velocities) will always be needed for a number of applications, e.g. POD, operational geodesy, including national & regional reference frames
- Continue updating ITRF2020 until significant change in origin or scale occurs
- Improve the stochastic model, weighting of techniques and local ties
- Continue exploring aperiodic displacements at co-location sites, despite the noise level, limited observation density, etc., esp. for SLR & VLBI
- Consider ITRF non-parametric solutions at the daily/weekly basis, for research and scientific purposes
- Advocate the importance of sustaining & improving the global geodetic infrastructure.

Conclusion

- More than 3 decades of R&D to improve the ITRF
 - The most precise/accurate reference frame available today
 - Recommended by a number of scientific organizations for Earth science & societal applications
 - Accessible everywhere & anywhere thanks to IGS products
-
- ITRF2020 and its updates: a step further in improving the ITRF:
 - PSD parametric models for stations impacted by major earthquakes
 - Seasonal signals in both CM and CF frames, and seasonal geocenter motion
 - For the first time, the scale difference between SLR & VLBI at the level of 0.15 ppb (~1 mm)
 - ITRF2020 and its updates share the same parameters (origin, scale, orientation)
 - The Global Geodetic infrastructure needs improvement & sustainability