The International Terrestrial Reference Frame: current status and future challenges

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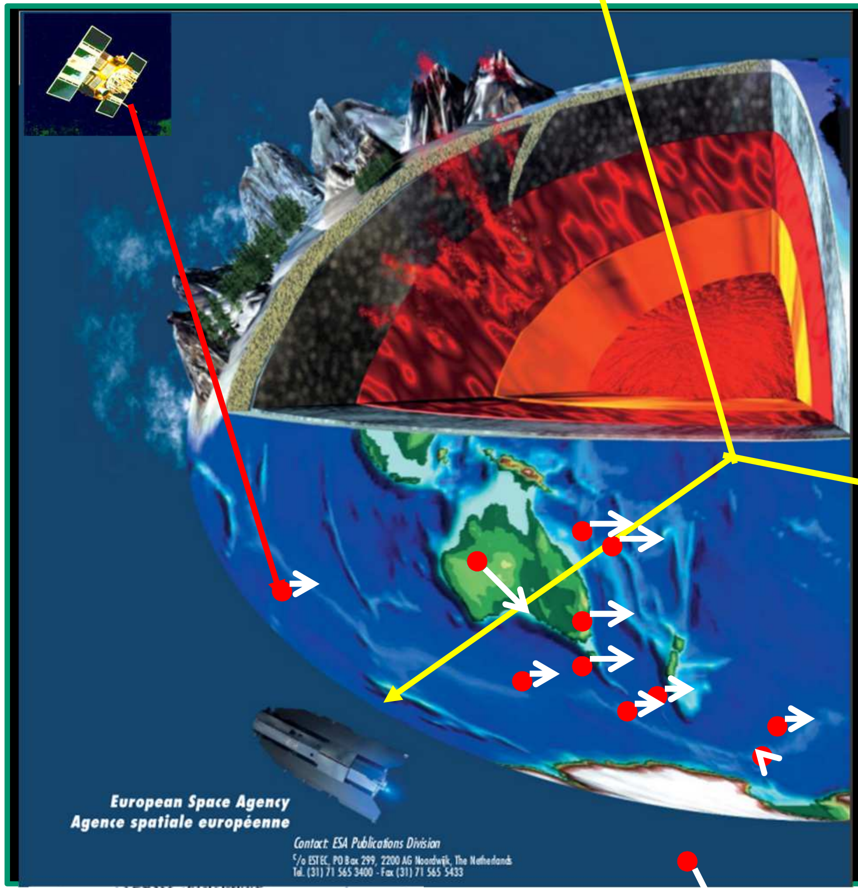
Outline

- **Introduction:**
  - **Brief description of space geodesy techniques**
  - **ITRF construction**
- **ITRF and science applications**
  - **Sea Level**
  - **Glacial Isostatic Adjustment (GIA)**
  - **Plate Motion**
- **Limiting factors and challenges for the future**
  - **Network configuration**
  - **Technique systematic errors**
  - **Site velocity and tie discrepancies at co-location sites**
  - **Discontinuities in station position time series**
  - **Site non-linear motions**
- **Conclusion**

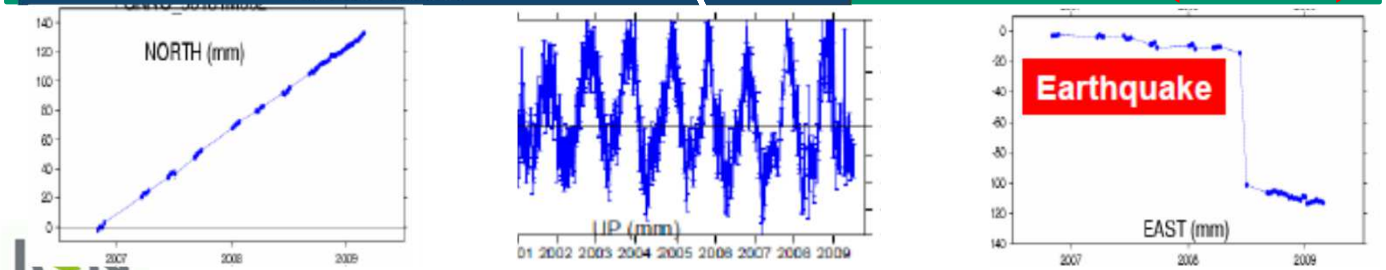
The ITRF: Combination of 4 techniques :



International Terrestrial Reference System (ITRS)

Origin,
Scale,
Orientation

International Terrestrial Reference Frame (ITRF)

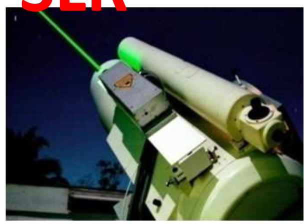


GNSS

DORIS

VLBI

SLR



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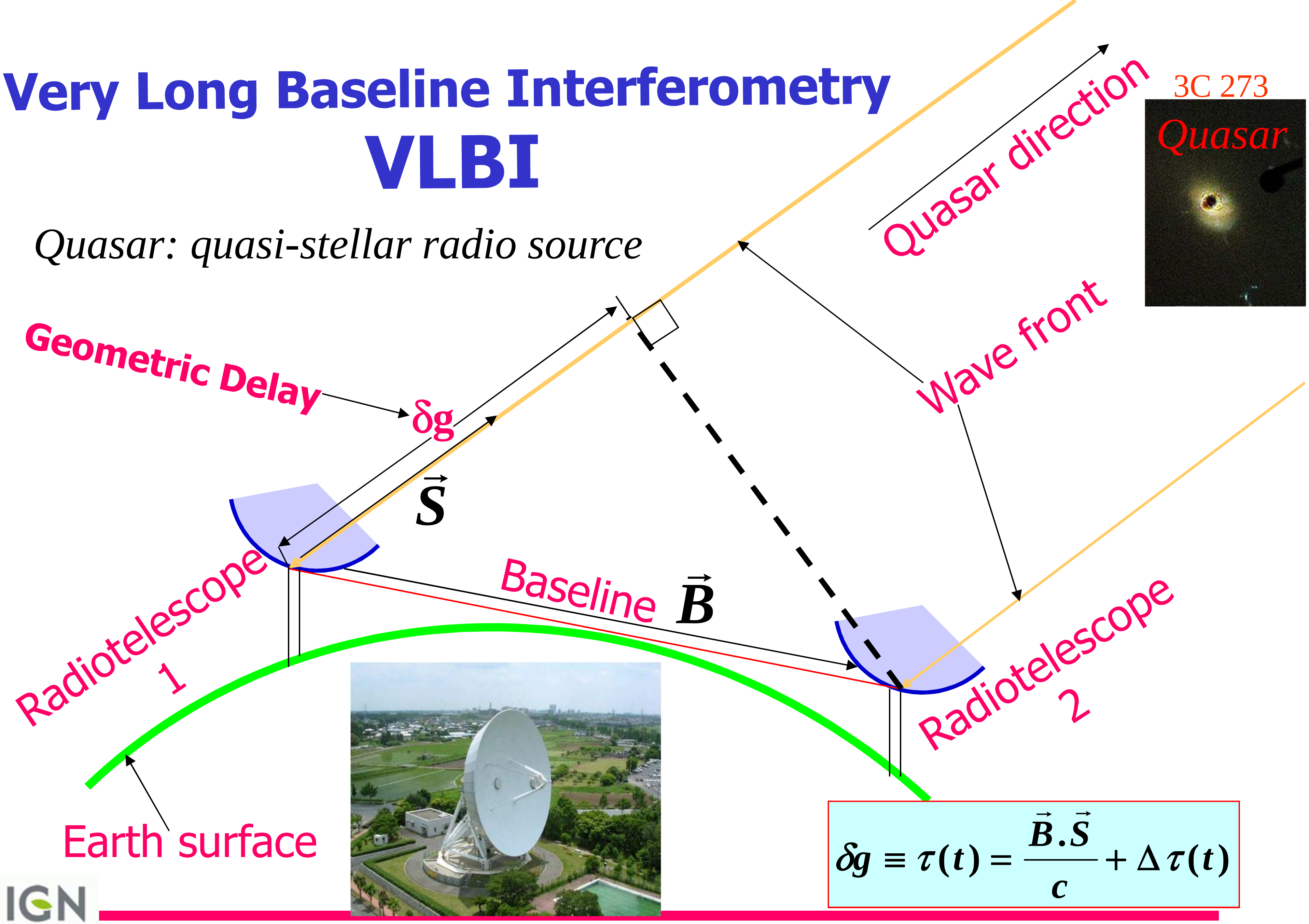
Very Long Baseline Interferometry
VLBI

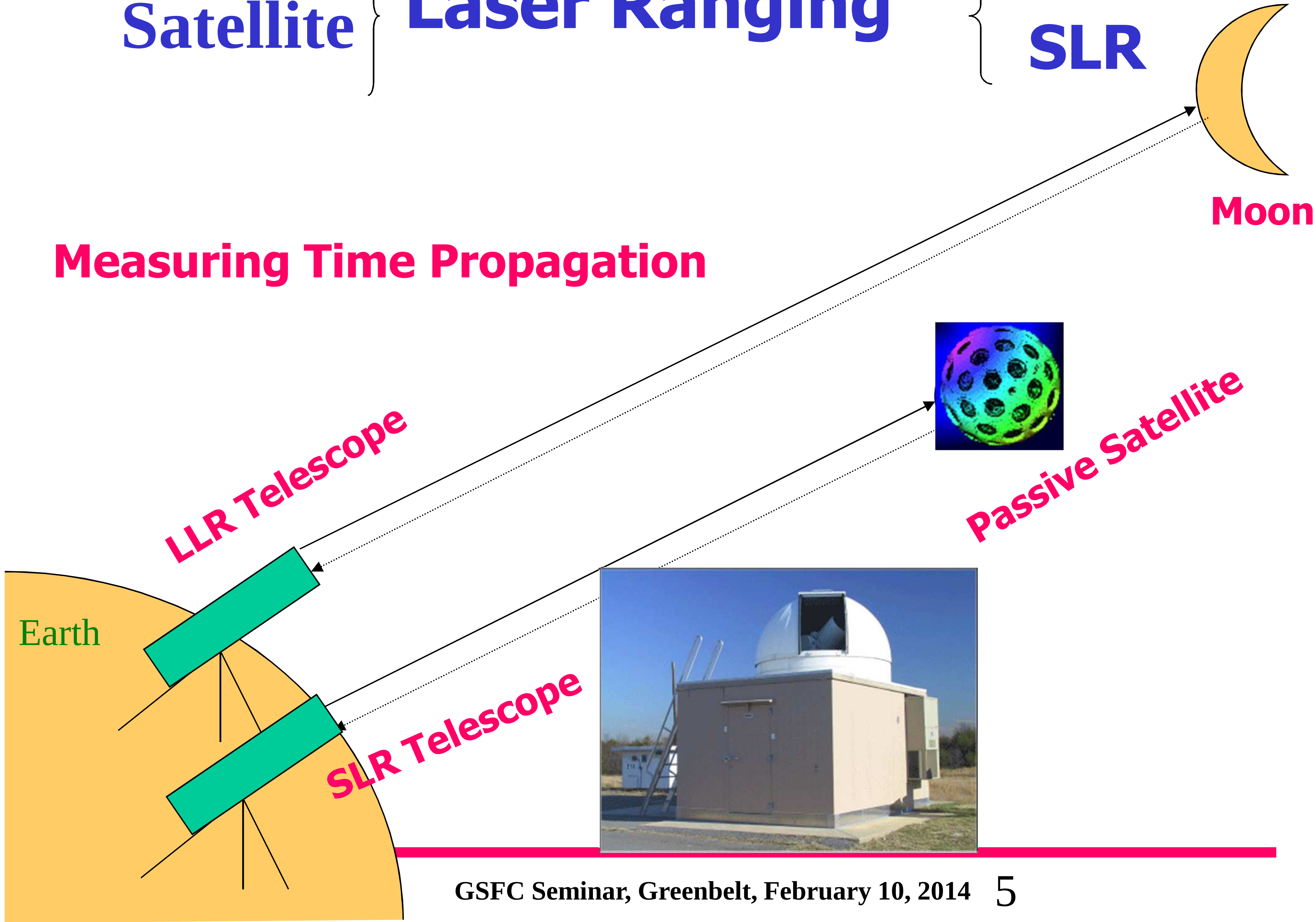
Quasar: quasi-stellar radio source

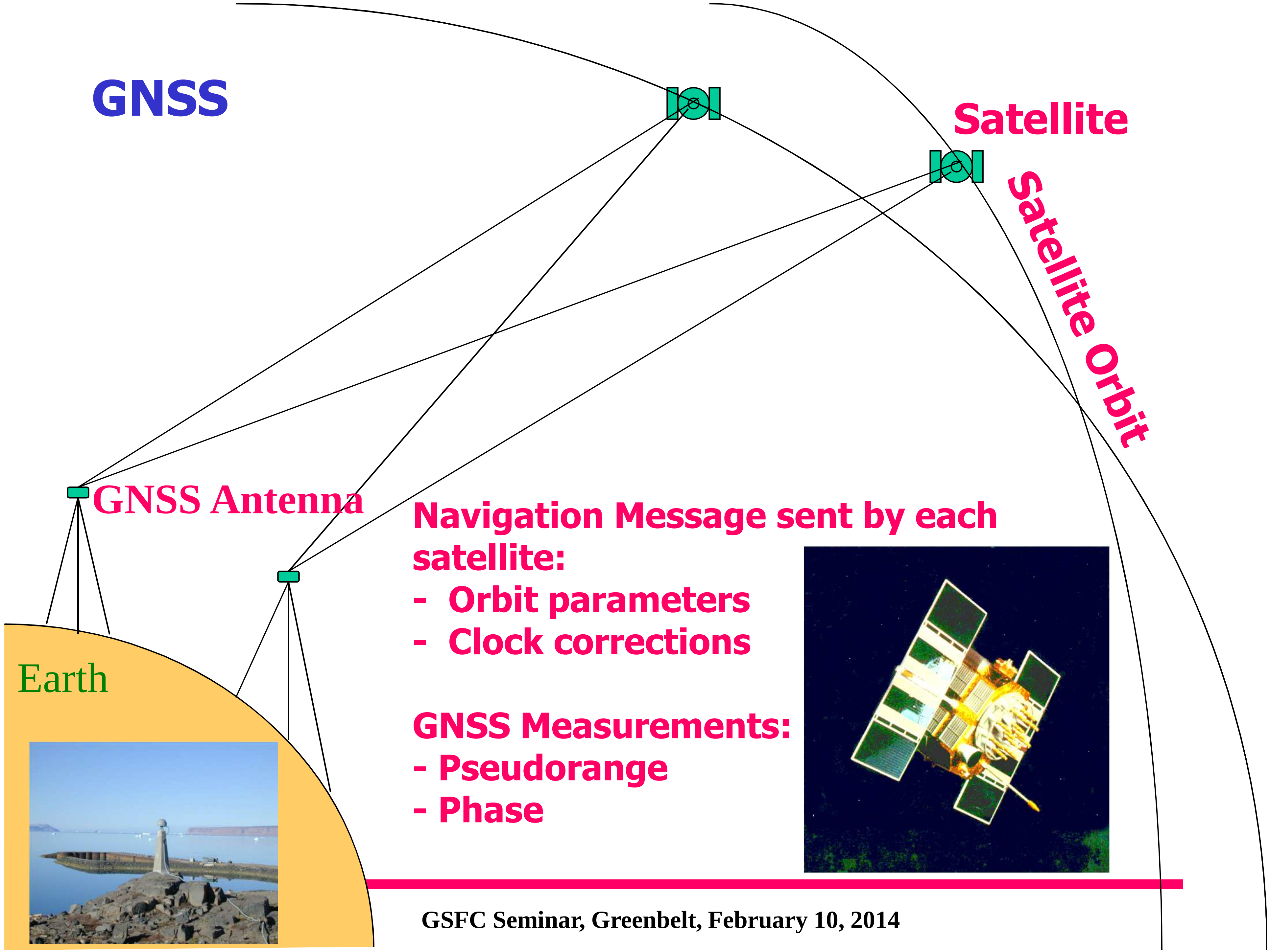


$$\delta g \equiv \tau(t) = \frac{\vec{B}.\vec{S}}{c} + \Delta\tau(t)$$

Lunar / Satellite Laser Ranging — LLR / SLR

Measuring Time Propagation





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

GNSS Measurements:
- **Pseudorange**
- **Phase**

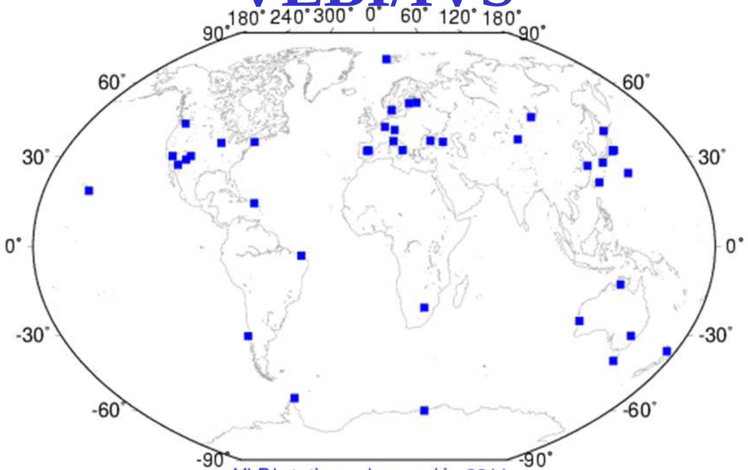
DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

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

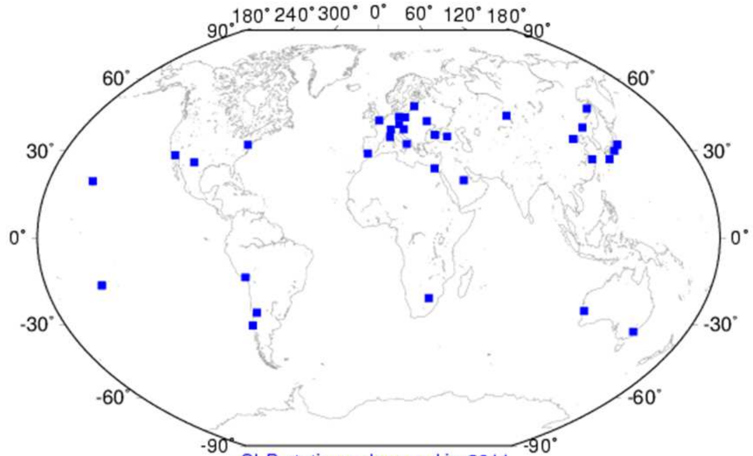
Current networks: stations observed in 2011

VLBI/IVS



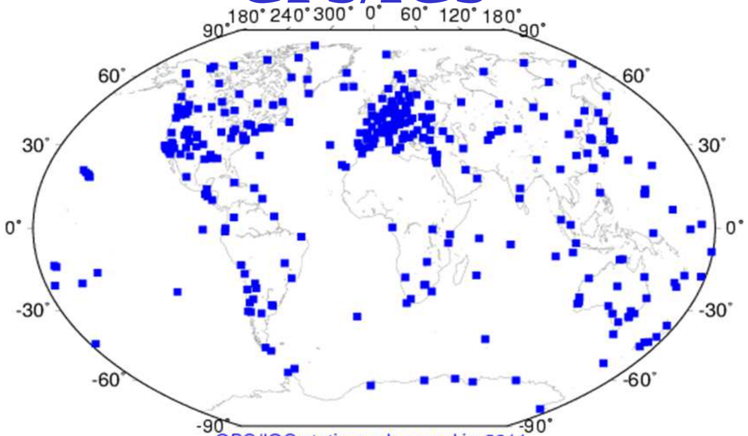
VLBI stations observed in 2011

SLR/ILRS



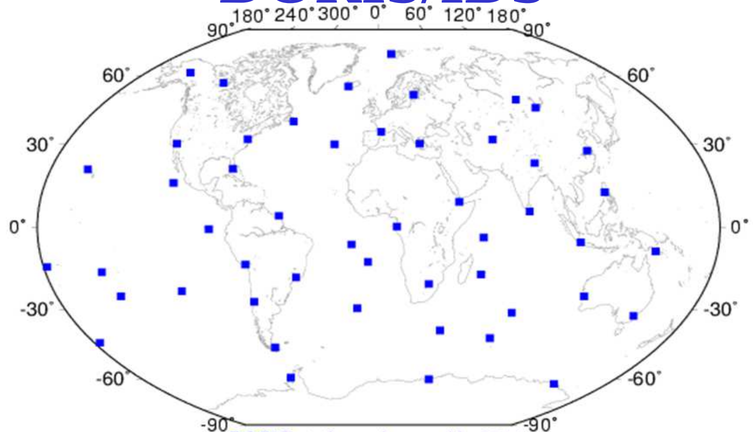
SLR stations observed in 2011

GPS/IGS



GPS/IGS stations observed in 2011

DORIS/IDS

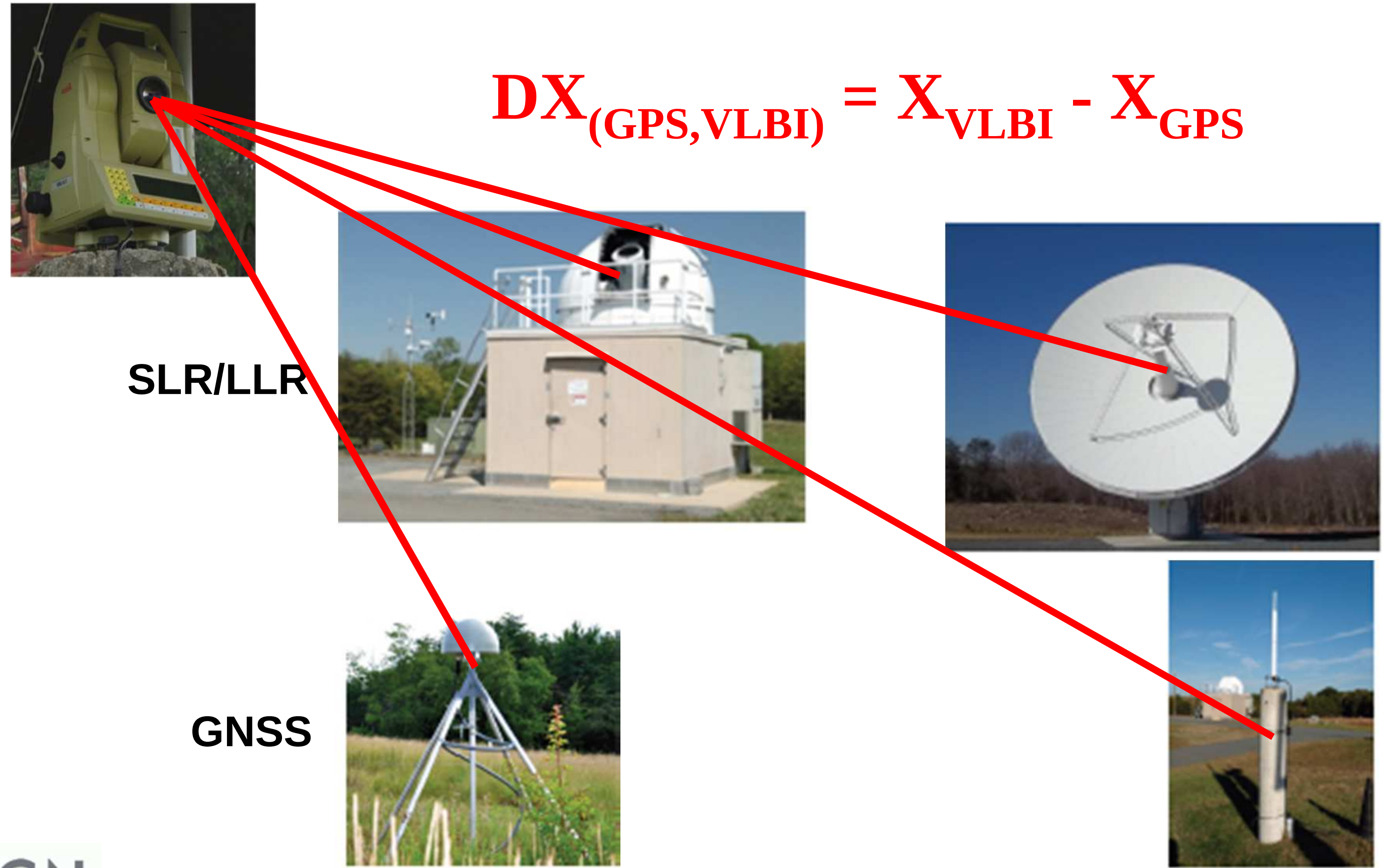


DORIS stations observed in 2011

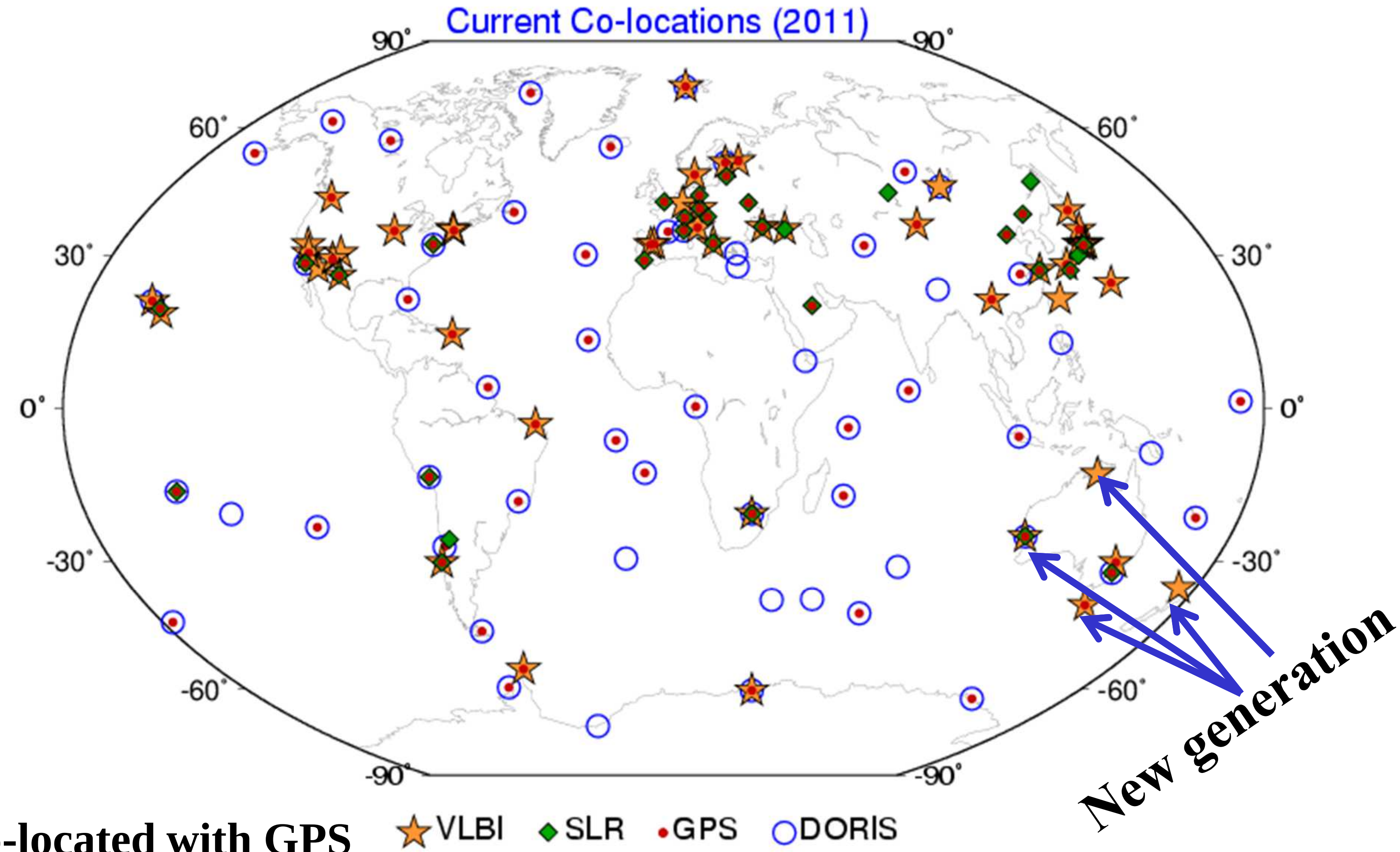
Co-location Site

Two or more geodetic instruments at the same site. Connected via local survey, example: GGAO

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



Total # of VLBI (48), SLR (32), DORIS (56) sites & their co-locations with GPS/GNSS



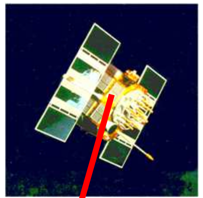
Co-located with GPS → 39 27 43

What is a Reference Frame?

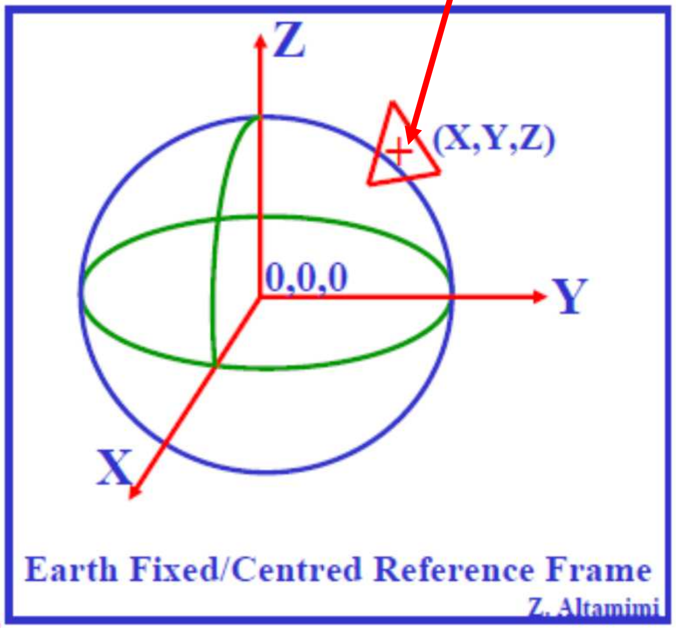
- **Earth fixed/centred RF: allows determination of station location/position as a function of time**

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

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



Origin, Scale & Orientation



Why is a Reference Frame needed?

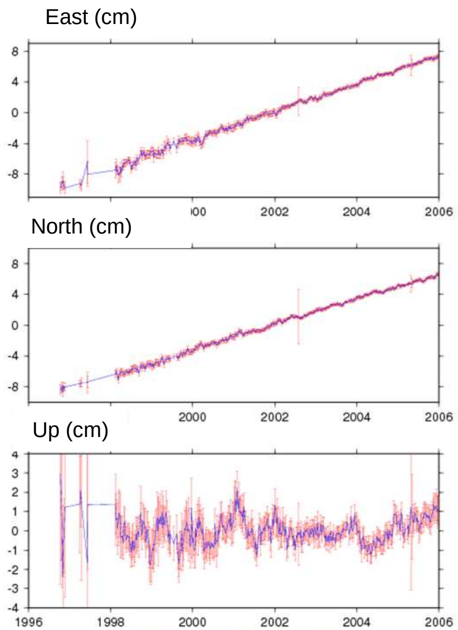
- **Precise Orbit Determination for:**
  - GNSS: Global Navigation Satellite Systems
  - Other satellite missions: Altimetry, Oceanography, Gravity

- **Earth Science & Societal Applications**
  - Mean sea level variations
  - Hazard mitigation and tsunami warning
  - Plate motion and crustal deformation
  - Glacial Isostatic Adjustment (GIA)
  - …

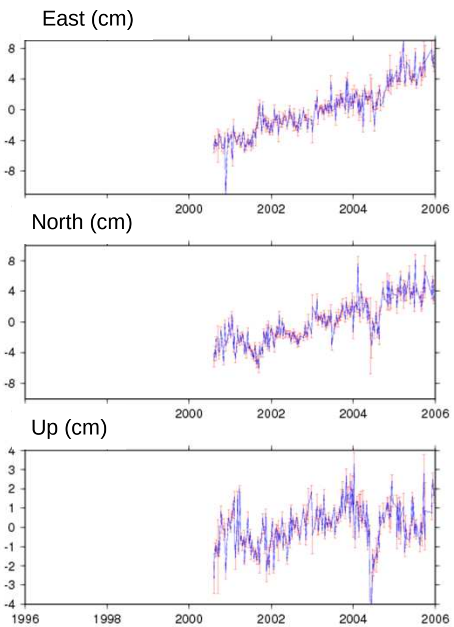
- **Geo-referencing applications : positioning, navigation, surveying…**

Input data: station position time series

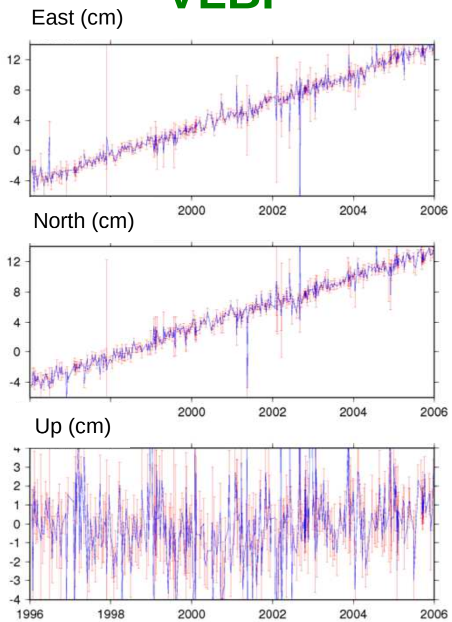
GPS



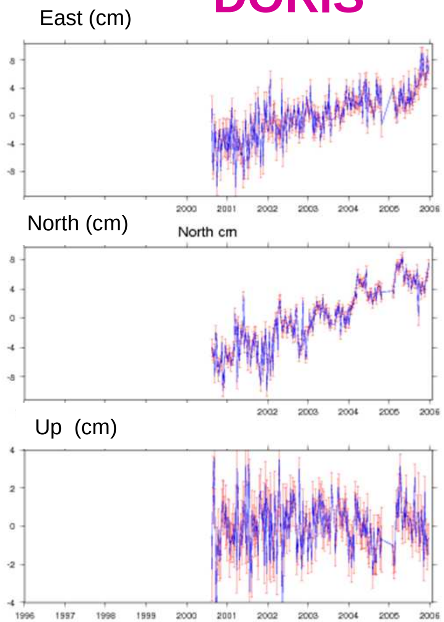
SLR



VLBI



DORIS



ITRF Construction

DORIS
GPS
SLR
VLBI
Time series stacking

Long-term Solutions

DORIS
GPS
SLR
VLBI
X V, EOPs

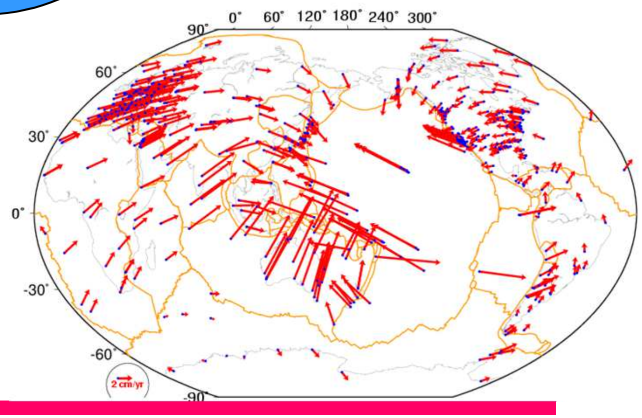
Combination

Local ties

Velocity equality

at co-location sites

ITRF
X V, EOPs

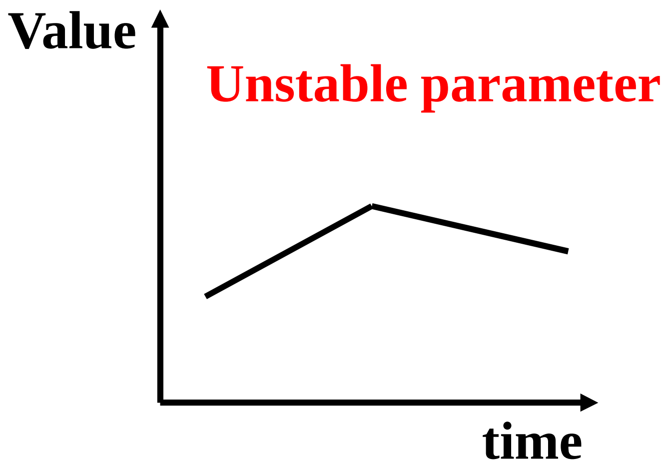


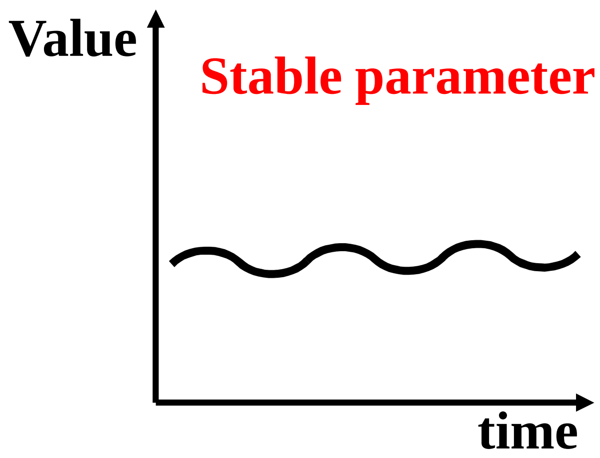
ITRF scientific requirements

- **ITRF stable in the long term : 0.1 mm/yr**

==> Stable: Linear time evolution (no discontinuities) of its defining parameters:

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

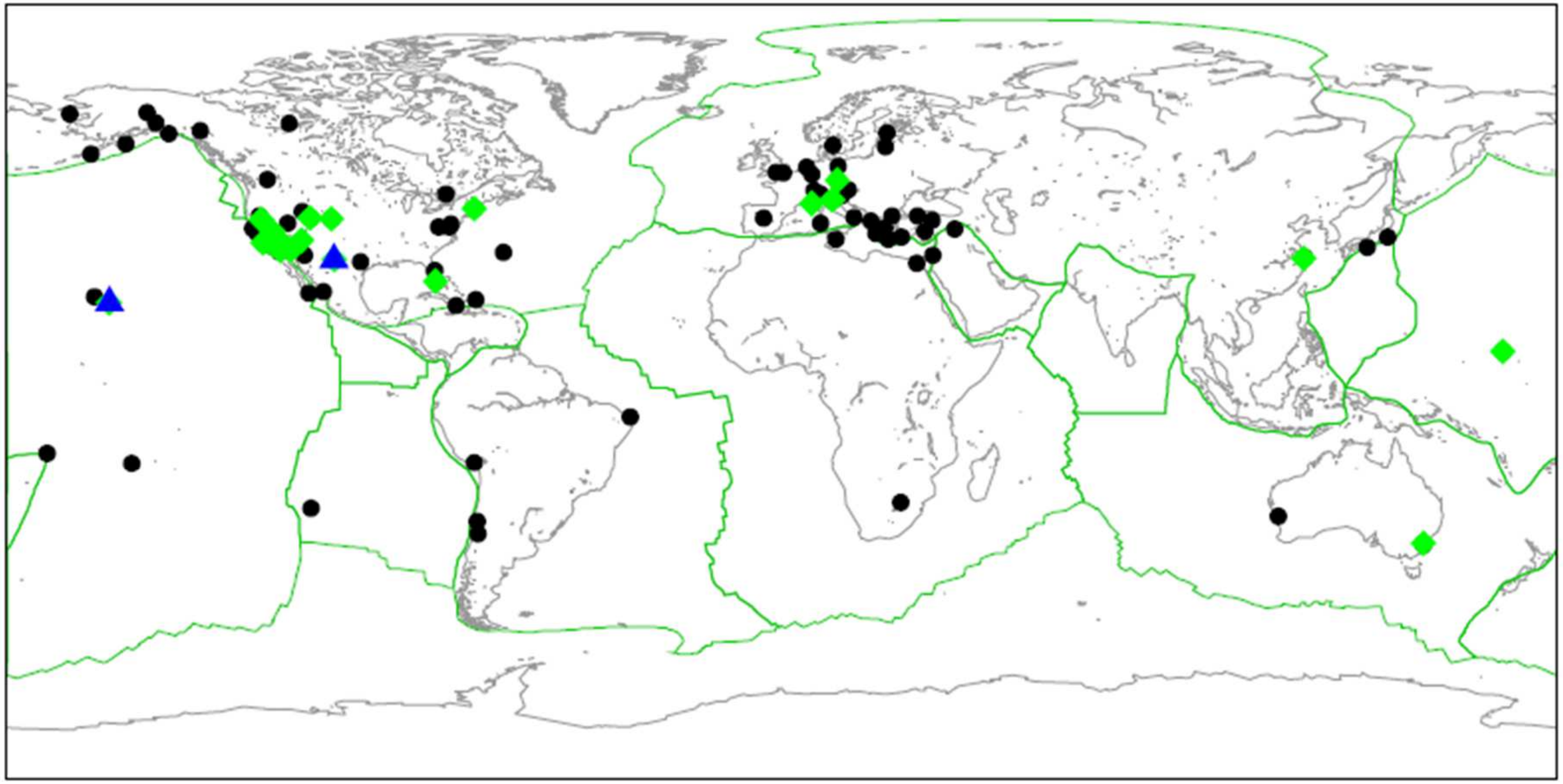




Current accuracy $\geq$ 1 mm/yr

ITRF evolution:
Network, Precision & Accuracy

Network evolution (ITRF88)



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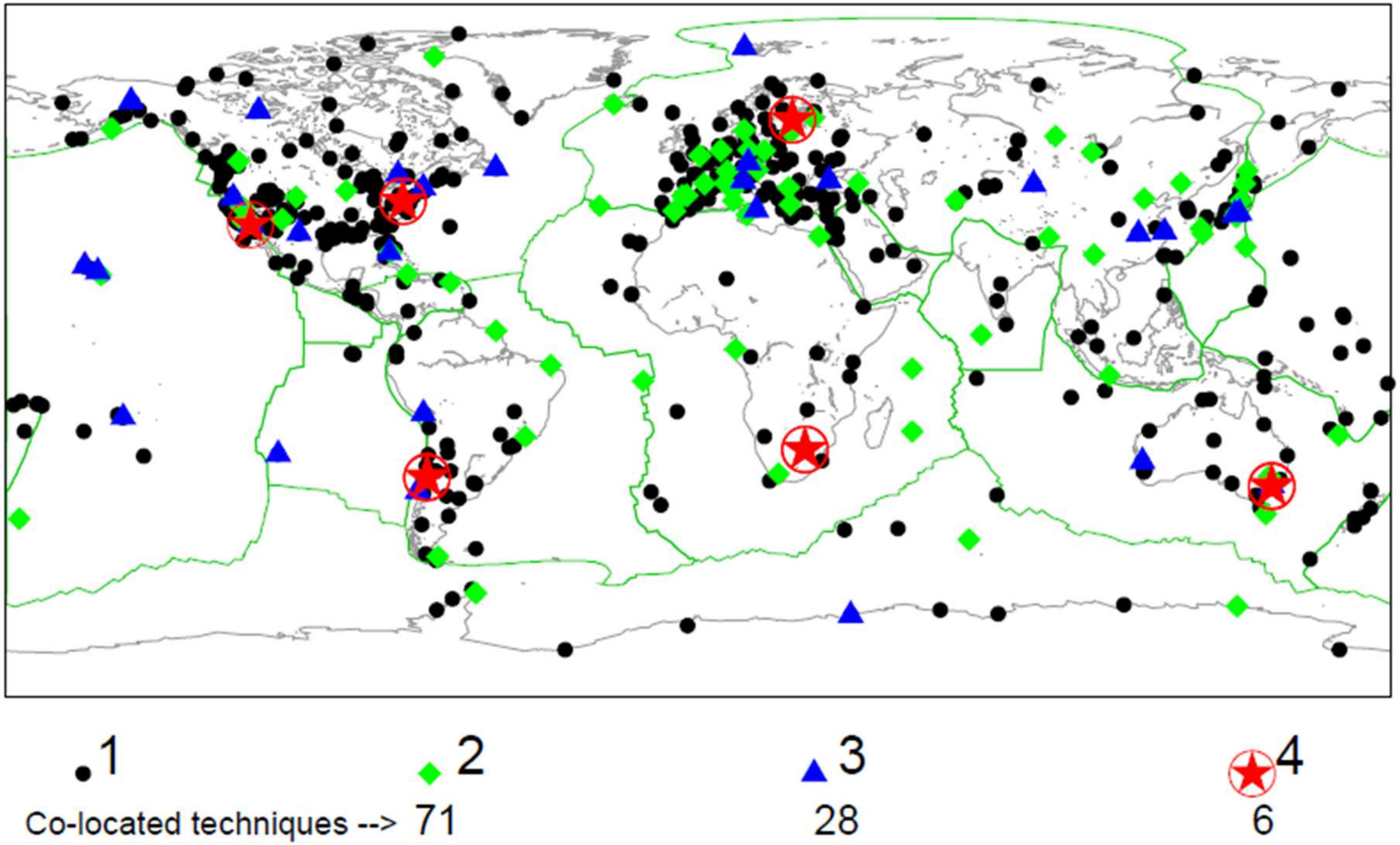
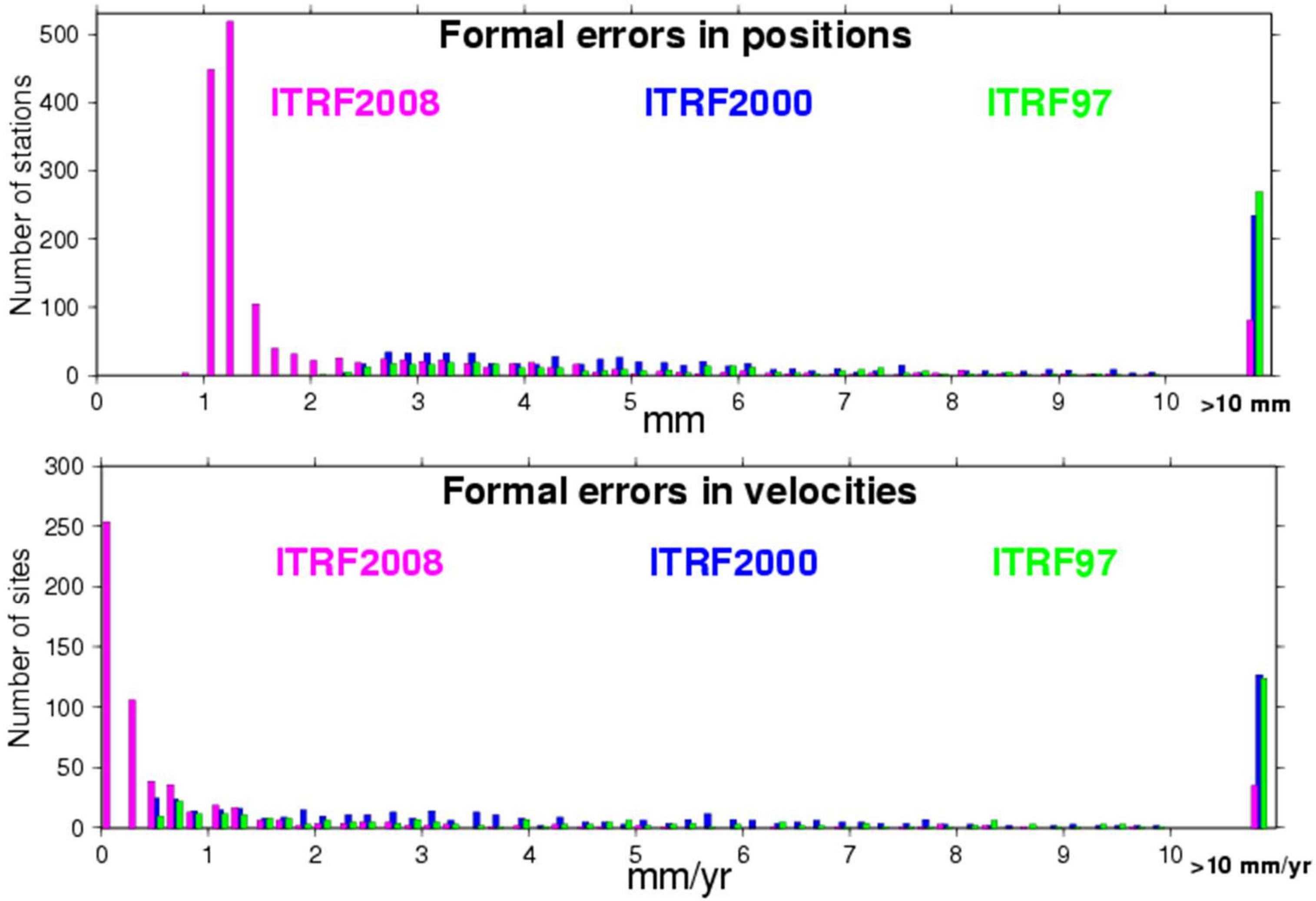
Co-located techniques --> 20 2

Network evolution (ITRF2008)

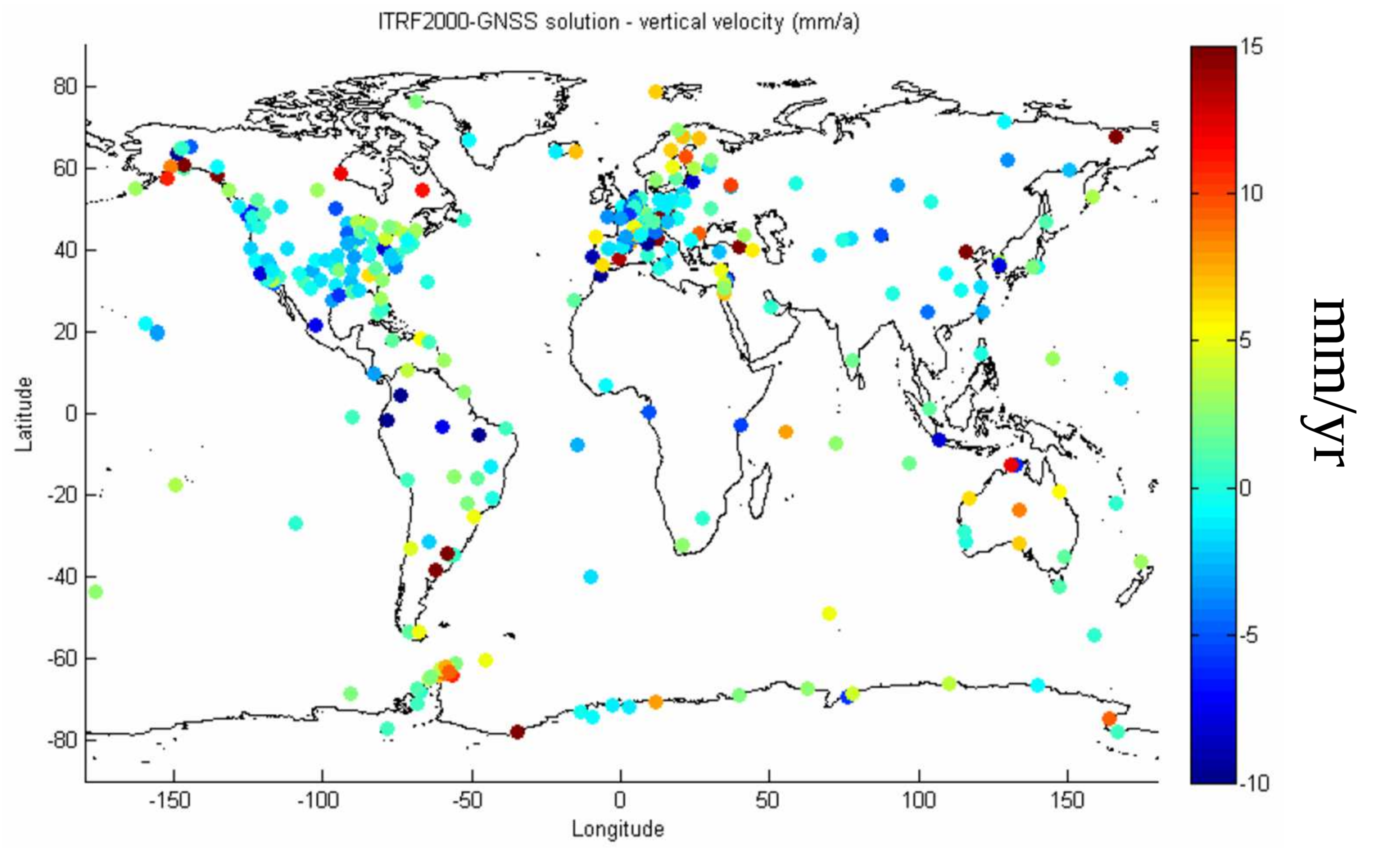


Precision evolution



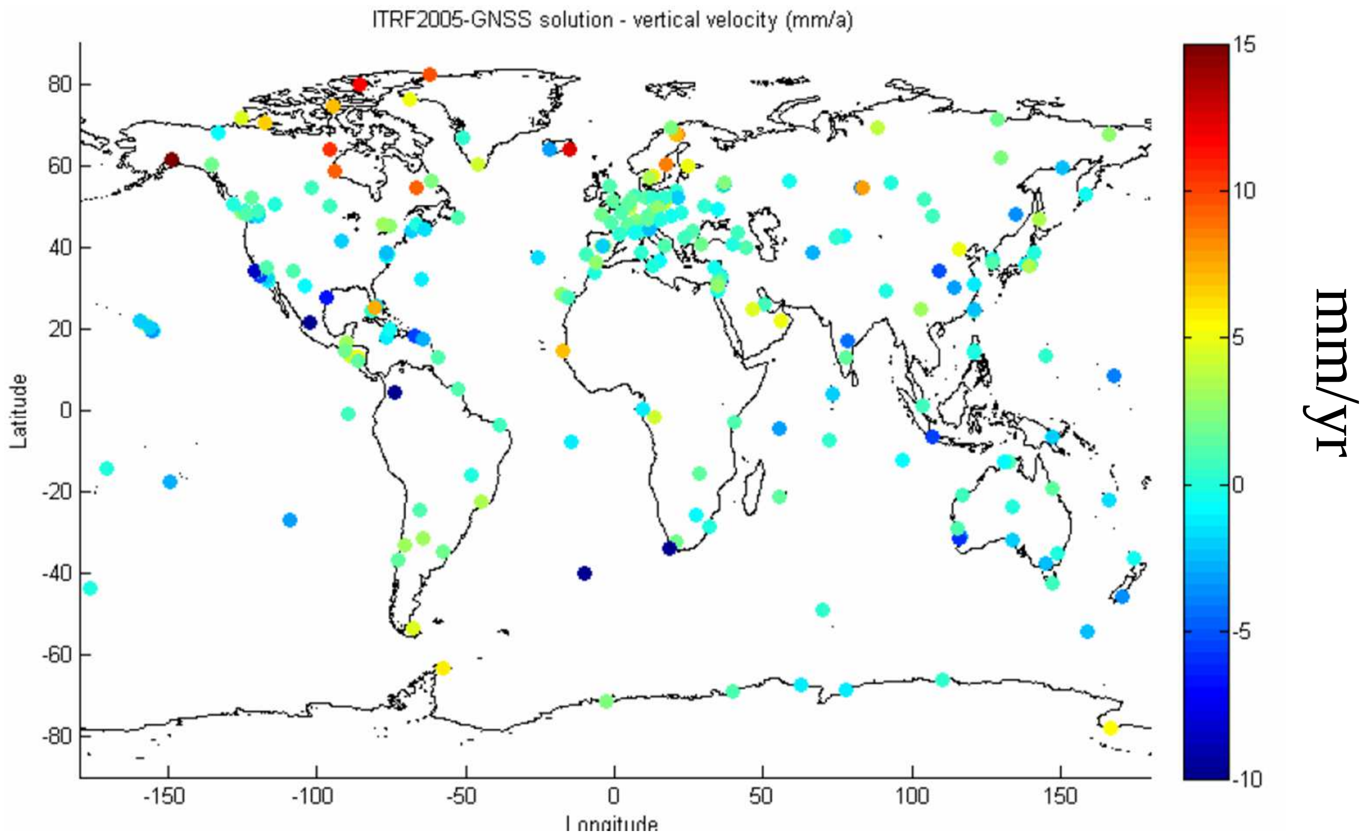
ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2000



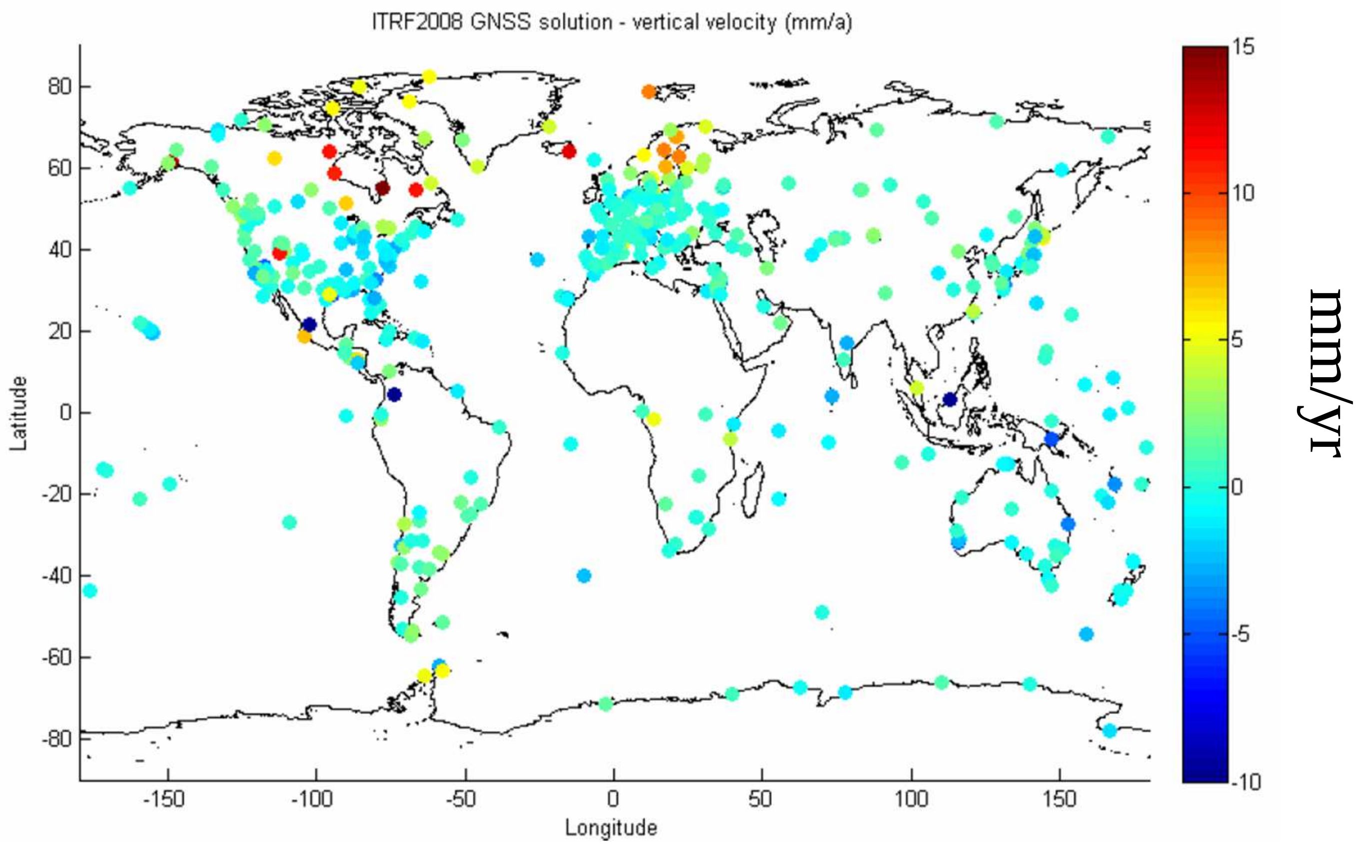
ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2005



ITRF accuracy

Evolution of the spatial consistency of vertical velocities: ITRF2008



ITRF and Science Applications

ITRF and Science Applications

- Sea level variability in space and time
  - An origin Z-drift of 2 mm/yr ==> errors in satellite altimetry data:
    - up to 0.3 mm/yr on global mean sea level
    - up to 1.8 mm/yr on regional sea level at high latitudes
  - A scale drift of 0.1 ppb/yr ==> drift up to 0.6 mm/yr in mean sea level determined by tide gauges records
- Glacial Isostatic Adjustment (GIA)
  - Z- and scale drifts ==> same impact as for sea level
- Plate motion (horizontal velocities)
  - Z-drift ==> change in North velocity

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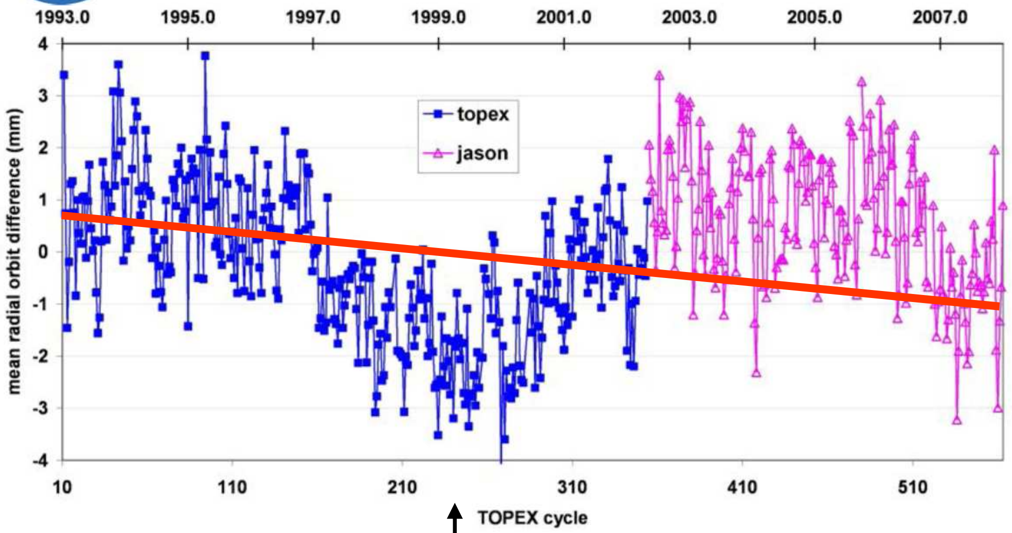
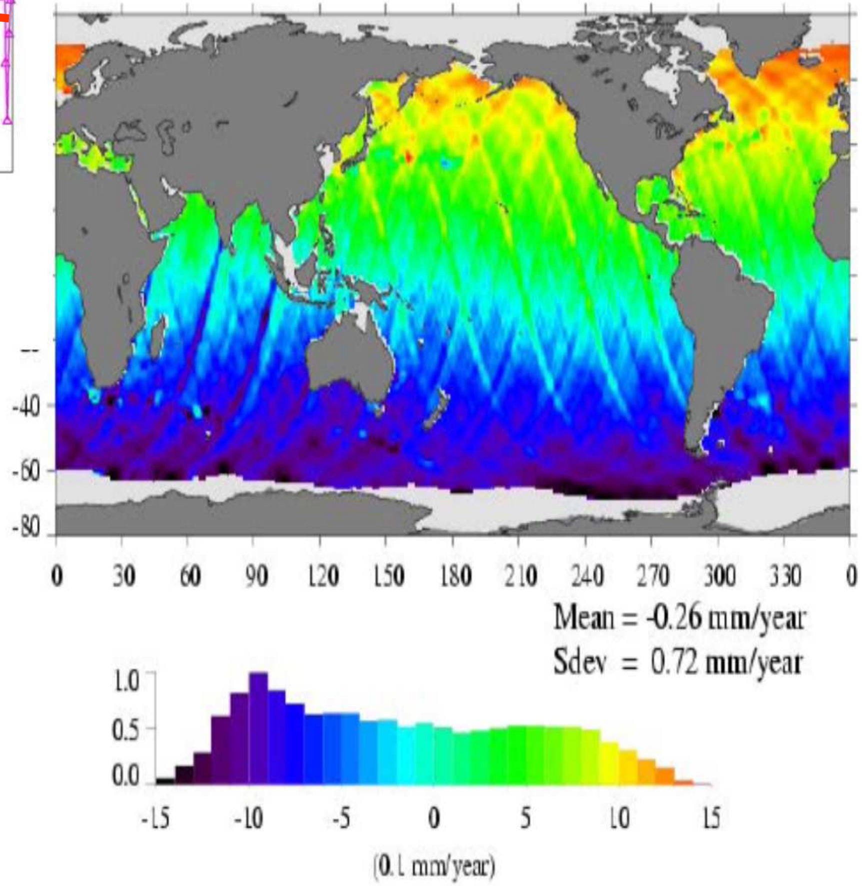
Impact of reference frame on mean sea level



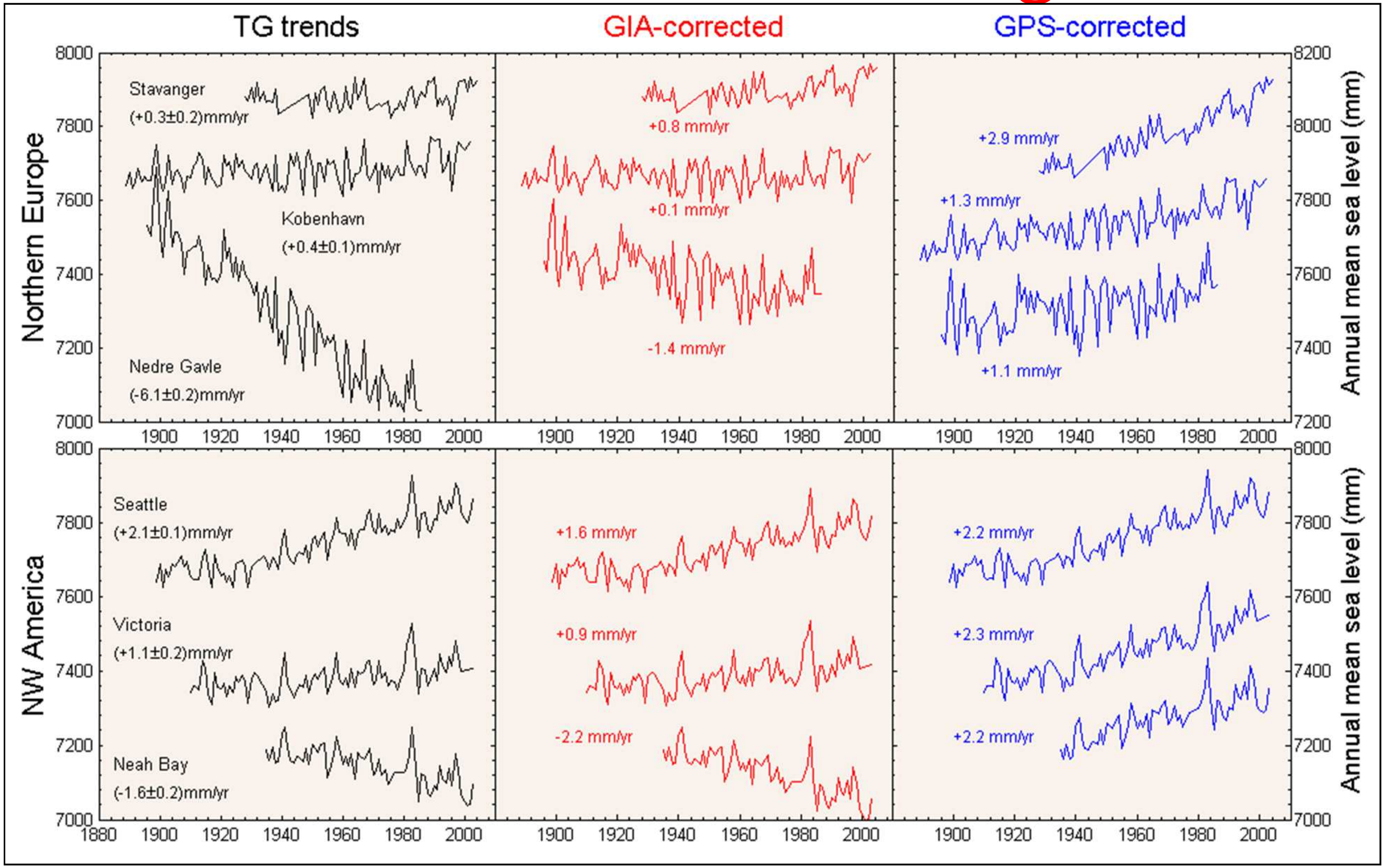
TP & Jason-1: Radial orbit diffs (ITRF2005 minus CSR95/ ITRF2000) (over the oceans)



Beckley et al., GRL, 2007

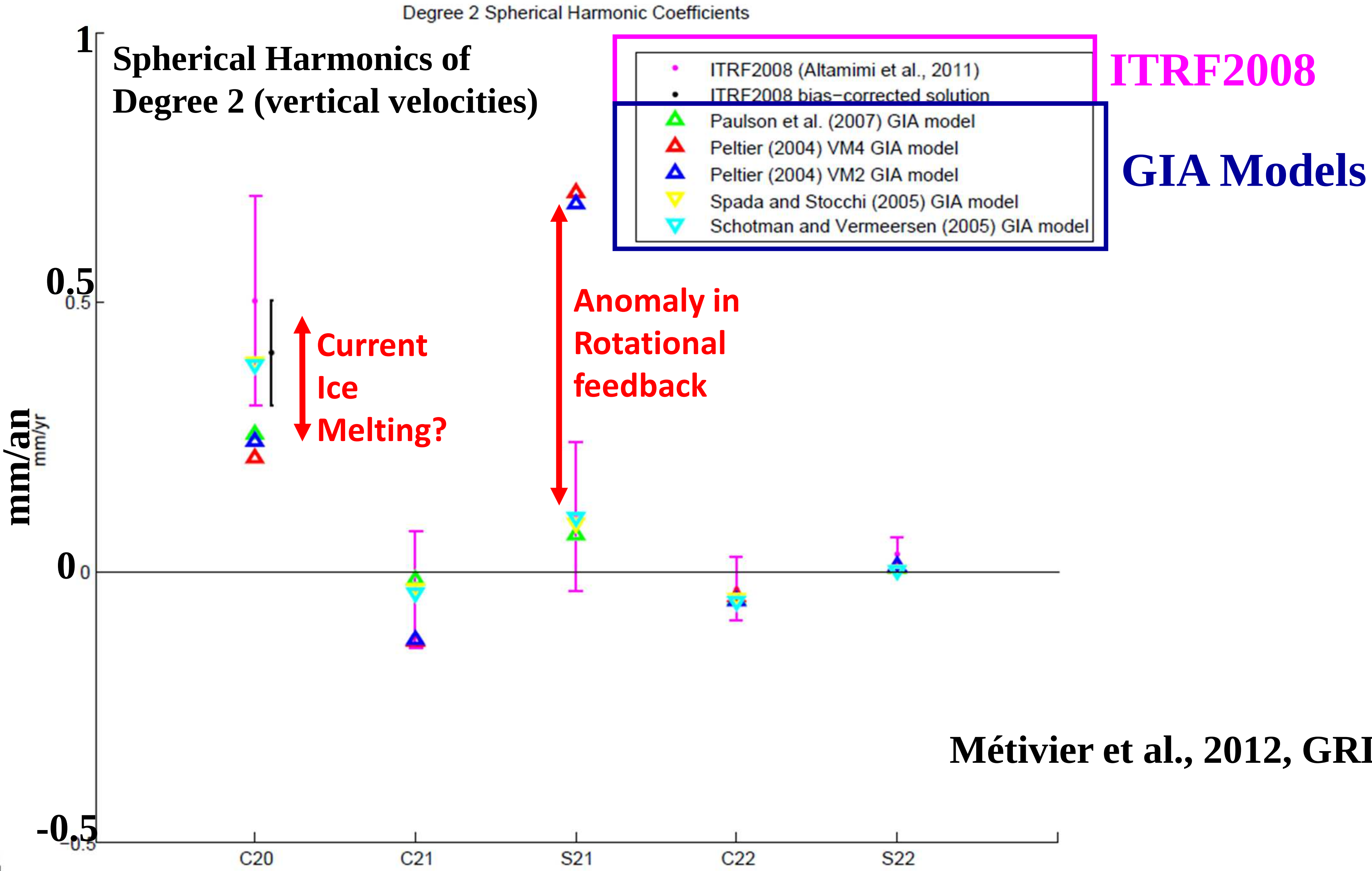
TOPEX (1993-2002): regional differences of sea level, via orbital parameters (ITRF2005 minus CSR95/ITRF2000)

ITRF2005 & Tide Gauges



Woppelmann et al., GRL (2009)

ITRF2008 & Post Glacial Rebound

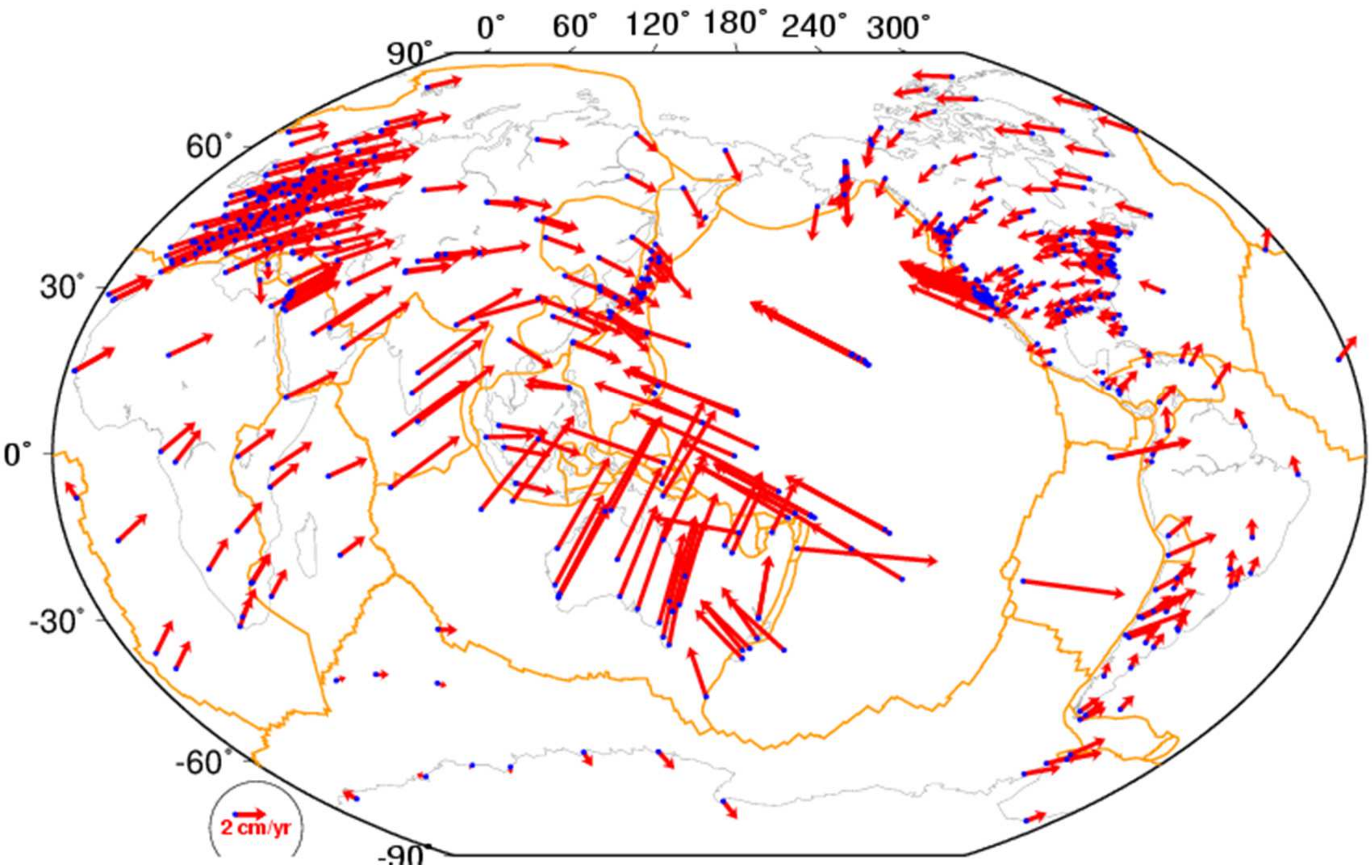


Métivier et al., 2012, GRL

ITRF and Plate motion

ALL ITRF2008 Site Velocities:
time-span > 3 yrs

509 sites



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Selected Site Velocities

Plate angular velocity ω_p is estimated by:

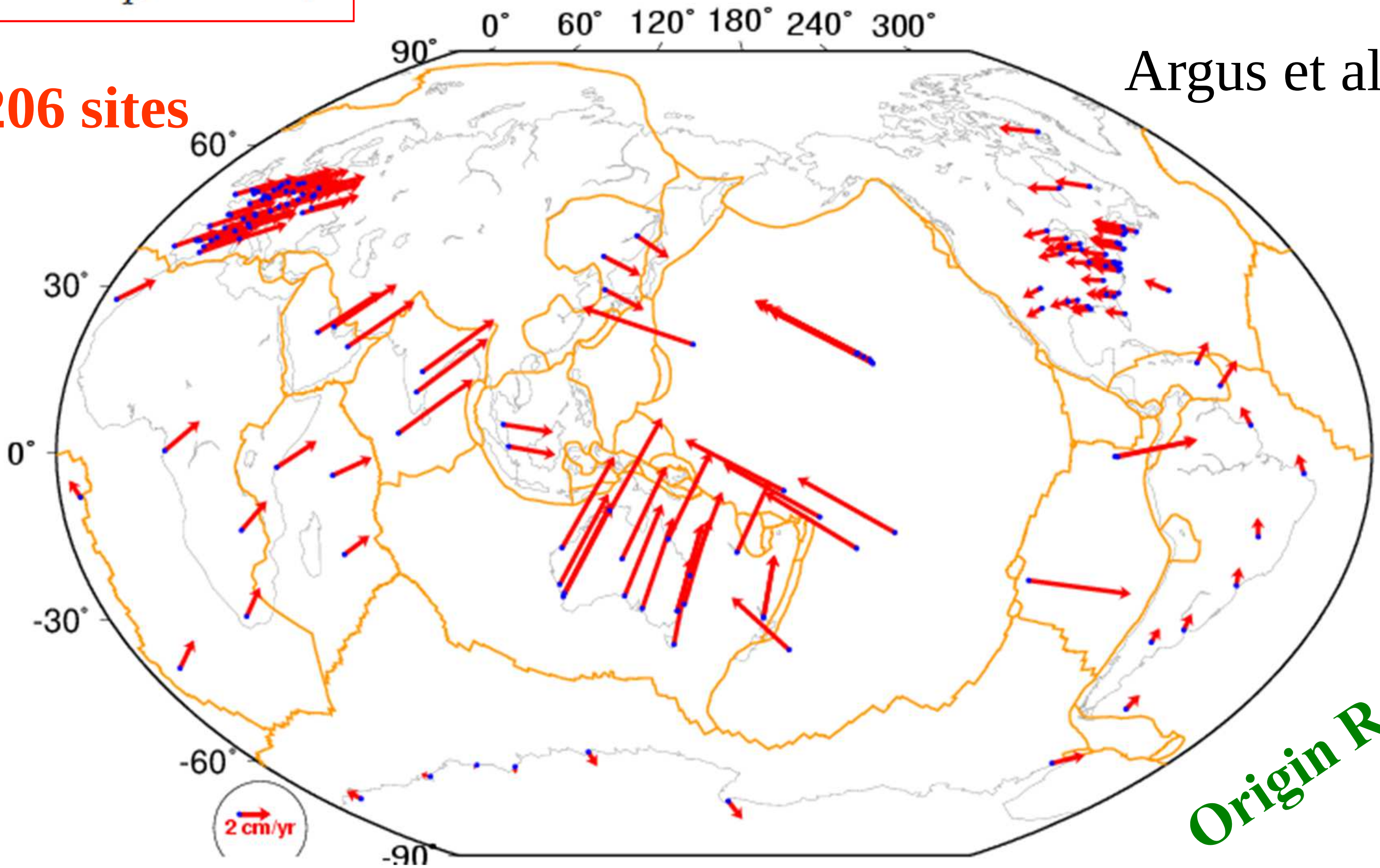
$$\boxed{\dot{X}_i = \omega_p \times X_i}$$

OR

$$\boxed{\dot{X}_i = \omega_p \times X_i + \dot{T}}$$

Argus et al. 2010

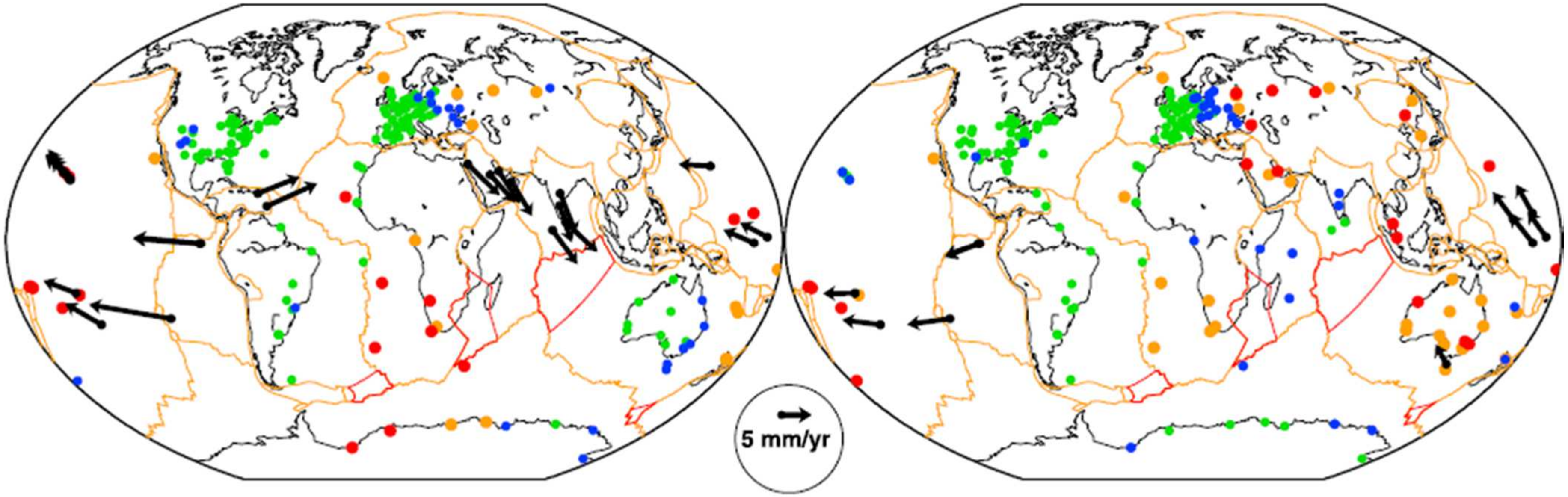
206 sites



Origin Rate Bias

Comparison btw ITRF2008 and NNR-NUVEL-1 and NNR-MORVEL56

Velocity differences after rot. rate transformation



NNR-NUVEL-1A		NNR-MORVEL56
RMS:	● Green: 1-2 mm/yr	RMS:
East : 2.5 mm/yr	● Blue : 2-3 mm/yr	East : 1.7 mm/yr
North: 2.0 mm/yr	● Orange: 3-4 mm/yr	North: 1.7 mm/yr
	● Red : 4-5 mm/yr	
Ry = 0.025 mas/yr	←• Black : > 5 mm/yr	Rx = 0.084 mas/yr

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ITRF: what are the challenges & questions ?

- Improving co-location sites (the big issue)
  - Network configuration
  - Tie discrepancies
  - Velocity discrepancies

- Mitigating Technique systematic errors ?

- Improving the process of detection of discontinuities in the station position time series

- Modeling site non-linear motions

Data used for this presentation & in preparation for ITRF2013

- **Space Geodesy:**

  SLR: ILRS contribution to ITRF2008, extended up to 2013.96 by ILRS operational weekly SNX solutions

  VLBI: GSFC 2011b session-wise solutions: 1983-2013.9

  GNSS: IGS operational weekly solutions: 1994-2013.9

  DORIS: Not used here

- **Local ties:**
  - **ITRF2008 local ties**
  - **New ties, including, Brewster, GGAO & McDonald, performed by the US National Geodetic Survey (NGS)**

Analysis Strategy

- **ITRF-type analysis:**
  - **Time series stacking ==> station Pos&Vel / technique**

    ==> Residual time analysis: stability analysis : discontinuities in positions & changes in velocities
  - **Inter-technique combination: Pos&Vel + local ties**

    ==> evaluate level technique agreement in velocities and with local ties

- **Analysis strategy**
  - **Weighting local ties: use lower bound sigma and down-weight discrepant ties**
  - **Equating velocities as a function of their agreement**

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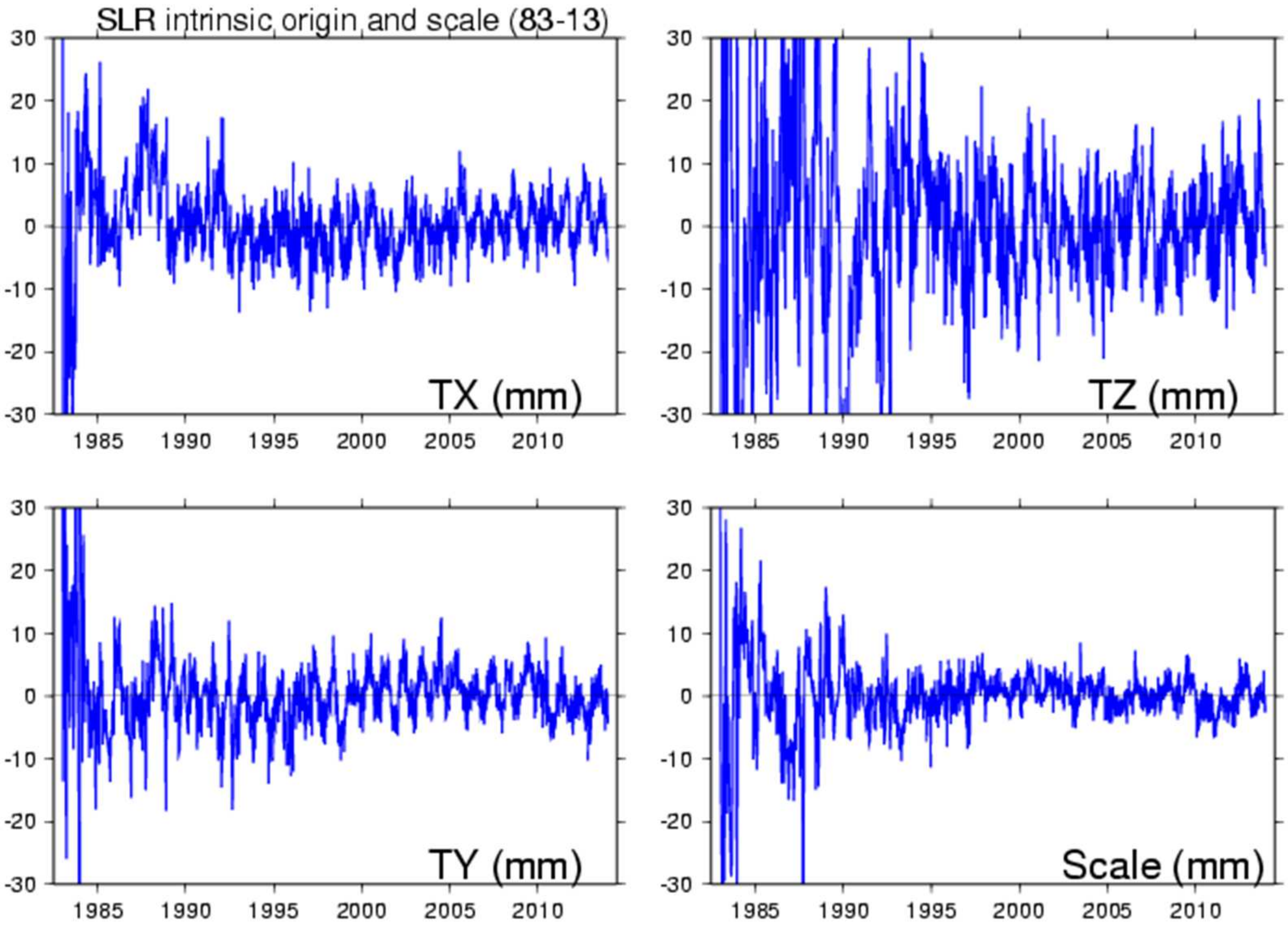
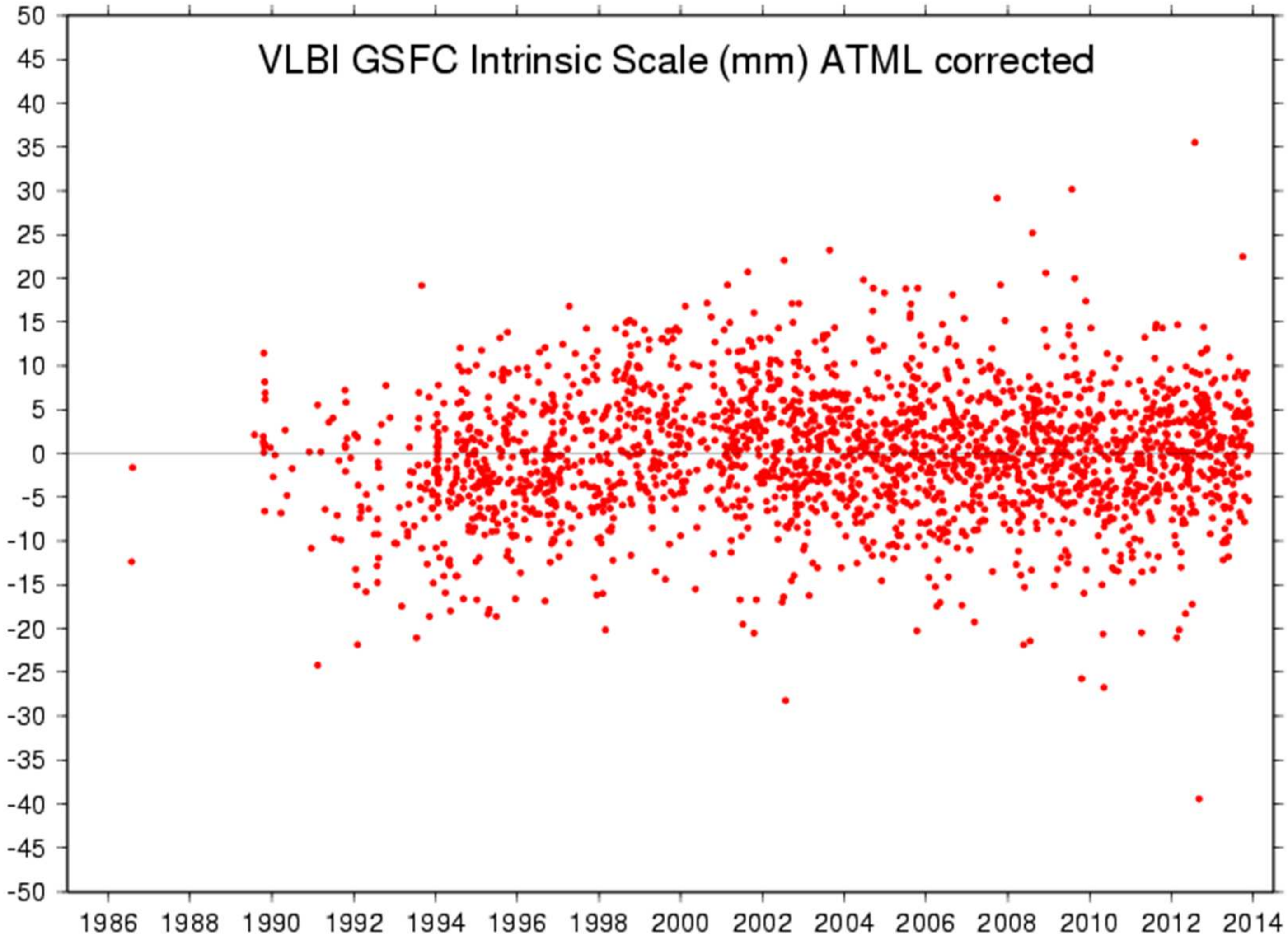
SLR/ILRS intrinsic origin & scale



VLBI/GSFC (2011b) intrinsic scale



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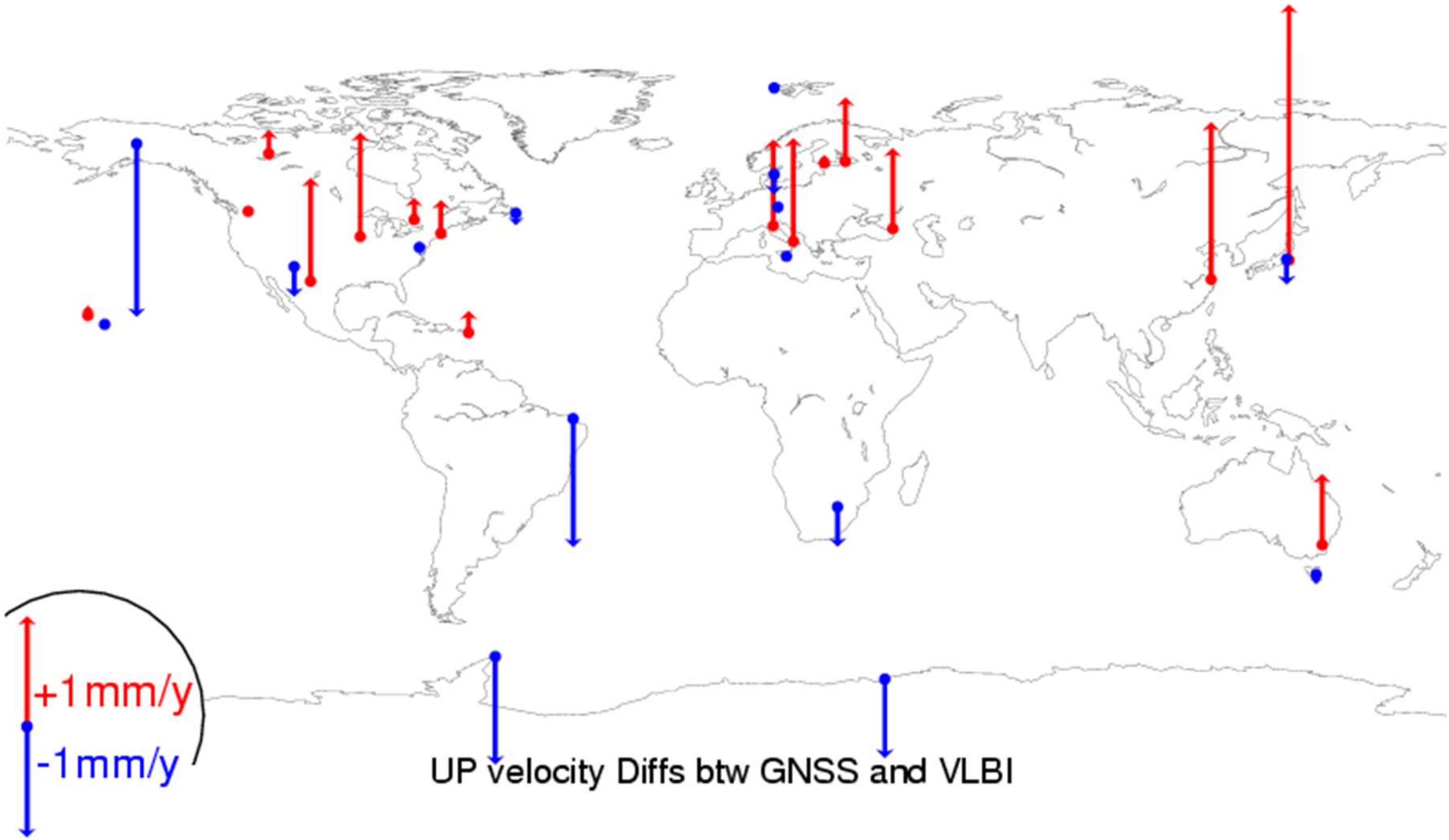
GNSS & VLBI vertical velocity discrepancies

Formal error ± 0.3 mm/yr



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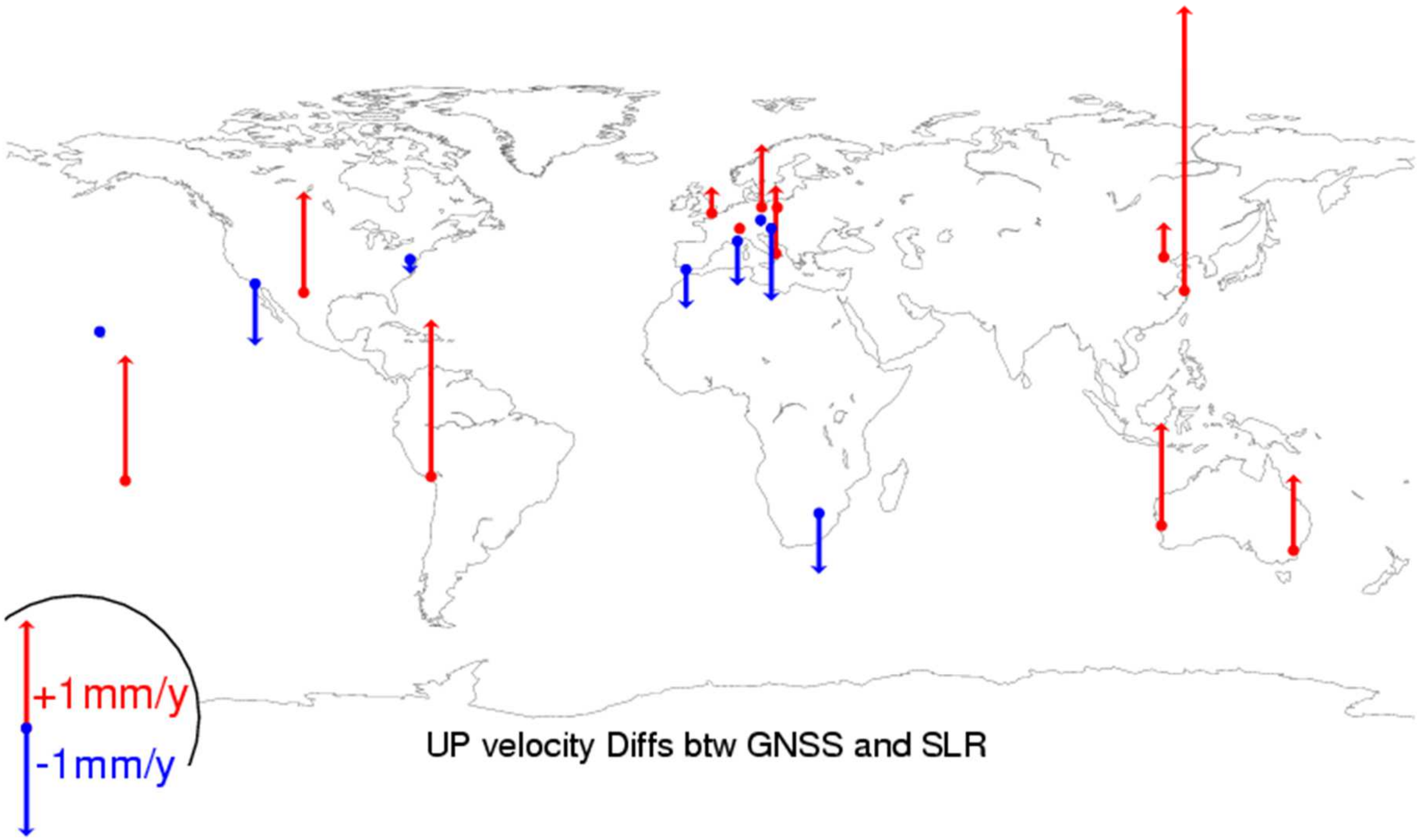
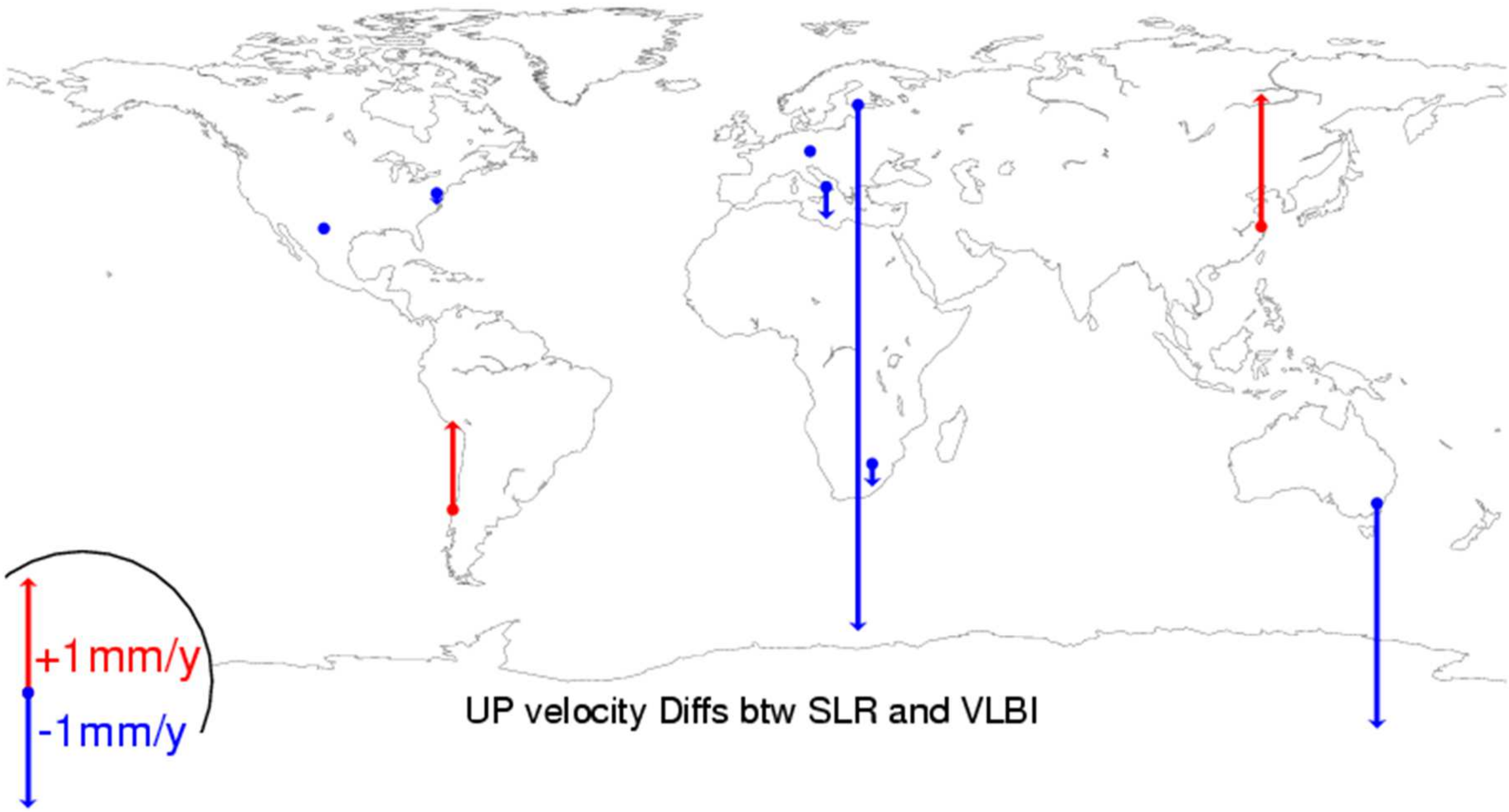
GNSS & SLR vertical velocity discrepancies

Formal error ± 0.3 mm/yr

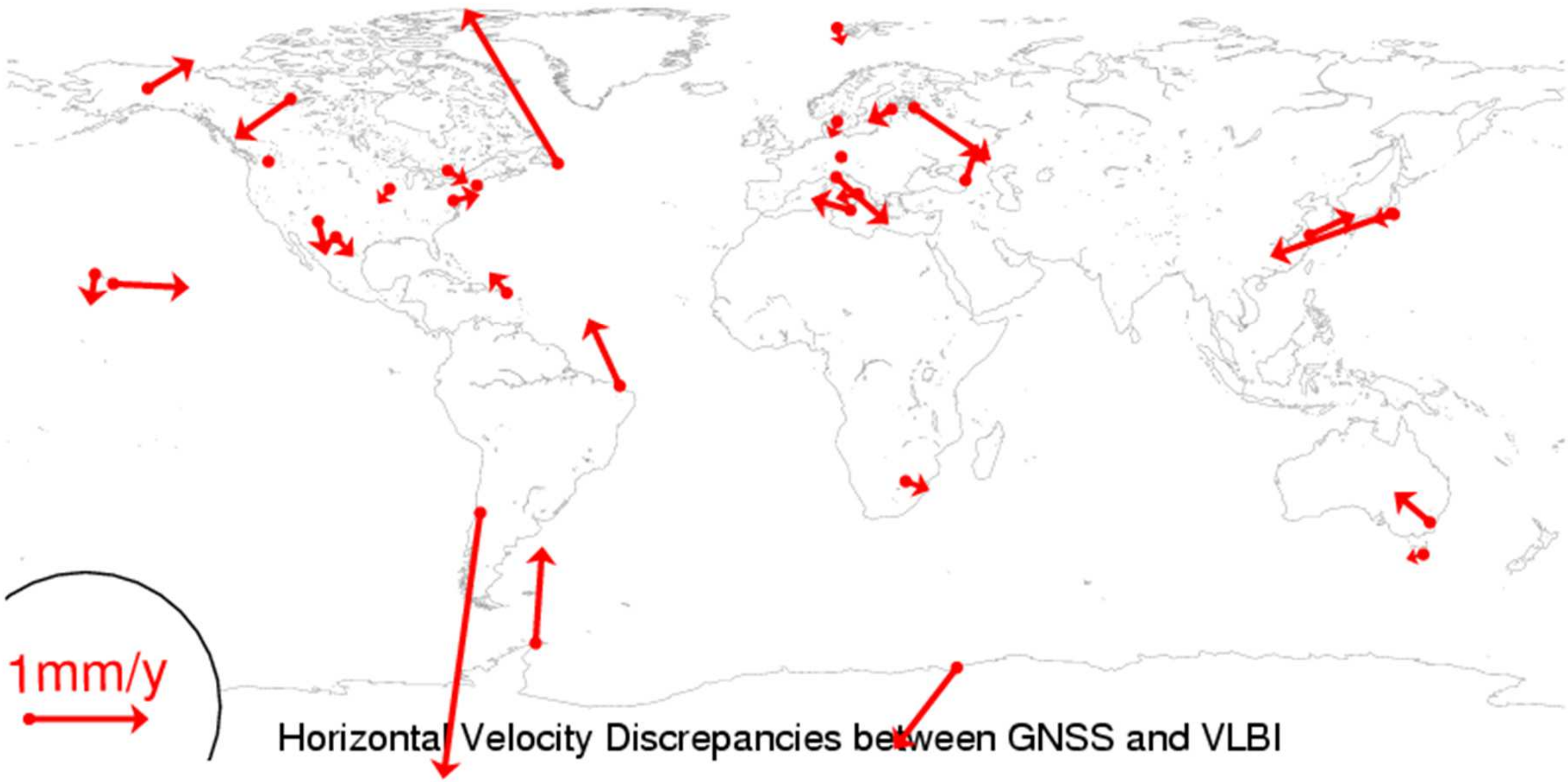


VLBI & SLR vertical velocity discrepancies



GNSS & VLBI horizontal velocity discrepancies

Formal error ± 0.2 mm/yr



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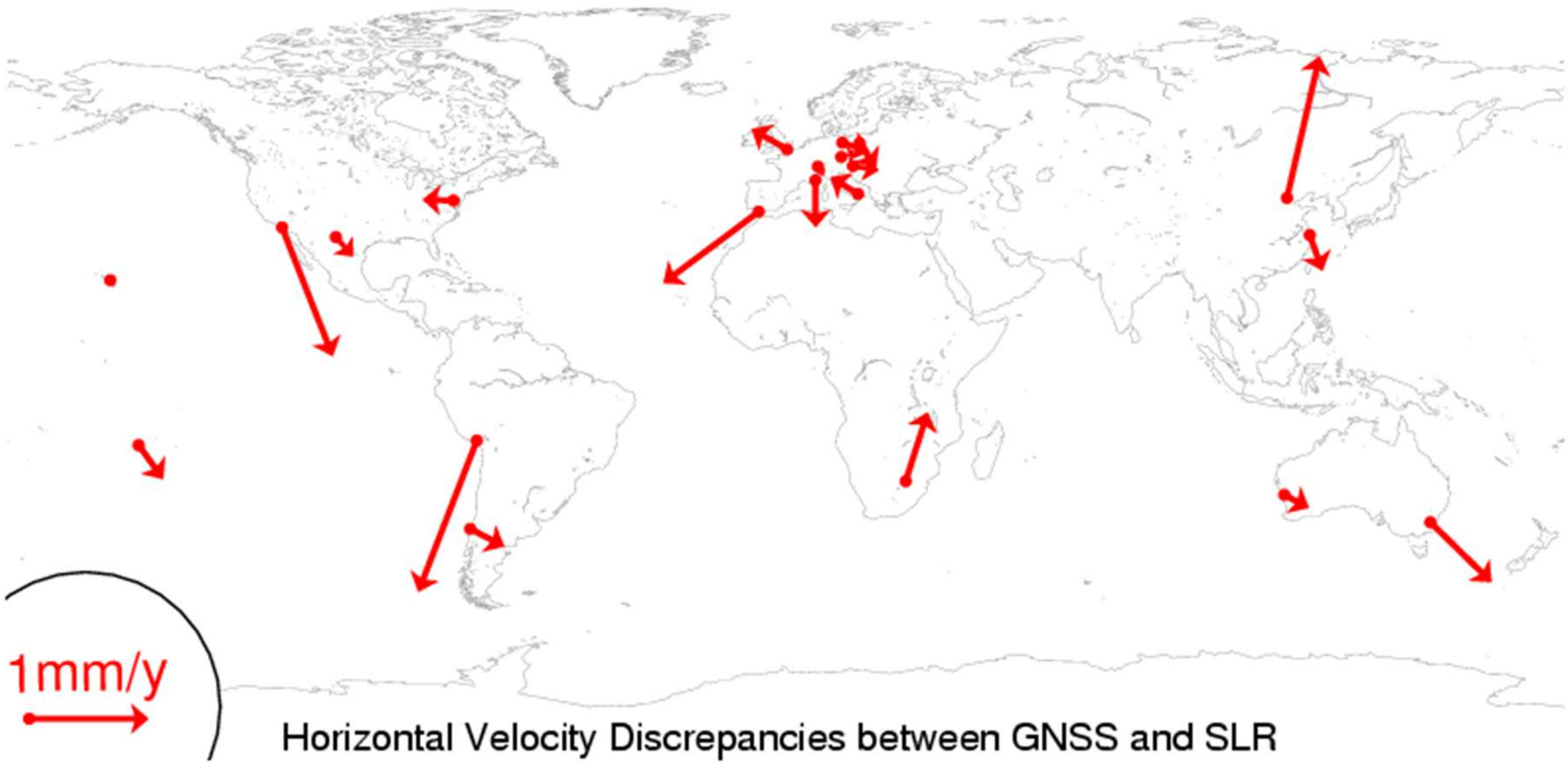
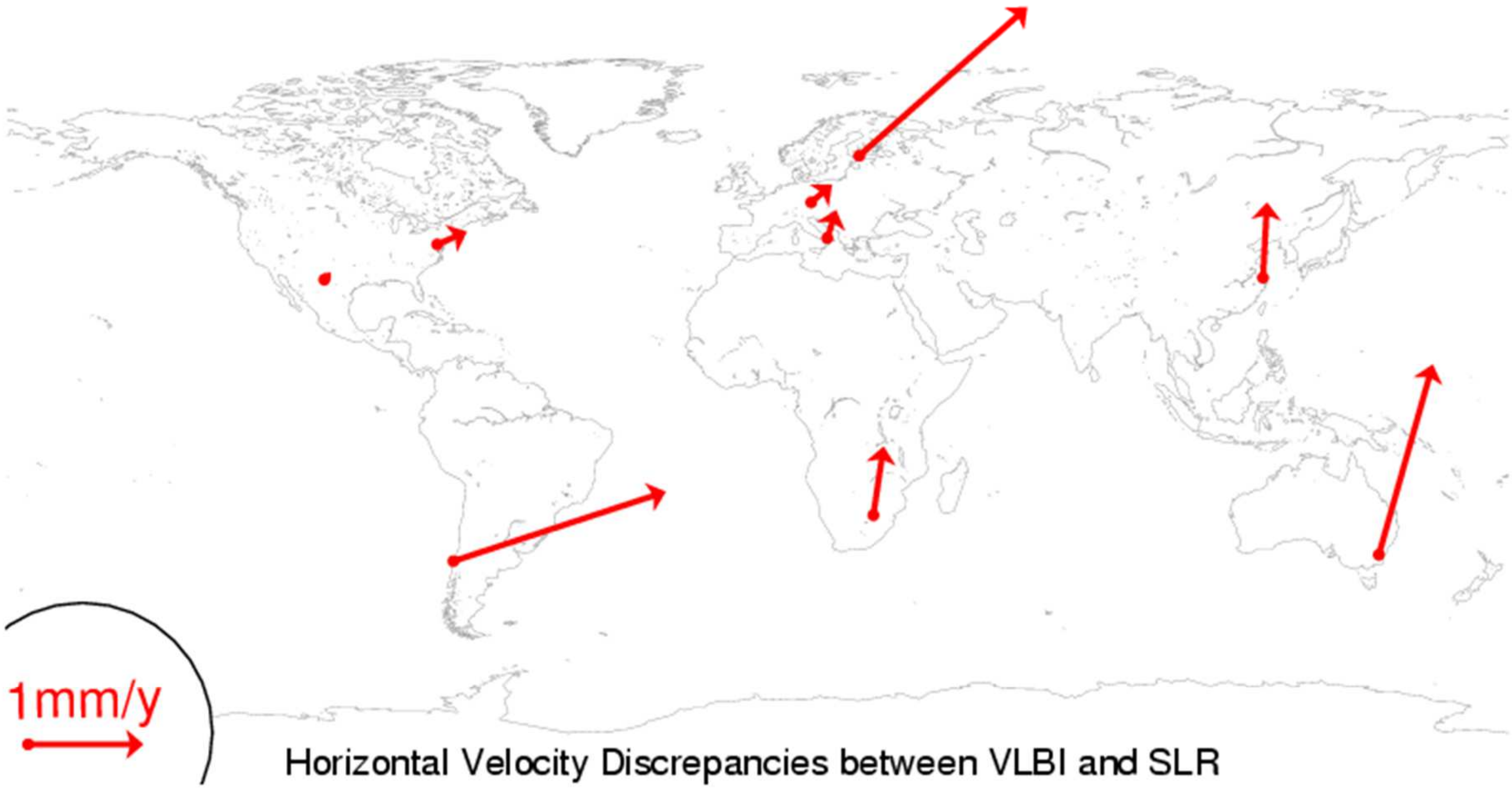
GNSS & SLR horizontal velocity discrepancies

Formal error ± 0.2 mm/yr



Horizontal Velocity Discrepancies between GNSS and SLR

VLBI & SLR horizontal velocity discrepancies

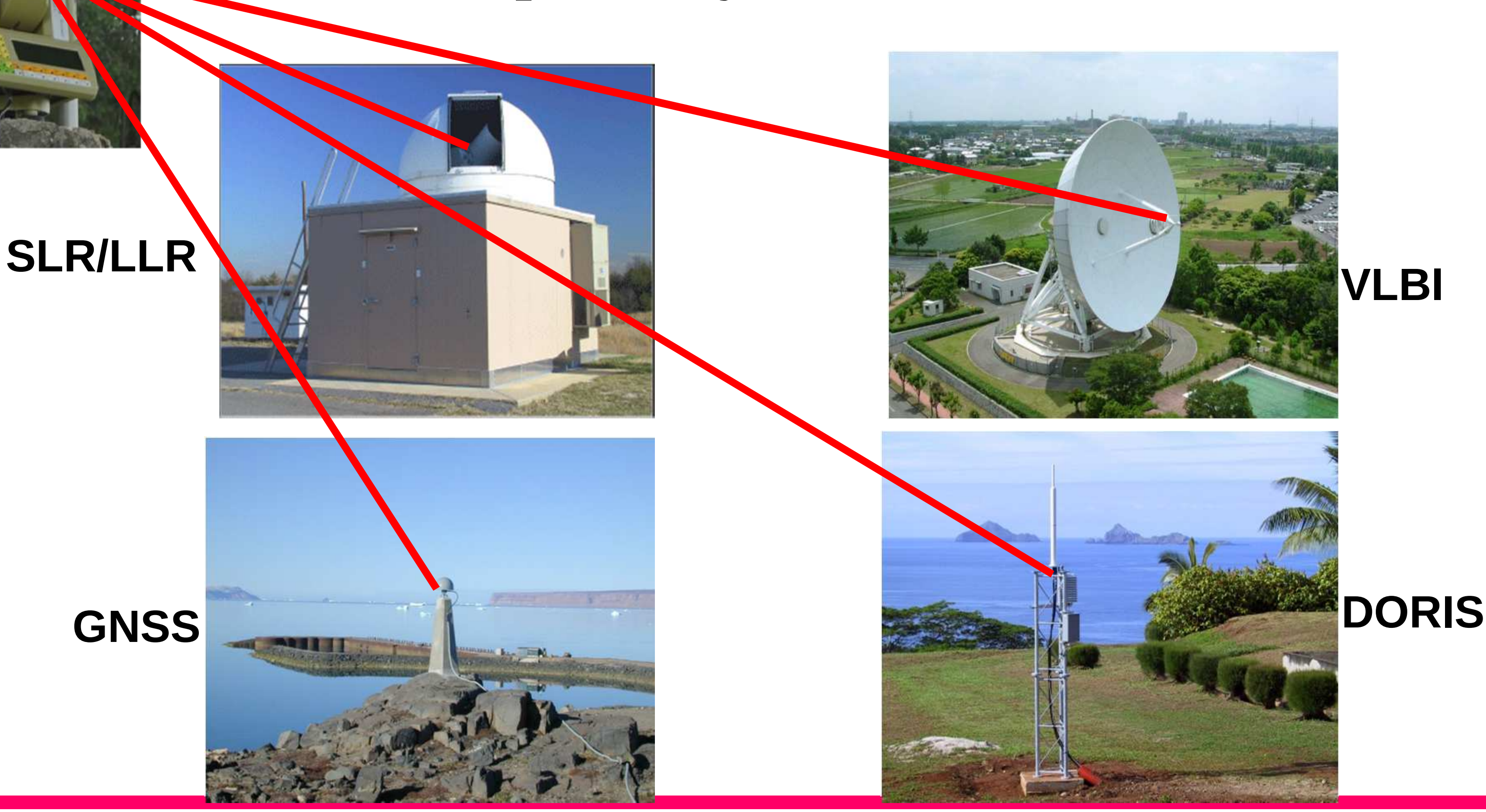


Tie Discrepancies

Differences between Terrestrial Tie and Space Geodesy estimates

Possible causes of tie discrepancies:
Local Survey &/or technique systematic errors

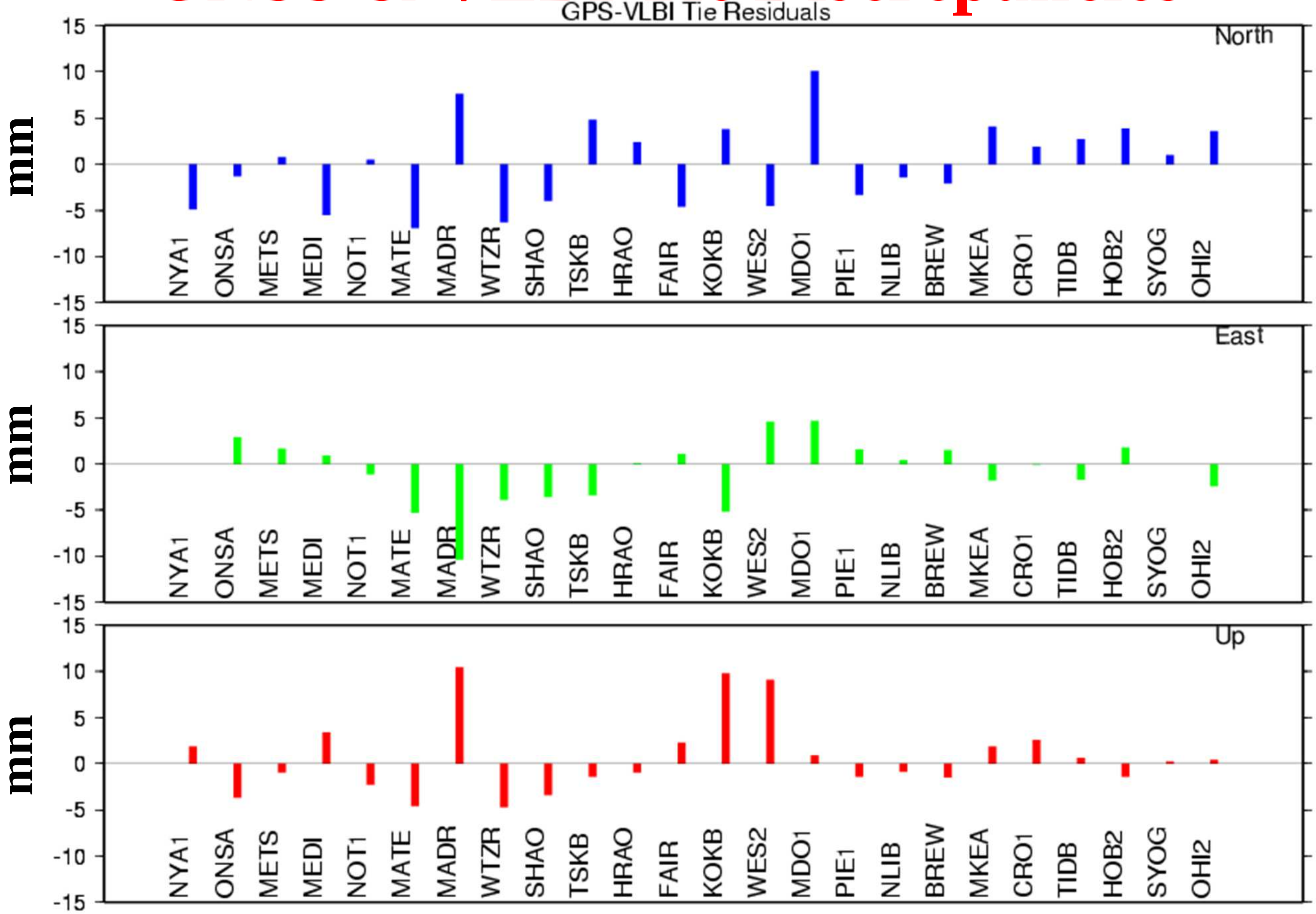
Precision of local survey:
probably not better that 3 mm



Current status of co-locations

- **Without GPS/IGS, we have:**
  - **VLBI-SLR :** **8 co-locations only (5 current)**
  - **VLBI/SLR-DORIS :** **10 co-locations only**
- **IGS-GPS IS the link between SLR, VLBI & DORIS**
- **Is GPS free from site-dependent errors, e.g. uncalibrated radomes ?**

GNSS & VLBI Tie Discrepancies



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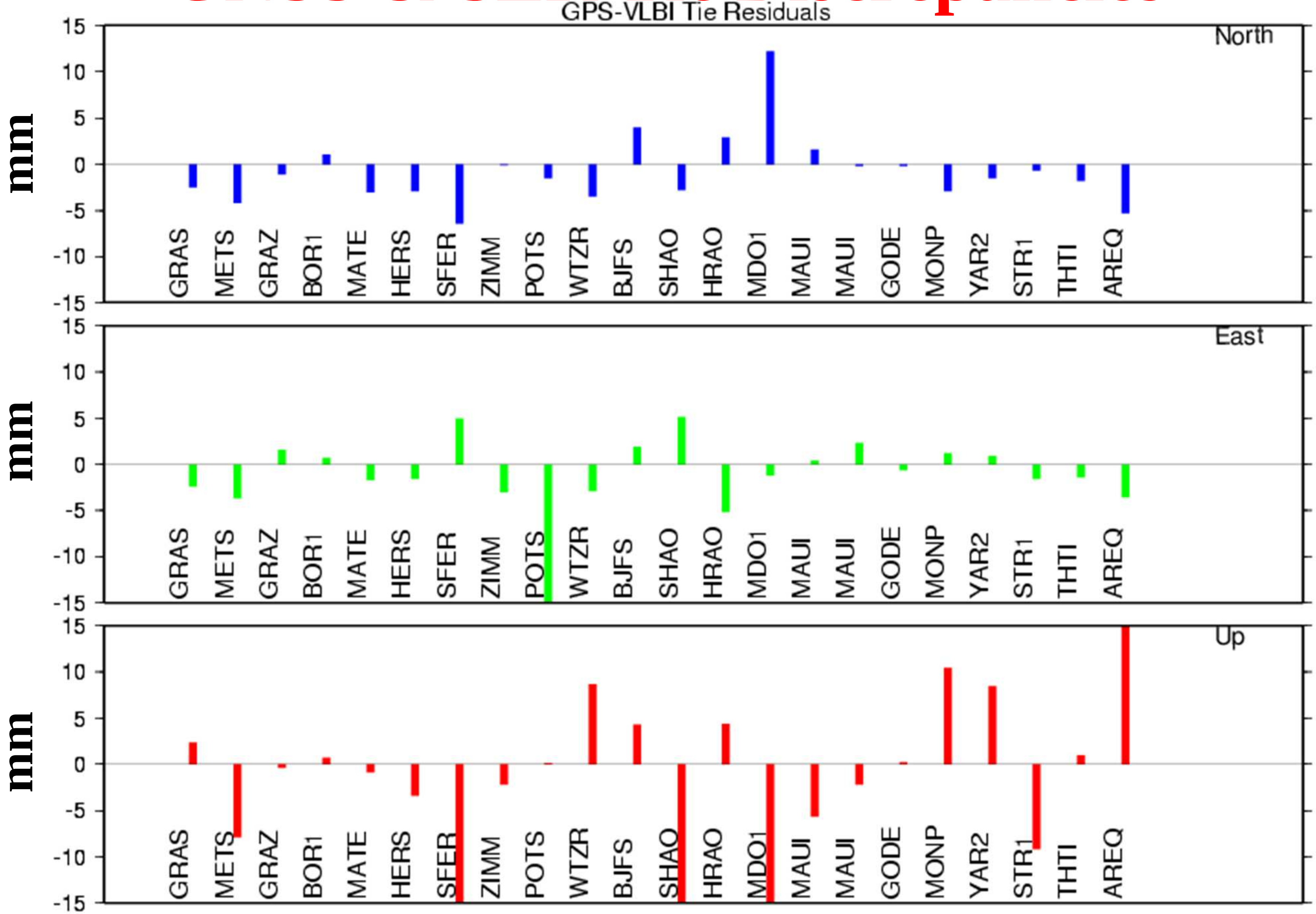
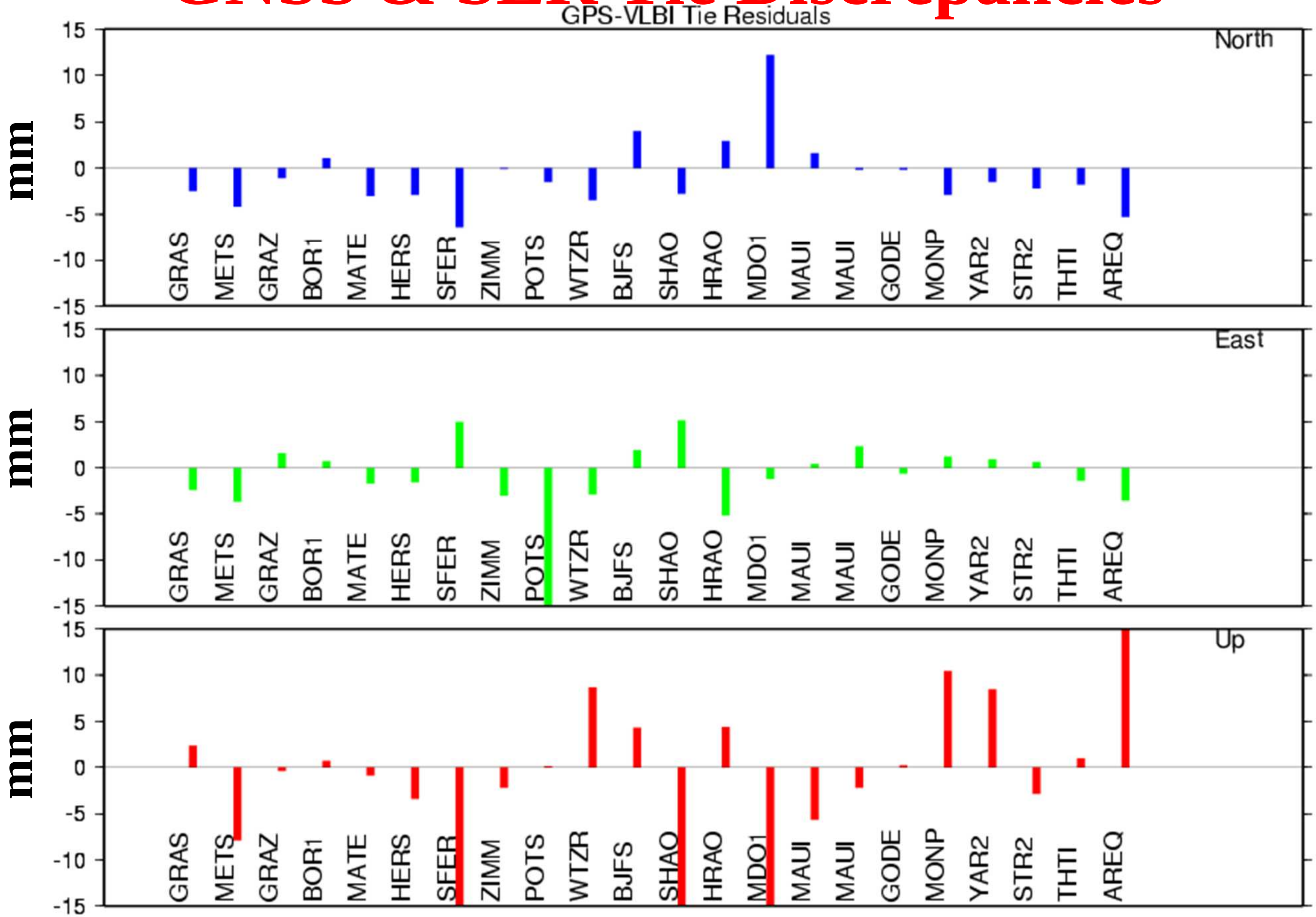
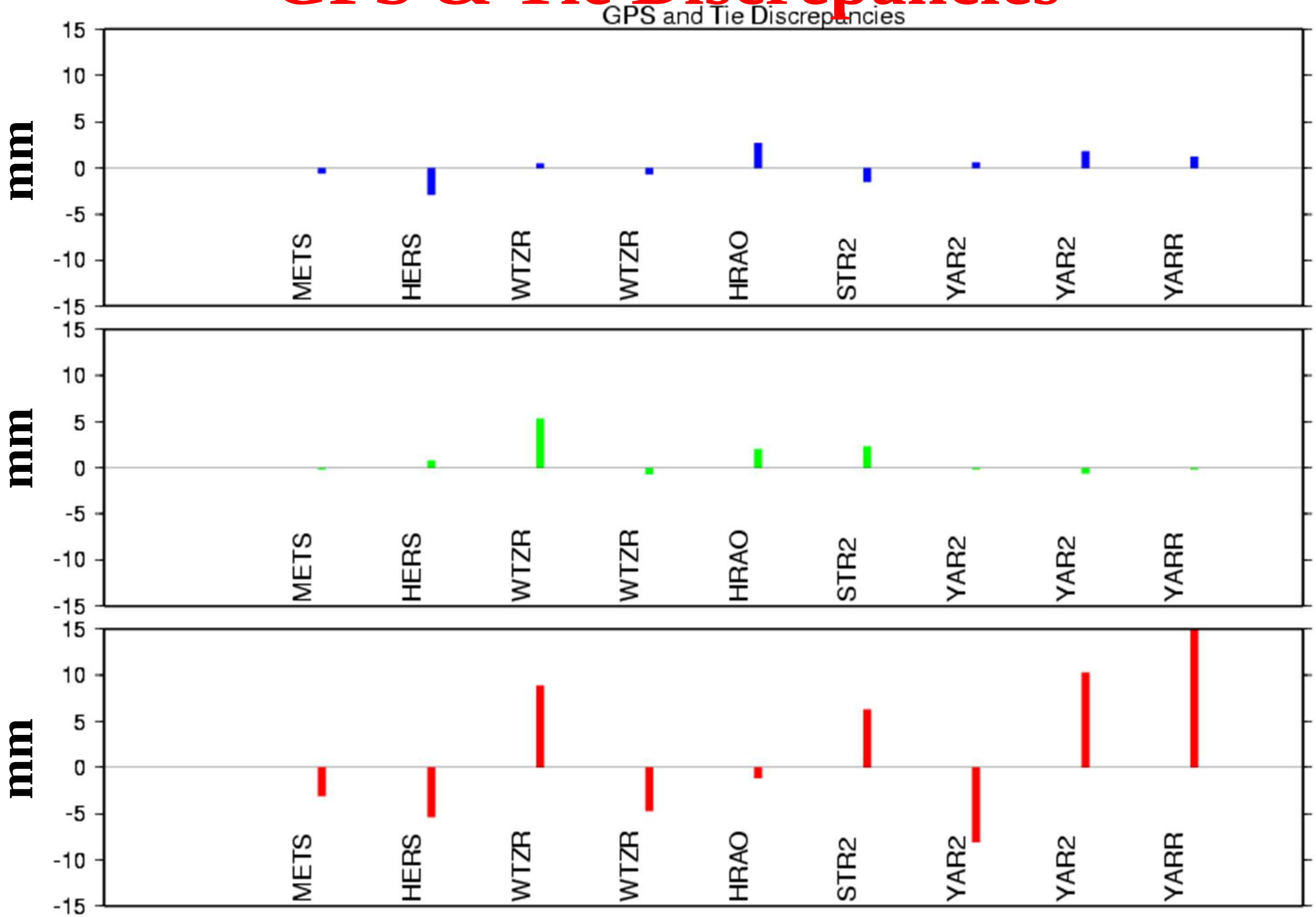
GNSS & SLR Tie Discrepancies



GNSS & SLR Tie Discrepancies

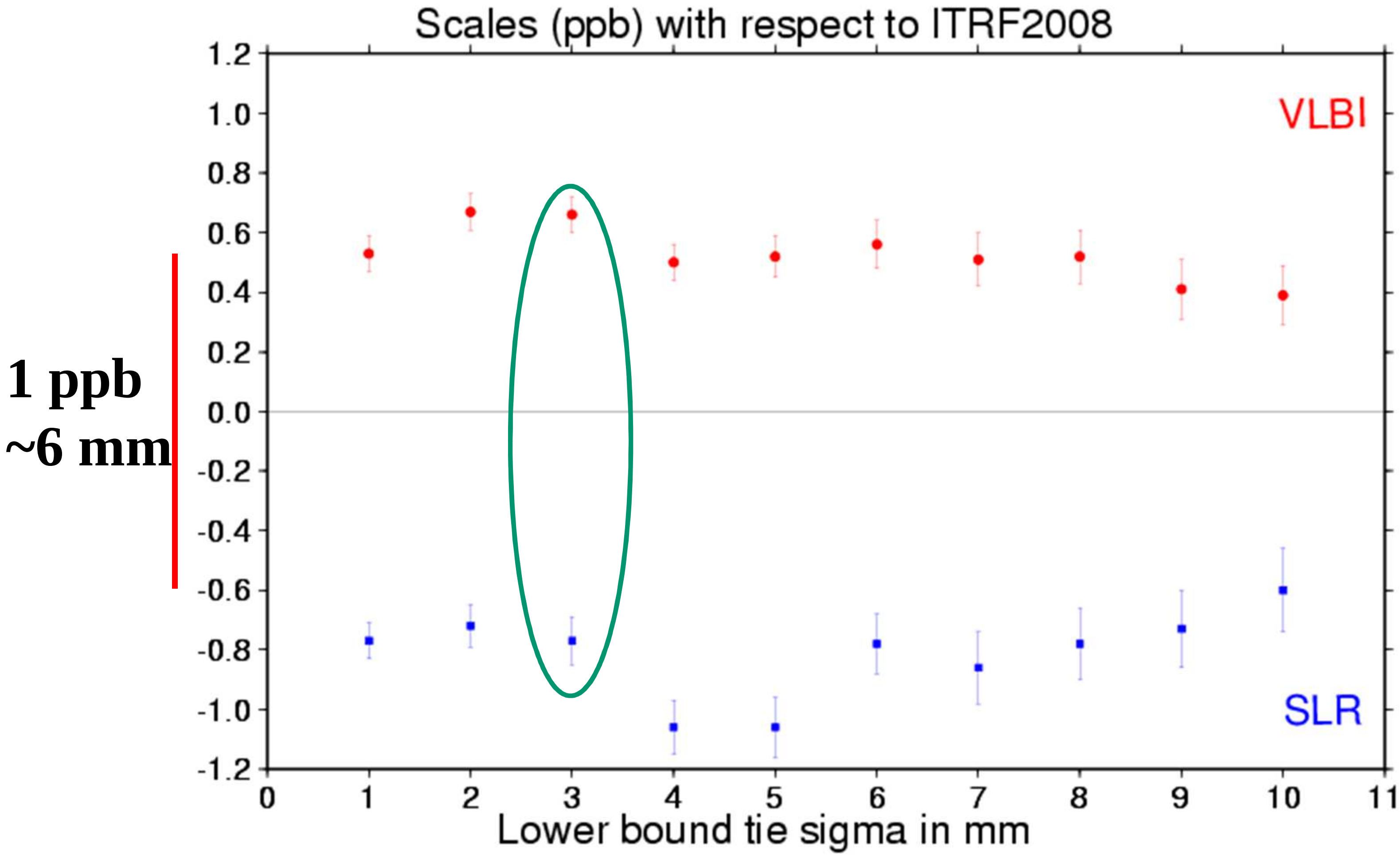


GPS & Tie Discrepancies



Scale Factors of VLBI & SLR wrt ITRF2008

Ten combination tests, varying the lower bound tie sigma



Still preliminary

3 mm as lower bound tie sigma is used in this analysis

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Technique systematic errors

Technique Systematic Errors: GNSS

- GNSS do not "see" the true geocenter (PhD work of Paul Rebischung)
- Under-determined TRF scale due to PCVs & PCOs of the ground & satellite antennas;
- Uncalibrated radomes (can be >1 cm errors)
- Local environment, esp near antenna (can be >1 cm)
- 50 % of the IGS sites have discontinuities in the position time series due to equipment changes

==>Serious impact on site velocities

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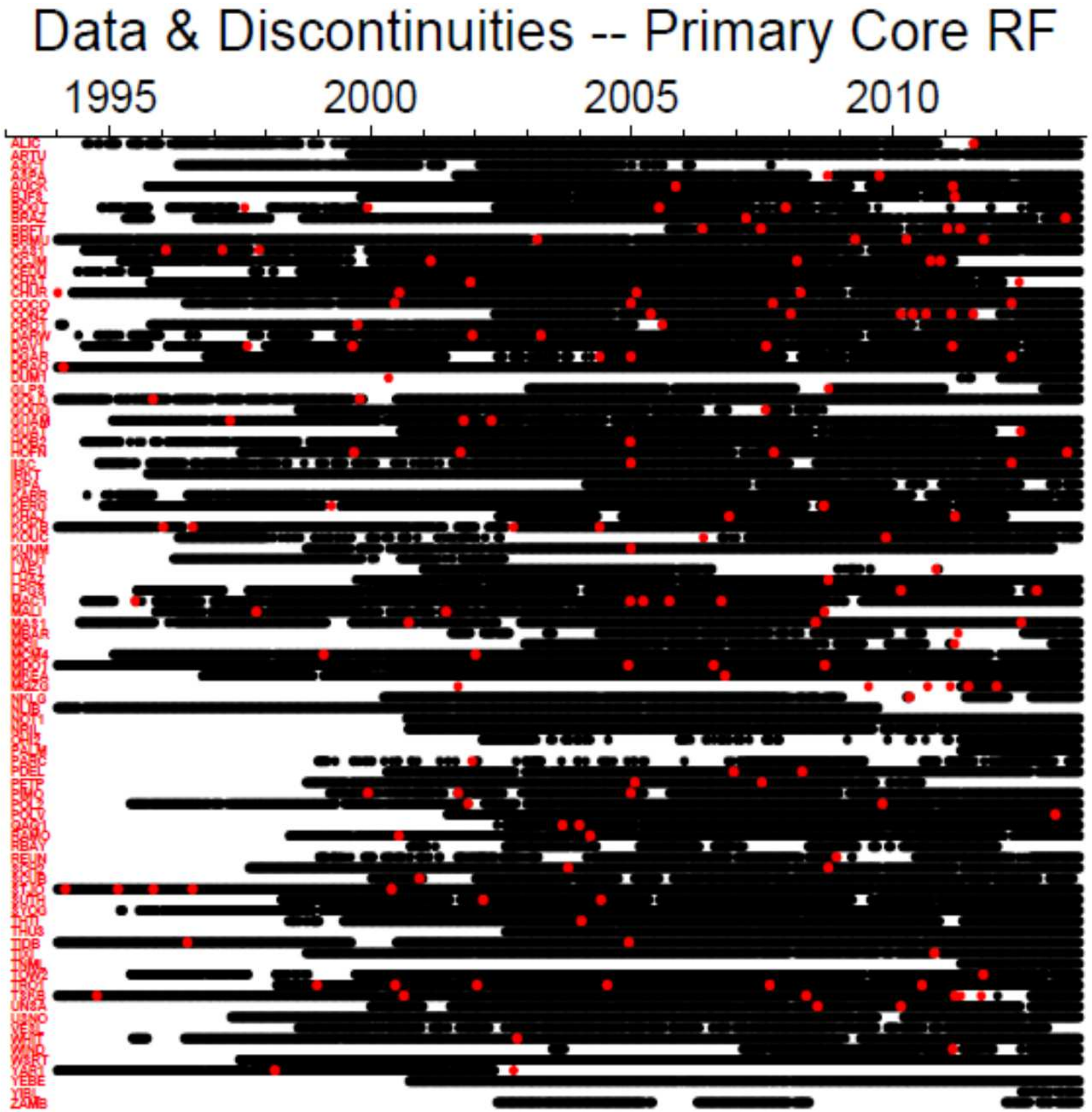
IGS/GNSS data availability for RF sites



- Discontinuities

Courtesy Jim Ray

Technique Systematic Errors: VLBI

- **Sparse sessions, not all designed for the reference frame (see next animation for sessions in 2011)**
  - **Usually 6-8 stations, twice a week –rarely ~20 stations**
- **Axis offset errors, (Sarti et al., 2011)**
- **Elevation-dependent antenna deformations, esp. for large antennas (can be ~1 cm height effect), (Sarti et al., 2009)**

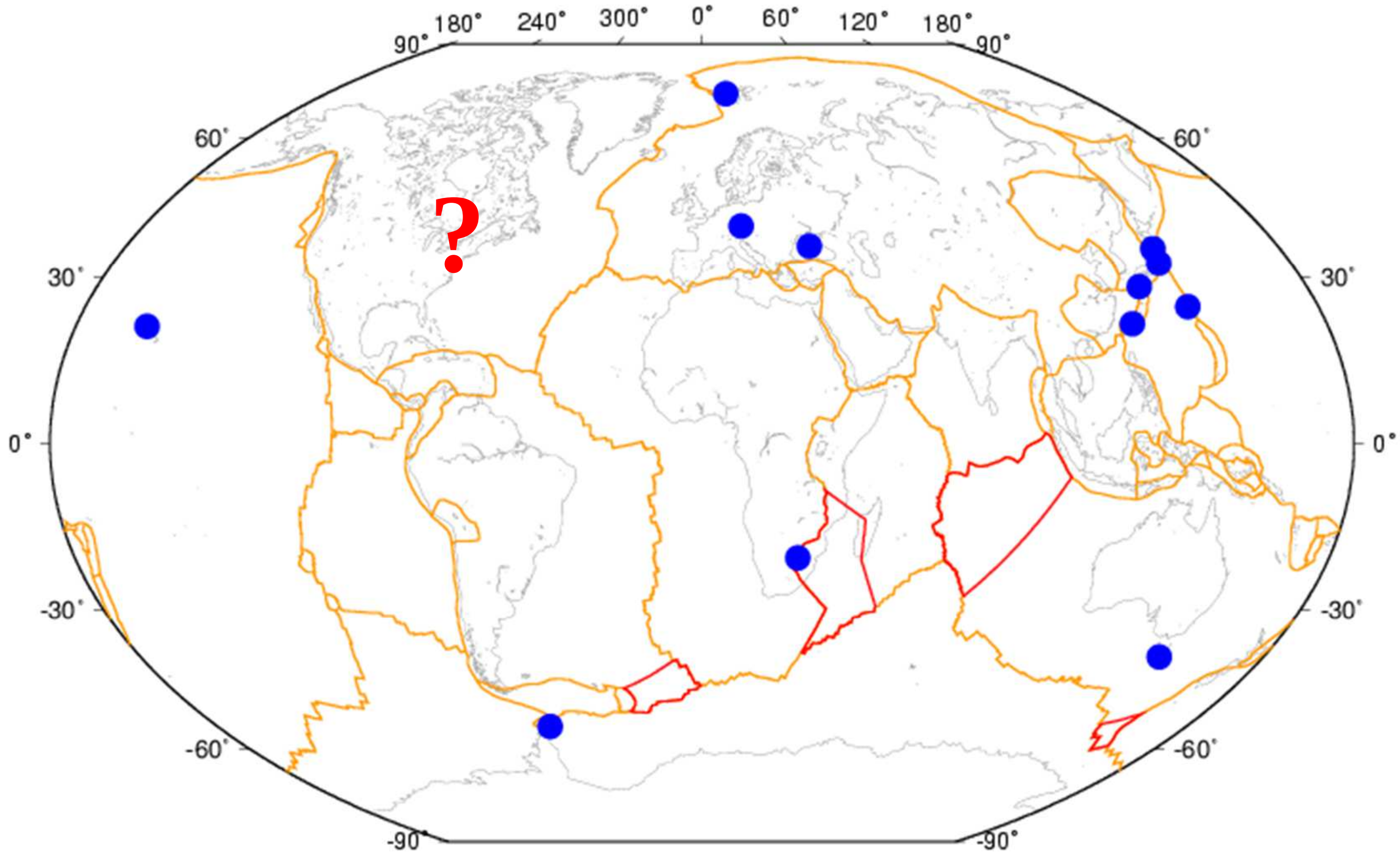
In the following slides :
Animation of VLBI site distribution

- **Per session during February 2011: 14 sessions – duration: 14 seconds**

And then:

- **Per month during 2011: duration: 12 seconds**

VLBI session February 01, 2011



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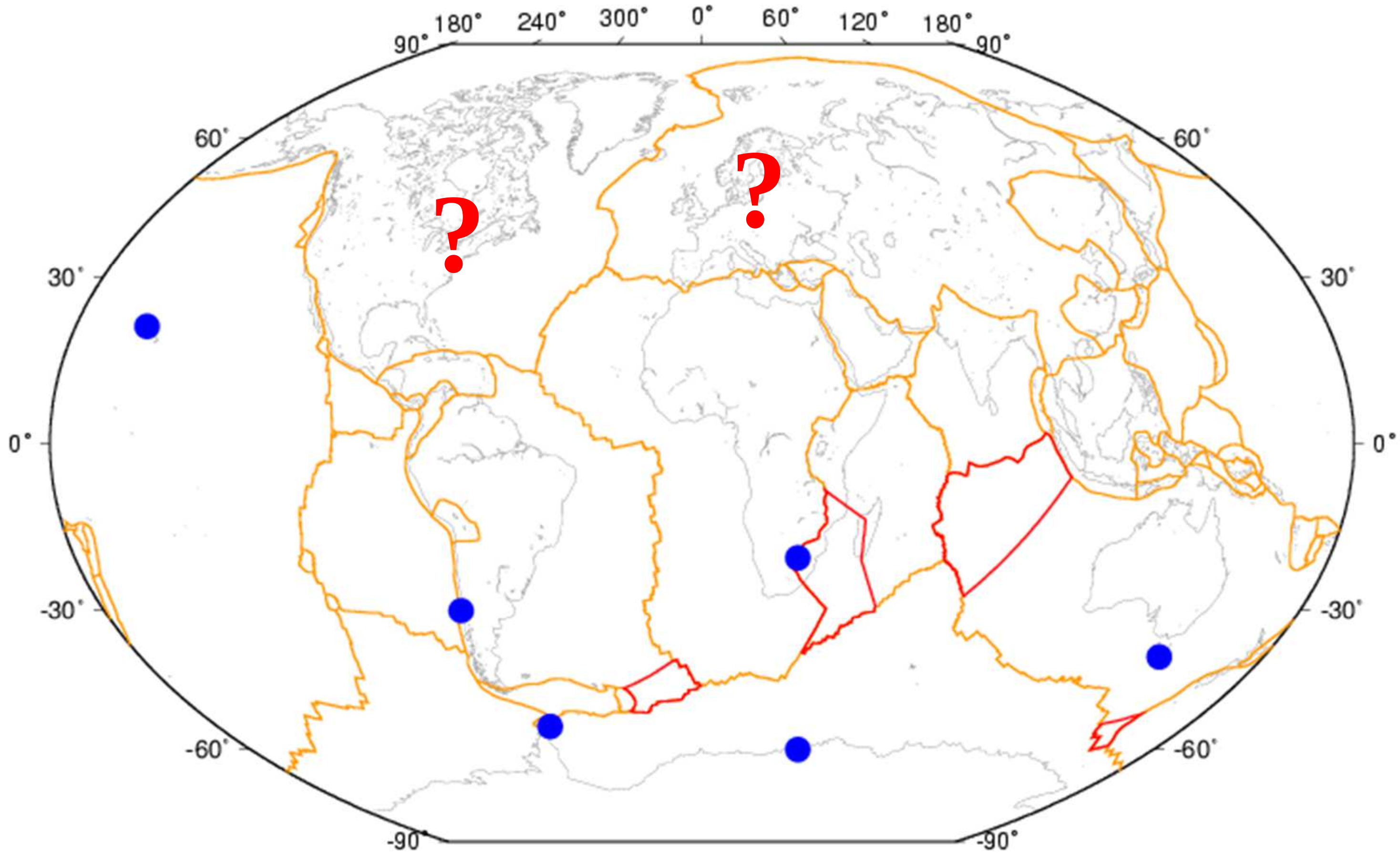
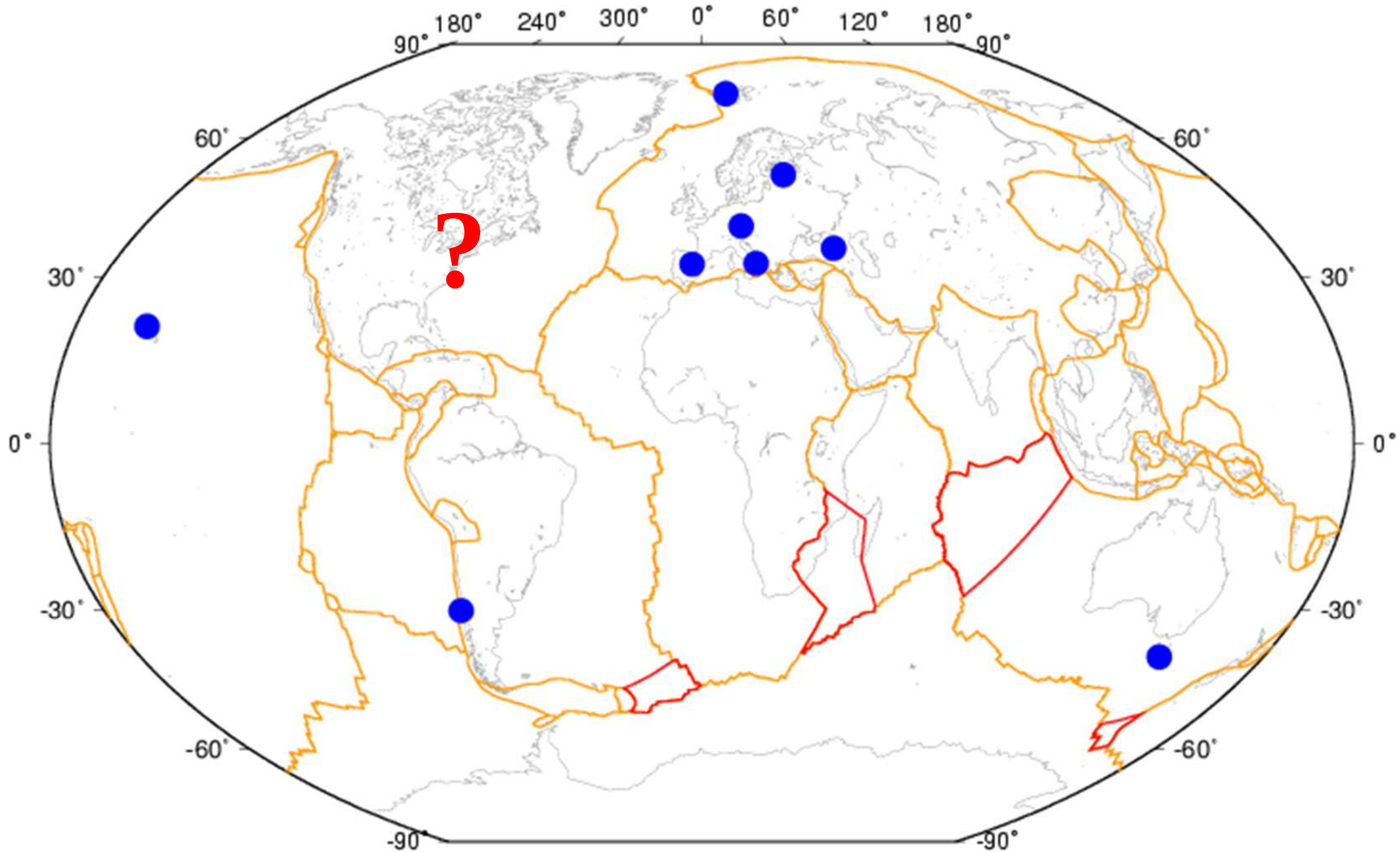
VLBI session February 02, 2011



VLBI session February 03, 2011



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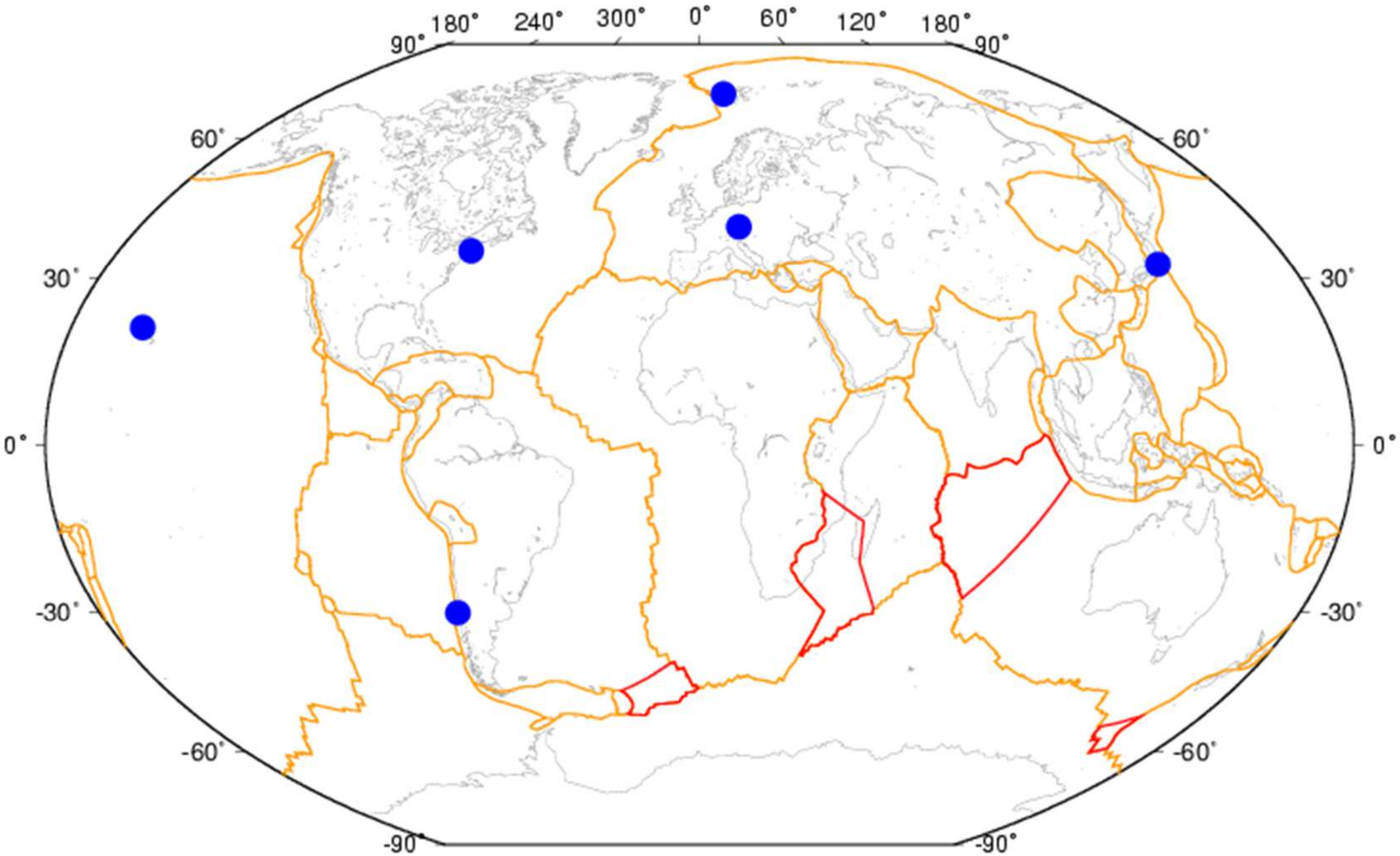
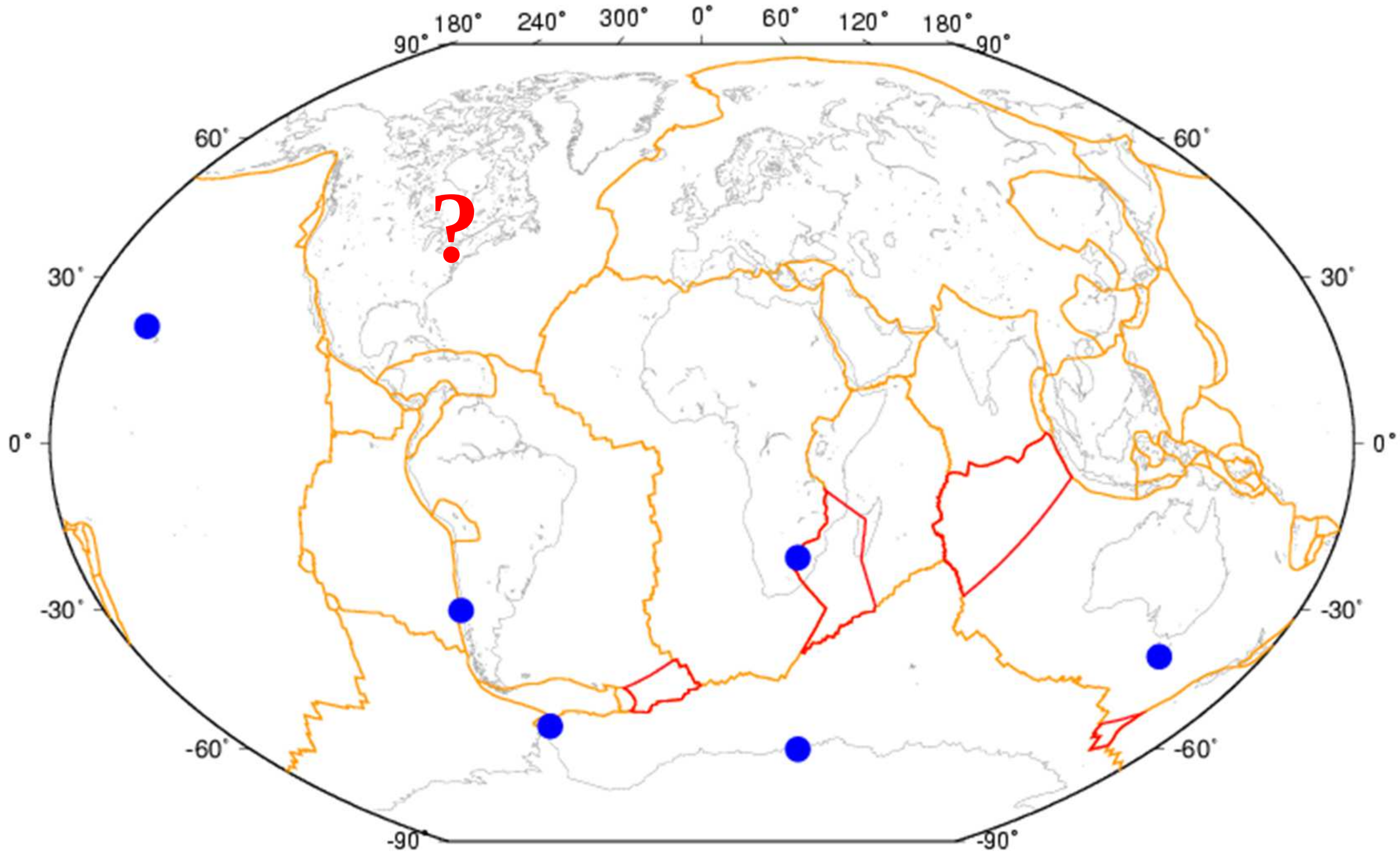
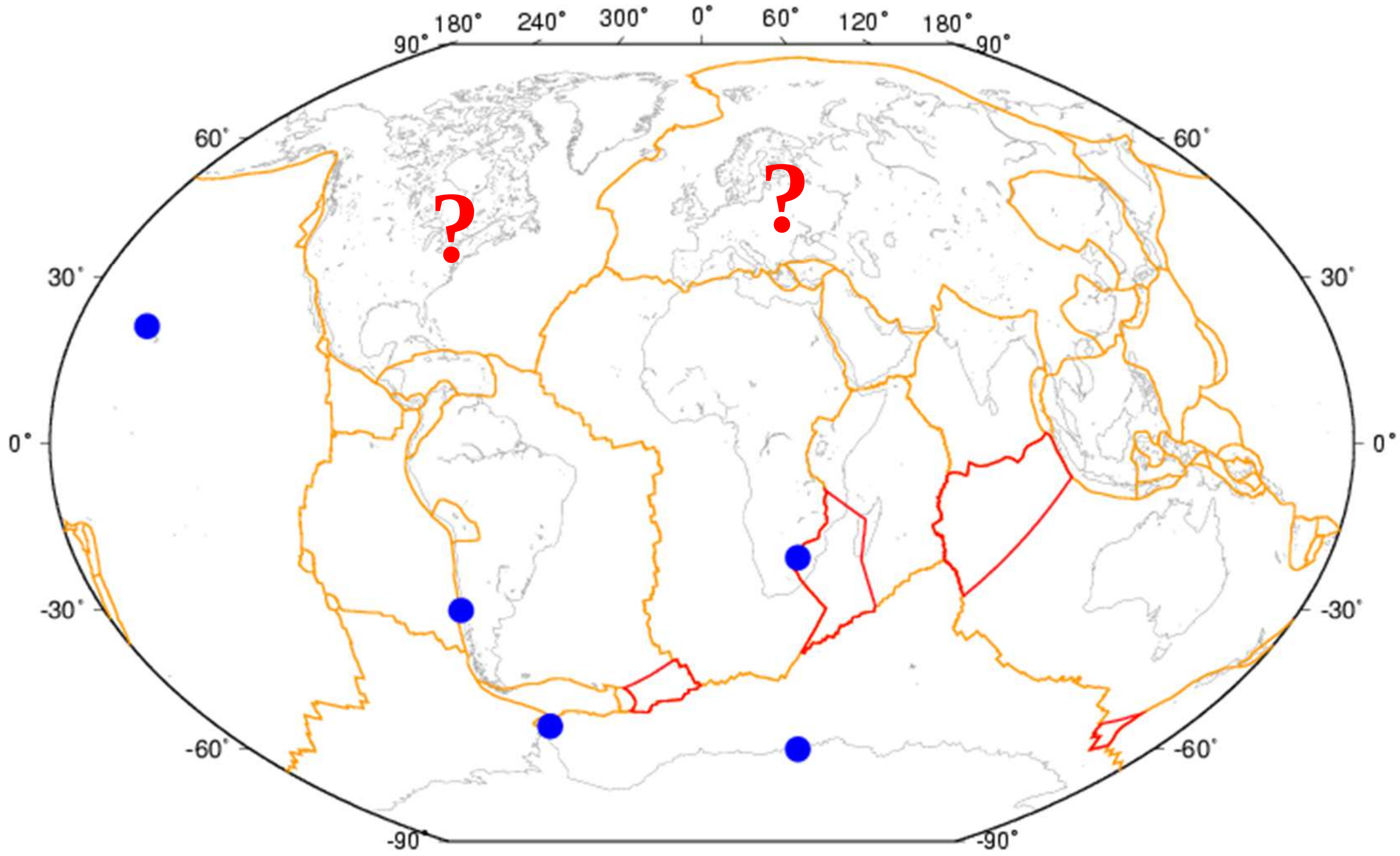
VLBI session February 07, 2011



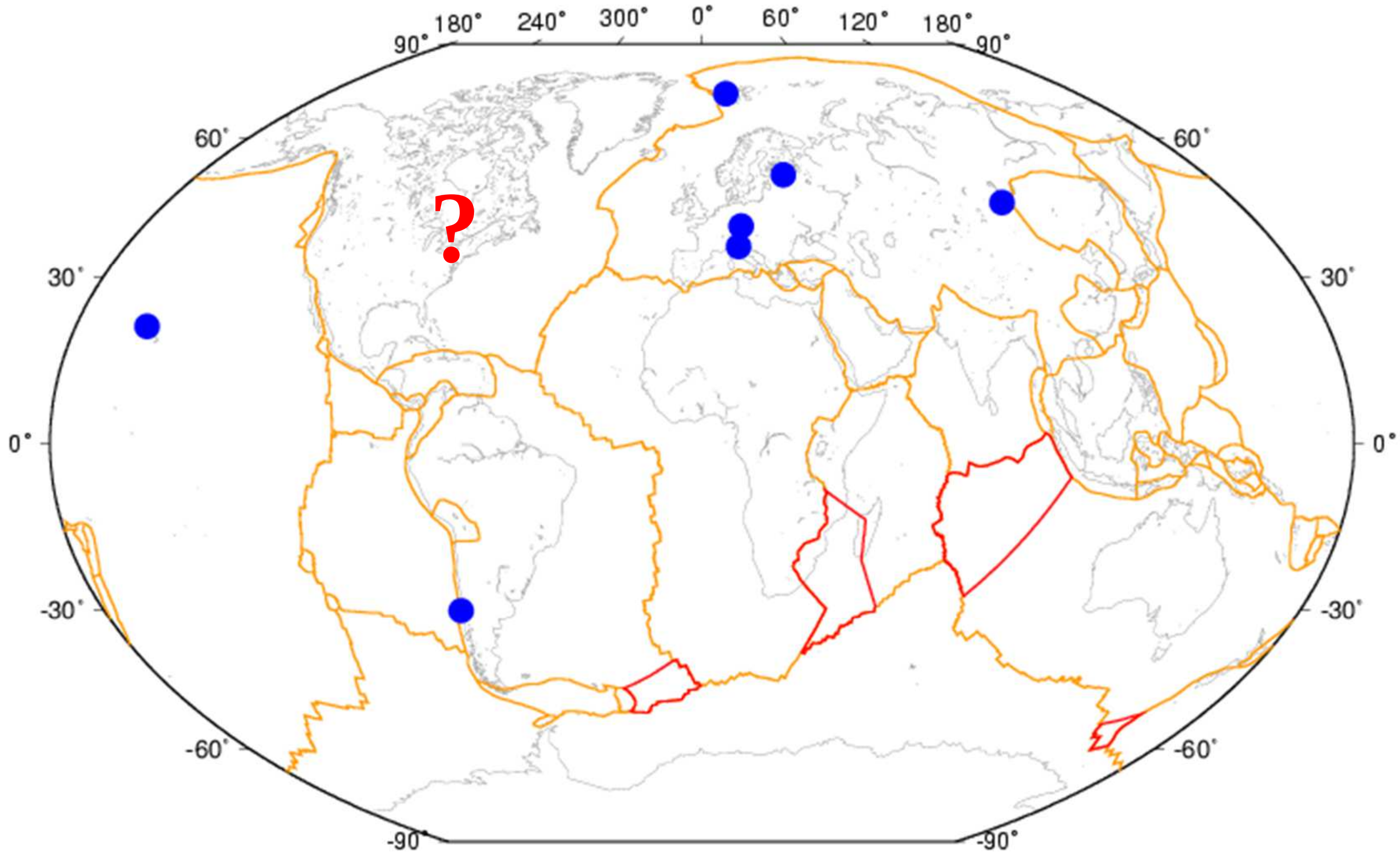
VLBI session February 08, 2011



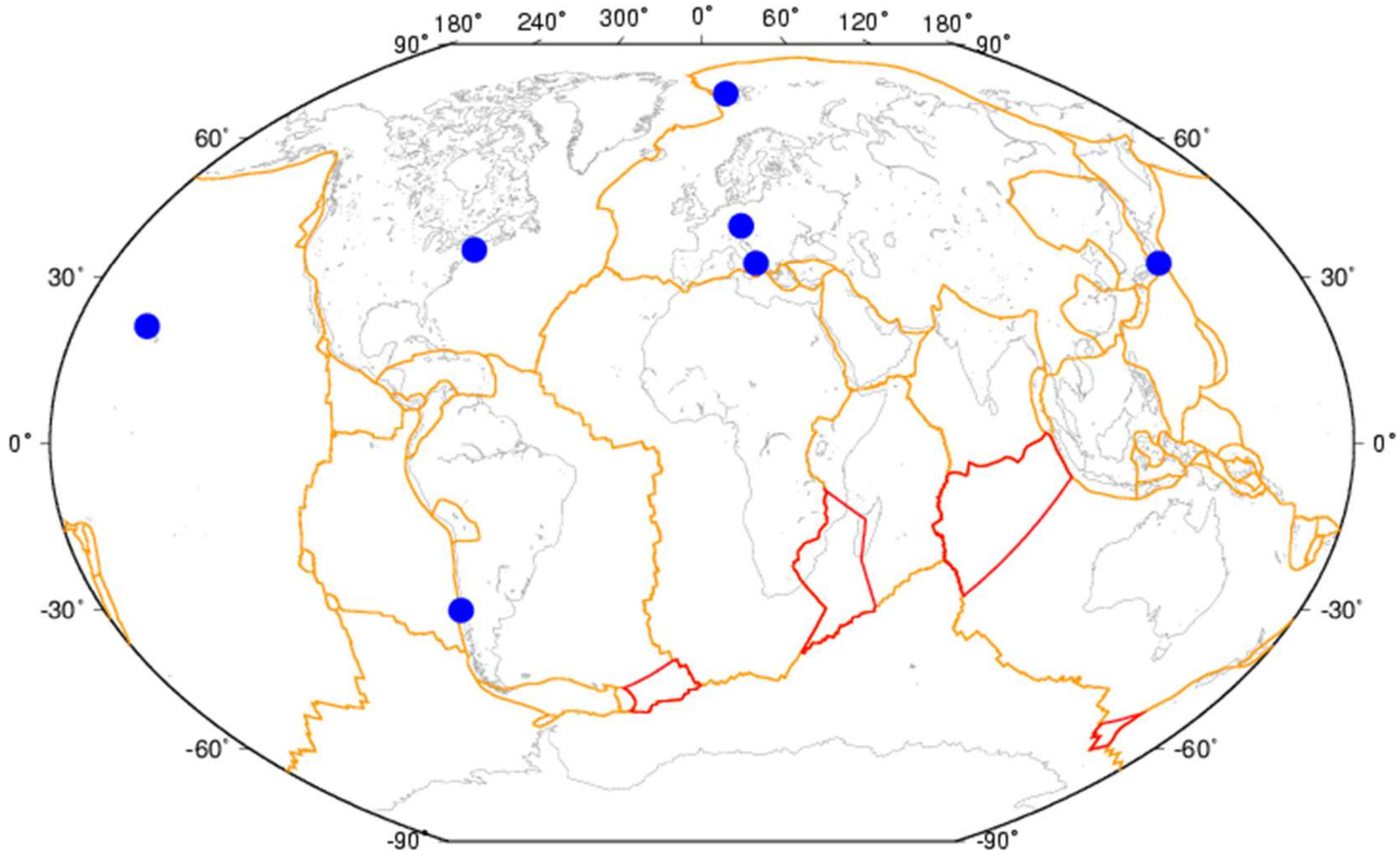
VLBI session February 09, 2011



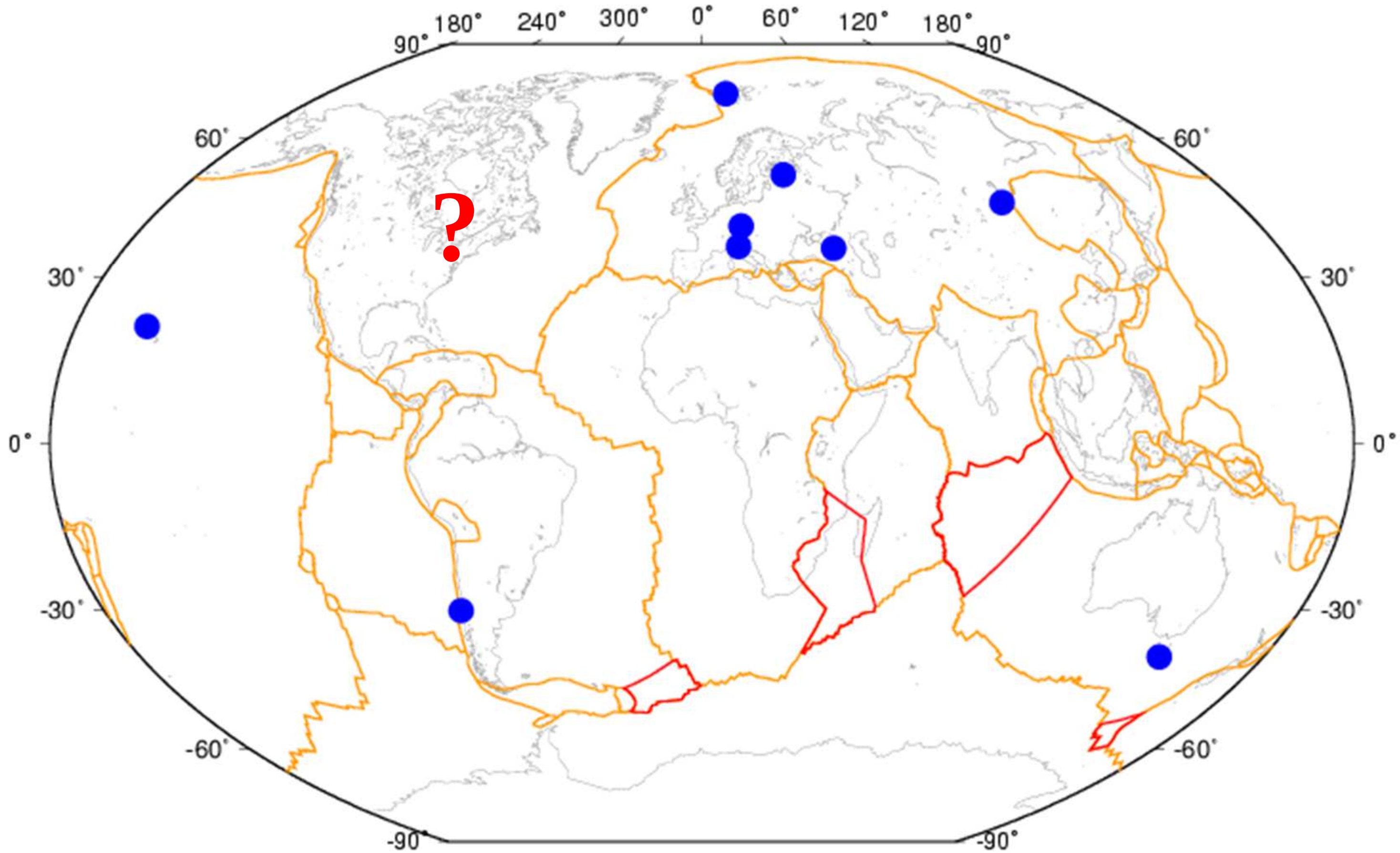
VLBI session February 10, 2011



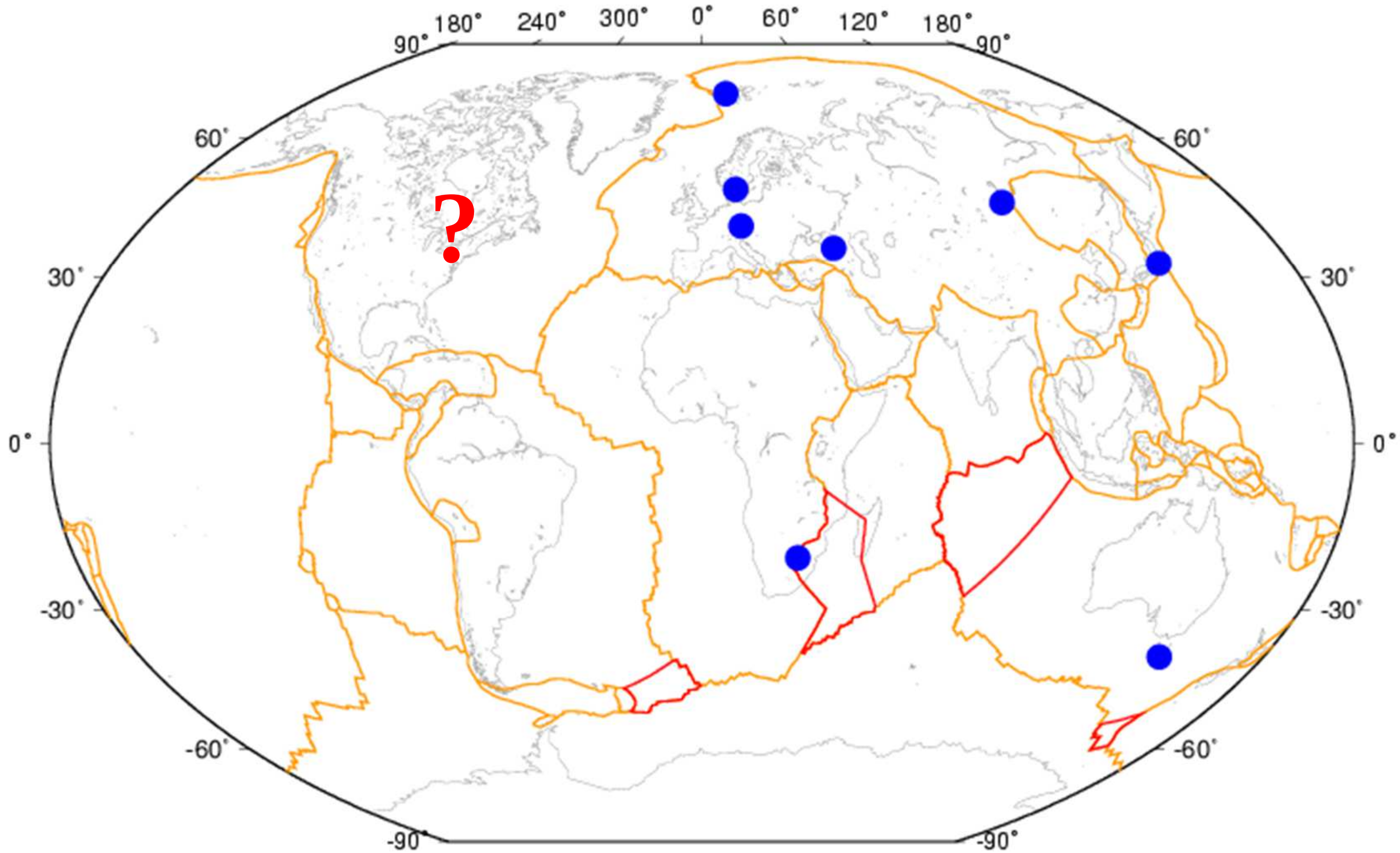
VLBI session February 14, 2011



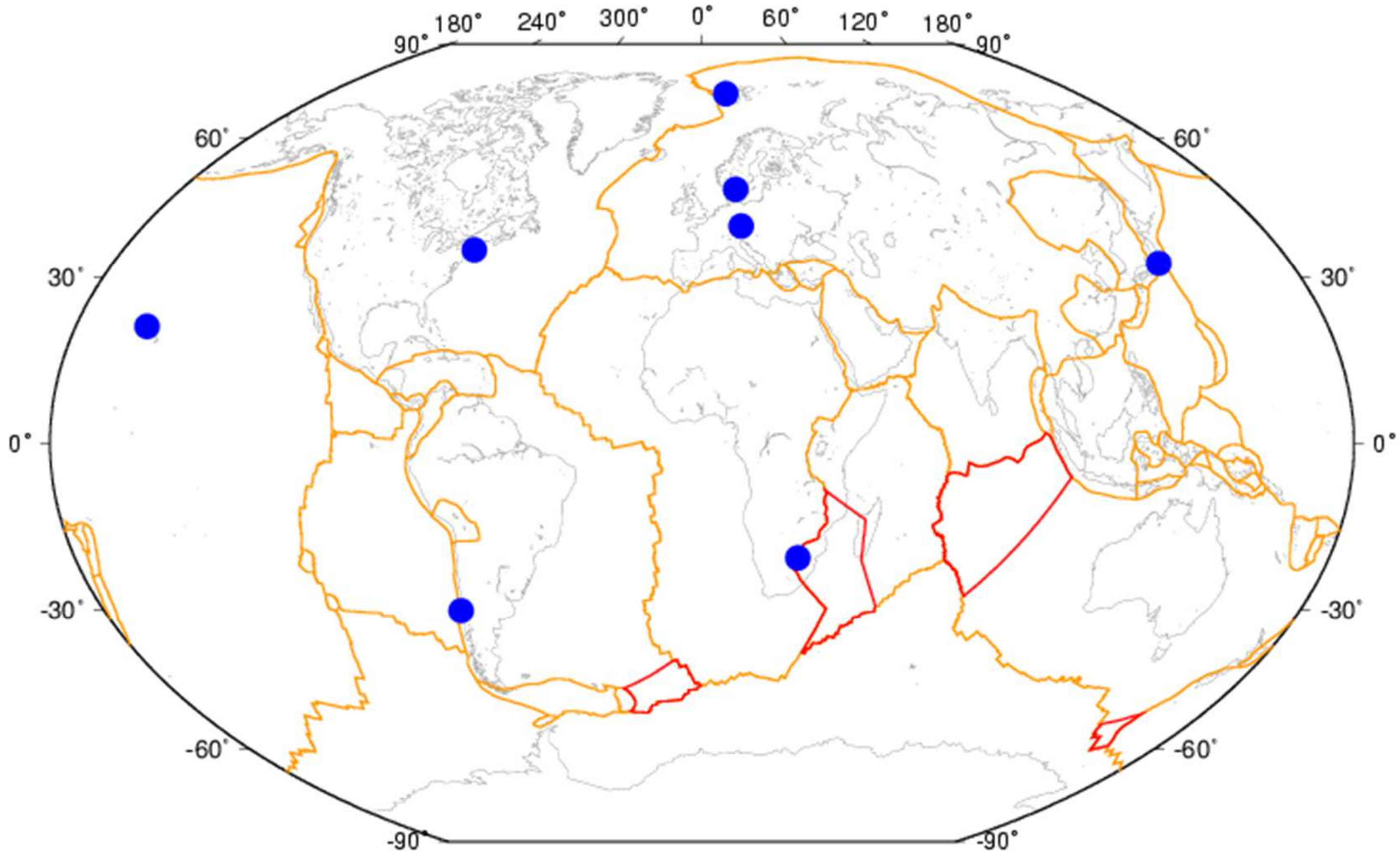
VLBI session February 17, 2011



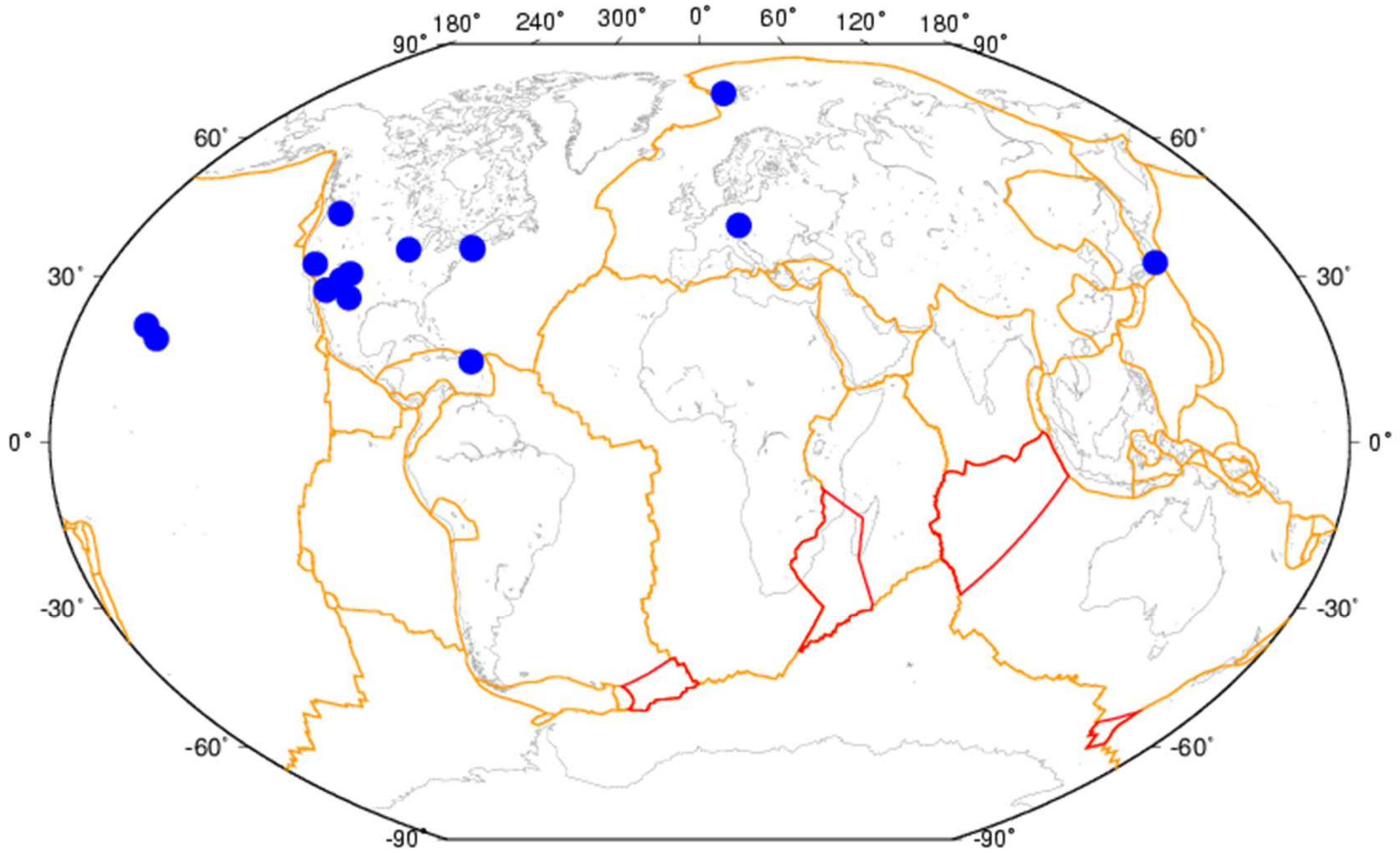
VLBI session February 21, 2011



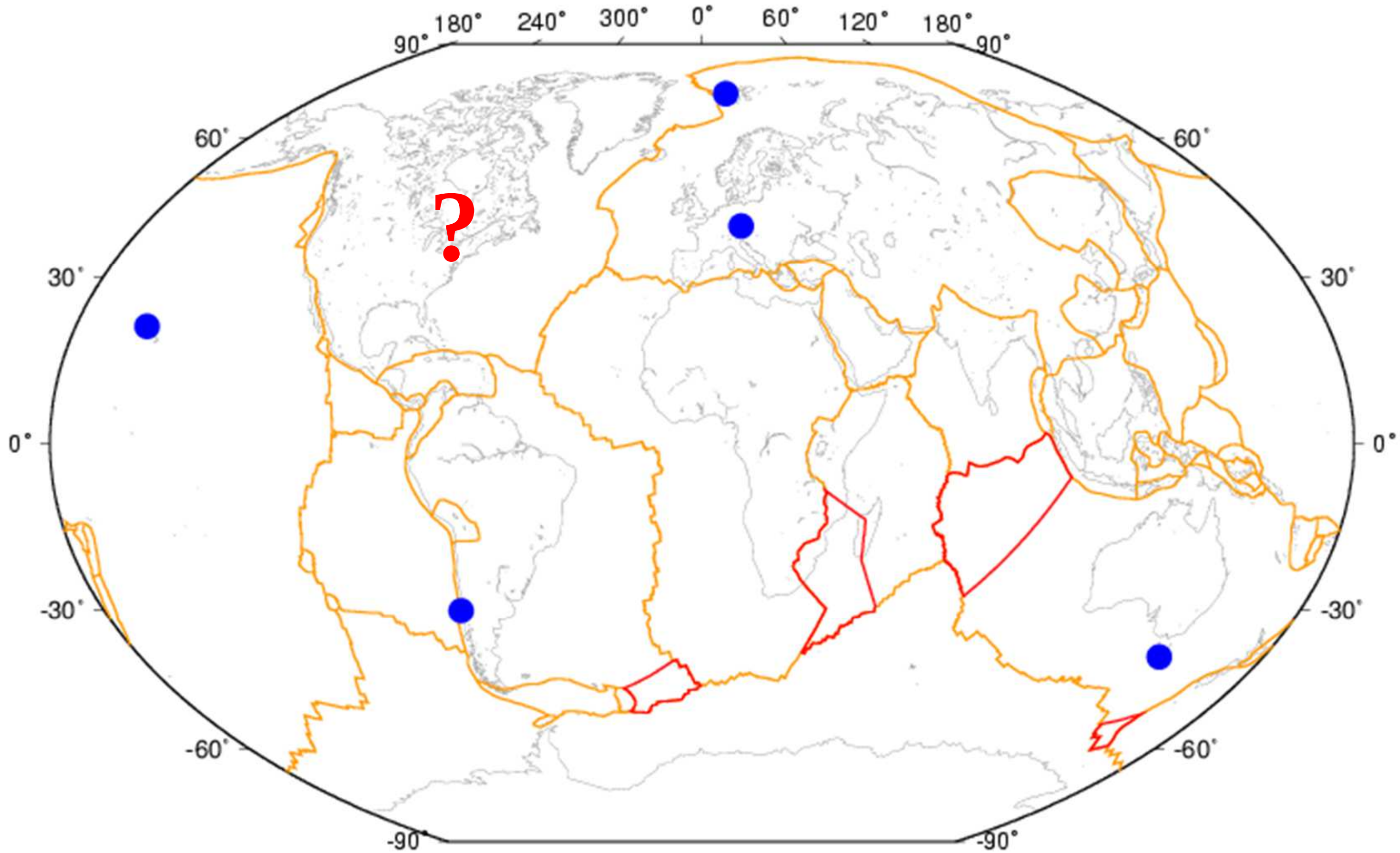
VLBI session February 22, 2011



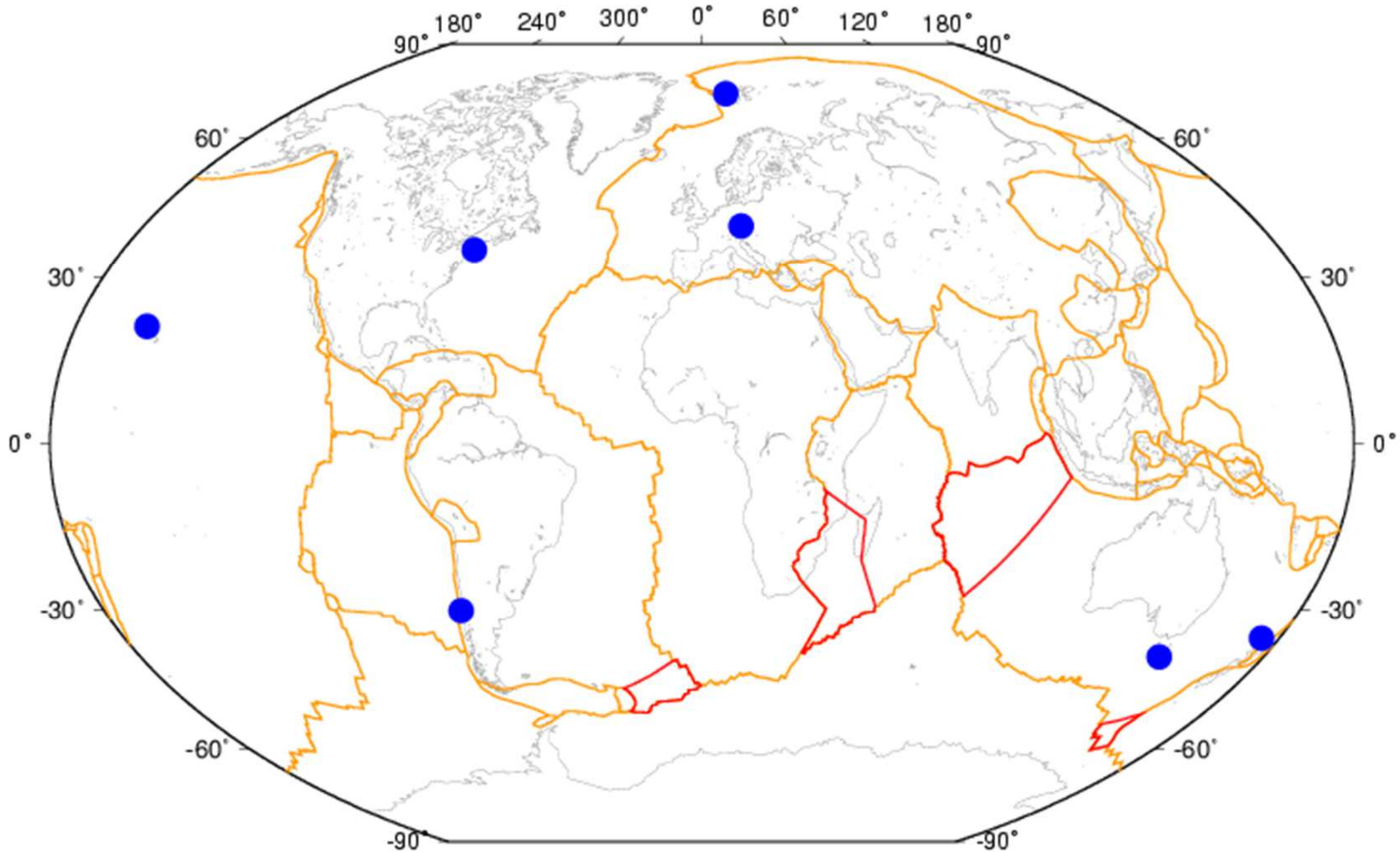
VLBI session February 23, 2011



VLBI session February 24, 2011

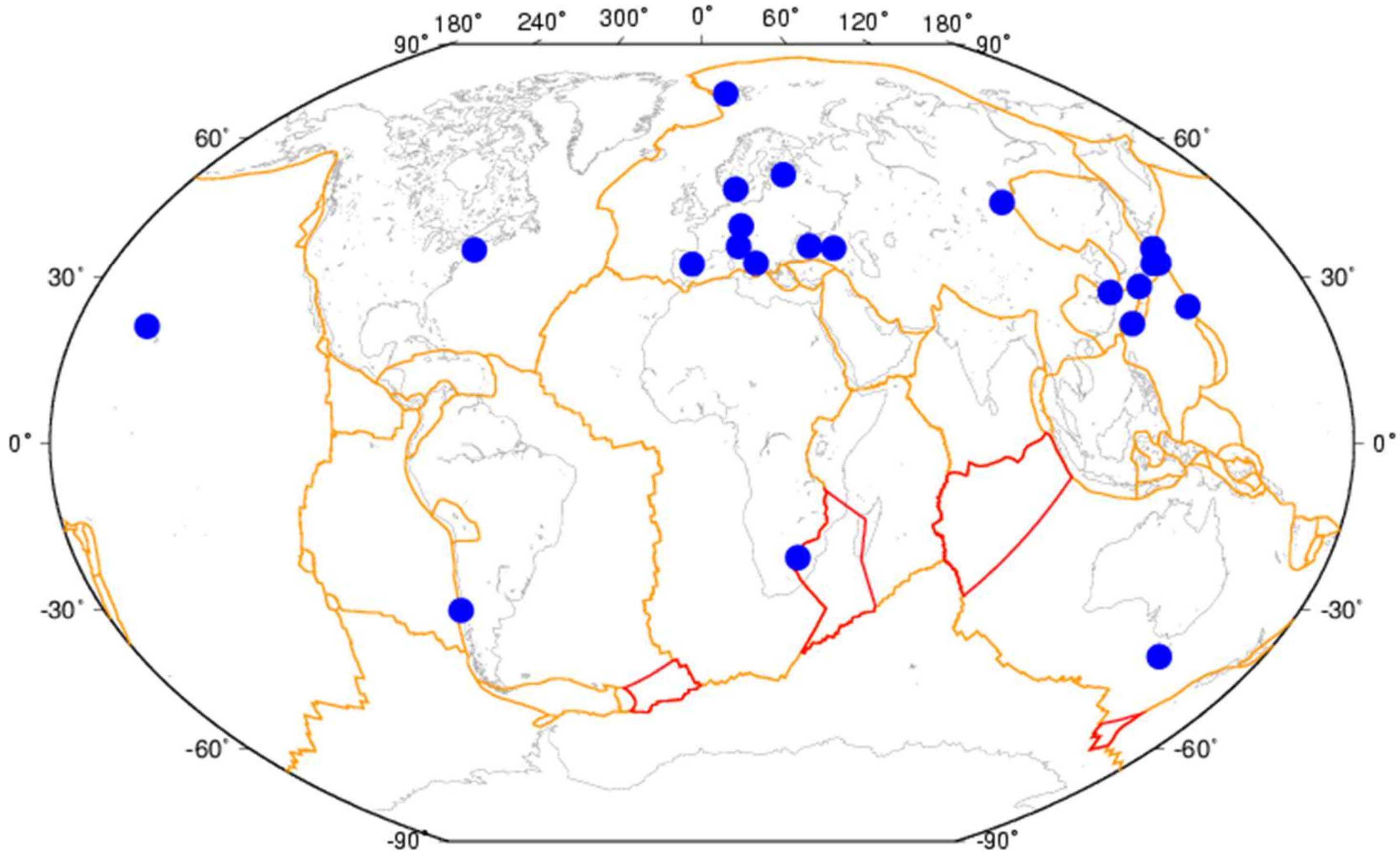


VLBI session February 28, 2011

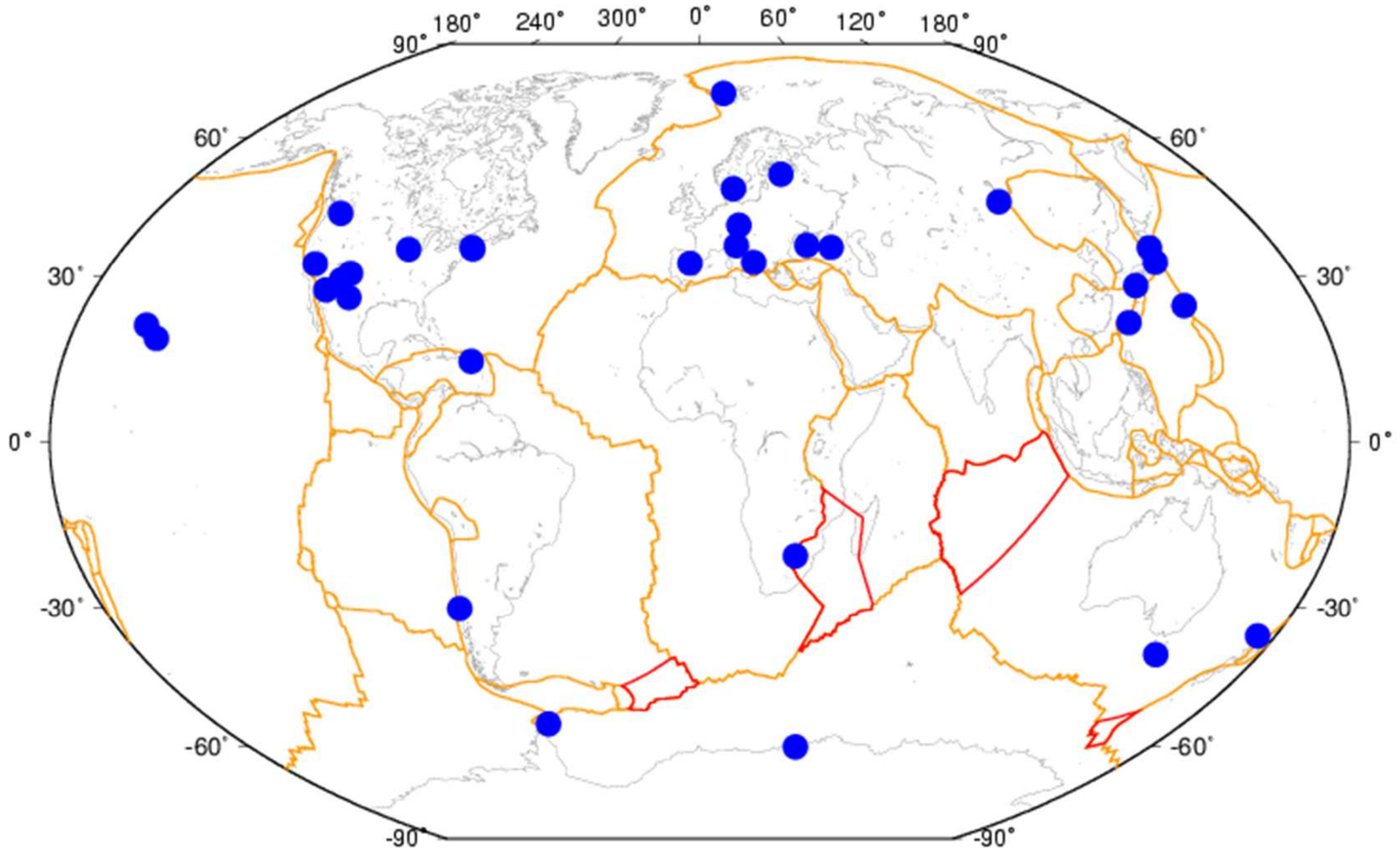


And now VLBI observed sites per month, during 2011

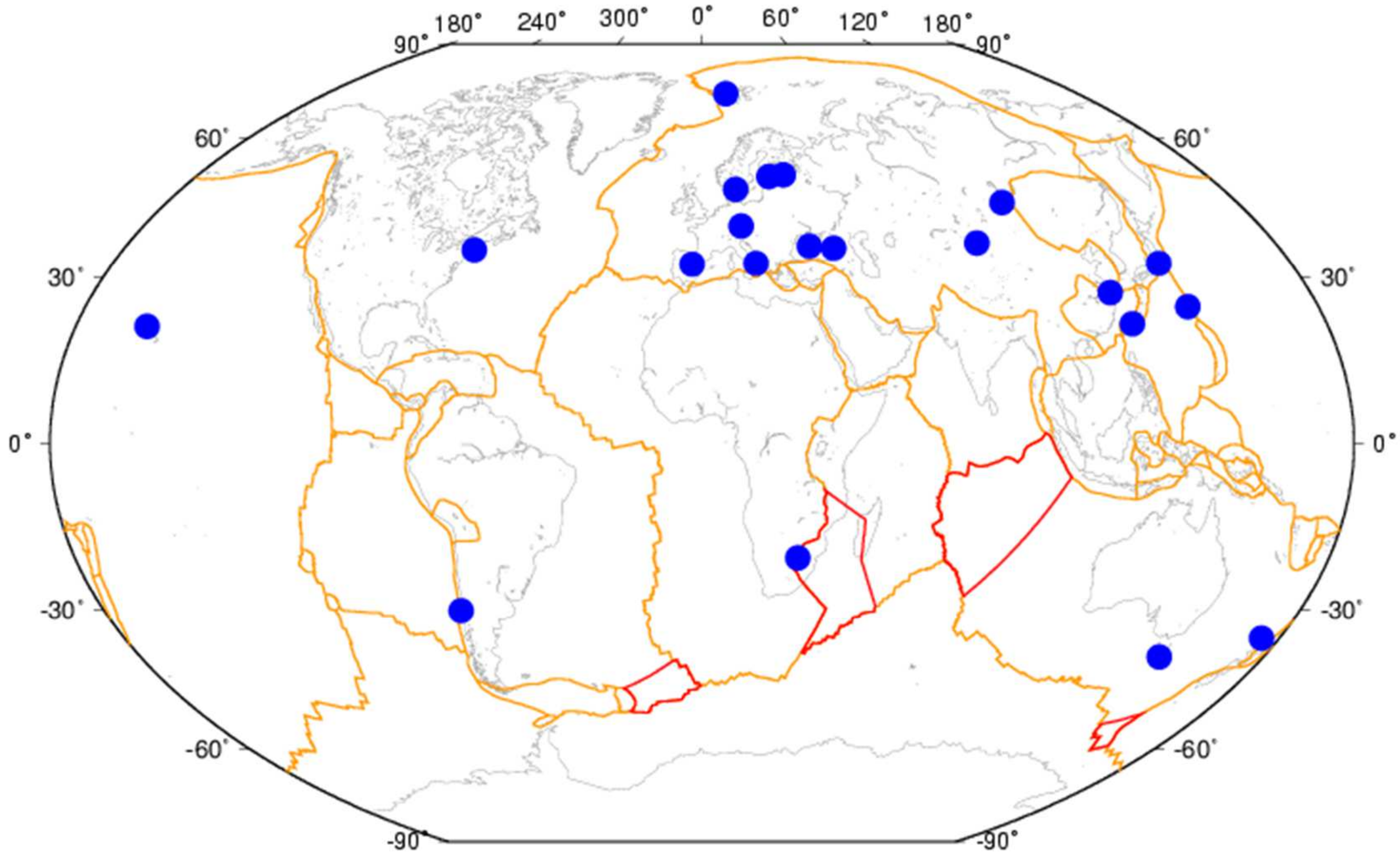
VLBI observed sites January



VLBI observed sites February



VLBI observed sites March



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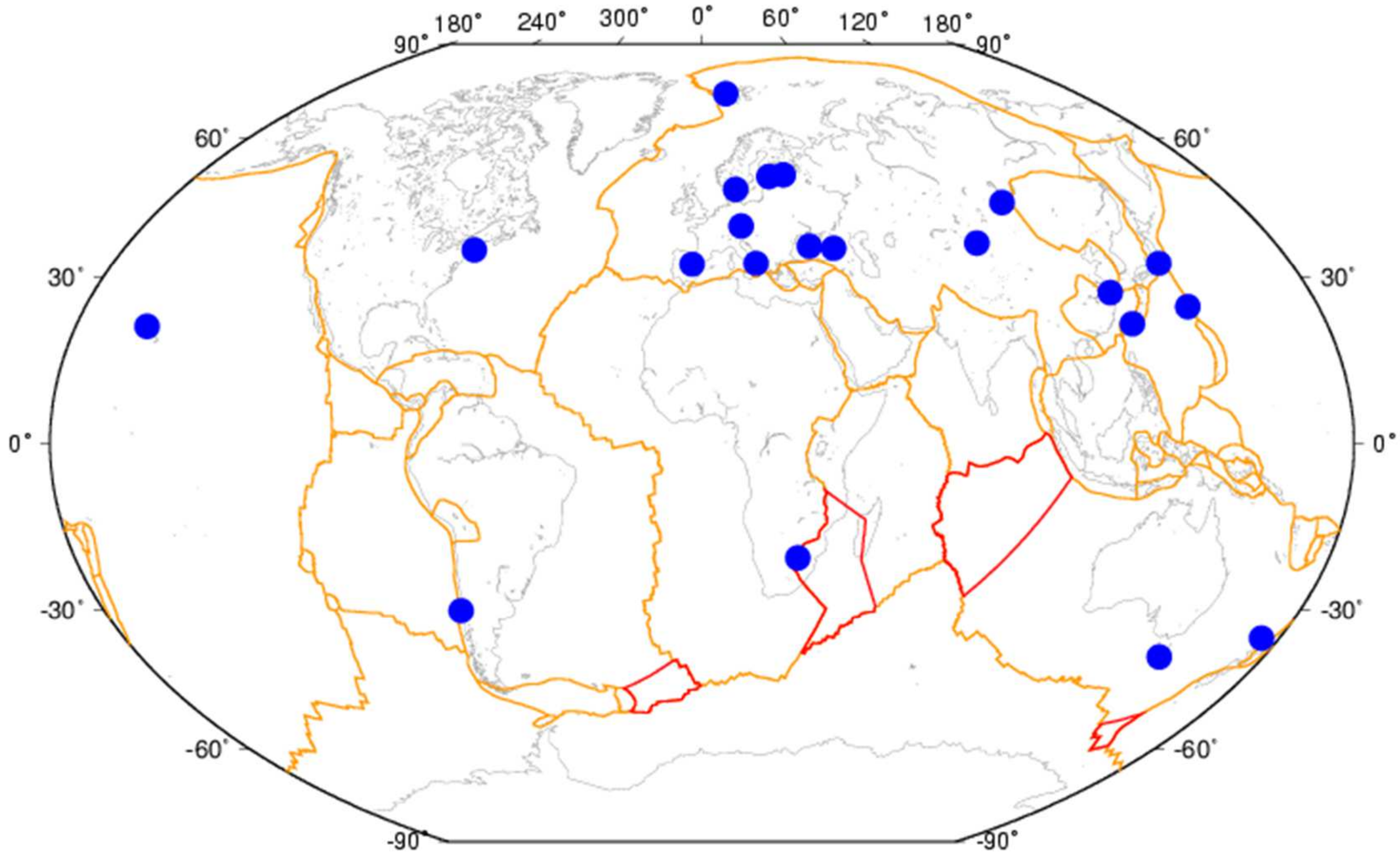
VLBI observed sites April



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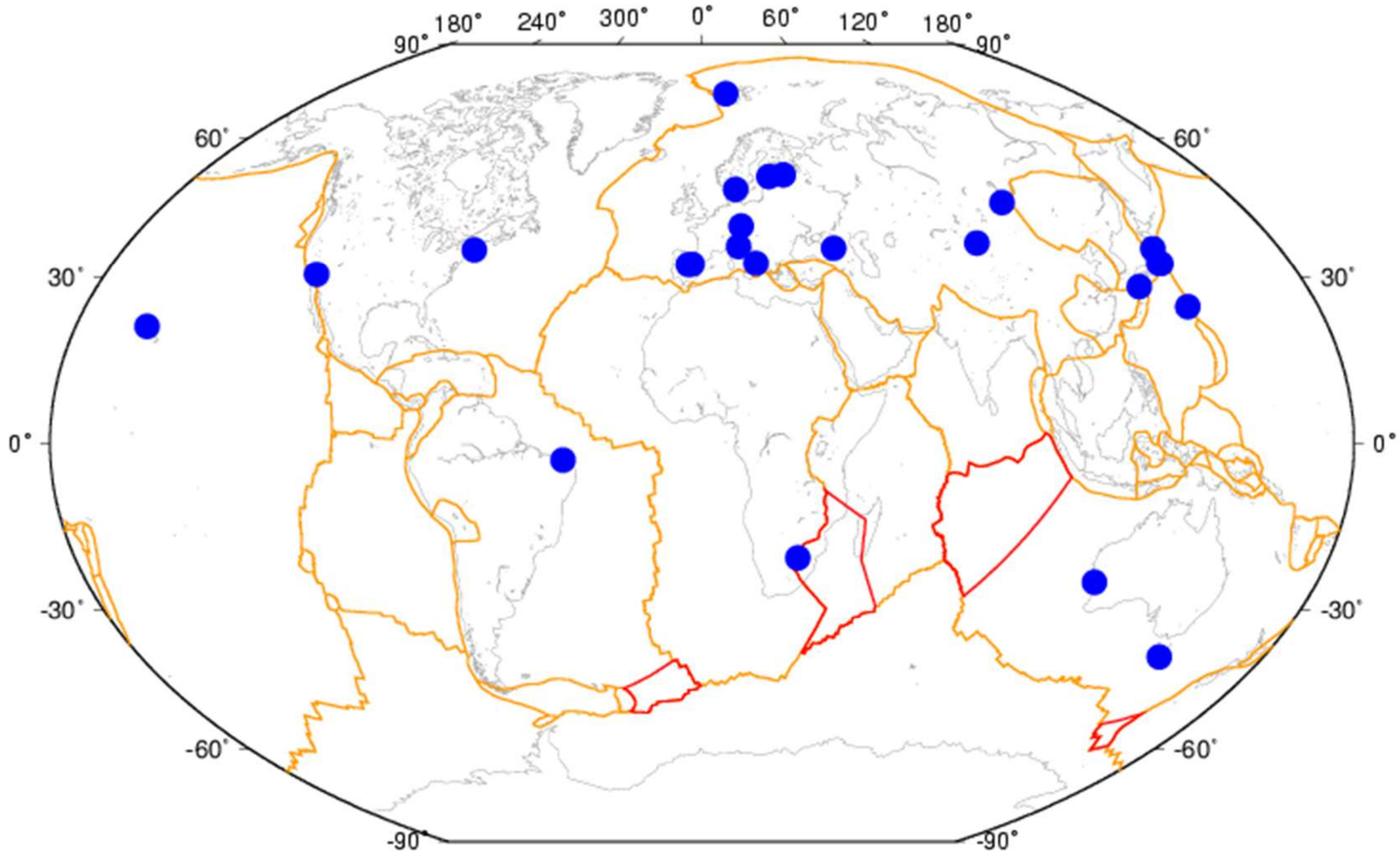
VLBI observed sites May



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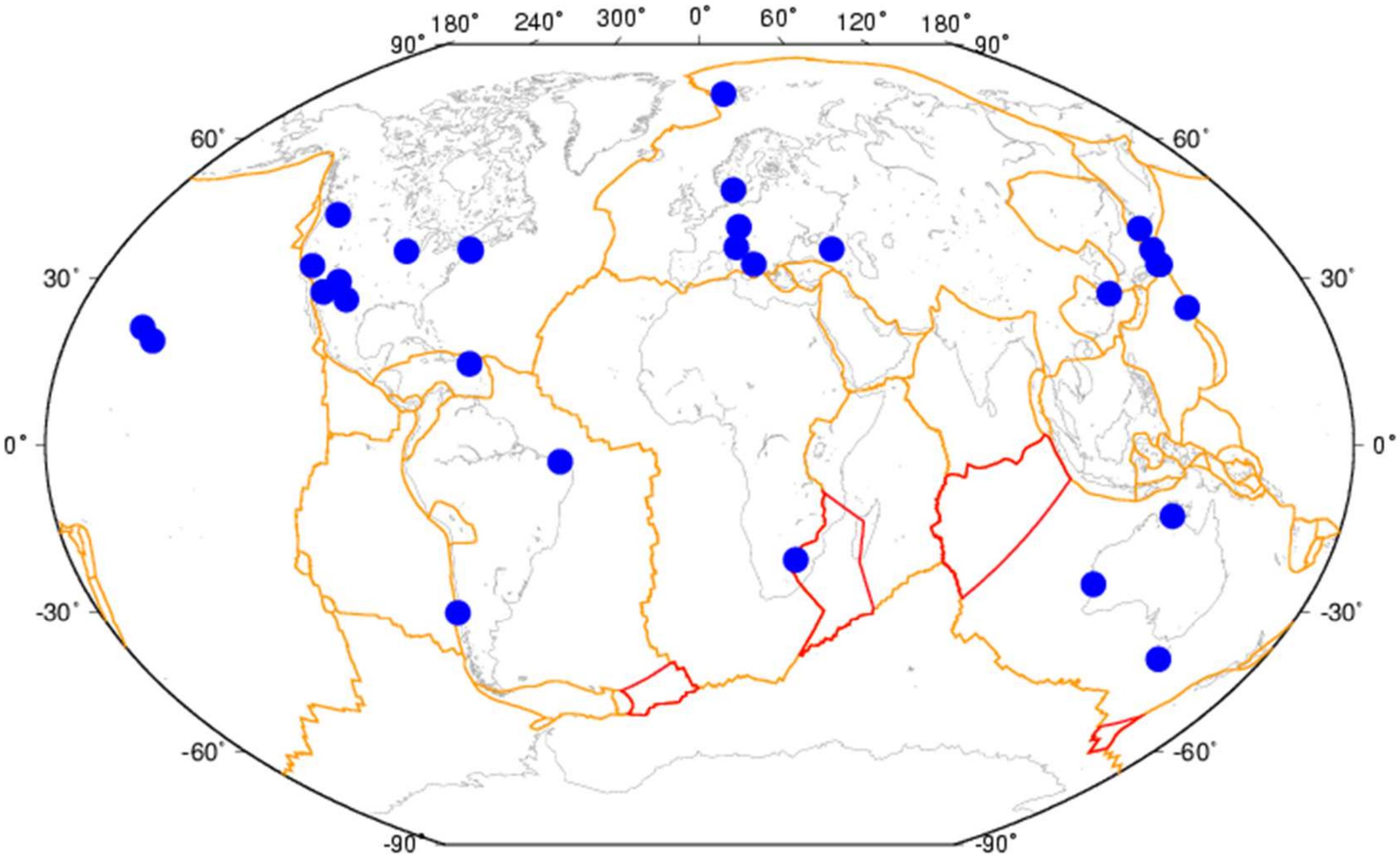
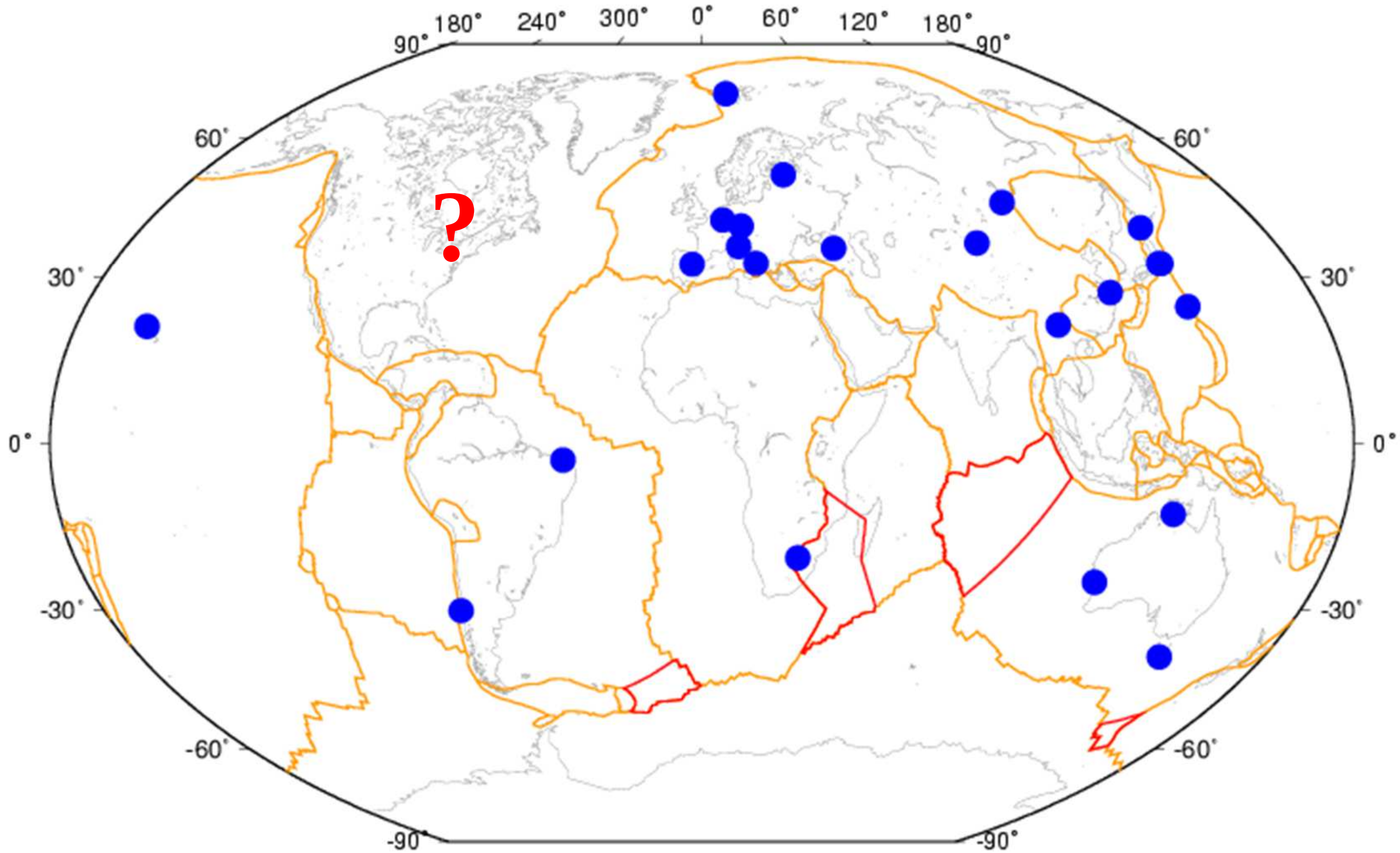
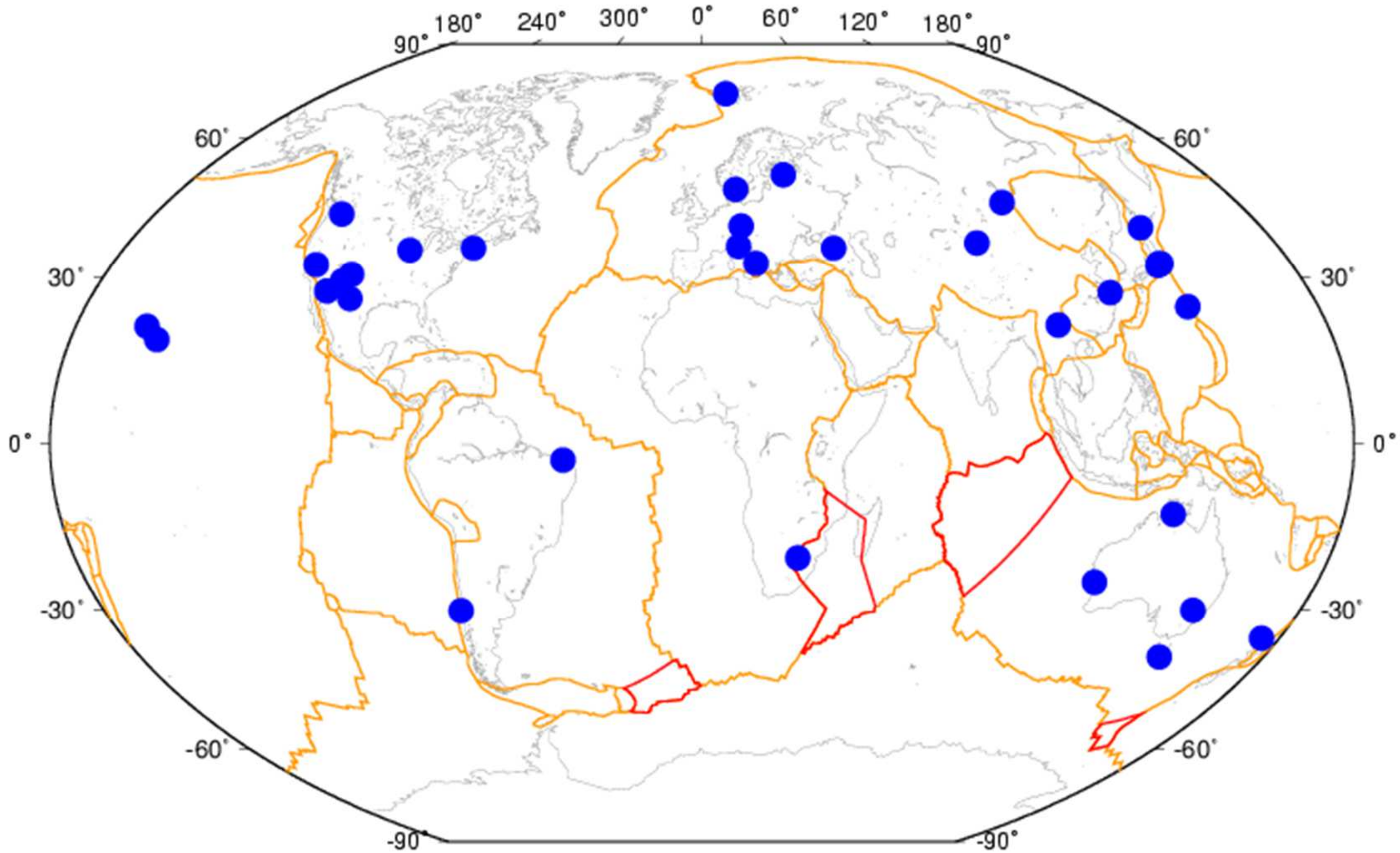
VLBI observed sites June



VLBI observed sites July



VLBI observed sites August



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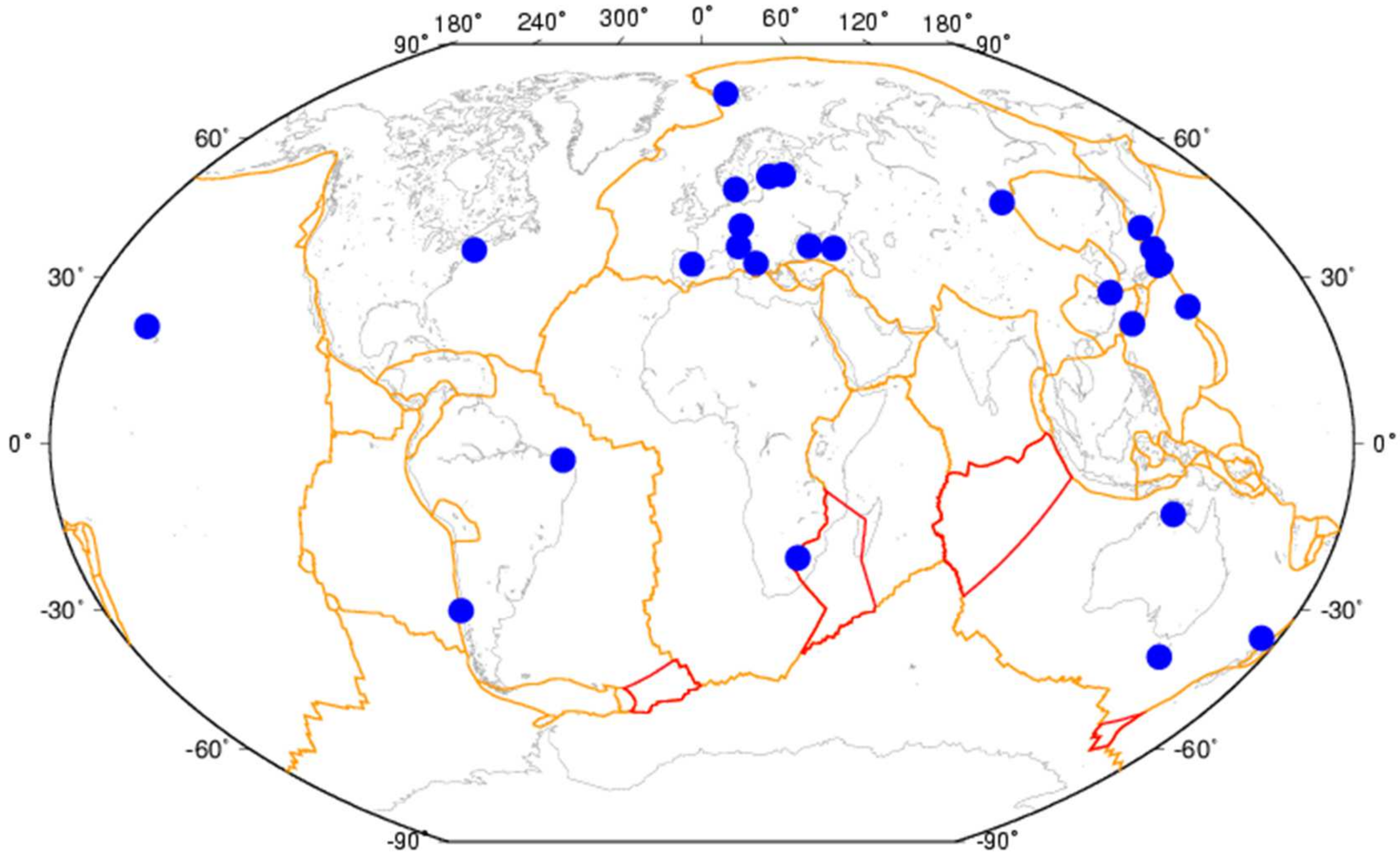
VLBI observed sites September



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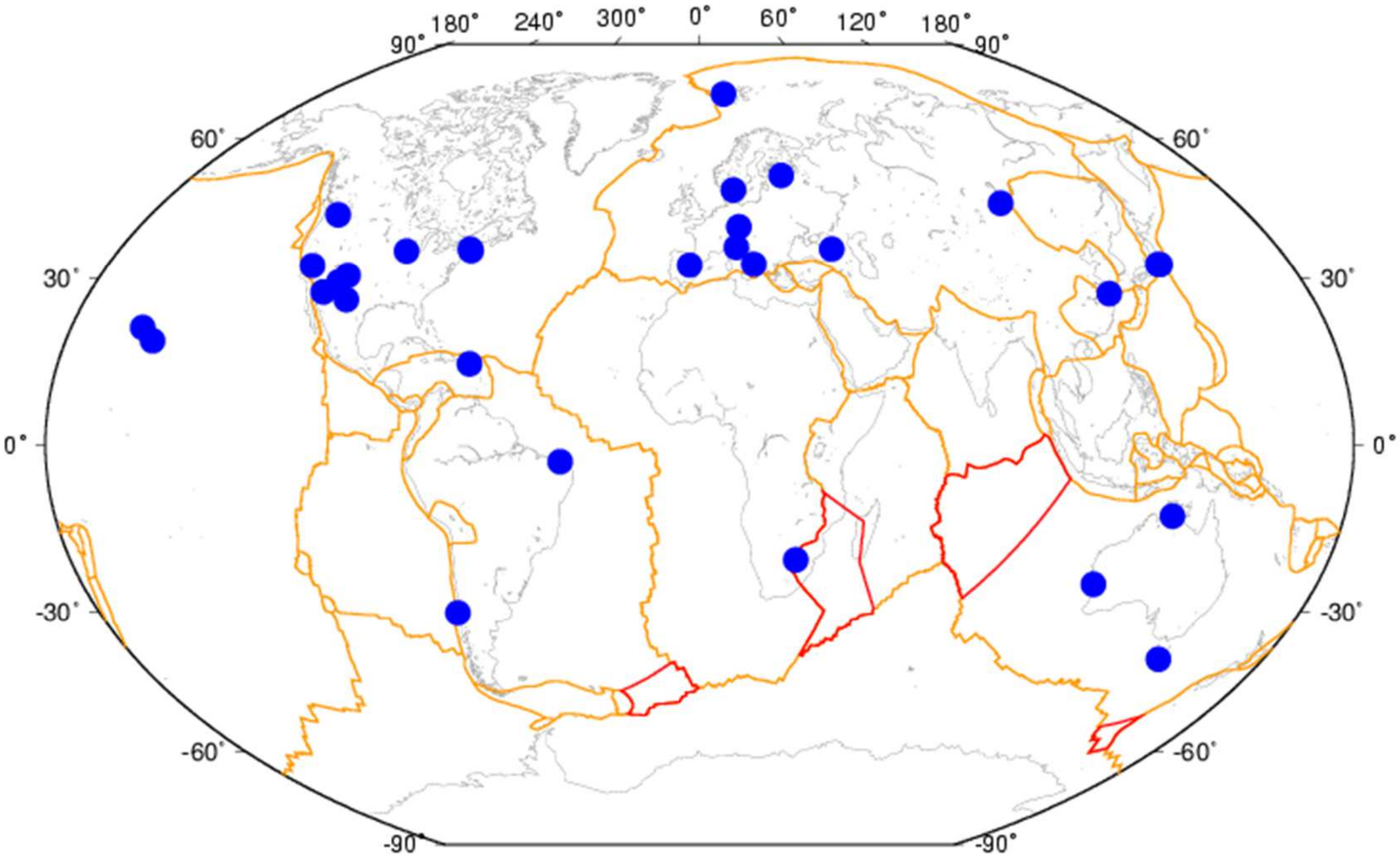
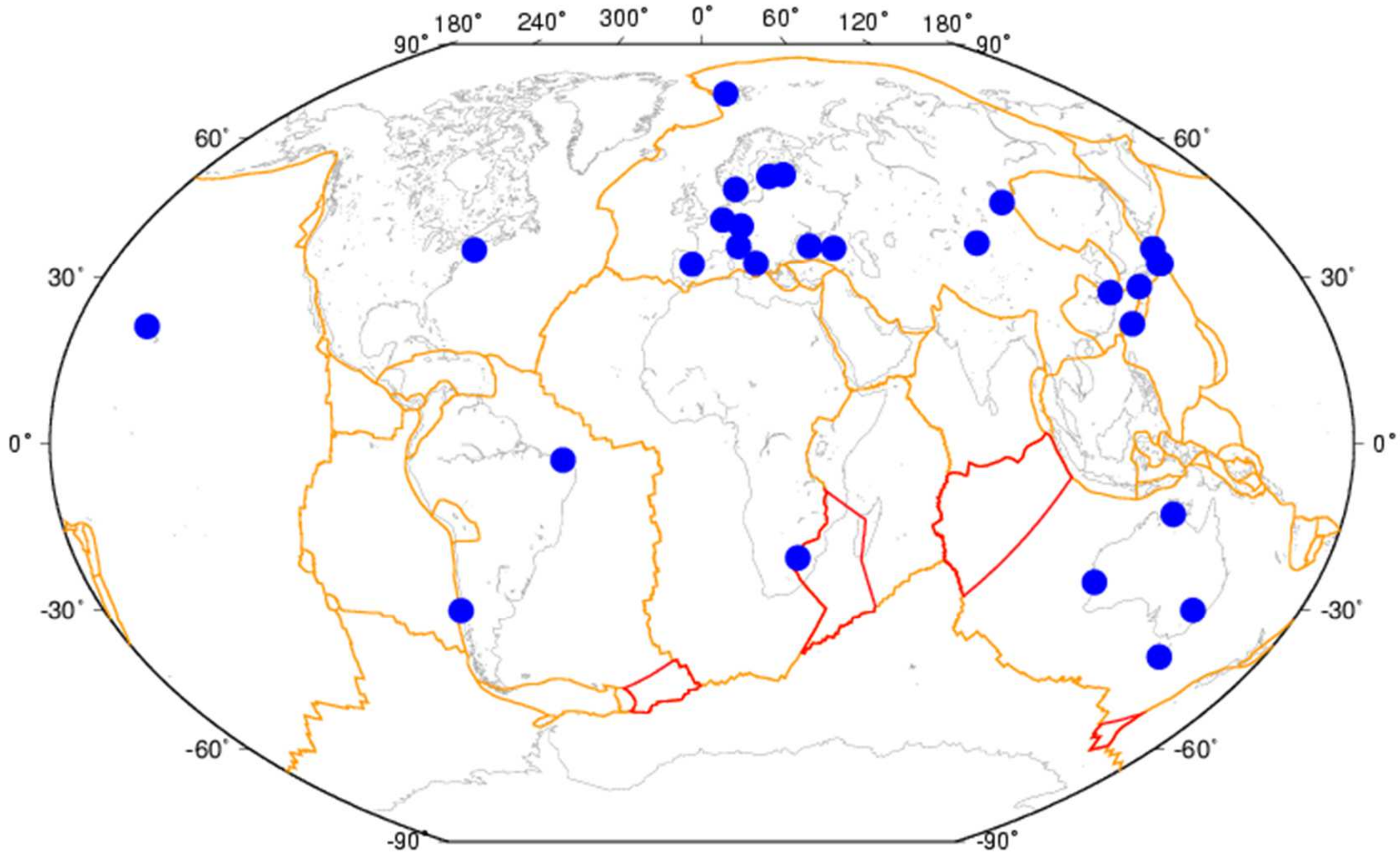
VLBI observed sites October



VLBI observed sites November



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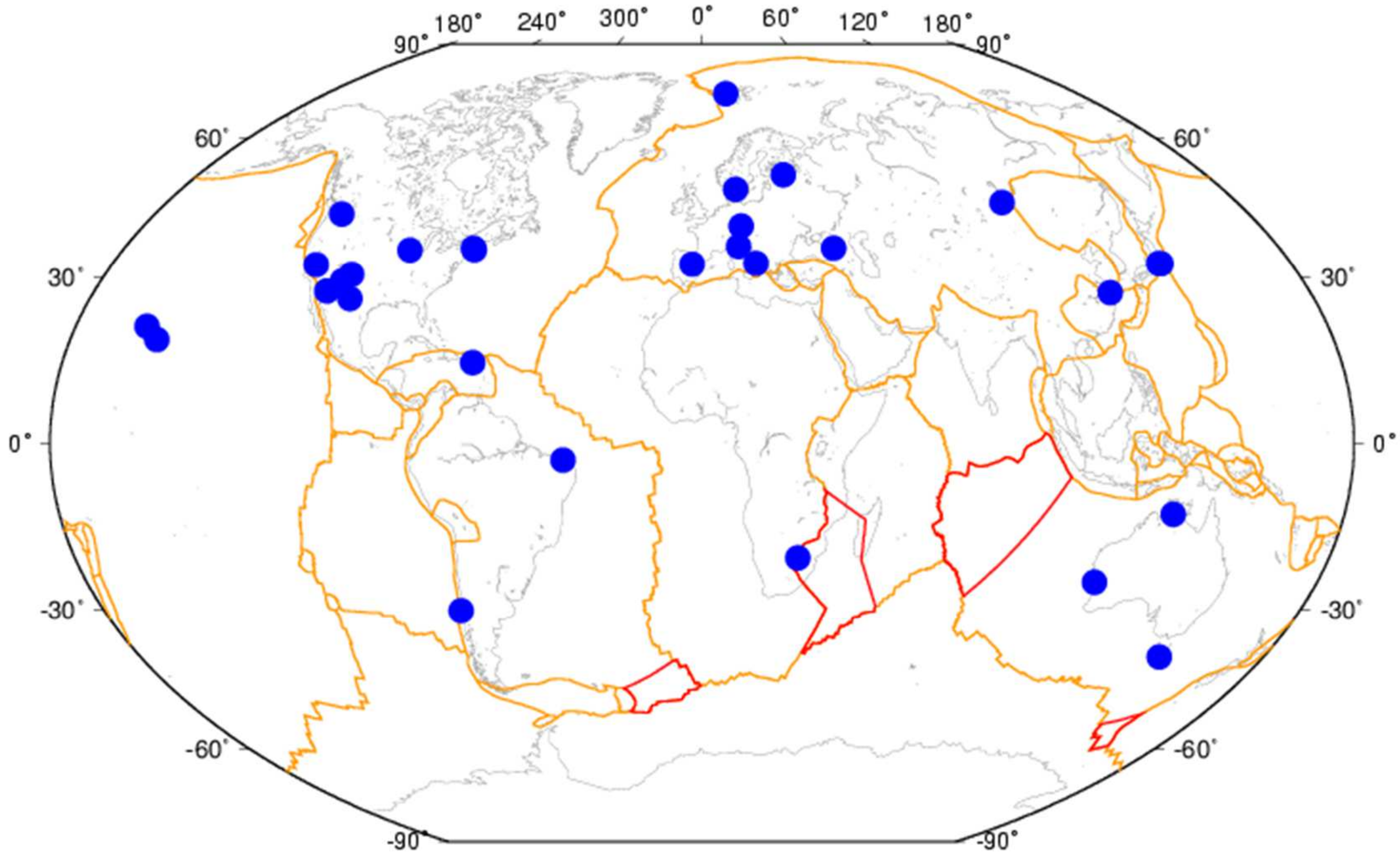
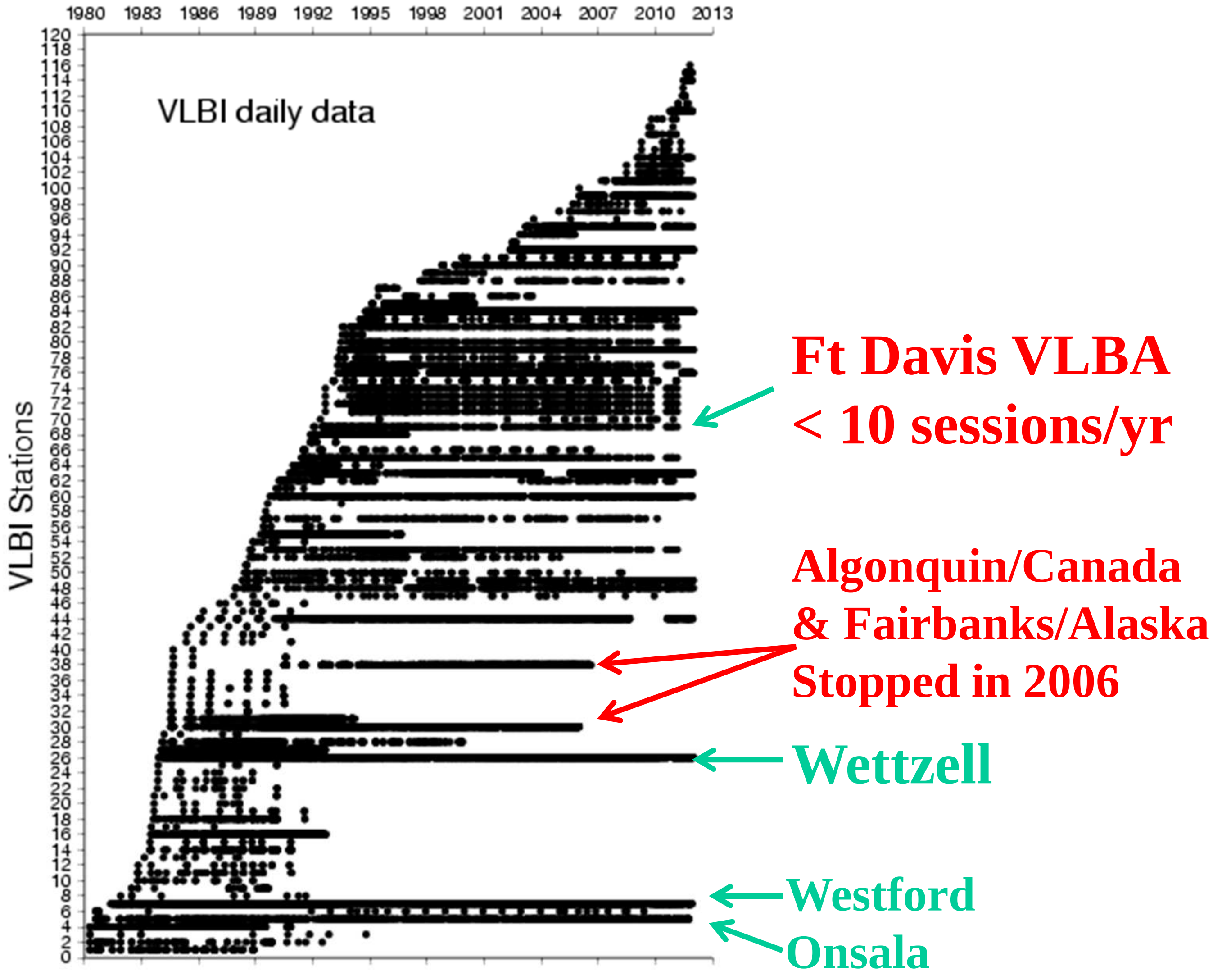
VLBI observed sites December



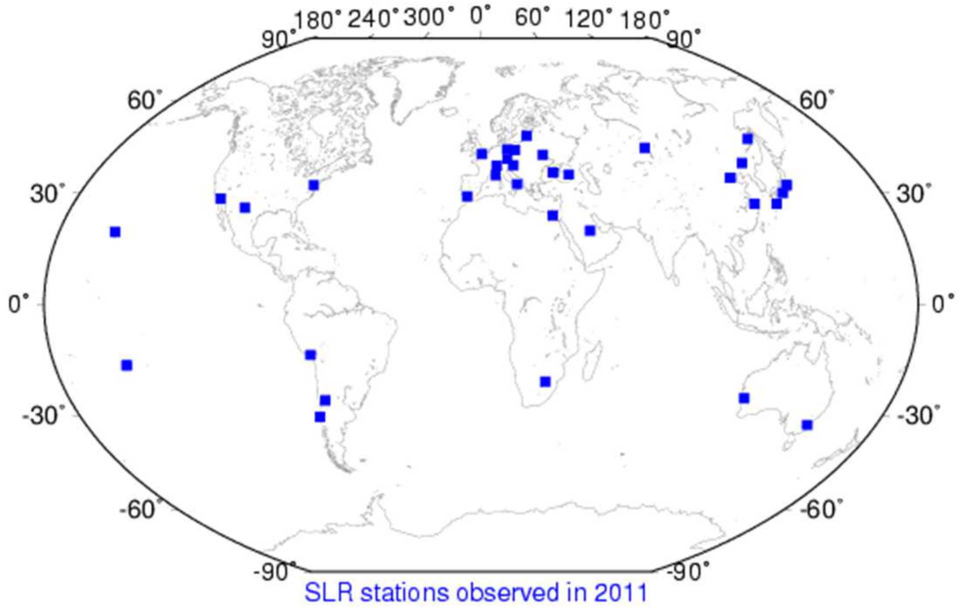
VLBI observation availability

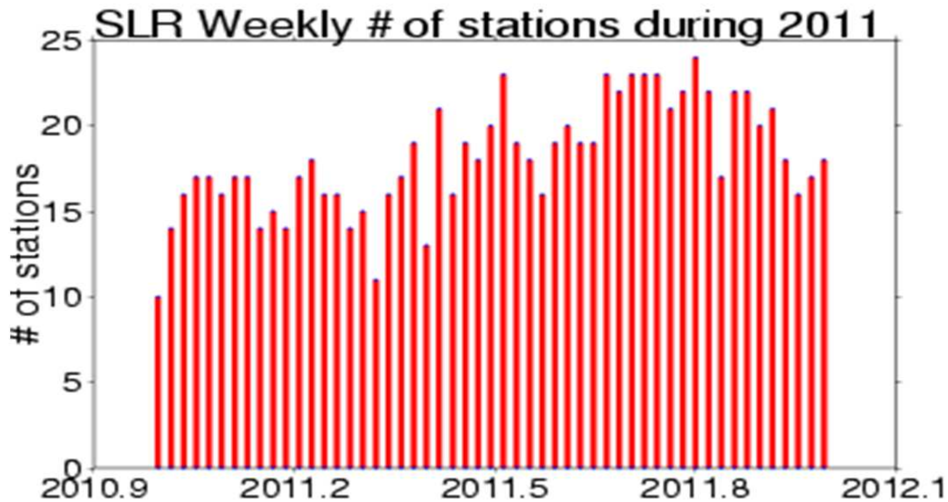


Technique Systematic Errors: SLR

- **Relatively poor network geometry**
- **Station-satellite range biases**
- **Station timing/counter biases**

Herstmonceux event timer example: 12 mm bias (Appleby, 2009)





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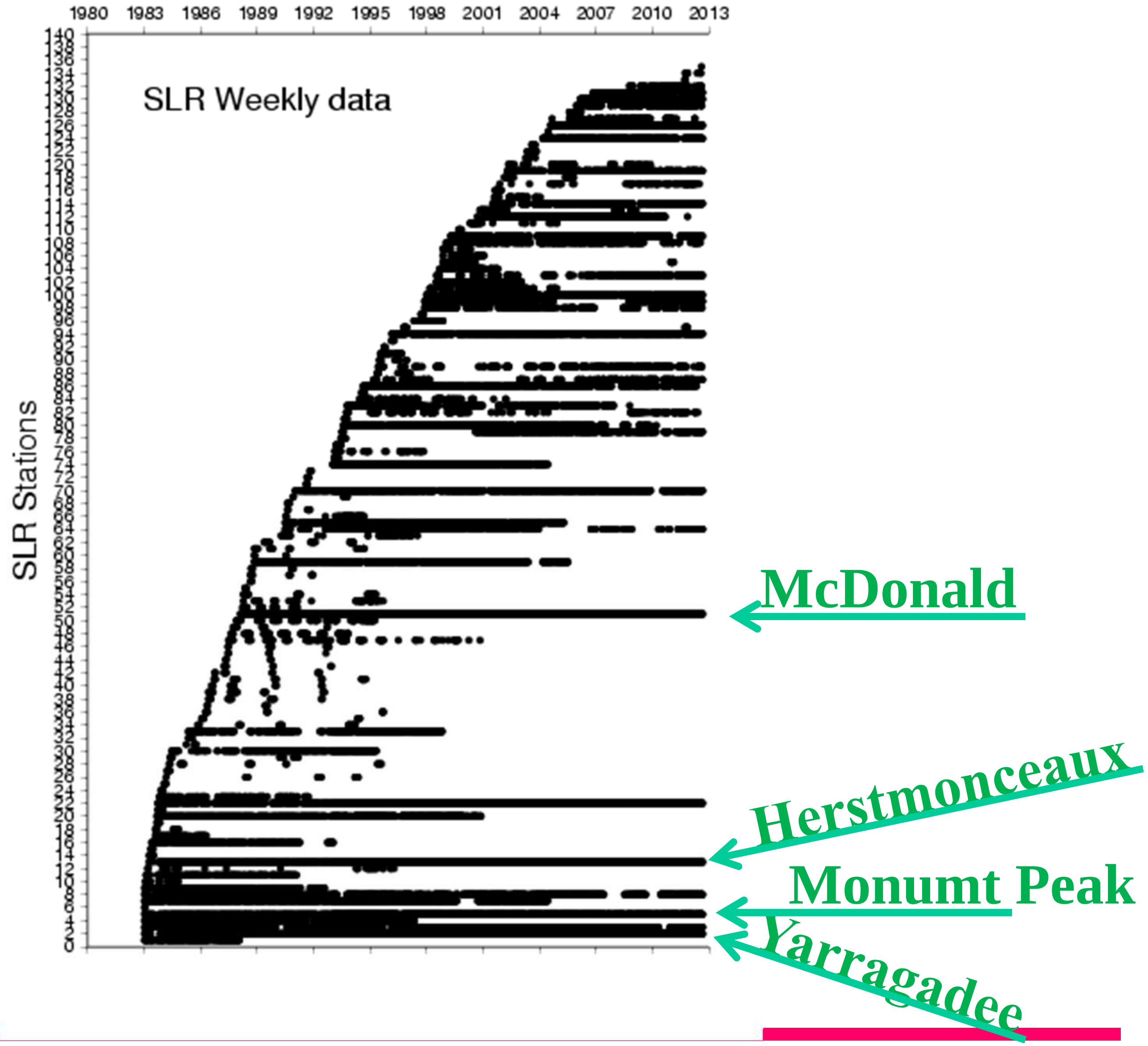
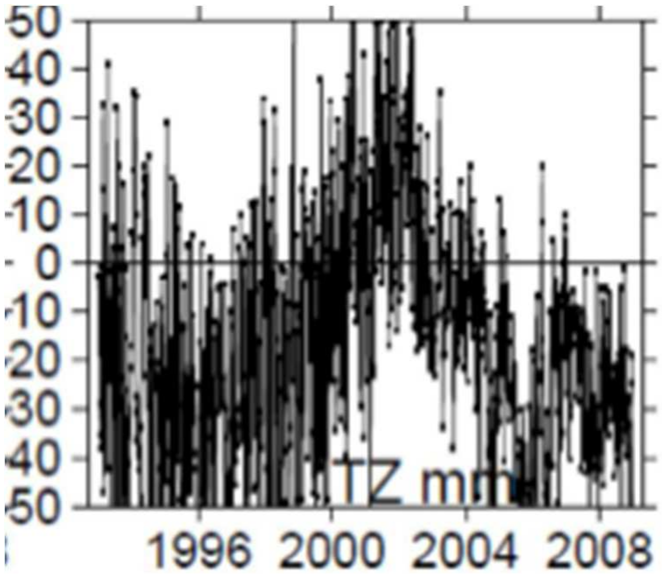
SLR observation availability

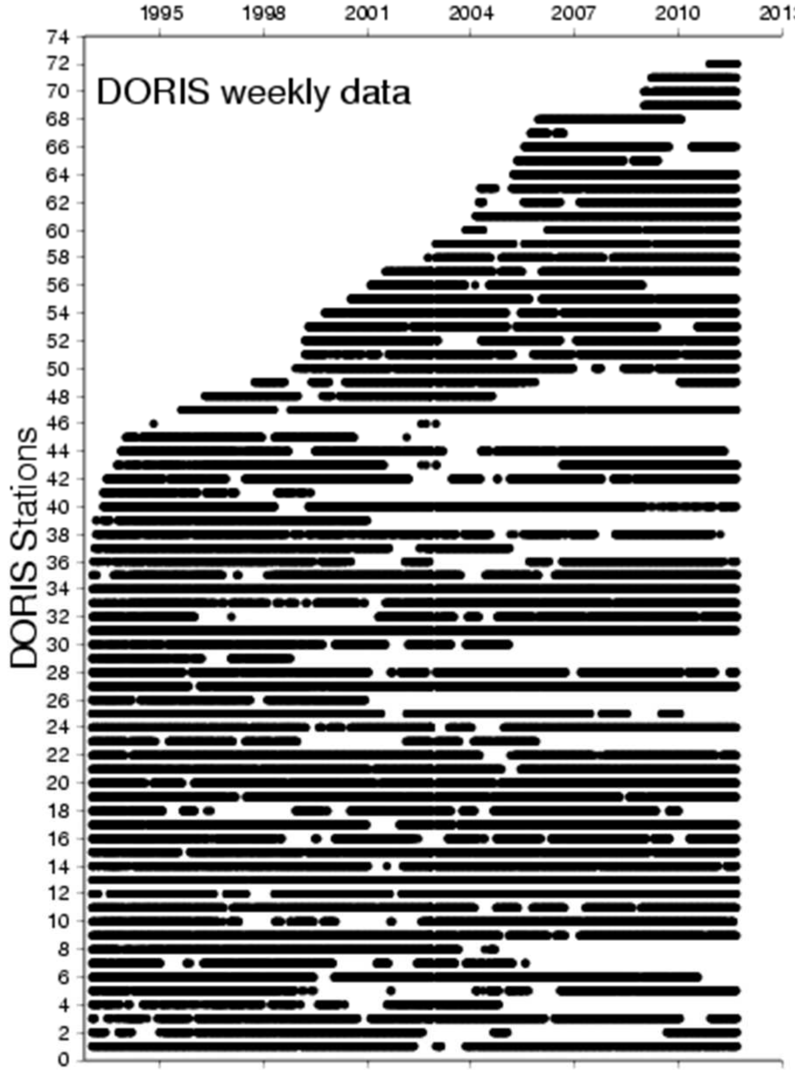


Technique Systematic Errors: DORIS



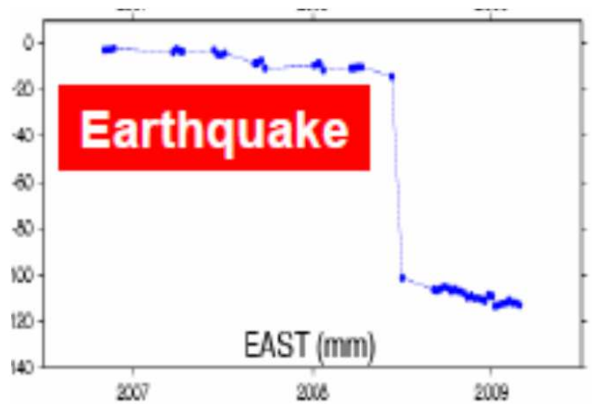
- **Z-geocenter is poorly determined, due mainly to Solar Radiation Pressure (Gobinddass et al., 2009)**
- **Uncalibrated beacon phase center pattern (Tourain et al., 2012)**
  - **Calibration tests/evaluation in progress by CNES and IDS…**

DORIS observation availability

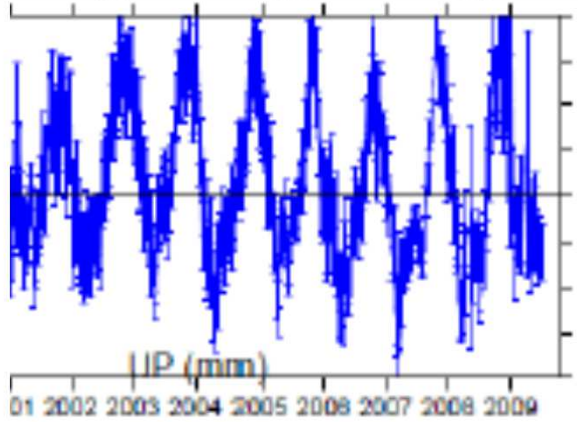


Site non-linear motion

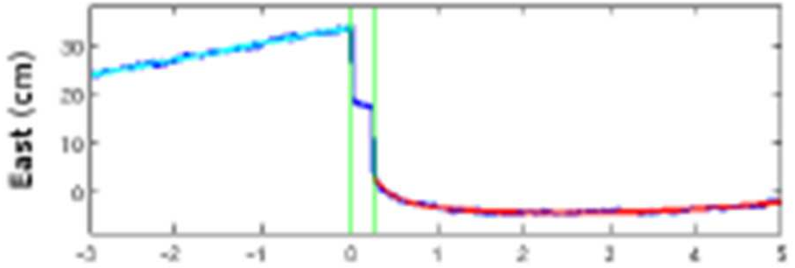
- Discontinuities in station position time series



- Seasonal signals
  - Loading effects
  - Errors at draconitic sub-periods for GPS
  - Other systematic biases (?)

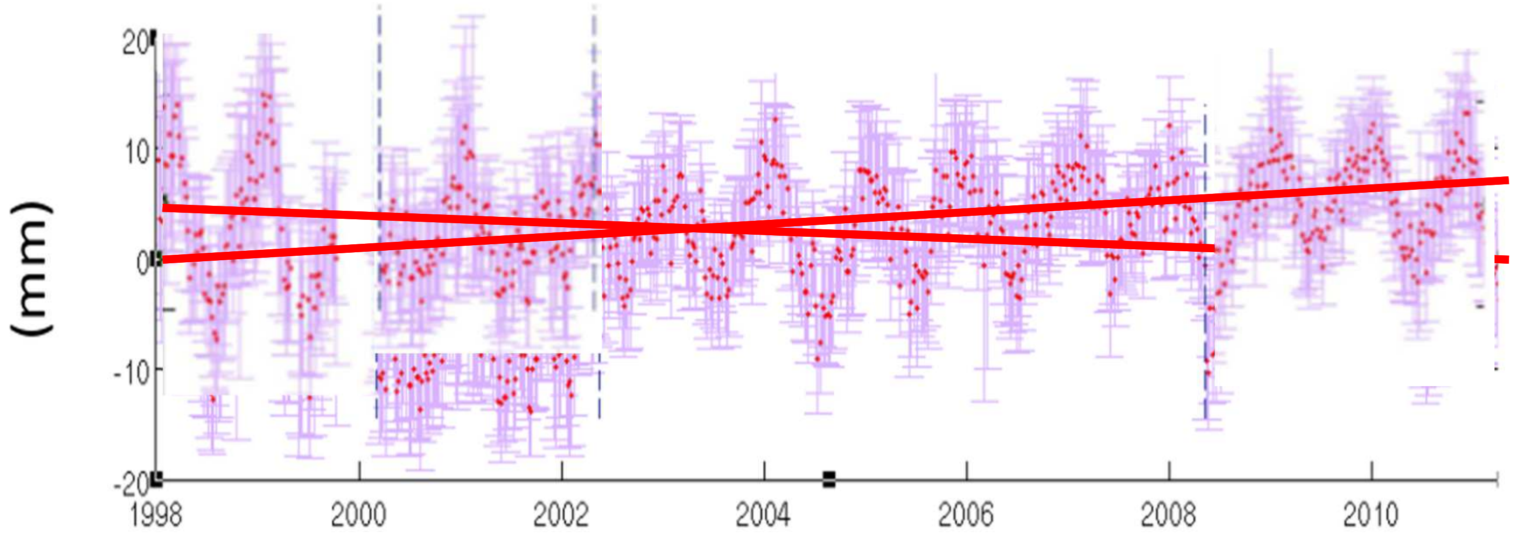


- Co- & Post-Seismic deformation



Impact of discontinuities on site velocities

Yarragadee GPS up component

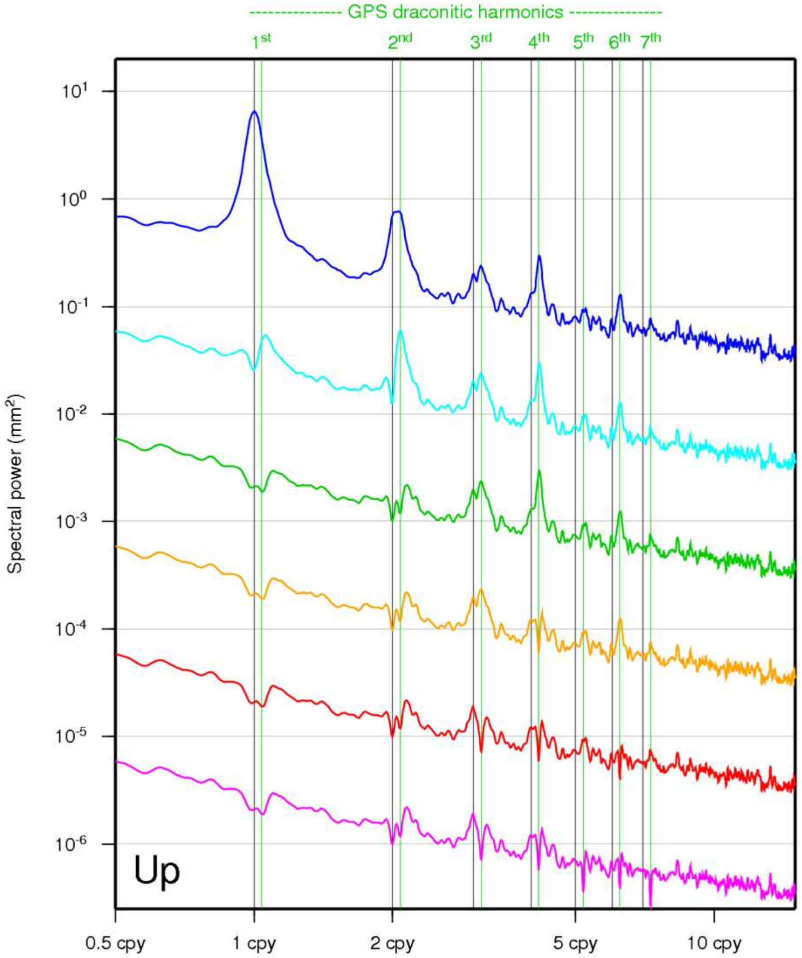


Up velocity = -0.18 ± 0.07 mm/yr (with 2 discontinuities)
= -0.29 ± 0.05 mm/yr (with 2 disc. + ann & semi-ann)

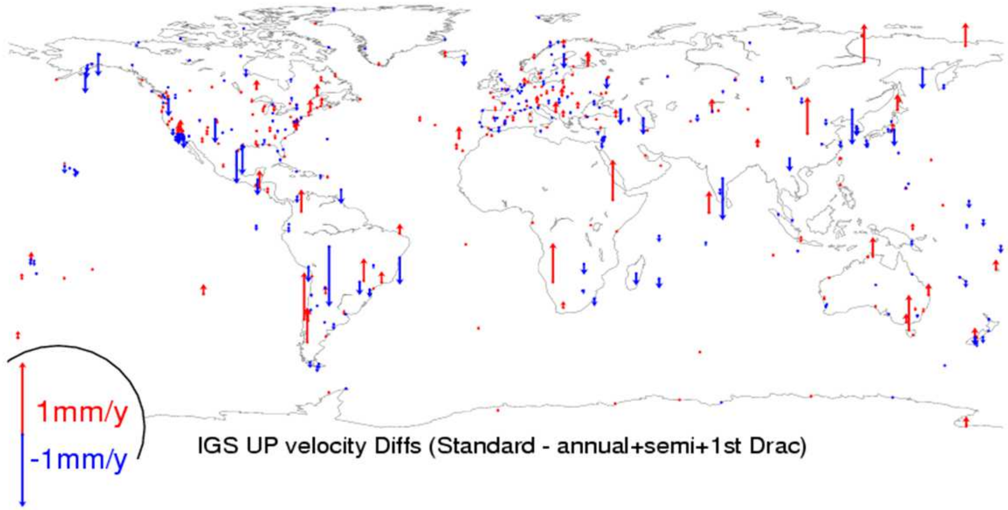
If we consider a 3rd discontinuity:

Up velocity = 0.73 ± 0.12 mm/yr (with 3 discontinuities)
= 0.33 ± 0.12 mm/yr (with 3 disc. + ann & semi-ann)

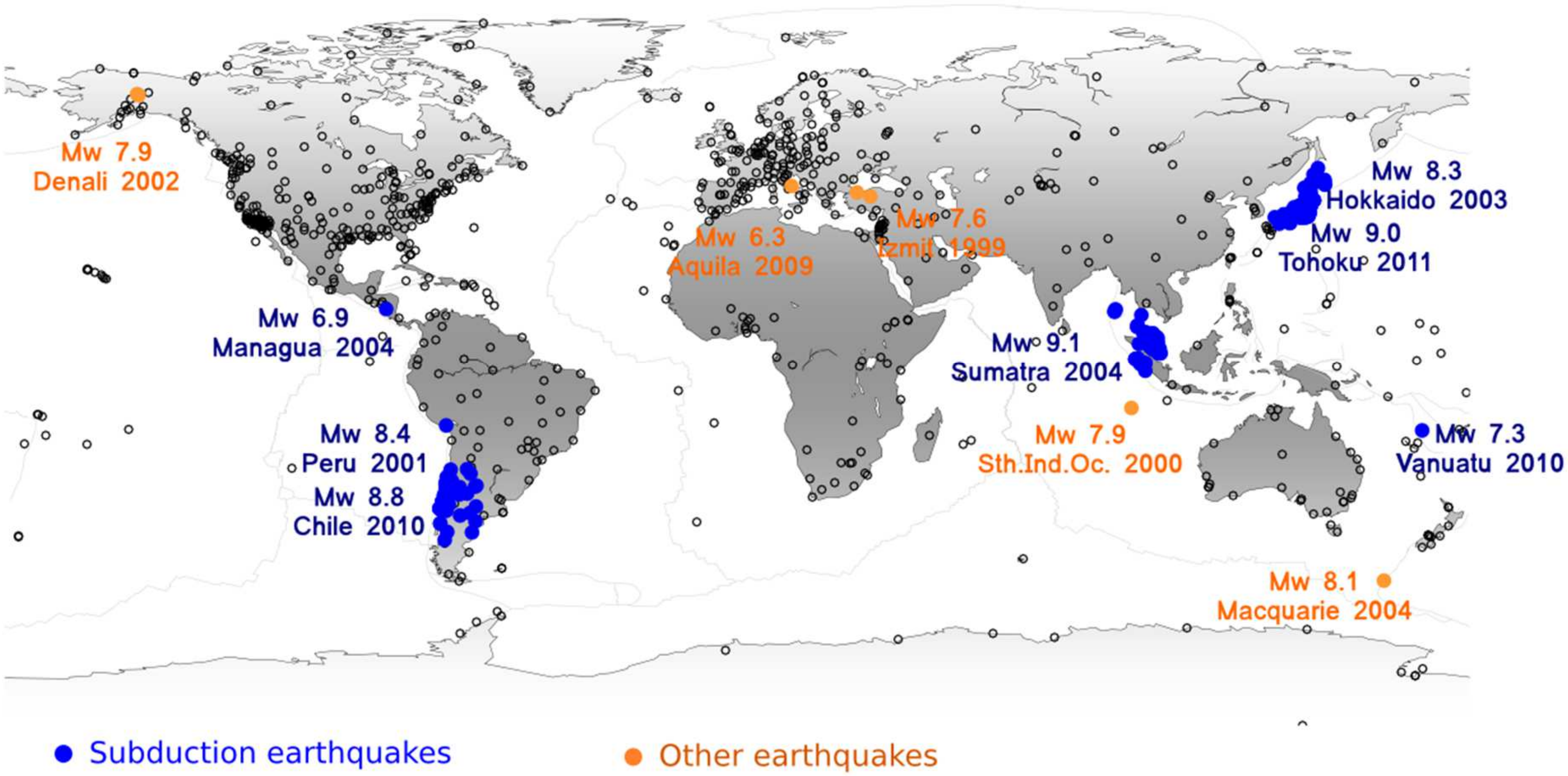
IGS station position Up residuals: stacked periodogram



Up velocity changes



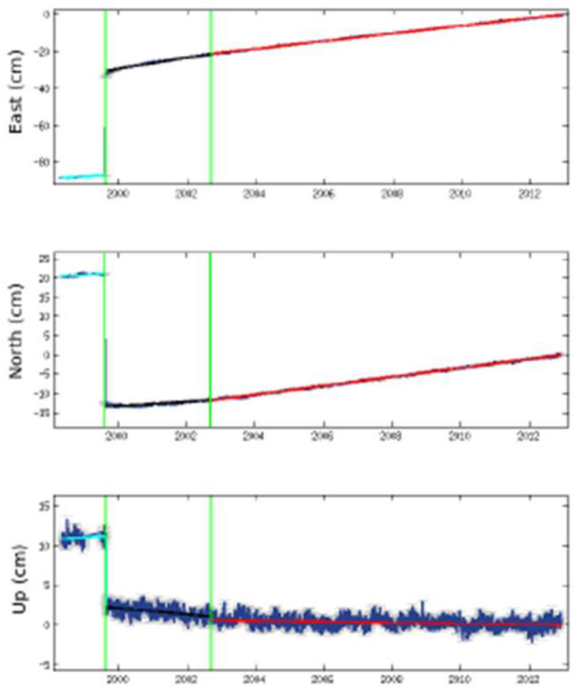
Modeling post-seismic deformations



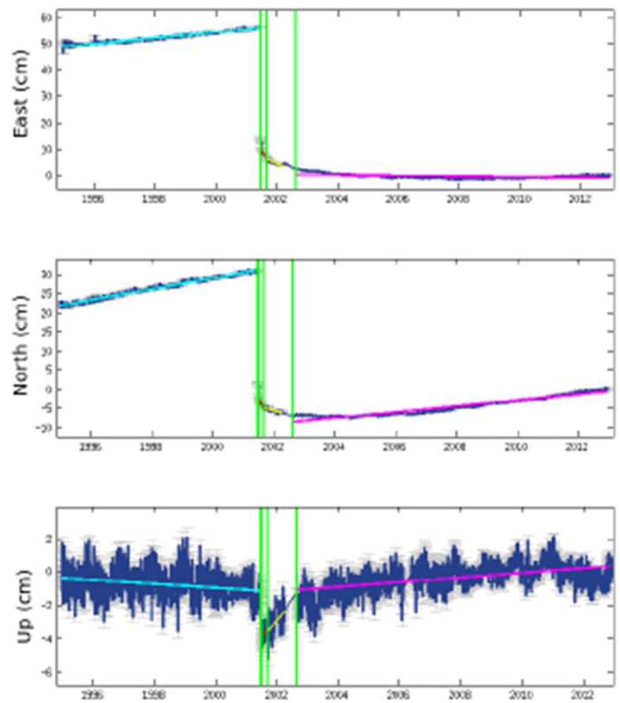
Current modelling of post seismic deformations in ITRF

It is based on a piecewise linear model for the time evolution of station coordinates.

$$X^i_{ITRF}(t) = X^i_{ITRF}(t_0) + \dot{X}^i_{ITRF}(t - t_0) + \sum_k d^i_k \; H(t - t_k) + \sum_l v^i_l (t - t_l) \; H(t - t_l)$$



TUBI station (Gebze, Turkey)
1999 Mw 7.6 Izmit Earthquake



AREQ station (Arequipa, Peru)
2001 Mw 8.4 Peru Earthquake

Parametric post seismic models

Parametric models for postseismic displacements :

$$\forall i \in \{E, N, U\}, X_i(t) =$$

$$\begin{cases} X_1(t_0) + V_1 \times (t - t_0) & , \quad t < t_{eq} \\ X_2(t_{eq}) + V_2 \times (t - t_{eq}) + D(t - t_{eq}), & t > t_{eq} \end{cases}$$

Parametric postseismic models use logarithmic or exponential functions :

$D(t - t_{eqk})$ with

$$D(t - t_{eqk}) = A \; log(1 + \frac{t - t_{eqk}}{\tau}) \tag{1}$$

or

$$D(t - t_{eqk}) = A \; (1 - e^{-\frac{t - t_{eqk}}{\tau}}) \tag{2}$$

[e.g. : Kreemer et al., 2006]

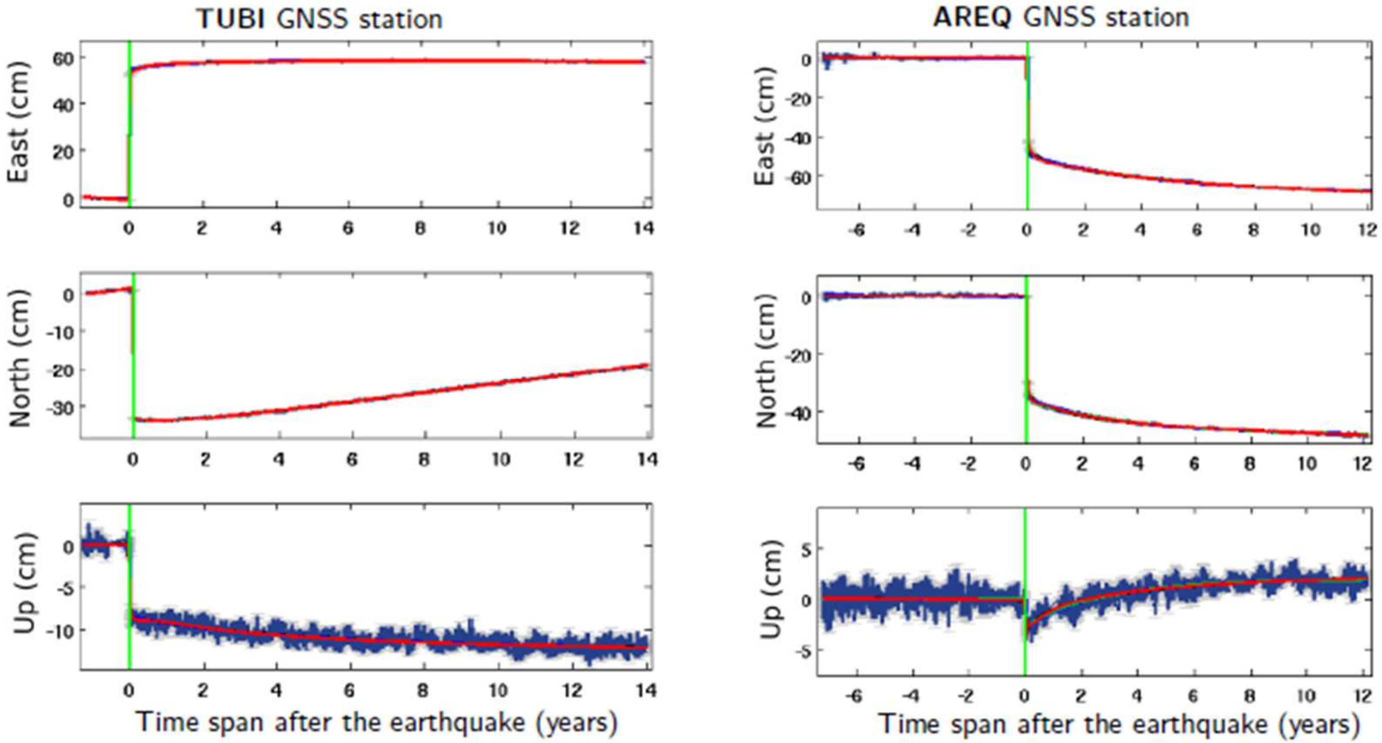
or

$$D(t - t_{eqk}) = A_1 \; log(1 + \frac{t - t_{eqk}}{\tau_1}) + A_2 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_2}}) \tag{3}$$

or

$$D(t - t_{eqk}) = A_1 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_1}}) + A_2 \; (1 - e^{-\frac{t - t_{eqk}}{\tau_2}}) \tag{4}$$

Agreement between data and models



Conclusion

- The ITRF has improved in precision & accuracy over time
- The most precise/accurate reference frame available today
- Largely disseminated by the four techniques
- Became critical with the increase of GPS/GNSS networks and their science applications
- Accessible everywhere continuously thanks to IGS products
- Most of current VLBI and SLR systems are old generation
- 50% of IGS sites have discontinuities
- Tie discrepancies > 5 mm for a number of co-location sites
- Need to mitigate technique systematic errors
- The ITRF is still not at the level of science requirement
- Needs to be improved by a factor of 10.

Coming this year ITRF2013

Thank you