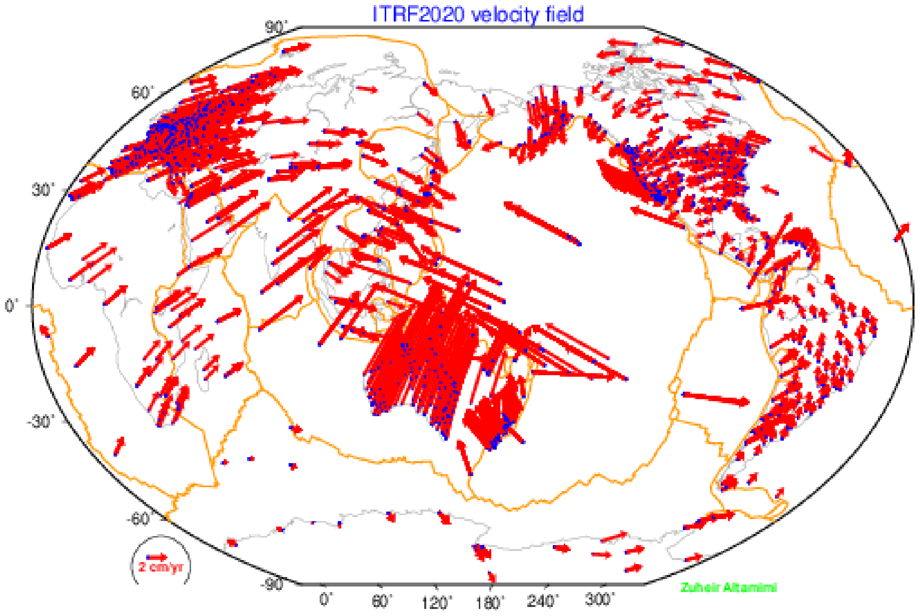
Current State of Global Geodesy Supply Chain
From the ITRF perspective/experience

Zuheir ALTAMIMI and the ITRF team + others
IGN-IPGP, France



Meeting of Expert Consultation on Strengthening the Global Geodesy Supply Chain
22-23 April 2024, GGCE, Bonn, Germany

Key points

- The ITRF supply chain, part of the Global Geodesy Supply Chain
- Space geodesy techniques contributing to the ITRF
- Why is the ITRF needed?
- Critical points impacting the ITRF accuracy
- Strengths and weaknesses of space geodesy techniques

- Focus on SLR and VLBI, and why?

- Illustrations based on ITRF2020 input data

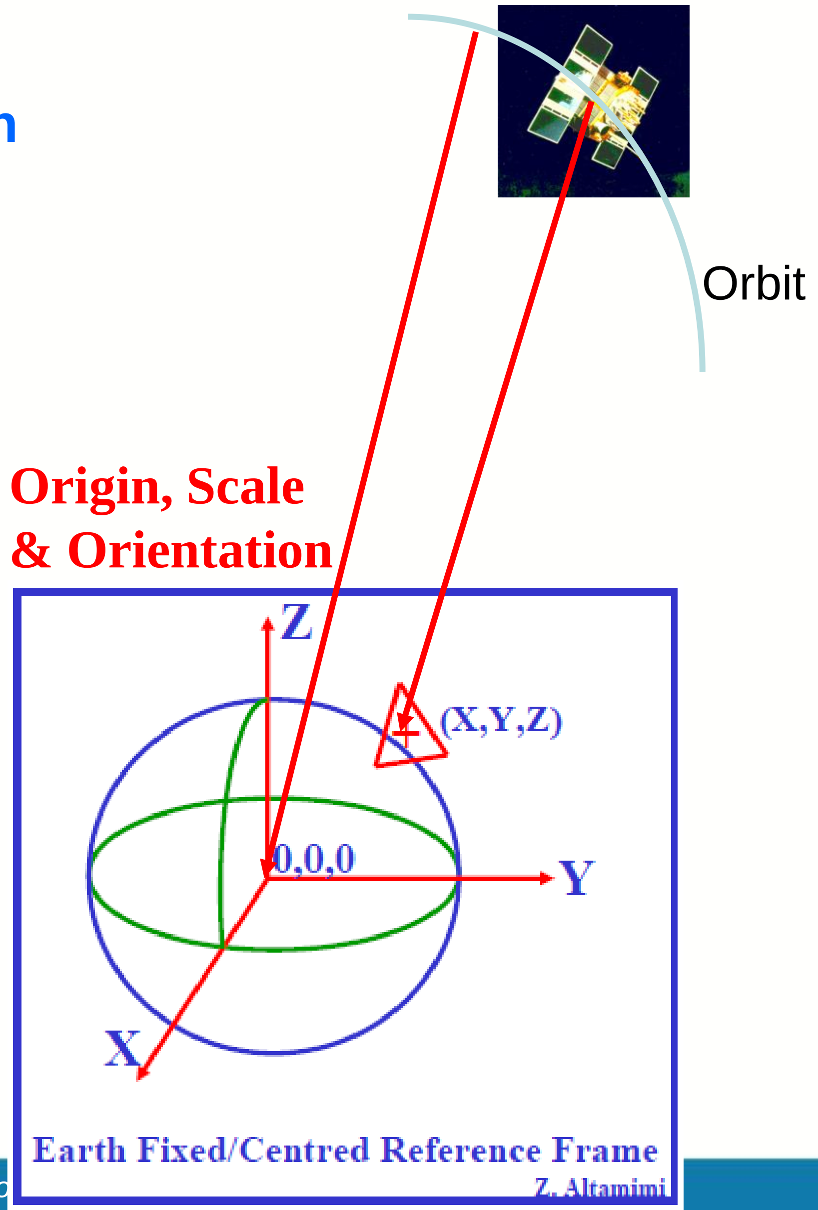
What is a Reference Frame in practice?

- Earth fixed/centered Reference Frame: allows determination of point positions and satellite orbits as a function of time

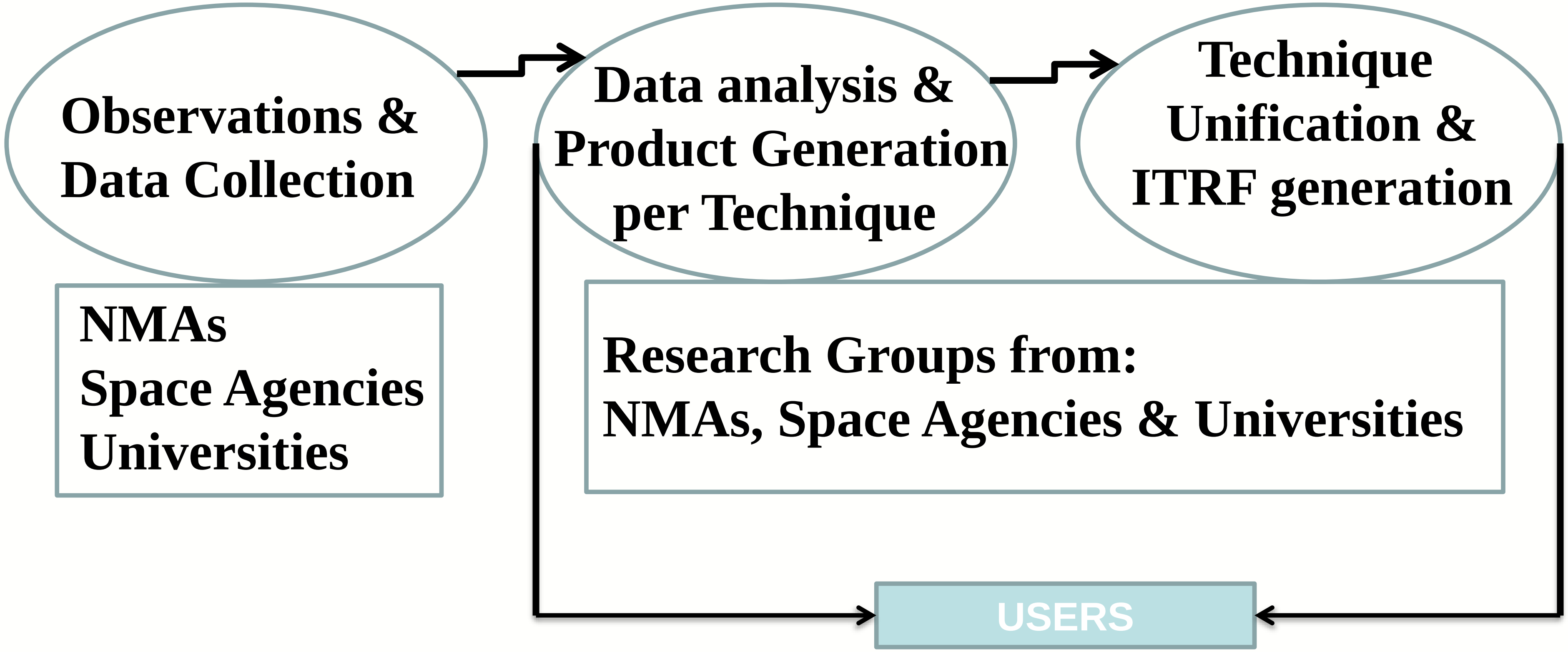
- When analyzing space geodesy data, we have to take into account:
  - Relativity theory
  - Forces acting on the satellite
  - The atmosphere
  - Earth rotation
  - Solid Earth and ocean tides
  - …
- Linear and nonlinear variations/deformations

==> Station coordinates are function of time

Accuracy: few mm and few 0.1 mm/yr for the best stations

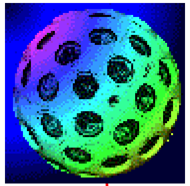


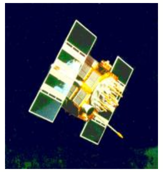
ITRF Supply Chain: an International Effort

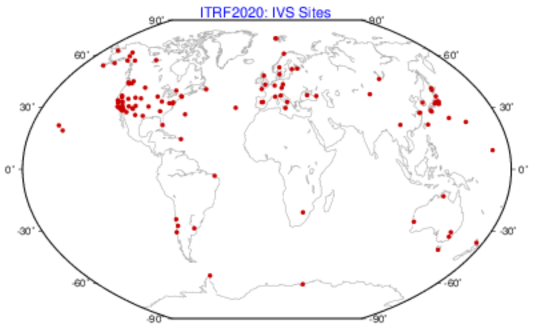


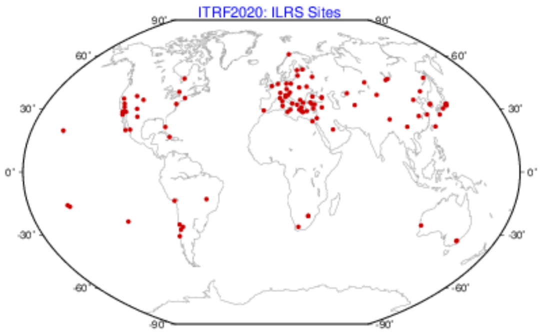
Schematic illustration of the chains leading to the ITRF generation

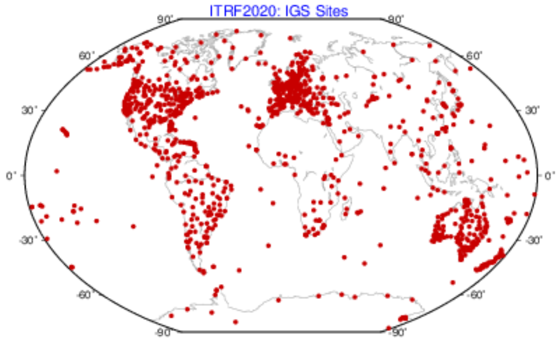
Space geodetic techniques contributing to the ITRF

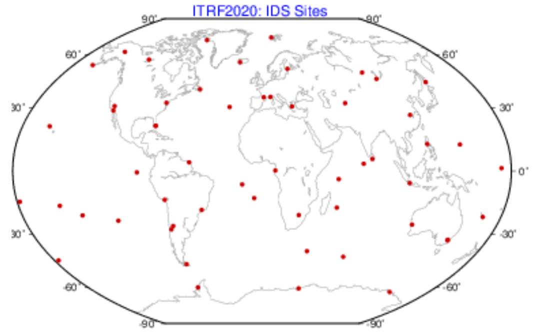




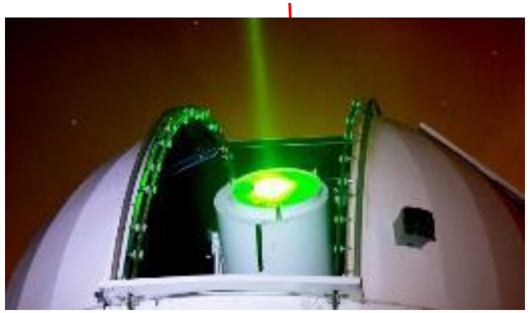








VLBI



SLR

GNSS

DORIS

Geodetic Infrastructure: our heritage

```
884 GNSS
124 VLBI
 96 SLR
 71 DORIS
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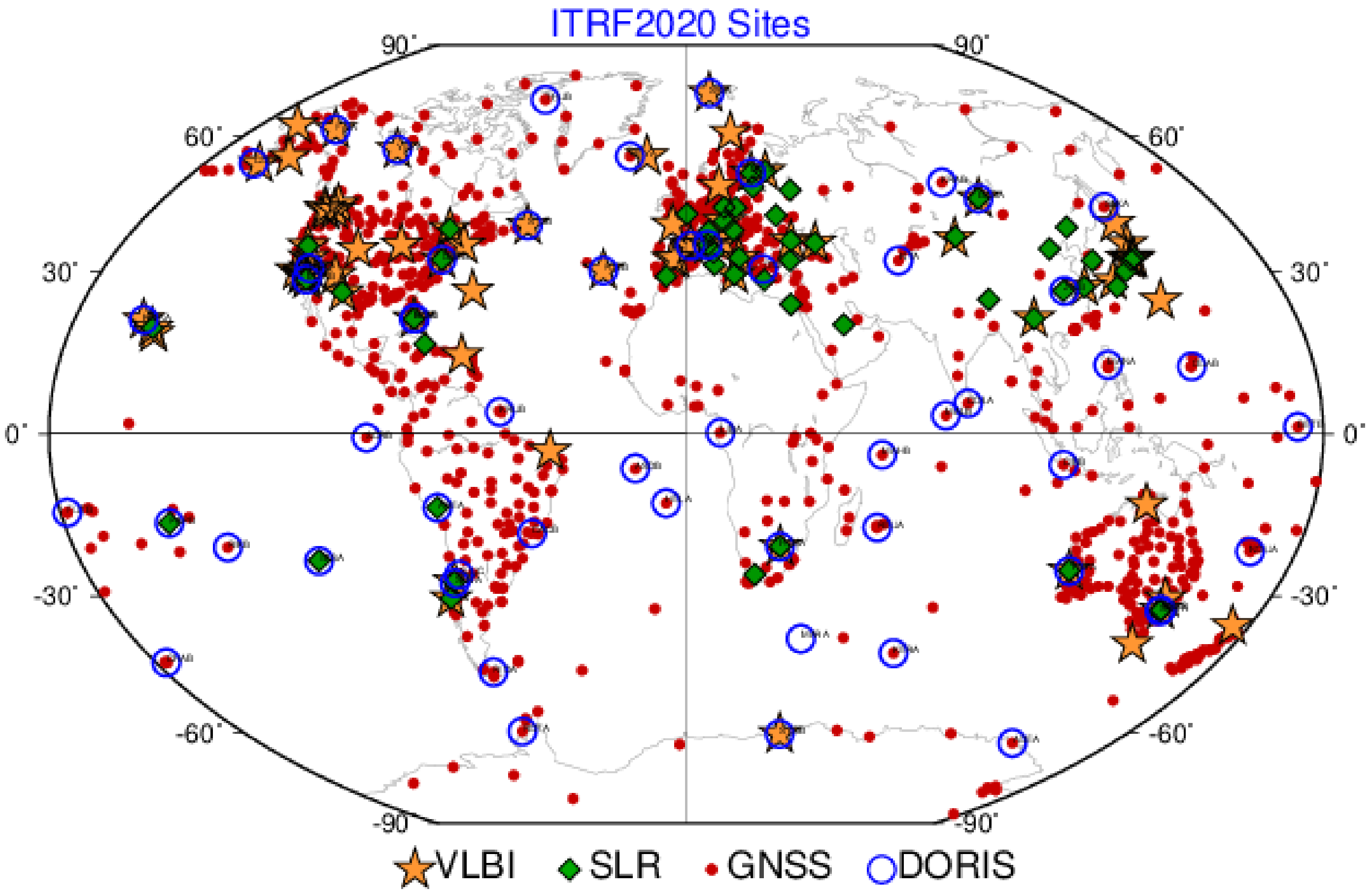


SLR

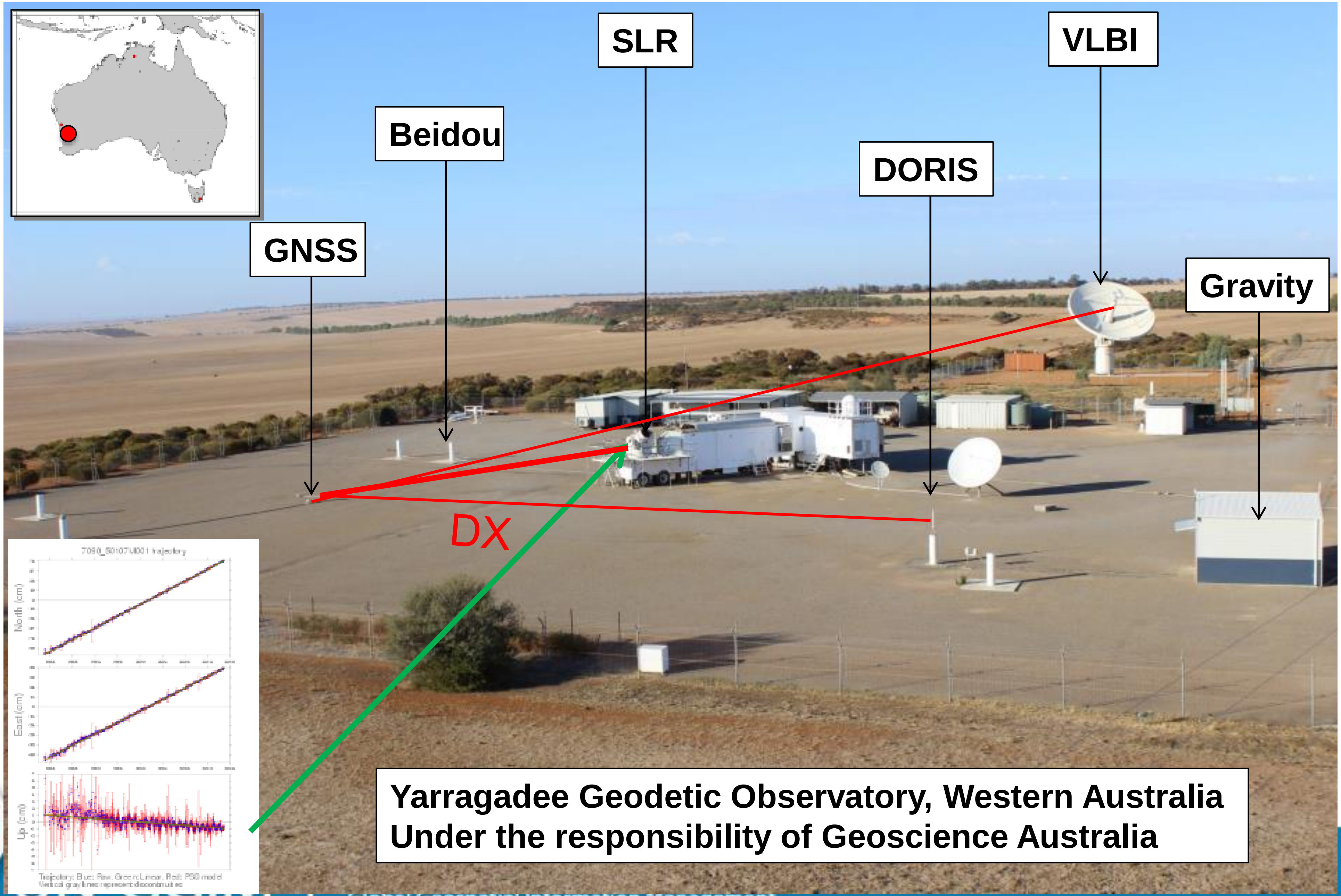
VLBI

GNSS

DORIS

BUT: only 35% of VLBI and SLR sites are in operation today
Most of the old decommissioned sites were of poor quality

Colocation site



Yarragadee Geodetic Observatory, Western Australia
Under the responsibility of Geoscience Australia

Why is the ITRF needed?

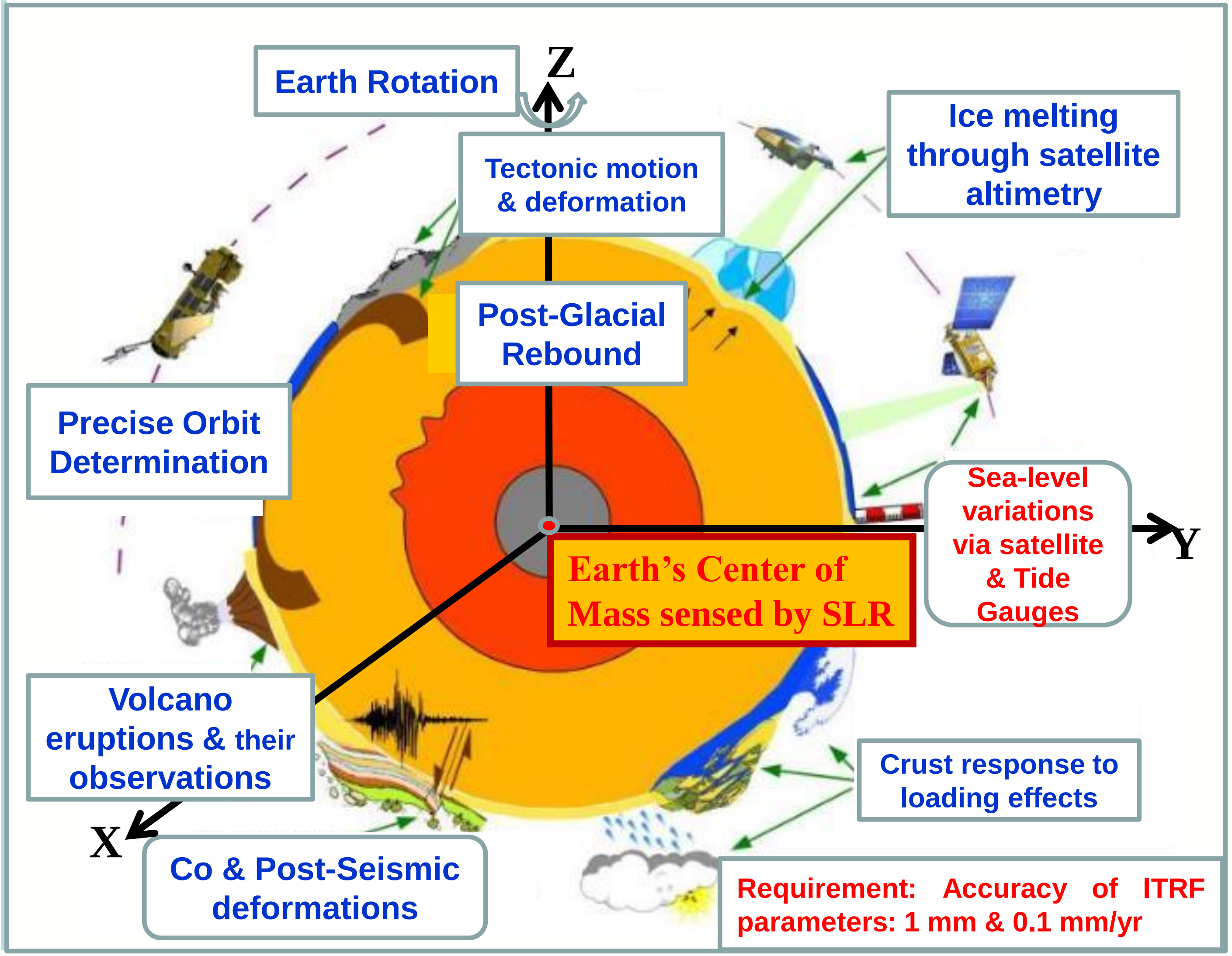
Operational geodesy applications:

- Positioning : Real Time or a posteriori
- Navigation: Aviation, Terrestrial, Maritime
- Regional/National geodetic frames
- Today: via GNSS only!
- Require the availability of the IGS 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

Science applications:



Continuous observations are fundamental

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

Critical points impacting the ITRF accuracy

1. **Reference frame definition :**
   - Origin, scale, orientation and their time evolution
   - Science requirement : 1 mm accuracy and 0.1 mm/yr stability

2. **Network geometry / coverage of the 4 technique networks over the Earth surface: Well distributed networks are needed**

3. **Accurate, continuous & regular observations to accurately model linear and nonlinear station motions: long time series are needed to maintain the frame over decades**

4. **Accurate / repeated local ties at colocation sites**

Why Multiple Techniques for the ITRF ?

- **VLBI & SLR:**
  - **Fundamental for an accurate definition of the ITRF physical parameters/properties**
  - **SLR determines Earth Center of Mass ==> ITRF origin**
  - **SLR & VLBI define the ITRF scale**
  - **VLBI places the Earth in space ==> Link to the ICRF**

$$[\mathrm{GCRS}] = Q(t)R(t)W(t)\ [\mathrm{ITRS}]$$

  - **But their ground networks are poorly distributed and in danger of degradation**

- **DORIS: disseminates ITRF in satellite orbit determination**

- **GNSS:**
  - **Ensures the link between SLR, VLBI & DORIS networks**
  - **Is the tool today to access the global ITRF by the regions and nations using IGS products**

Technique systematic errors

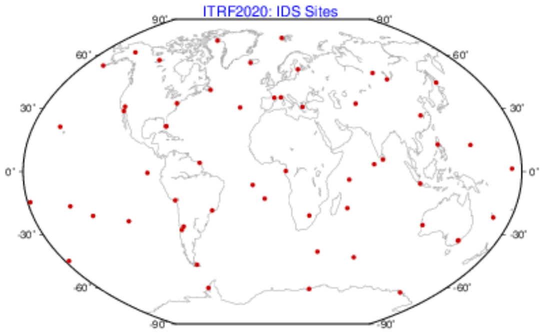
- DORIS: mis-modelling of the solar radiation pressure ==> inaccurate geocenter components, and nonlinearity in the long-term TRF scale
- GNSS have multiple weaknesses in recovering the Earth center of mass position and the TRF scale (in the absence of satellite metadata)
- SLR range biases have significant impact on the TRF scale
- VLBI antenna gravitational deformation ==> impact on the TRF scale

- Progress towards improving the TRF scale determination :
  - GNSS : Metadata are now available for Galileo, Beidou, QZSS, GPS Block III
  - SLR : ILRS adjusts RBs since ITRF2020, improving the scale and its agreement with VLBI
  - VLBI : Deformation models for a number of antennas are now available
  - DORIS : Investigations by IDS are in progress

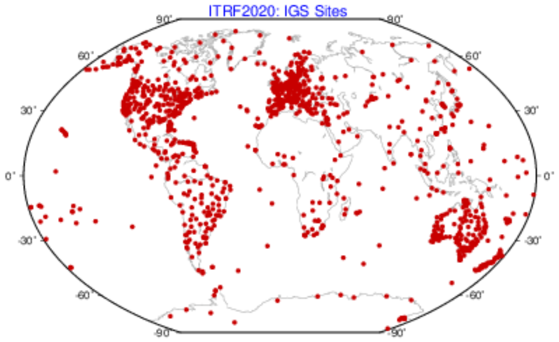
ITRF2020 Input Data

TC	# of solutions	Time-span	# of sites	Frame Origin
IDS/DORIS	1456 weekly	1993.0 – 2021.0 (28 yrs)	87	CM
IGS/GNSS/GPS	9861 daily	1994.0 – 2021.0 (27 yrs)	1159	CN
ILRS/SLR	243 fortnightly 1460 weekly	1983.0 – 1993.0 1993.0 – 2021.0 (38 yrs)	100	CM
IVS/VLBI	6178 session-wise	1980.0 – 2021.0 (41 yrs)	117	CN

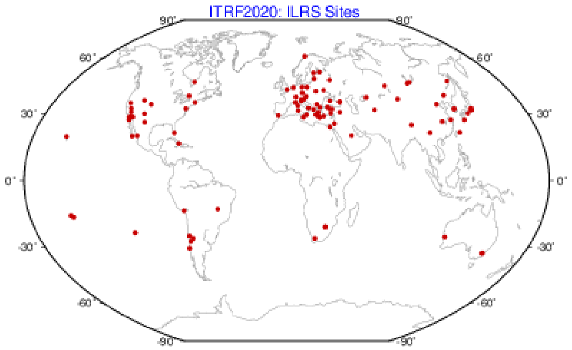
IDS/DORIS



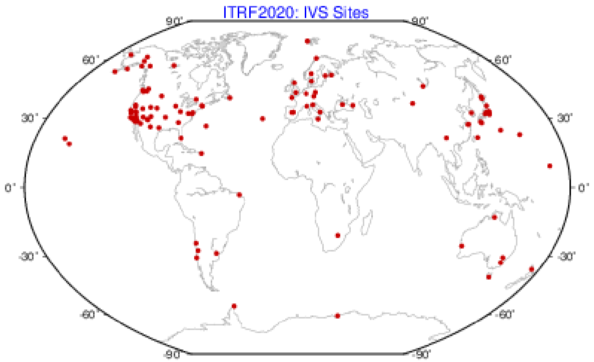
IGS/GNSS



ILRS/SLR

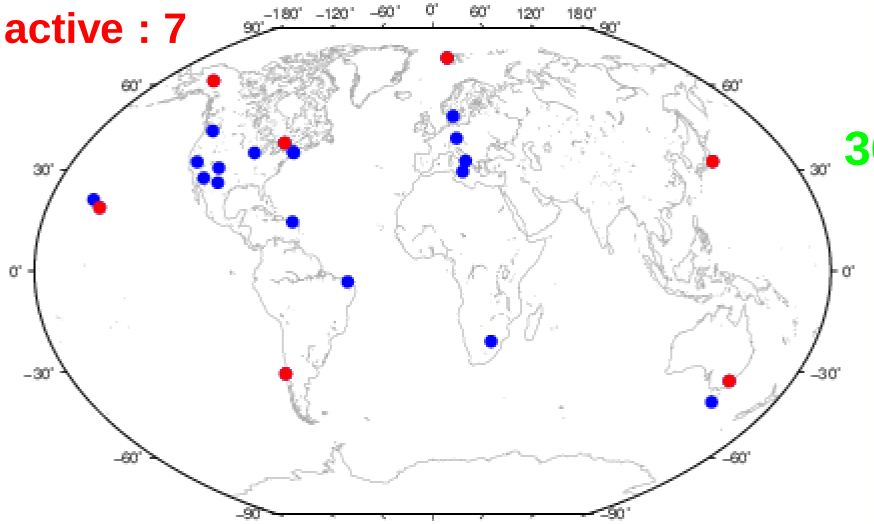


IVS/VLBI



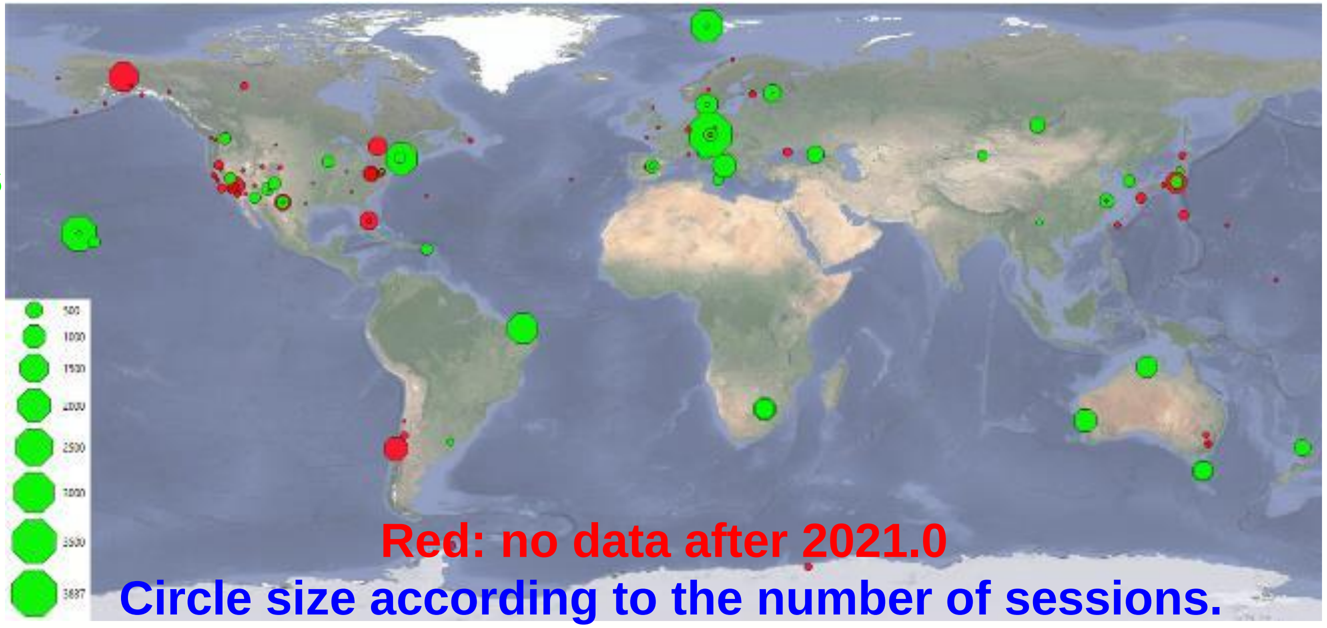
VLBI and SLR stations used in ITRF2020

RF stations : 24
Not active : 7

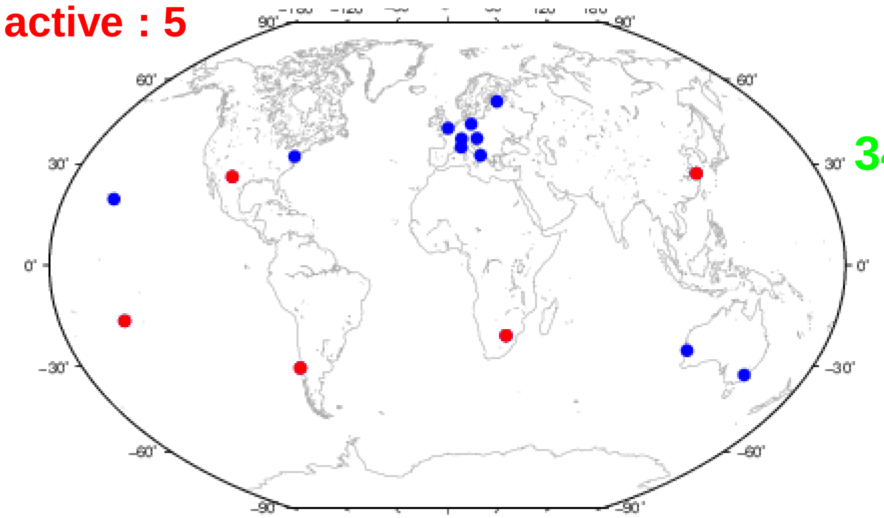


VLBI

36 stations

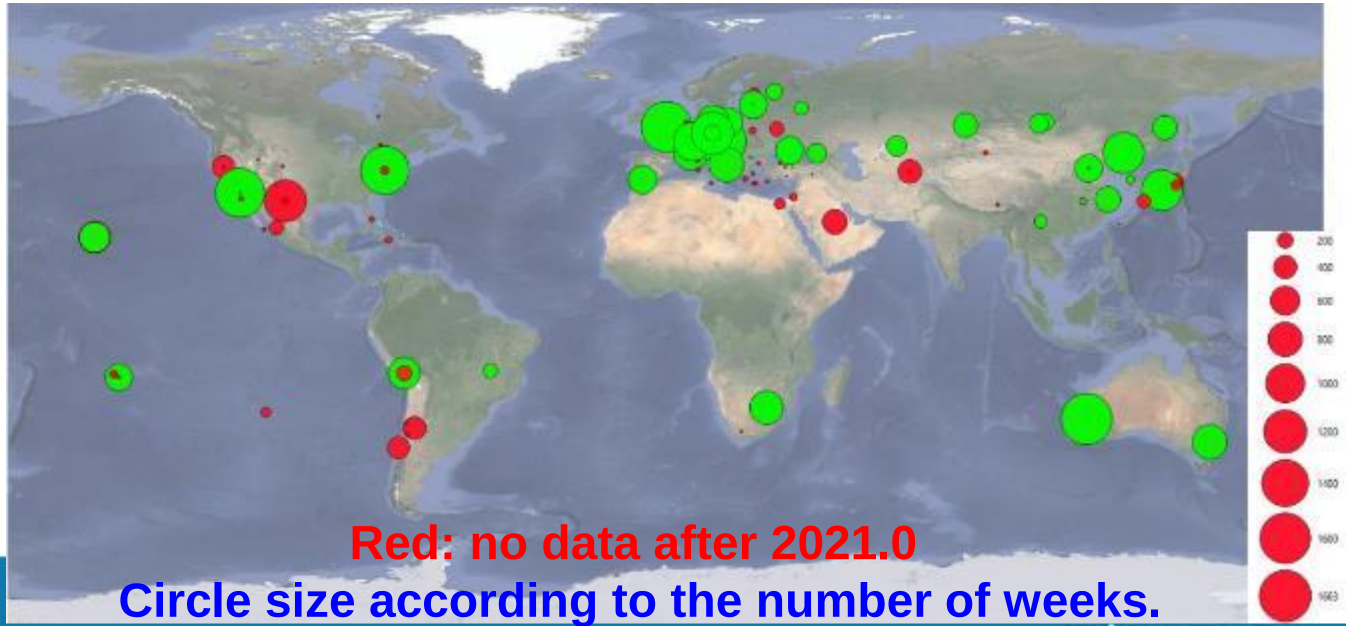


RF stations : 16
Not active : 5

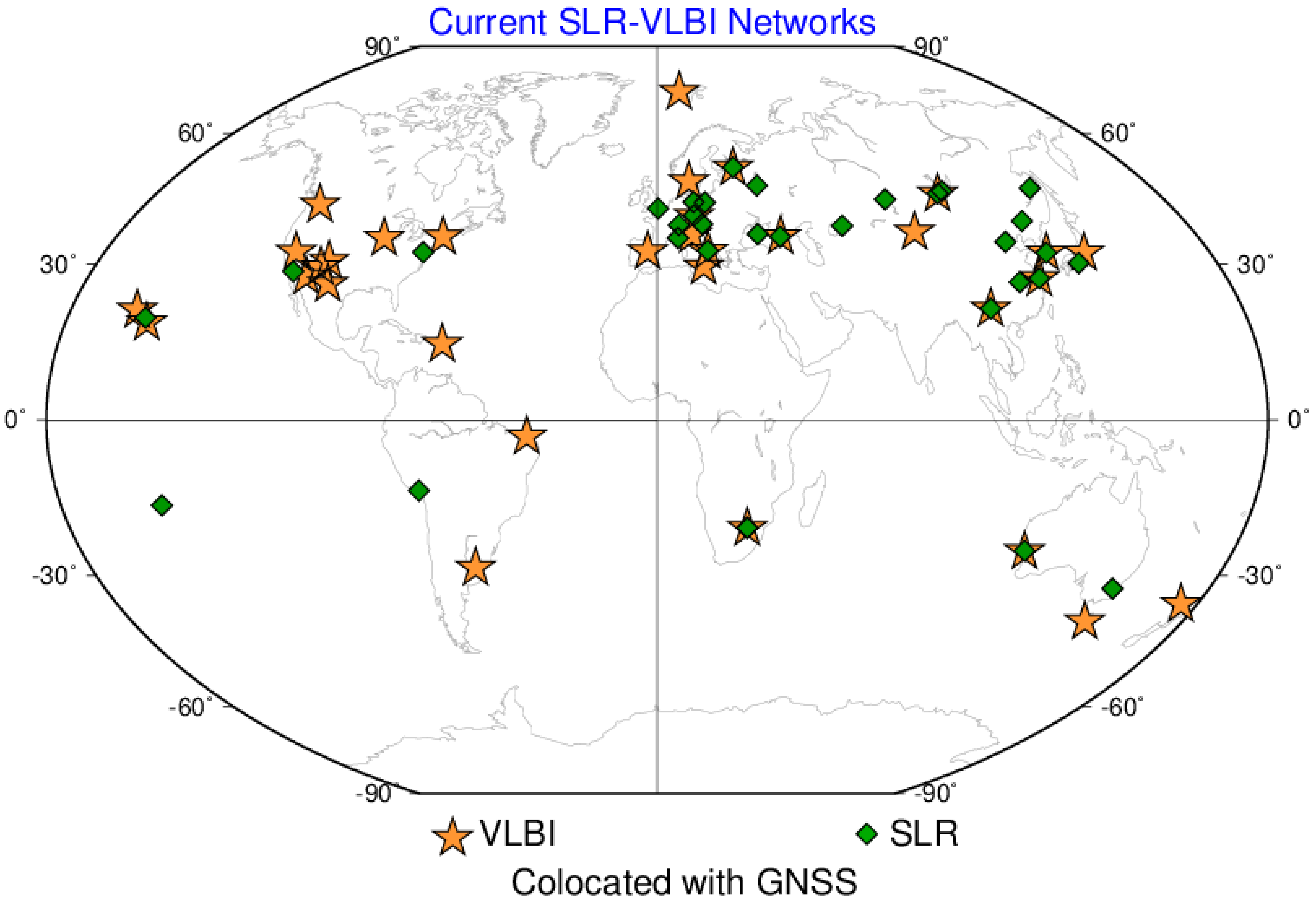


SLR

34 stations



Curent SLR & VLBI Networks

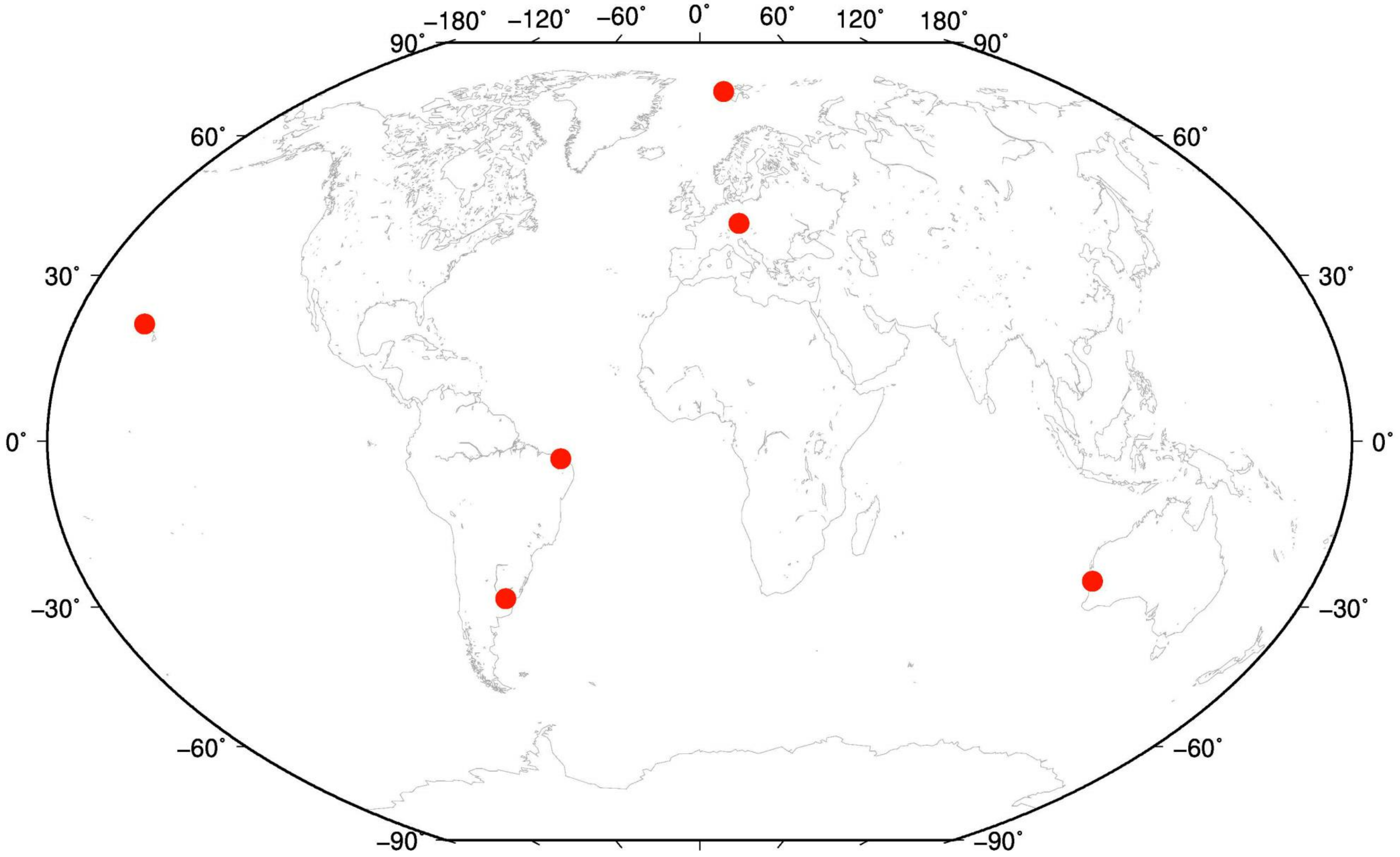


Animation / movie

Evolution of VLBI Sessions during the year 2020:

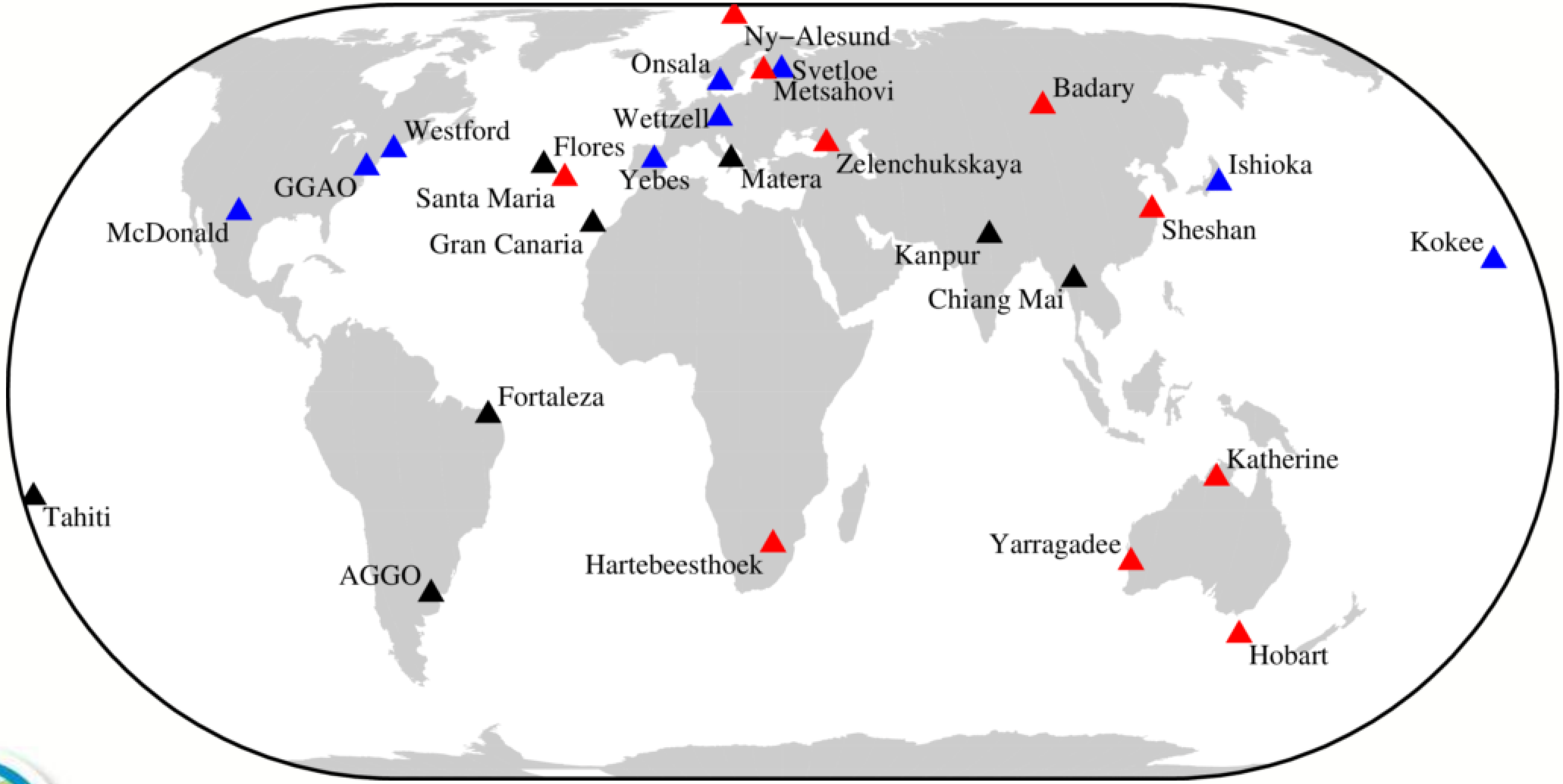
142 sessions all in all

Notice regional sessions not well designed for the TRF: xxx sessions

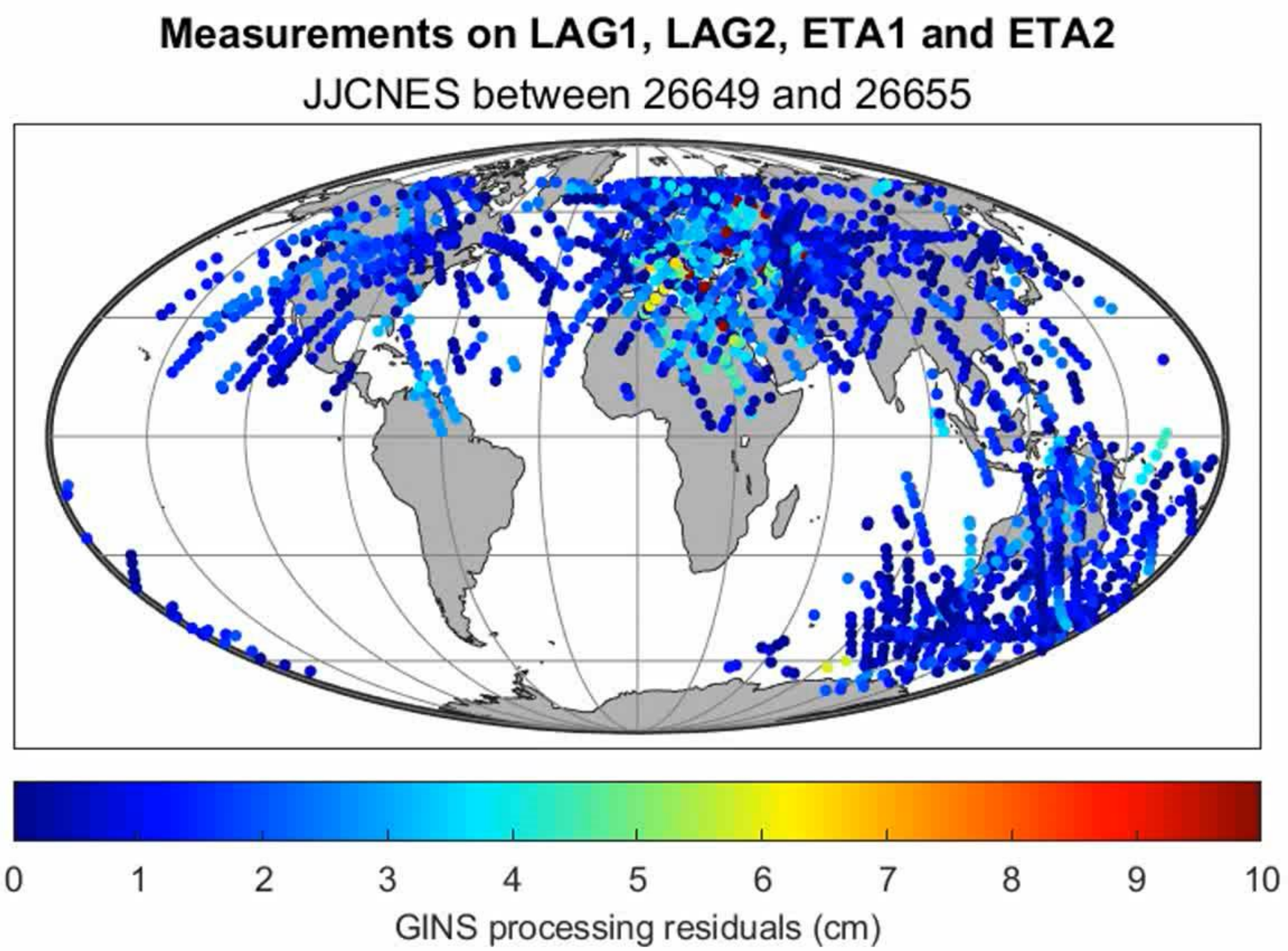


−180˚
−120˚
−60˚
0˚
60˚
120˚
180˚
90˚
90˚
60˚
60˚
30˚
30˚
0˚
0˚
−30˚
−30˚
−60˚
−60˚
−90˚
−90˚

VGOS Stations



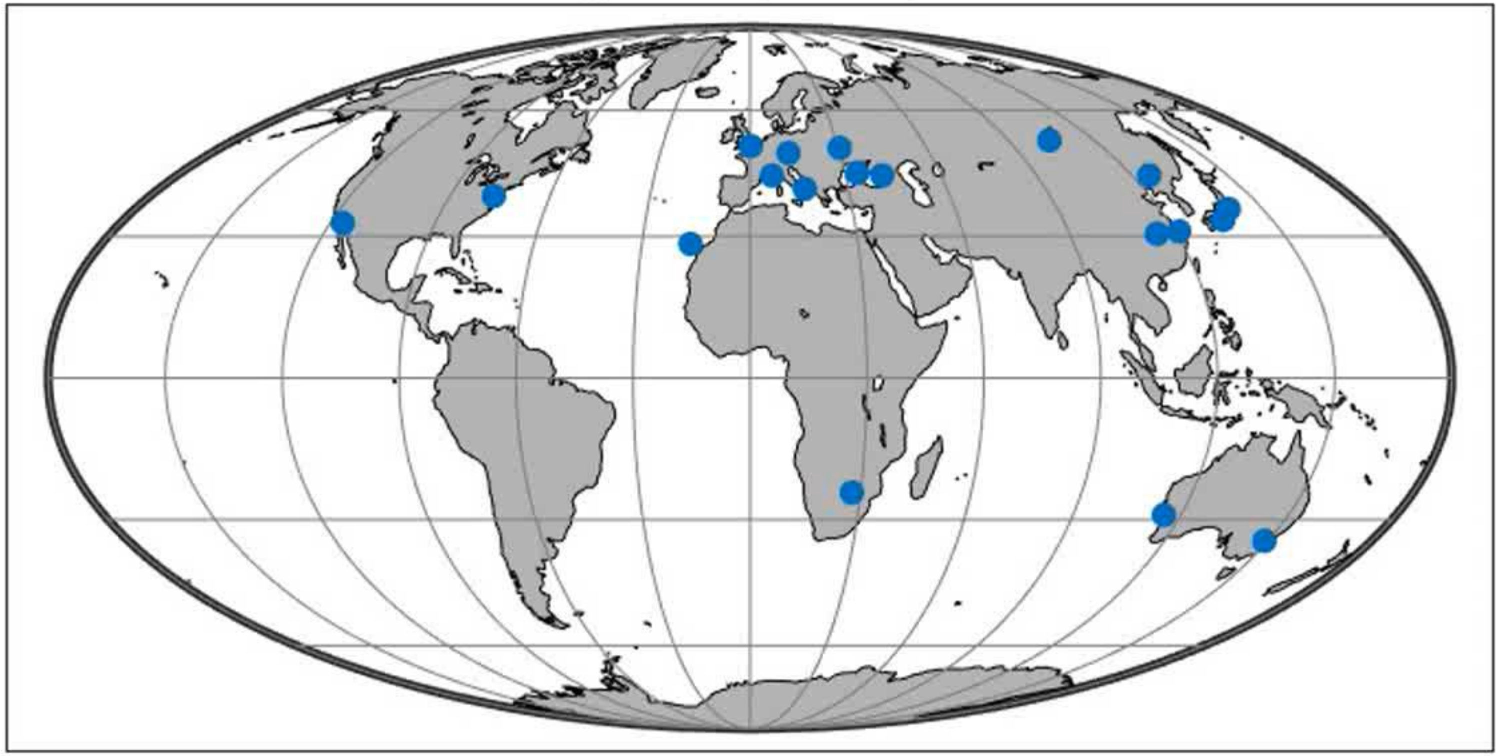
Animation / movie
Weekly SLR processing residuals using measurements of Lageos I & II, Etalon I & II, Year 2023


Measurements on LAG1, LAG2, ETA1 and ETA2
JJCNES between 26649 and 26655
0
1
2
3
4
5
6
7
8
9
10
GINS processing residuals (cm)

Animation / movie
Evolution of weekly SLR network during the year 2023

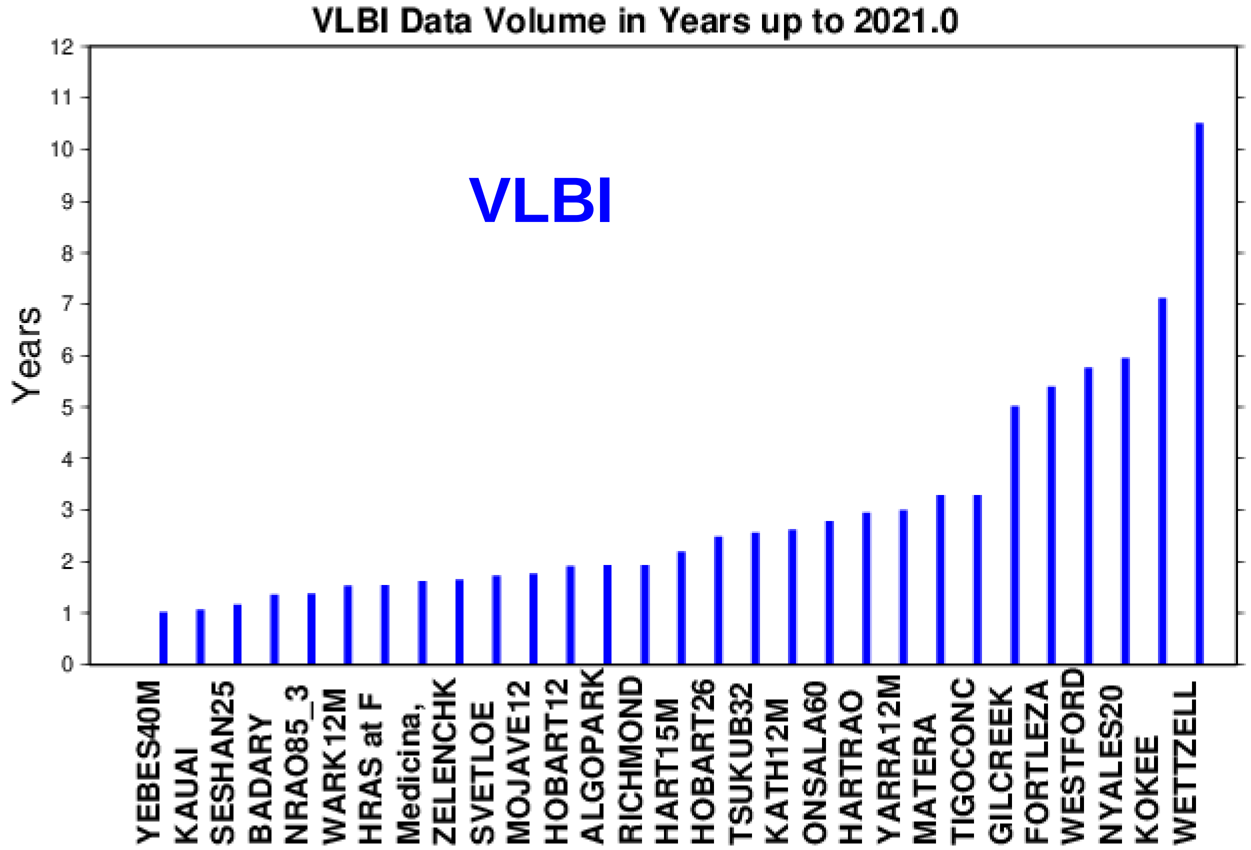
List of all stations used between JJCNES 26649 and 26655

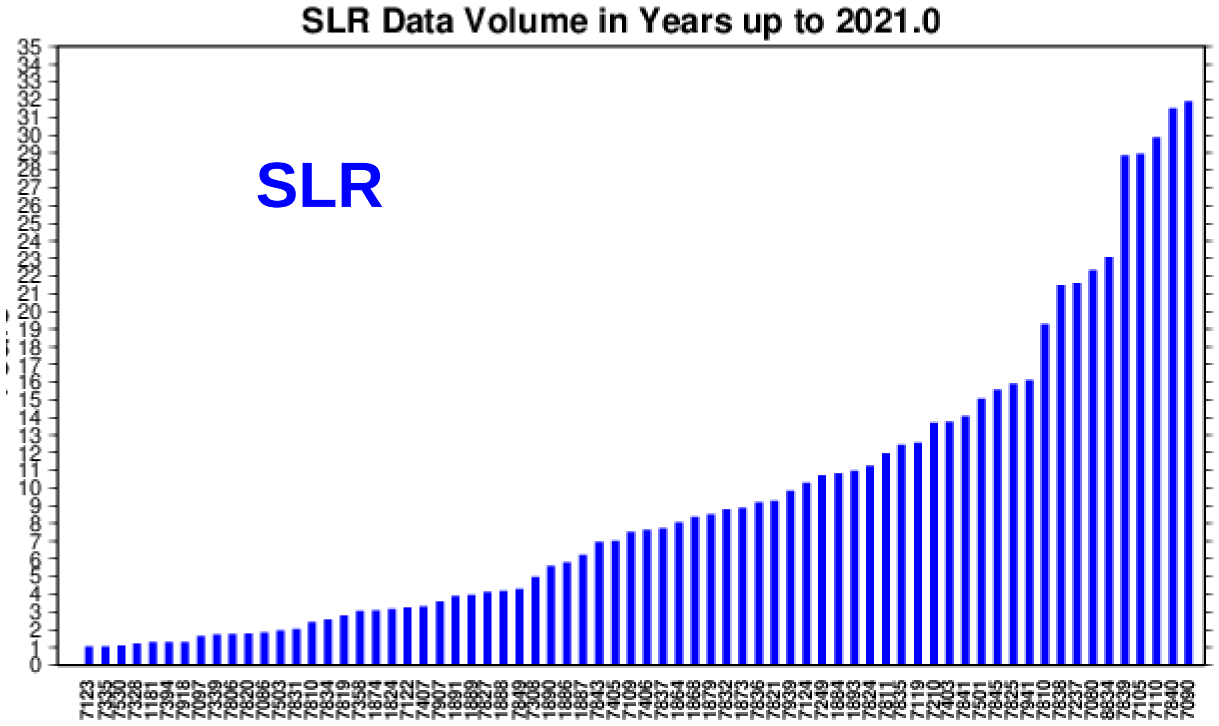
Stations observing LAG1, LAG2, ETA1 and ETA2



VLBI & SLR Data Volume in years up to 2021.0

Shown are stations with data volume > 1 year





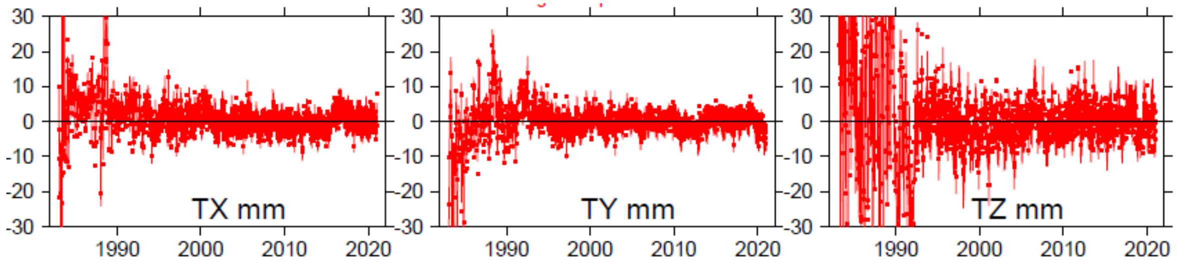
ITRF2020: Local tie Discrepancies

LT Discrepancies: Differences between terrestrial ties and space geodesy estimates
Local tie vectors between GNSS and the 3 other techniques at co-location sites

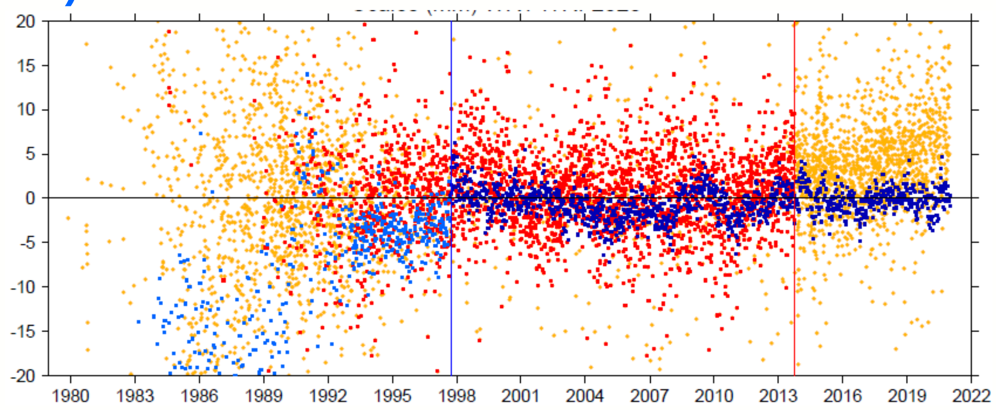
GNSS to :	Total tie vectors ITRF2020	Discrepancy > 5 mm	% Discrepancy > 5 mm
VLBI	77	39	50
SLR	53	34	64
DORIS	123	84	68

ITRF : Uncertainty in the frame definition/specification

- **Origin: Rely on one technique : SLR**
  - **Long-term uncertainty: at epoch 2015.0: up to 5 mm**
  - **Stability / rate : up to 0.5 mm/yr**



- **Scale: Average of SLR & VLBI**
  - **Long-term uncertainty (level of agreement between SLR & VLBI):**
    - **ITRF2014: 1.4 ppb (~8 mm at the equator)**
    - **ITRF2020: 0.15 ppb (~1 mm at the equator)**
  - **Stability / rate : depend on “agreement of site velocities”**
  - **SLR & VLBI scale time series are not linear!!**



- **Orientation: Alignment of successive ITRF solutions using a selection of reference frame stations**
  - **Long-term & stability / rate uncertainty : dictated by the so-called network effect: up to 30µas (1mm)**

Future / Planned VGOS stations

Known project by IVS member institutions

Location	Lat, Lon	Country	Type	Responsible Agency	Planned Commissioning Date
Seshan13	31 N, 121 E	China	upgrade of core site by new VGOS station	CAS – Chinese Academy of Sciences	2024
Tianma13	31 N, 121 E	China	new VGOS station	CAS – Chinese Academy of Sciences	2024
Urumqi13	44 N, 88 E	China	upgrade of core site by new VGOS station	CAS – Chinese Academy of Sciences	2024
Matera	40 N, 16 E	Italy	upgrade of core site by new VGOS station	ASI – Italian Space Agency	2024
Metsähovi	60 N, 24 E	Finland	upgrade of core site by new VGOS station	FGI – Finnish Geodetic Institute	2024/2025
Hartebeesthoek	25 N, 27 E	South Africa	upgrade of core site by new VGOS station	SARAO – South African Radio Astronomy Observatory	2024/2025
Gran Canaria	28 N, 15 E	Spain	new VGOS station	IGN – Instituto Geographico National	2025/2026
Fortaleza	4 S, 38 W	Brazil	upgrade of core site by new VGOS station	NASA – National Aeronautics and Space Administration	2025/2026
Flores	39 N, 31 W	Portugal	new VGOS station	GRA – Regional Government of Azores	2030?
La Plata	35 S, 58 W	Argentina	upgrade of core site by new VGOS station	BKG – Bundesamt für Kartographie und Geodäsie	2030?
Tahiti	17 S, 149 W	Tahiti	new VGOS station	CNES – Centre national d'études spatiales NASA – National Aeronautics and Space Administration	2030?

Projects by institutes that are not yet part of IVS

Location	Lat, Lon	Country	Type	Responsible Agency	Planned Commissioning Date
Kuala Lumpur	4 N, 101 E	Malaysia	new VGOS station	UTM – University of Technology Malaysia	2025/2026
Chiang Mai	18 N, 99 E	Thailand	new VGOS station	NARIT – National Astronomical Research Institute of Thailand	2025/2026
Shongkhla	7 N, 100 E	Thailand	new VGOS station	NARIT – National Astronomical Research Institute of Thailand	2028
Kanpur	26 N, 80 E	India	new VGOS station	IIT – Indian Institute of Technology	2028?
Jatiluhur	7 S, 107 E	Indonesia	Upgrade of radio telescope to VGOS station (?)	Institut Teknologi Bandung CAS – Chinese Academy of Sciences	2030?
Timau	10 S, 124 E	Indonesia	new VGOS station	Institut Teknologi Bandung CAS – Chinese Academy of Sciences	2030?

Future / Planned SLR stations

Table 1. Future ILRS Network Developments

Site Name	Type	Agency	Timeframe
La Plata, Argentina	Upgraded core site	BKG, Germany	2024 – 2025
San Juan, Argentina	Upgraded SLR system	NAOC, China	2024 – 2025
Metsähovi, Finland	New SLR system	FGI, Finland	2024 – 2025
Greenbelt, MD, USA	Replacement core site	NASA, USA	2024 – 2024
Haleakala, HI, USA	Replacement core site	NASA, USA	2024 – 2026
McDonald, TX, USA	Replacement core site	NASA, USA	2024 – 2025
Ny Ålesund, Norway	New core site	NMA, Norway/NASA, USA	2024 – 2025
Ensenada, Mexico	New SLR site	IPIE, Russian Federation*	2024 – 2026
Java, Indonesia	New SLR site	IPIE, Russian Federation*	2024 – 2026
Gran Canaria, Spain	New SLR in core site	IPIE, Russian Federation*	2024 – 2026
Tahiti, French Polynesia	New SLR system	IPIE, Russian Federation*	2024 – 2026
Mt Abu, India	New SLR site	ISRO, India*	2025 – 2026
Ponmundi, India	New SLR site	ISRO, India*	2025 – 2026
Ishioka, Japan	New SLR site	Hitotsubashi U., NAOJ and U. Tokyo, Japan	2024
Yebes, Spain	New SLR site	IGS, Spain	2024
Irkutsk (Tochka)	New SLR site	VNIIFTRI, Russia	2025 – 2026
Mendeleevo (Tochka)	New SLR site	VNIIFTRI, Russia	2025 – 2026

*Situation uncertain

Summary

- ITRF is fundamentally based on colocations: Strengthen ITRF parameters
- The origin (CM) of the ITRF needs improvement by a factor of 5.
- SLR & VLBI are critical for the frame definition : origin (SLR), scale (SLR & VLBI)
- SLR & VLBI collocations (~ 10 sites) are poorly distributed
- A number of SLR & VLBI instruments are old-generation systems
- Both networks need improvement, especially in the southern hemisphere
- Quantitatively : Data yield is poor for both techniques
- VLBI sparse sessions, with less than 10 stations in average
- Need to evolve toward more frequent global sessions, with increased number and well-distributed stations

- GNSS links together SLR, VLBI & DORIS networks
- More than 50 % of tie discrepancies are larger than 5 mm,
- Caused mainly by technique systematic errors

SCoG Geodetic Infrastructure Questionnaire 2019/2020
Summary of SLR & VLBI needs

# Instruments needed to fill the gaps in the network	# of additional Data Centers	# of additional Analysis Centers	New technology development
20 Cost for one instrument: ~$8M	4 Total annual cost per center: ~$250K	6 Total annual cost per center: ~$600K	~$200M

Many Thanks for their contributions

- ILRS and IVS
- Florent Deleflie (IMCCE, Paris)
- David Sarrocco (ASI, Italy)
- ITRF Team at IGN:
  - Arnaud Pollet
  - Xavier Collilieux
  - Paul Rebischung
  - Julien Barnéoud