Science Overview

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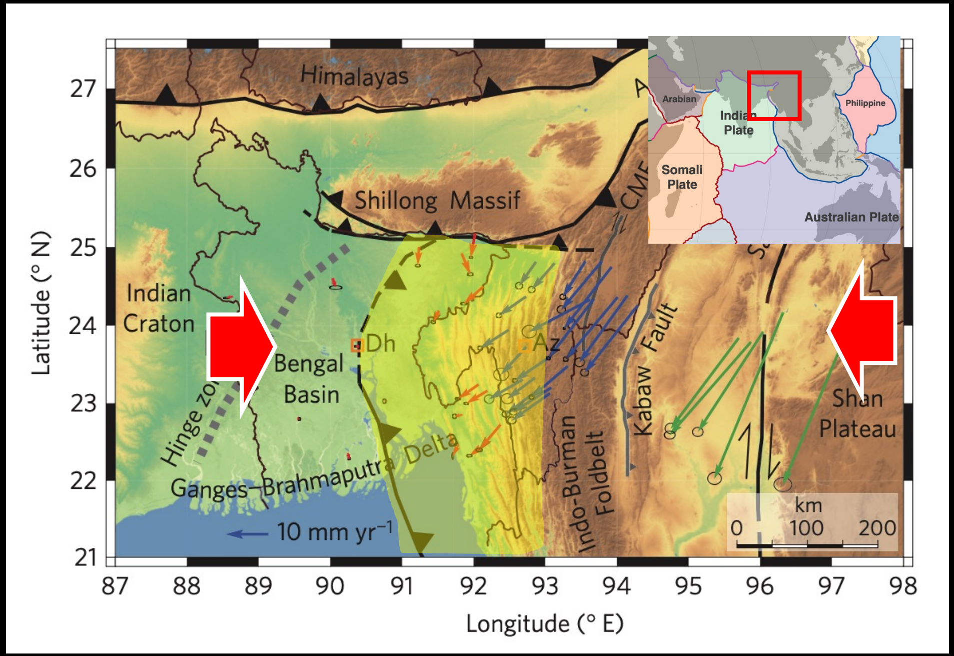
Haystack Observatory
Massachusetts Institute of Technology

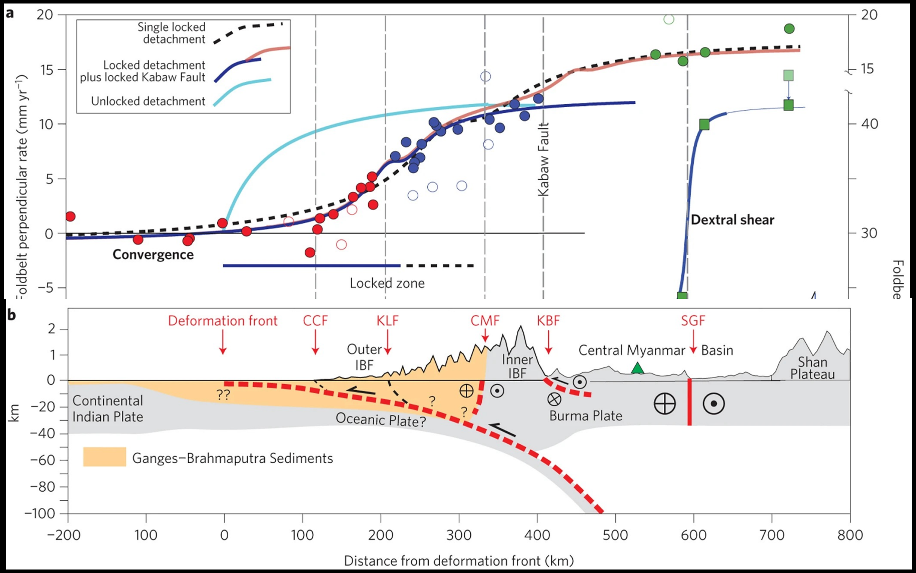
13th IVS Technical Operations Workshop

May 5 -8, 2025

With contributions from Frank Lemoine and other sources

Hidden megathrust beneath megacities, a personal seismo-geodetic story





nature geoscience
LETTERS
PUBLISHED ONLINE: 11 JULY 2016 | DOI: 10.1038/NGEO2760

Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges

Michael S. Steckler[1]*, Dhiman Ranjan Mondal[2,3], Syed Humayun Akhter[4], Leonardo Seeber[1], Lujia Feng[5], Jonathan Gale[1], Emma M. Hill[5] and Michael Howe[1]

Giant 'megathrust' fault is discovered in the Earth's crust under the most densely populated part of the globe that could wipe out 'tens of millions' in an earthquake Daily Mail .com

- A giant fault in the earth's crust has been found underneath Bangladesh
- Some 140 million people live within 60 miles of the potentially deadly fault
- Experts fear the fault could unleash a 9.0 magnitude earthquake at any time
- Researchers claim Bangladesh needs to build earthquake resistant homes

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Dahabo's "Track and Save a Life" with geodesy

- In Kenya, Marsabit County is a community of 80% pastoralists (nomadic) and has the highest maternal mortality rates.
- Nomadic women moved from one place to another, thus having no access to healthcare.

Solar-Powered tracking bracelets reduces maternal mortality in Kenya

Friday, November 20, 2020

- Maternal and child death was reduced by approximately 40%
- Immunization coverage increased by 80-85%

Source:https://old.aasciences.africa/news/solar-powered-tracking-bracelets-reduces-maternal-mortality-kenya

High Mortality → Track and Treat → Low Mortality

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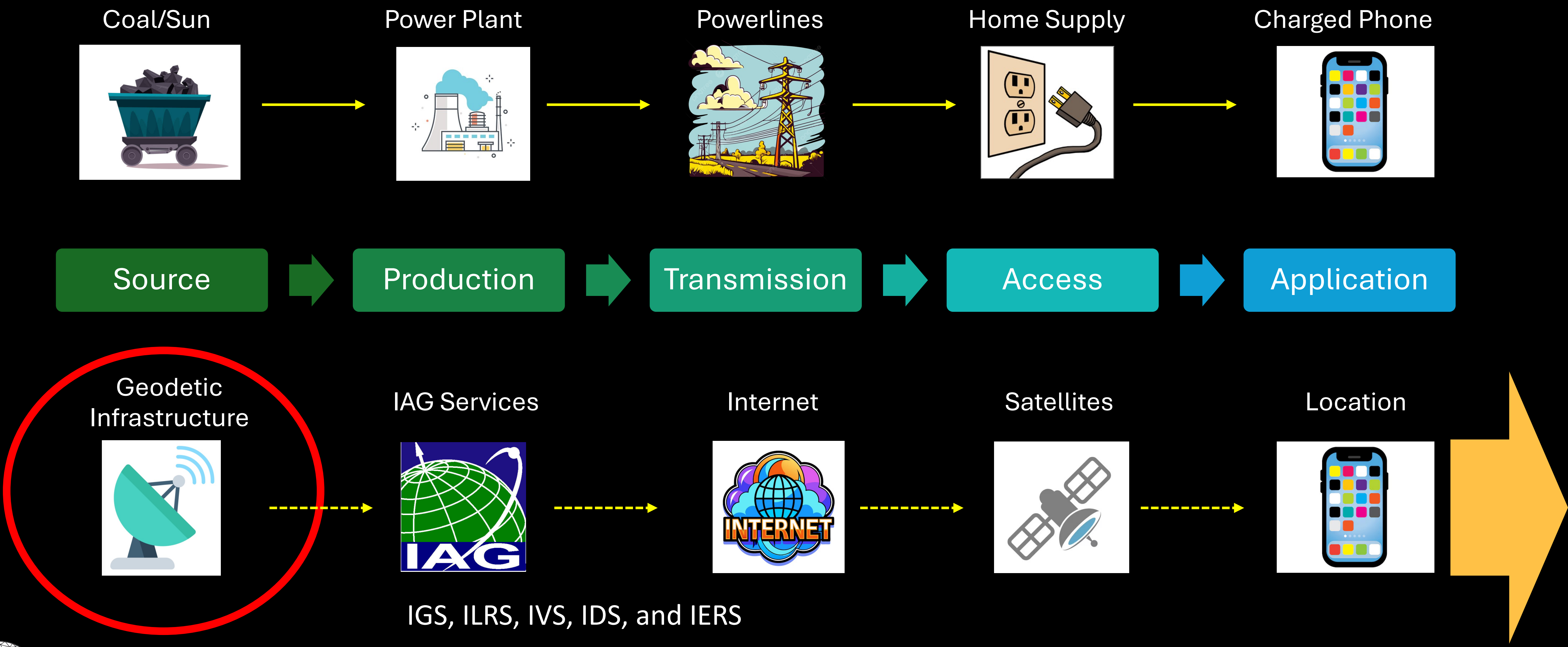
Sustain the entire value chain



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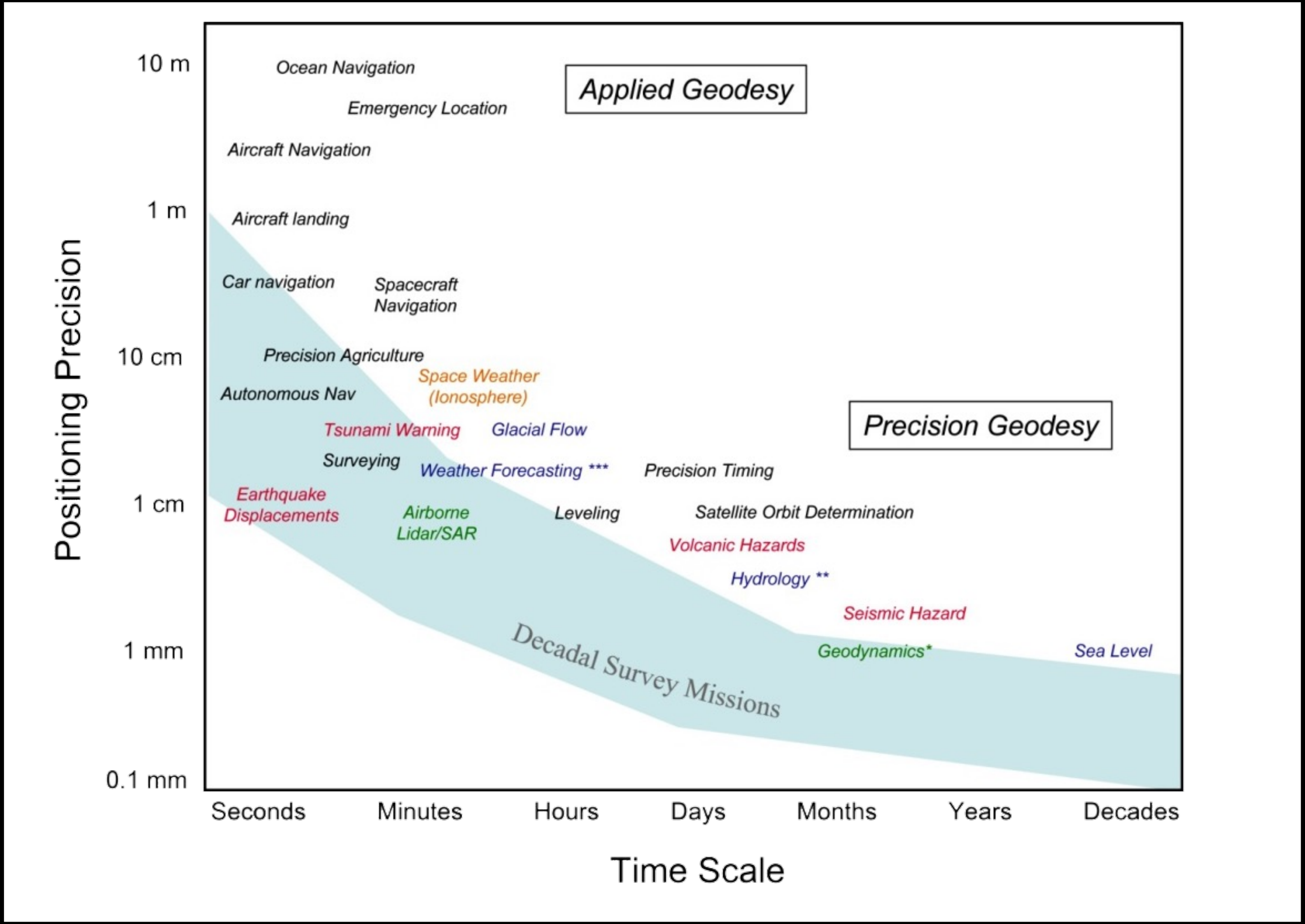
Modified after: https://ggim.un.org/meetings/2021/Global_Geodesy_Forum/documents/Global_Geodesy_Forum-Presentation.pdf

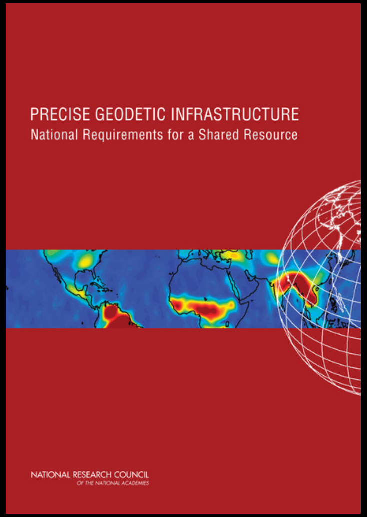
Where on Earth am I now?

How well do I know it?

How frequently do I know it?

Positioning in various spatio-temporal scales





Source: https://nap.nationalacademies.org/catalog/12954/precise-geodetic-infrastructure-national-requirements-for-a-shared-resource

Outline

- What is Geodesy?
- Techniques of Space Geodesy
- Applications of VLBI
  - EOP, TRF, CRF
  - EOP/Earth rotation in the news
- Geodesy and change in global mean sea level

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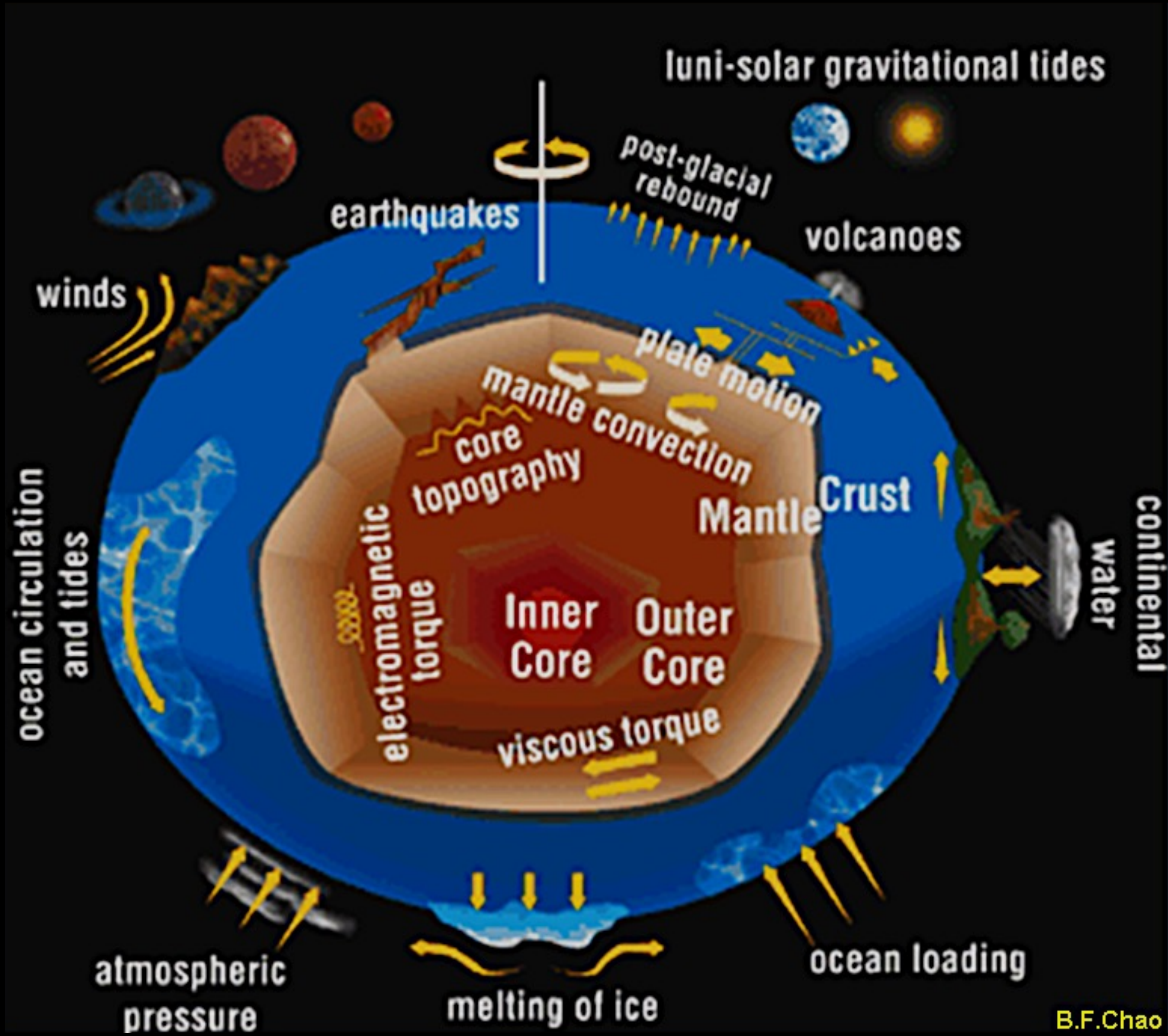
What is Geodesy?

- The science of the Earth's **shape, rotation,** and **gravity**, including their evolution in time
- Earth's dynamic and complex system needs continuous and reliable global geodetic monitoring
- Techniques used to observe the geodetic properties of the Earth provide the basis for the International Terrestrial Reference Frame (ITRF)
- ITRF is
  - the foundation for all airborne, space-based, and ground-based Earth observations, and
  - important for interplanetary spacecraft tracking and navigation



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Geodesy Toolbox for Monitoring

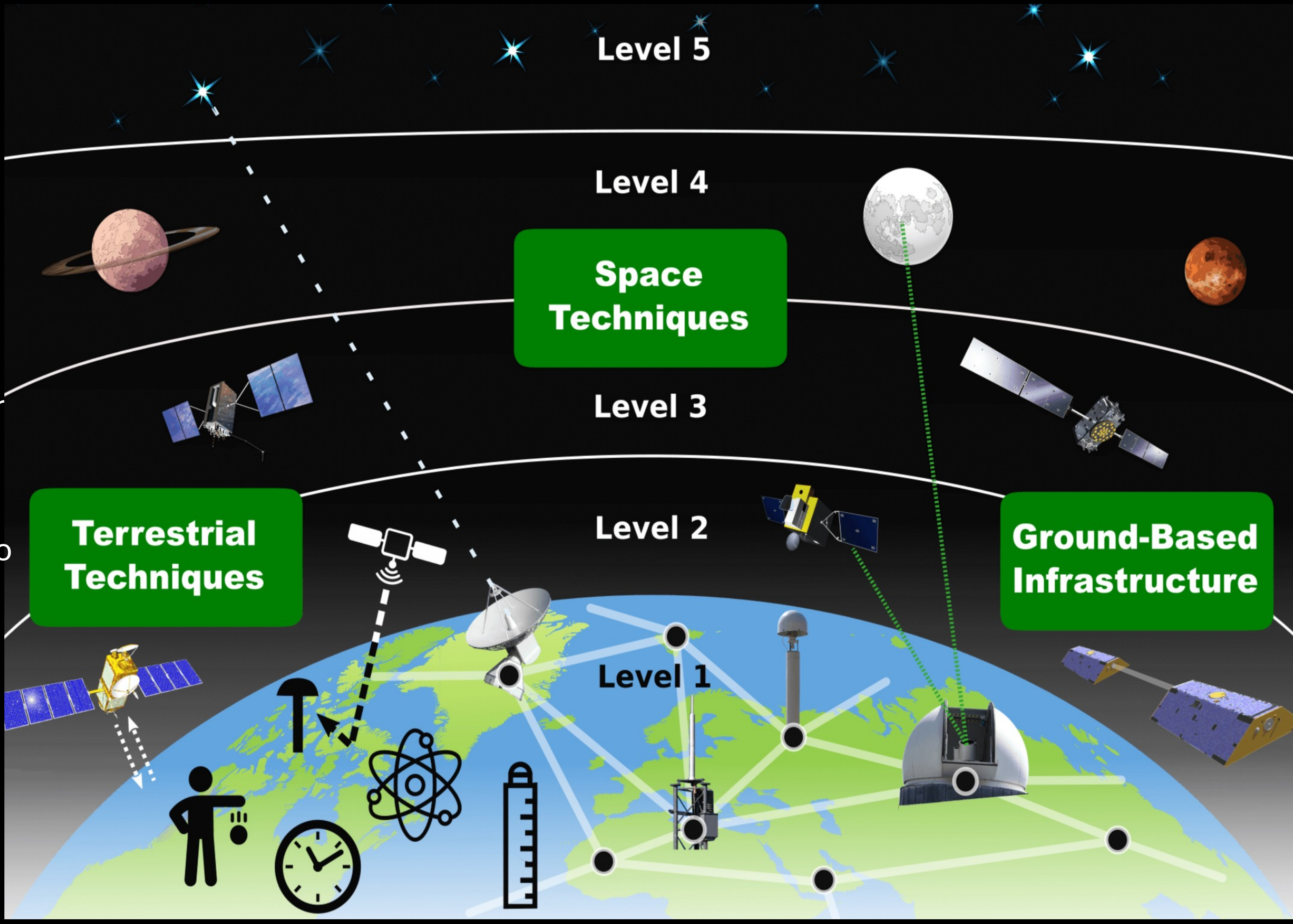
L5. Extragalactic Objects: Quasars and other compact radio sources (provide fixed references in the sky).

L4. Planetary Objects: Planetary missions and geodetic infrastructure on planets and natural satellites, especially the Moon.

L3. High Altitude Satellite Missions: MEO and GEO satellite missions (with altitudes up to 36,000 km) used mainly for GNSS and SLR.

L2. Low Altitude Satellite Missions: LEO satellite missions (altitudes 180 km to 2,000 km) used mainly for monitoring the land, ocean, and ice surfaces as well as the Earth's gravity field and its temporal variations.

L1. Geodetic Terrestrial Infrastructure: Consisting of all terrestrial networks of geodetic ground stations.



“Space Geodesy” Toolbox

SLR

GNSS

DORIS

VLBI

International Laser Ranging Service

IGS INTERNATIONAL GNSS SERVICE

IDS International DORIS Service

IVS INTERNATIONAL VLBI SERVICE FOR GEODESY AND ASTROMETRY

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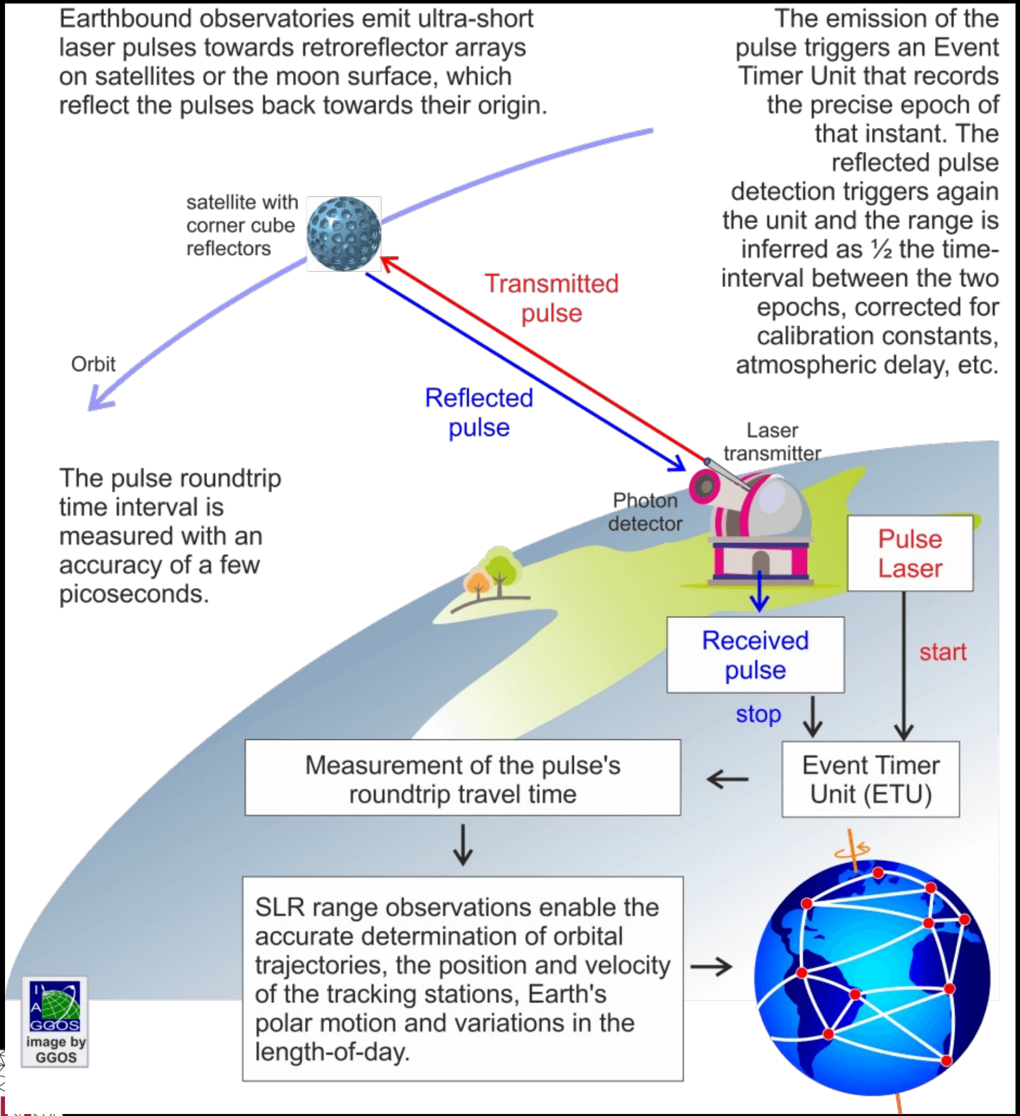
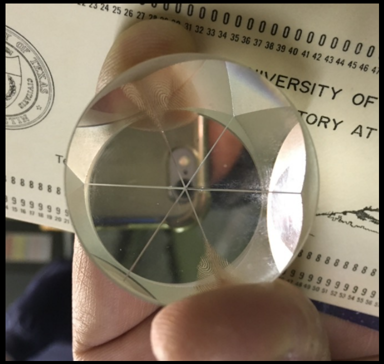
Satellite Laser Ranging (SLR)



https://ggos.org/item/slr-llr/



- Wavelength: 532, 1064 nm.
- Best stations have mm precision.
- Preponderance of stations in N. Hemisphere.
- First satellite ranging 1964, NASA GSFC

VLBI-SLR Colocations:
- Badary
- Greenbelt
- Hartebeesthoek
- Matera
- Shanghai
- Svetloe
- Wettzell
- Yarragadee
- Zelenchuskaya

In near future
- La Plata
- McDonald
- Metsähovi
- Ny Ålesund
- Yebes

Long-term plan
- Tahiti

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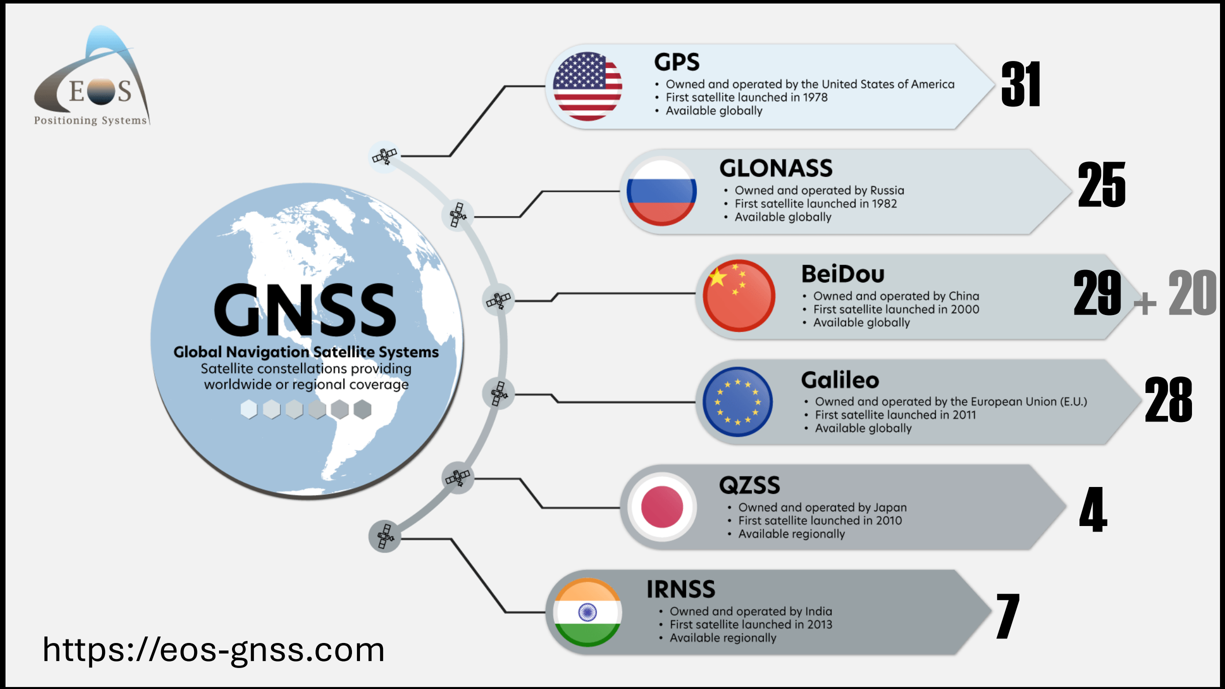
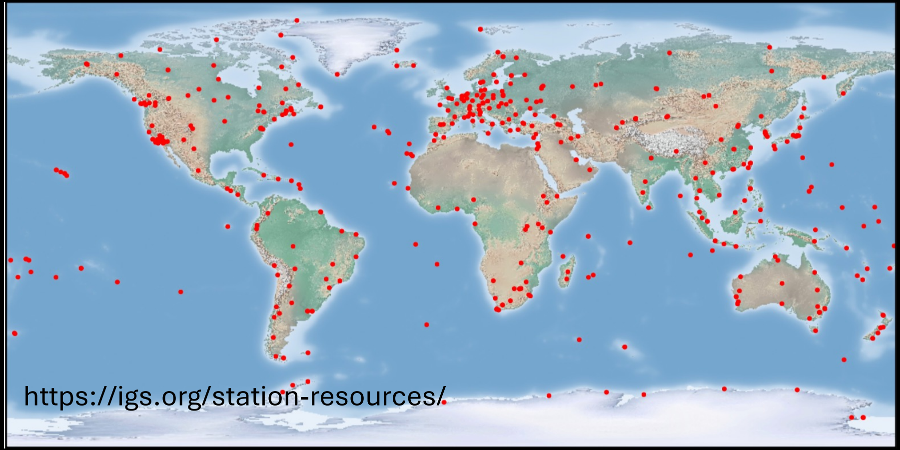
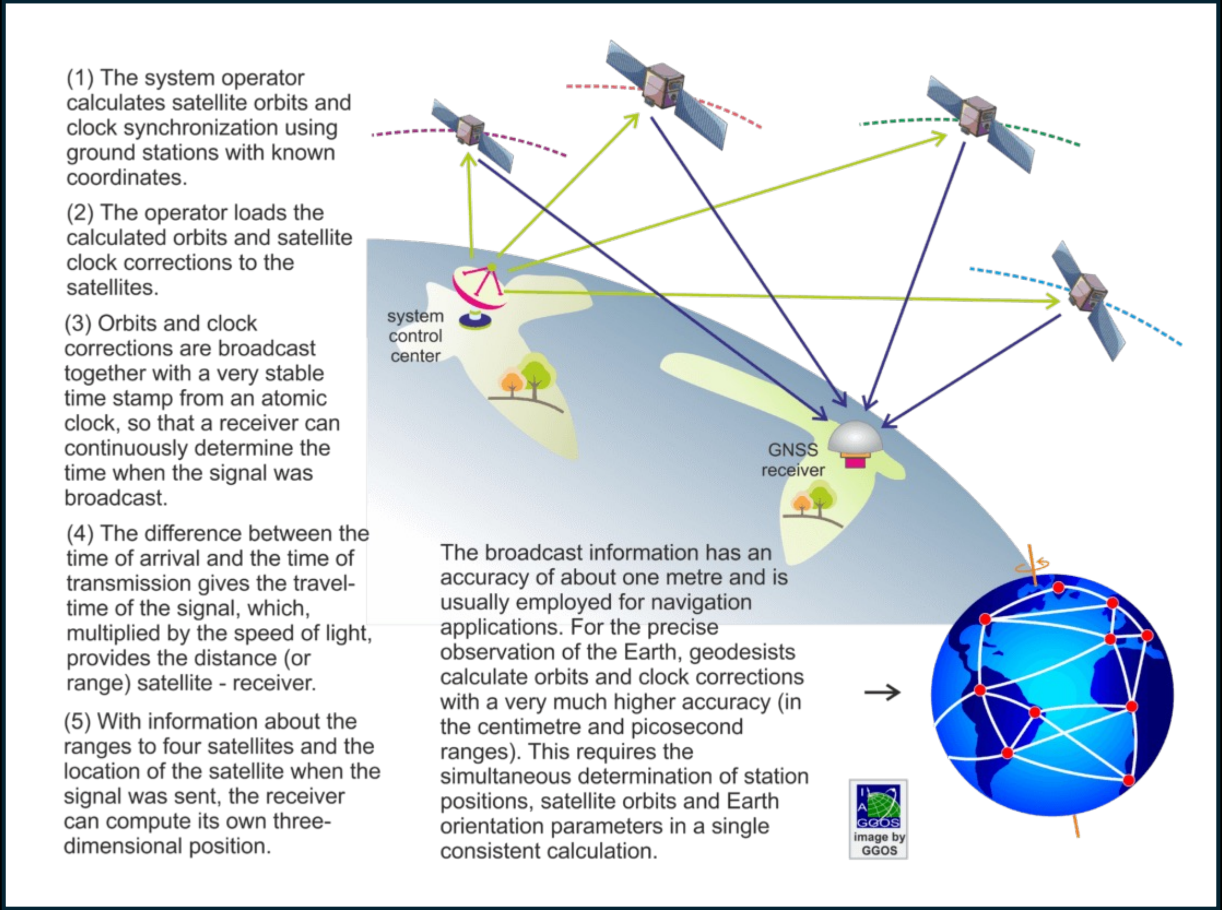
Global Navigation Satellite Systems (GNSS)



GNSS helps Precise Orbit Determination (POD) of sattelites (e.g., Sentinel-6A tracks GPS & Galileo).





- IGS Network has ~514 stations (as of April 17, 2023).
- Regional networks have hundreds to thousands of stations.
- Products: Positions, orbits of GNSS satellites, Troposphere & Ionosphere products.

https://ggos.org/item/gnss/

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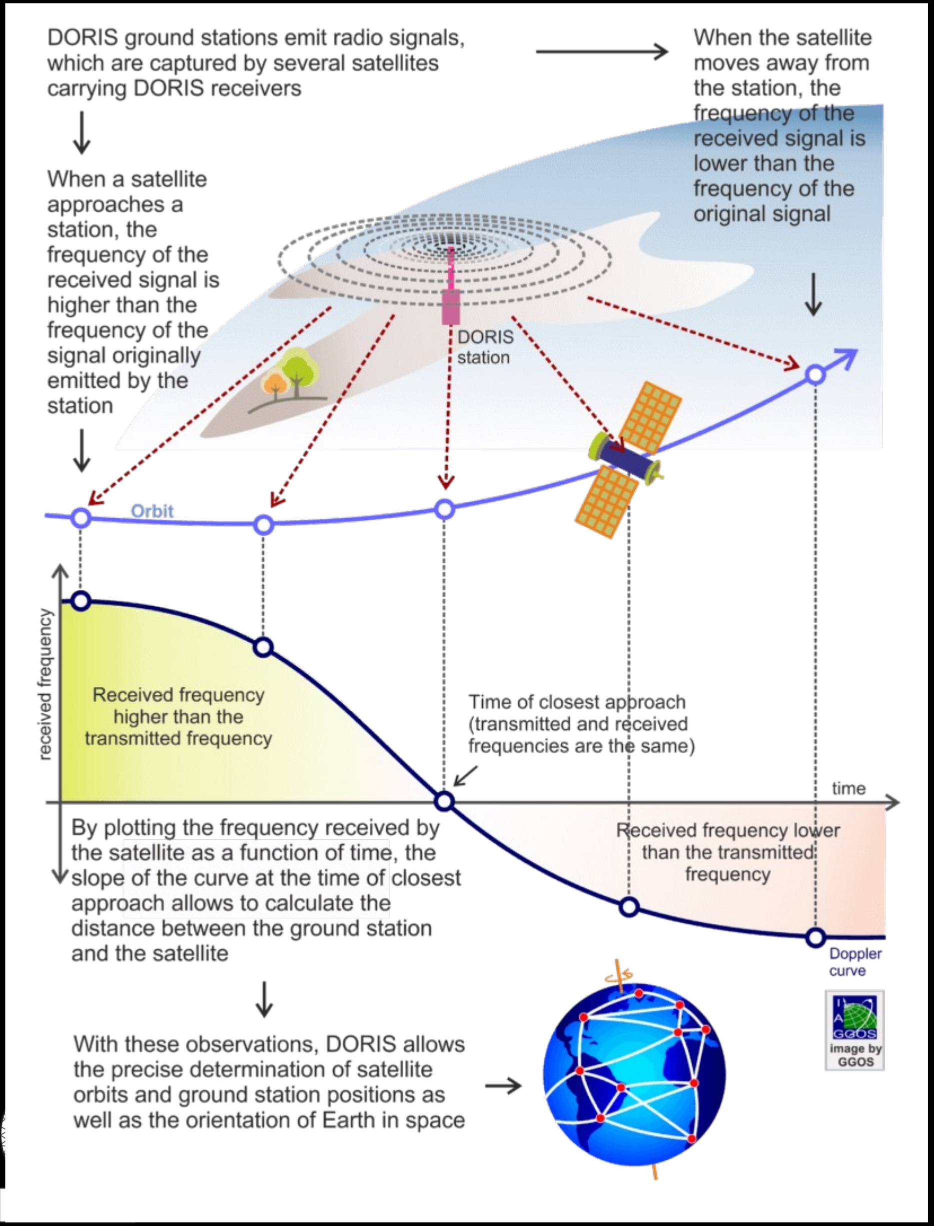
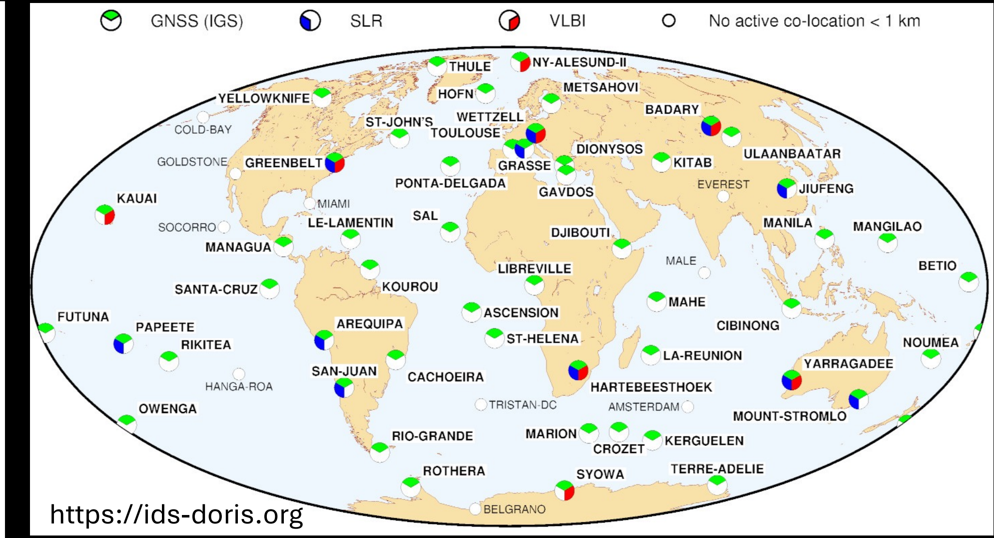
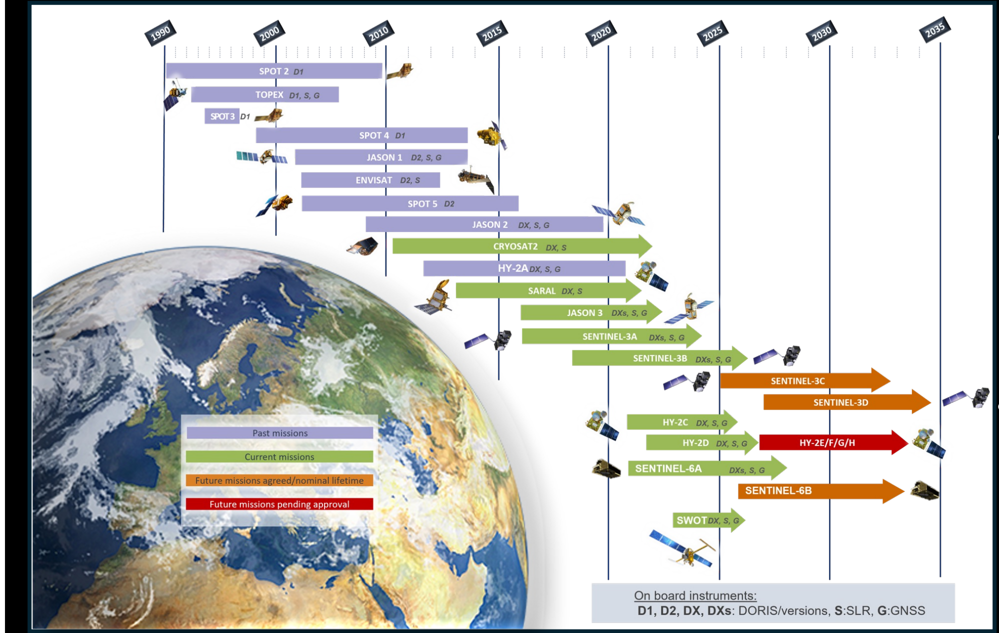
Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

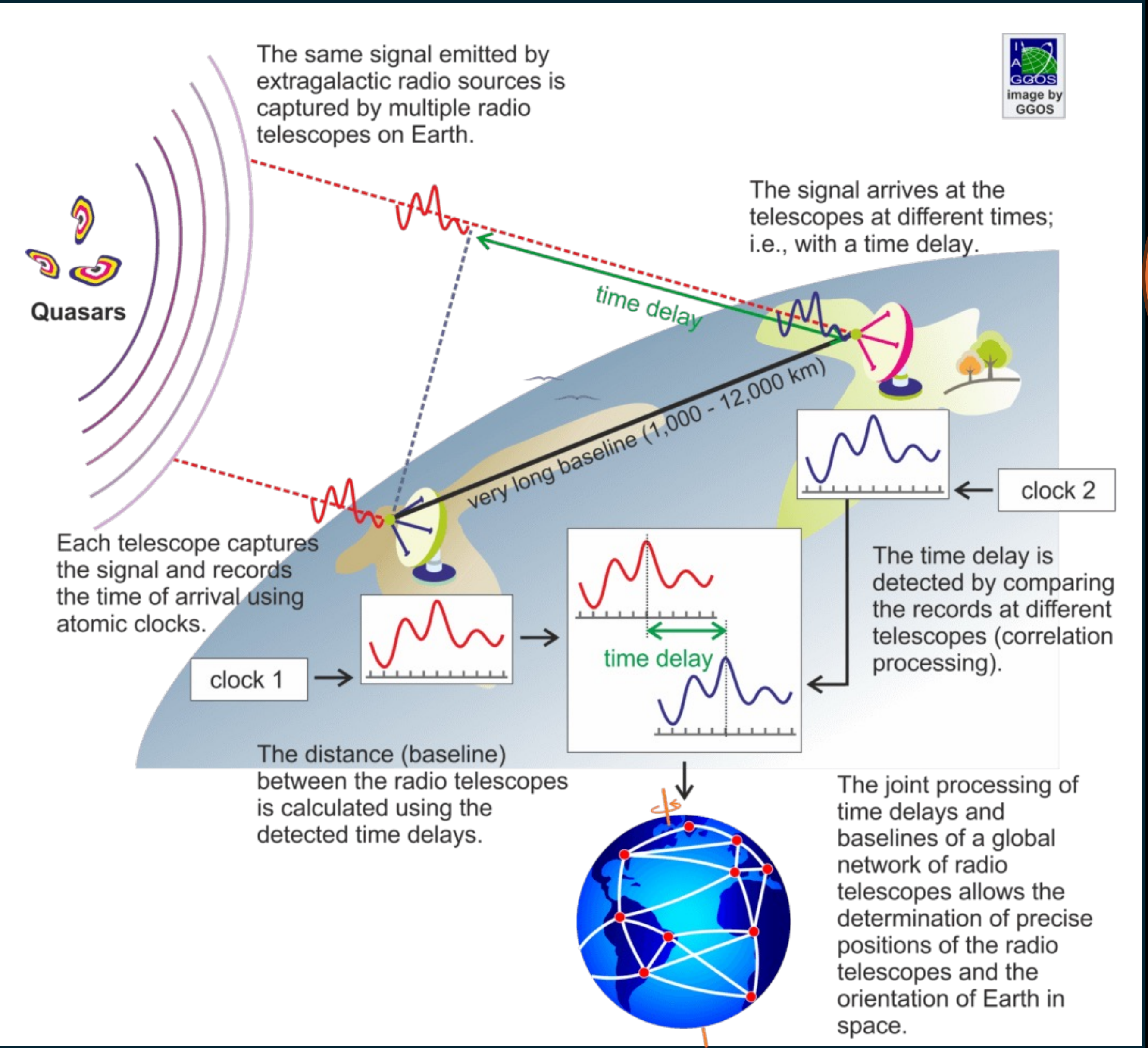


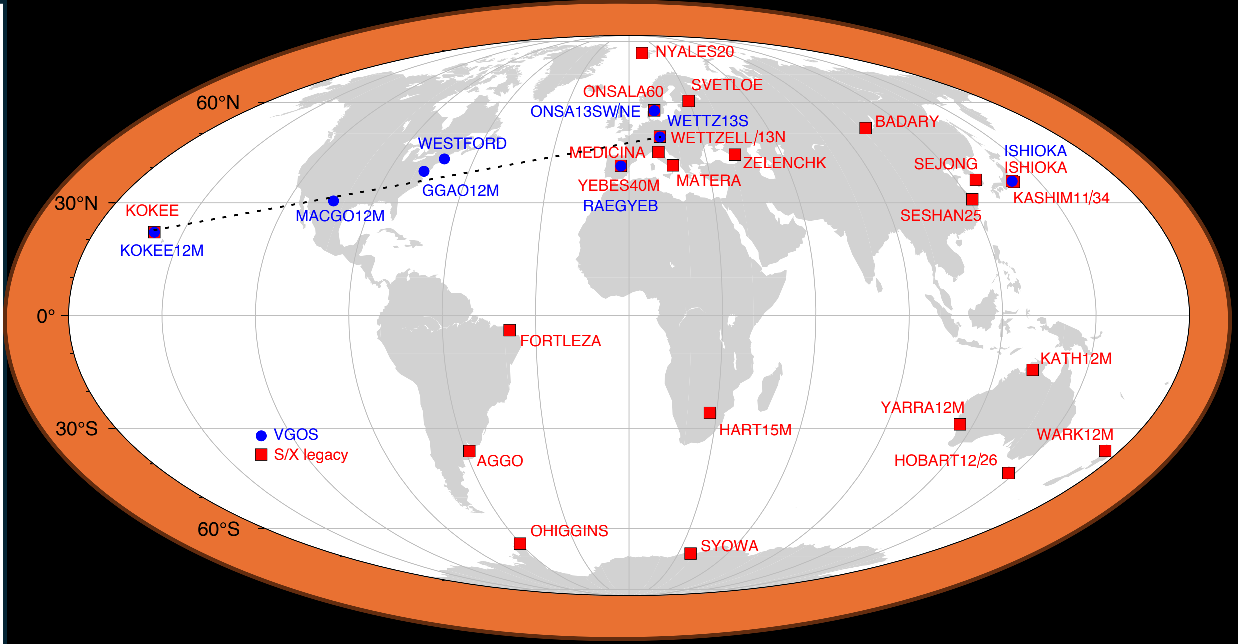




- The DORIS system includes:
  - Ground station contains dual-frequency transmitters (2 GHz and 400 MHz), an ultra-stable oscillator, a control system, weather sensors, and a reference antenna
  - Master stations provide the system's time reference
  - A control center based in Toulouse, France
- An important product of the DORIS system is the precise orbit determination of low-altitude Earth satellites, primarily used for altimetry and remote sensing
- Around 50 DORIS stations are co-located with other space techniques (VLBI, SLR, GNSS)

Very Long Baseline Interferometry (VLBI)





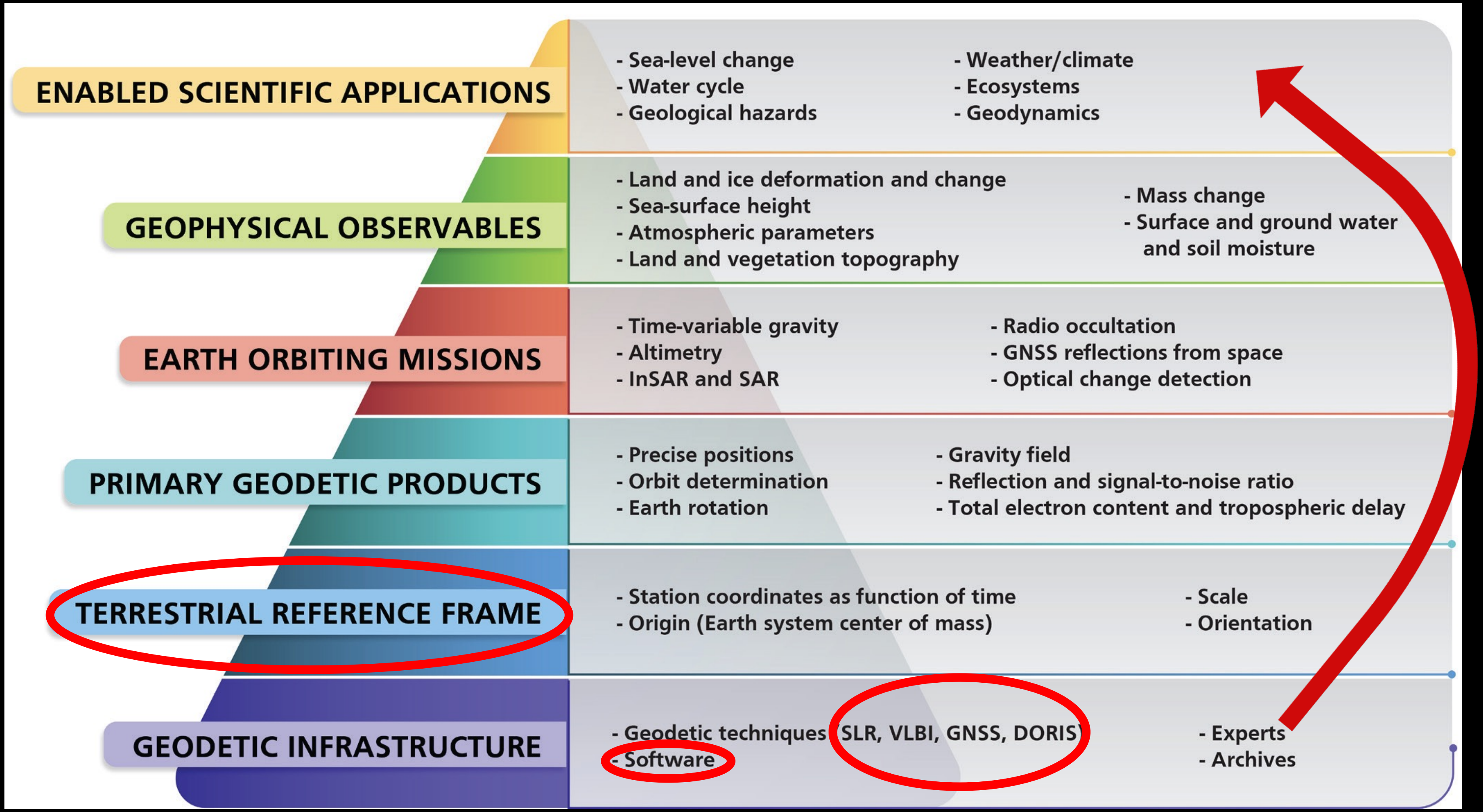
Measured vs Modeled

$$\tau = \tau_g + \tau_{clk} + \tau_{ins} + \tau_{ion} + \tau_{trop} + \tau_{rel} + \tau_{other} + \in$$

- **Signal** (geometry => position)
- Rest is **"noise"**
  - Clocks
  - Ionosphere
  - Troposphere
  - Electronics, etc.

Space Geodesy – Terrestrial Reference Frame (TRF)

- The space geodetic infrastructure (e.g., VLBI and GNSS) is vital to meet pressing scientific and societal needs
- Geodesy realizes a TRF that enables satellite methods, geophysical observations, and key science applications such as sea-level change, weather, and climate

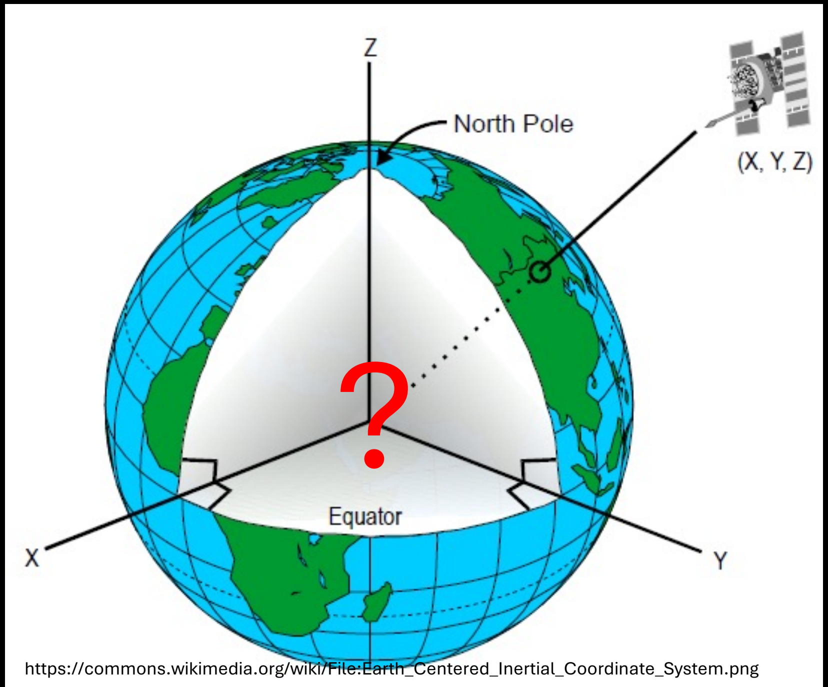


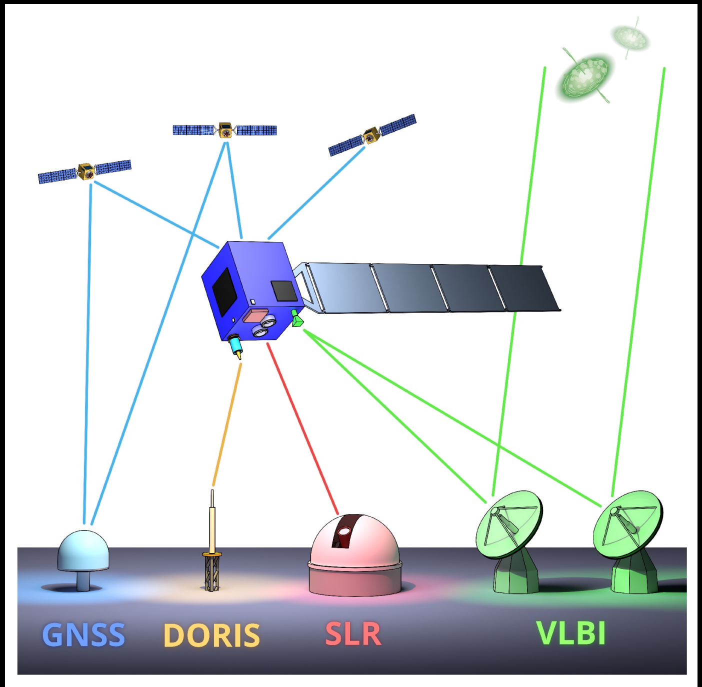
[NASEM, 2020]

Terrestrial Reference Frame (TRF)

[Schunck et al., (2024)]

- TRF is the foundation for all ground- and space-based Earth observation programs
- The positions of objects are determined in relation to an underlying TRF
- Space-geodetic observing systems define terrestrial and celestial reference frames, serving as the universal standard for measuring Earth's shape, rotation, and linking Earth observations across space and time





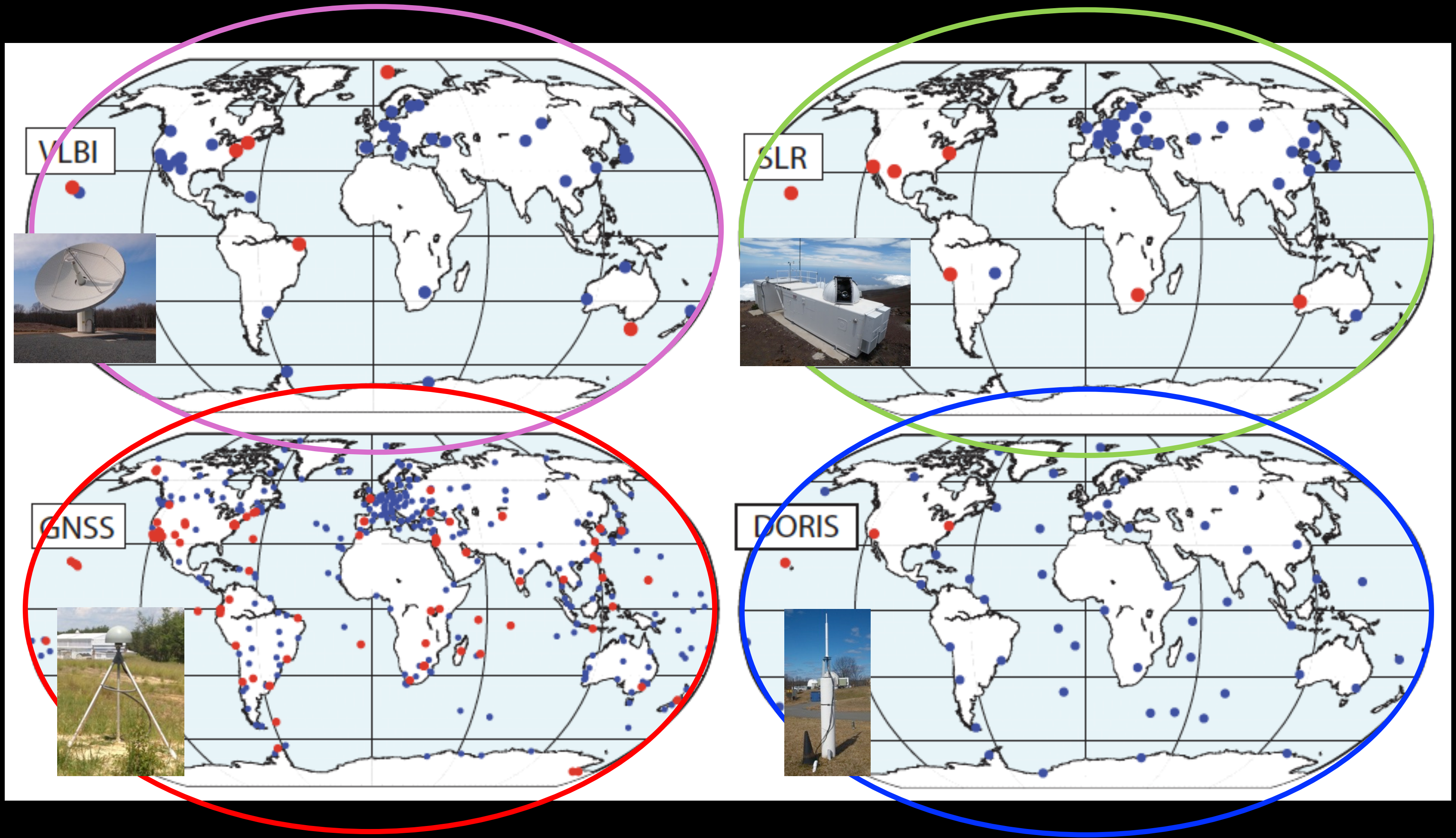
Space-geodetic observing systems

The goal is to realize TRF with 1 mm accuracy and 0.1 mm/yr stability

Improving TRF requires - improved technology and improved techniques

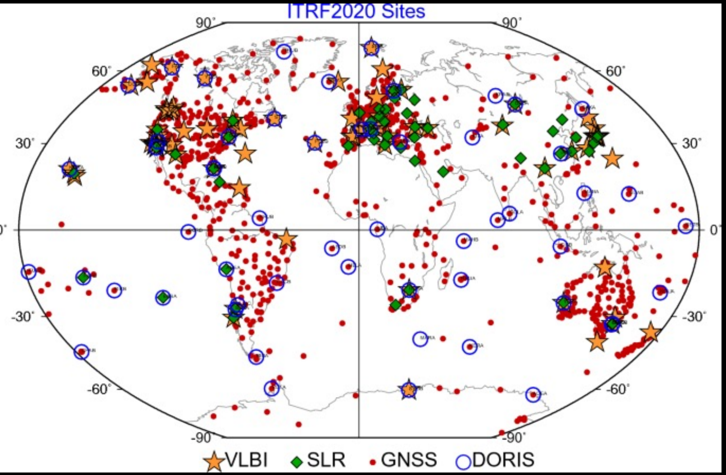
Independent ("disconnected”) TRFs

- Each geodetic technique realizes an independent TRF, each having different strengths and weaknesses
- A far more robust TRF can be achieved by robustly combining the individual TRFs (i.e., applying inter-technique vector ties)



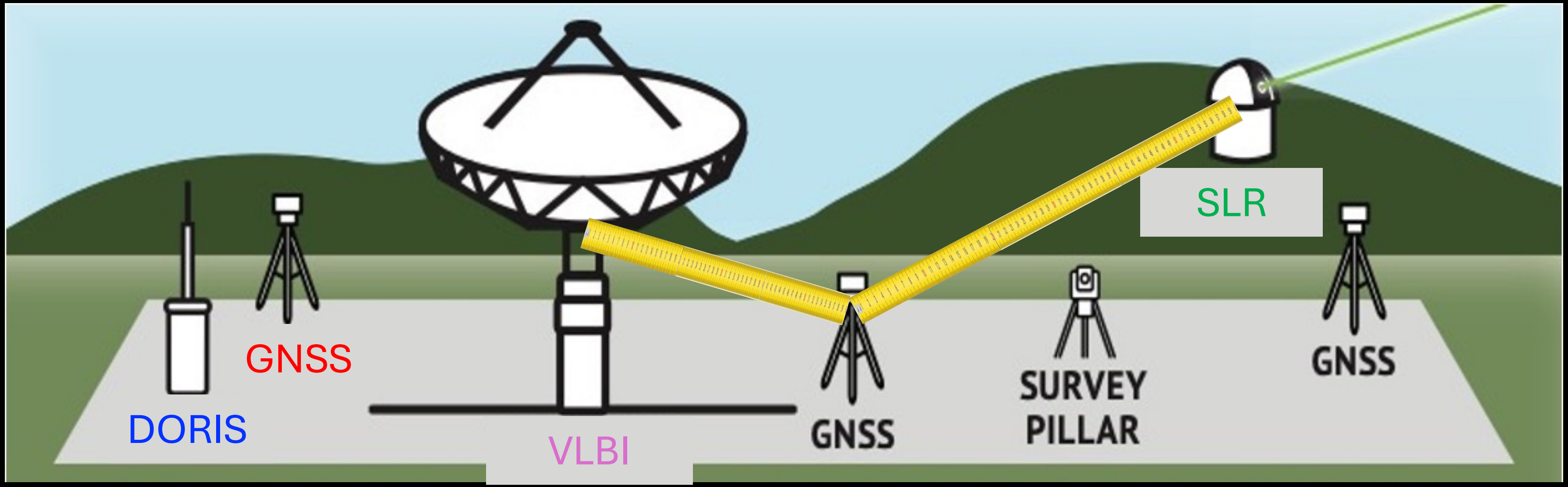
[NASEM, 2020]

Tying geodetic techniques (hence TRFs) at core sites

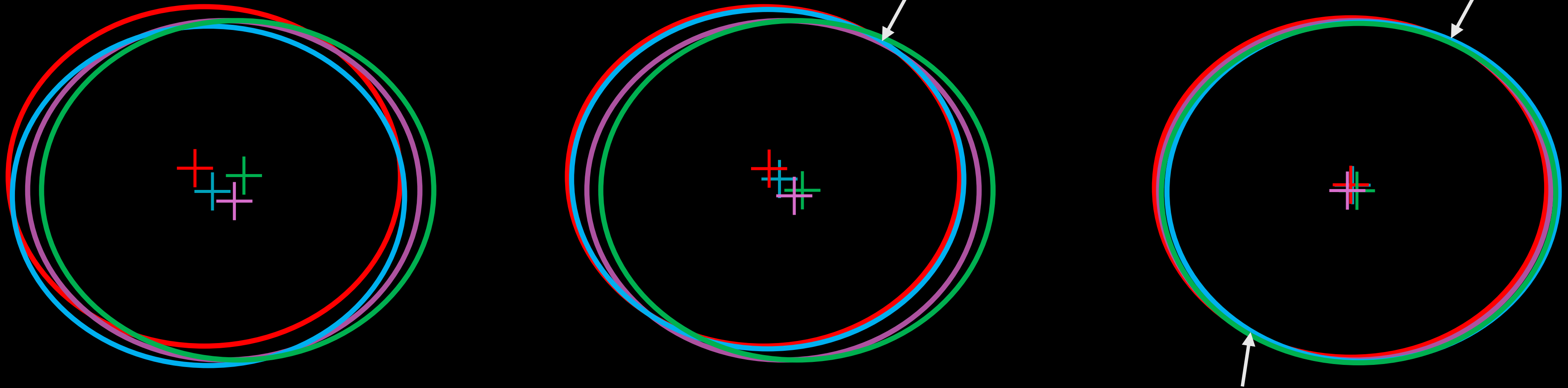


- Co-located geodetic techniques at core sites can tie the individual TRFs together as long the vectors between instruments are accurately (<<1 mm) known

- Inter-technique vector ties at core sites nudges the independent TRFs into a single, improved TRF



Aligning four space geodetic (VLBI, GNSS, DORIS, SLR) techniques with local ties



[Modified after Mondal et al., 2024; Hippenstiel, 2024]

Problem – Why tying the TRFs together is important

- Local geodetic ties are a limiting error source in establishing an accurate (1 mm positioning) and stable (0.1 mm/yr) TRF
- What are local geodetic ties?
  - The baseline vectors between antenna reference points at co-located sites necessary to effectively tie the otherwise disconnected reference frames of the individual space geodetic techniques, such as VLBI and GNSS, into a unified TRF
- Unfortunately, the disagreement between local (surveying) ties and geodetic position estimates can be significantly larger (i.e., several mm) than their combined error estimates

GNSS to	# of tie vectors		# of tie discrepancies < 5 mm		% of tie discrepancies < 5 mm	
	ITRF2014	ITRF2020	ITRF2014	ITRF2020	ITRF2014	ITRF2020
VLBI	60	77	27	38	45	50
SLR	49	53	14	19	29	36
DORIS	103	123	23	39	22	32

[Altamimi et al., 2022]

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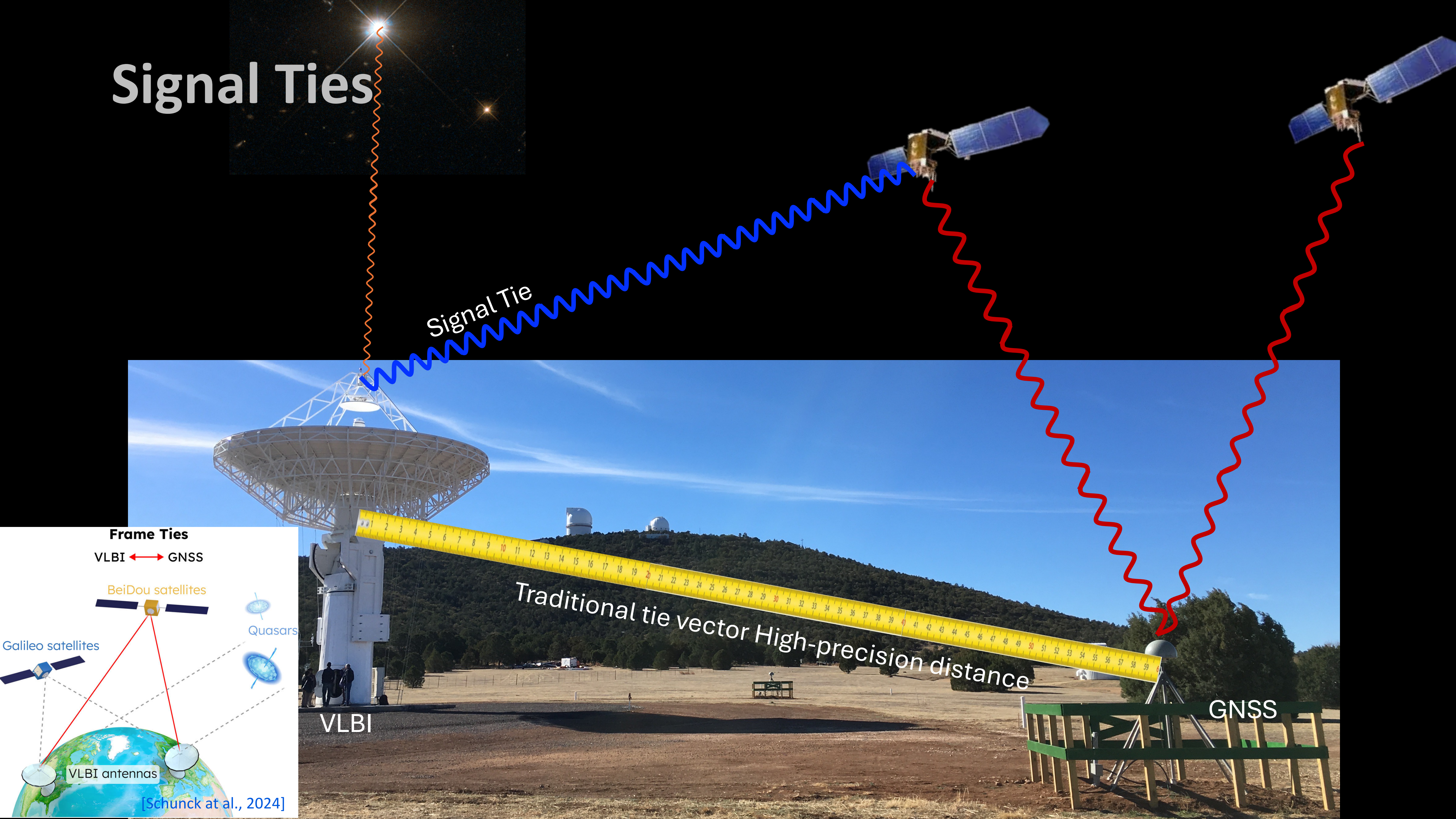
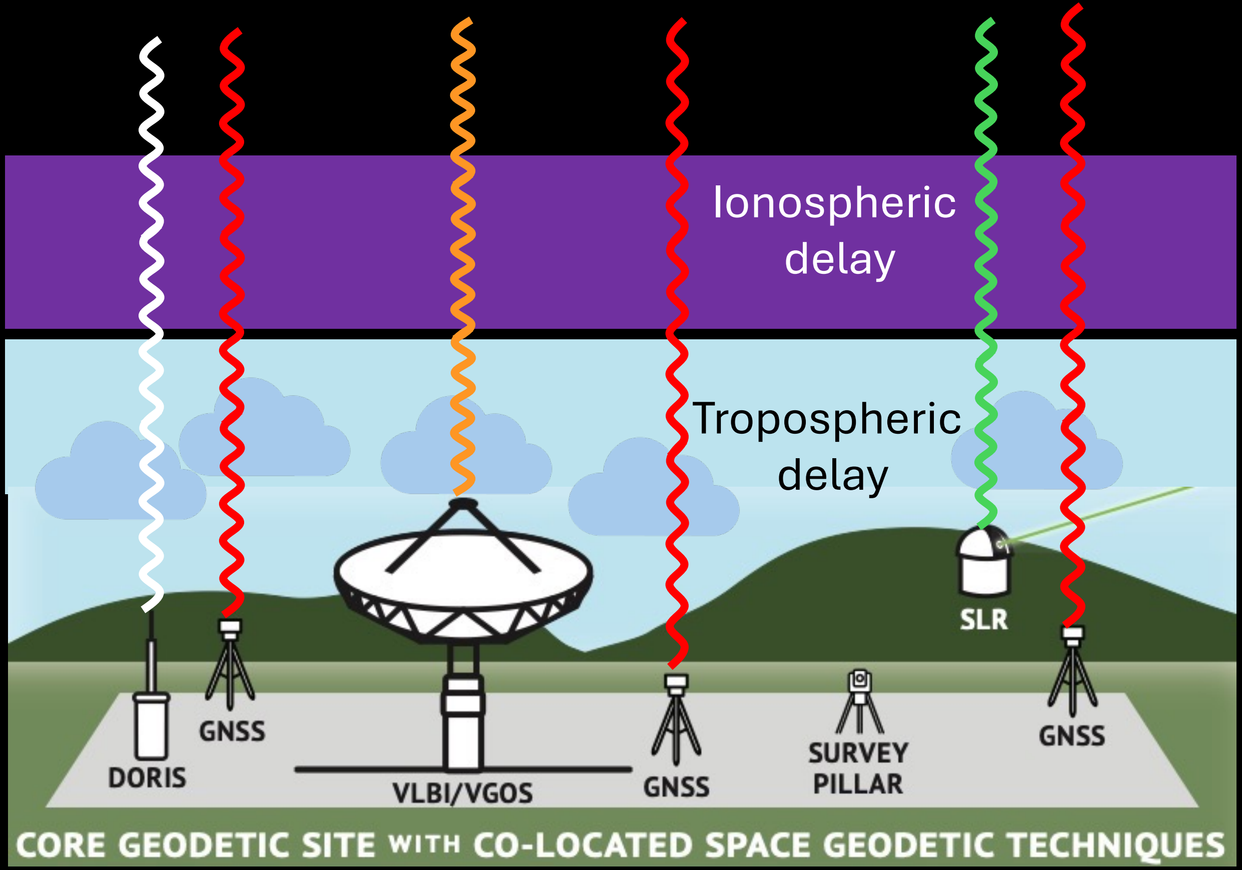


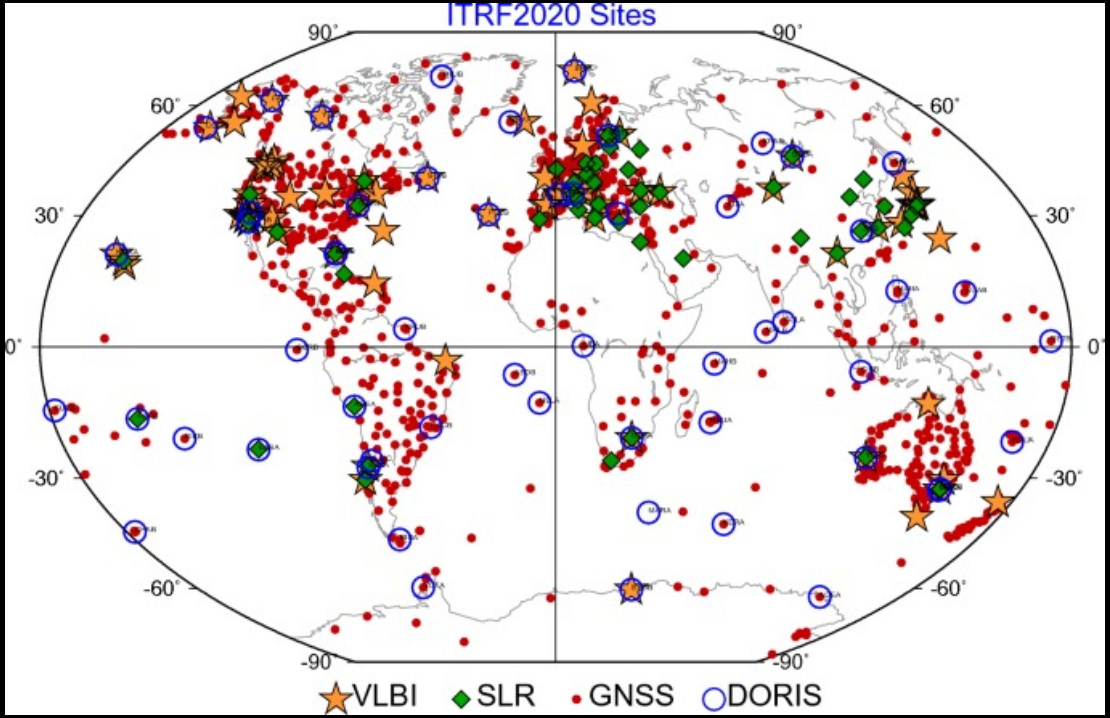
Signal Ties
Signal Tie
Traditional tie vector High-precision distance
VLBI
GNSS
Frame Ties
VLBI ⟷ GNSS
BeiDou satellites
Quasars
Galileo satellites
VLBI antennas
[Schunck at al., 2024]

Advanced technique — Atmospheric ties



[Modified after Mondal et al., in prep.]

$$\Delta t \approx \Delta t_{geom} + \Delta t_{iono} + \Delta t_{trop} + \Delta t_{noise}$$



[Modified after Altamimi et al., 2023]

- Measuring local ties is a challenge for some techniques
- Tie uncertainties for 60 % of the collocation sites are more than 5 mm
- But stations at core sites share the same atmosphere, hence new ties can be achieved via atmospheric constraints

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Technique-specific contributions to ITRF2020

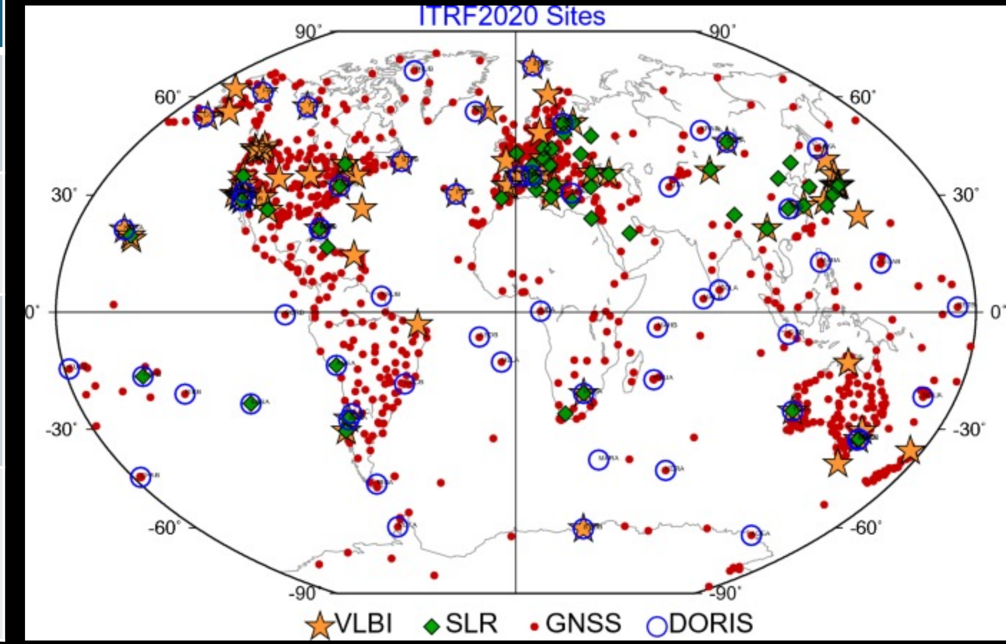
Technique	VLBI	SLR	GPS	DORIS
Signal	Microwave	Optical	Microwave	Microwave
Source	Quasars	Satellite	Satellite	Satellite
Obs. Type	Time difference	Two-way range	Range	Range
Origin	No	Yes	No	No
Scale	Yes	Yes	Yes	Yes
Celestial Frame and UT1	Yes	No	No	No
Polar motion	Yes	Yes	Yes	Yes
Density	No	No	Yes	No

Technique-specific contributions to ITRF2020

	# of Solutions	Time-Span	# of sites	Origin of the Frame	EOP
IDS/DORIS	1465 weekly	1993-2021 (28 yrs)	87	CM	PM
IGS/GNSS	9861 daily	1994-2021 (27 yrs)	1159	CN	PM, LOD
ILRS/SLR	243 fortnightly 1460 weekly	1983-1993 1993-2021 (38 yrs)	100	CM	PM, LOD
IVS/VLBI	6178 session-wise	1980-2021 (41 yrs)	117	CN	PM, PMr, LOD, UT1-UTC, δX , δY

PM Polar motion, *PMr* Polar motion rate, *LOD* Length of day, *UT1-UTC* UT1 minus UTC, δ*X* and δ*Y* : Nutation offsets

[Modified after Altamimi et al., 2023]



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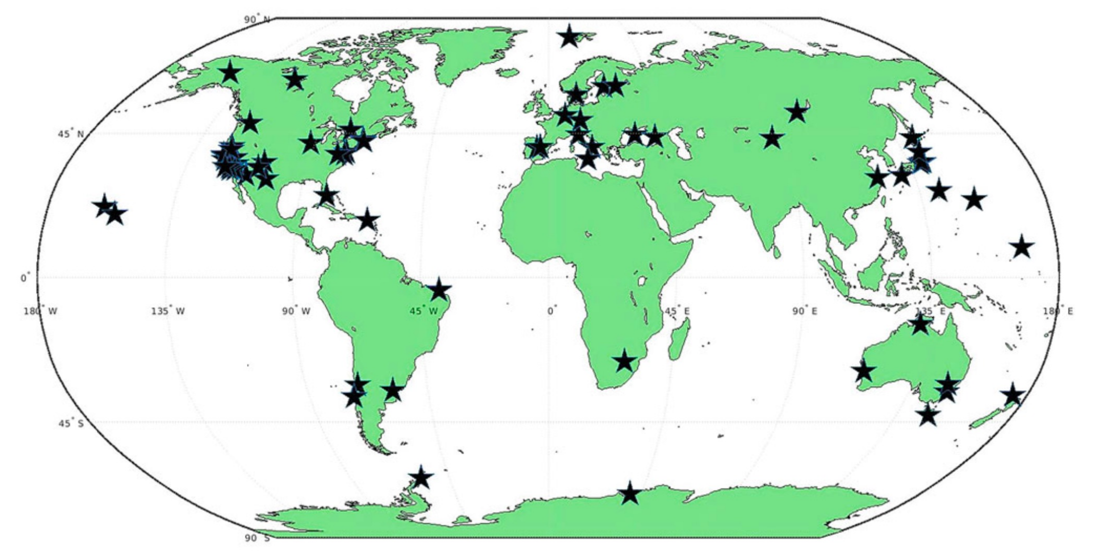
IVS contributions to ITRF2020



[Hellmers et al., 2022]

- 11 analysis centers (ASI, BKG, DGFI-TUM, GFZ, GCFS, IAA, NMA, OPA, OSO, USNO, VIE)
- 7 software packages: ASCOT, Calc/Solve, DOGS-R1, PORT, QUASAR, VieVS

- VGOS Sessions were included for the first time
- Includes some mixed-mode sessions

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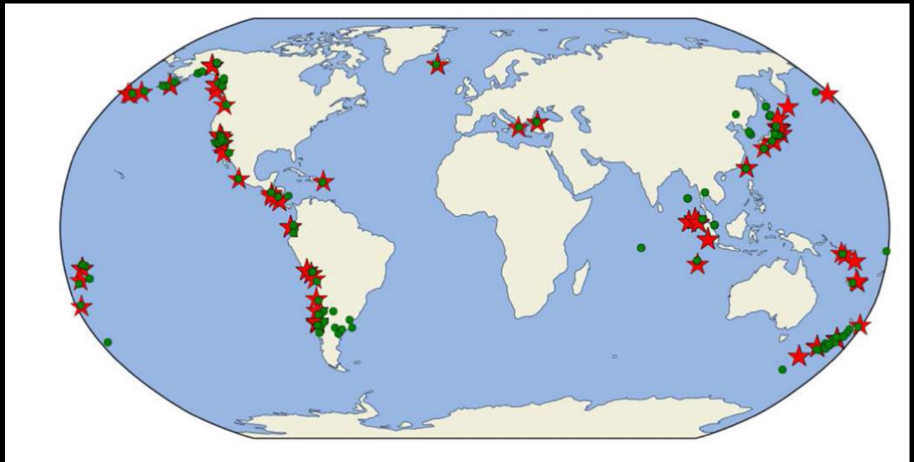
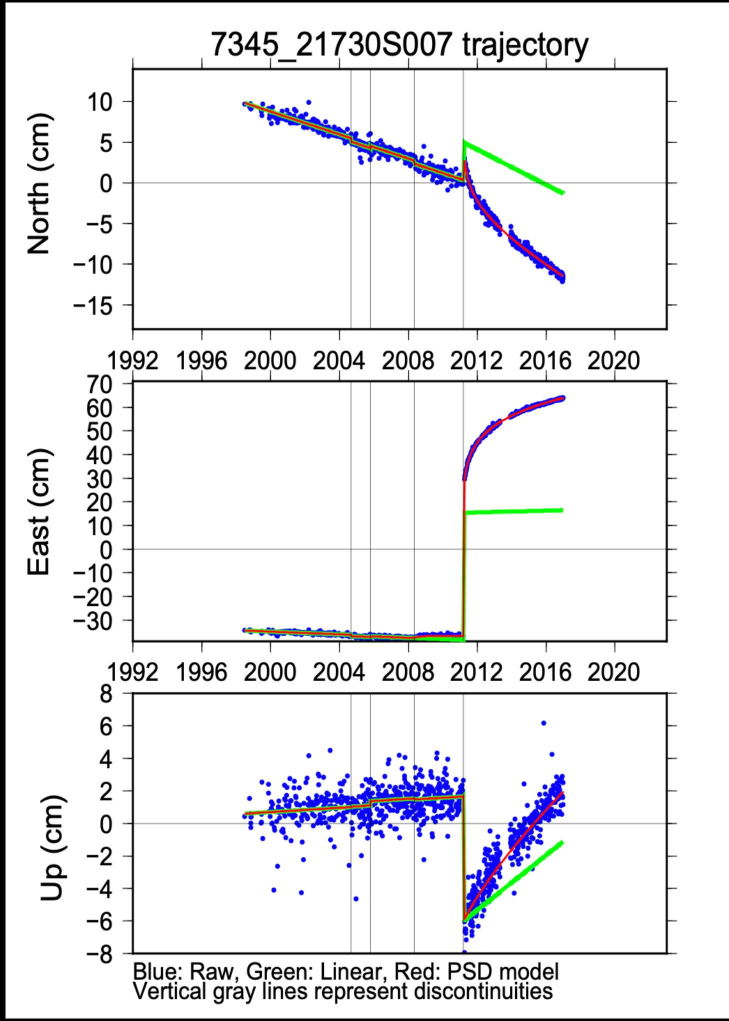
ITRF2020 solutions

- ITRF2020 includes a model for post-seismic deformation and solves for periodic terms to accommodate loading & draconitic effects per geodetic technique

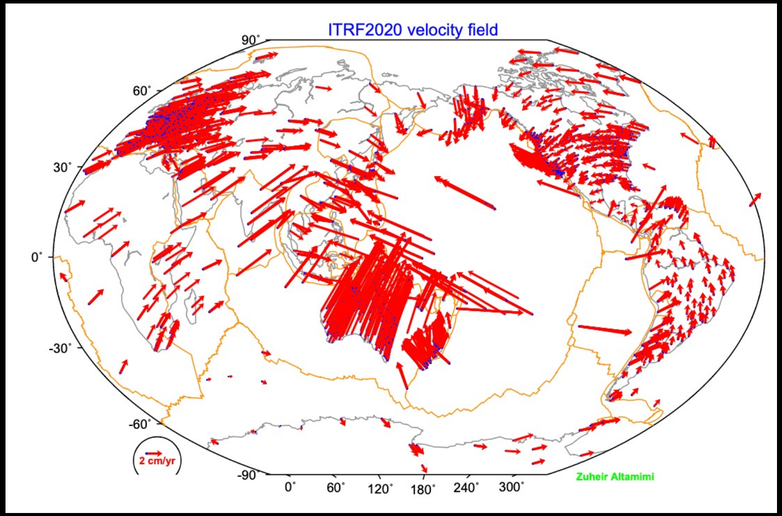


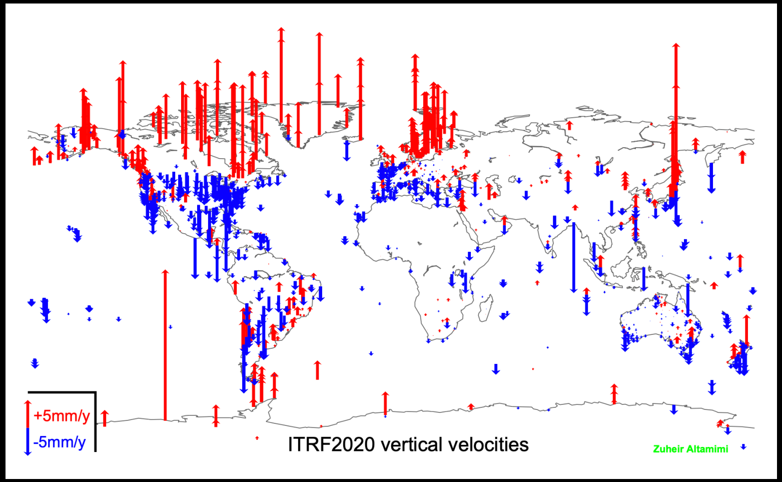
Red stars: Earthquakes (65)
Green stars: ITRF2020 Sites (118)



Trajectory of Tsukuba VLBI site

Site with velocity formal error < 1 mm/yr





[Modified after Altamimi et al., 2023]

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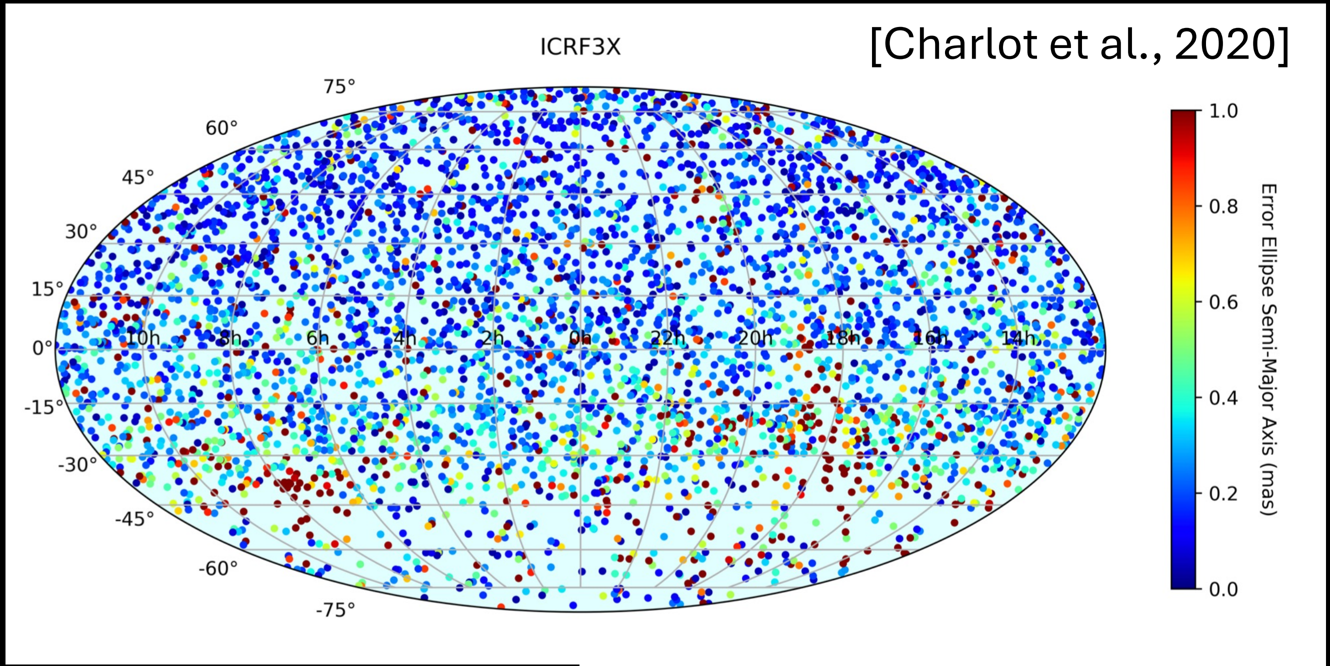
Celestial Reference Frame (e.g., ICRF3)

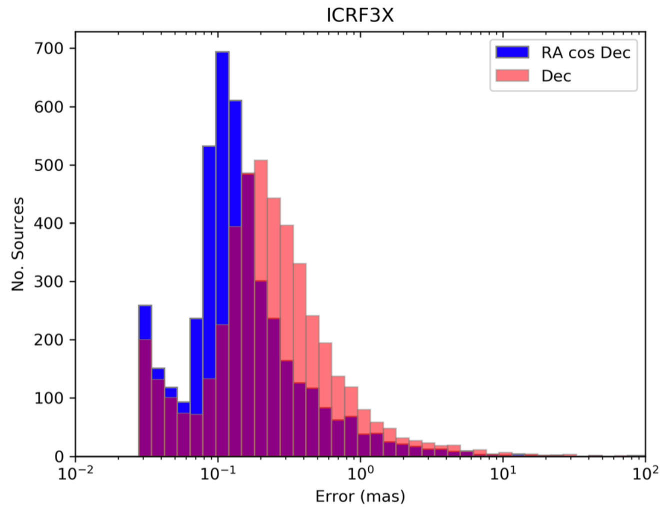
- ICRS is the current celestial reference system adopted by the International Astronomical Union (IAU)
- The ICRF is a realization of the ICRS using celestial reference sources. It is a set of coordinates of these objects derived from observations
- Current Realization is ICRF3 (2019)



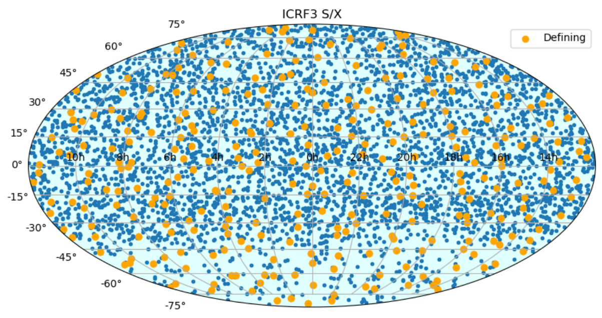
[Charlot et al., 2020]

ICRF3 Facts & Figures:

- 15 million S/X + X/Ka + K-Band VLBI observations
- Three catalogs of sources:
    - S/X: 4536 source; X/Ka: 678 sources, 824 (K) sources.
- 38.5 years of data
- 167 telescopes @126 sites from the IVS, VLBA, DSN & others contributed

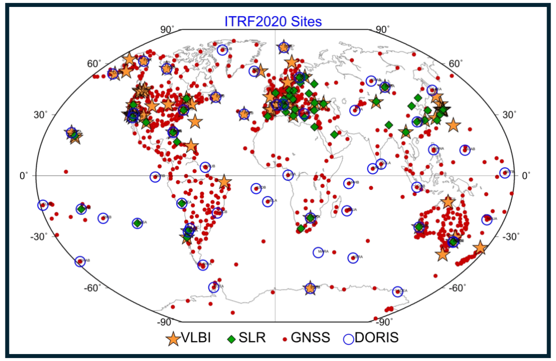


VLBI as Matchmaker

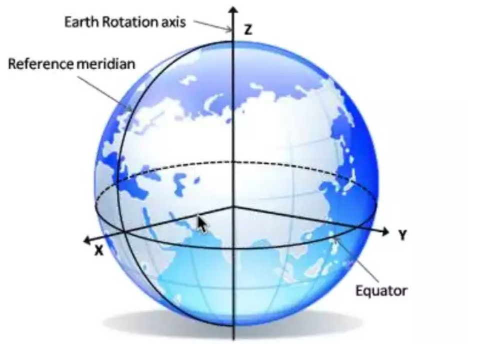


CRF

EOP



TRF



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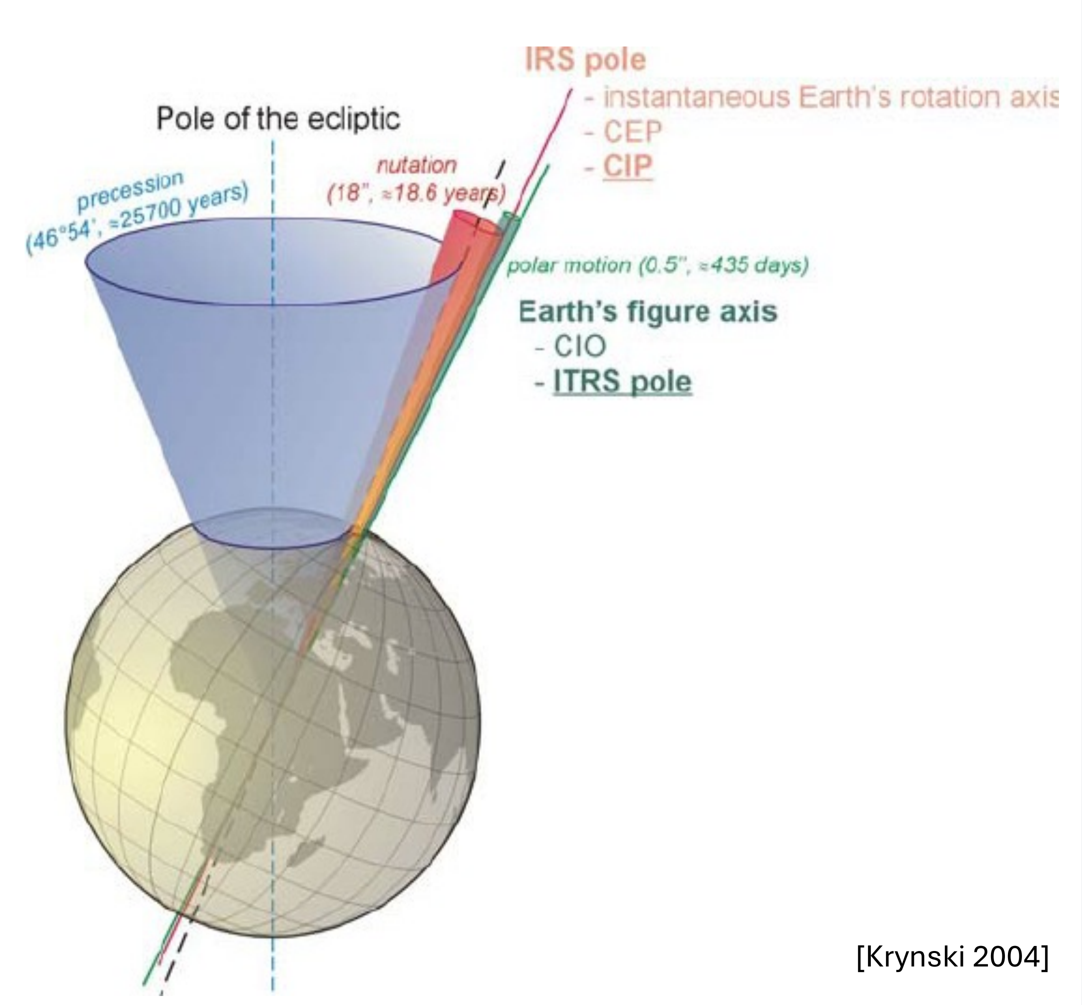
Earth Orientation Parameters (EOP)

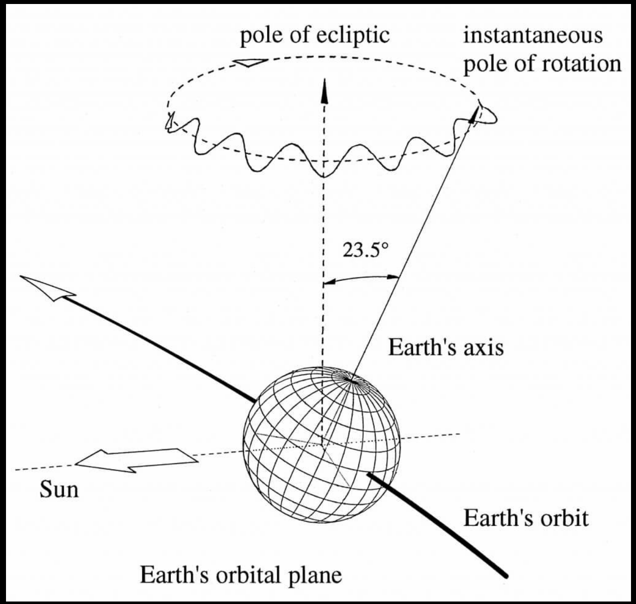


[Krynski 2004]

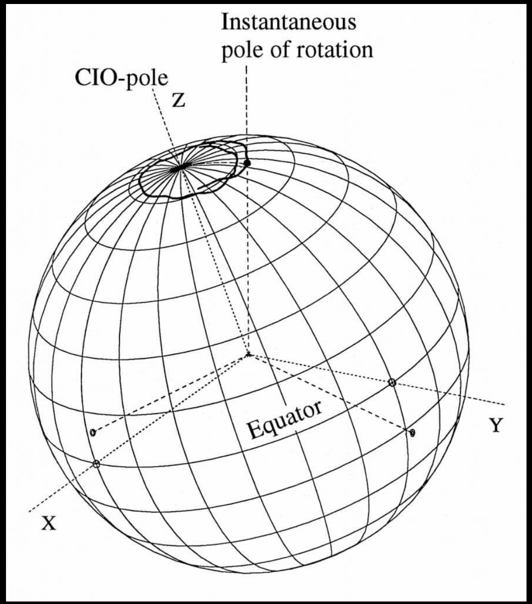
- Precession and Nutation
  - Precession/Nutation refers to the orientation of the spin axis in inertial space. The difference between P/N is the time scale and the origin of the effect.
- Polar Motion
  - Polar motion refers to the motion of the spin axis in an Earth-fixed frame ('relative to its crust').
- UT1/LOD
  - UT1 is a time scale based on the actual rotation of the Earth; in other words, one "UT1 day '' corresponds to one full rotation of the Earth .
  - Variations of the Earth's angular velocity are expressed as d(UT1-UTC) or as the change in the length of day ***Δ*** LOD.

$$\Delta \text{ LOD} = d(\text{UTC1-UTC})/dt$$

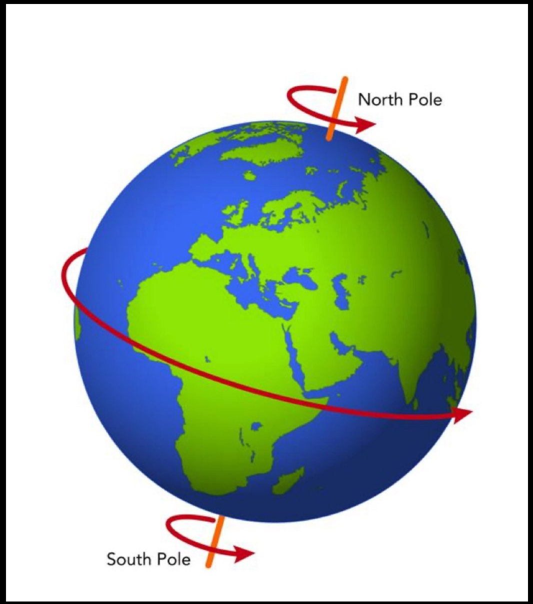
EOPs — Scale of motions



- Periods
  - Precession: ~26000 yrs
  - Nutation: ~18 yrs
- Scale of motion
  - Precession: ~1.5 km/yr
  - Nutation: ~600 m



- Periods
  - Chandler wobble ~430 days, annual and irregular variation
- Scale of motion
  - Typically, a few meters on the surface

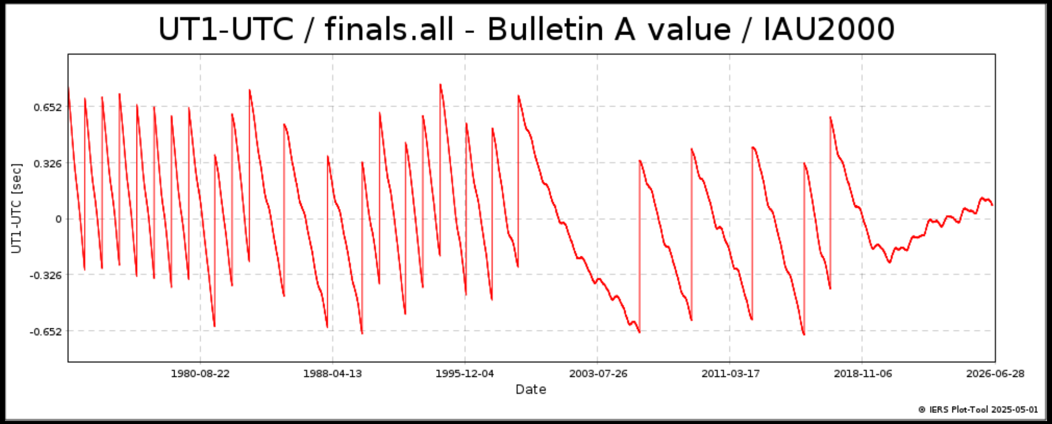


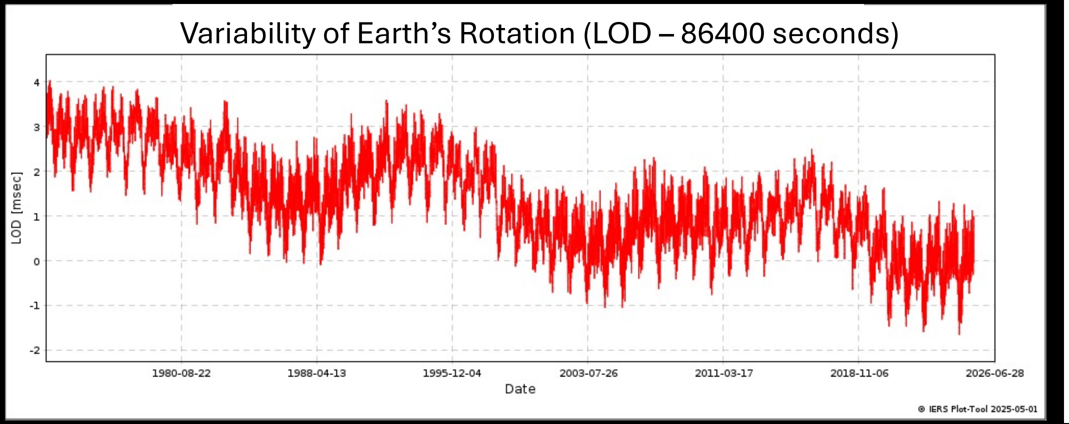
- Periods
  - Annual, semi-annual, Chandler wobble ~430, annual, tidal, fortnightly, nodal
- Scale of motion
  - 1 second of dUT1 ≈ 464 meters of shift in longitude

IC : ggos.org

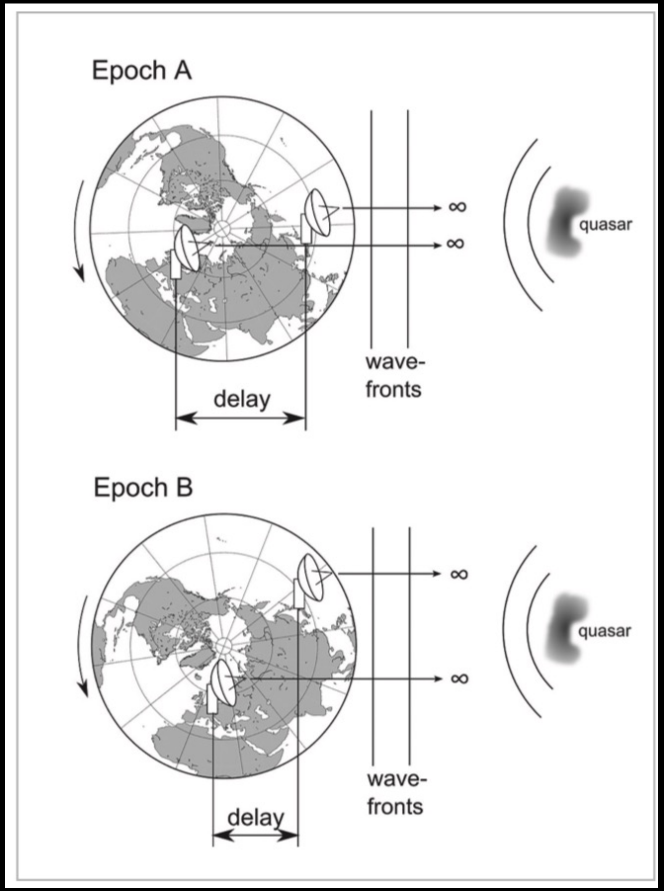
UT1 from VLBI

- IVS runs the so-called intensive sessions (INT1, INT2, etc) almost every day with VGOS and S/X legacy stations.
- USNO provides rapid predictions using AAM.
  (Please see Stamatakos presentation from TOW 2021)
- UT1 predictions in 1-5 days in advance is crucial for many users.



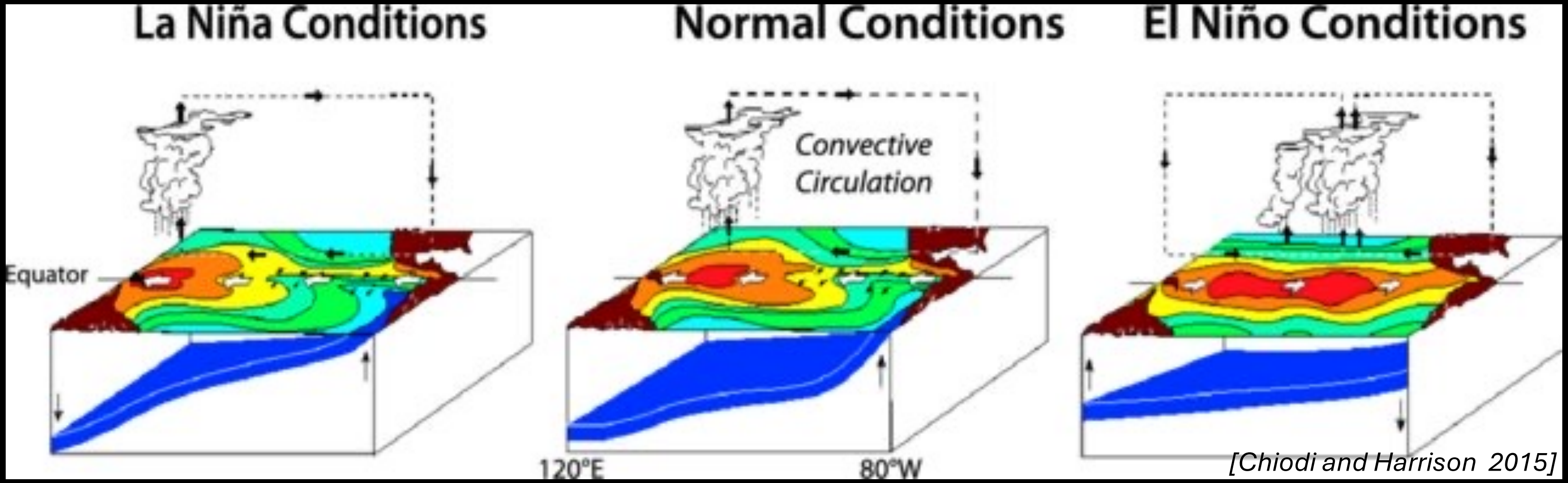


[www.iers.org]

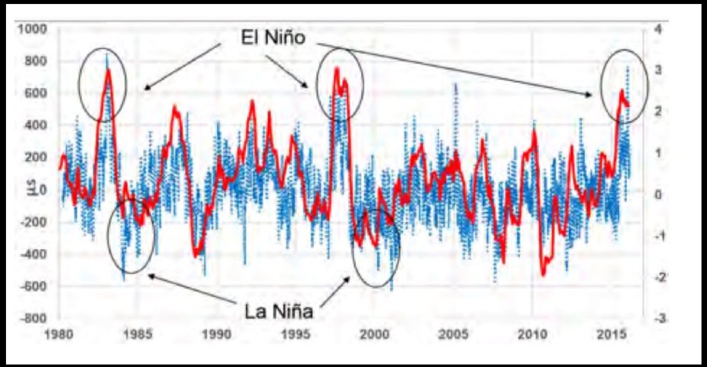


[Hobiger et al., 2010]

Major climate events affects Earth's rotation

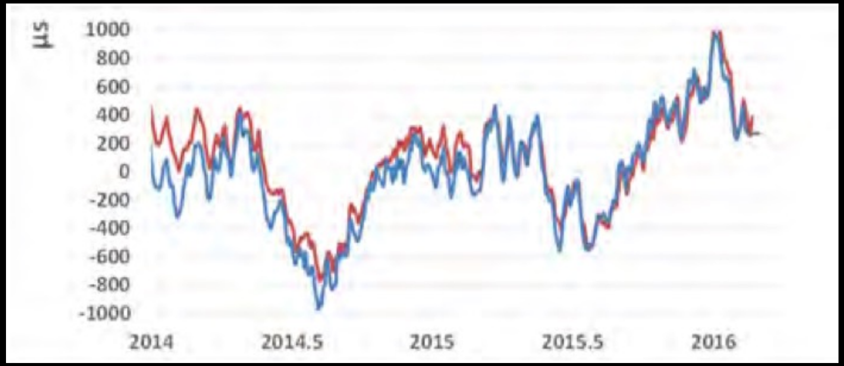


Residual LOD and Climate



[Gipson 2016]

Residual LOD and AAM



- El Niño and La Niña produce a strong signal in the Earth's rotation (after removing tidal, seasonal & long-period terms)

Why is tracking Earth's rotation important?

CNN Climate | Solutions | Weather

Polar ice is melting and changing Earth's rotation. It's messing with time itself

By Laura Paddison and Rachel Ramirez, CNN
4 minute read · Updated 7:52 AM EDT, Thu March 28, 2024

https://www.cnn.com/2024/03/27/climate/timekeeping-polar-ice-melt-earth-rotation/index.html

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Article | Published: 27 March 2024

A global timekeeping problem postponed by global warming

Duncan Carr Agnew

Nature **628**, 333–336 (2024) | Cite this article

15k Accesses | **18** Citations | **2722** Altmetric | Metrics

Article: https://www.nature.com/articles/s41586-024-07170-0

- Increased melting of ice in Greenland and Antarctica, measured by satellite gravimetry and altimetry, has decreased the angular velocity of Earth more rapidly than before
- For example, if the Greenland ice sheet melts completely
  - Sea level would rise by 7 meters (23)
  - The length of the day would be 2 milliseconds longer (https://climate.nasa.gov)

CNN World | Africa | Americas | Asia | Australia | China | Europe | India | More | Watch | Liste

Humans pump so much groundwater that Earth's axis has shifted, study finds

By Mindy Weisberger, CNN
4 minute read · Updated 7:42 PM EDT, Mon June 26, 2023

Geophysical Research Letters

Research Letter | Open Access

Drift of Earth's Pole Confirms Groundwater Depletion as a Significant Contributor to Global Sea Level Rise 1993–2010

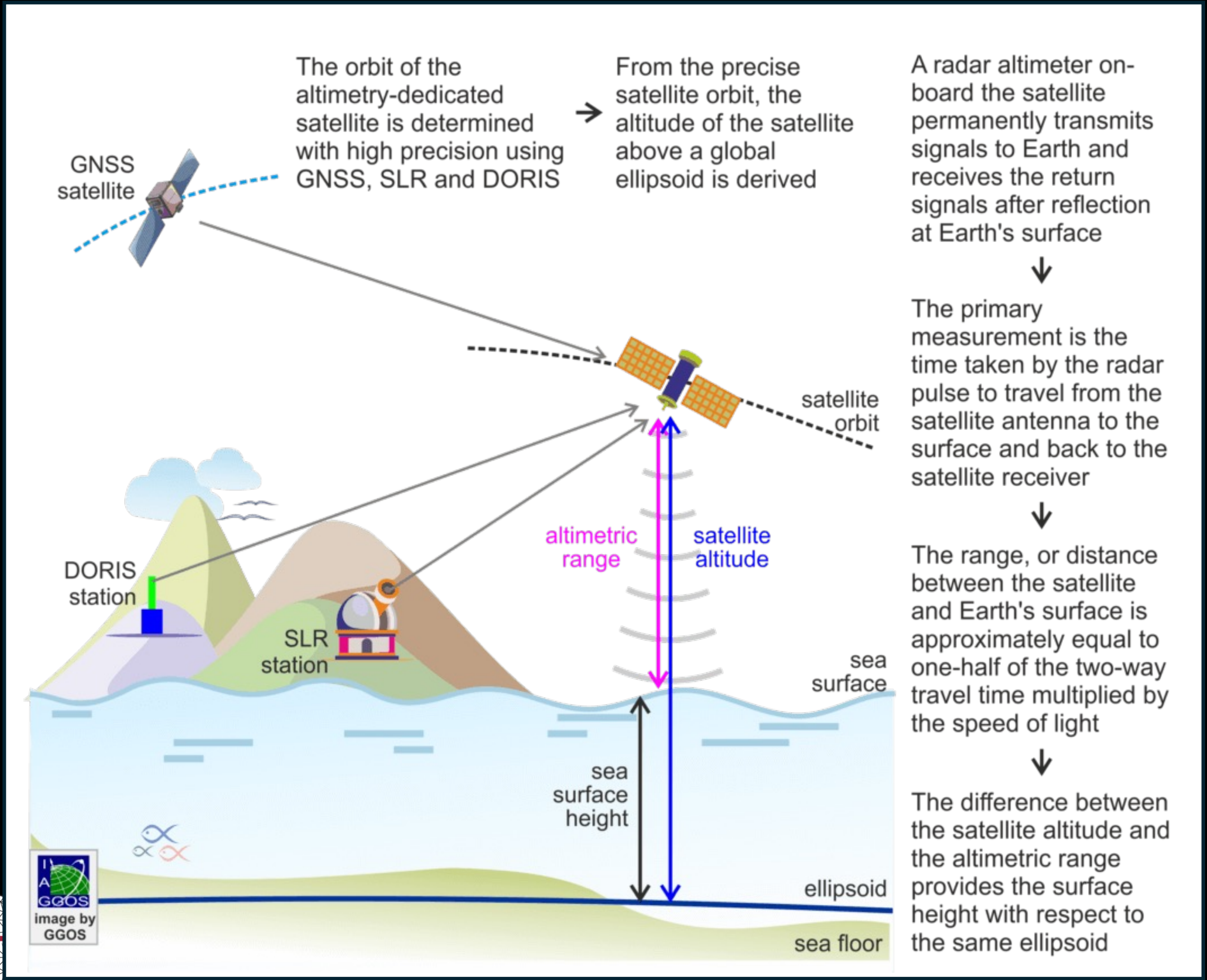
Ki-Weon Seo, Dongryeol Ryu, Jooyoung Eom, Taewhan Jeon, Jae-Seung Kim, Kookhyoun Youm, Jianli Chen, Clark R. Wilson

First published: 15 June 2023 | https://doi.org/10.1029/2023GL103509 | Citations: 15

- Earth's pole shifted 4.36 cm/yr toward 64.16°E from 1993 to 2010 due to groundwater loss and sea level rise.
- When groundwater loss is included, predicted pole drift closely matches observations.

MIT HAYSTACK OBSERVATORY

Satellite altimetry and TRF



- The satellite's altitude above a global reference ellipsoid is determined from orbit computations within a geocentric reference frame, such as the International Terrestrial Reference Frame (ITRF).
  - TOPEX/Poseidon (1992-2006) altimeter mission revolutionized oceanography in the same way as the Hubble Space Telescope revolutionized astronomy.
  - ICESat/CryoSAT helped obtain the snow and ice surface measurements to understand the cryosphere process.

(1) Ocean currents: +/- 2 m
(2) ENSO (El Nino, La Nina): +/- 20 cm
(3) Ocean tides: e.g. M2: 130 cm
(4) The ocean geoid: many meters
(5) Changes in Mean Sea Level: 3.4 mm/yr

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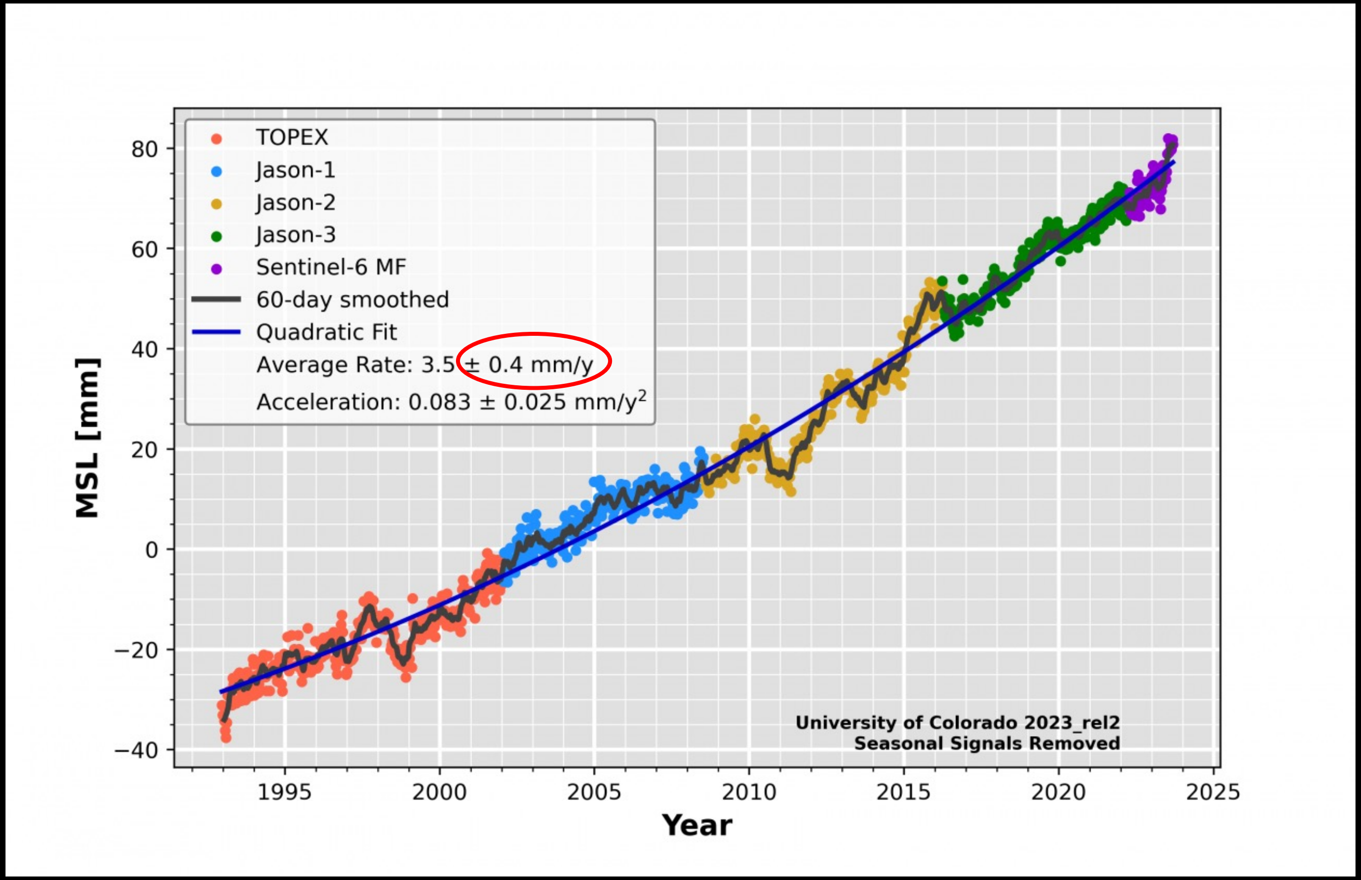
How well do we know the global sea-level-rise rate?



- The precise orbits for Topex and Jason-1/2/3, all computed in a consistent global reference frame, are used to compute the global change in mean sea level from satellite ocean radar altimeter data
- Next-generation sea level measurements require a **global reference frame** accuracy of 1 mm with a stability of 0.1 mm/yr

Source: https://sealevel.colorado.edu/data/2023rel2

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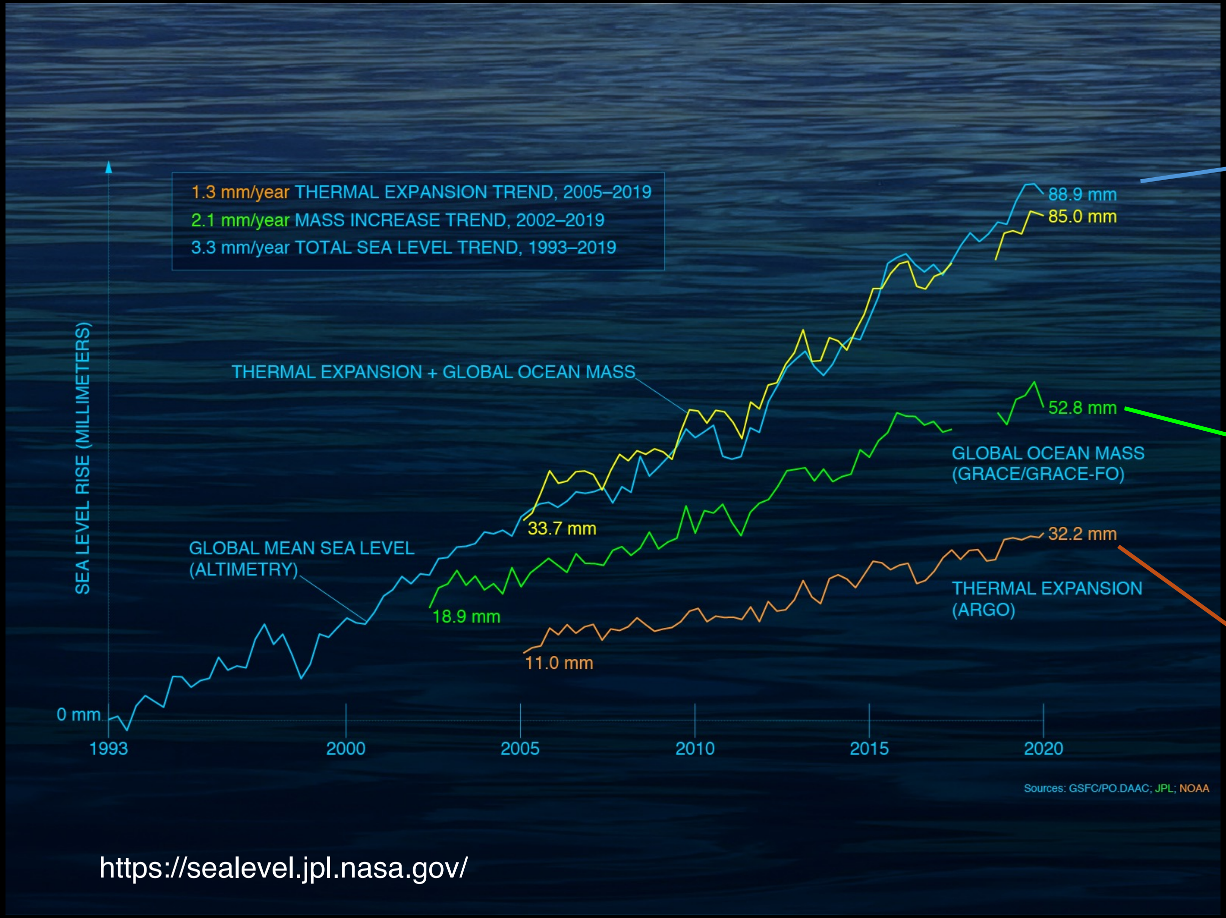
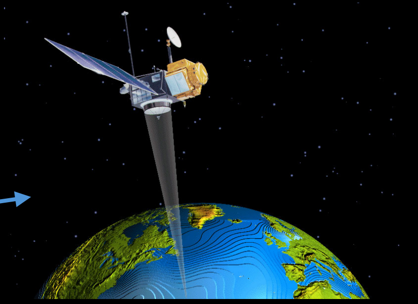
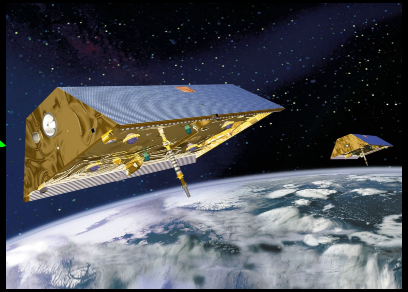
Understanding global mean sea level (GMSL)



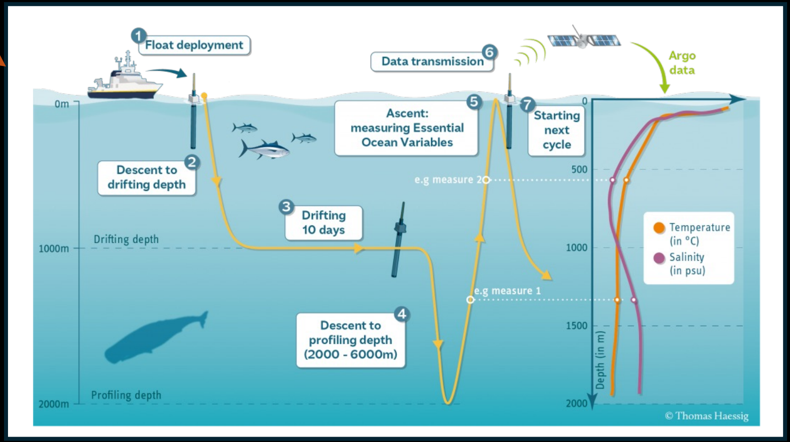
https://sealevel.jpl.nasa.gov/



Total GMSL: ~3.35 mm/y (measured by satellite altimetry)



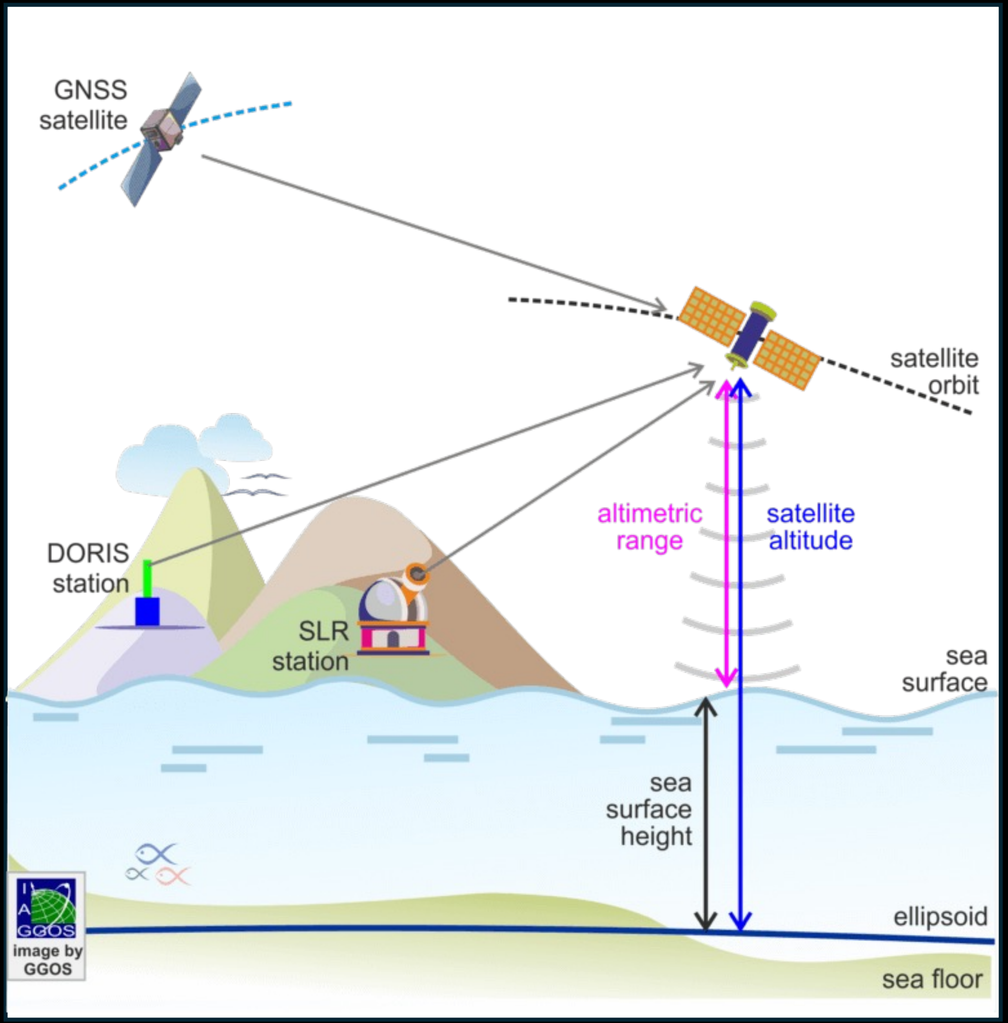
Mass components ~2.1 mm/yr (Measured by GRACE & GRACE-FO)



Thermal expansion: ~1.3 mm/yr (measured by Argo ocean floats)

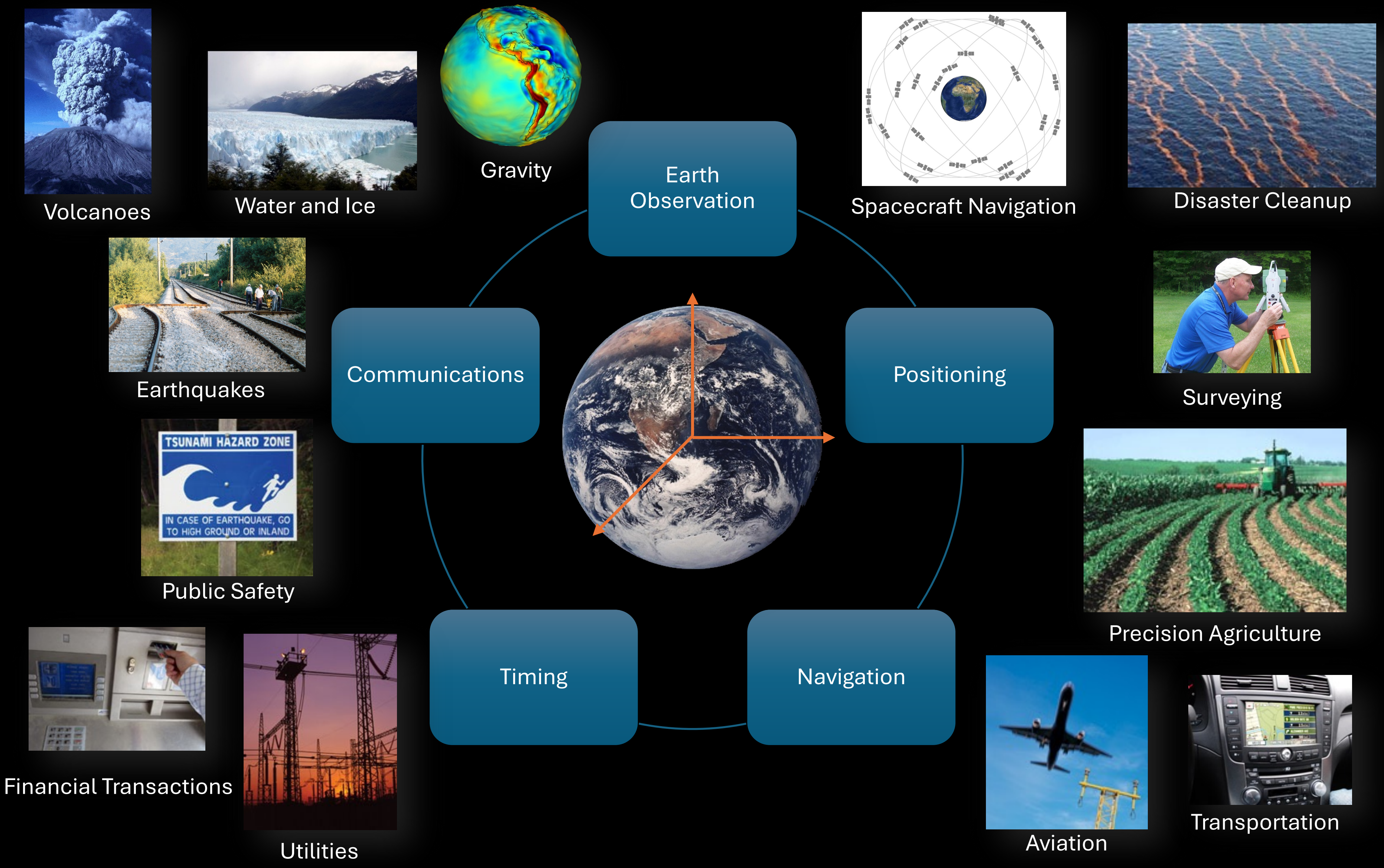
https://argo.ucsd.edu/

Requirements for satellite altimetry and sea surface height measurement



- A stable and accurate reference frame is required across the observation period
  - **VLBI is crucial for the TRF**
- POD needs <10 mm radial orbit accuracy (RMS)
  - Accurate UT1 is vital for precise orbit determination

Geodesy and Society



Contents lists available at ScienceDirect

Tectonophysics

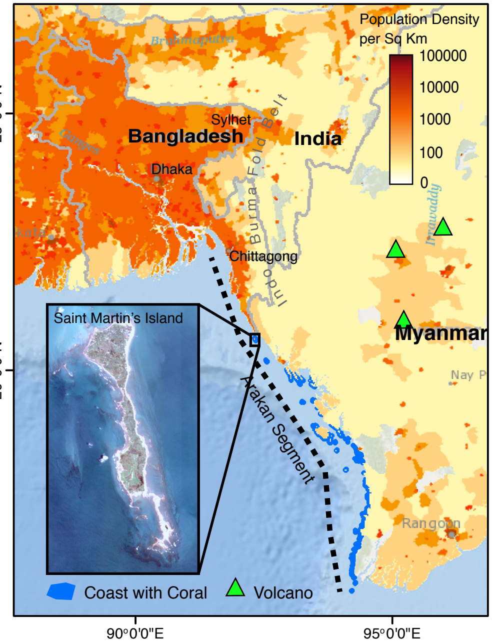
journal homepage: www.elsevier.com/locate/tecto

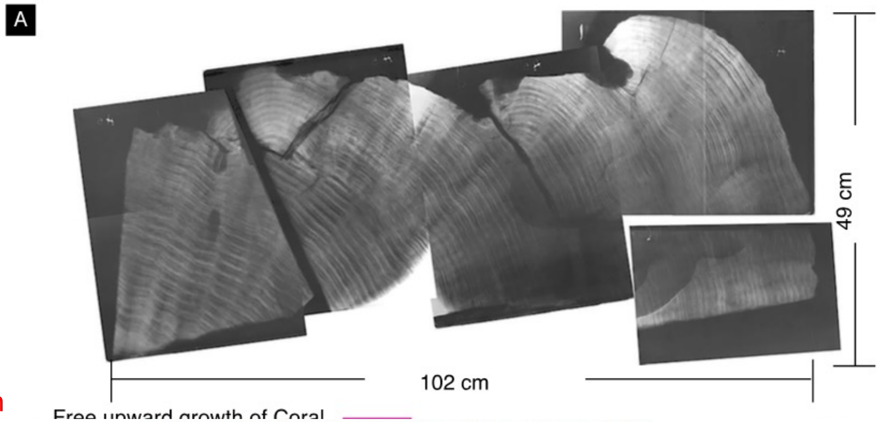
Microatolls document the 1762 and prior earthquakes along the southeast coast of Bangladesh

Dhiman R. Mondal[a,b,*,1], Cecilia M. McHugh[a,b,c], Richard A. Mortlock[d], Michael S. Steckler[c], Sharif Mustaque[a], Syed Humayun Akhter[e]

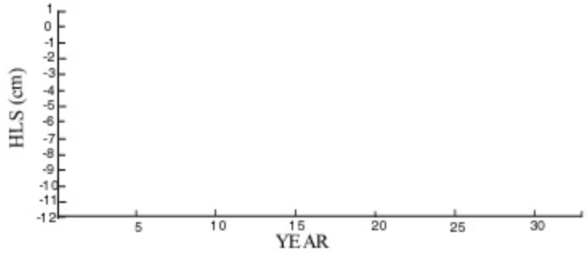
[a] School of Earth and Environmental Sciences, Queens College, City University of New York, Flushing, NY 11367, USA
[b] Earth and Environmental Sciences, Graduate Center, City University of New York, New York, NY 10016, USA
[c] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
[d] Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA
[e] Department of Geology, University of Dhaka, Dhaka, Bangladesh

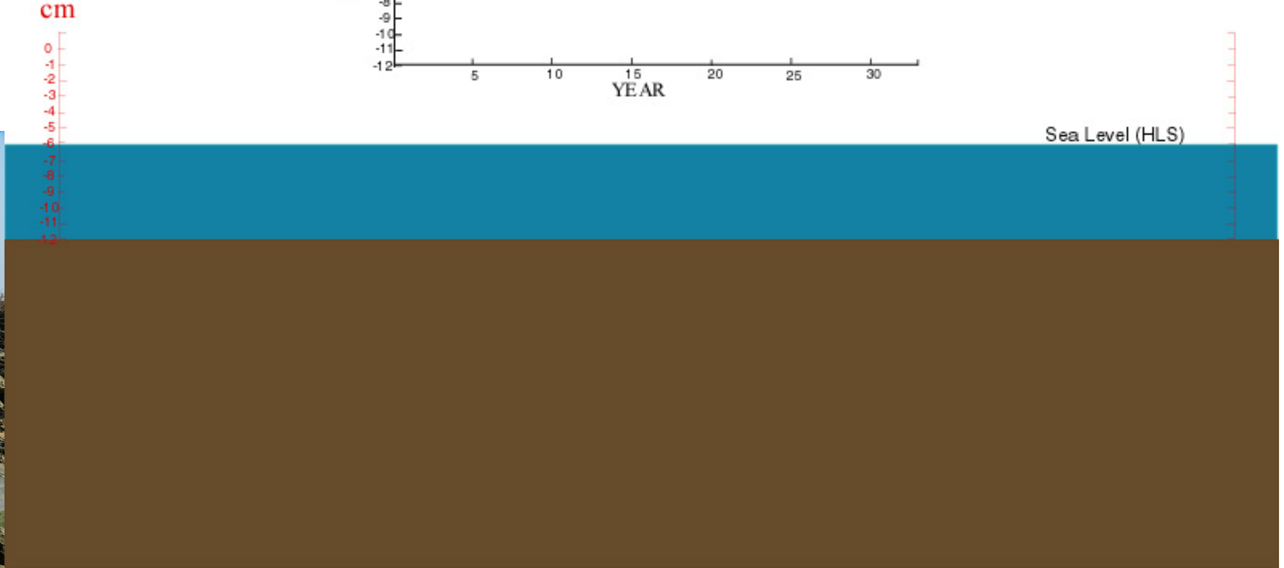
The 1762 (2 April, M8.7) Arakan earthquake
Epicenter was somewhere along the coast from Chittagong (modern Bangladesh) to Arakan in modern Myanmar.





MICROATOLL NATURAL GAUGE





Two quotes from ITRF2014/2020 papers

"VLBI in particular needs to evolve toward more frequent global observational session schedules, with an increased number and well-distributed stations."

"Improving the geodetic infrastructure is a prerequisite for long-term sustainability and accuracy of the ITRF, as recognized by the United Nations General Assembly resolution (2015) on the global geodetic reference frame for sustainable development."

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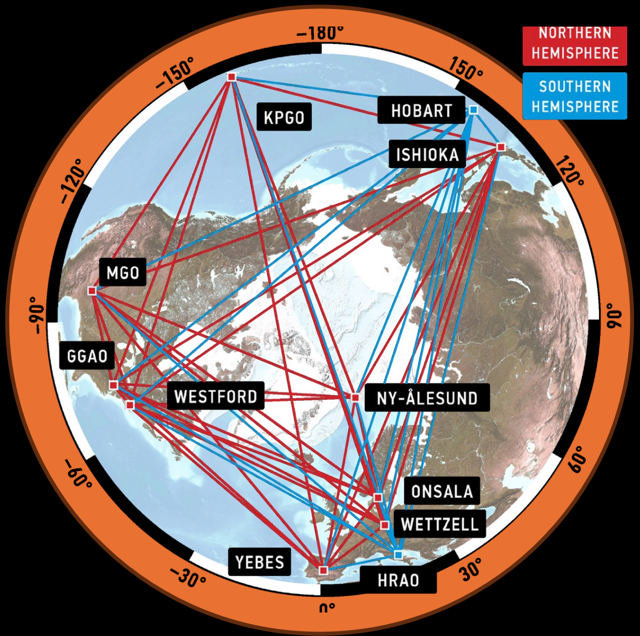
Good news: the precision/accuracy are improving!!

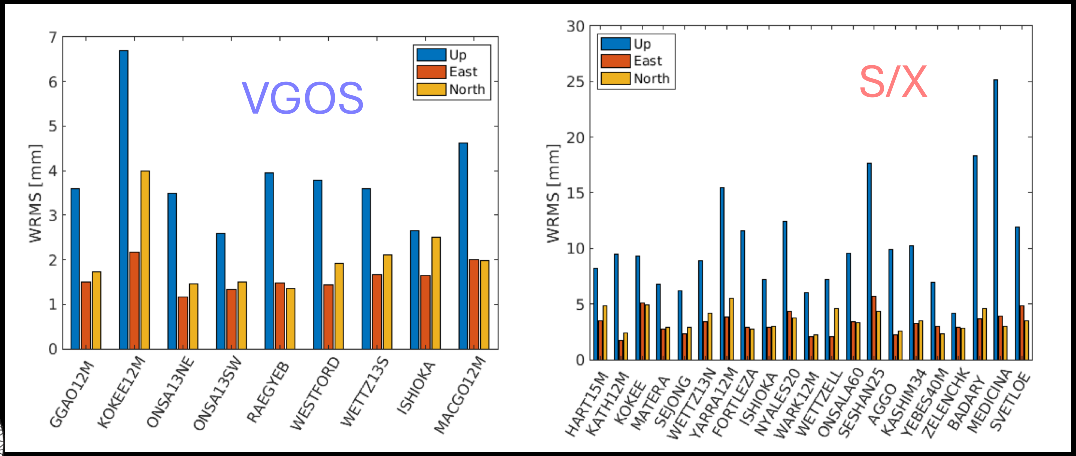


Antennas

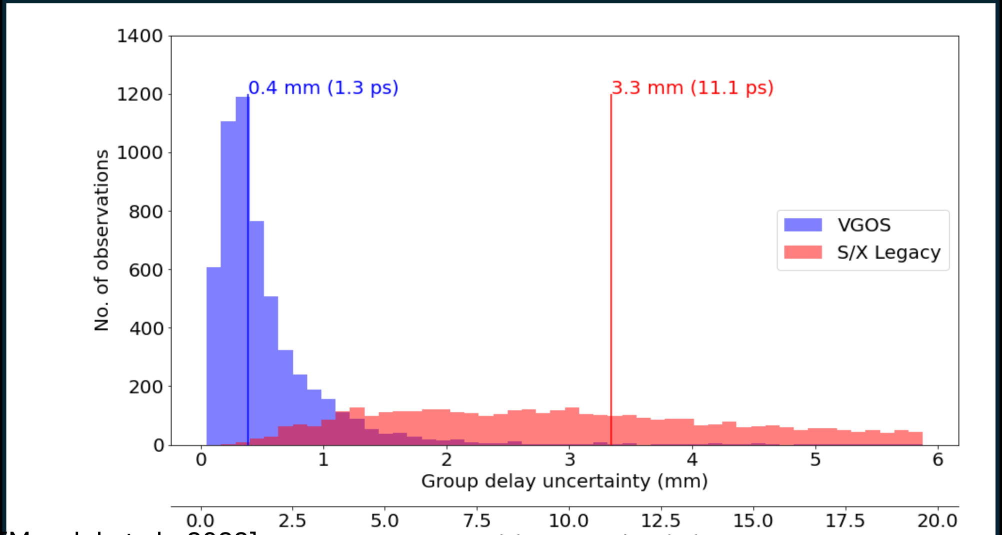
Receiver & Payload

Converters, Digitizers, Recorders

Correlator



[Nilsson et al., 2022; IVSGM22]



[Mondal et al., 2022]

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Thank you!!

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