Science Overview

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12th IVS Technical Operations Workshop

(TOW2023)

April 30 – May 4, 2023

Outline

I. What is geodesy?

II. Techniques of Space Geodesy (including VLBI).

III. Main Applications of VLBI

   (A). EOP, TRF, CRF.

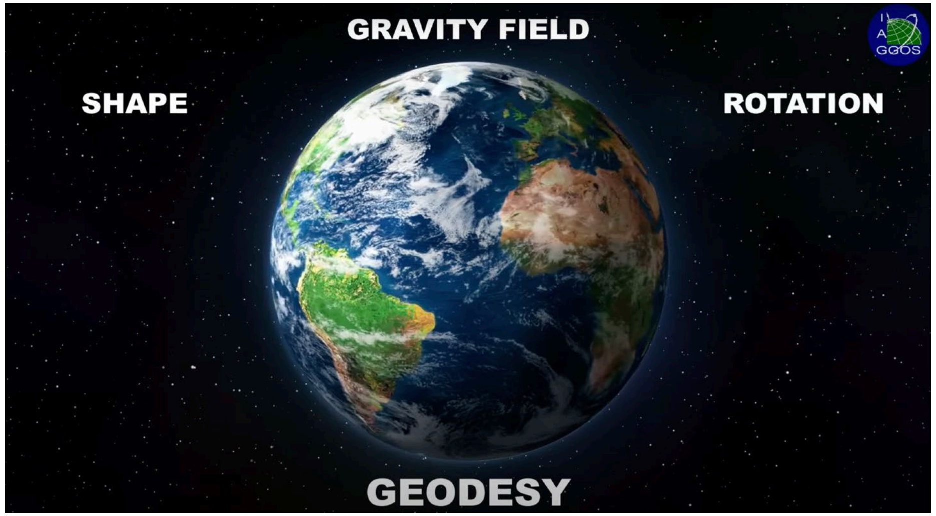
   (B). EOP/Earth rotation in the News.

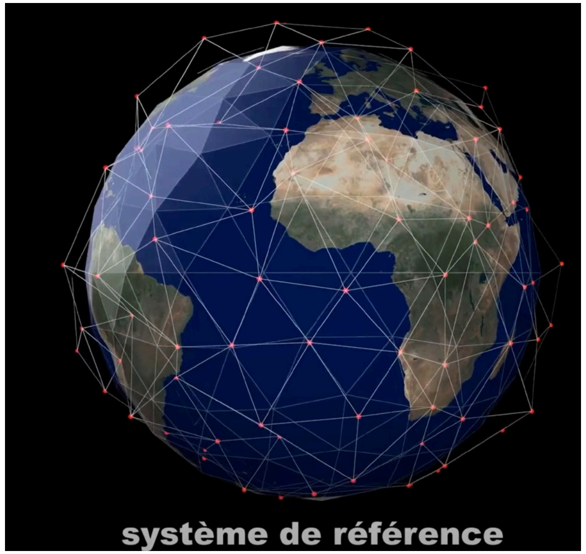
IV. Geodesy & the Global Change in Mean Sea Level.

What is geodesy?

Geodesy is the science of determining the **shape of the Earth**, its **gravity field**, and its **rotation** as functions of time.

The essential basis of Geodesy are stable and consistent **geodetic reference frames**, which provide the fundamental layer for the determination of time dependent coordinates of points or objects, and for describing the motion of the Earth in space.

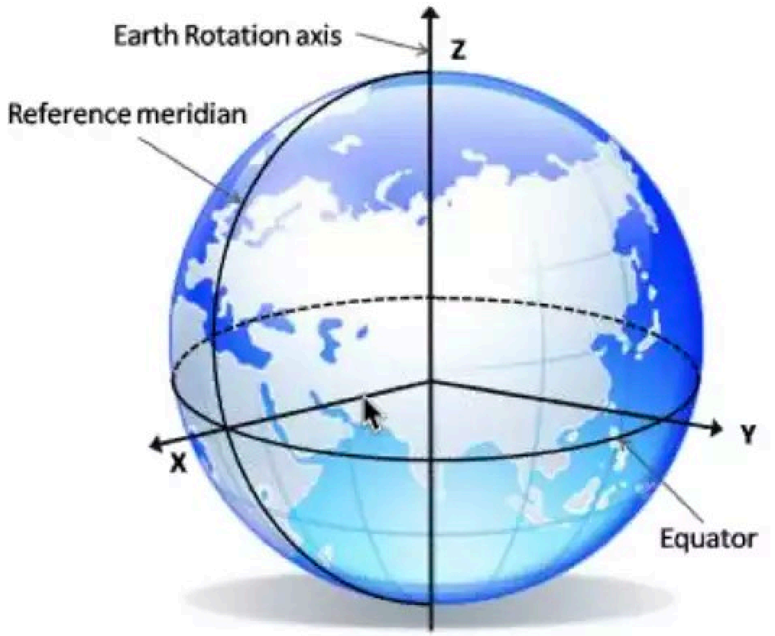




What is a Terrestrial Reference Frame?

- The Terrestrial Reference Frame (TRF) is an accurate, stable set of positions and velocities of reference points on the surface of the Earth.

- The TRF provides the stable coordinate system that allows us to link measurements over space and time for numerous scientific and societal applications including climate and sea level change studies.



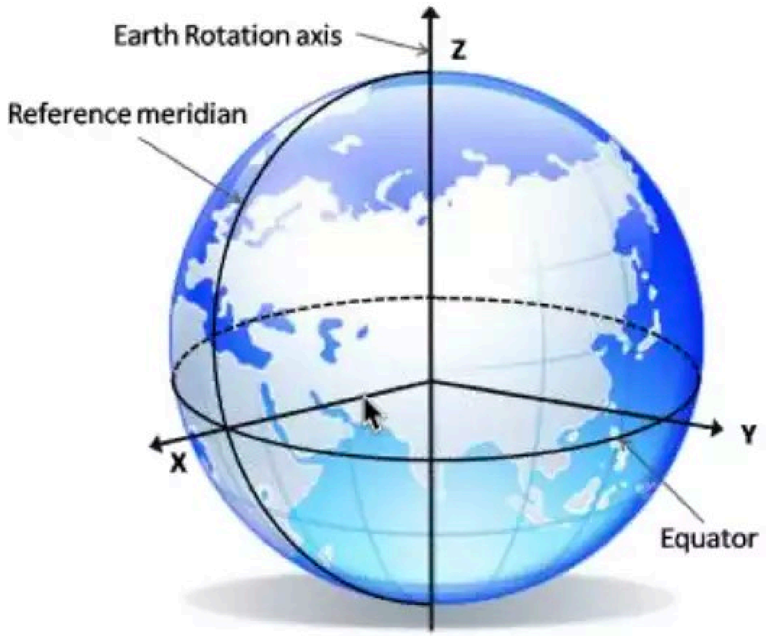
Terrestrial Reference Frame

Why do we need a Terrestrial Reference Frame?

• For accurate and safe navigation, on the land, the sea and in the air.

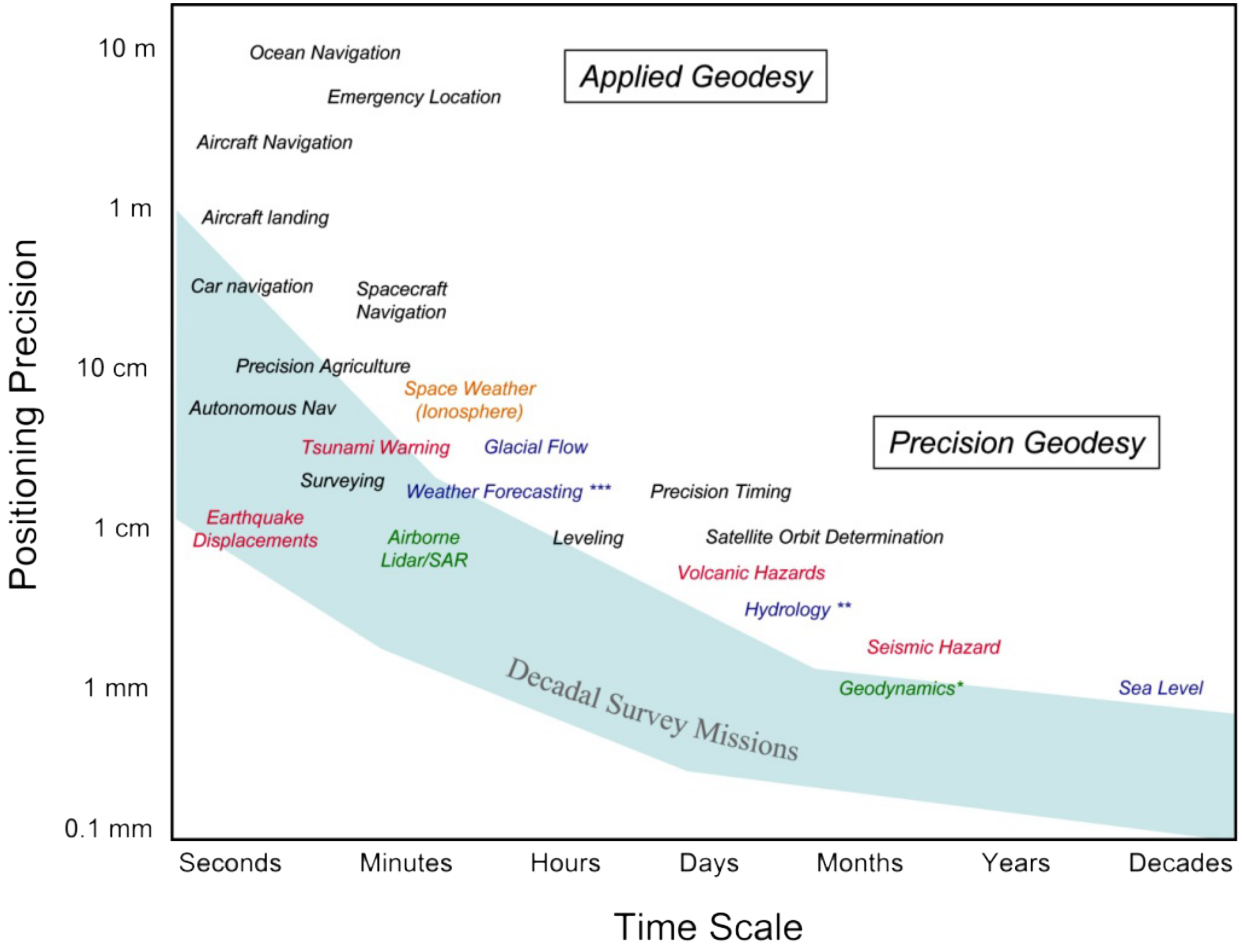
• To quantify deformations and displacements of the Earth's surface that are caused by climate change, natural hazards, plate tectonics, seismic activity.

• To geolocate remote sensing observations from satellites or flying platforms in space & time (e.g. images, altimeter measurements).



Terrestrial Reference Frame

Space Geodesy Supports Positioning, and Earth System Observations on a Variety Spatial and Temporal Scales



National Research Council. 2010.
Precise Geodetic Infrastructure: National Requirements for a Shared Resource.
Washington, DC: The National Academies Press.
https://doi.org/10.17226/12954

Space Geodesy & the Terrestrial Reference Frame

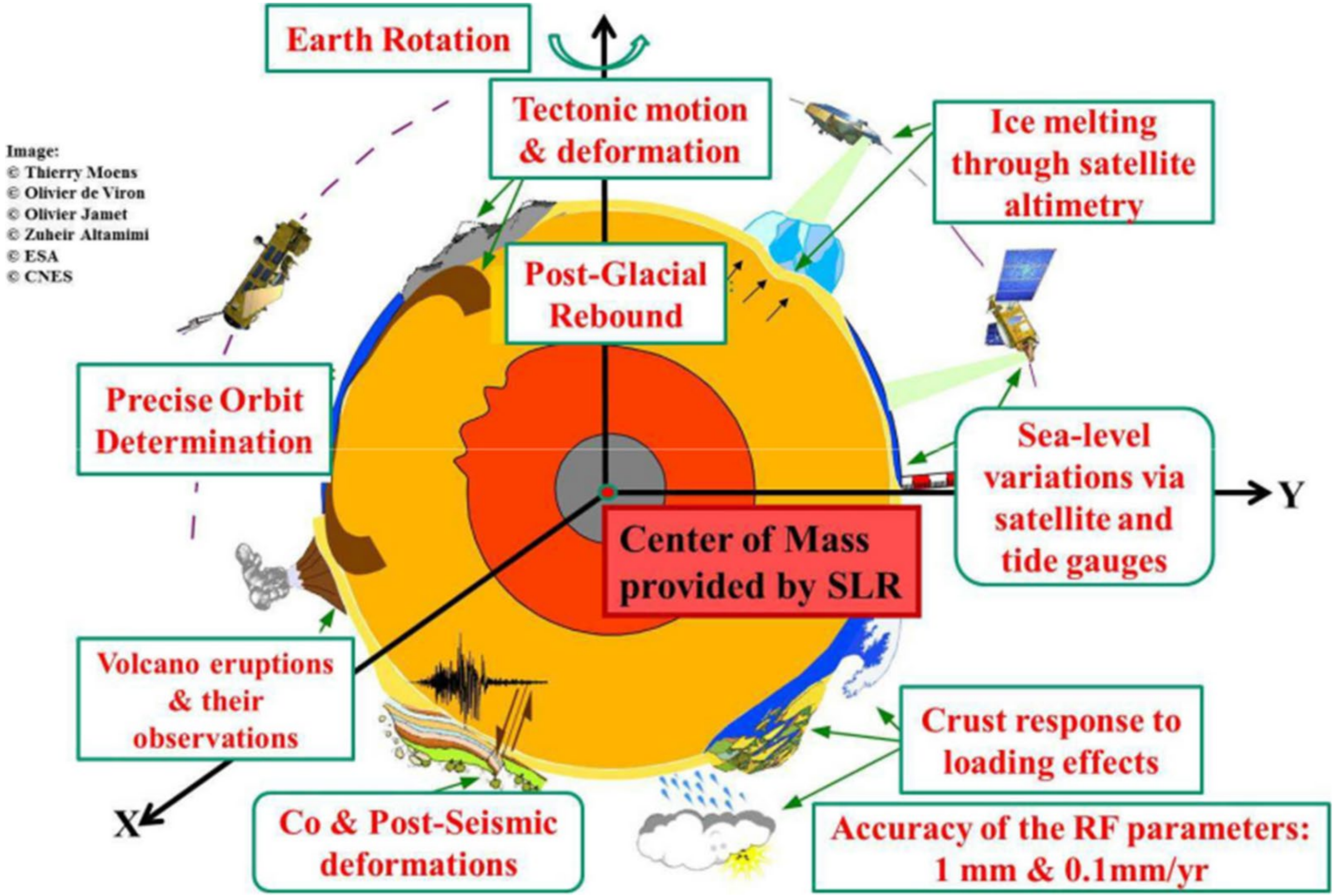


Figure from Delva, P., *et al. Earth Planets Space* **75**, 5 (2023).
https://doi.org/10.1186/s40623-022-01752-w

I. What is geodesy?

II. Techniques of Space Geodesy (including VLBI).

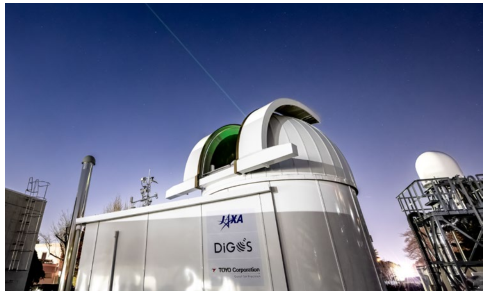
III. Main Applications of VLBI

(A). EOP, TRF, CRF.

(B). EOP/Earth rotation in the News.

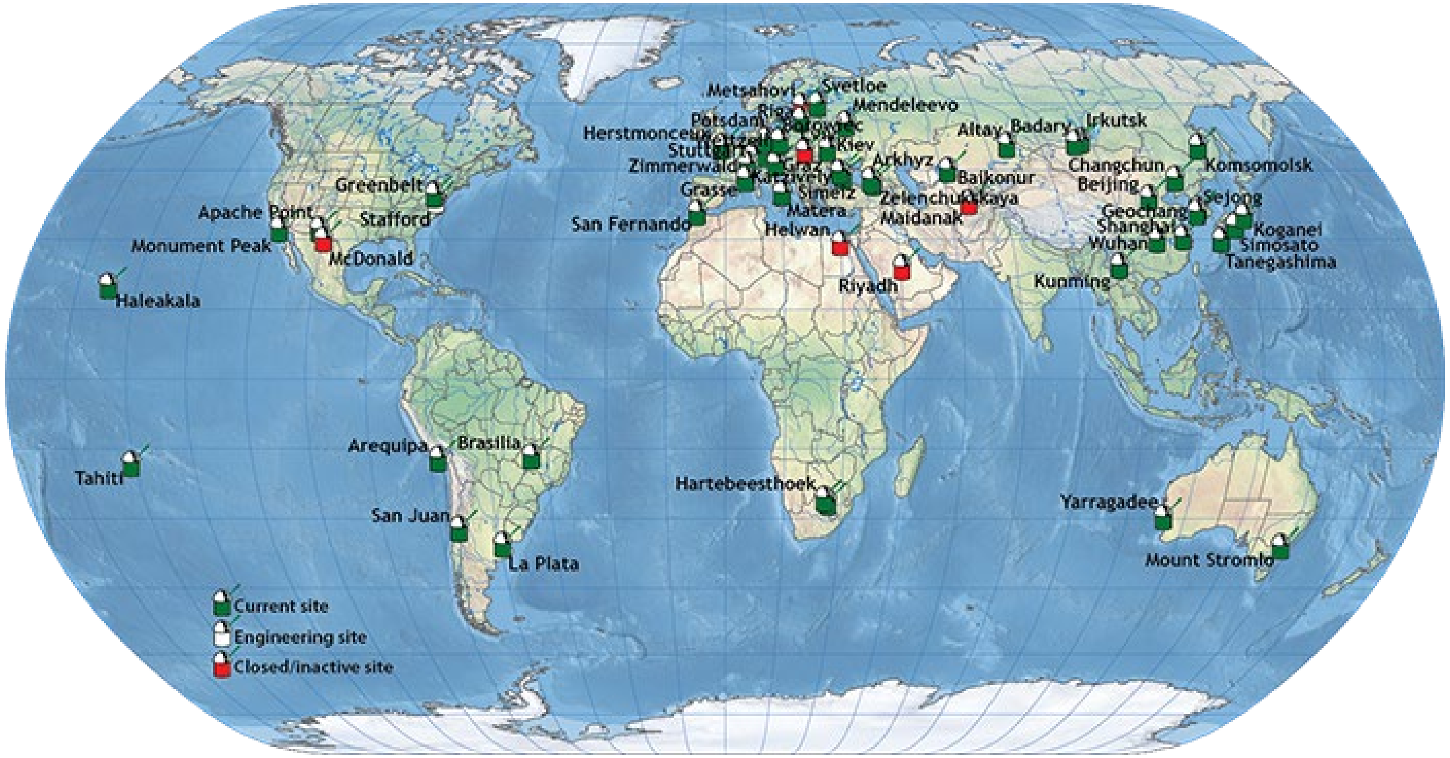
IV. Geodesy & the Global Change in Mean Sea Level.

The Techniques of Space Geodesy:
Satellite Laser Ranging (SLR)



SLR, Tsukuba, Japan
(dedicated 3/30/23)

SLR, Yarragadee, Australia



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

http://ilrs.gsfc.nasa.gov

International Laser Ranging Service

VLBI-SLR Colocations:

- Badary
- Greenbelt
- Hartebeesthoek
- Matera
- Shanghai
- Svetloe
- Wettzell
- Yarragadee
- Zelenchuskaya

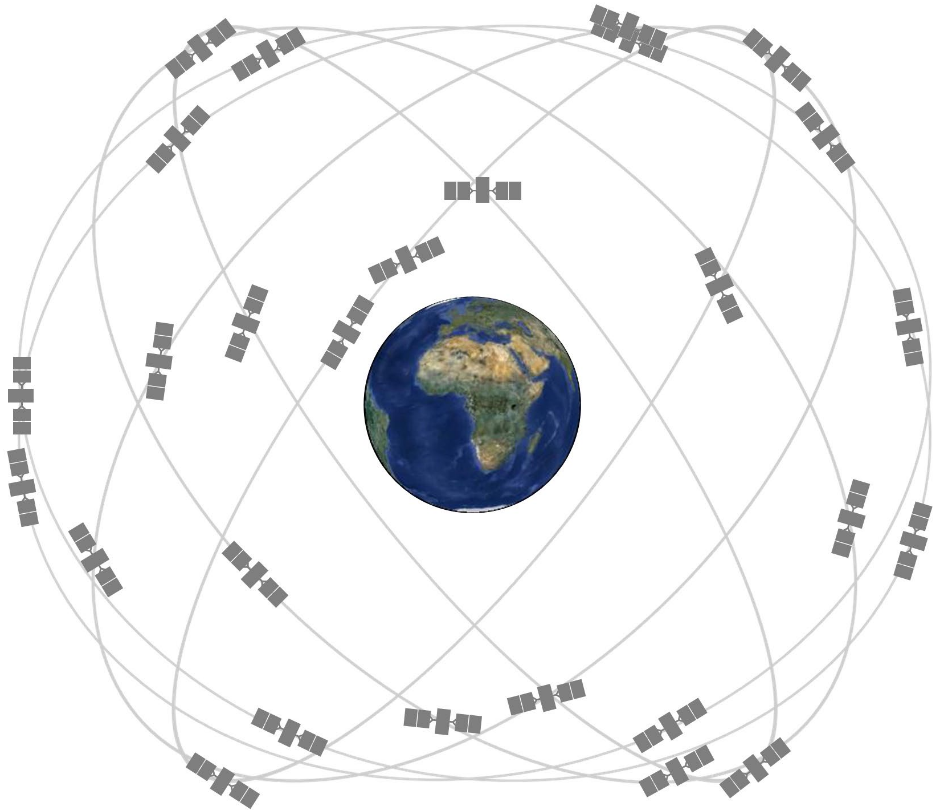
In near future

- La Plata
- McDonald
- Metsähovi
- Ny Ålesund
- Yebes

Long-term plan

- Tahiti

The Techniques of Space Geodesy:
Global Navigation Satellite Systems (GNSS)



GNSS Constellation schematic

GNSS Constellations:
- **Beidou***
- **Galileo**
- **Glonass**
- **GPS**
- **IRNSS***
- **QZSS***

• includes geosynchronous satellites

IGS INTERNATIONAL GNSS SERVICE

• 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.
Near-Real-Time (NRT) & Longer Latency.

Sentinel-6A
(ocean radar altimeter satellite)

An important application of GNSS is satellite Precise Orbit Determination (POD).
Sentinel-6A can track both GPS & Galileo.

The Techniques of Space Geodesy:

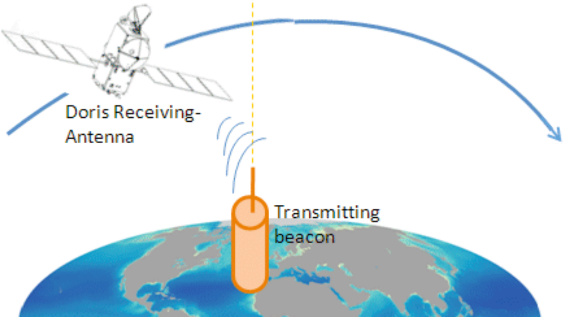
DORIS (Doppler Orbitography Radiopositioning Integrated by Satellite)

How DORIS works

The satellite is **upright** the beacon, it's the TCA point (*Time of Closest Approach*). The frequency of the received signal is **equal** to the frequency of the transmitted signal.

The satellite is **approaching** the beacon : The frequency of the received signal is **greater** than the frequency of the transmitted signal.

The satellite is **moving away** the beacon : The frequency of the received signal is **lower** than the frequency of the transmitted signal.

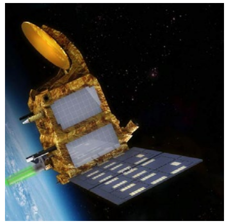


Greenbelt

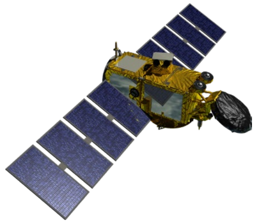
DORIS Network Map

Current DORIS Satellites (2023)

CryoSat-2

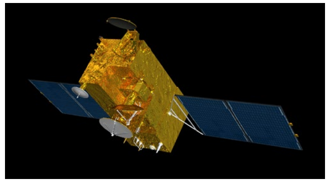


Saral/AltiKa



Jason-3

Sentinel-3A,3B



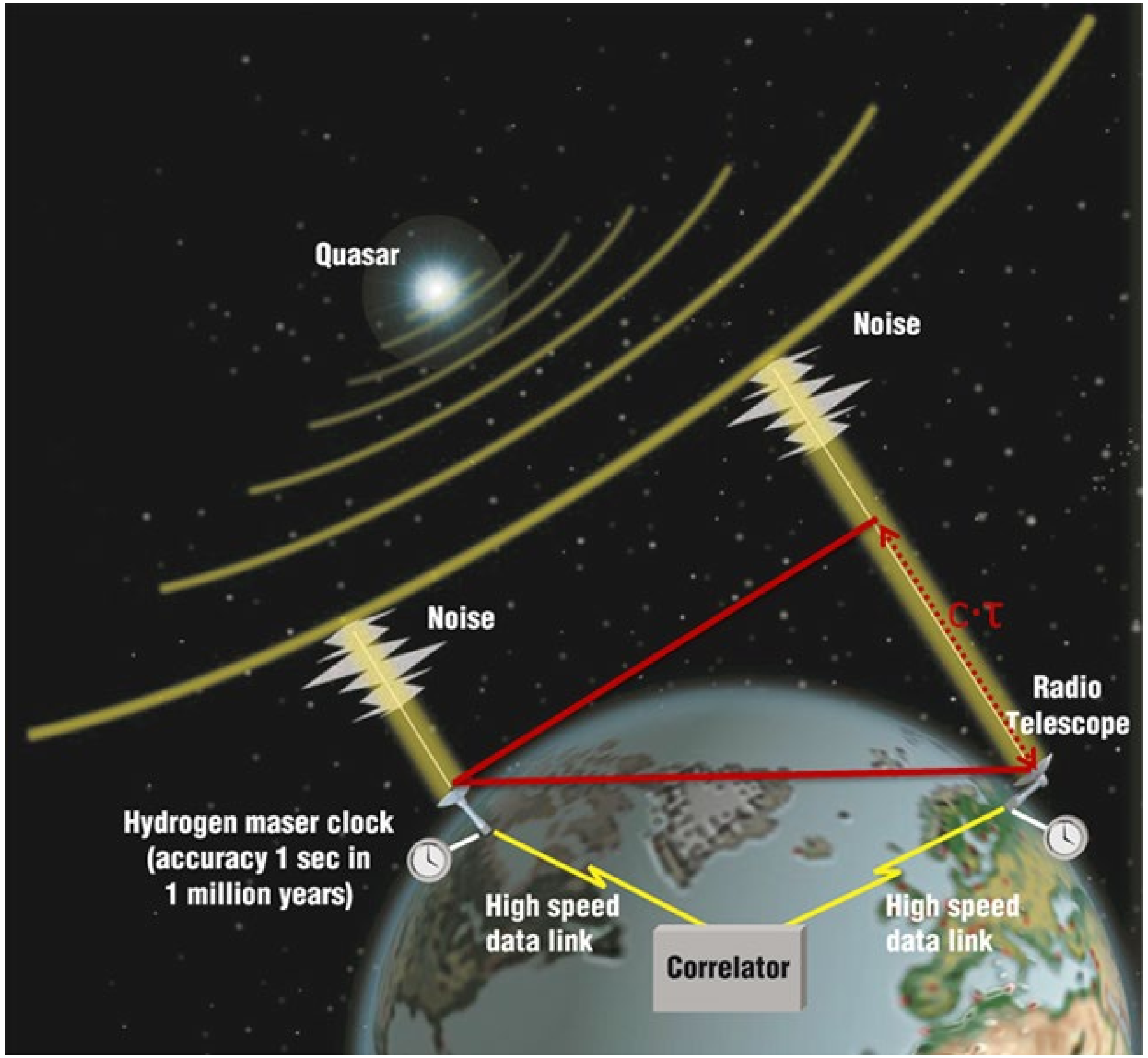
HY-2C & HY-2D

Sentinel-6A

SWOT

The Techniques of Space Geodesy:

VLBI (Very Long Baseline Interferometry)



The VLBI technique consists of measuring the difference in the arrival time of a signal from a distance source at two (or more) VLBI antennae. The difference in arrival time is called the "delay".

The delay is influenced by anything that affects the propagation of the radio signals, or that changes the position of the VLBI telescope.

The Techniques of Space Geodesy:
Contributions of the Techniques

SLR

Regular SLR measurements are used to improve the orbit determination of ~100 active satellites, uniquely define the ITRF geocenter, and contribute to the EOP products. Contributes to scale of TRF.

GNSS

Global Navigation Satellite Systems (GNSS) stations provide positioning for users on land, sea and in the air, & distribute the terrestrial reference frame to users. GNSS provides EOP (*polar motion & polar motion rate*), troposphere & ionosphere products.

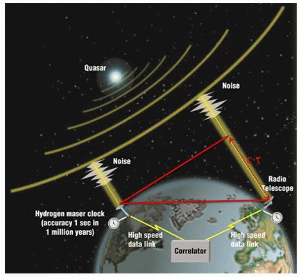
VLBI

Daily VLBI measurements are vital for determining and predicting the time-varying alignment of the Terrestrial Reference Frame with respect to the celestial reference frame (Earth Orientation Parameters).

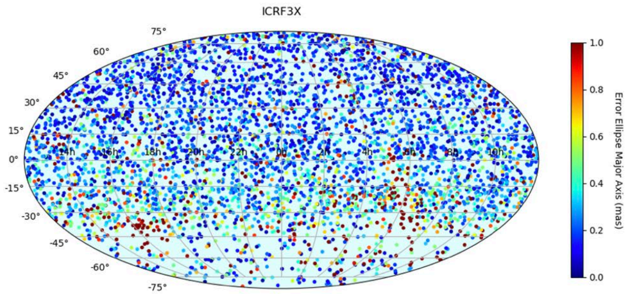
DORIS

DORIS provides precise orbit determination to LEO satellites, primarily altimeter satellites that measure ocean surface topography. Provides Near Real Time (NRT) and longer latency orbit products.

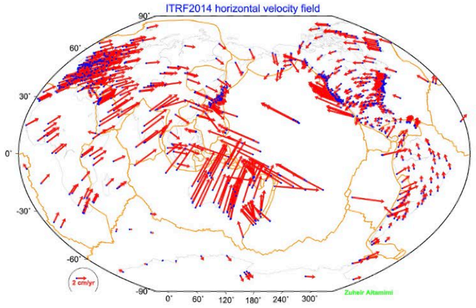
Main VLBI Products



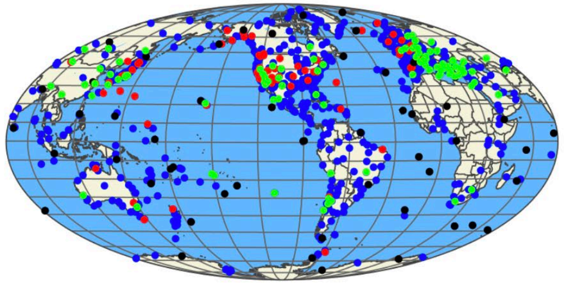
Celestial Reference Frame (CRF)



EOPs



Terrestrial Reference Frame (TRF)

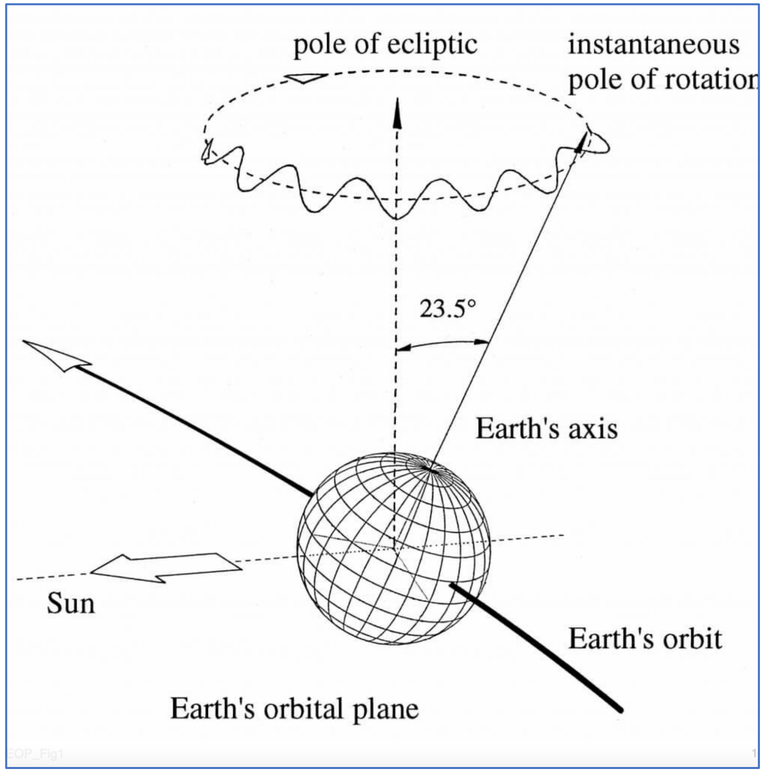


Earth Orientation Parameters (EOP)

Image Courtesy USNO

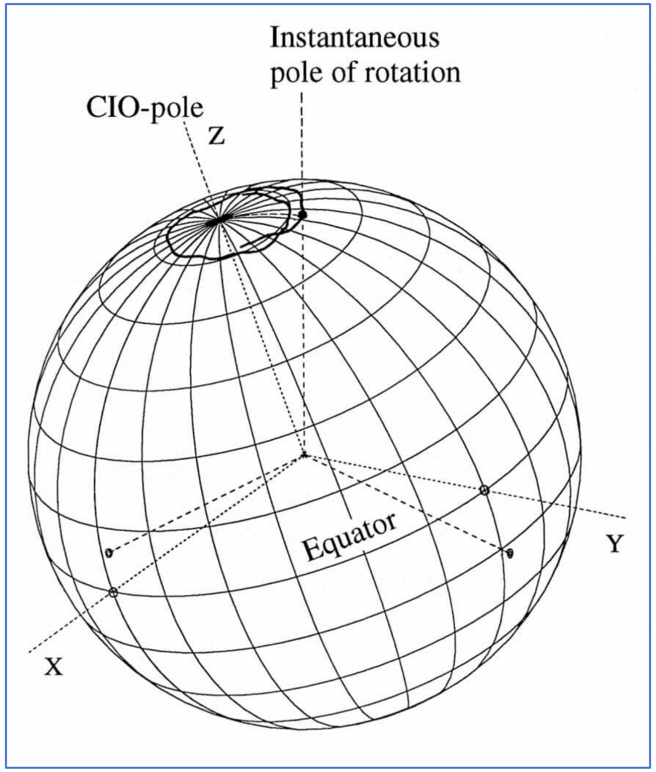
Components of EOP (1)

Precession & Nutation



Precession/Nutation refer to the orientation of the spin axis in inertial space. The difference between P/N is time-scale & 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').

Images courtesy ggos.org

UT1/LOD

Variations of the Earth's angular velocity are expressed as d(UT1-UTC) or as the change in the length of day *Δ* LOD.

Δ LOD = d(UTC-UTC)/dt

- **Changes in Earth rotation are caused by solid Earth & ocean tides, mass motion in the atmosphere & hydrosphere, and changes in the solid Earth.**

- **Changes in Earth rotation occur due to the conservation of angular momentum in the Earth system.**

Components of EOP (2)

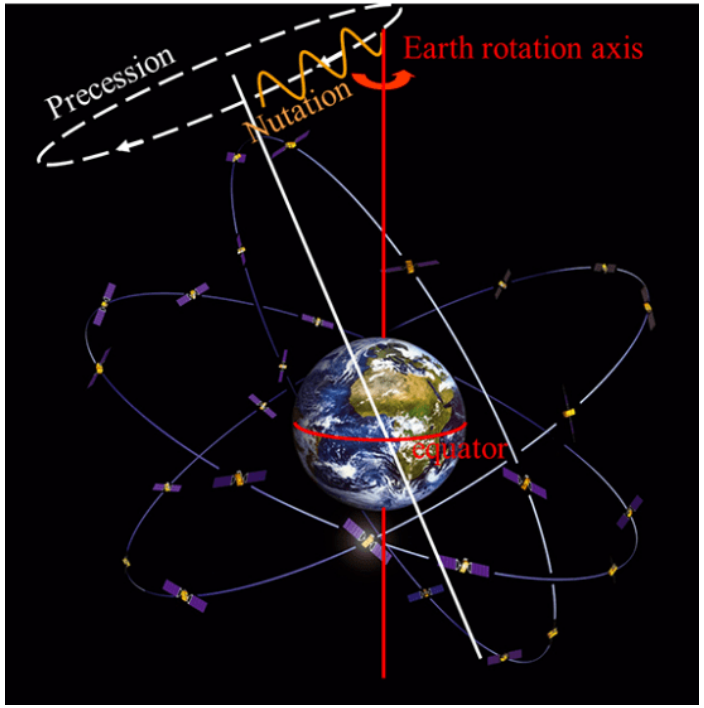
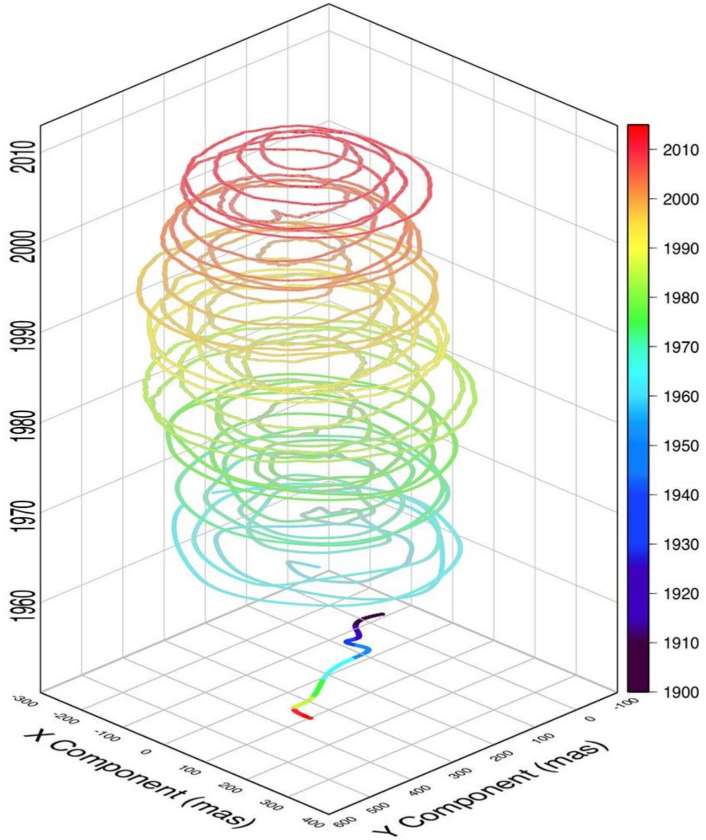
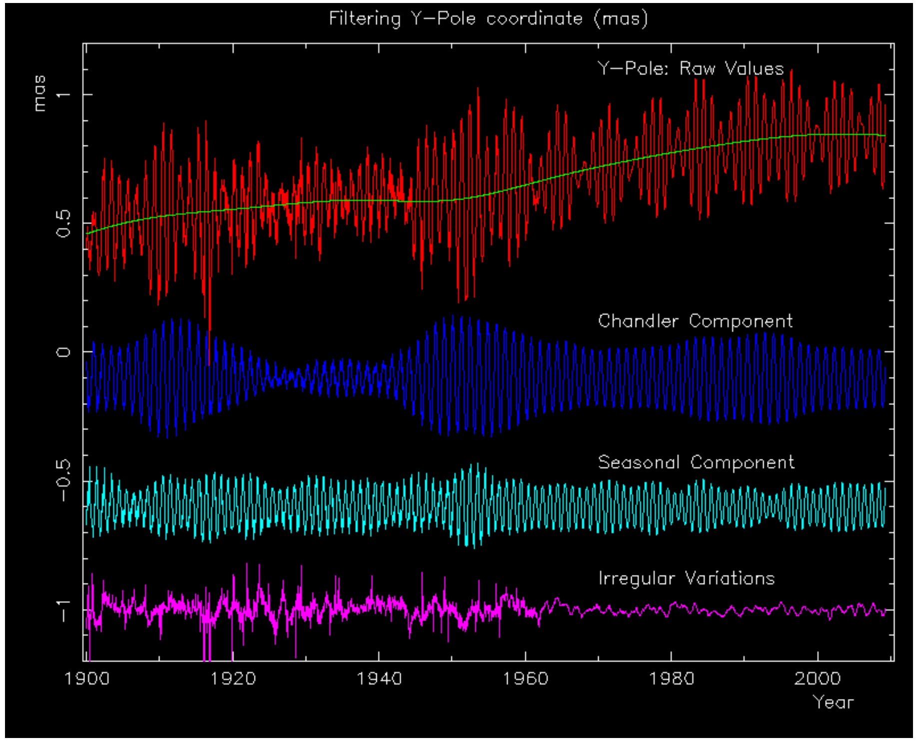


Image courtesy ESA



(E.C. Pavlis et al. 2016)

Polar motion, Y component

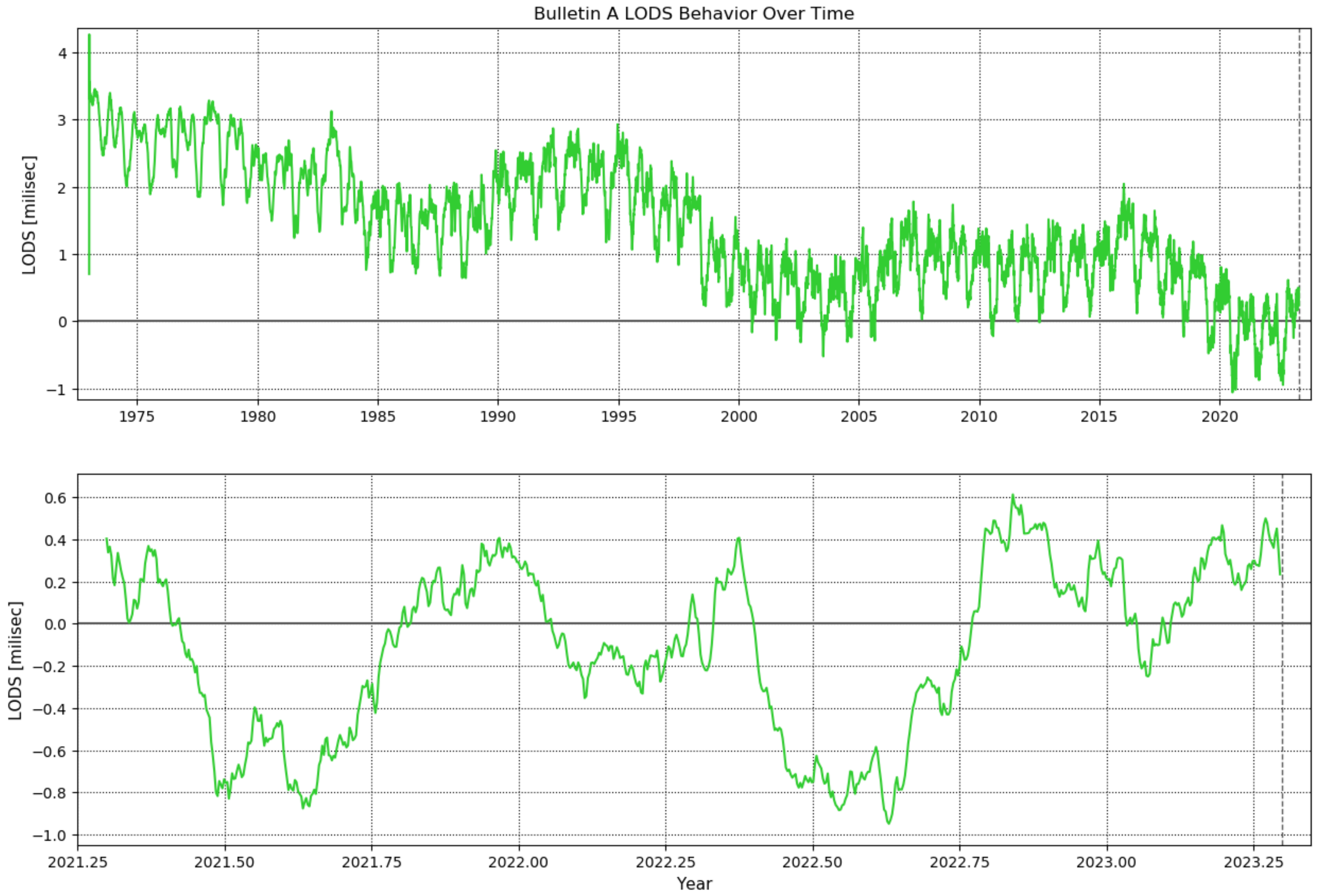


https://hpiers.obspm.fr/eop-pc/earthor/polmot/pm.html

<u>Scale of motions</u>:
Precession: 1.5 km/yr;
Nutation: ~600 m
Differences between observations and predictions are at levels of a few cm.

<u>Polar Motion:</u>
The variation is a few meters on the surface of the Earth; the main components of polar motion are annual, Chandler wobble (~430 days), and a long-term drift.

Variations in Earth rotation

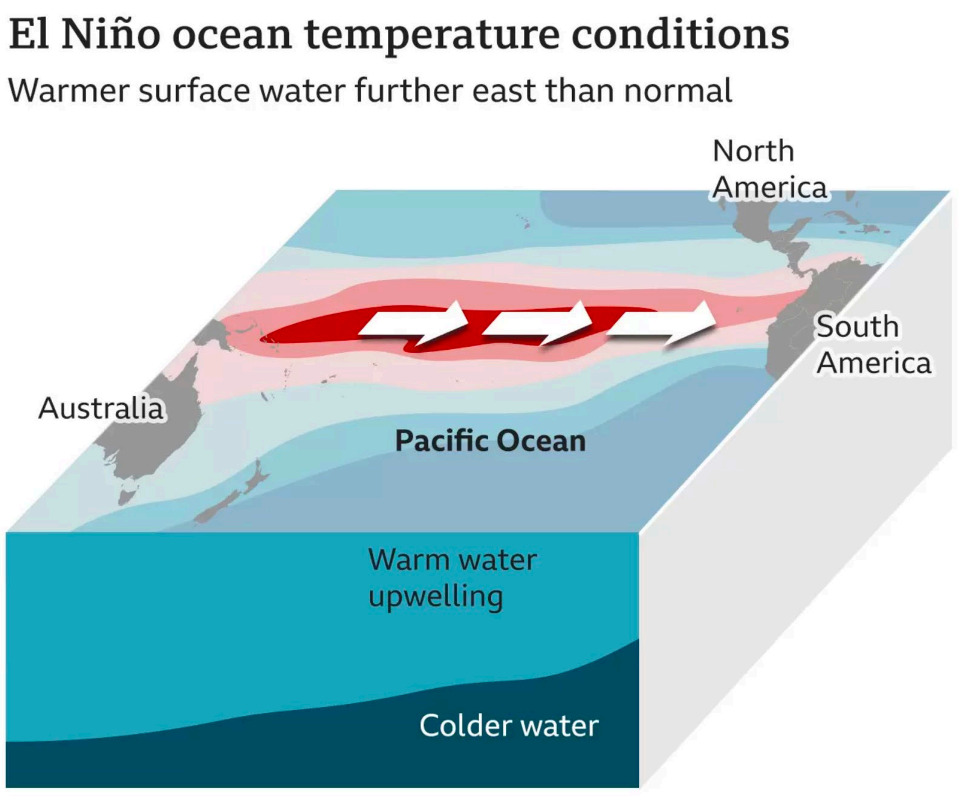


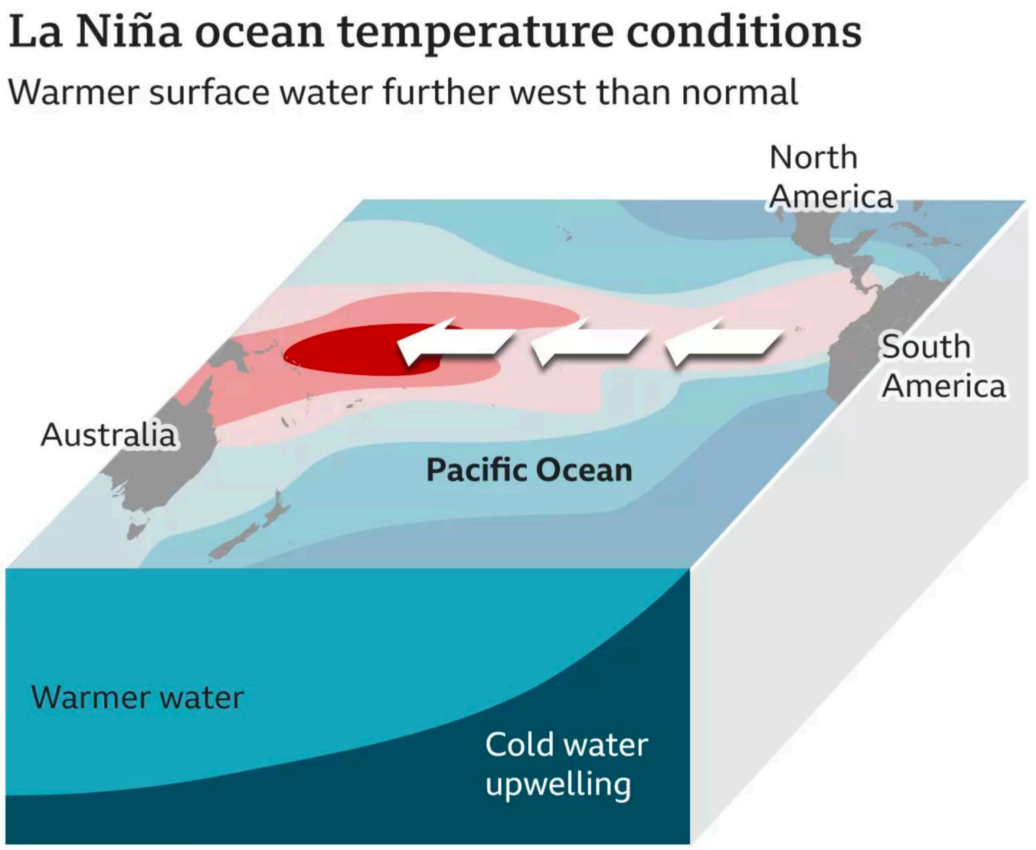
Prominent signals:
(1) long-term secular change
→ due to tidal friction.
(2) Decadal variations (internal processes within the Earth).
(3) Changes with period < 2 yrs caused by changes in the Earth's atmosphere (includes seasonal effects).

Image courtesy USNO

LODS = LOD corrected for known tidal effects.

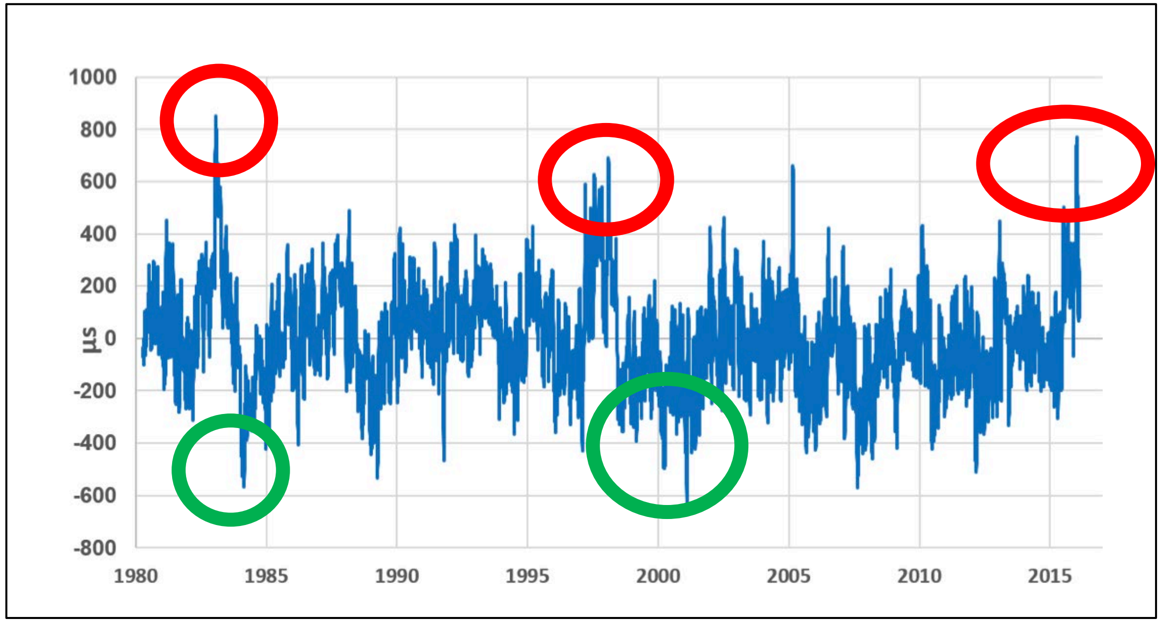
El Niño Southern Oscillation (ENSO) have big effects on Earth’s climate and on human societies





Variations in Earth rotation (El Niño & La Niña)

Residual LOD
(Removing Tidal, Seasonal & Long-Period terms)



Gipson, IVS GM 2016 proceedings

Major Climatic events such as El Niño (**e.g. red circles**) & La Niña (**e.g. green circles**) produce strong signatures in Earth rotation

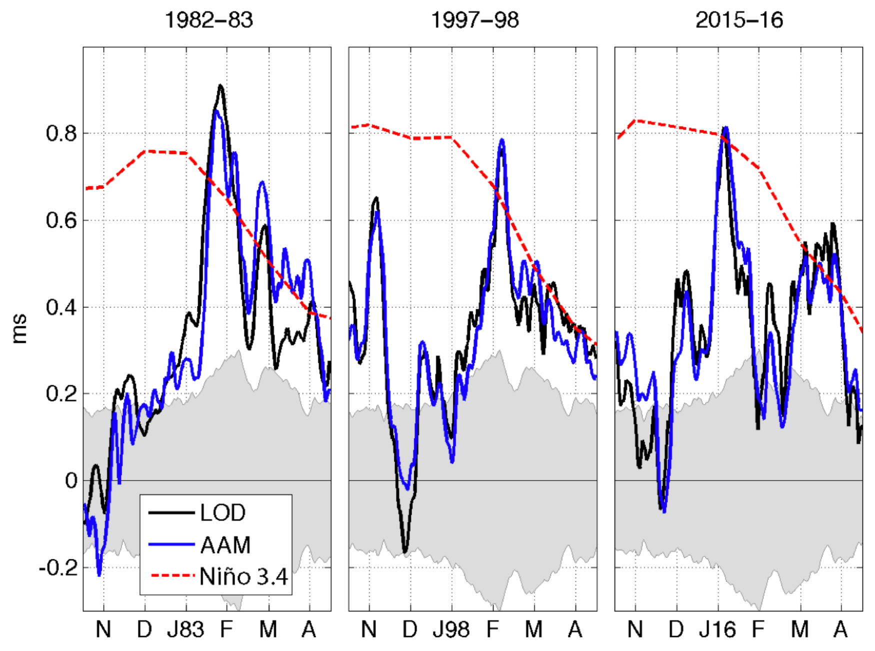


Figure 2. The time series of daily AAM (blue) and LOD (black) values around the three extreme events. The red dashed line represents the scaled monthly Niño 3.4 index. The shaded area represents 1 standard deviation around the climatological mean. The *x*-axis ticks indicate the first day of each month.

Lambert et al., Earth Syst. Dyn. (2017)
https://doi.org/10.5194/esd-8-1009-2017

Earth rotation in the news (1)

USA TODAY NEWS

Shortest day in history: Earth completes fastest rotation ever on June 29, English lab says

SARAH RAZA | Detroit Free Press

DETROIT — The days are indeed getting shorter. Earth had its shortest day ever recorded on June 29, with the day ending 1.59 milliseconds sooner than usual, according to the National Physical Laboratory in England.

LCI

La Terre a battu un nouveau record : pourquoi sa rotation s'accélère-t-elle ces derniers temps ?

Par Matthieu DELACHARLERY

Publié le 4 août 2022 à 17h58, mis à jour le 5 août 2022 à 10h36

The Guardian

Analysis

Oh my days! Midnight comes a fraction sooner as Earth spins faster

Ian Sample
Science editor

Analysis: Reflecting a recent trend, 29 June was the shortest day on our planet since the 1960s. What's going on?

Kürzester Tag in der Atomuhr-Ära: Die Erde dreht sich plötzlich schneller

Noch ist unklar, warum sich die Tageslänge der Erde verkürzt. Hält die Verkürzung aber an, muss sich die Menschheit wohl auf eine Veränderung einstellen.

Carola Tunk

01.08.2022 | 02:04 Uhr

Earth rotation in the news (2)

nature geoscience

Article

https://doi.org/10.1038/s41561-022-01112-z

Multidecadal variation of the Earth's inner-core rotation

Received: 21 December 2021

Accepted: 5 December 2022

Published online: 23 January 2023

Check for updates

Yi Yang & Xiaodong Song

Differential rotation of Earth's inner core relative to the mantle is thought to occur under the effects of the geodynamo on core dynamics and gravitational core–mantle coupling. This rotation has been inferred from temporal changes between repeated seismic waves that should traverse the same path through the inner core. Here we analyse repeated seismic waves

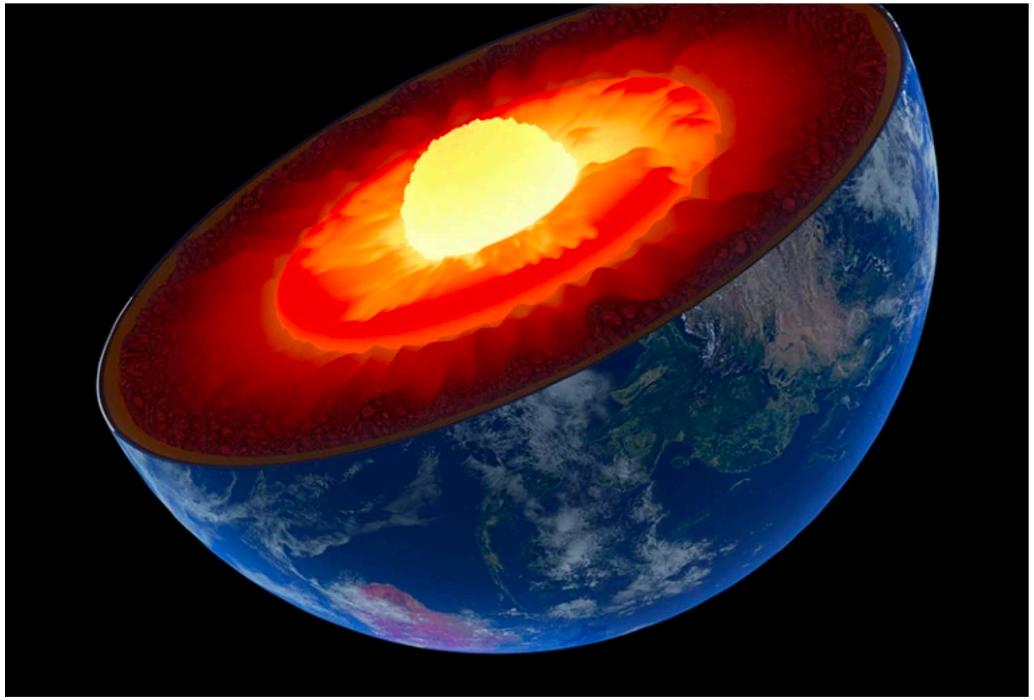
Yang, Y., Song, X. Multidecadal variation of the Earth's inner-core rotation. *Nature Geosci.* **16**, 182–187 (2023). https://doi.org/10.1038/s41561-022-01112-z

Nature magazine

NEWS | 23 January 2023

Has Earth's inner core stopped its strange spin?

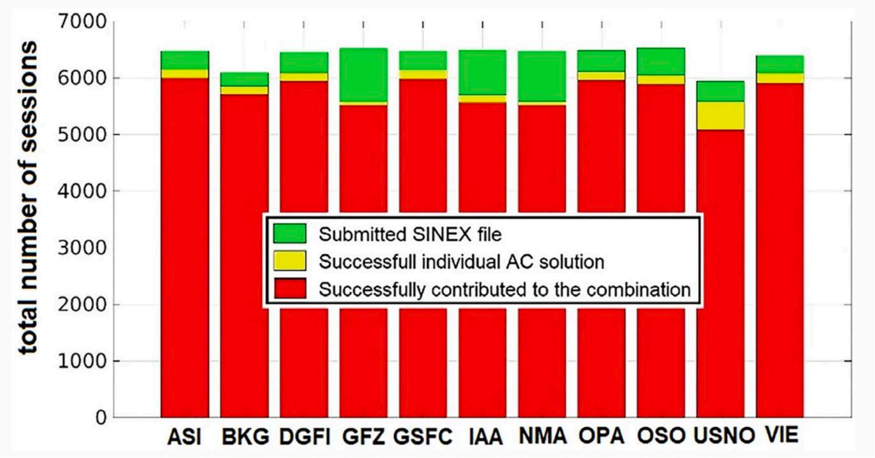
Earthquake data hint that the inner core stopped rotating faster than the rest of the planet in 2009, but not all researchers agree.



Earth's inner core is made mostly of solid iron, and can rotate separately from the outer parts of the planet. Credit: Johan Swanepoel/SPL

Terrestrial Reference Frame:
The IVS Contribution to ITRF2020

- **11 Institutions.**
- **7 Software packages:**
  ASCOT, Calc/Solve, DOGS-R1, PORT, QUASAR, VieVS, Where
- **~6600 sessions (S/X & some VGOS).**
- **Time span, August 1979 – Dec. 2020.**



IVS Sessions contributed by each AC

IVS Station network for ITRF2020

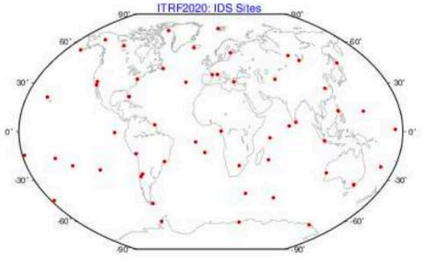
Hellmers et al., 2022, https://doi.org/10.1007/1345_2022_170

Terrestrial Reference Frame:

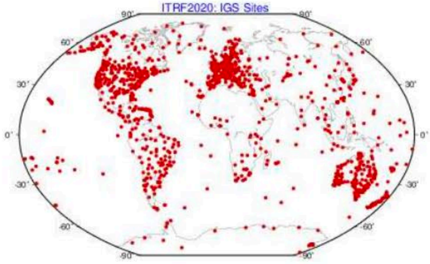
ITRF2020 Input Data – All the techniques

TC	# of solutions	Time-span	# of sites	Theoretical 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

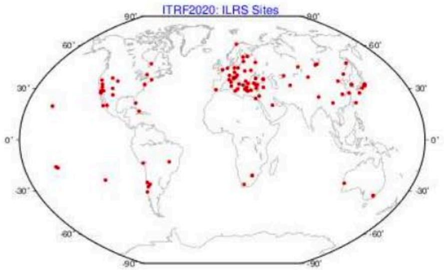
IDS/DORIS



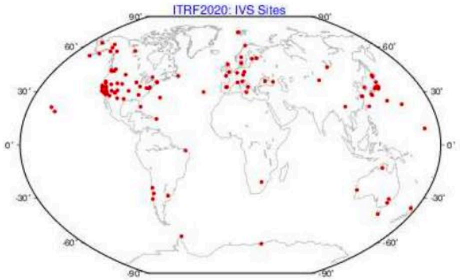
IGS/GNSS



ILRS/SLR



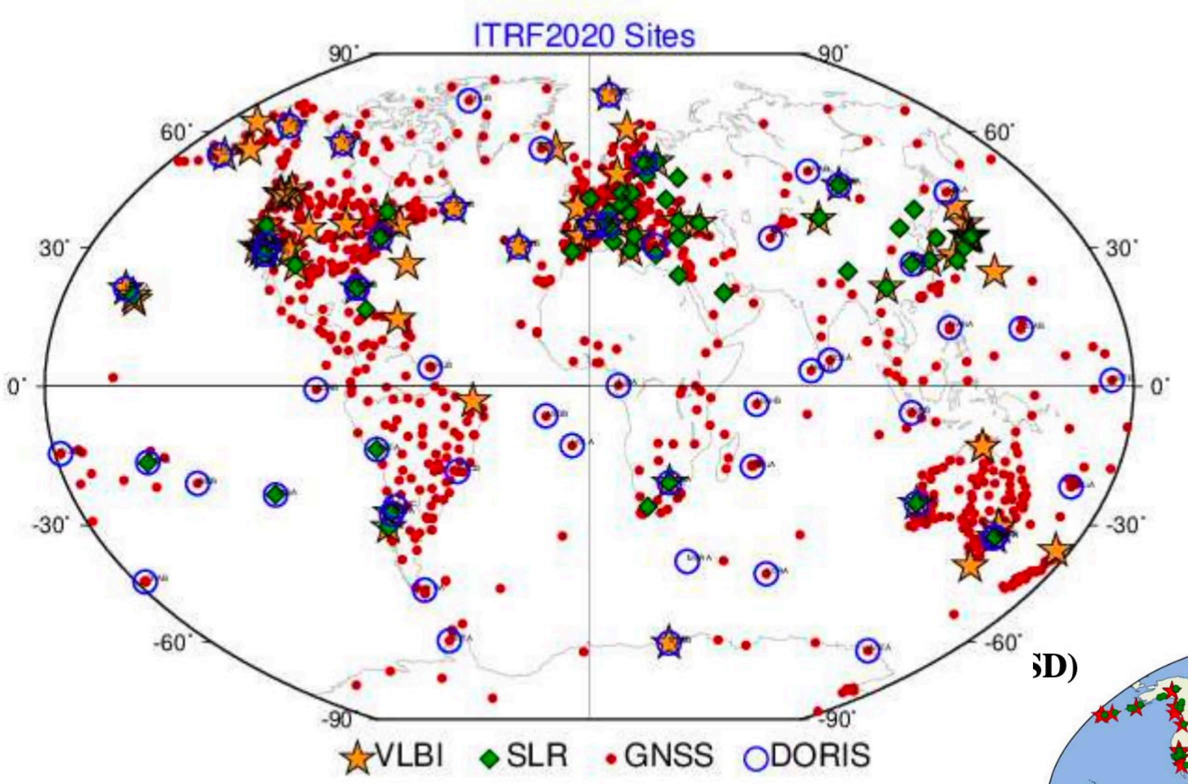
IVS/VLBI



Altamimi, 2022, ICG-16

Terrestrial Reference Frame: (IGN)

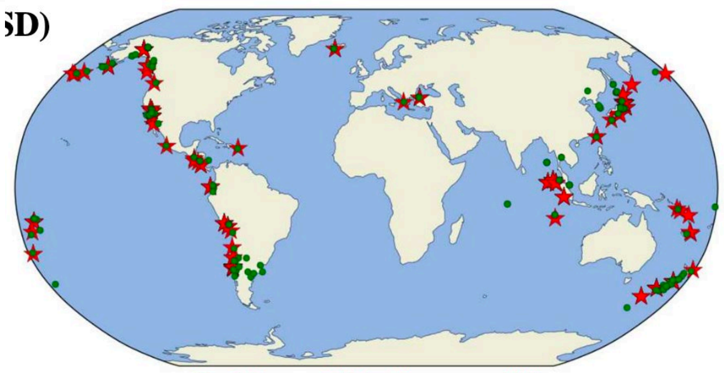
ITRF2020 Network & Solution



- 1800 stations at 1223 sites.
- 878 sites (Northern Hemisphere).
- 355 sites (Southern Hemisphere)

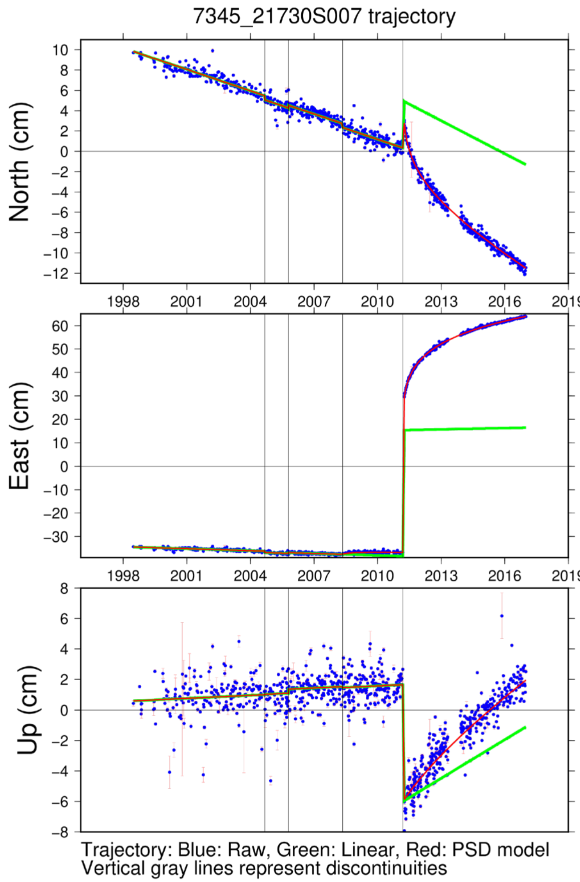
Altamimi, 2022, ICG-16

ITRF2020 includes models for post-seismic displacement, and explicitly solves for periodic terms to accommodate loading & draconitic effects per geodetic technique.



Red Stars: EQ Epicenters (65)
Green circles: ITRF2020 sites (118)

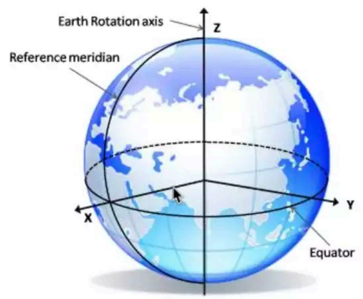
Tsukuba, Japan



https://itrf.ign.fr/en/timeseries

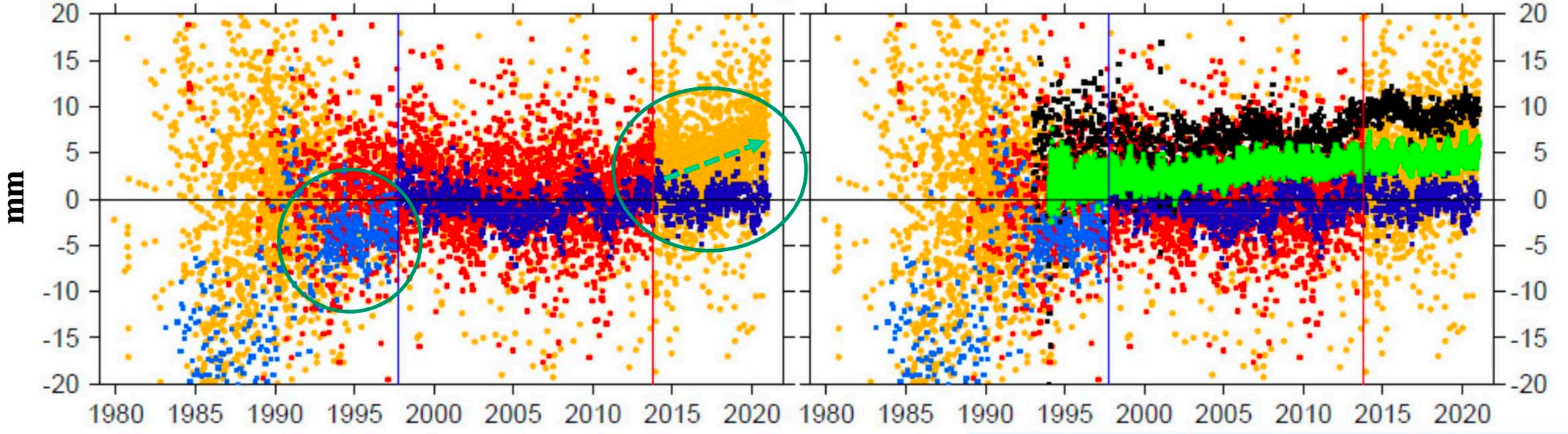
Terrestrial Reference Frame: (IGN)

ITRF2020 Scale Realization



Terrestrial Reference Frame

Scales with respect to ITRF2020



- **Orange: all VLBI Sessions**
- **Red: Selected VLBI Sessions (convex hull volume ≥ 10^{19} m^3)**
- **Light blue: all SLR time series**
- **Dark blue: Selected SLR time series**
- **Green: IGS/Repro3**
- **Black: DORIS**

ITRF2020 scale: Average of red (VLBI) and dark blue (SLR)

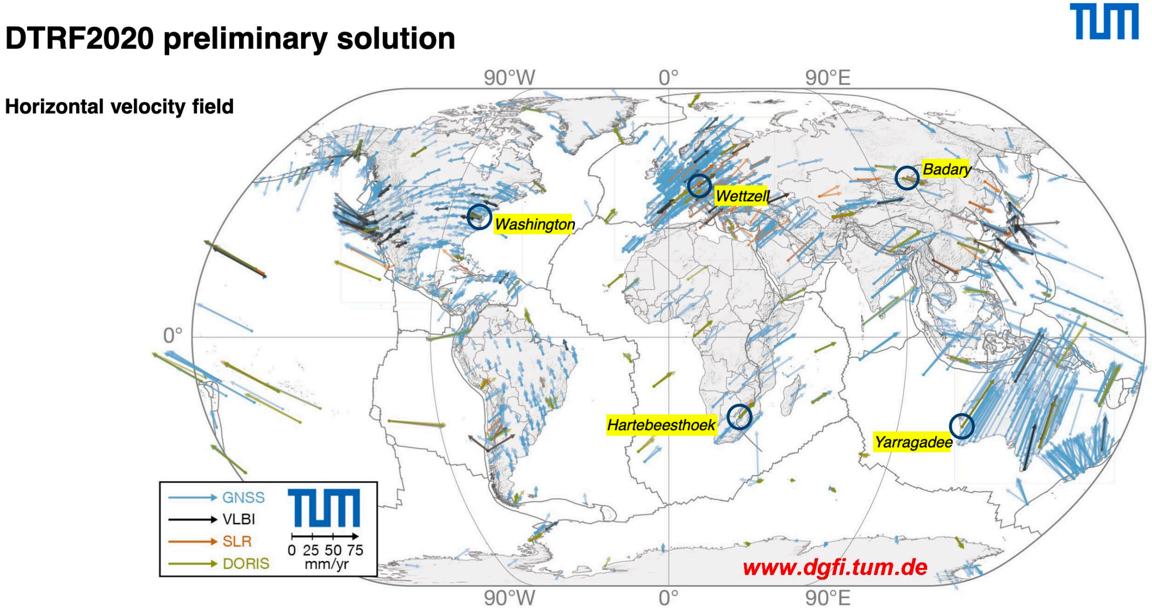
Scale offset between SLR & VLBI is 0.15 ppb (1 mm at the equator)

Solution	Scale at 2015.0 (ppb)	Scale rate ppb/yr
IGS/GNSS	0.682 ±0.018	0.018 ±0.001
IVS/VLBI	0.075 ±0.040	0.000 ±0.003
ILRS/SLR	-0.075 ±0.038	0.000 ±0.004
IDS/DORIS	1.386 ±0.037	0.028 ±0.003

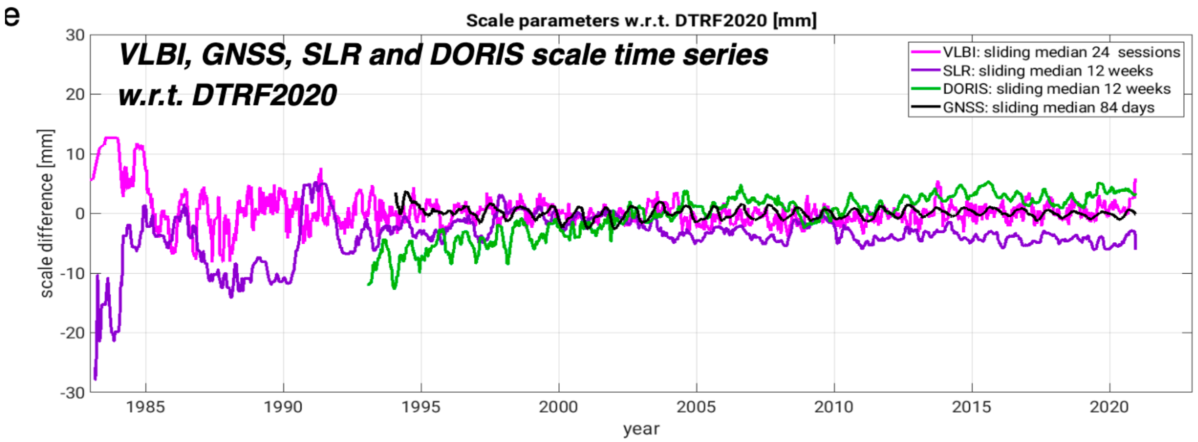
IGN

Altamimi, 2022, ICG-16

Terrestrial Reference Frame: (DGFI/TUM)
DTRF2020P Network & Solution



- **VLBI and GNSS:** agree within **0.25 mm** (epoch 2010.0) and **0.05 mm/yr**
- **SLR:** small offset and drift w.r.t. **GNSS and VLBI** of **2.2 mm (epoch 2010.0)** and **-0.1 mm/yr**



Seitz et al., UAW2022, https://doi.org/10.5281/zenodo.7247233

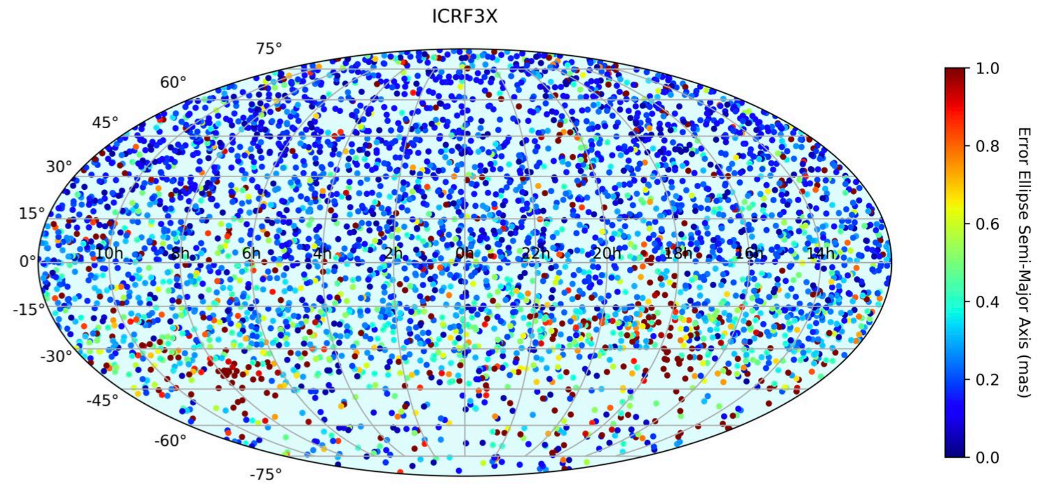
Major differences with ITRF2020 (IGN) solution:
1. Same input data from the four techniques processed differently.
2. Atmosphere & Hydrology Loading are reduced at the Normal equation level.
3. Scale of TRF is realized by combination of **VLBI + GNSS**, instead of VLBI +SLR for IGN.

International Celestial Reference Frame: ICRF3

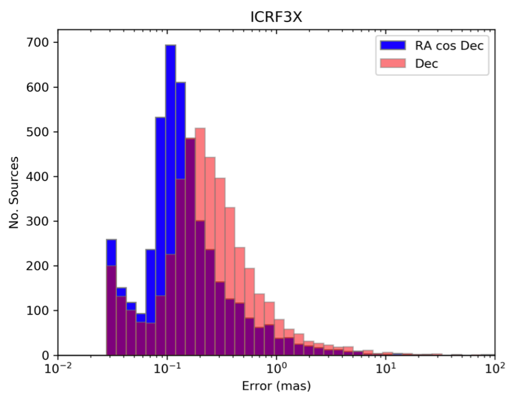
• ICRS is current celestial reference system adopted by the International Astronomical Union (IAU).

• 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).



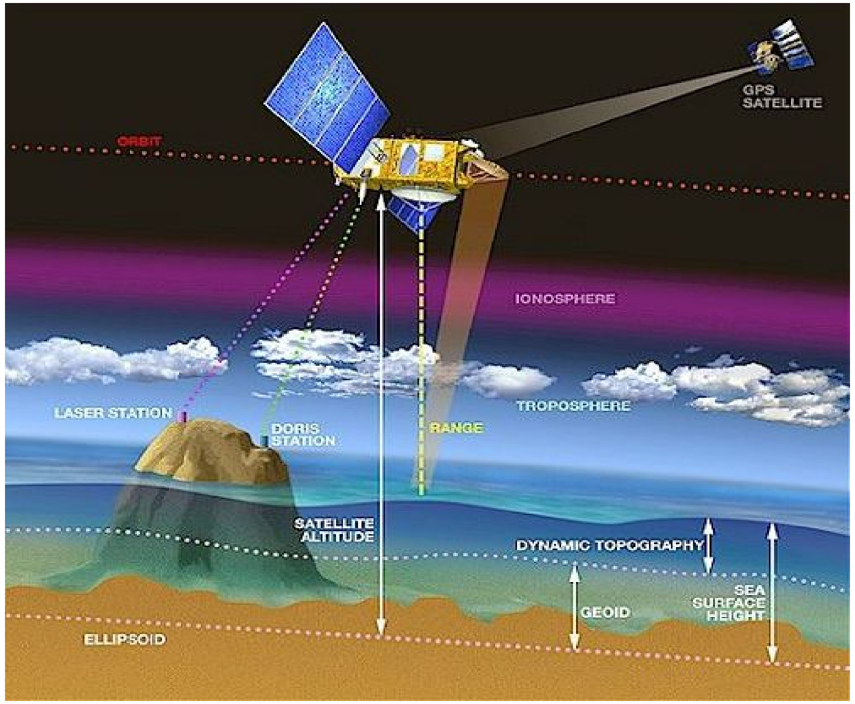
Charlot et al., A&A, 2020, https://doi.org/10.1051/0004-6361/202038368

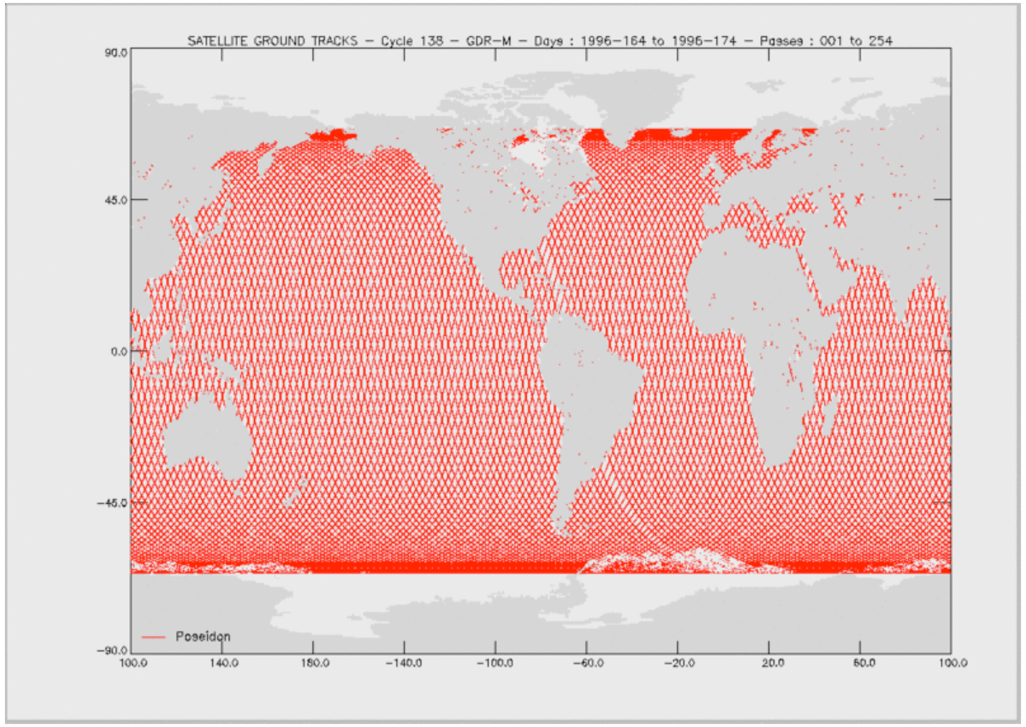


ICRF3 Facts & Figures:
• 15 million S/X + X/Ka + K-Band VLBI observations.
• Three catalogs of sources:
S/X: 4536 source; X/Ka: 678 sources, 824 (K) sources.
• 38.5 years of data.
• 167 telescopes @126 sites from the IVS, VLBA, DSN & others contributed.

Also see de Witt et al, 2022, Universe, for an overview & current work. https://doi.org/10.3390/universe807037

Satellite altimetry is a highly useful tool to monitor the changes in the ocean surface topography





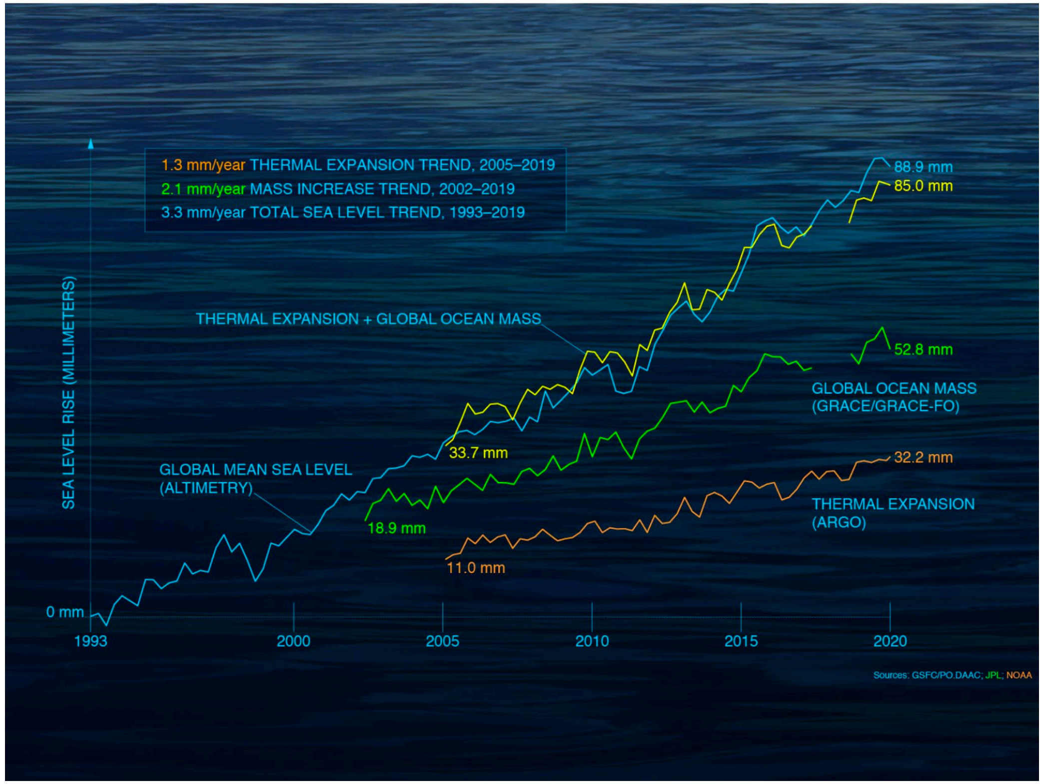
TOPEX/Poseidon (1992-2006): The altimeter mission revolutionized oceanography in the same way as the Hubble Space Telescope revolutionized astronomy.

- **The success of TOPEX was made possible by satellite geodesy.**

(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**

Change in Global Mean Sea Level:
A key indicator of climate change & a societal threat

GMSL. (1993 - 2019): Closing the sea level budget

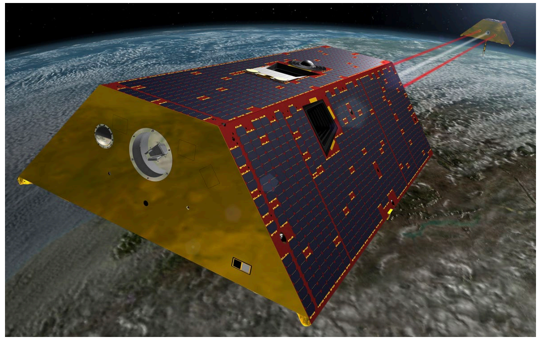


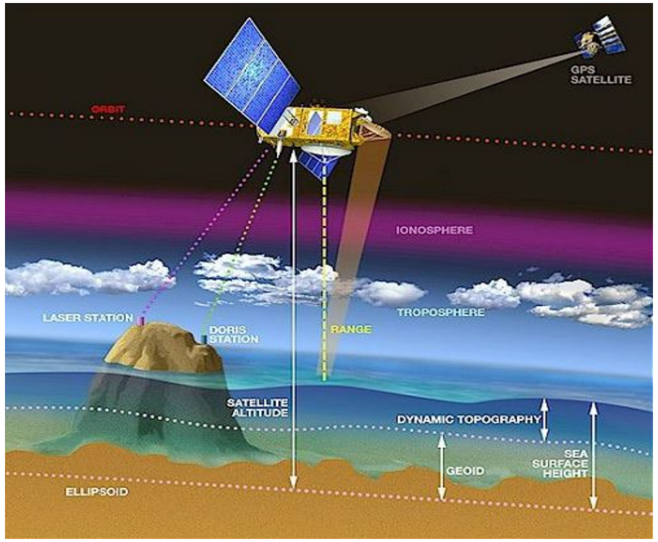
https://sealevel.jpl.nasa.gov/

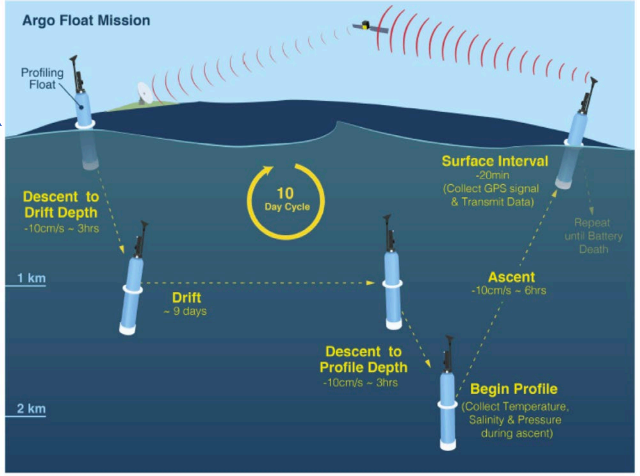
Total GMSL: ~3.35 mm/y
(measured by satellite altimetry)

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

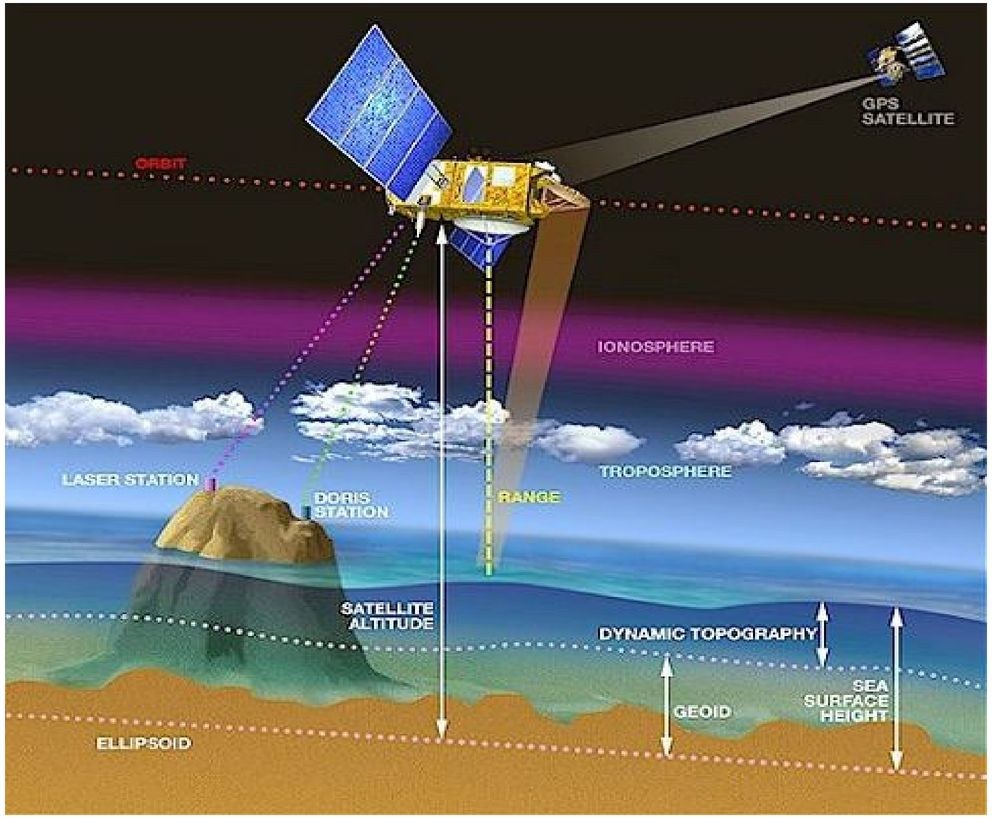
Mass components
~2.1 mm/y
Measured by GRACE & GRACE-FO







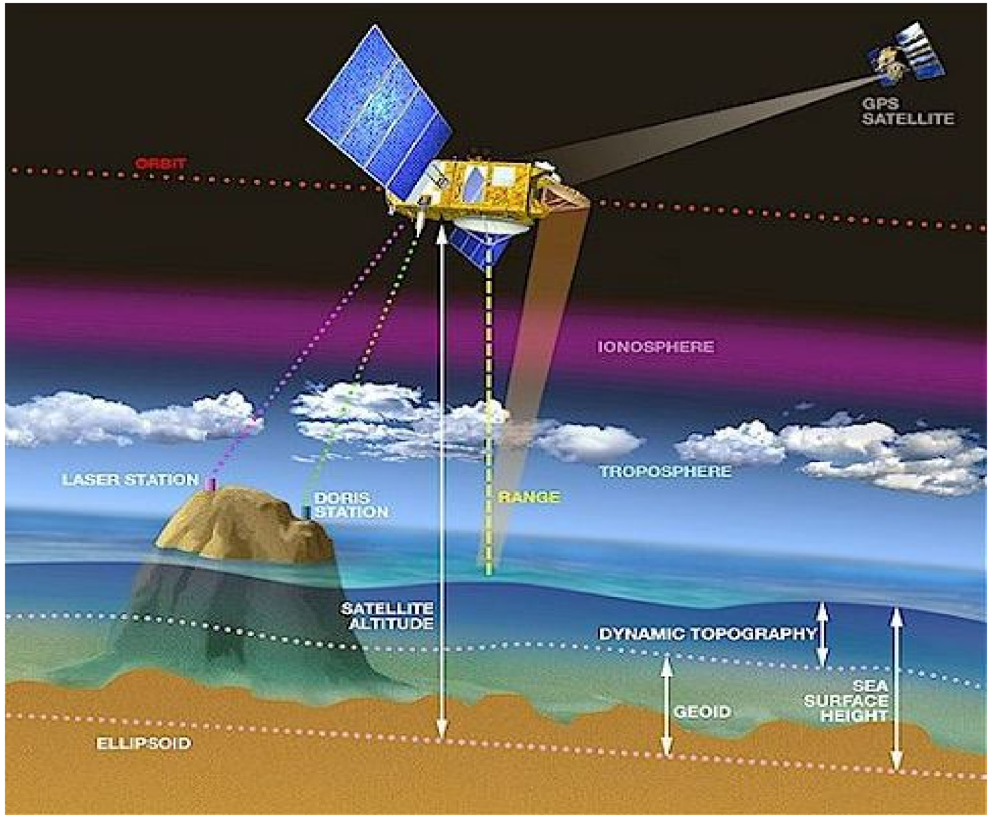
Requirements for Satellite Altimetry & Measurement of Sea Surface Height



- Stable Accurate Reference Frame over the Span of observations.

- Precise Orbit Determination (Radial orbit accuracy of < 10 mm radial RMS).

Requirements for Satellite Altimetry & Measurement of Sea Surface Height



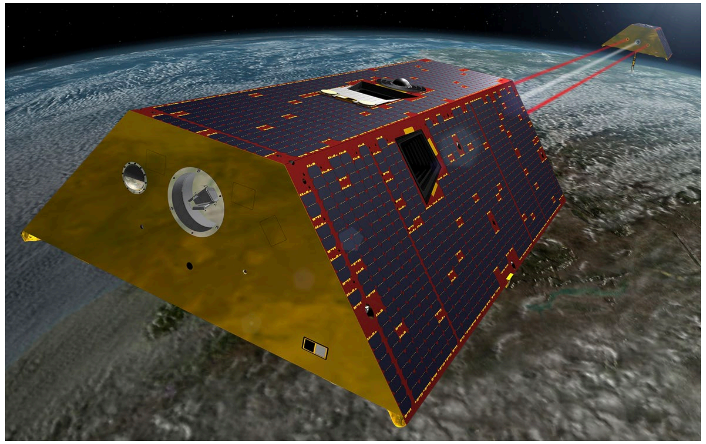
- A stable & accurate Reference Frame over the span of observations.

➡ As we have seen VLBI is a key contributor to the Terrestrial Reference Frame.

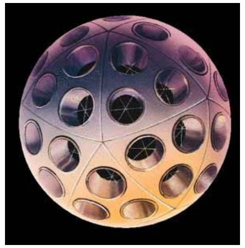
- Precise Orbit Determination (Radial orbit accuracy of < 10 mm radial RMS is required).

➡ An accurate determination of UT1 is essential for POD.

How does VLBI contribute to measurements of Mass Change?

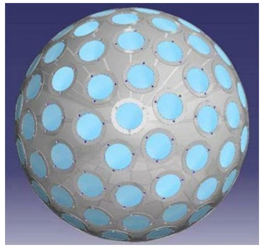


LAGEOS 1,2



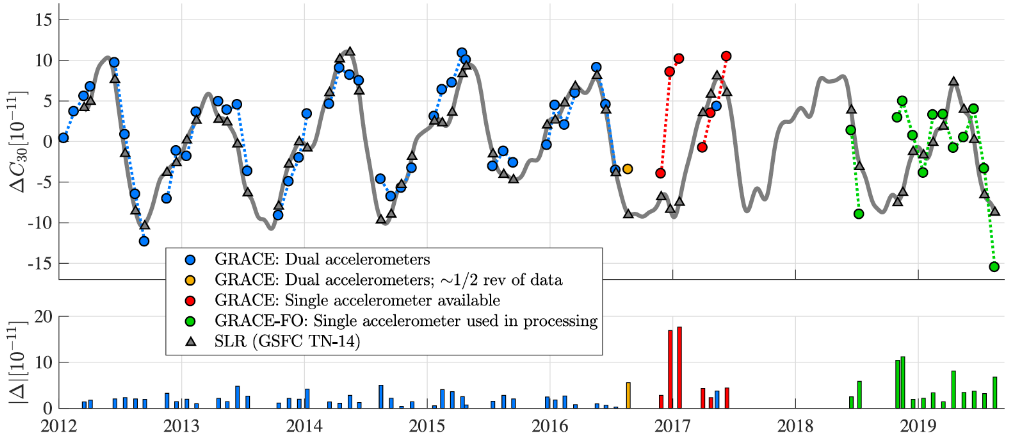
Starlette, Stella

Ajisai



LARES

C_{30} Determined from GRACE, GRACE-FO & SLR



Loomis et al., GRL, 2020, https://doi.org/10.1029/2019GL085488

- **POD for the GRACE & GRACE-FO Satellites with GNSS.**
  (GNSS POD supplies *a priori* orbits accurate to 10-15 mm radial RMS).

- **Through POD for SLR geodetic satellites to independently determine C_{20} & C_{30}.**
  (Due to problems with the precision accelerometers, GRACE & GRACE-FO solutions for the C_{20} & C_{30} coefficients are noisy and unreliable).

Antarctic ice mass loss (Aug. 2016 – Aug. 2019)
- **without SLR C_{30} Replacement: −92 Gt/yr.**
- **with SLR C_{30} Replacement: −170 Gt/yr.**

Impact of UT1 error on POD: Another example

LAGEOS 1

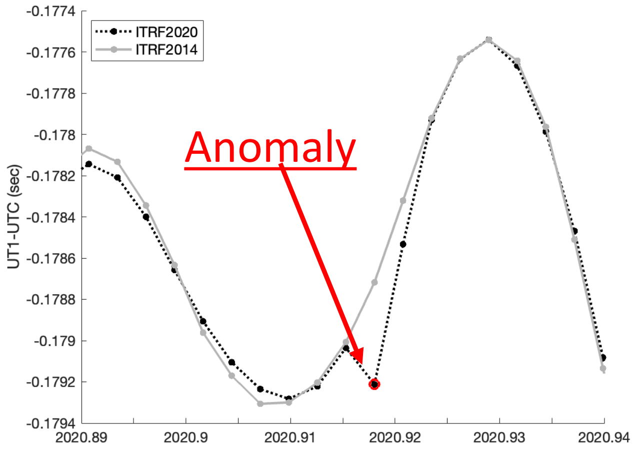
- The NASA GSFC GRACE Team is responsable for producing Technical Note 14, the monthly SLR solutions for C_{20} & C_{30} that replace the GRACE-data (KBRR)-determined monthly values.

- They recently evaluated the new IERSC04 (ITRF2020) EOP series, compared to the older series (IERSC04, ITRF2014). On 2020-DOY337 there is a difference of ~500 μsec between the new and old value of UT1-UTC that causes a degradation in the SLR fit to LAGEOS (& other satellites).

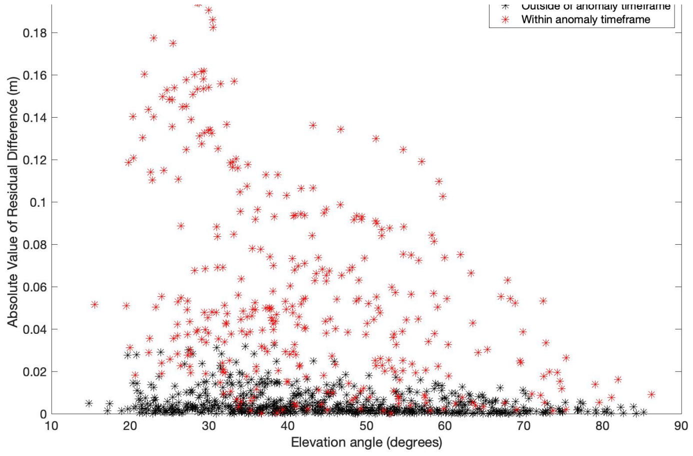
- Other than for this anomaly, on average the new EOP series improves the SLR RMS of fit by an mean of ~0.1 mm.

Example provided Bryant Loomis & Kenneth Rachlin, NASA GSFC GRACE team, Greenbelt, MD, USA

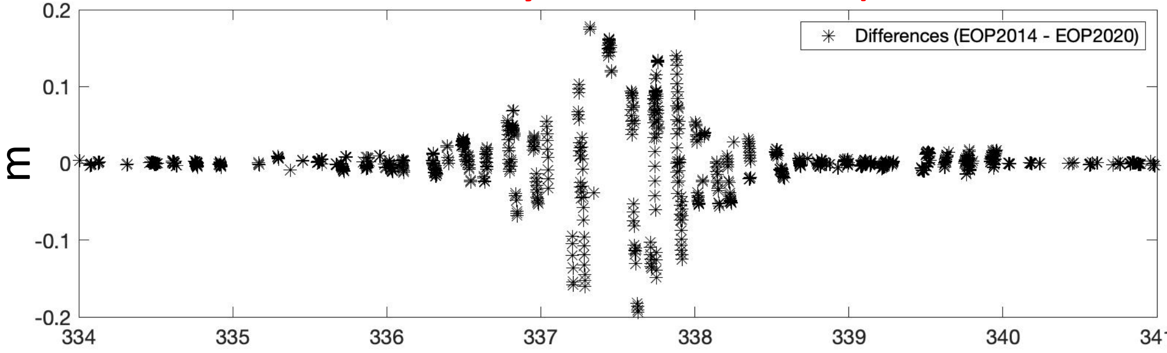
UT1-UTC: ITRF2014 Vs. ITRF2020



Residual differences vs. elevation

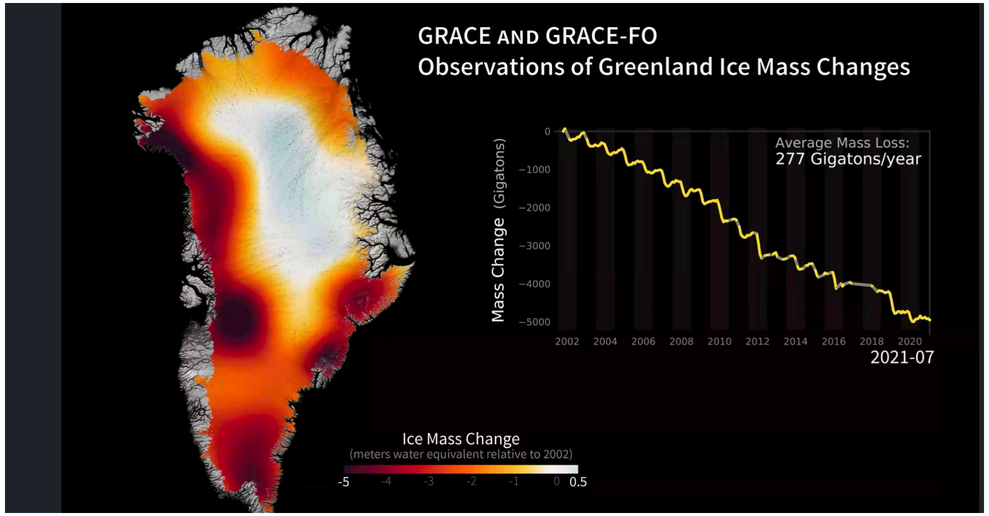


Differences in SLR Residuals for LAGEOS (EOP2014– EOP2020 For 7-day Arc 2020-DOY334)

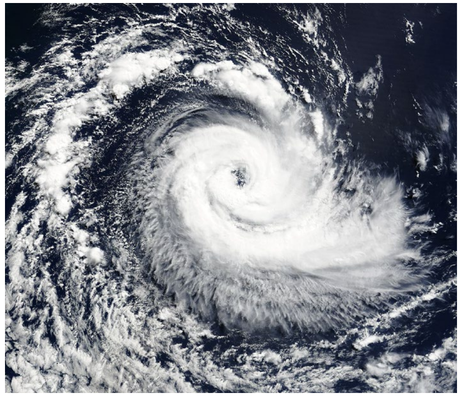


To Monitor a dynamic Earth ….

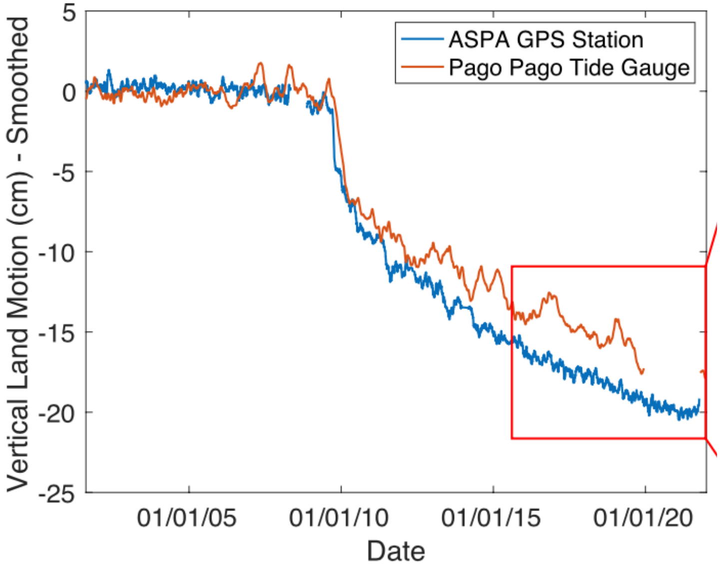
Greenland Ice mass loss (2002-2021)



Effects & impacts of extreme weather



Natural Hazards, e.g. Earthquake Impacts



Vertical Land Motion in Pago, Pago American Samoa, After the 2009 M8.1 earthquake

Huang S. et al., GRL, 2022, https://doi.org/10.1029/2022GL101363

Tidal flooding

To Monitor a dynamic Earth ….

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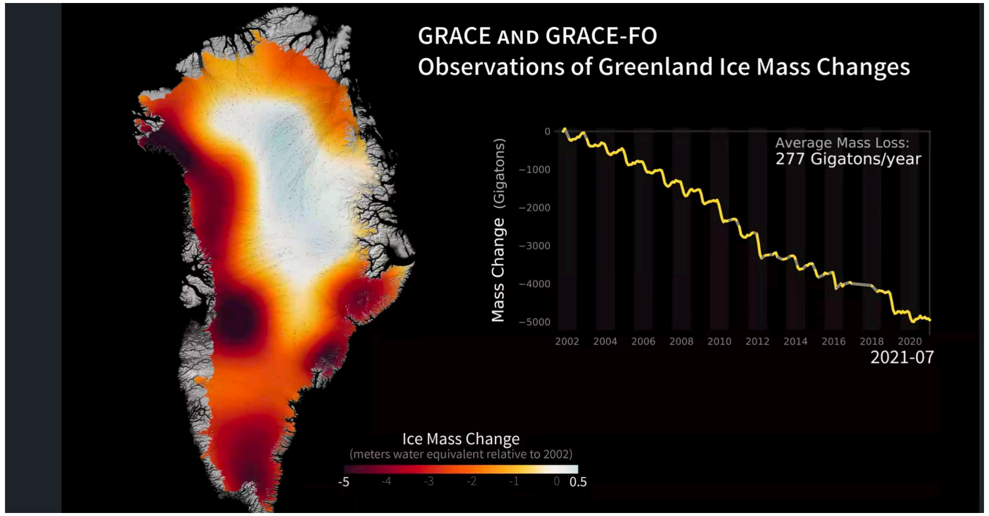

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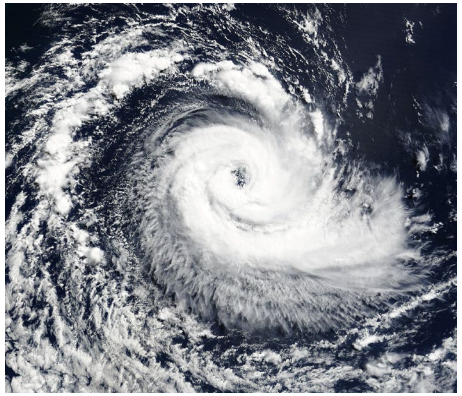

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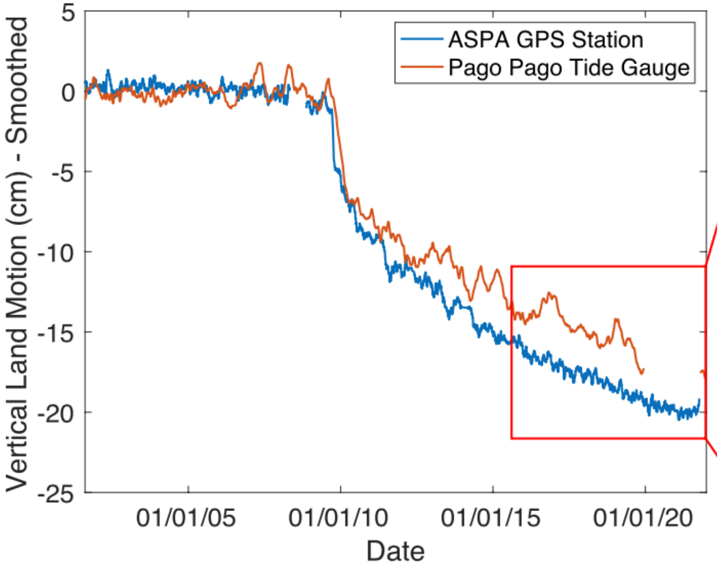


Vertical Land Motion in Pago, Pago American Samoa, After the 2009 M8.1 earthquake

Huang S. et al., GRL, 2022, https://doi.org/10.1029/2022GL101363

Tidal flooding

We need a stable & accurate global reference frame and the contributions of all the Space Geodesy techniques, including VLBI.

Backups

More information

Geodesy and the ITRF:

- **Disocover GGOS & Geodesy (~8 minute Videos)**
  - English: https://www.youtube.com/watch?v=YrekrxNiLLU
  - German: https://www.youtube.com/watch?v=6sjp4cGbKT8
  - Spanish: https://www.youtube.com/watch?v=biqkQ8Iy5rI
  - Portuguese: https://www.youtube.com/watch?v=ZTo34spW8ME
  - Japanese: https://www.youtube.com/watch?v=SQ6k64IkQ1g
  - Italian: https://www.youtube.com/watch?v=qKapCr_TM1U
  - French: https://www.youtube.com/watch?v=9CLlDXIl_al
- **Geoscience Australia Lecture Video (April 20, 2022): "The Value of Geodesy to Society"** https://www.youtube.com/watch?v=ih4nd5FNEk4

Earth Orientation Parameters:

- **IERS Earth Orientation Center:** https://hpiers.obspm.fr/eop-pc/index.php
- **USNO:** https://crf.usno.navy.mil/global-solutions-eop
- **Videos showing EOP angles from NASA GSFC:** https://svs.gsfc.nasa.gov/20196
- **Lecture "Rotation de la Terre et des planètes (**Rotation of the Earth and the Planets**), by Dr. Véronique Dehant; Royal Observatory of Belgium at the Collège de France; April 8, 2013 (**In French**).** https://www.youtube.com/watch?v=pMnPujwDb1s

The Space Geodesy Techniques:

- **Overview of SLR and the International Laser Ranging Service (ILRS):**

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

- **ILRS Virtual Station Tour 2021. Presentations & Videos:** https://ilrs.gsfc.nasa.gov/ILRS_Virtual_World_Tour_2021/Program/index.html
- **Overview of DORIS, presented at IAG/SIRGAS/GGRF Meeting, Buenas Aires, Sept 2019:** https://www.sirgas.org/fileadmin/docs/GGRF_Wksp/26_Soudarin_et_al_2019_DORIS_and_IDS.pdf
- IDS Website: https://ids-doris.org/
- **Technical Mini-workshop Series and Presentations on GNSS & the IGS:** https://igs.org/tour-de-ligs/presentations/

The Geodetic Measurement System for the TRF

VLBI
- Orientation of ITRF with respect to ICRF
- ITRF Scale

SLR
- Origin of ITRF (Earth’s CM)
- ITRF Scale
- Position spacecraft in ITRF (“Orbits”)

GNSS
- Precise monitoring of Polar Motion and Rotation Rate
- Position spacecraft in ITRF (“Orbits”)
- Position instruments on Land and Sea (Tide Gauges and Buoys, Geodetic Instruments)

DORIS
- Position spacecraft in ITRF (“Orbits”)
- Enhances global distribution of ITRF Station positions and velocities

Technique Connectivity (Station Co-Location)

Fully Define ITRF

Origin, Scale, Orientation

VTS: ITRF Performance Improvement

Low-Density Global Distribution

High-Density Global Distribution

Impact of UT1 error on POD: A concrete example

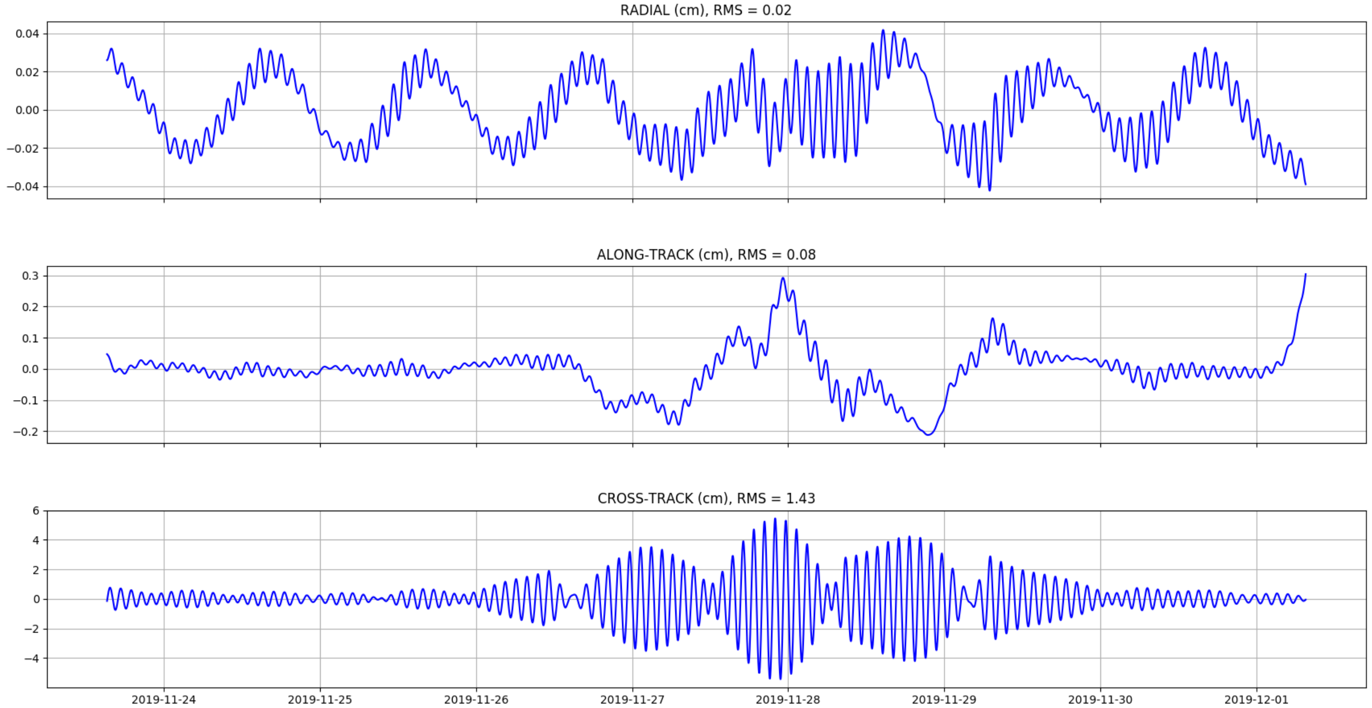
CryoSat-2

- At the end of November 2019 the CNES POD team noticed an unusual increase in the cross-track orbit differences between the CNES POE dynamic and reduced-dynamic solutions, for all altimeter satellites, whatever the tracking system used (**DORIS or GPS**).

- Looking at the official IERS14 C04 solution for UT1, it appeared that a change had occured for UT1 over 27-28-29 November 2019 in the IERS EOP file. Those differences in UT1 ranged from 100 μsec to 500 μsec.

- An updated file was later provided, which allowed to compute the POD differences. This change was documented with an IERS Message (No. 392) on January 09, 2020.

Unusual increase in cross-track error for CryoSat-2 dynamic orbits (± 5 cm or 1.42 cm RMS over the data arc).



CNES CENTRE NATIONAL D'ÉTUDES SPATIALES

Example provided by Alexandre Couhert & Sabine Houry, CNES POD Team, Toulouse, FR