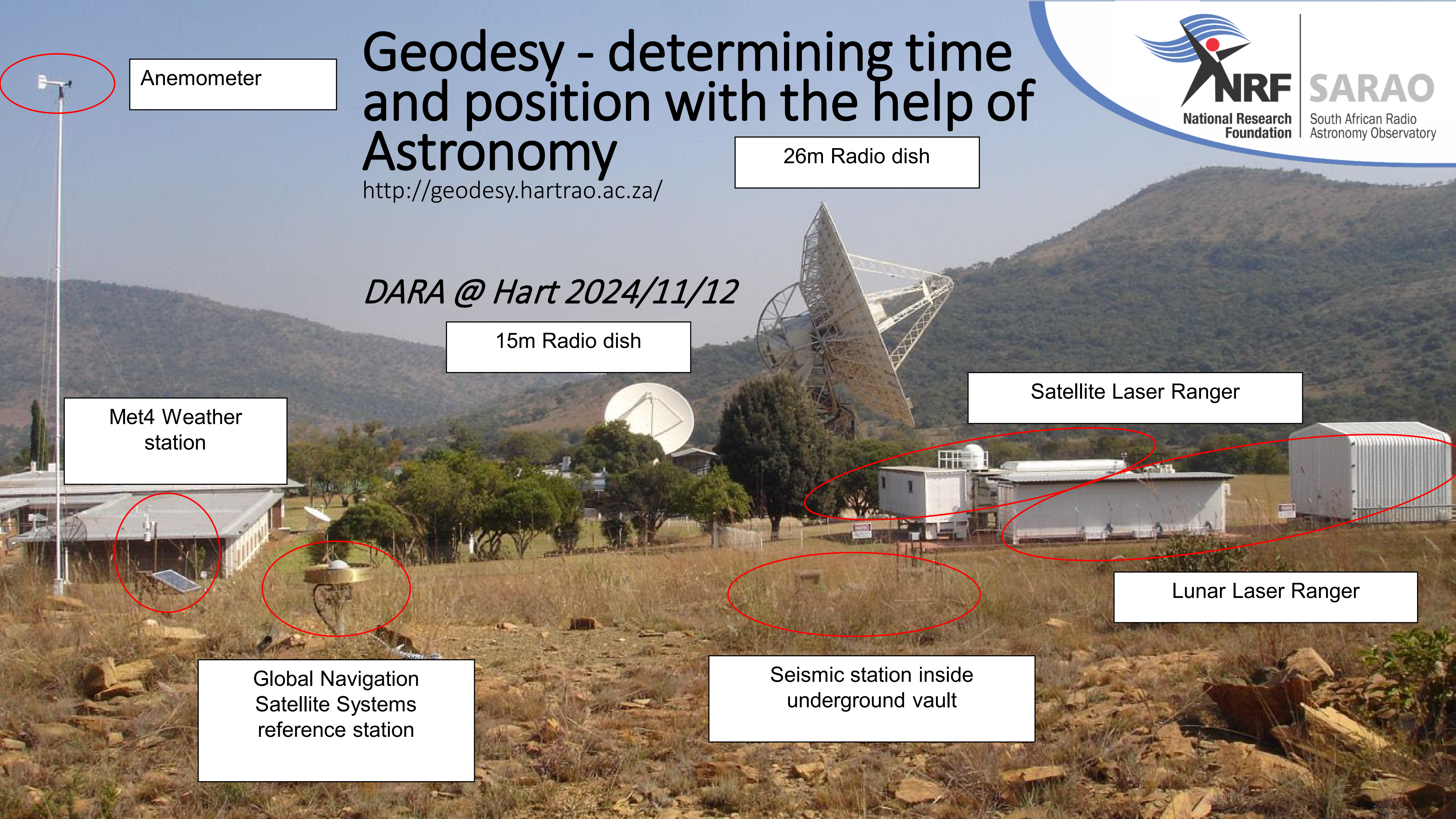
Geodesy - determining time and position with the help of Astronomy

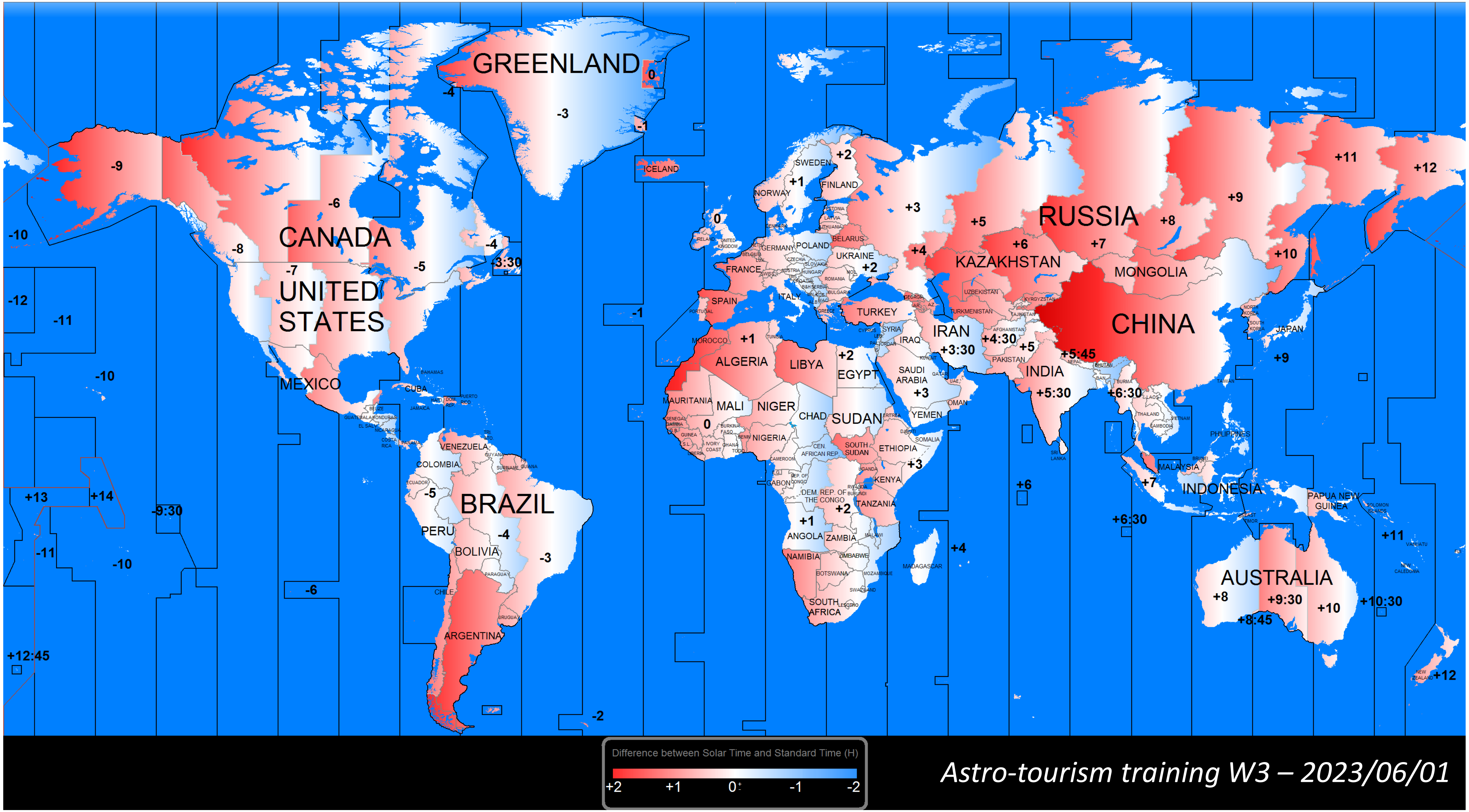
http://geodesy.hartrao.ac.za/

DARA @ Hart 2024/11/12

NRF National Research Foundation | SARAO South African Radio Astronomy Observatory



1 -Using Astronomy to help define position and time on Earth



Astro-tourism training W3 – 2023/06/01

Overview

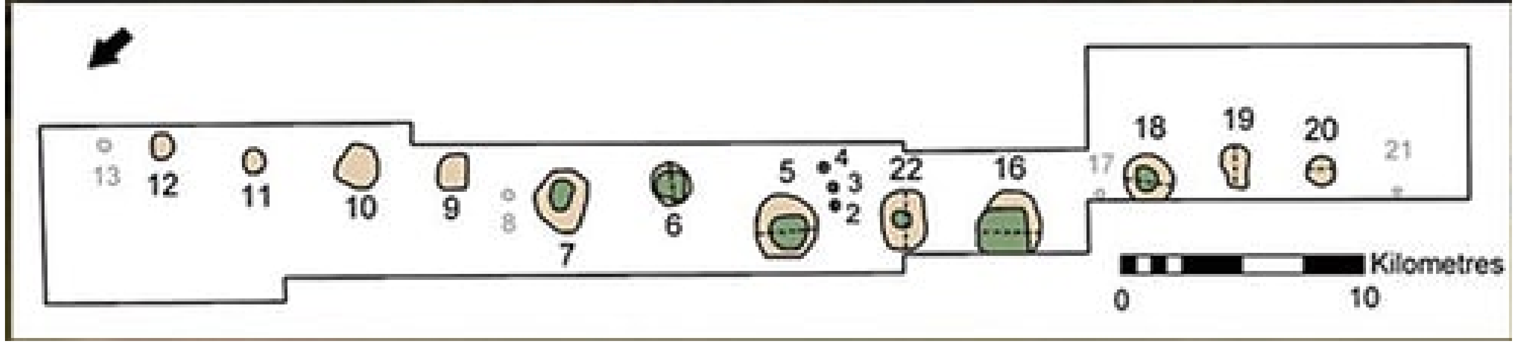
- The first astronomers
- Time and positions on Earth as defined using Astronomical objects
- Exploration and navigation
- Where we are today

Some of the first Astronomers ?

Farmers ‘navigating’ the seasons

- Early farming societies at the mercy of the seasons
- Recognized that the Sun and stars had repeating patterns, coinciding with the seasons
- Early civilizations built elaborate structures to determine when the Sun is at a specific point in the cycle

Astronomy timeline



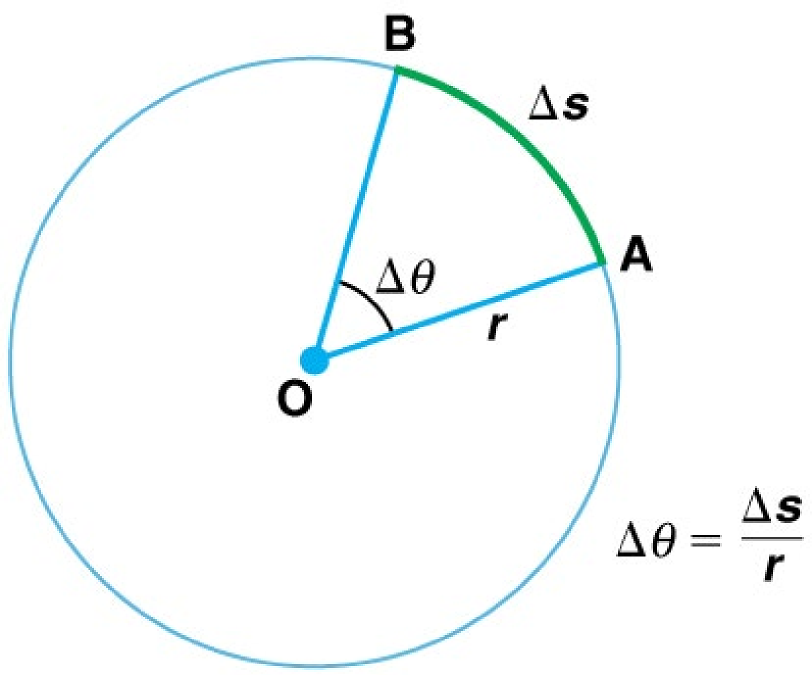
- 8000 BC: Warren Field lunar calendar
- 750 BC: Mayan astronomers discover the 18.6 year cycle of the Moon
- 400 BC: Babylonians use the zodiac to divide the heavens in 12 equal segments of 30 degrees each
- 270 BC: Aristarchus proposes heliocentric model
- 4 BC: First stellar catalogue by Shi Shen
- 400 AD: The *Surya Siddantha* depicts a sidereal year as 365.2563627 days (1.4 seconds longer than the modern value)
- 1610 AD: Galileo Galilei among the first to use a telescope, promotes the heliocentric model
- 1932 AD: Karl Jansky detects the first radio waves coming from space, 1942 radio waves of the Sun, 1949 radio waves from intra- and extra-galactic sources
- 1967 AD: Jocelyn Bell Burnell and Anthony Hewish detects the first pulsar

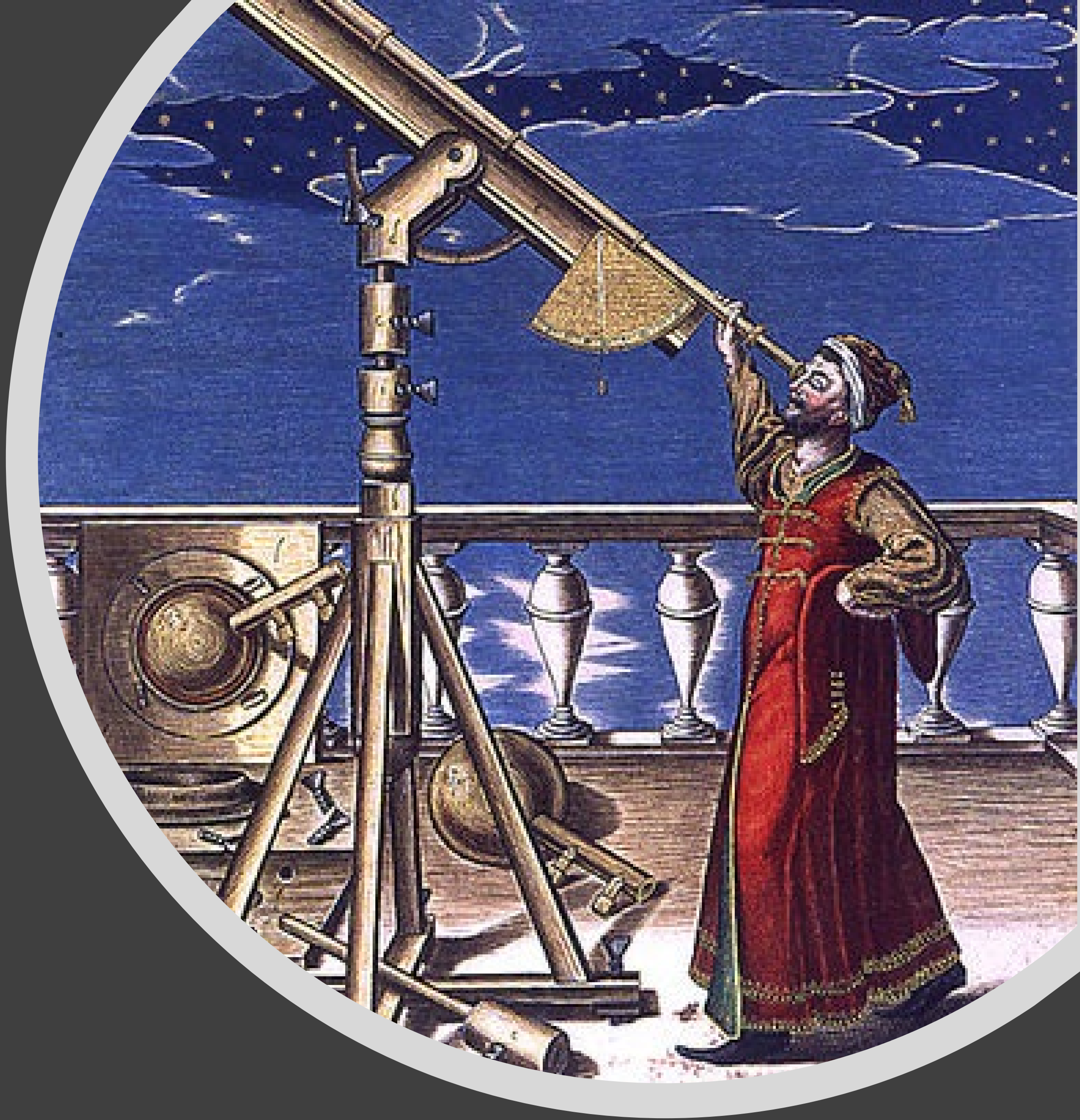
Astronomers need to know…

- the position from which they observe
- the local time,

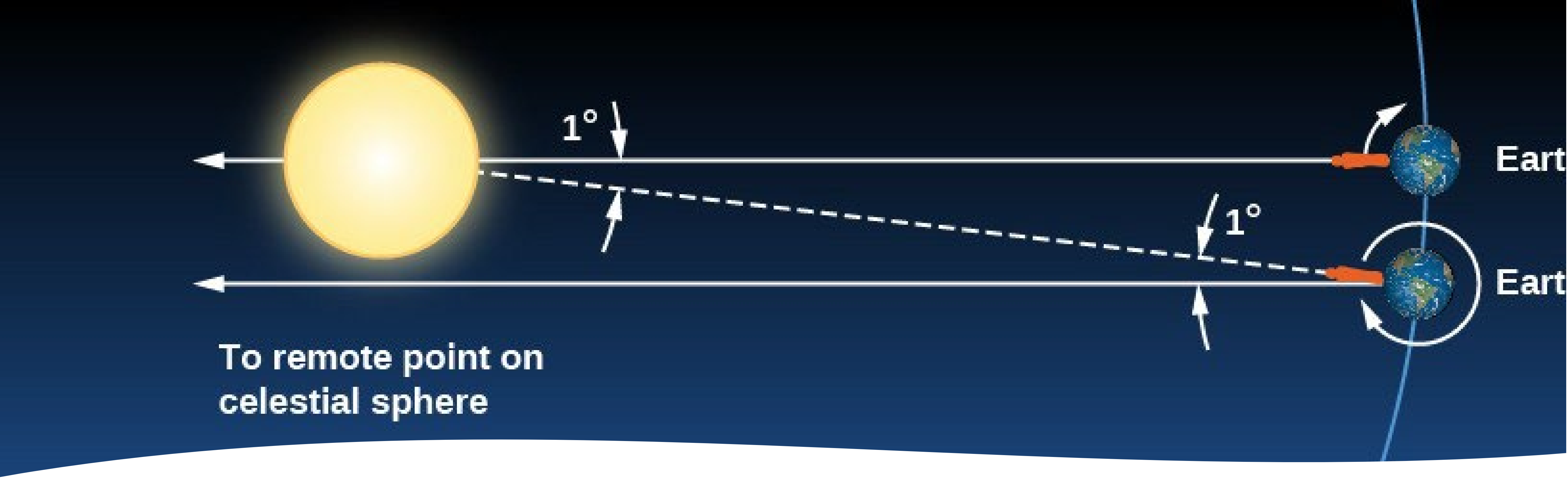
to be able to find celestial objects…

Q: Which is the most critical?





Time and positions on Earth as defined using Astronomical objects



Length of Day

- The most fundamental astronomical unit of time
- Measured in terms of the rotation of the Earth

- For most people this is with respect to the Sun, our closest star – solar day
- For astronomers this is with respect to the distant stars – sidereal day

Apparent and Mean Solar time

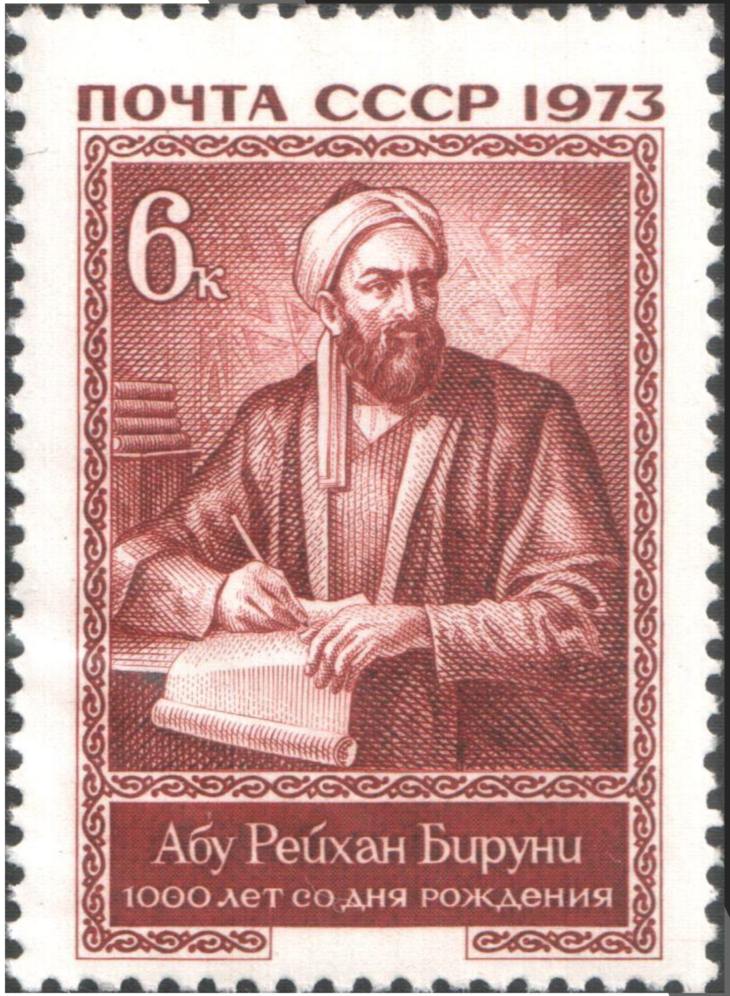
Apparent solar time is determined by the actual position of the Sun (in the sky or below the horizon)

- Midday is defined when the Sun passes through the local meridian – the great N-S circle in the sky that passes through our zenith.
- Exact length of day varies slightly during the year

Mean Solar time:

- Based on the average value of the solar day over the course of a year – 24 hours

Q: Is this sundial in the Northern or Southern hemisphere?

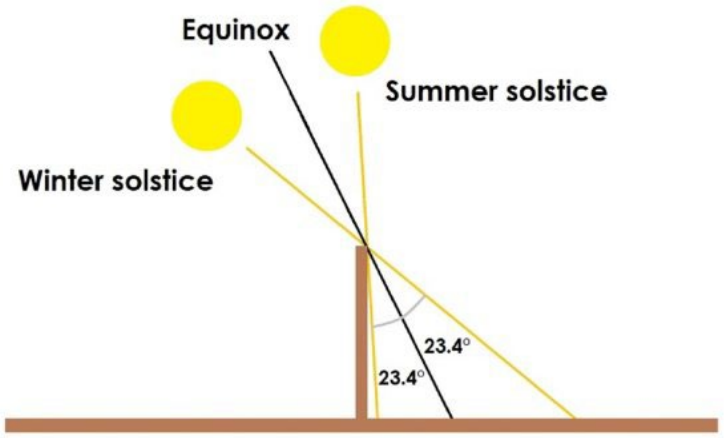


Latitude and Longitude

- 5th century BC: Ancient Greek philosophy conceptualises the round Earth
- 3rd century BC: Eratosthenus proposed a system of latitude and longitude
- 2nd century BC: Hipparcus the first to use such a system to uniquely specify places on Earth – he also proposed longitude determination by comparing local time of a place with absolute time
- 11th century AD: **Al-Biruni** believed the Earth rotated on it's axis and this forms our modern notion of how time and longitude are related

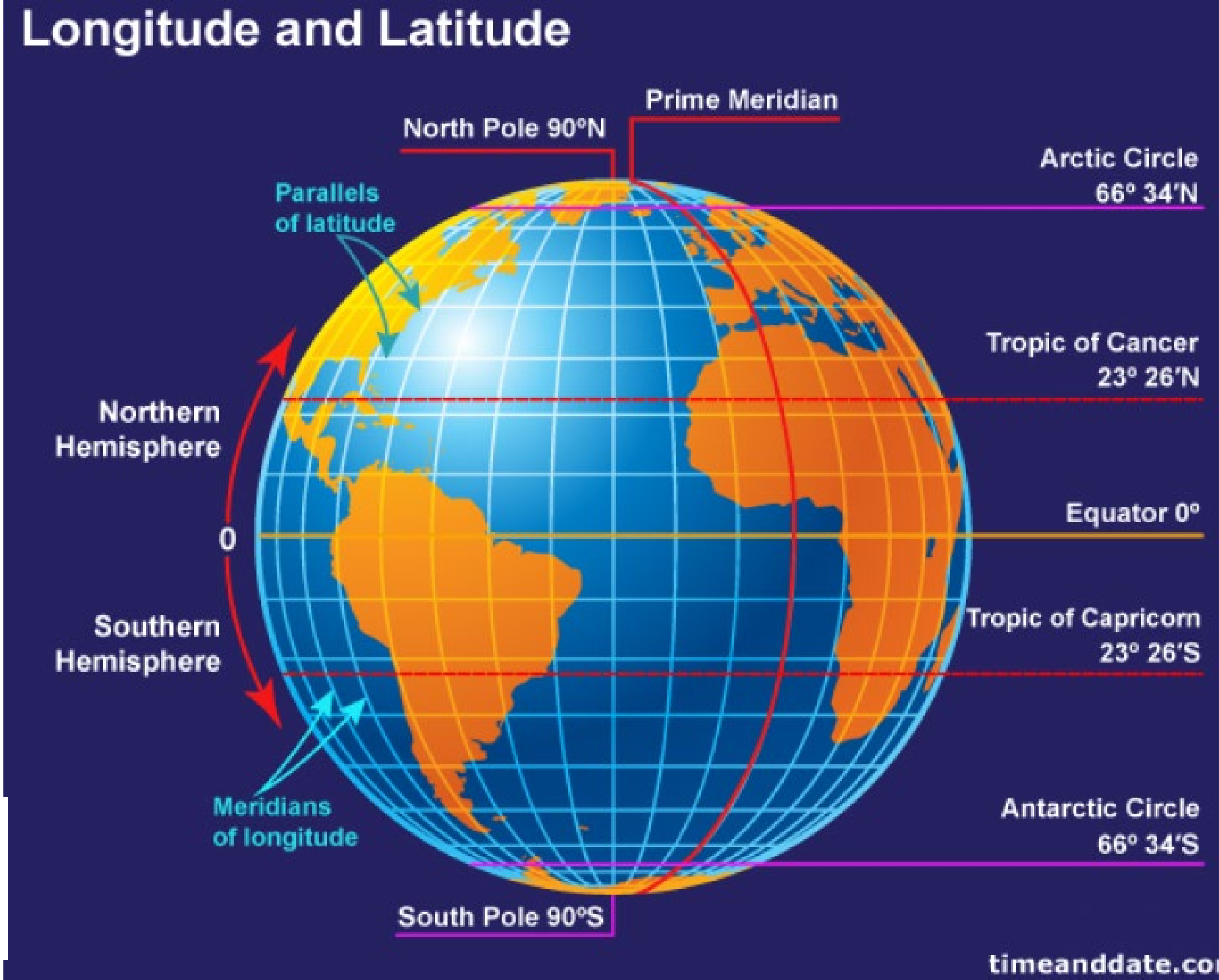
Latitude and Longitude

Equinox (equal night): March and September, when the Sun is exactly above the Equator – signifies the start of the next season

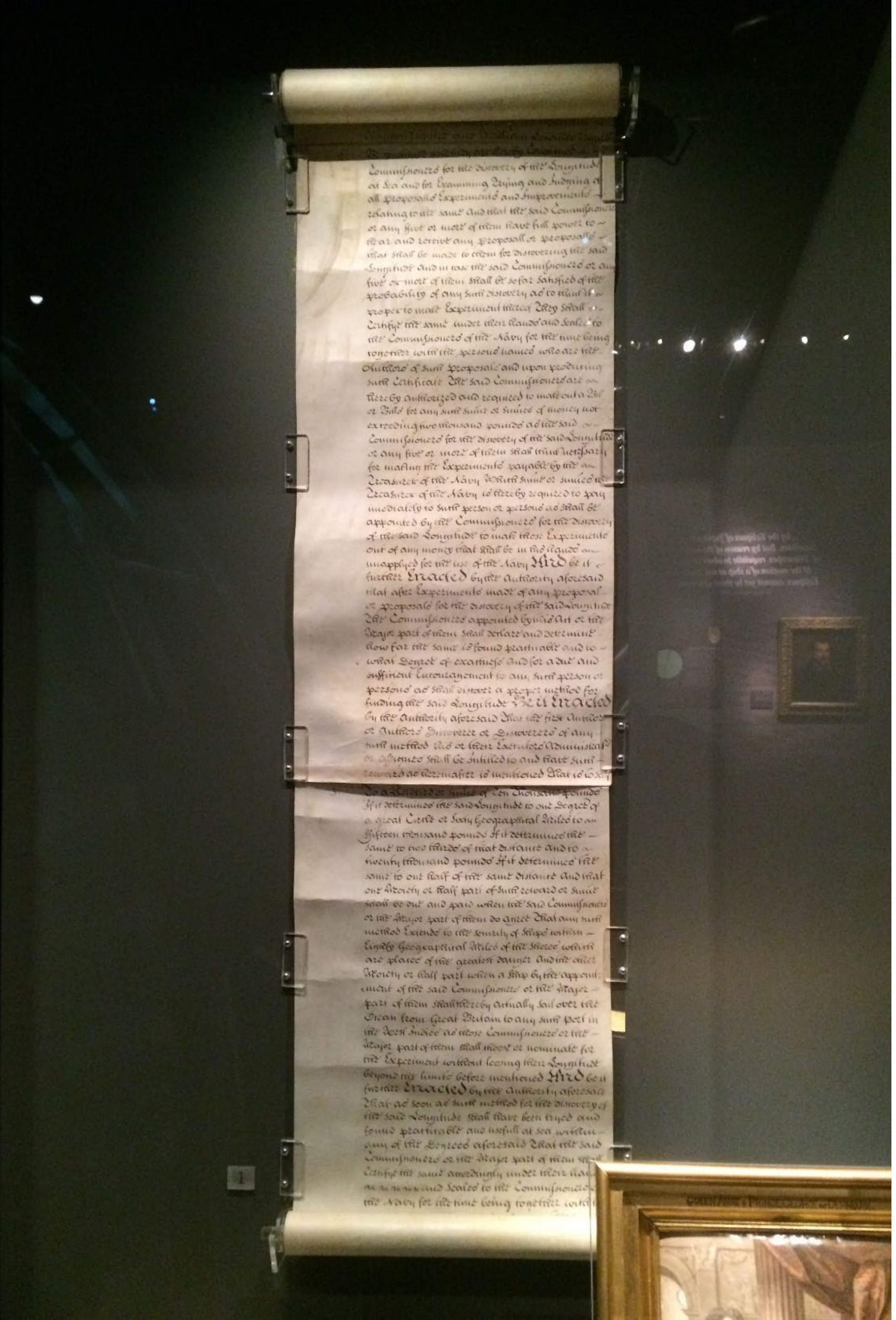


Q: Our location?

Receiver	Position
PolaRx5-3052128 (hrtb)	Lat: S25°53'24.3004" 0.903m
IP Address (Eth): 10.254.1.5	Lon: E27°41'13.0649" 0.725m
Uptime: 17d 10:01:09	Hgt: 1432.669m 1.910m



Exploration
&
navigation

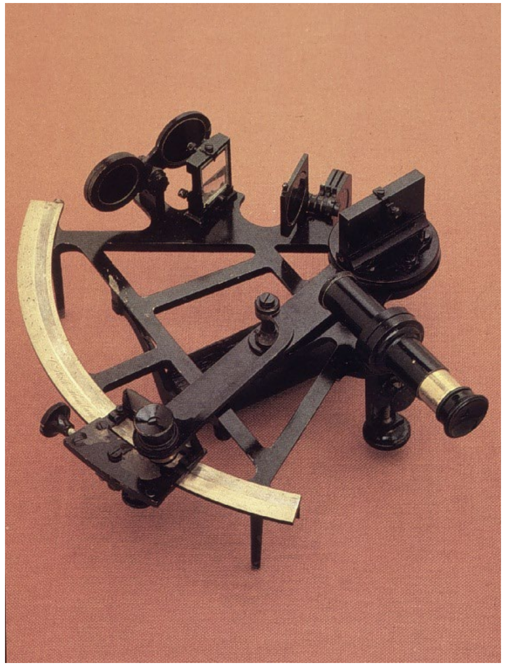


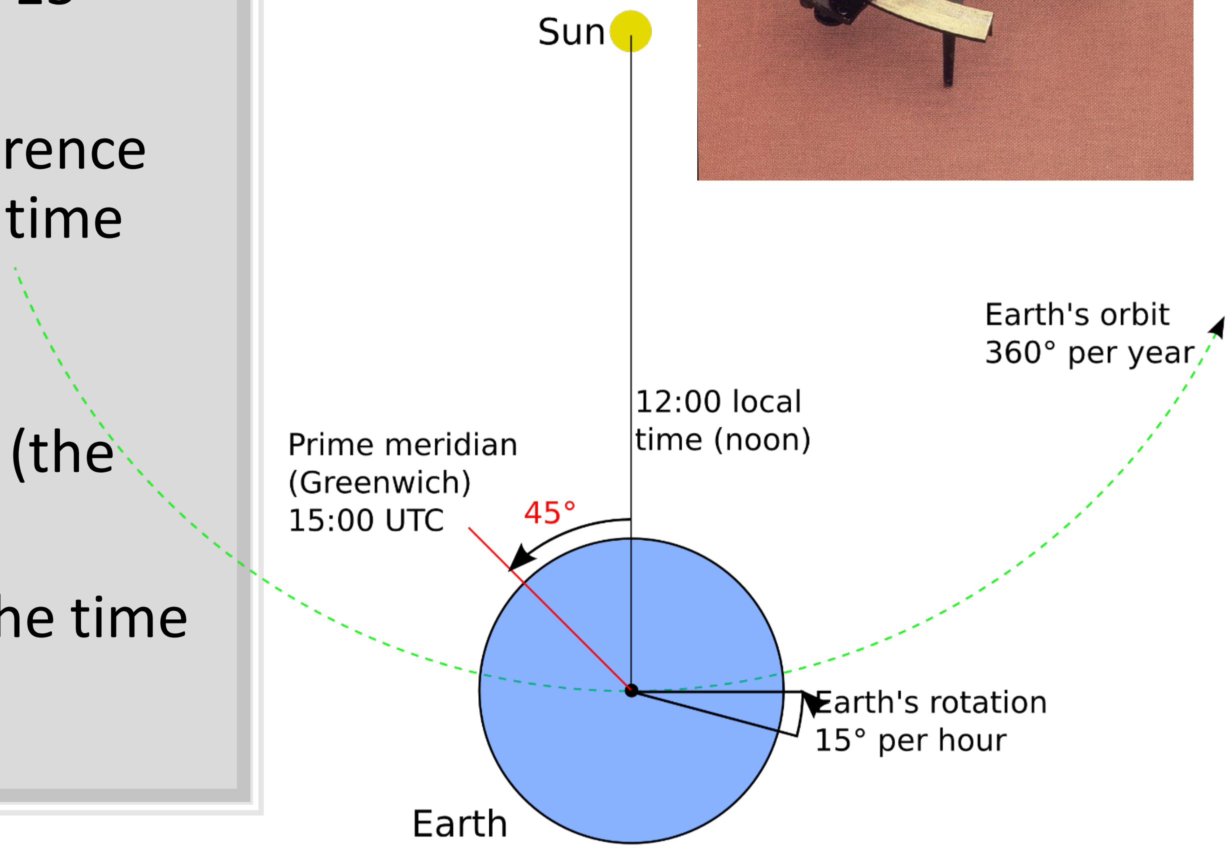
Latitude and Longitude

- **Latitude** can easily be determined from:
  - the altitude of the Sun at noon,
  - or from stars at night.
- **Longitude** was determined by dead reckoning (calculate current position by using the previous value and advancing it for an estimated speed over a certain time) – cumulative errors!
  - Much harder while at sea than on land
  - Sailors would sail to latitude of destination, and then follow that latitude E or W *(running down a westing or easting*)
  - Errors in longitude led to many disasters
  - 1714: British government establishes the Board of Longitude. Prizes were offered for the discovery and demonstration of a practical method to determine longitude while at sea.

Time equals longitude…

- Local solar time varies by one hour for every 15 degrees change of longitude
- If the navigator knew the time at a fixed reference point, the difference between the reference time and the apparent local time would give the position relative to the fixed reference point
- Finding apparent local time is relatively easy (the Sun, the Moon and stars)
- The problem, ultimately, was to determine the time at the reference point…





Proposed methods of determining time

- 1514 AD: Johannes Werner proposes using the Moon – tedious calculations
- 1612 AD: Galileo proposes the Jovian (Jupiter's) moons – difficult from the deck of a ship, rather used on land
- 1683 AD: Halley proposed lunar occultations, appulses, magnetic deviation – never used due to inaccuracies
- 1755 AD: Tobias Mayer proposed Lunar distances (based on motion of the Moon) – labour intensive
- 1766 AD: Nevil Maskelyne refined this to a **pre-calculated** *nautical almanac*, published first for data of 1767. Since this was based on the Royal Observatory as the 'reference point', it later led to the *Greenwich Meridian*

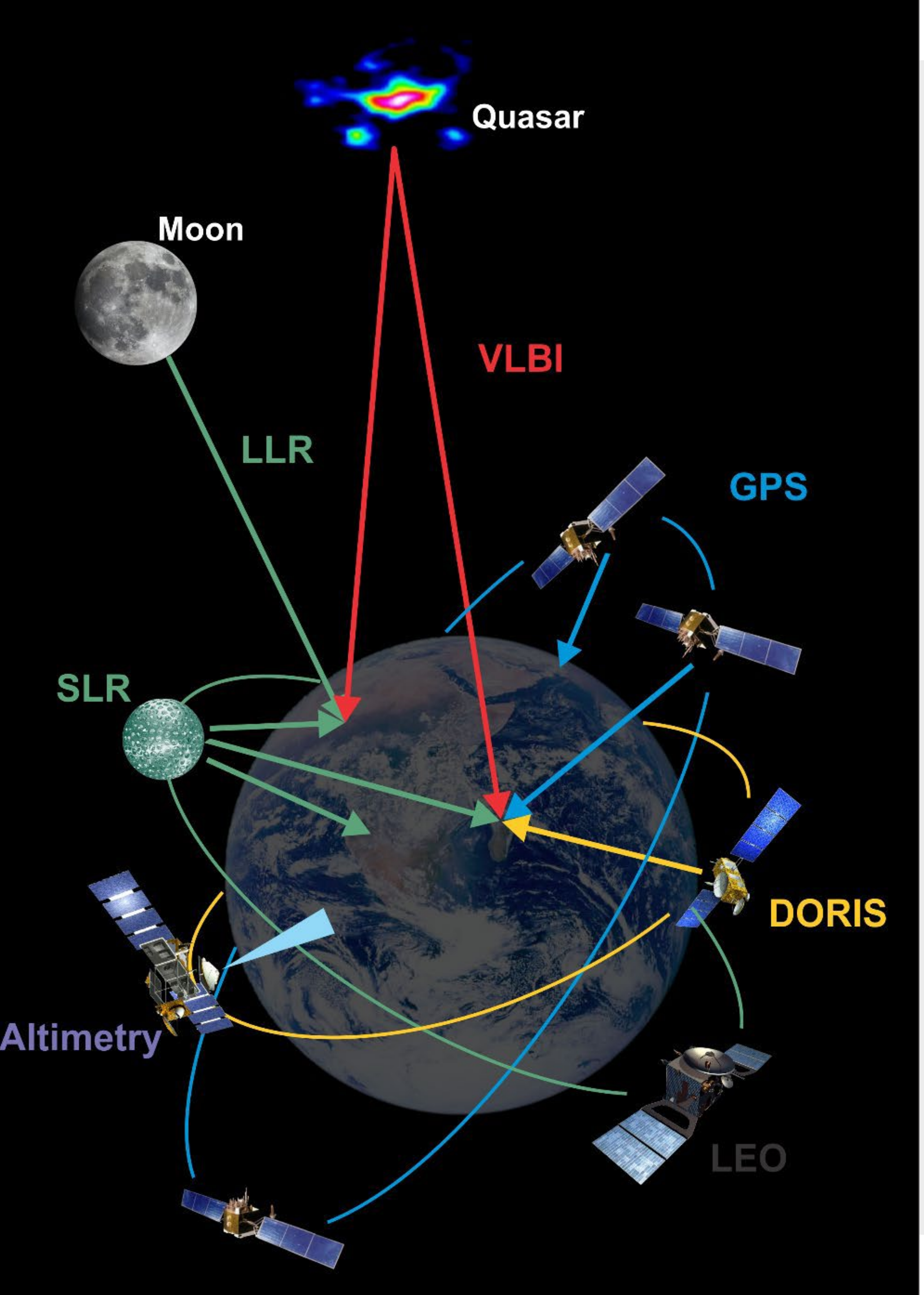
The age of the chronometer…

- 1773 AD: John Harrison awarded the the Longitude Prize by the British Parliament for his H-4 chronometer, but very expensive
- 1836 AD: Thomas Earnshaw made a chronometer suitable for general nautical use, still very expensive
- BUT – the Nautical Almanacs were still generally used for several decades and as late as 1906 AD
- By 1850: Chronometers used more widely, but ideally 3 per vessel:
  "Never go to sea with 2 chronometers; take one or three"
- Some vessels like the HMS Beagle carried 22 chronometers

Modern clocks and clock signal distribution

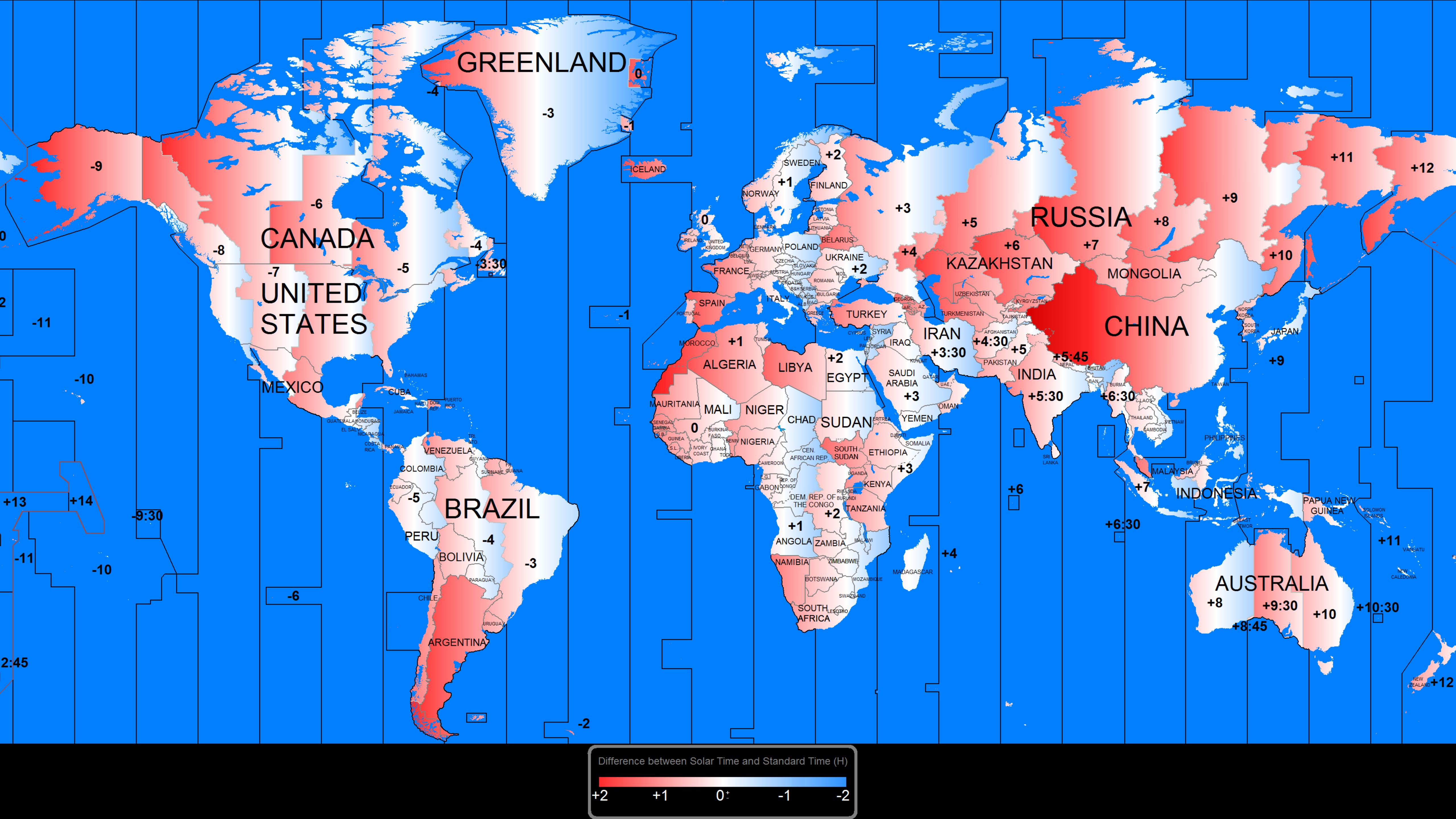
- 1865 AD: Telegraph signals for time coordination between astronomers
- 1904 AD: Wireless telegraphy used for time signals, to correct on-board chronometers
- 1972 AD: Hamilton introduced the first commercial electronic digital wristwatch (driven by a crystal oscillator)
- 1980 AD: GPS-provided time (and position)

Where we are today



- VLBI (with Radio Antennas) provides the most precise positions on Earth's surface – it is one of the most accurate measurement methods known to science
- VLBI is used to determine the Earth Orientation Parameters (EOPs), which are used for example by astronomers and for spacecraft navigation
- Pulsars are highly-accurate clocks in space
- So from Astronomy we get to Geodesy –

  "the science of accurately measuring and understanding Earth's dynamic shape, orientation in space and gravitational field…. relying on datums and coordinate systems"


GREENLAND
CANADA
UNITED STATES
MEXICO
CUBA
VENEZUELA
COLOMBIA
BRAZIL
PERU
BOLIVIA
CHILE
ARGENTINA
ICELAND
SWEDEN
NORWAY
FINLAND
POLAND
GERMANY
FRANCE
SPAIN
ITALY
UKRAINE
BELARUS
TURKEY
RUSSIA
KAZAKHSTAN
MONGOLIA
CHINA
JAPAN
IRAN
IRAQ
SYRIA
SAUDI ARABIA
YEMEN
OMAN
PAKISTAN
INDIA
MOROCCO
ALGERIA
LIBYA
EGYPT
MAURITANIA
MALI
NIGER
CHAD
SUDAN
SOUTH SUDAN
NIGERIA
ETHIOPIA
SOMALIA
KENYA
TANZANIA
DEM. REP. OF THE CONGO
ANGOLA
ZAMBIA
NAMIBIA
BOTSWANA
SOUTH AFRICA
MADAGASCAR
MALAYSIA
INDONESIA
PHILIPPINES
PAPUA NEW GUINEA
AUSTRALIA
NEW ZEALAND
Difference between Solar Time and Standard Time (H)
+2
+1
0
-1
-2

2 - Geodesy for establishing and maintaining Terrestrial Reference Systems

National Research Foundation | SARAO South African Radio Astronomy Observatory

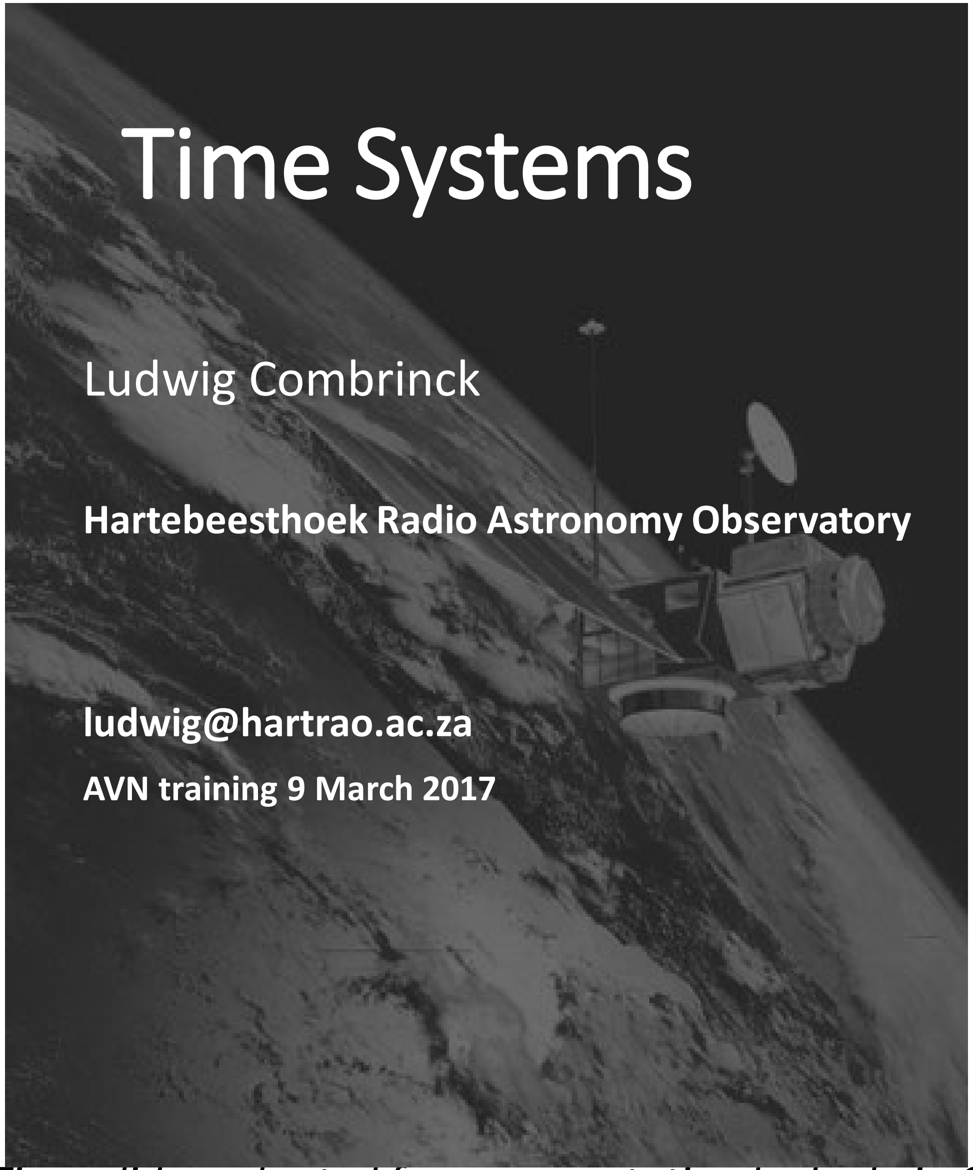
Roelf Botha

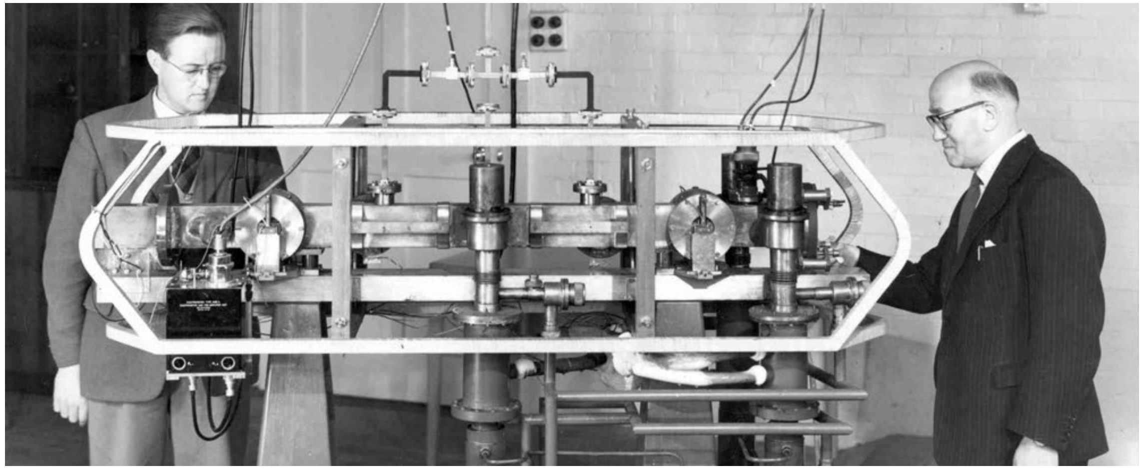
Manager: Geodesy

OVERVIEW

- Time
- What is Geodesy?
- SARAO Geodesy activities on- and off-site
- The international geodesy network and related products
- Societal benefits

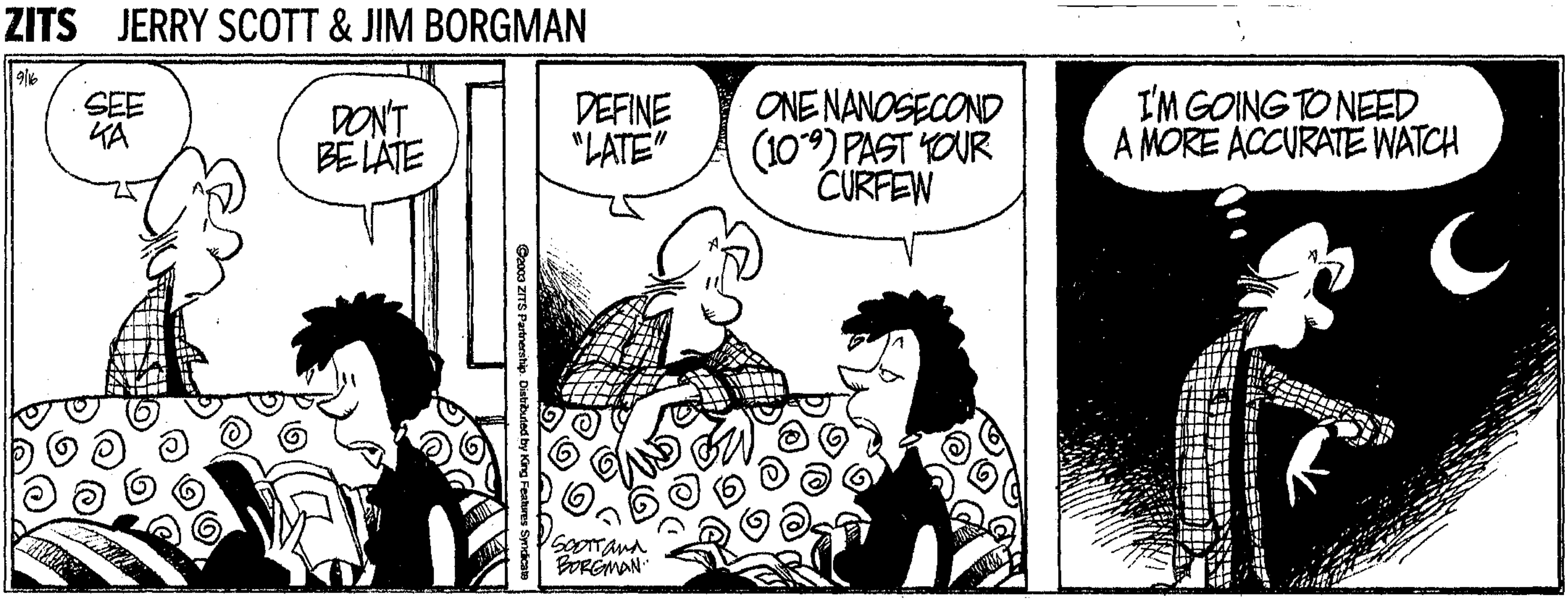
The previous message – TIME





Time-slides adapted from presentation by Ludwig Combrinck: Time Systems, presented at AVN Training School, 9 March 2017, Hartebeesthoek Radio Astronomy Observatory

The previous message – TIME

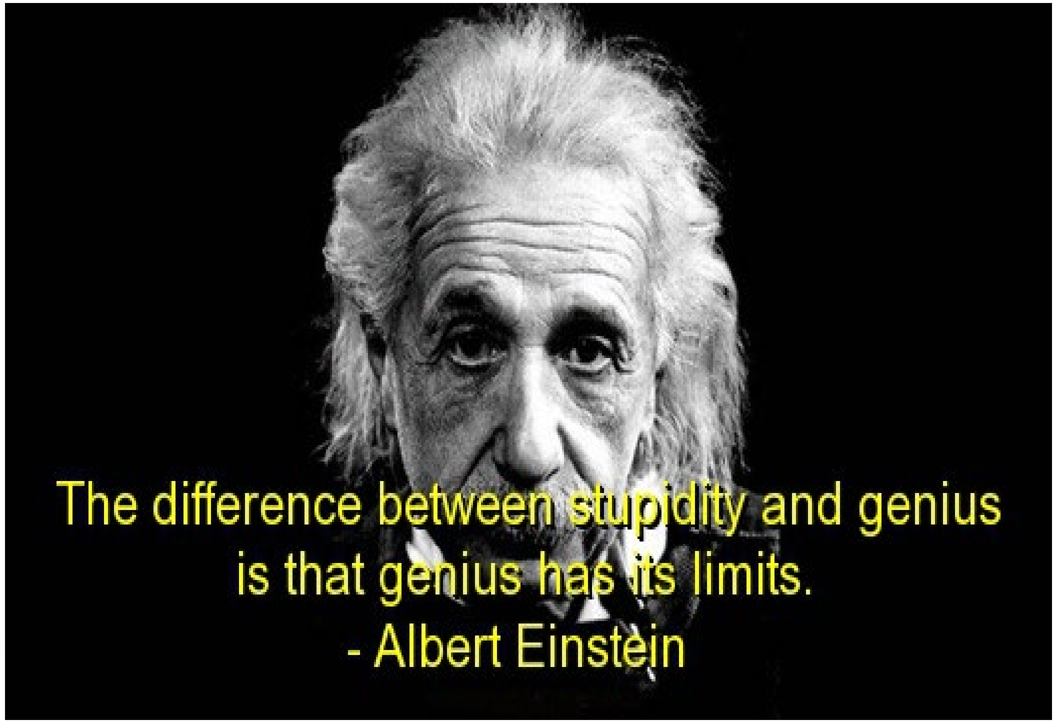


TIME

Wikipedia:

Time is a measure in which events can be ordered from the past through the present into the future, and also the measure of durations of events and the intervals between them. Time is often referred to as the fourth dimension, along with the three spatial dimensions.

So we all have an idea what time is, until we are asked to explain it…but that's OK.



TIME – Practical Time Systems

There are several time systems used in astronomy and navigation.

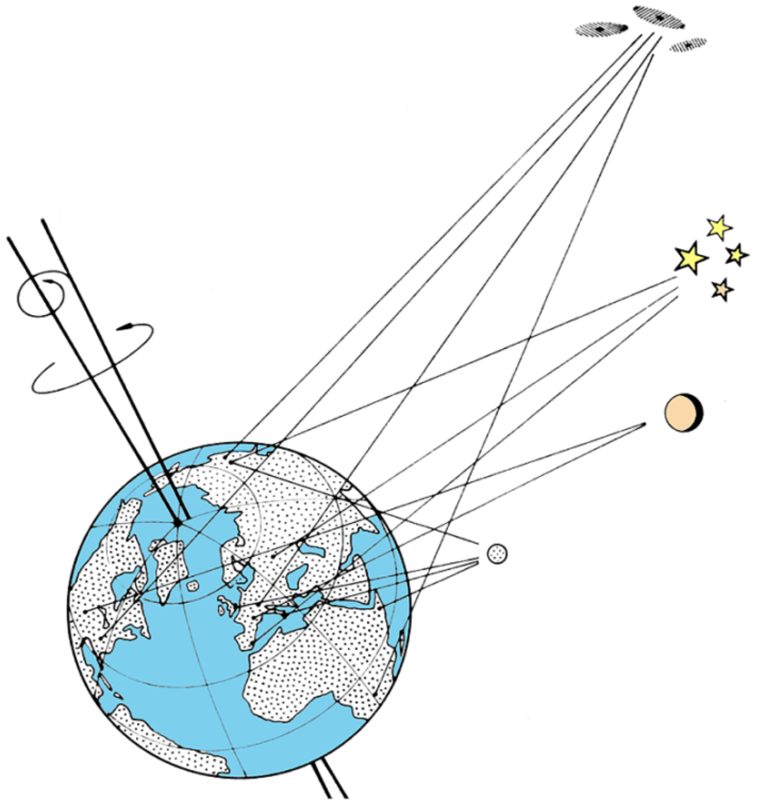
- Time as seen on your watch is related to Universal Time Coordinated (UTC). Previously called Greenwich Mean Time (GMT)
- UTC is based on atomic time standards (cesium/maser clocks) and is based on the averaged time of atomic clocks (~400) operated globally.
- The International Earth Rotation Service (IERS) coordinates these activities and publishes corrections to the time systems operated in each country. The IERS was established in 1987 by the International Astronomical Union and the International Union of Geodesy and Geophysics, it provides data on Earth orientation, on the International Celestial Reference System/Frame, on the International Terrestrial Reference System/Frame, and on geophysical fluids. It maintains also Conventions containing models, constants and standards.

TIME - Systems

- Time as defined by atomic clocks has a constant rate.
- As we live on Earth, our perception of time is linked to the rotation of the Earth.
- This rotation rate is not uniform. Compared to UTC the Earth "clock" loses 1 second every 18 months; this is not uniform either as there are fluctuations due the exchange of angular momentum, resulting from mass movement of the Earth (atmospheric winds, processes in the fluid core). The 1 sec/18mths is an accumulative effect due to Earth-Moon gravitation coupling that causes the Earth to rotate slower by 1.7 ms per century (the reason for leap seconds).
- Time defined by the rotation of the Earth is called UT1 and realizes the mean solar day. A solar-day is the average time it takes for the Sun to move from midday to midday. Mean solar time is the hour angle of the mean Sun plus 12 hours; this is realized by the UT1 time scale.
- Currently, UT in relation to International Atomic Time (TAI) is determined by Very Long Baseline Interferometry (VLBI) observations of quasars, and can determine UT1 to within 4 milliseconds.

TIME – Universal Time (UT)

- Time measured by the Earth's rotation with respect to the Sun
  - Elementary conceptual definition based on the diurnal motion of the Sun
  - Mean solar time reckoned from midnight on the Greenwich meridian
- Traditional definition of the second used in astronomy
  - Mean solar second = 1/86 400 mean solar day
- Three Forms
  - UT1 is measure of Earth's rotation angle
    - Defined
      - By observed sidereal time using conventional expression
        - GMST= f_1(UT1)
      - by Earth Rotation Angle
        - q = f_2(UT1)
  - UT0 is UT1 plus effects of polar motion
  - UT2 is UT1 corrected by conventional expression for annual variation in Earth's rotational speed



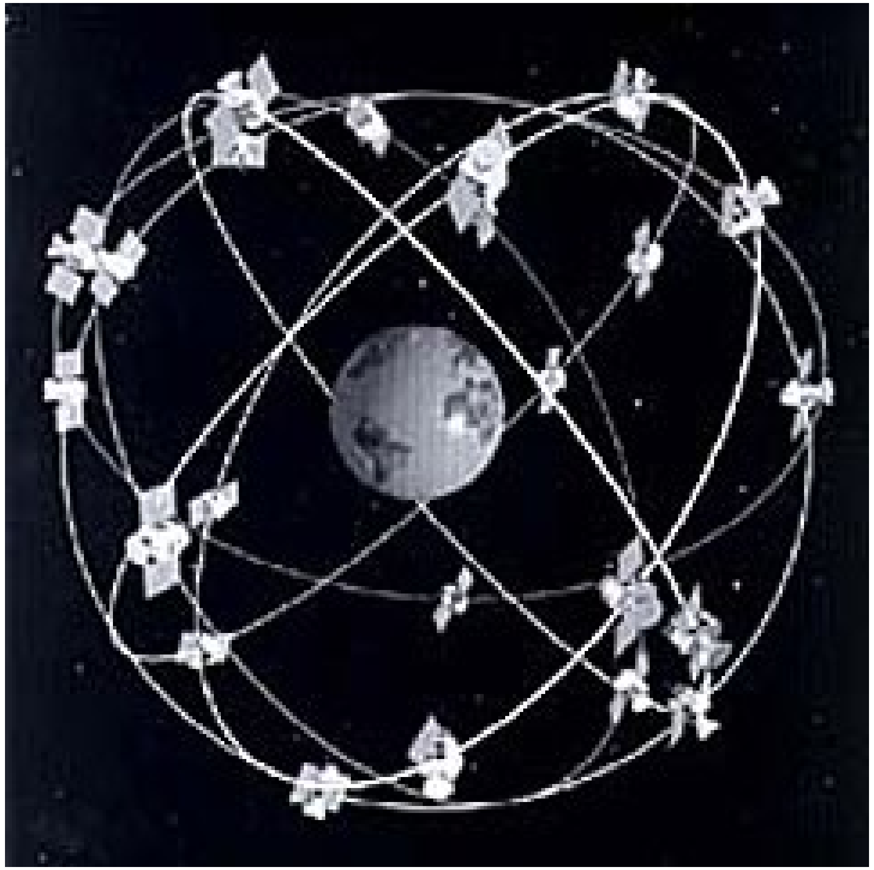
TIME – GPS System Time

- ***Each satellite carries a suite of cesium or rubidium atomic clocks***
- ***Satellite and global tracking network atomic clocks are used to form a common statistical time scale known as GPS Time***
- ***No leap seconds***
- ***Origin is midnight of January 5/6, 1980 UTC***
- ***Steered to within 1 μs of UTC(USNO), except no leap seconds are inserted***
- ***Relationships with TAI and UTC (within statistical error)***
- ***GPS Time = TAI – 19 s = constant***

- Re-computed every 15 minutes based on satellite ranging measurements made by GPS monitor stations
- OCS software estimates clock differences of GPS satellite and monitor station clocks
- Satellite clock differences uploaded to each satellite approximately once a day
- The additional correction contained in the GPS broadcast message allows a GPS timing user to produce TAI or UTC time.

TIME - Implementing GPS Time

- USNO continuously monitors GPS satellites
  - Provides GPS Master Control Station differences between GPS Time and UTC(USNO)
- Master Control Station Kalman Filter (MCSKF) generates clock solutions to minimize UTC(USNO)-GPS
- Corrections to create both GPS Time and GPS's delivered prediction of UTC(USNO) are applied in GPS receiver by applying correction contained in the GPS data message
- VLBI stations use GPS to steer maser clocks, we are therefore linked to USNO(UTC).



TIME - What Timing Performance Does VLBI need?

- The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the two oscillators at the ends of the interferometer to maintain relative stability of

$$\approx [10°/(360° \blacklozenge 10^{10}\text{Hz} \blacklozenge 10^{3}\text{sec})] \approx 2.8 \blacklozenge 10^{-15} \text{ @ 1000 sec}$$

- In Geodetic applications, the station clocks are modeled at relative levels ~30 psec over a day $\approx [30 \blacklozenge 10^{-12}/86400 \text{ sec}] \approx 3.5 \blacklozenge 10^{-16}$ @ 1 day

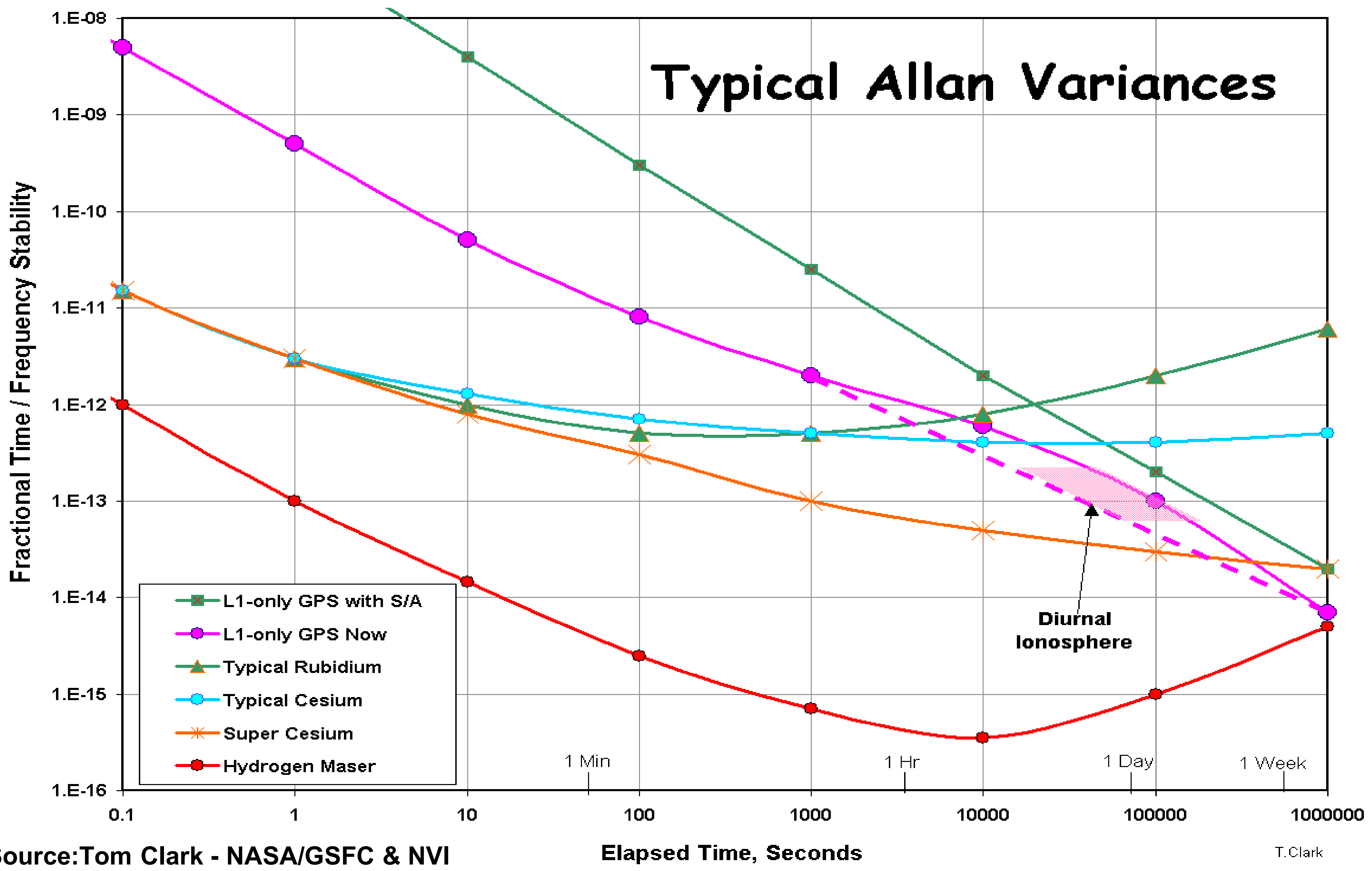
- To correlate data acquired at 16Mb/s, station timing at relative levels ~50 nsec or better is needed. After a few days of inactivity, this requires

$$\approx [50 \blacklozenge 10^{-9}/ 10^{6} \text{ sec}] \approx 5 \blacklozenge 10^{-14} \text{ @ } 10^{6} \text{ sec}$$

and in conjunction

- Since VLBI defines [UT1-UTC], we need to control the accuracy of our knowledge of $[UTC_{(USNO)} - UTC_{(VLBI)}]$ to ~100 nsec or better.

TIME – Allan variance of clocks



Source:Tom Clark - NASA/GSFC & NVI

The message from last time – TIME

Earth Rotation

•Sidereal Time
- ▪Measure of Earth's rotation angle wrt Celestial Reference Frame
- ▪Determined by conventional expression

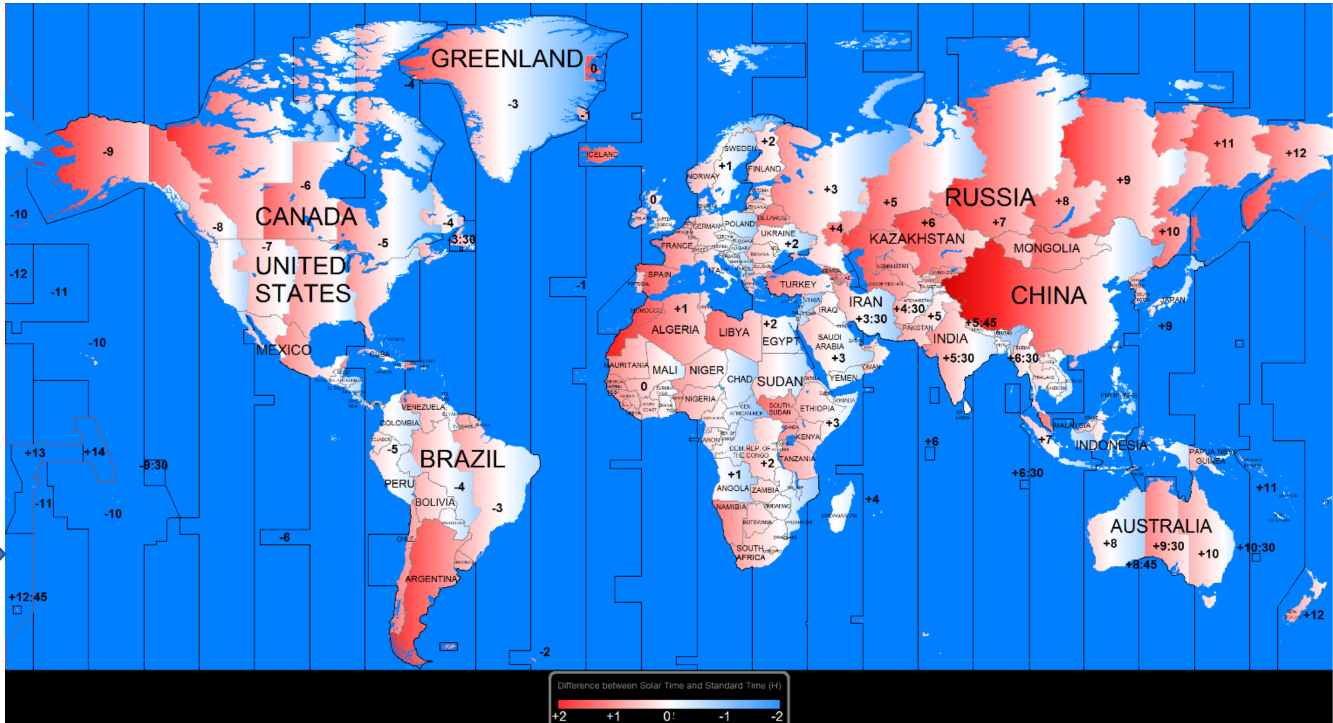
UT1 (Universal Time)
- ▪Measure of Earth's rotation angle wrt Sun
- ▪Determined by conventional expression
  - ▪Earth Rotation Angle
  - ▪Greenwich Mean Sidereal Time
- ▪UT0 = UT1 including polar motion
- ▪UT2 = UT1 with conventional Seasonal Correction

Atomic Time

Echelle Atomique Libre (EAL)

International Atomic Time (TAI)
averaged time of atomic clocks (~400) operated globally

Coordinated Universal Time (UTC)
* TAI corrected by leap seconds
* Basis for civil time

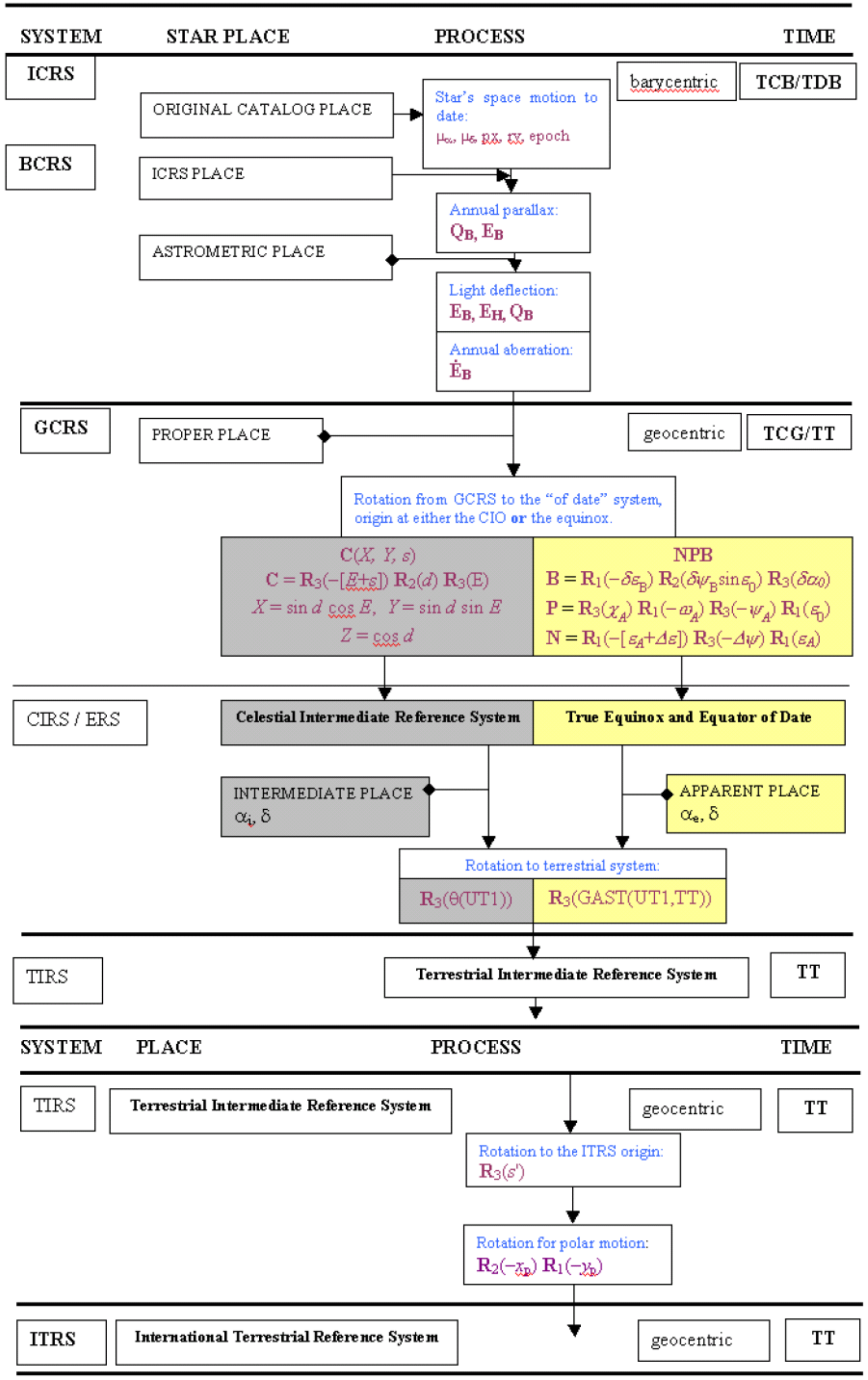


TIME

Transformation from the celestial to terrestrial system is based on standards and models set by the IAU and IUGG, including IERS Earth Orientation Parameters (EOP).

These include

i. polar motion (represented by the x and y coordinates of the direction of the pole in the terrestrial system), which is quasi-periodic and essentially unpredictable, (measured by VLBI)
ii. Universal Time, UT1 that provides the variations in the Earth's diurnal angle of rotation and
iii. small adjustments (denoted dX and dY) to the celestial direction of the pole as predicted by the a priori precession-nutation model

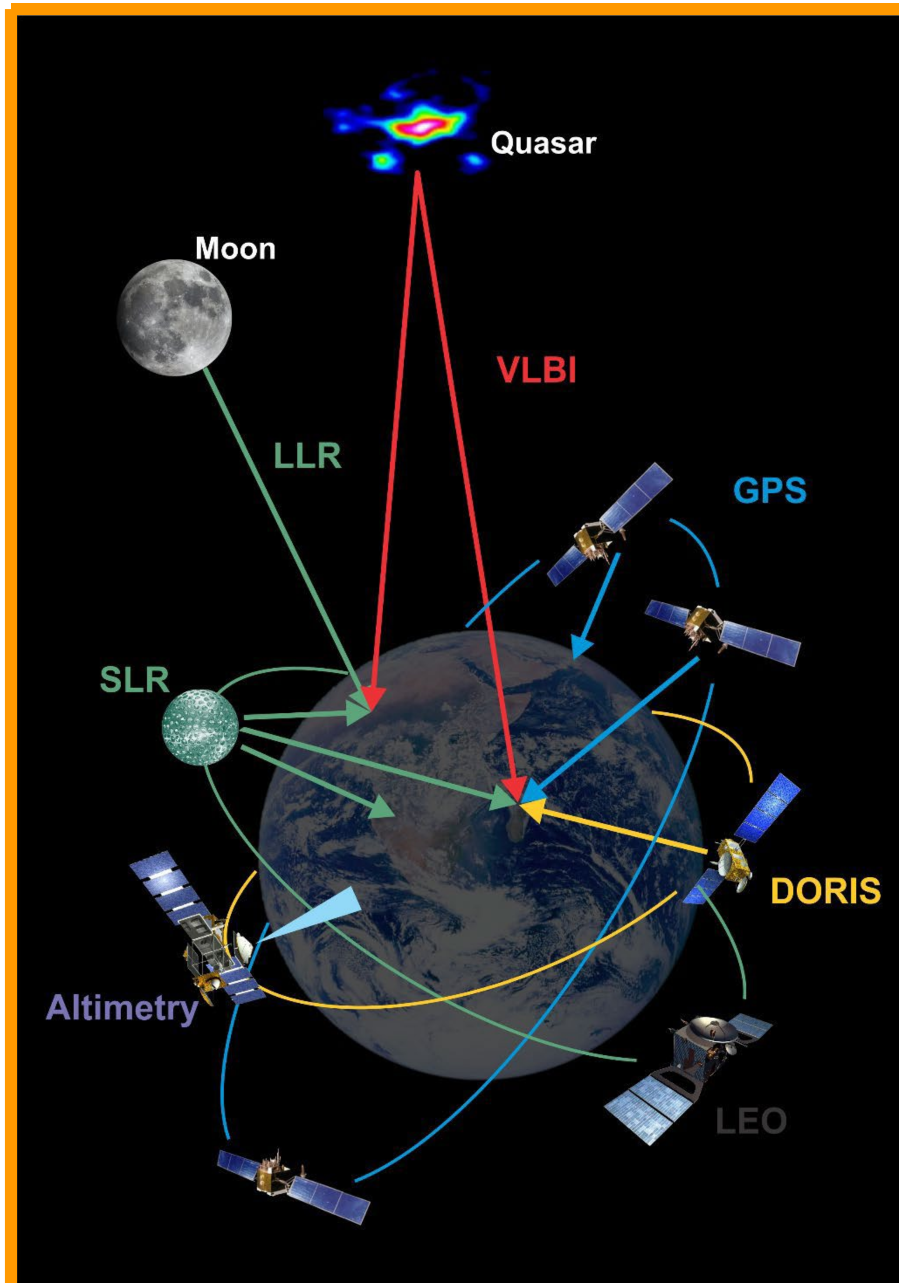


What is Geodesy?

The science using “fancy rulers”:

- Traditionally: Optical EM radiation from stars or terrestrial beacons
- Radio Waves:
  - ➢ From extra-galactic sources → Relative positions in the Celestial Reference Frame
  - ➢ From satellites → For position in the Terrestrial reference frame eg GPS
  - ➢ From satellites → For accurate clock alignments
- Lasers (special form of optical EM radiation):
  - Time of Flight → Distance eg. Satellite orbits
  - Interference pattern changes → Distance variations / Gravity Waves
- Weather sensors
  - Barometric pressure → vertical displacement
- Seismometer and accelerometer instruments
  - Vibrations
  - Displacements eg post-event shifts in position
  - Accelerations measuring the energy in such a movement
- Gravity, indicating vertical displacement / internal mass redistribution

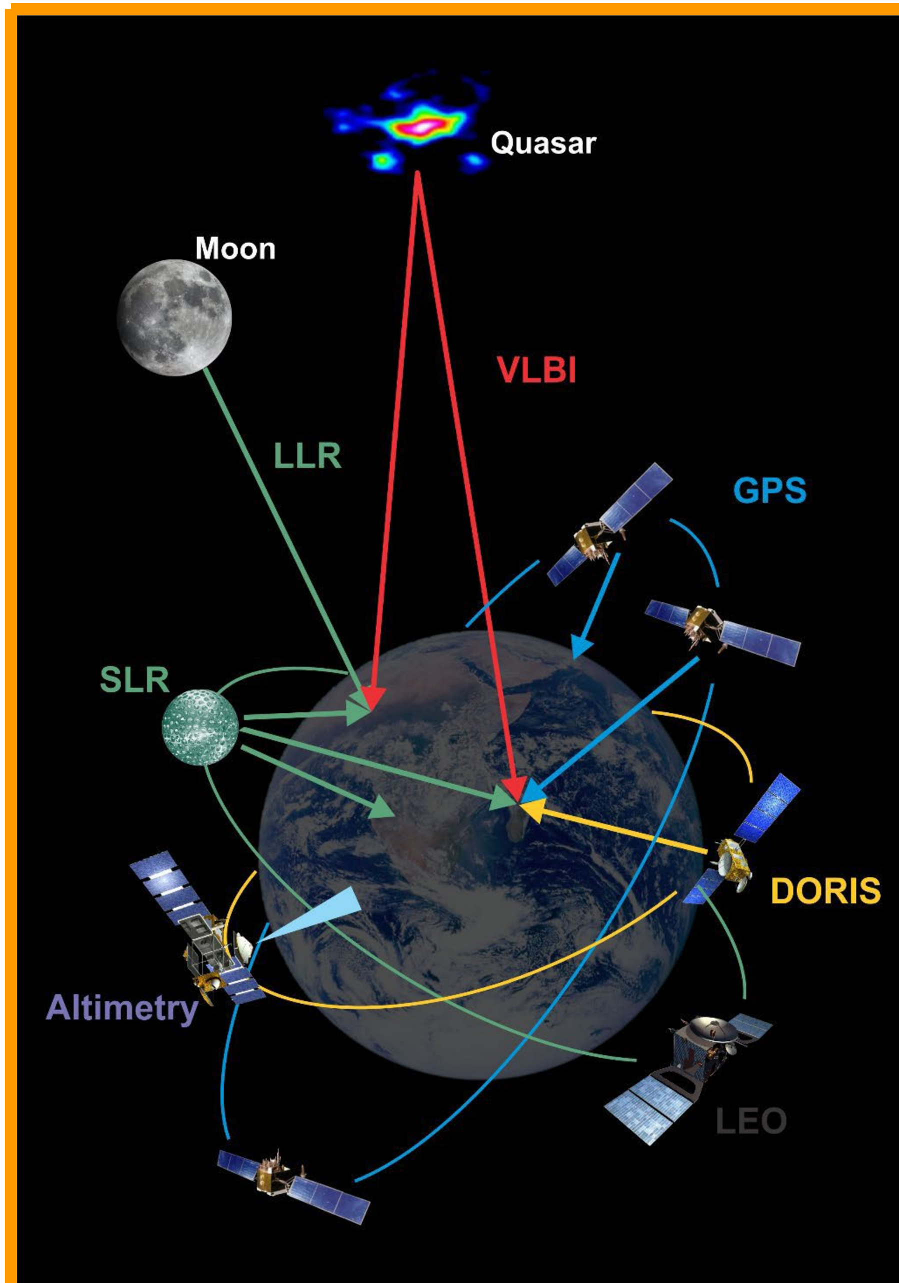
Formally: Geodesy is the science of the measurement and mapping of the Earth’s surface, gravity field, rotation and temporal variations thereof.



SARAO's Geodesy activities: on-site at Hartebeesthoek

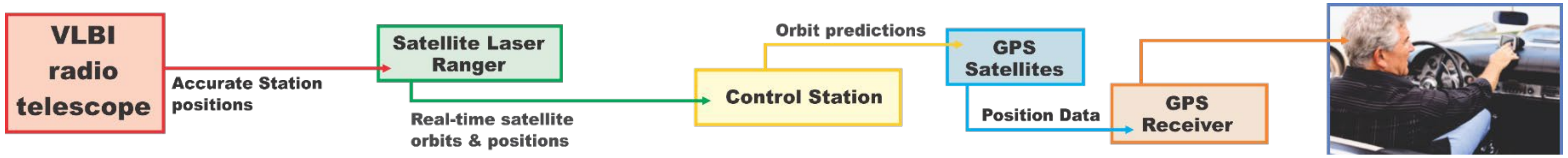
Various techniques, like:

- Global Navigation Satellite Systems:
  - ➢ Global Positioning System (GPS)
  - ➢ Global Orbiting Navigation Satellite System (GLONASS)
  - ➢ The European Navigational System (Galileo)
  - ➢ Chinese Satellite Navigational System "Compass" (Beidou)
- Very Long Baseline Interferometry (VLBI)
- Laser Ranging to satellites and the Moon (SLR and LLR)
- Doppler Orbitography and Radio-positioning (DORIS)
- Local automated Site-tie
- Geo-physical measurements: seismicity, gravity, meteorological data



These techniques are used both separately *and in conjunction* with each other in Geodesy

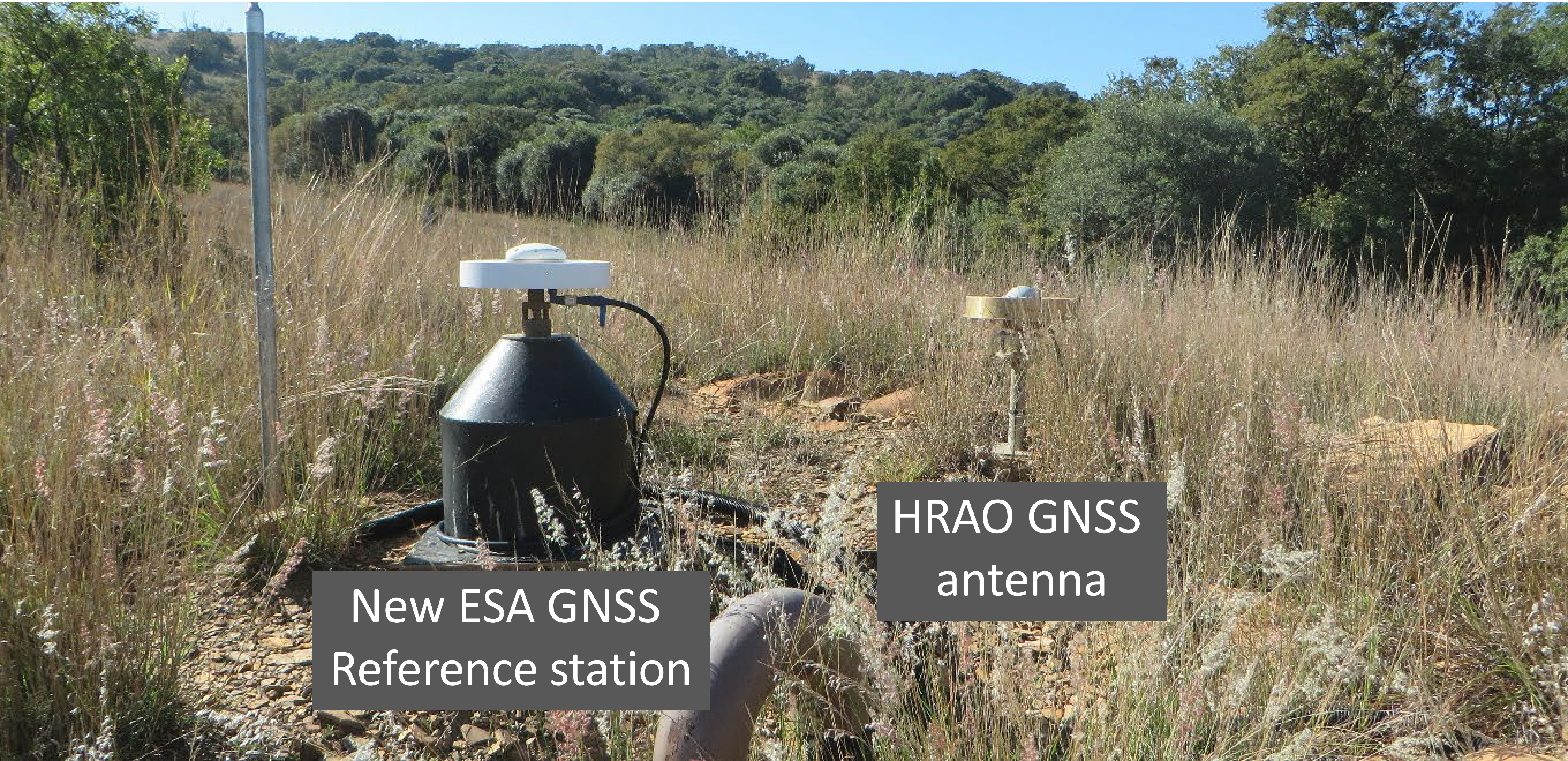
The Secret: *C O L L O C A T I O N*



Geodesy Techniques at Fundamental sites

Parameter type	VLBI	GPS/ GLON.	DORIS/ PRARE	SLR	LLR	Alti-metry
Quasar Coord. (ICRF)	X					
Nutation	X	(X)			X	
Pole Coord. X, Y	X	X	X	X	X	
UT1	X					
Length of day (LOD)		X	X	X	X	
Sub-daily ERPs	X	X				
ERP Amplitudes of ocean tides	X	X		X		X
Station Coord.+ Velocities (ITRF)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity field		X	X	X	(X)	X
Satellite orbits		X	X	X	X	X
LEO orbit determination		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time/Frequency transfer	(X)	X	X			

Core site: GNSS Reference Stations

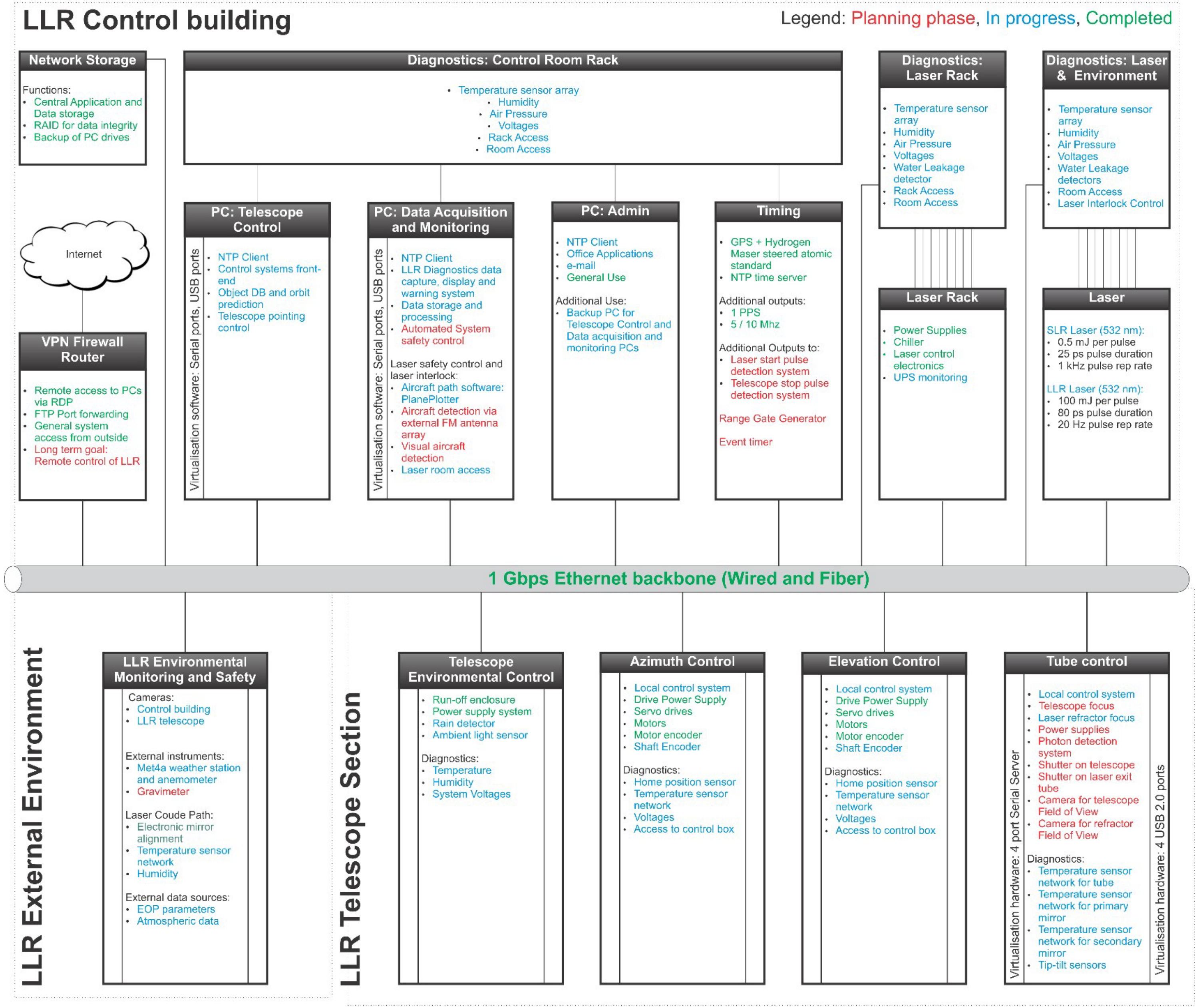


Core site: Radio Astronomy antennas

Core site: Laser Ranging

Photo credit:
Jacoline Schoonees / DIRCO

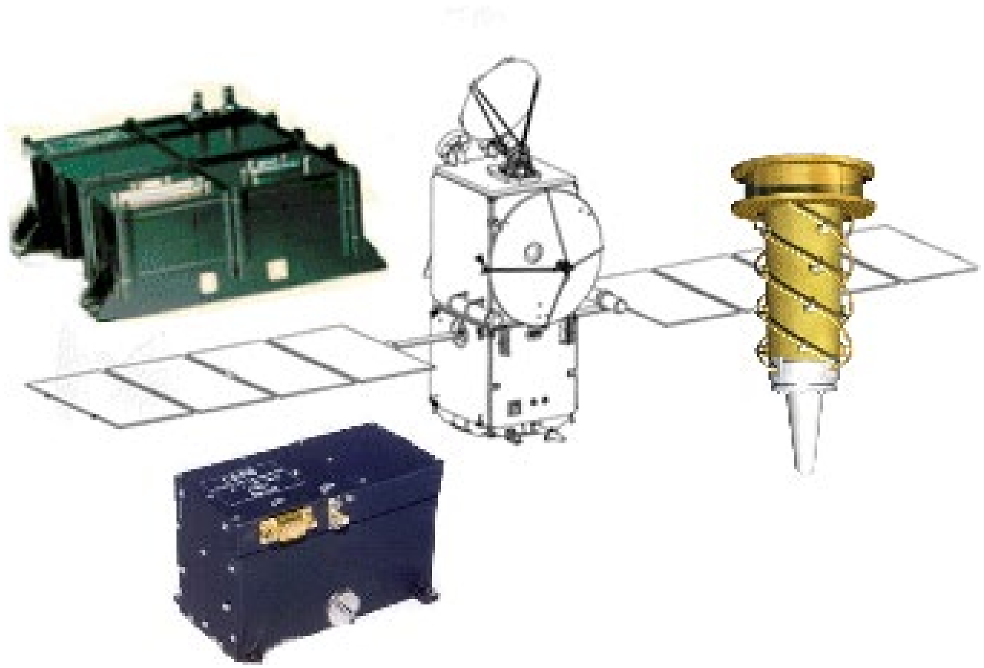
Core site: SA's Laser Ranger



Planned:

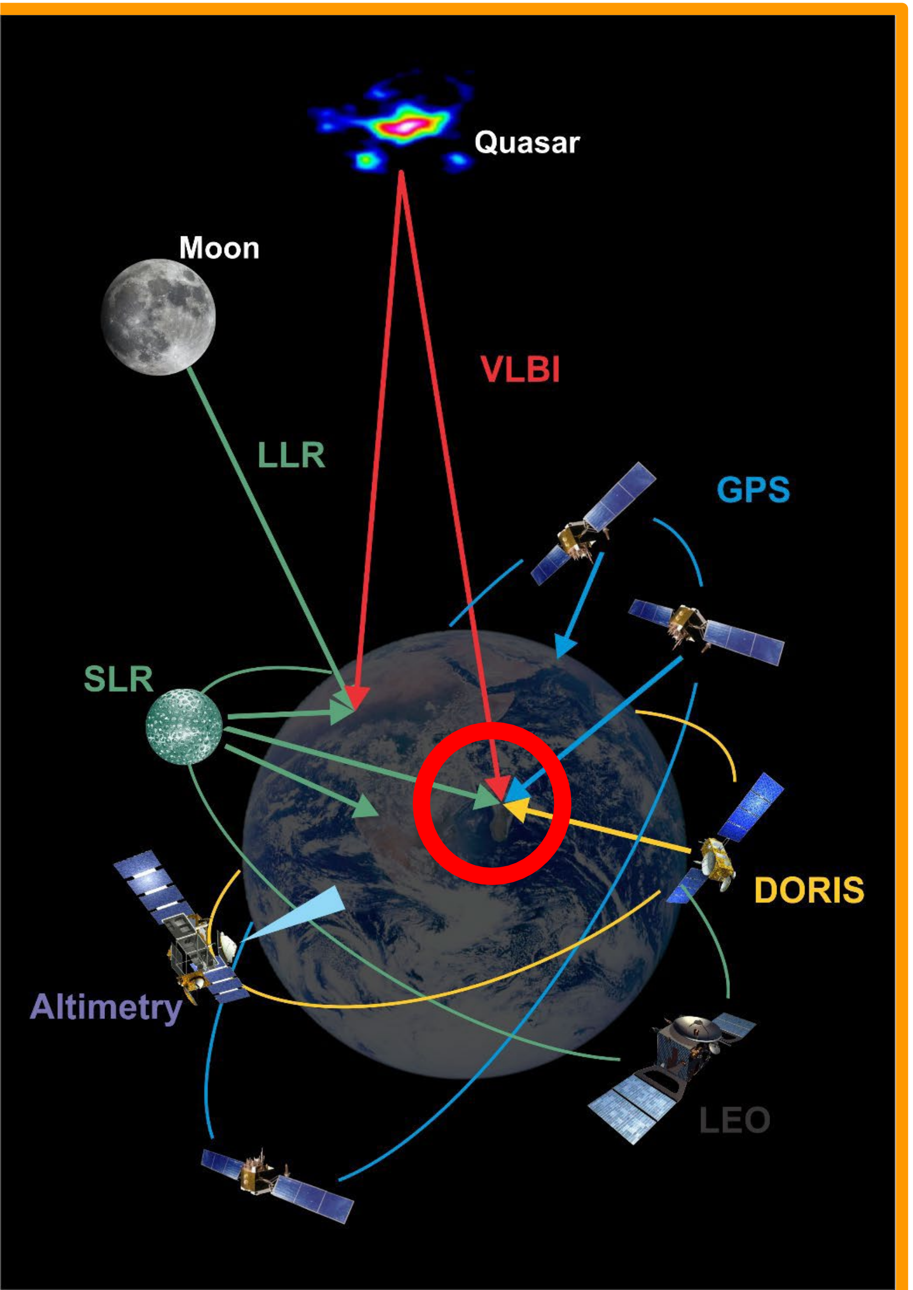
- DiGOS control software
- Complete system integration
- Optical subsystem SLR-ready
- Testing and calibration
- Lunar ranging capability
- Time transfer with European stations
- Deep space communications

Core site: DORIS (at SANSA)



https://www.aviso.altimetry.fr/en/techniques/doris/doris-system/instruments-onboard.html

Core site: 1mm Site



Core site: Site Tie

Leica MS50 total station
With at least a Leica GRZ4 360° prism and Leica GPH1P prism
on each major instrument on site

SARAO's Geodesy activities: OFF-SITE

Network of remote stations / equipment:

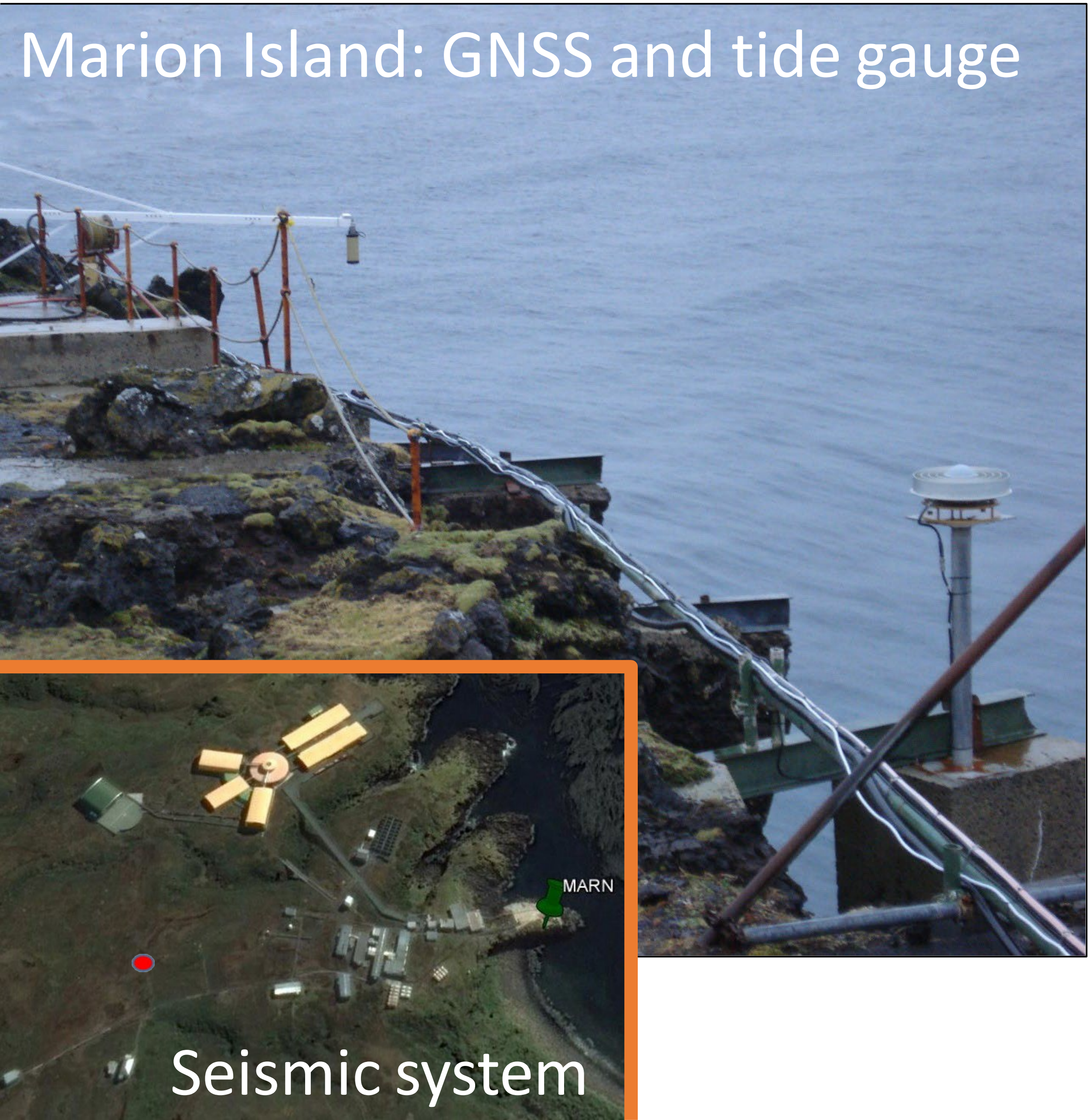
- (Nearly) Always a GNSS station
- Collocation of various geodetic equipment

Sites are chosen based on:

- specific research interest in a local / regional phenomena
- supporting other sciences / measurements / instruments

Bongani Ngcobo to give an overview of our remote sensor network on Thursday…

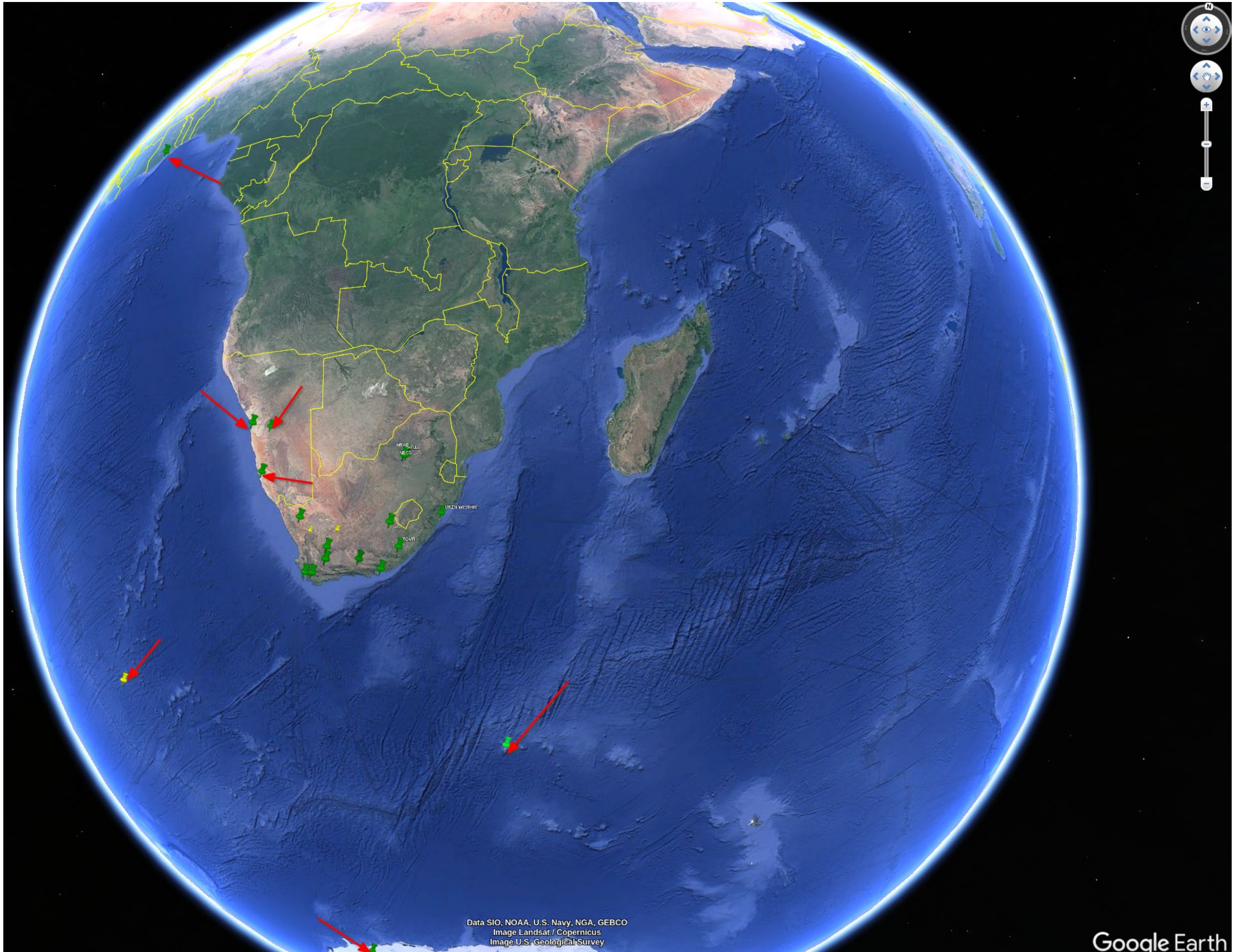
HartRAO's Geodesy activities: off-site



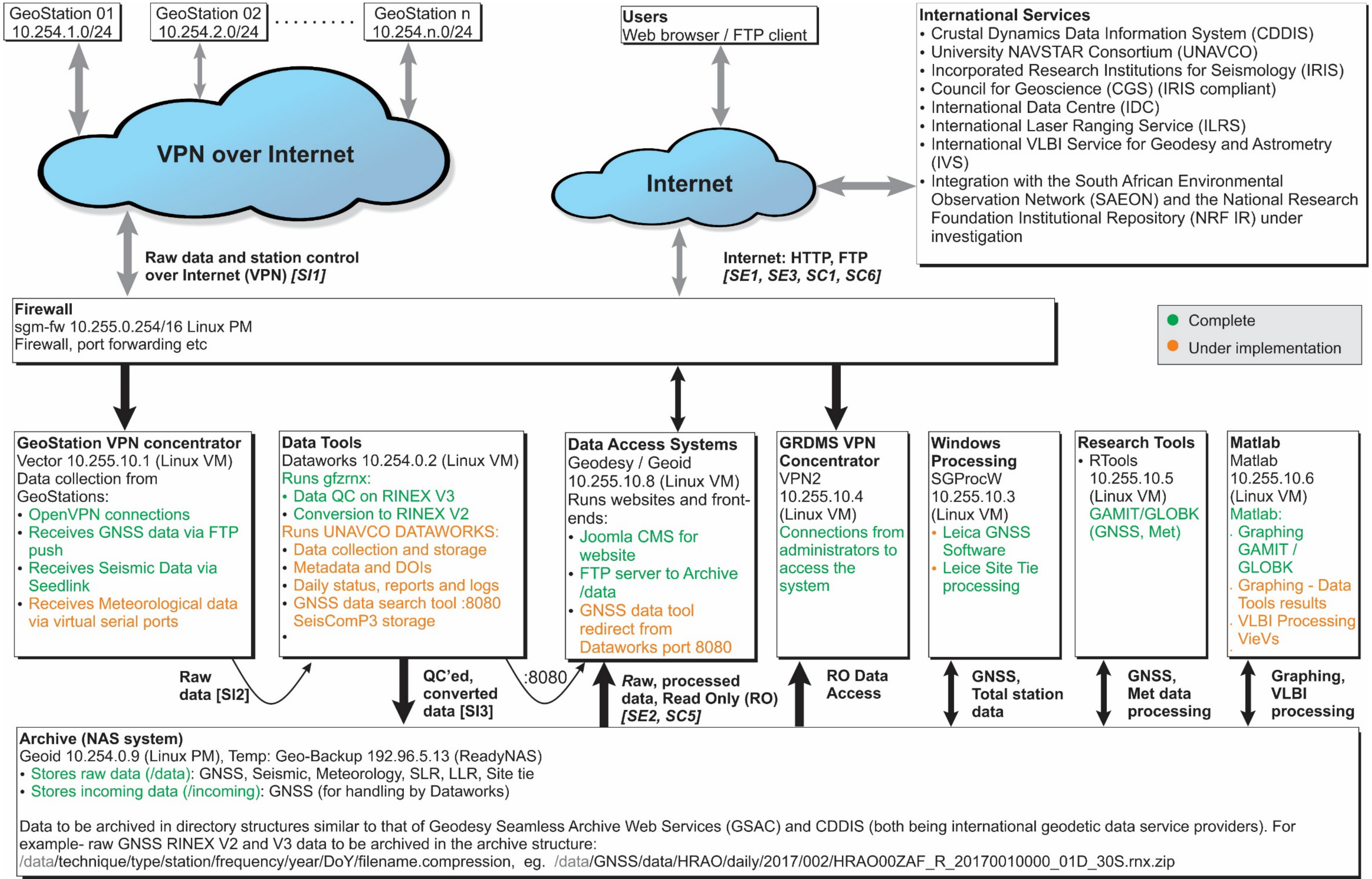
- Global Navigation Satellite Systems:
  - Global Positioning System (GPS)
  - Global Orbiting Navigation Satellite System (GLONASS)
  - The European Navigational System (Galileo)
  - Chinese Satellite Navigational System (Beidou)
- Very Long Baseline Interferometry (VLBI)
- Laser Ranging to satellites and the Moon (SLR and LLR)
- Doppler Orbitography and Radio-positioning (DORIS)
- Manual Site-tie
- Geo-physical measurements: seismicity, gravity, meteorological data
- Collocation with Ocean Level Tide Gauges

GeoStations: network map

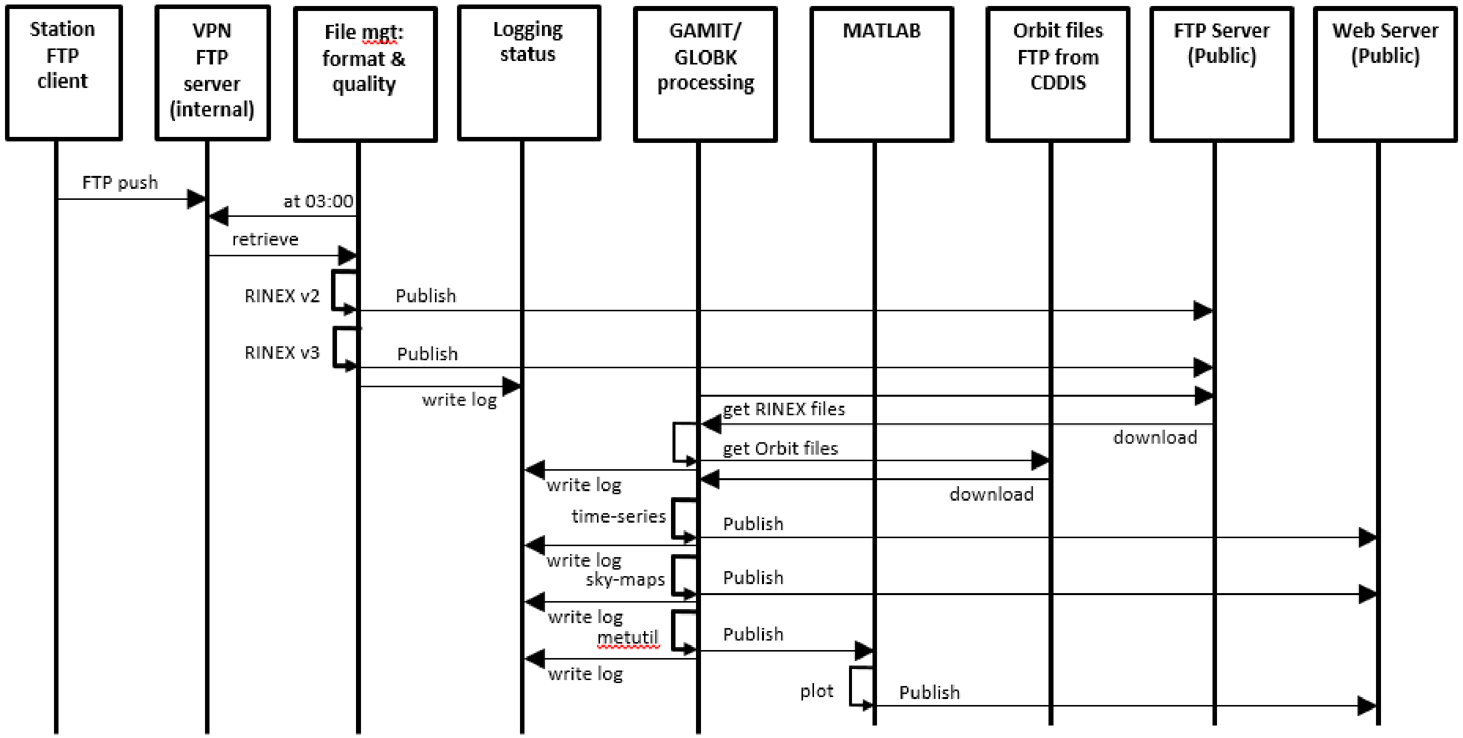
- Active
- To be installed

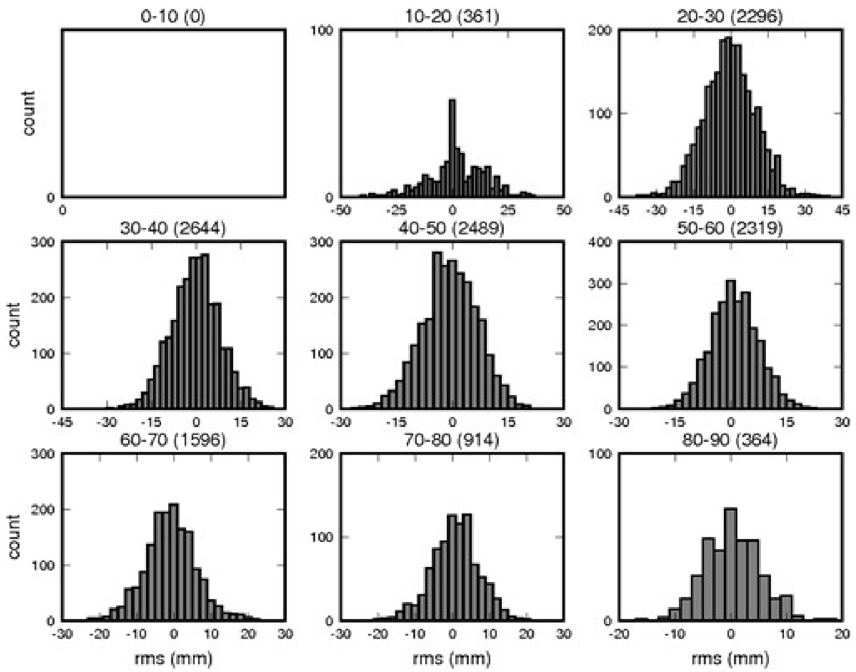


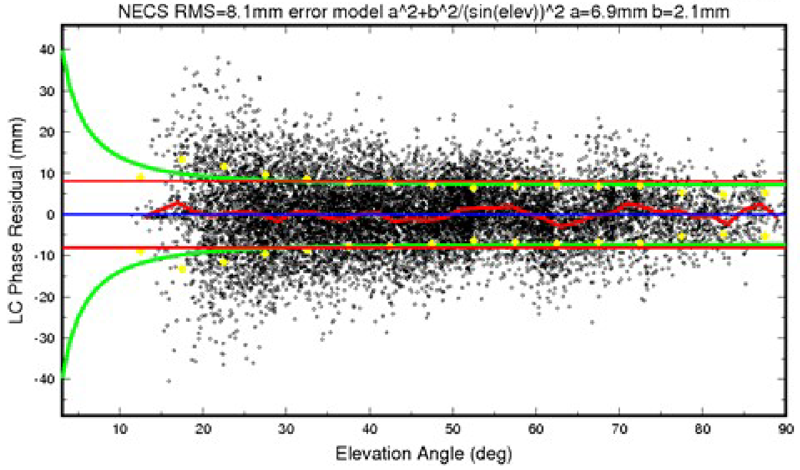
Geodetic Research Data Management system (GRDMS)

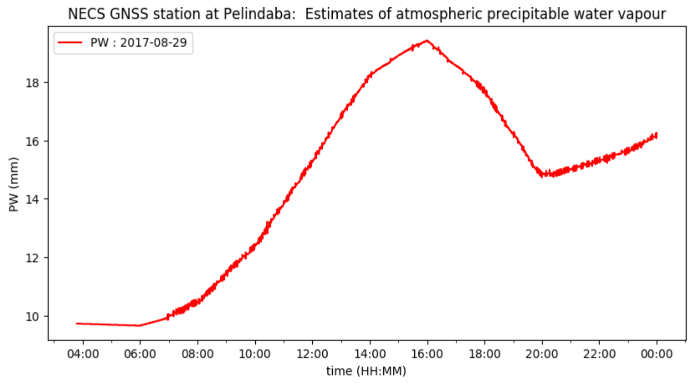


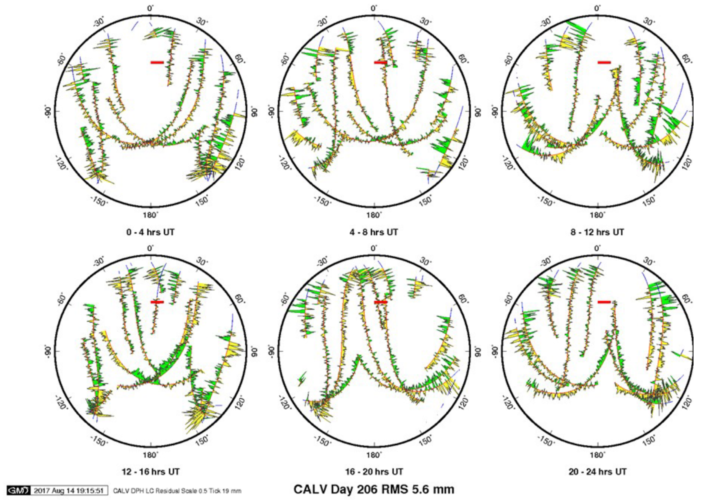
Raw Data and Automated Products – GNSS + Met



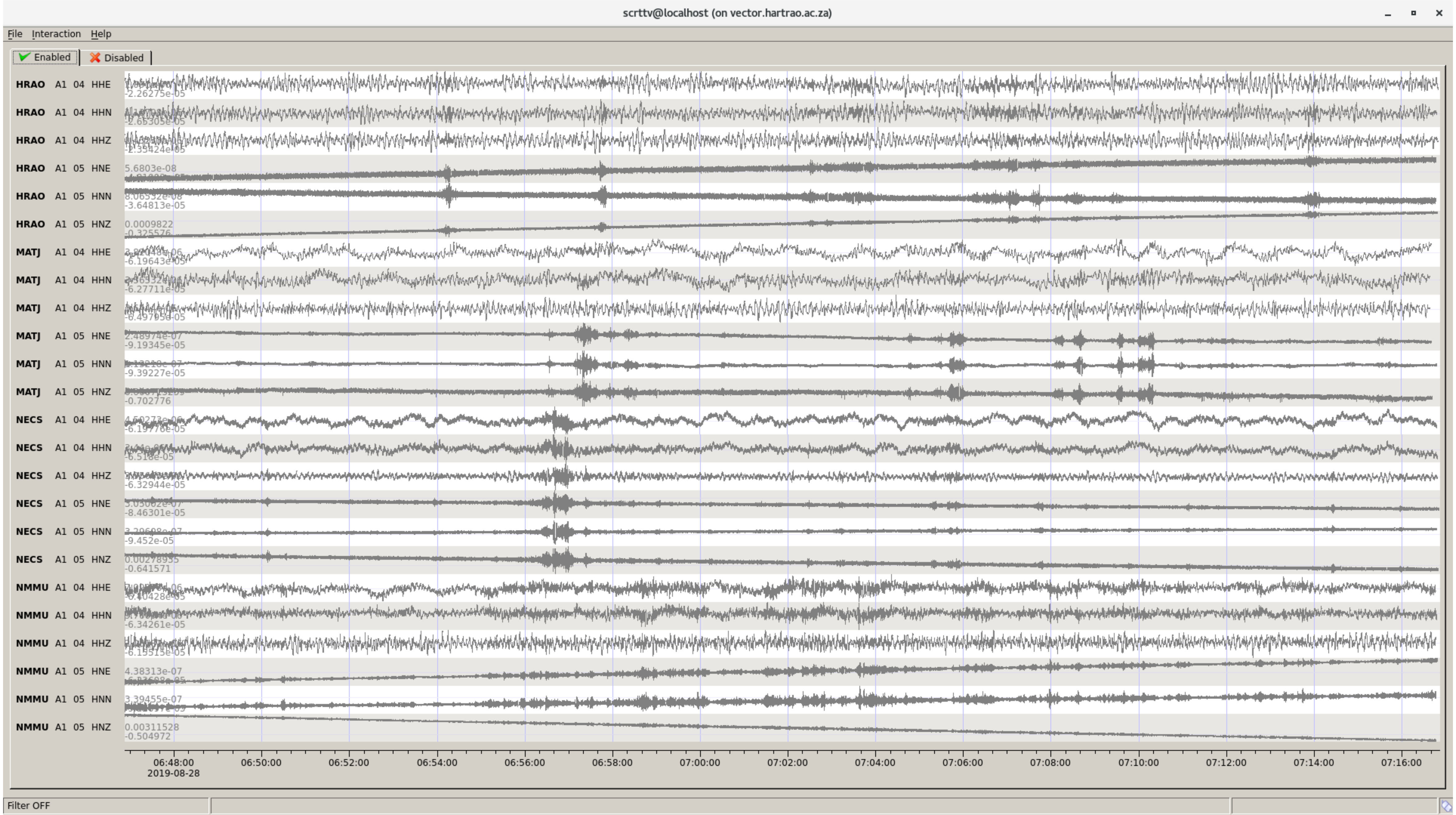








Raw Data - Seismic



Automated Products - Seismic

Council for Geoscience

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geoscience@tip-offs.com

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SEISMIC EVENTS

General Disclaimer

Earthquake information published on the Council for Geoscience Website ("the Website") is obtained from waveforms recorded by the South African National Seismograph Network. The information provides automated assessment of the earthquake parameters. Viewers of the Website are cautioned that the parameters shown are considered preliminary, unless otherwise indicated. Users are cautioned that the intended purpose and use is exclusively for information and that the Council for Geoscience does not accept liability arising from use of or inferences made from the information as published on the Website.

Listed Events

Origin Time	Latitude	Longitude	Magnitude	Magnitude Type	Status	Location
2019-08-27 17:15:46	-26.005	29.143	2.1	M	A	View location
2019-08-27 15:25:11	-25.574	28.771	2.0	M	A	View location
2019-08-26 17:13:37	-25.798	29.831	2.0	M	A	View location
2019-08-26 15:52:18	-26.236	29.203	2.7	M	A	View location
2019-08-26 15:26:42	-23.973	28.824	2.2	M	A	View location
2019-08-26 14:29:18	-25.991	29.333	2.6	M	A	View location
2019-08-26 13:37:02	-26.102	29.977	2.0	M	A	View location
2019-08-26 13:18:12	-26.019	29.513	2.3	M	A	View location
2019-08-26 08:51:55	-26.147	30.005	2.1	M	A	View location
2019-08-26 05:31:42	-26.885	26.564	2.5	M	A	View location
2019-08-25 22:42:34	-26.538	27.585	2.1	M	A	View location
2019-08-25 21:24:46	-26.735	29.215	2.1	M	A	View location
2019-08-25 15:20:54	-25.932	29.325	2.1	M	A	View location
2019-08-24 15:28:15	-25.696	29.417	2.2	M	A	View location

SEISMIC EVENTS

- Live
- Archives

SEARCH

Start Date
dd/mm/yyyy

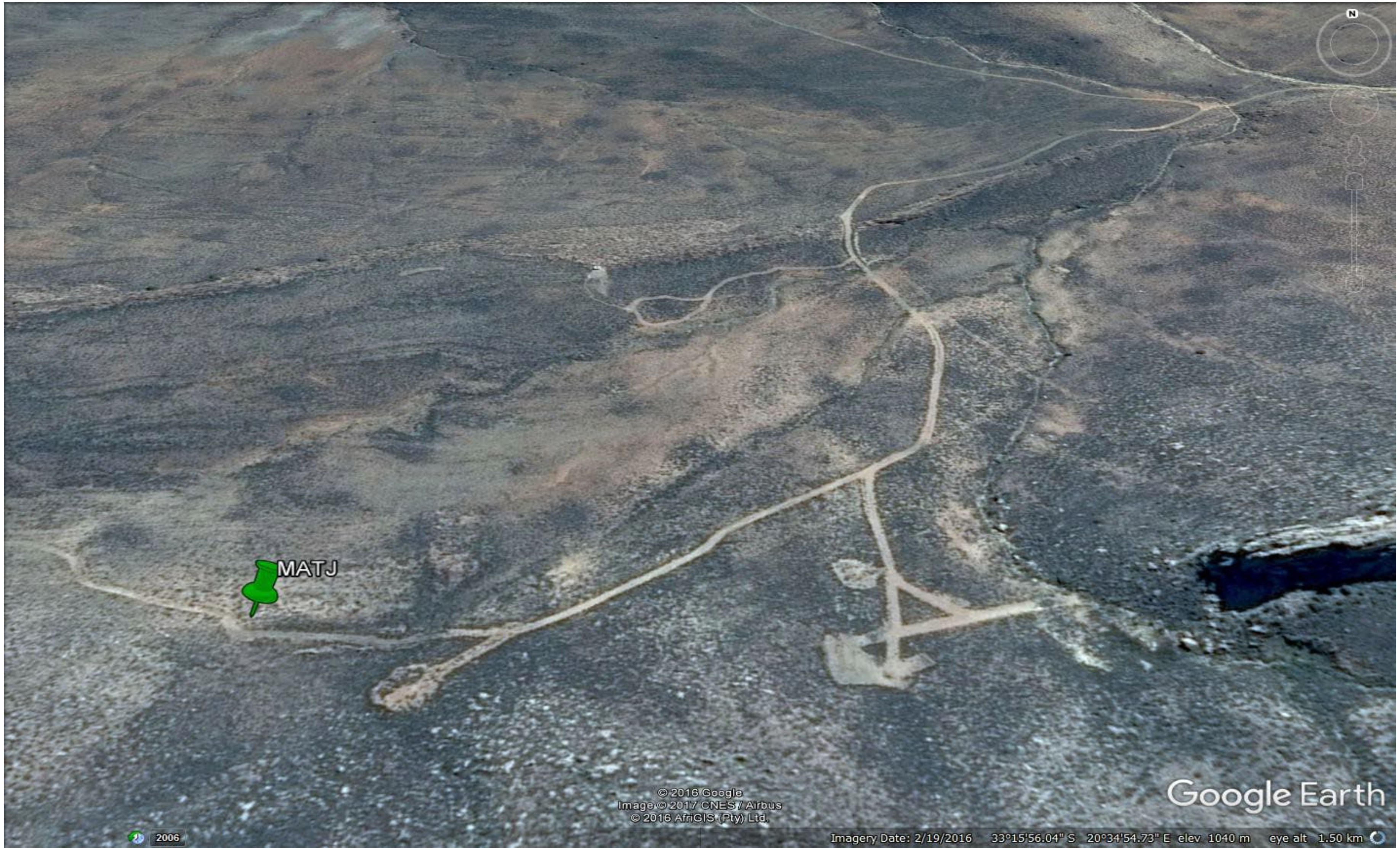
End Date
dd/mm/yyyy

Magnitude
Greater Than

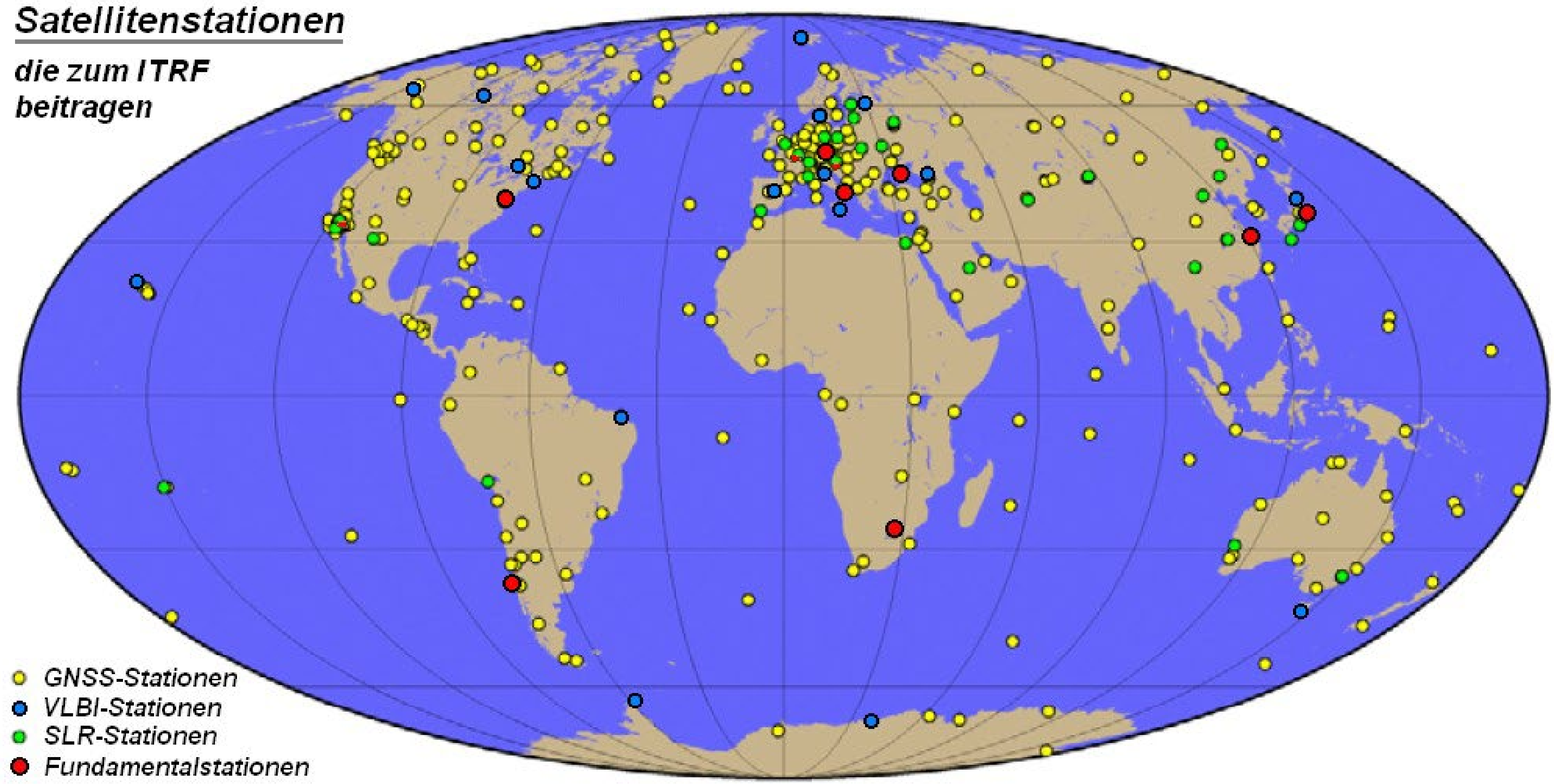
Search

SEISMIC QUESTIONAIRE

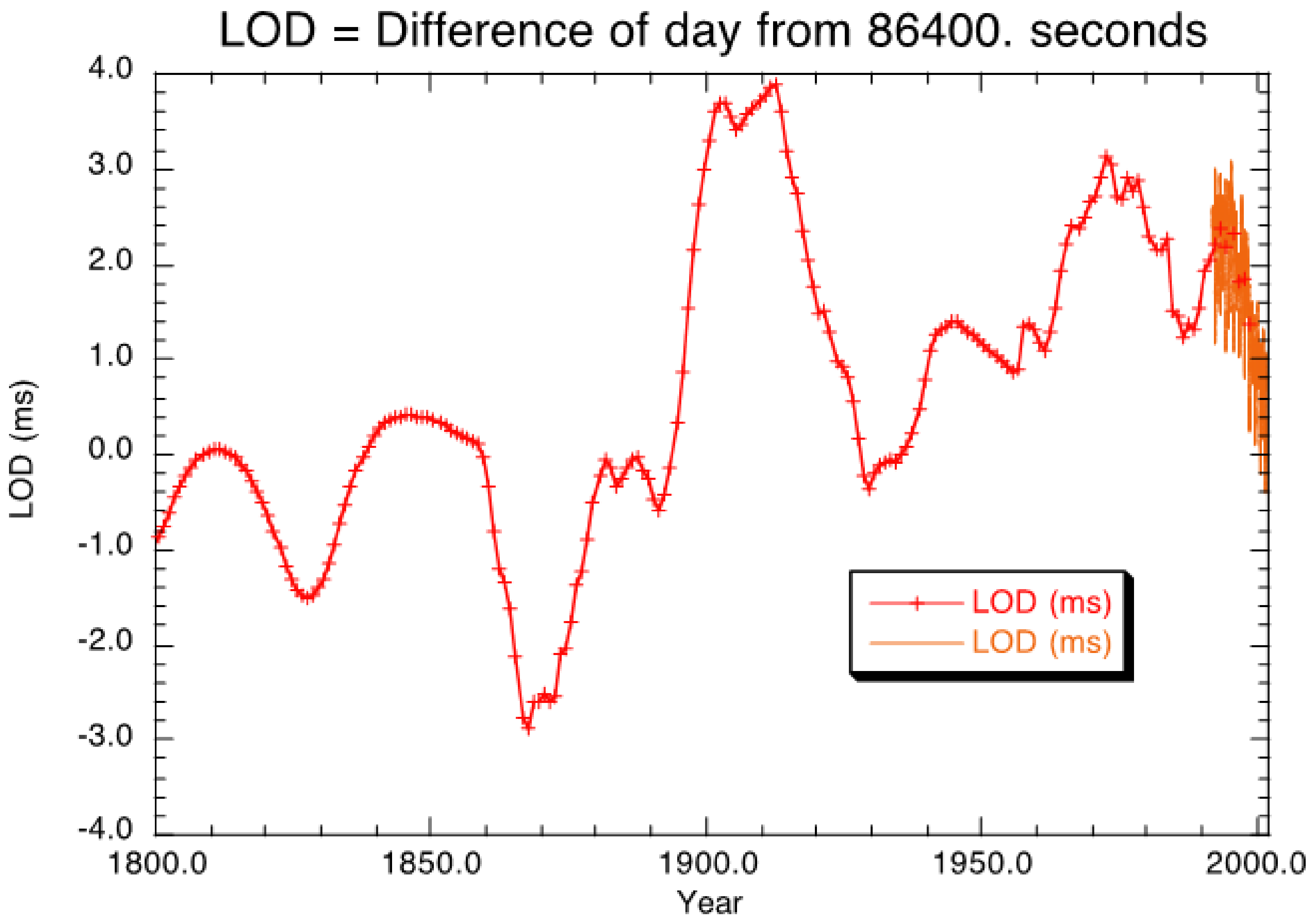
Additional fundamental site: Matjiesfontein



We participate in and support a global network…



Geodesy products: Length of Day

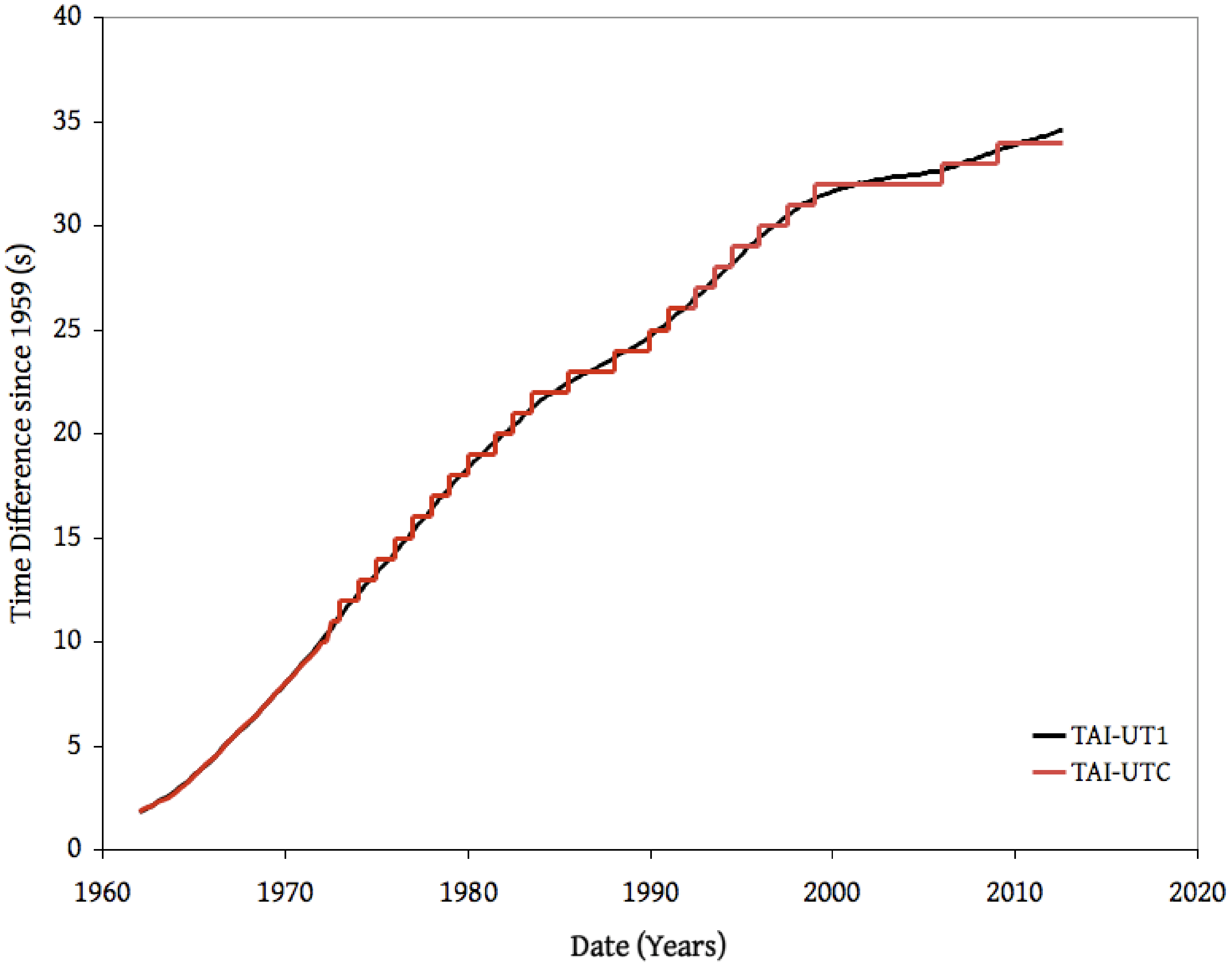


Geodesy products: Leap seconds

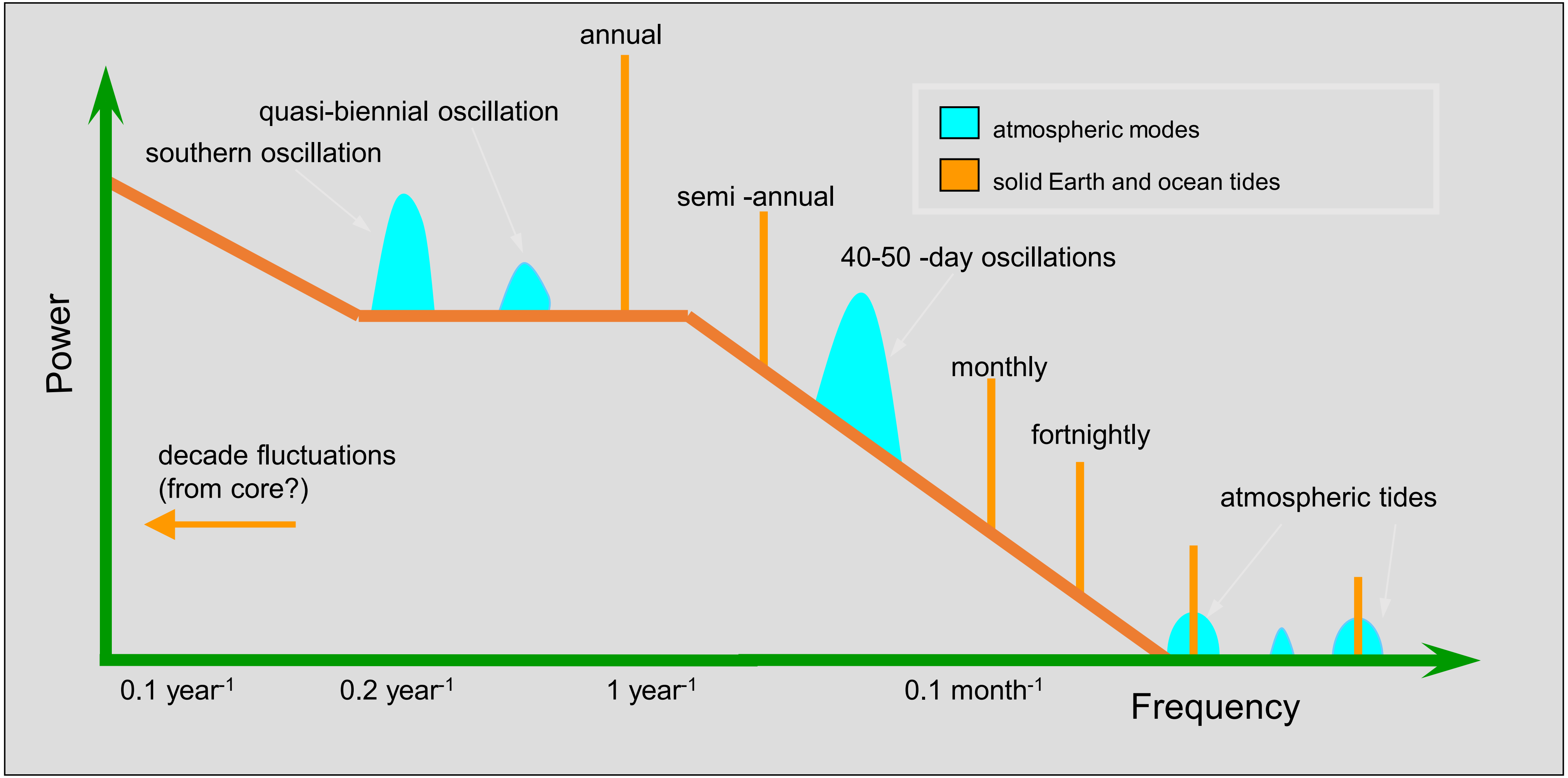
- In 1972 present UTC system was implemented, with 1 s (leap second) steps but no frequency offsets to maintain agreement with UT1 within 0.9 s
- 1980 GPS Time introduced – no leap seconds in clock, added manually

Leap Second Information	
Current number of leap seconds	18
Announced number of leap seconds	18
Effectivity date and time (UTC)	2017-01-01 00:00:00

- Definition of UTC is a compromise to provide both the SI second and an approximation to UT1 for celestial navigation in same radio emission

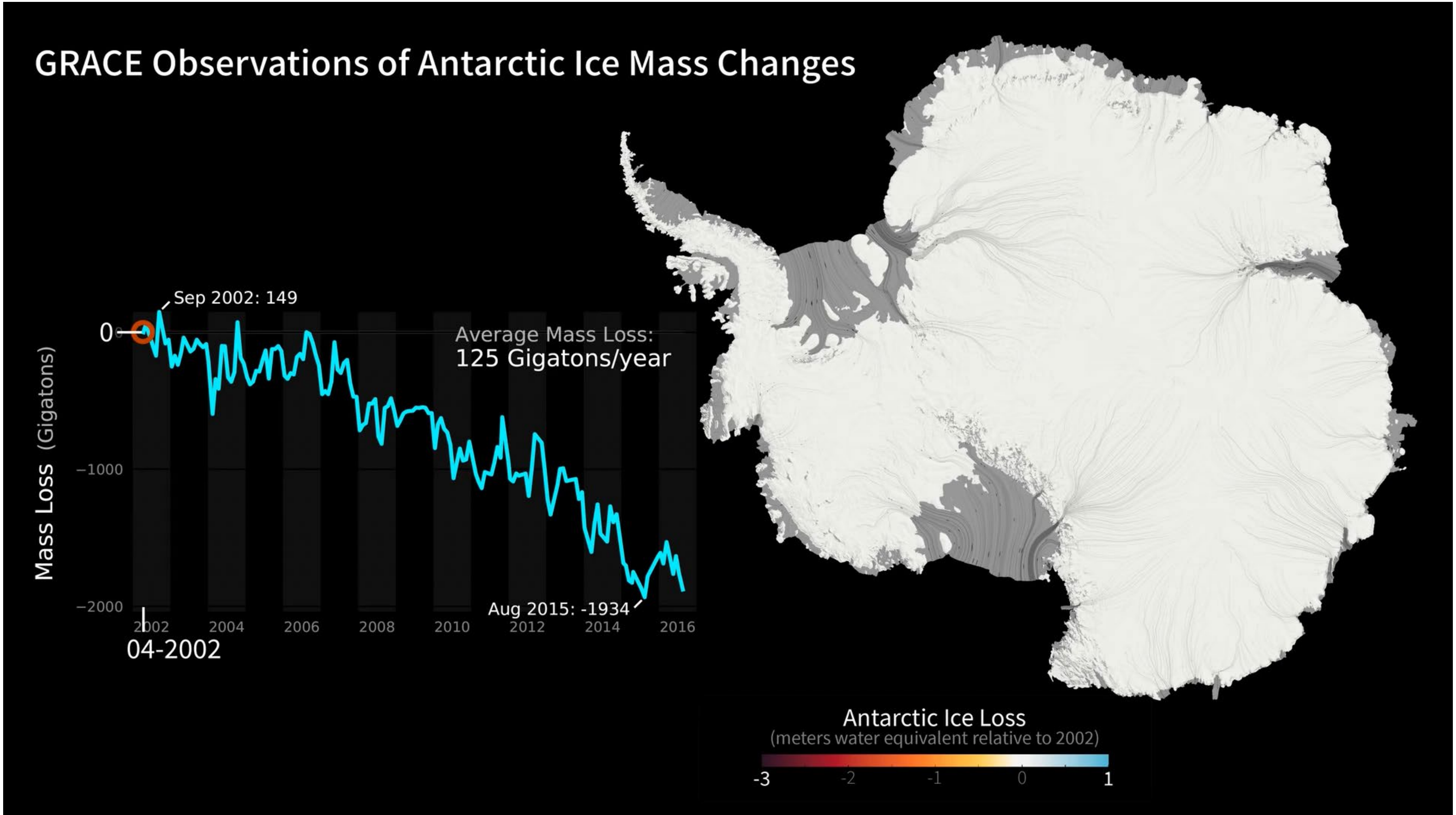


Geodesy products: UT1 – UTC Spectrum

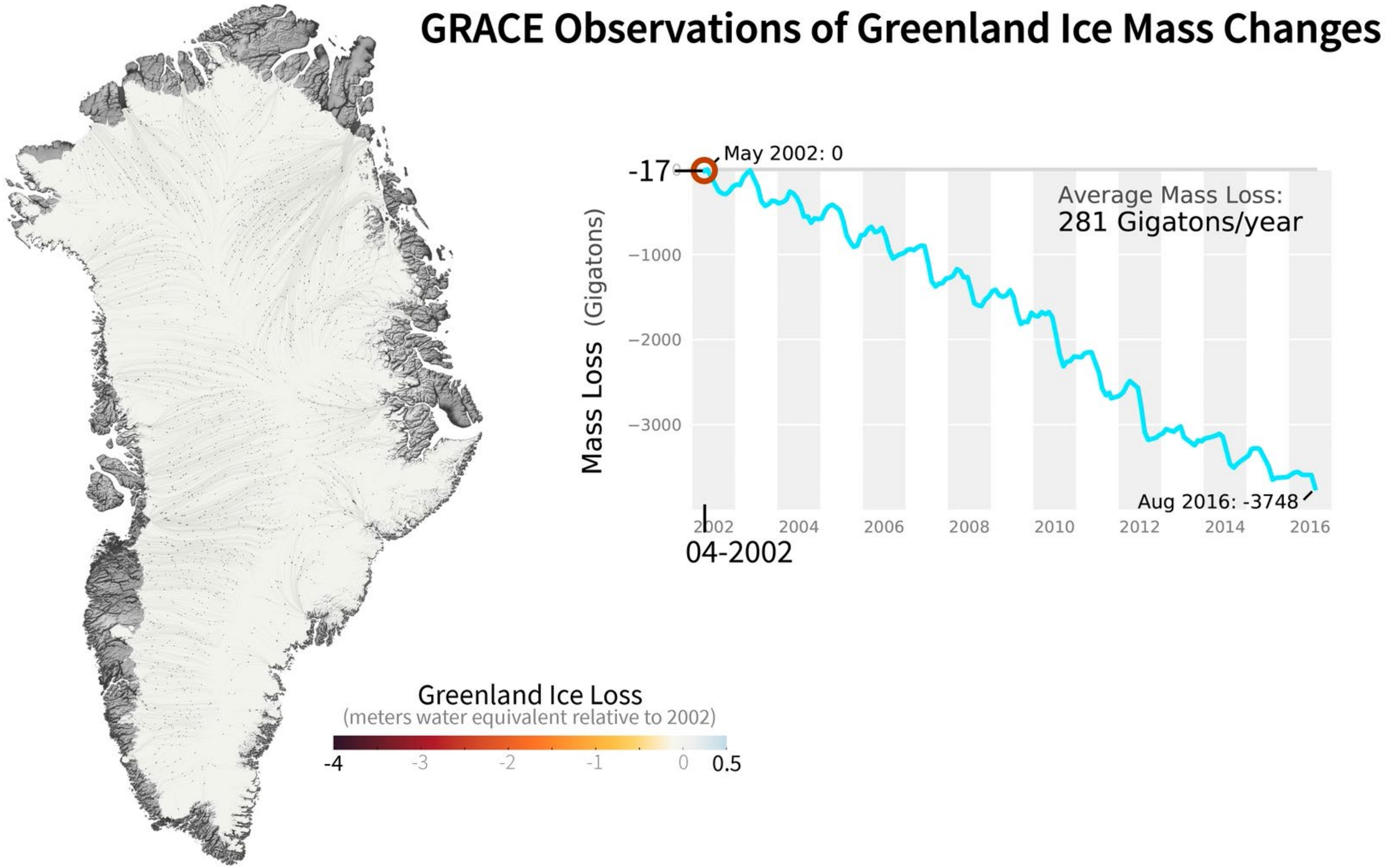


Source: The Fundamental Reference Systems Tutorial (USNO)

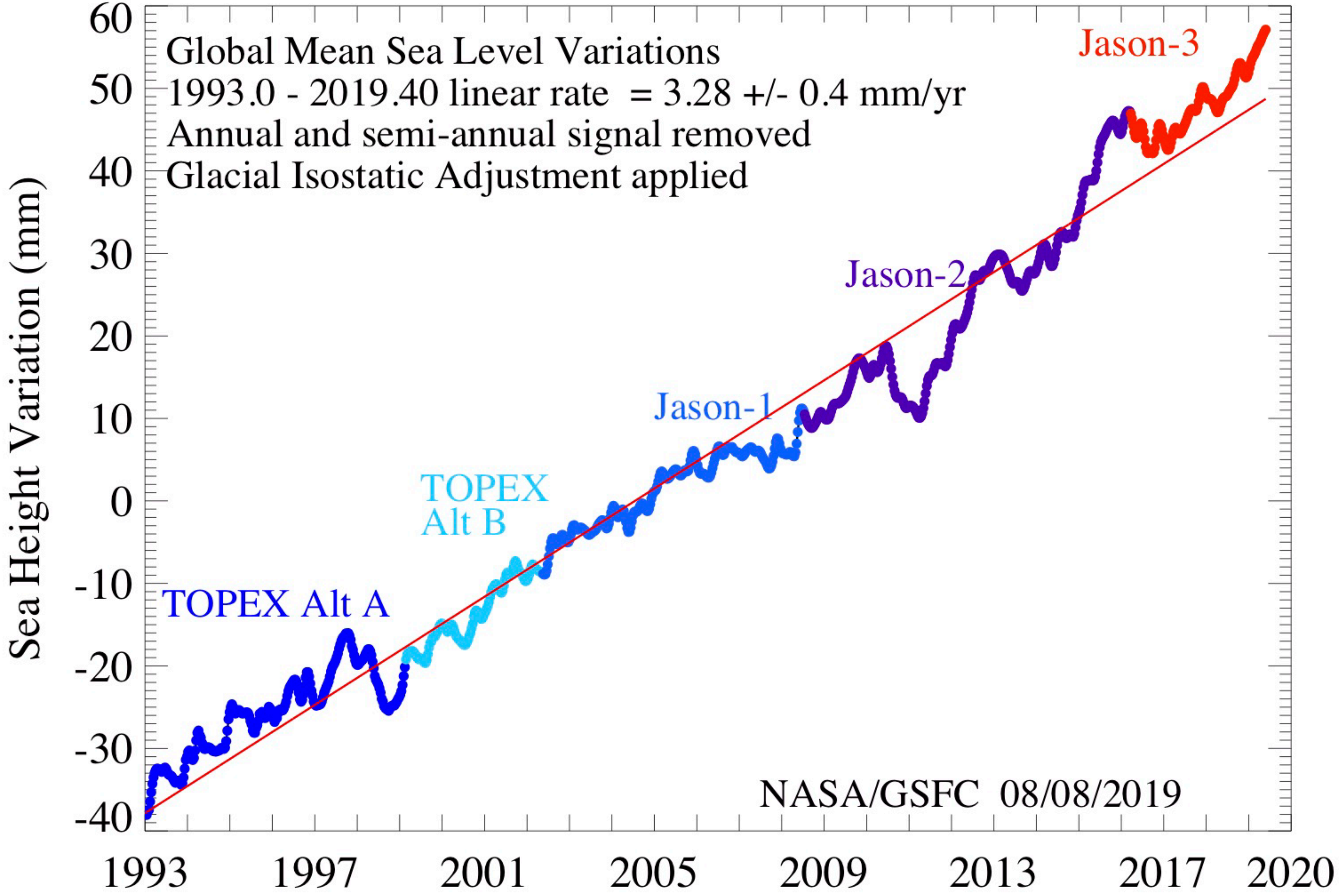
Geodesy products: Ice sheet change



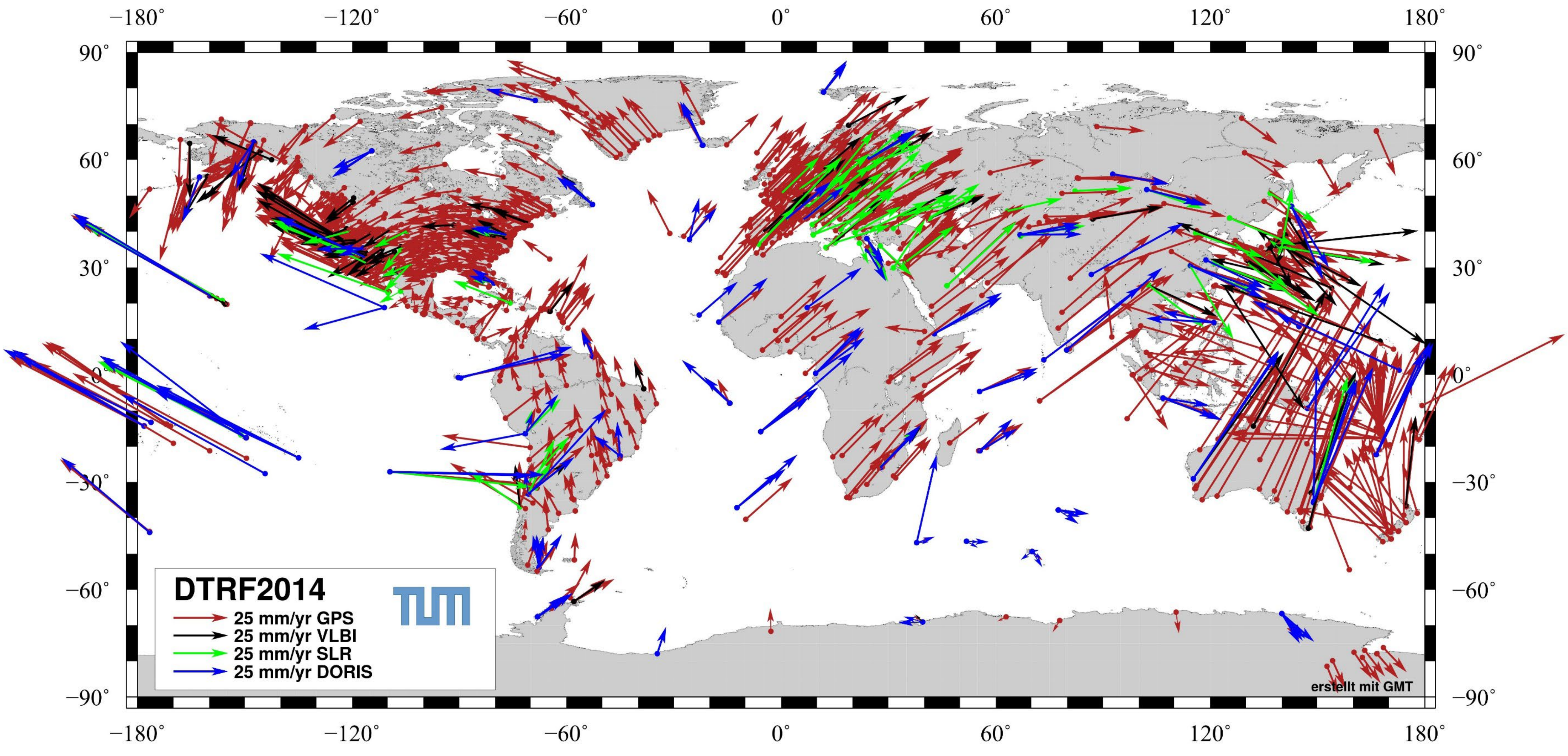
Geodesy products: Ice sheet change



Geodesy products: Ocean level rise



Geodesy products: Continental drift



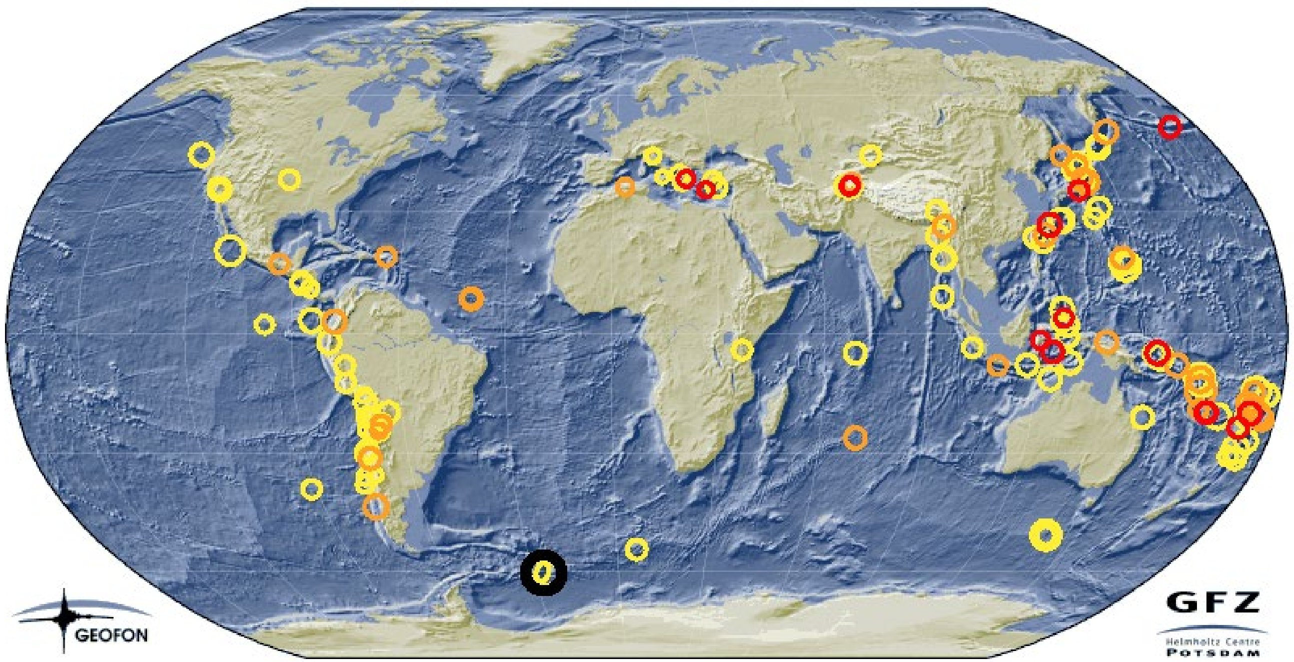
Geodesy products: Seismic monitoring

GFZ
Helmholtz-Zentrum Potsdam

GEOFON
GEOFON Program

Helmholtz-Zentrum Potsdam
Deutsches GeoForschungsZentrum

Automatic GEOFON Global Seismic Monitor



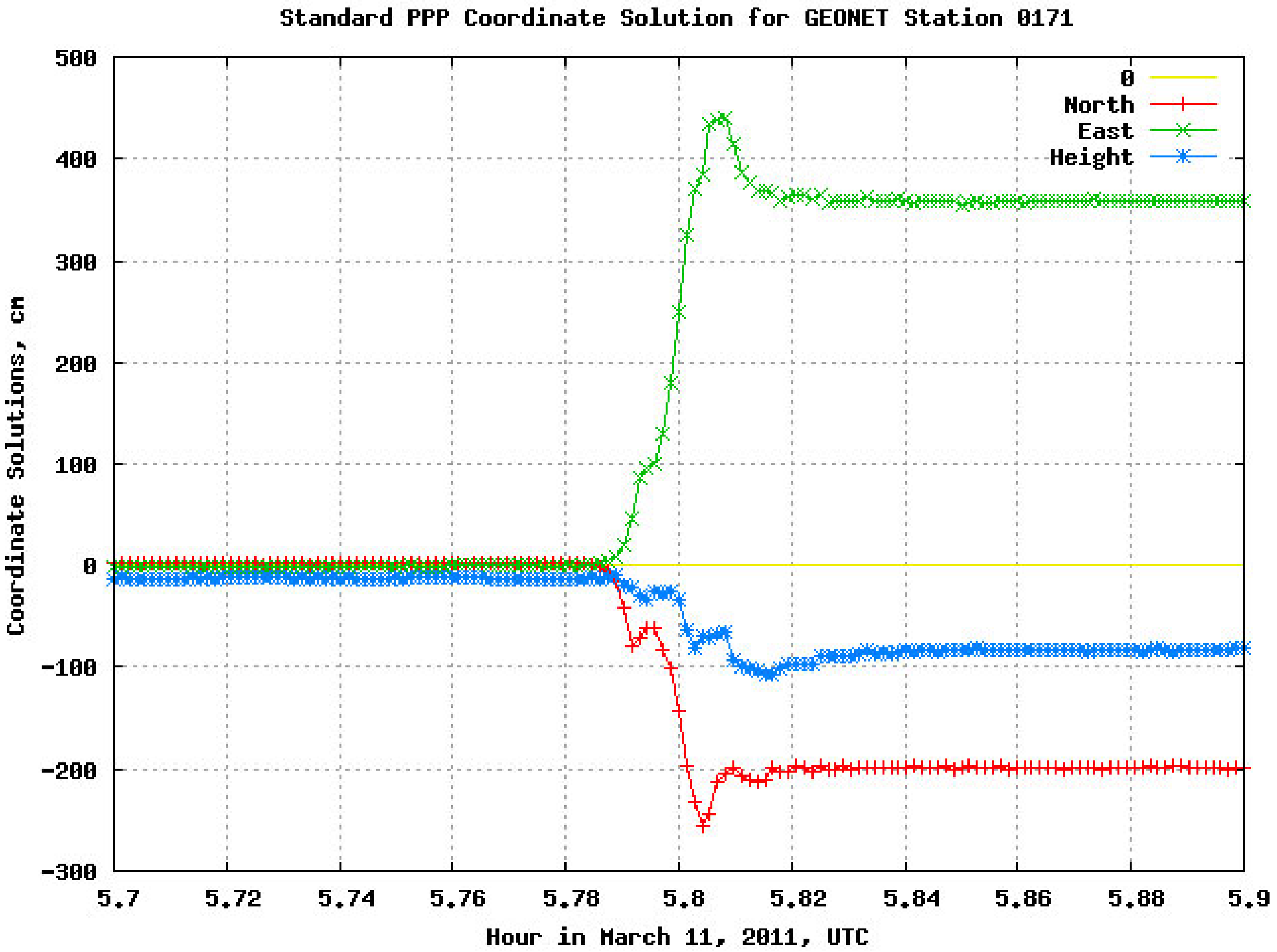
The events displayed occurred within the last 24 hours / 1-4 days / 4-14 days .

Most recent large event:

South Sandwich Islands Region

Magnitude: **6.5 (Mw)**
Origin time: **2019-08-27 23:55:18 UTC**
Epicenter: **26.43°W 60.32°S**
Depth: **10 km**
Location status: **confirmed**

Geodesy products: Pre-, co- and post-seismic monitoring



11 March 2011, Mw=9.0 Tohoku, Japan Earthquake and Tsunami

5 second GPS coordinate solutions of GEONET station 0171 on the Japanese coast, provided by GPS Solutions. Shown are PPP results post processed using realtime orbit and clock corrections from the VERIPOS/APEX service. Time series shows nearly 5 meters of co-seismic displacement and one meter of subsidence.

Societal benefits of Geodesy, globally and for Africa (AVN)

Reference frames (terrestrial and celestial) and timing provision are core to geodesy…

GNSS is an important tool:

- A single IGS reference station can help with local mapping ITRF transformation
- Has numerous applications such as monitoring, farming, disaster management
- Having students learning + utilising GNSS from a scientific point of view creates a generation of skilled potential entrepreneurs

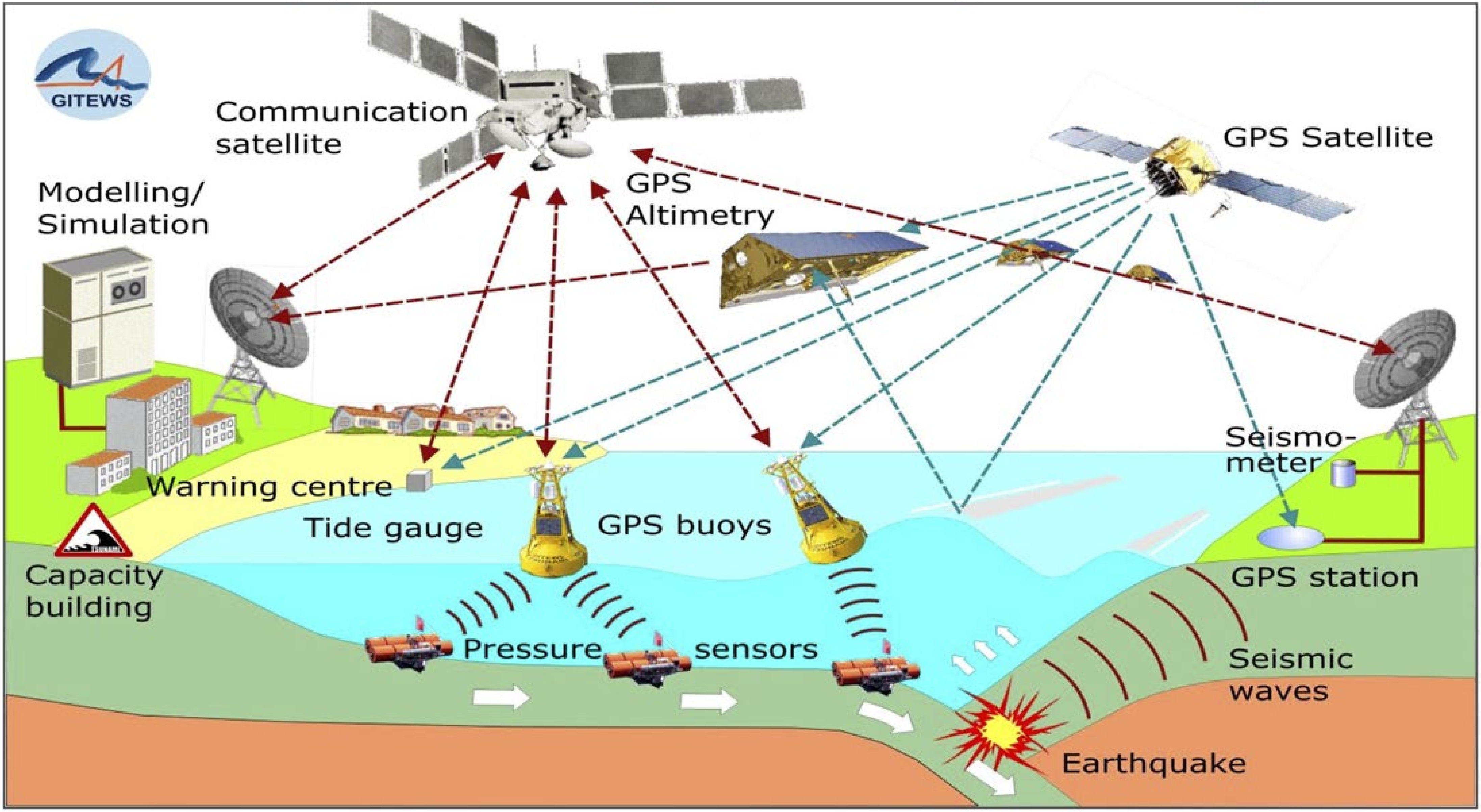
Having a Radio Astronomy Antenna + GNSS implies you have various instruments requiring novel approaches in:

- integration + communication
- data management + data visualisation
- data processing + data products (integrated from multiple datasets)

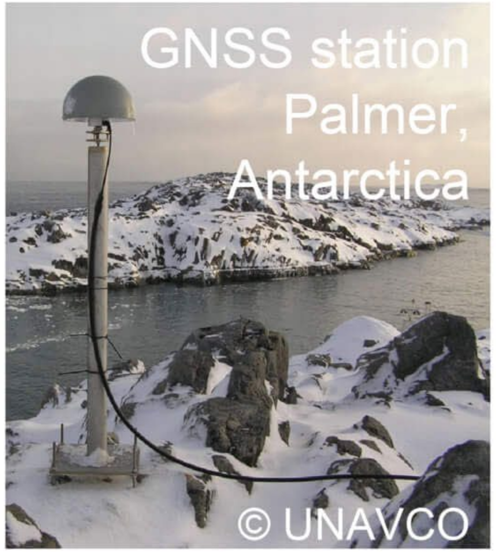
All of these create knowledge with potential spin-offs in:

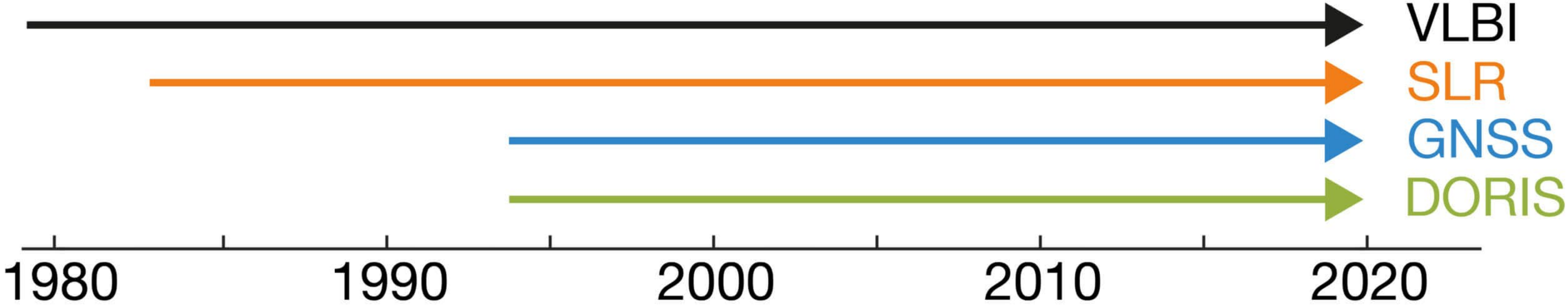
- Start-up companies / entrepreneurship
- Intellectual Property
- Next generation of skilled workers (stay in science / move to industry)

Societal benefits of Geodesy



History of modern (space) Geodesy





Thank you

http://geodesy.hartrao.ac.za/