l'Observatoire de Paris SYRTE

Systèmes de Référence Temps-Espace

Geodesy What is it, and why do I like it?

AVN Training School 2019, HartRAO

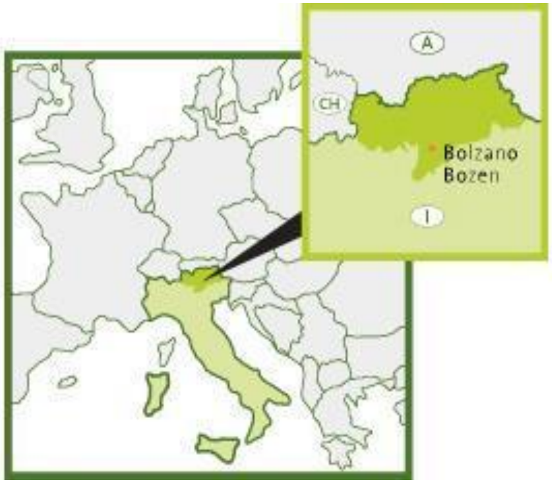
Maria Karbon

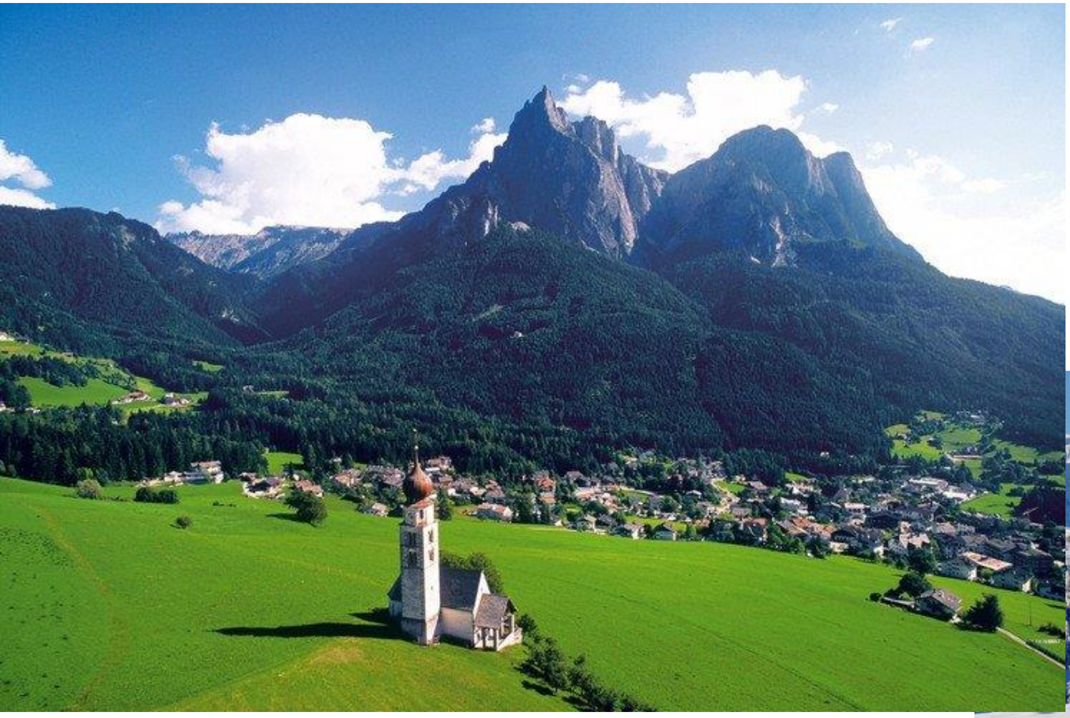
SYRTE, Observatoire de Paris

Introducing myself

I am…

- Maria Karbon
- from Seis am Schlern, South Tyrol, Italy

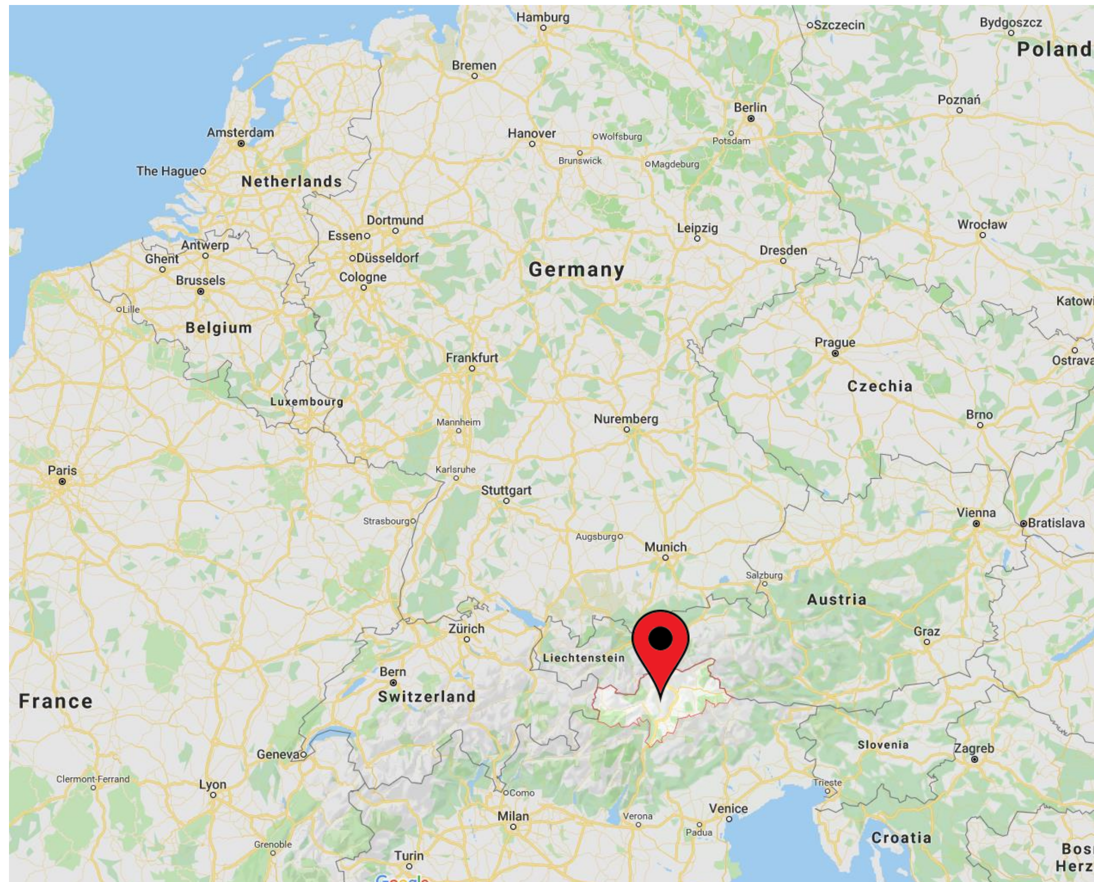




I studied…

- Informatics in high school (2003)

Max VALIER Gewerbeoberschule



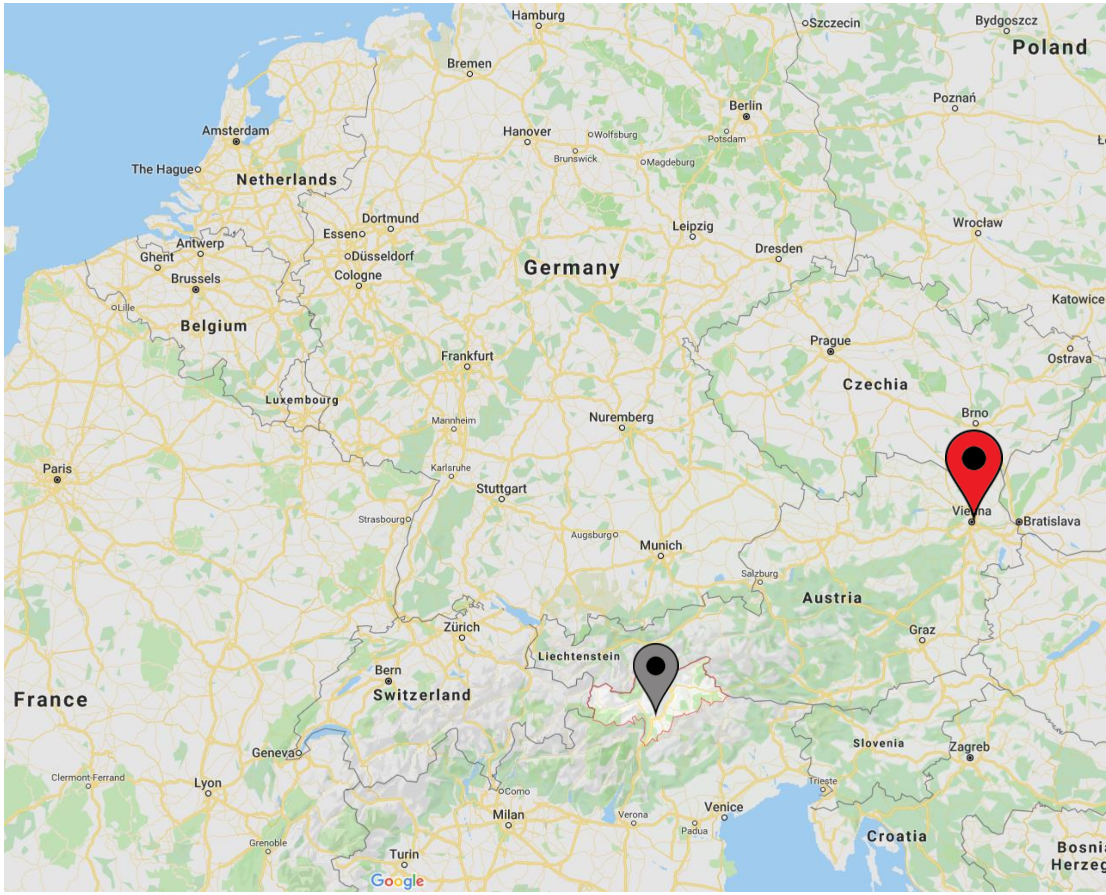
Introducing myself

I studied…

- Informatics in high school (2003)
- Diploma in Geodesy

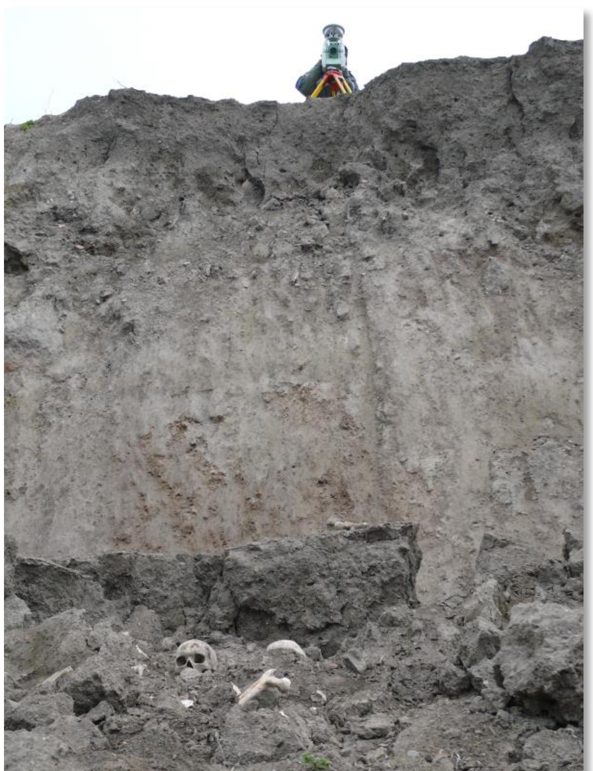
TU WIEN

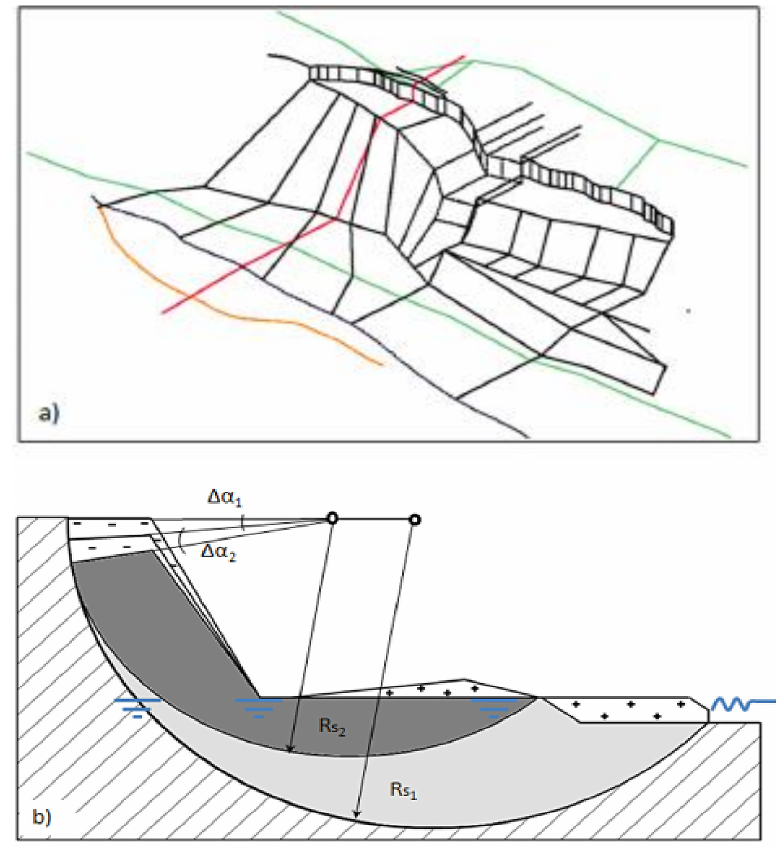
TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria



Diploma thesis

- Kinematics of a mass movement constrained by sparse and inhomogeneous data



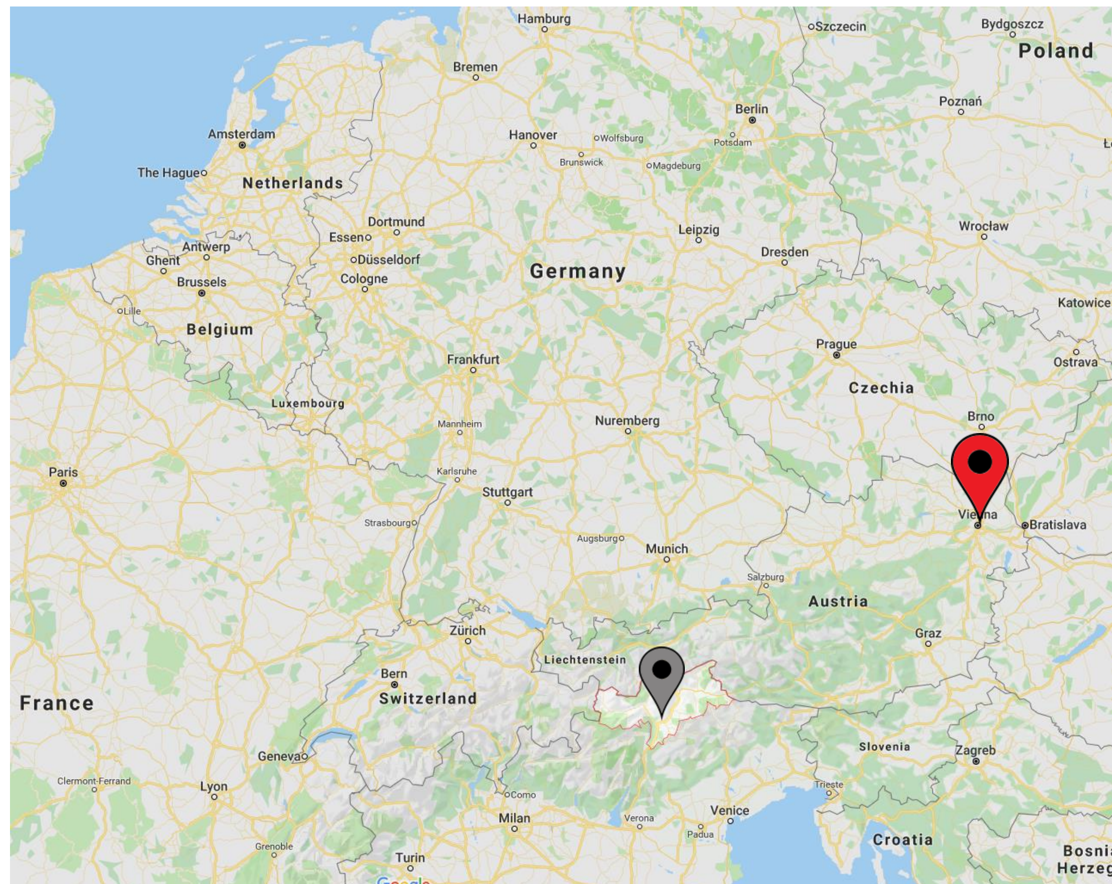


Introducing myself

I studied…

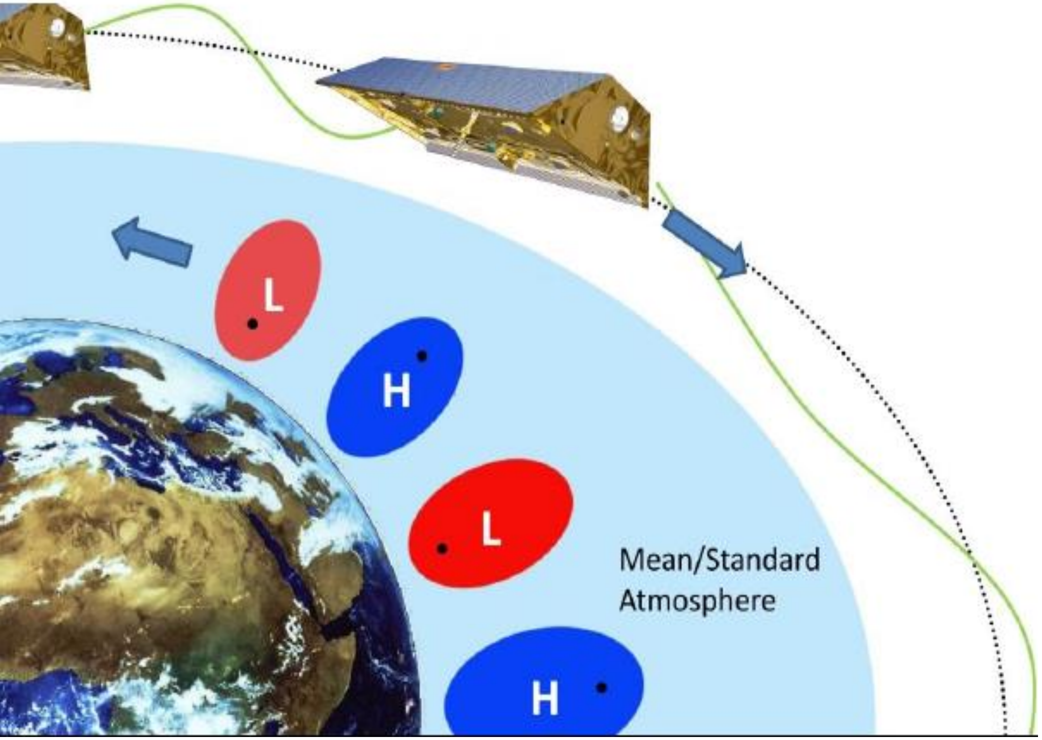
- Informatics in high school (2003)
- Diploma in Geodesy
- PhD

TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria



PhD (2013)

- Atmospheric effects on measurements of the Earth gravity field

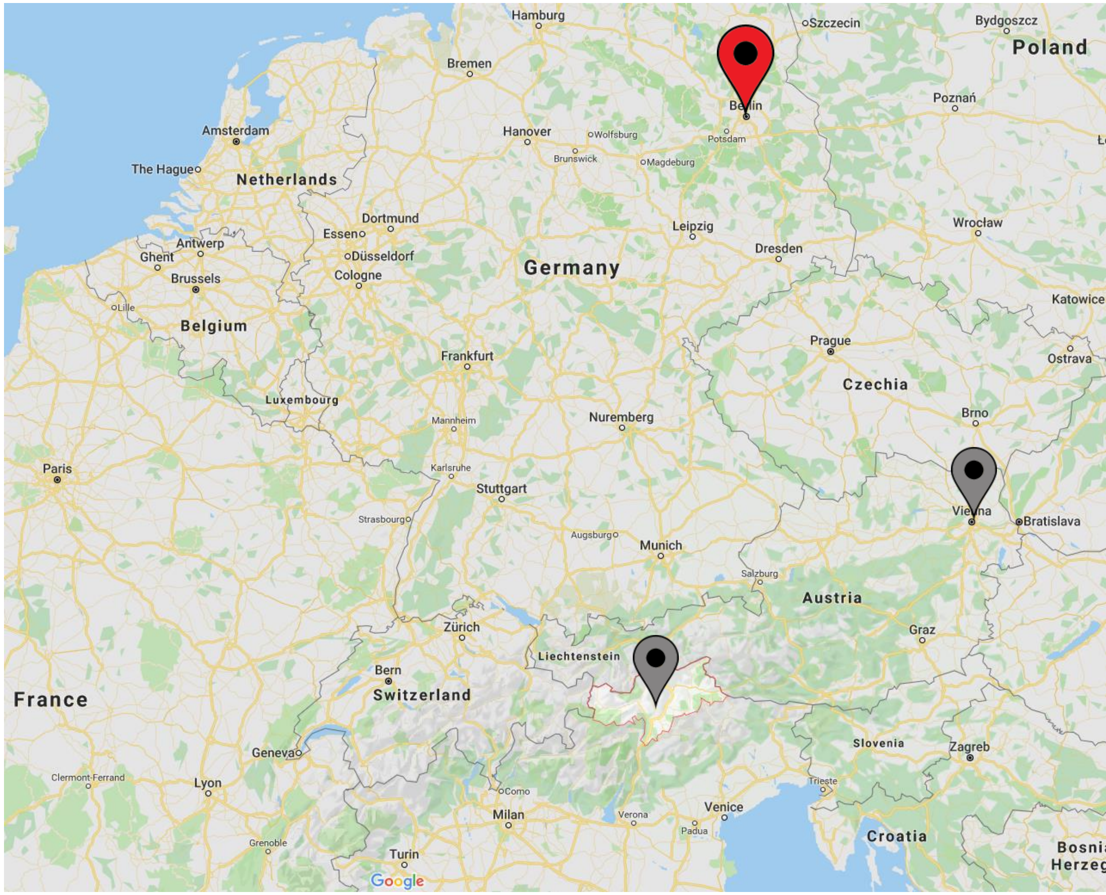


Introducing myself

I studied and worked…

- Informatics in high school (2003)
- Diploma in Geodesy
- PhD
- PostDoc

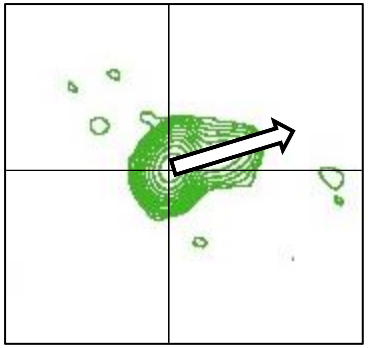
GFZ
Helmholtz Centre
Potsdam



Introducing myself

PostDoc (2013- May 2017)

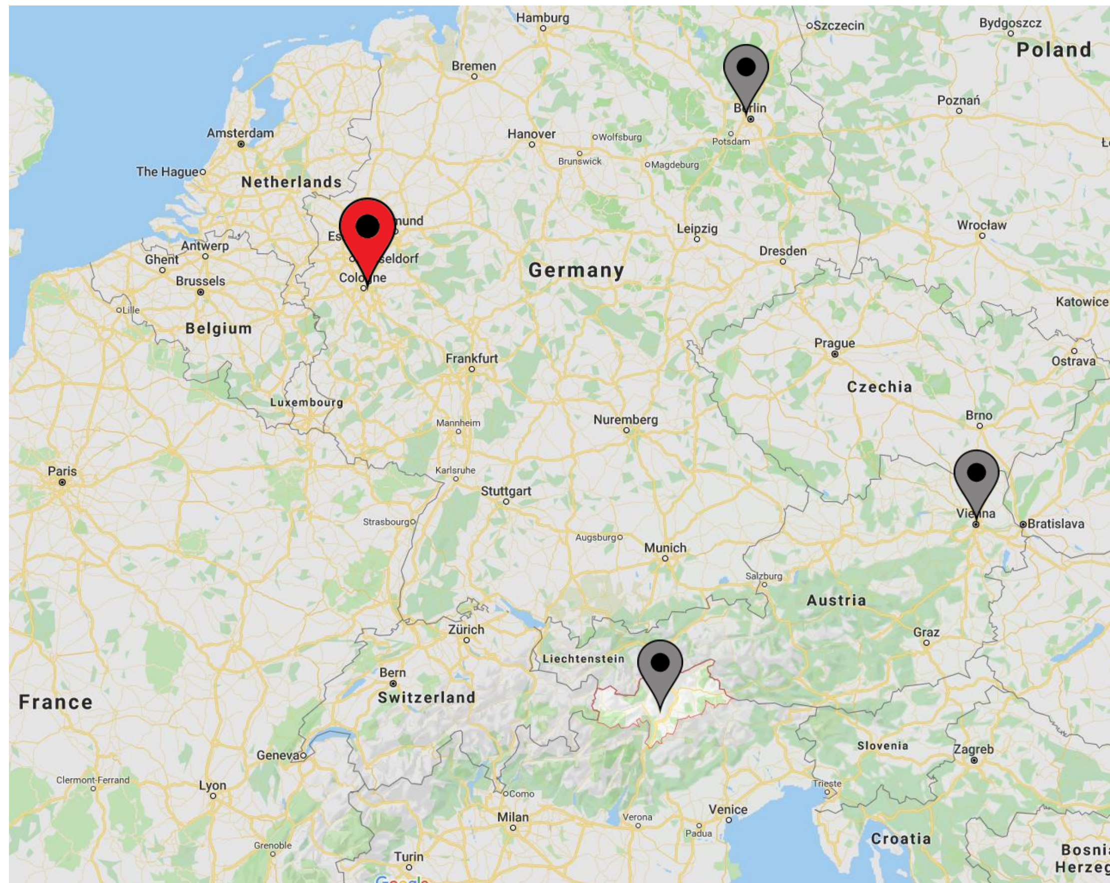
- Earth orientation parameters from VLBI determined with a Kalman filter [Karbon et al., 2014]
- The extension of the parametrization of the radio source coordinates in geodetic VLBI and its impact on the time series analysis. [Karbon et al., 2016]
- Long term evaluation of ocean tidal variation models of Earth rotation. [Karbon et al., 2018]



Introducing myself

I studied and worked…

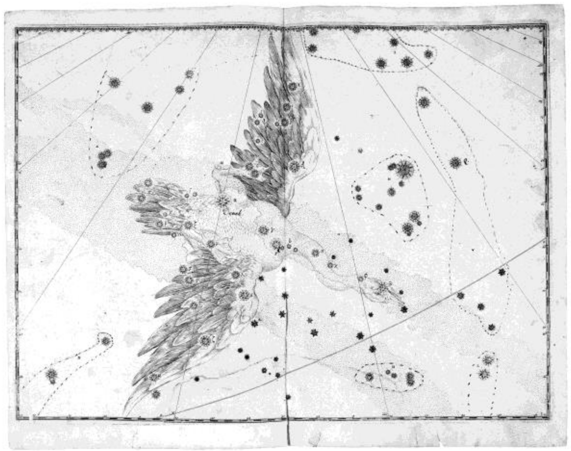
- Informatics in high school (2003)
- Diploma in Geodesy
- PhD
- PostDoc



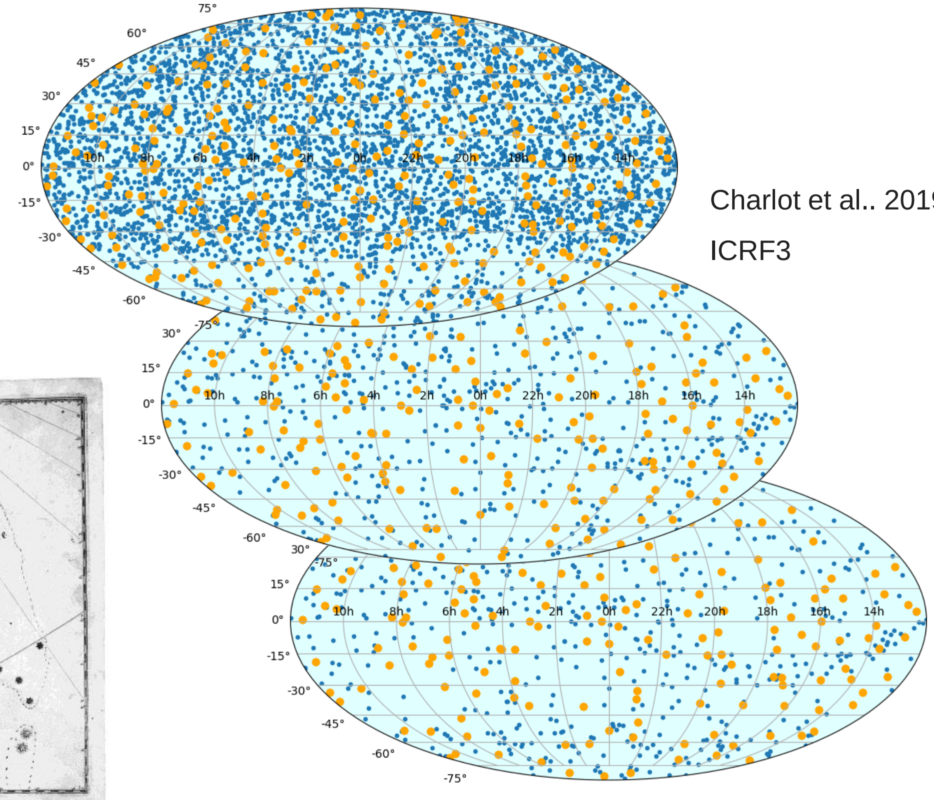
PostDoc (October 2017 – March 2018)

- Combination of celestial reference frames on normal equation level

Nebra sky disk 2100-1700 BC



Johann Bayer, 1603: Uranometria



Charlot et al.. 2019:

ICRF3

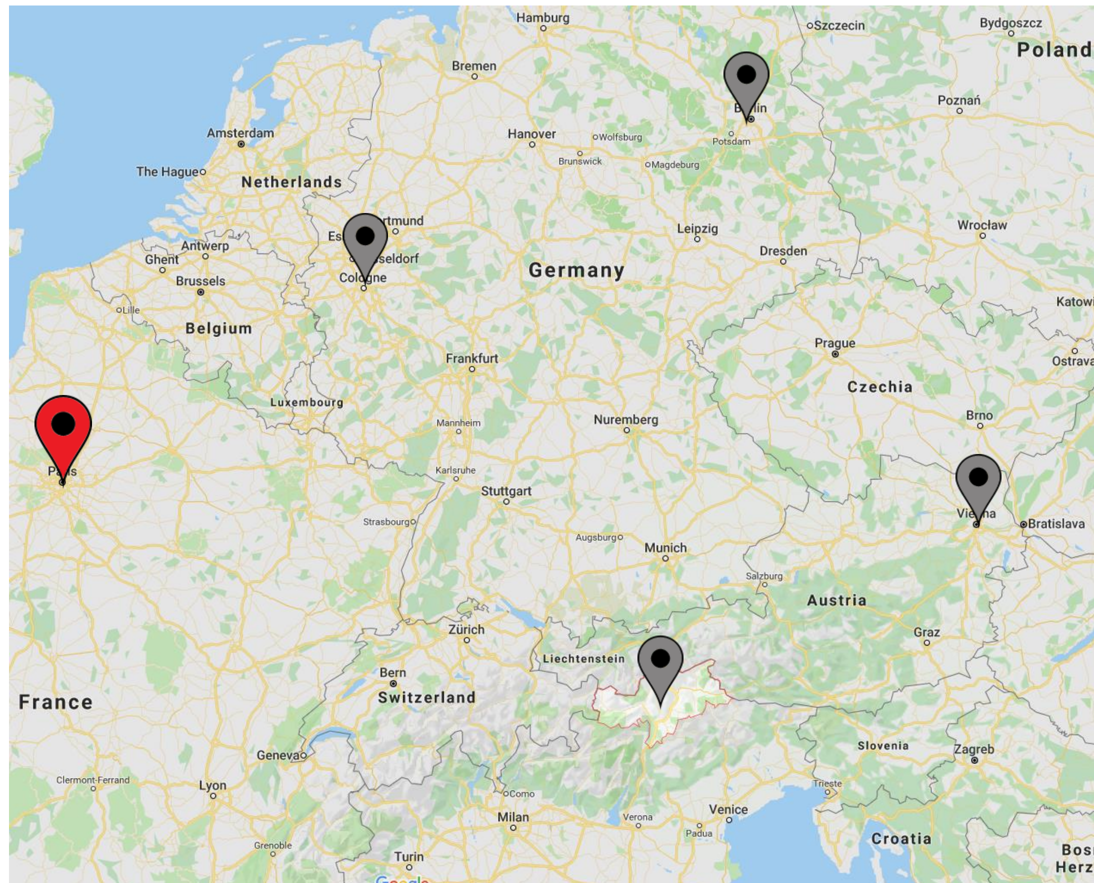
Introducing myself

I studied and worked…

- Informatics in high school (2003)
- Diploma in Geodesy
- PhD
- PostDoc

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace



What is it?

What does it mean?

- Geo – desy = Earth – dividing
- geo (← γη)
  - Gaia, goddess of the Earth
  - Earth, land, town, acre, soil, estate
- desy (← δαιομαι, δαιεσθαι) = divide, allot, distribute

- Example: Nile valley
  - border demarcation
  - surveying
  - mapping
  - cadaster
  - real estate regulation

Geodesy

What is it?

- Geodesy is the science of measuring and mapping the Earth surface.

Friedrich Robert Helmert
1843 - 1917

What is it?

- The objective of geodesy is the determination of the potential function W(x,y,z).

Ernst Heinrich Bruns
1848 - 1919

Geodesy

What is it?

- Geodesy is what geodesists do for their living.

Helmut Moritz
1933-

What is it?

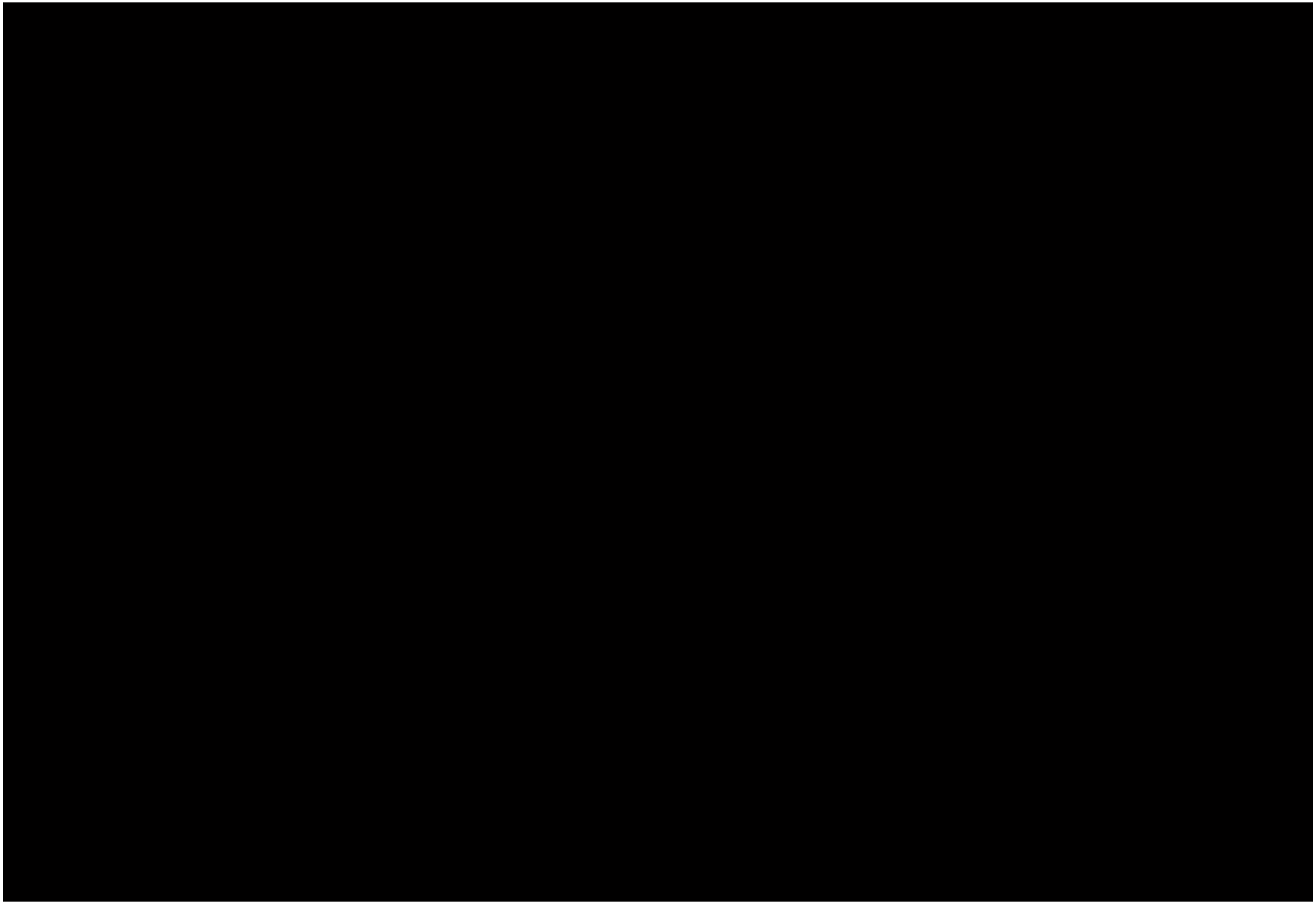
- Geodesy is a discipline that deals with measurement and representation of the Earth, including its gravity field, in a three-dimensional time varying space.

National Research Counci of Canada, 1973
Vanicek & Krakiwsky, 1982

What is it?

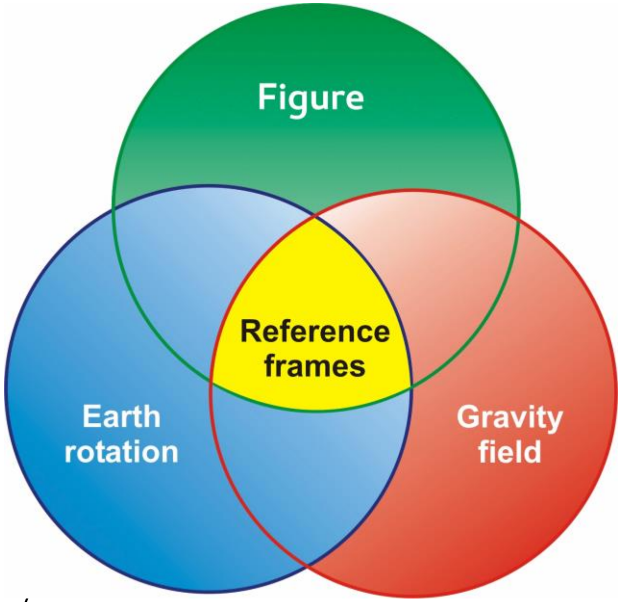
- Geodesy is a discipline that deals with the measurement and representation of the shape of the Earth, its orientation in space and its gravity field, in a 3D time varying space.

Geodesy



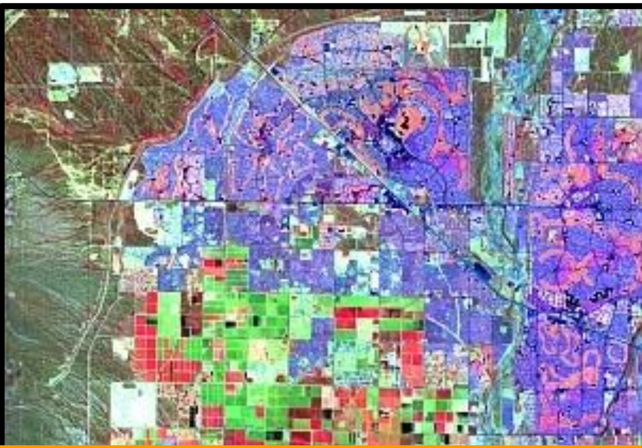
Three pillars of Geodesy

- Figure of the Earth
  - topography, bathymetry, ice surface, sea level
- Earth rotation and orientation
  - polar motion, Earth rotation, nutation, precession
- Gravity field of the Earth
  - gravity, geoid

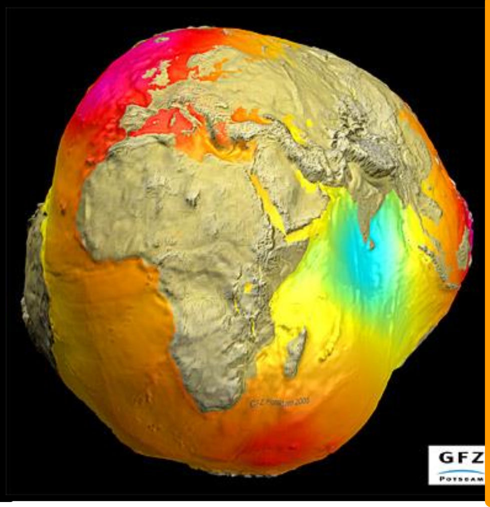


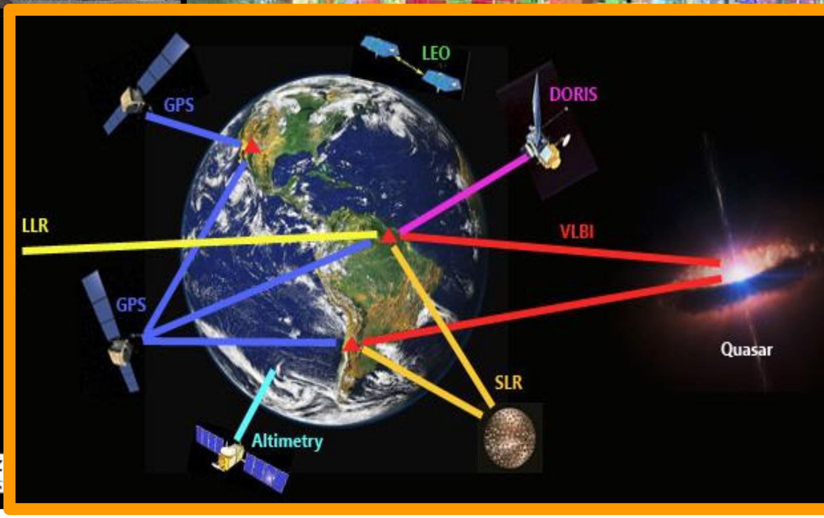
http://www.iag-aig.org/

Geodesy



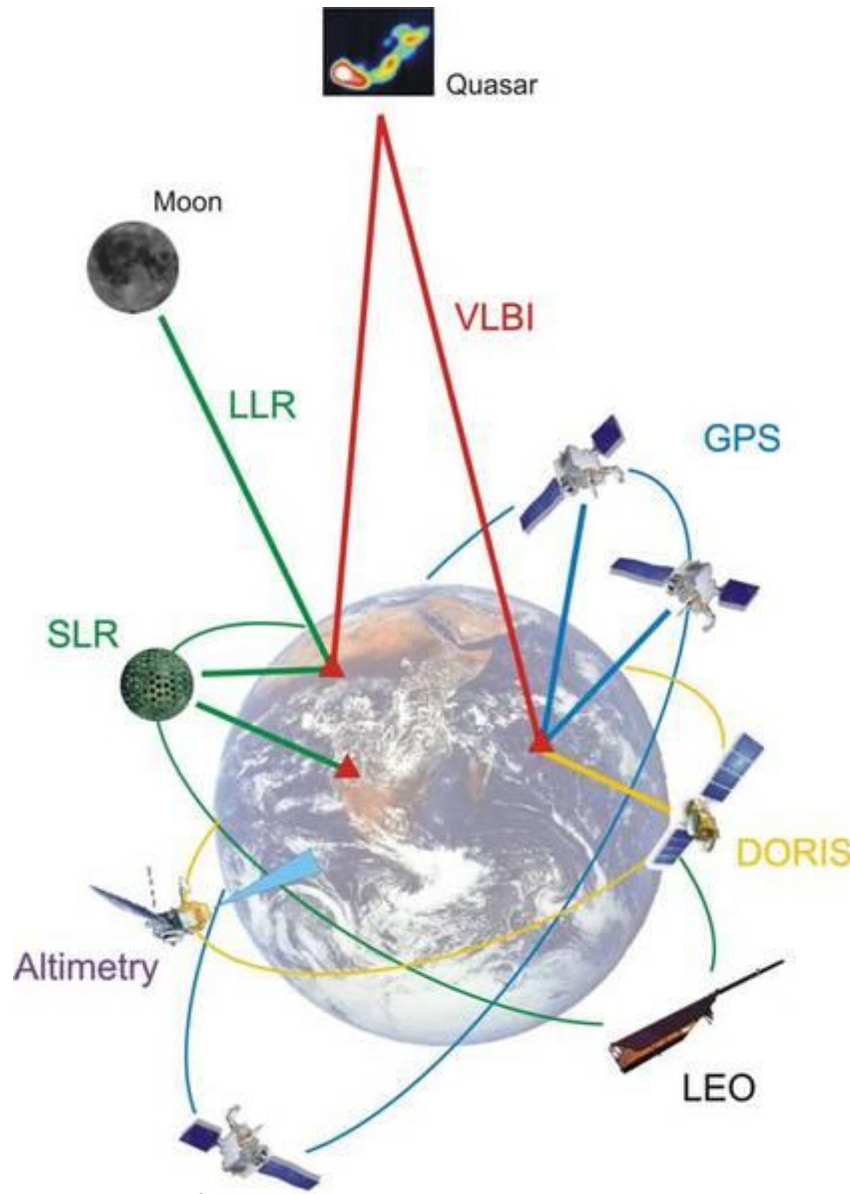

PULHEIM
BERGISCH GLADBACH
KÖLN
FRECHEN
KERPEN
HÜRTH
RÖSRATH
BRÜHL
LOHMAR


GFZ


LEO
GPS
DORIS
LLR
VLBI
GPS
Quasar
SLR
Altimetry

Space geodesy…

- studies the aspects of geodesy by using natural or artificial celestial bodies as observed objects or as observing platforms.

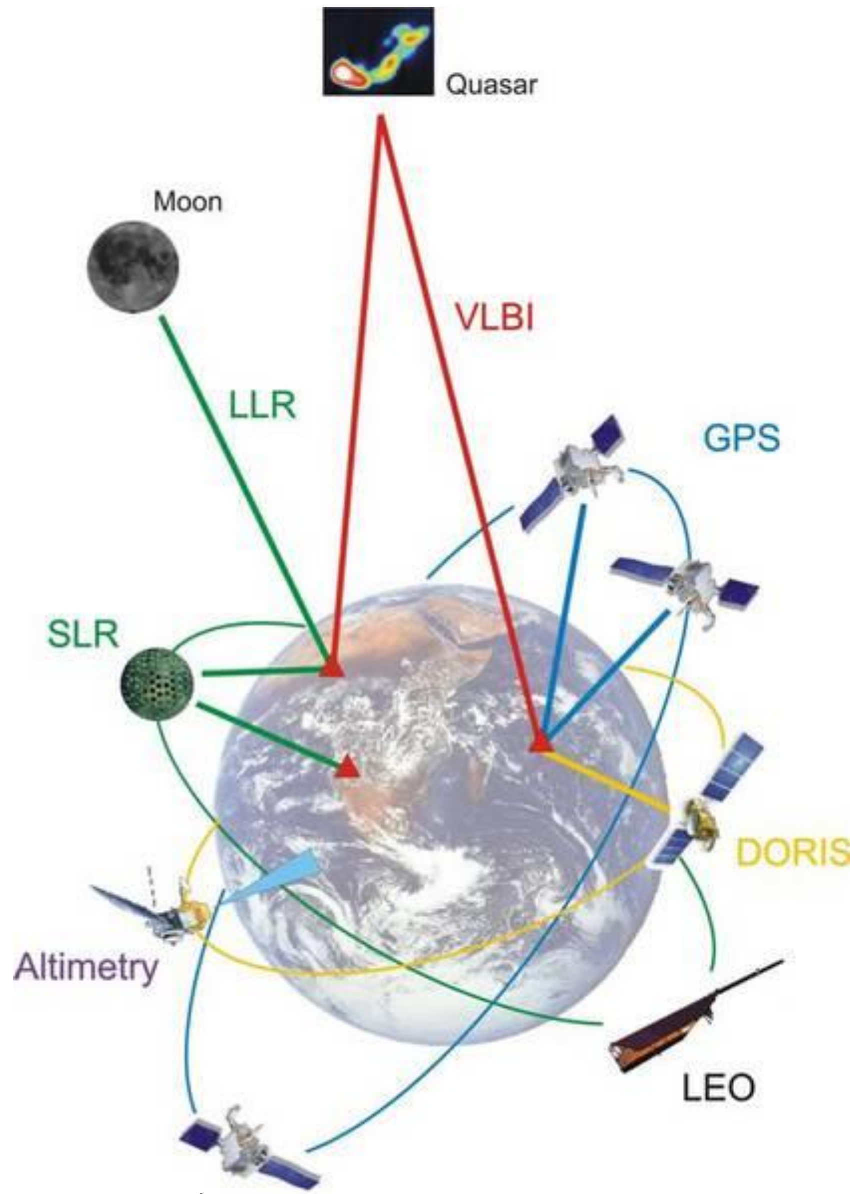


http://www.iag-aig.org/

Space geodesy…what for?

- studies the aspects of geodesy by using natural or artificial celestial bodies as observed objects or as observing platforms.

Global monitoring of the System Earth

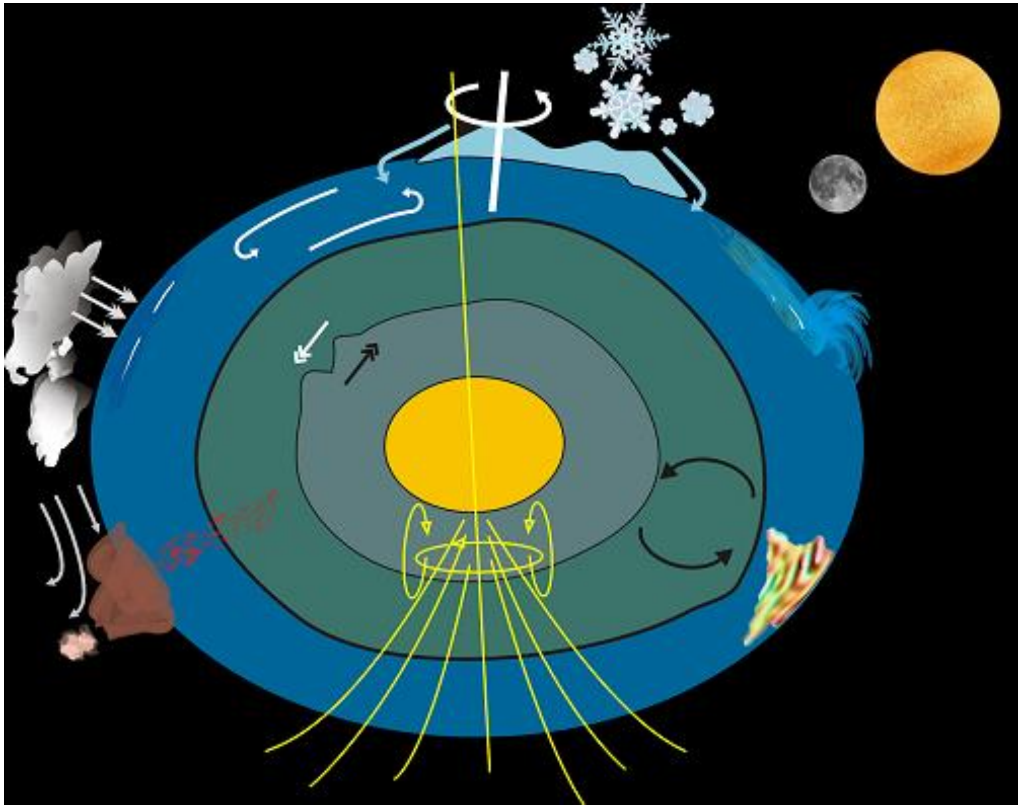


http://www.iag-aig.org/

Subsystems of the Earth

- Geodetic parameters are closely related to changes of mass distributions within and between the Earth‘s subsystems and the related interactions.

- Solid Earth
- Atmosphere
- Hydrosphere
- Cryosphere
- Biosphere
- Anthroposphere
- (Space)



Geometry and deformation of the Earth

- Everything moves!
  - Problem and fascination of geodesy

- Examples:
  - Earth rotation
  - Solid Earth tides
  - Plate tectonics
  - Earthquakes
  - Global weather
  - Sea level change
  - Loading (ice, ocean, atmosphere)

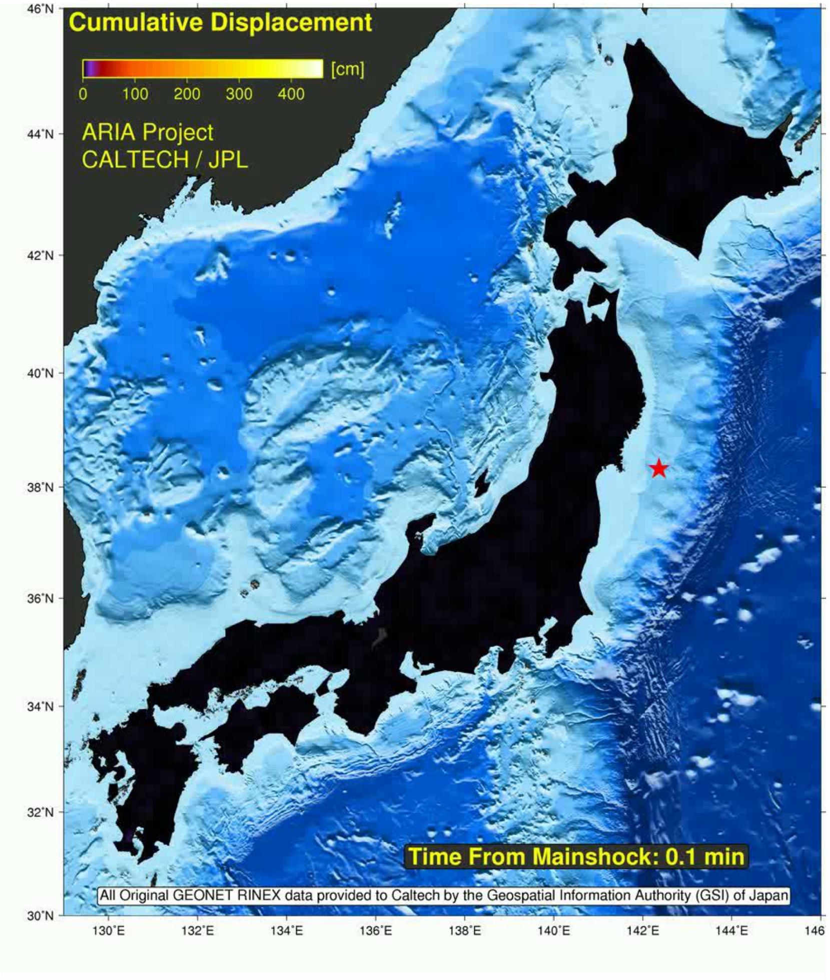
Christchurch, New Zealand,M: 7.1, 04.10.2010.

Time scales of changes

- Sudden
  - Earthquake (*local, regional)*
  - Rockslide and -avalanche *(local)*
  - Land slide *(local)*
  - Mud slide *(local)*
- Emerging
  - Volcanic eruption *(regional, global)*
  - Tsunami *(local to trans regional)*
  - Hurricane, Storm *(regional)*
  - Flood *(regional)*
- Long term
  - Climate change (sea level, temperature, weather activity, atmospheric structure, etc.) *(global)*
  - Tectonic plate motion *(global)*

Monitoring System Earth

Sudden: M 9.0 Tohoku earthquake ,11. March 2011

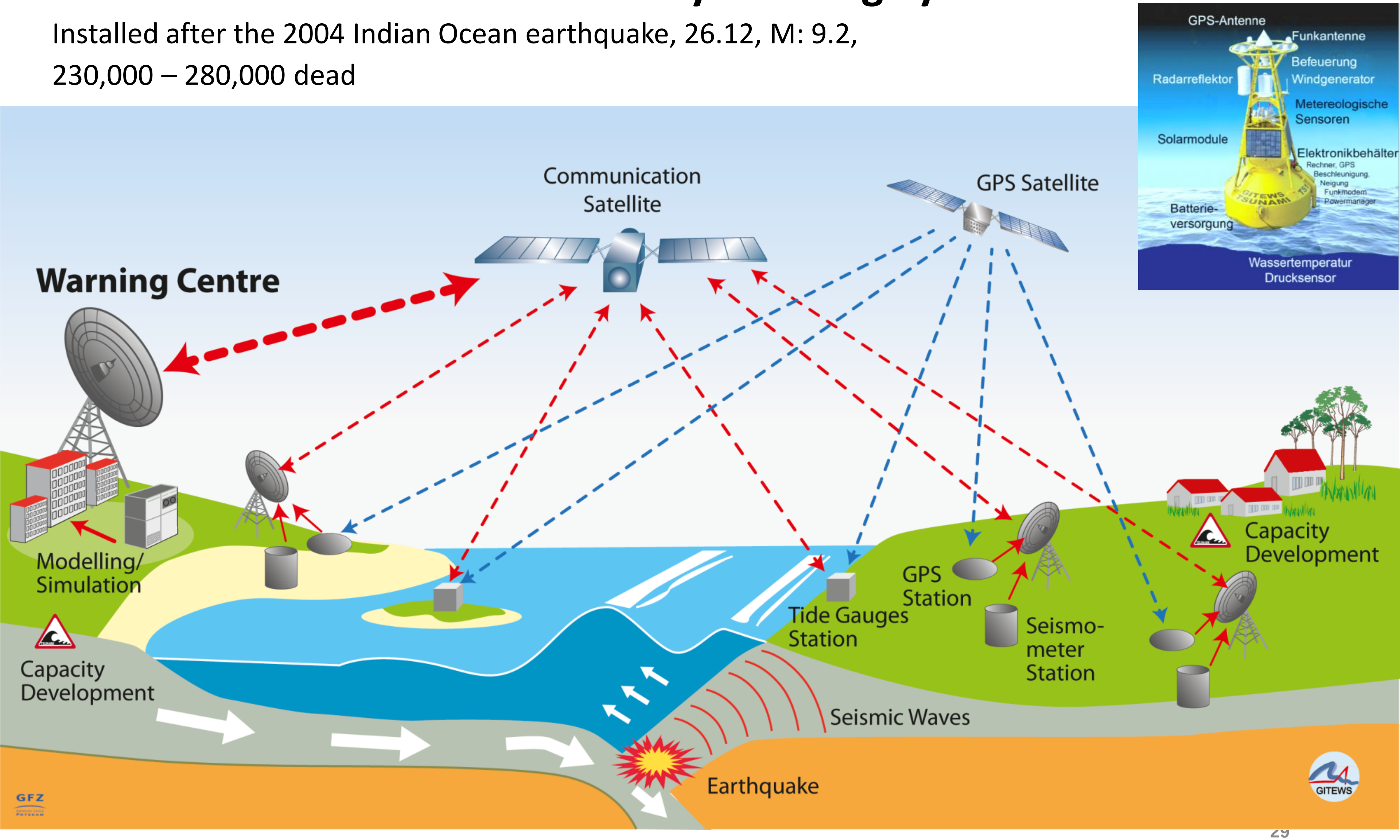


Sudden: M 9.0 Tohoku earthquake ,11. March 2011

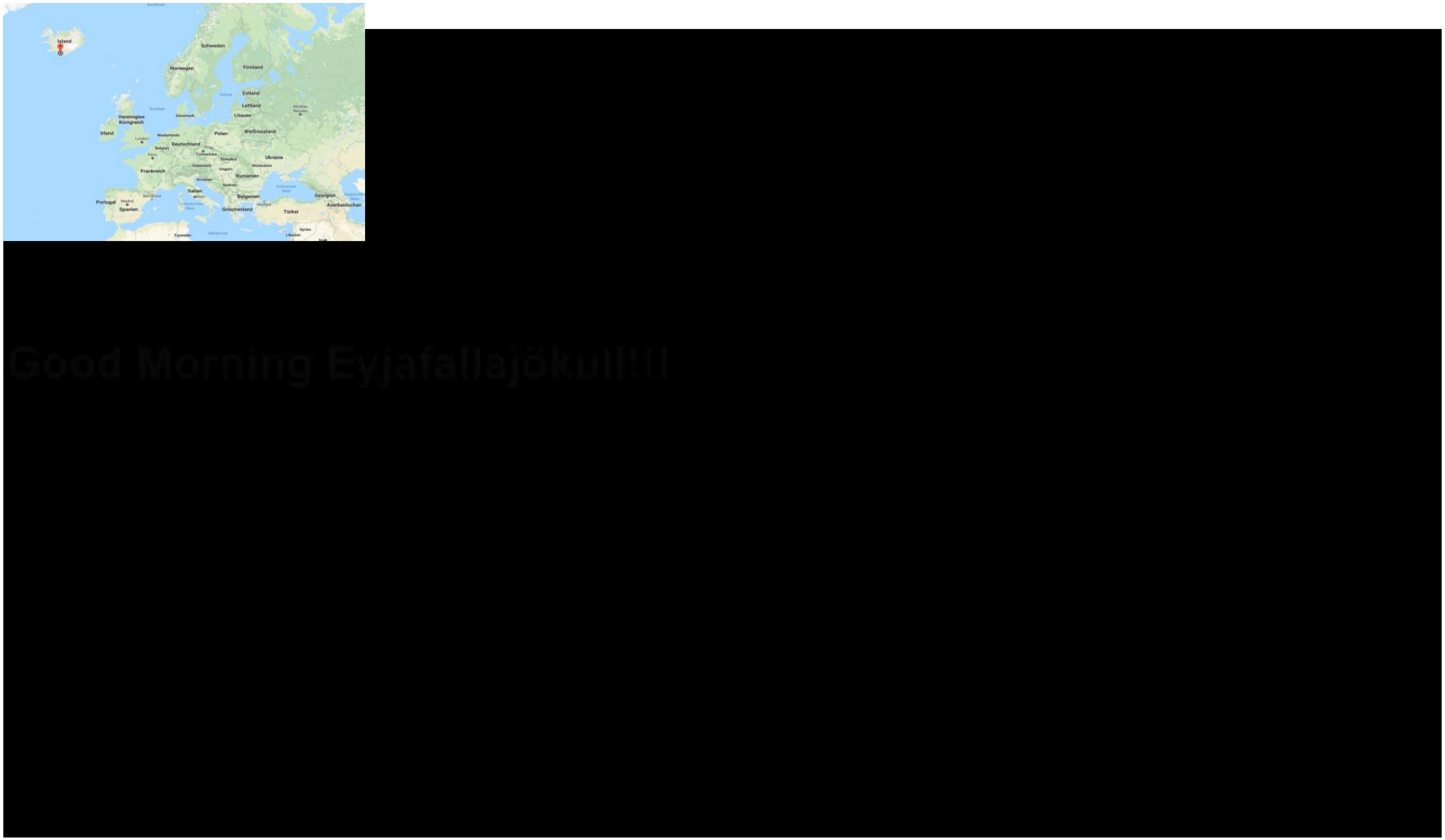
Monitoring System Earth

German Indonesian Tsunami Early Warning System

Installed after the 2004 Indian Ocean earthquake, 26.12, M: 9.2,
230,000 – 280,000 dead

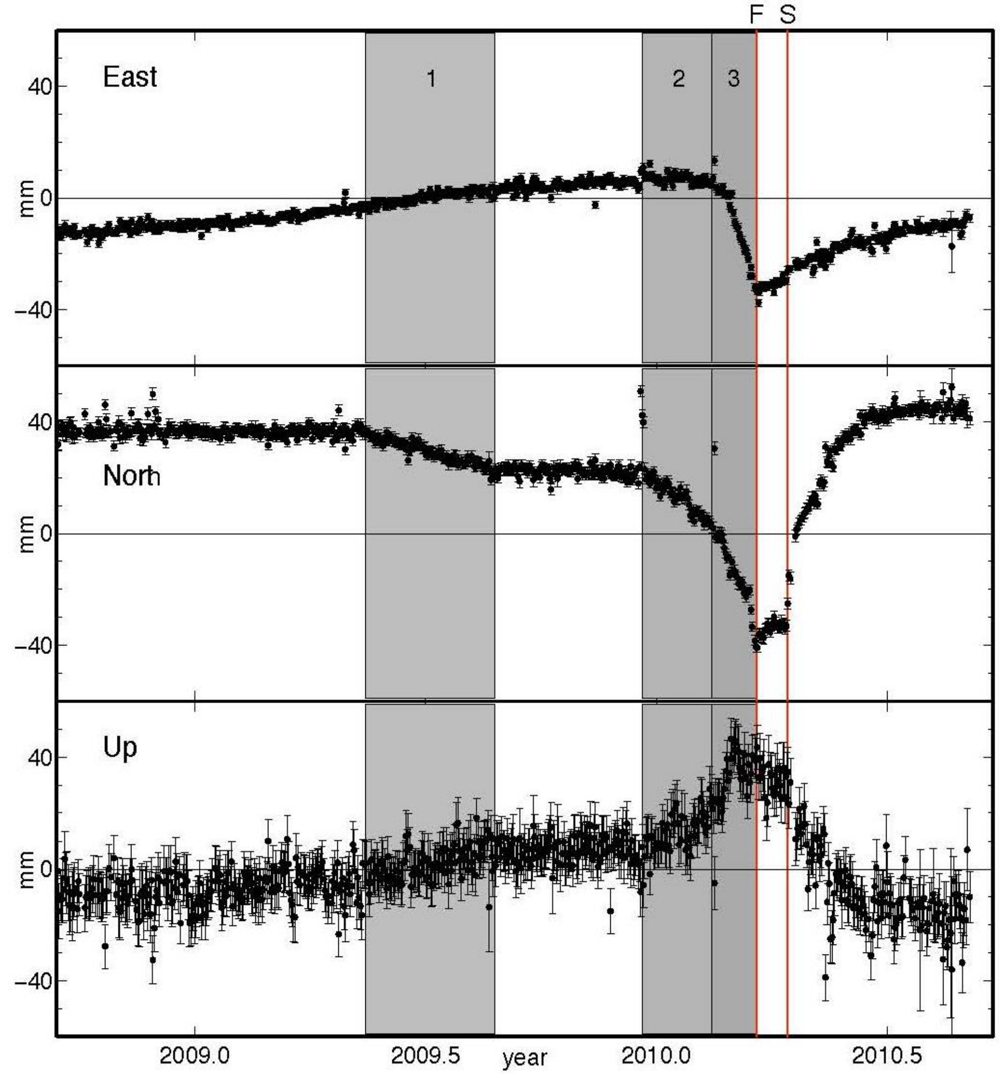


Emerging: Eyjafjallajökull, March-April 2010



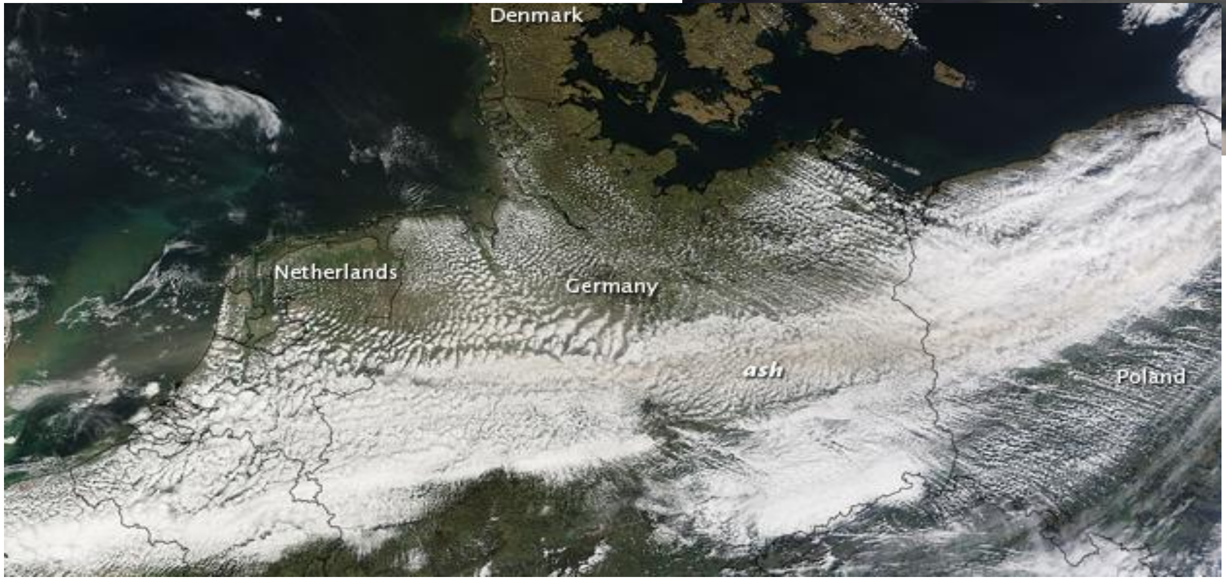
Emerging: Eyjafjallajökull, March-April 2010

- GPS time series of the station THEY
  - (south of the Eyjafjallajökull)
  - Relative to station REYK (Reykjavík)
- Grey areas (intrusions phases)
- Red line F (lateral eruption)
- Red line S (peak eruption)



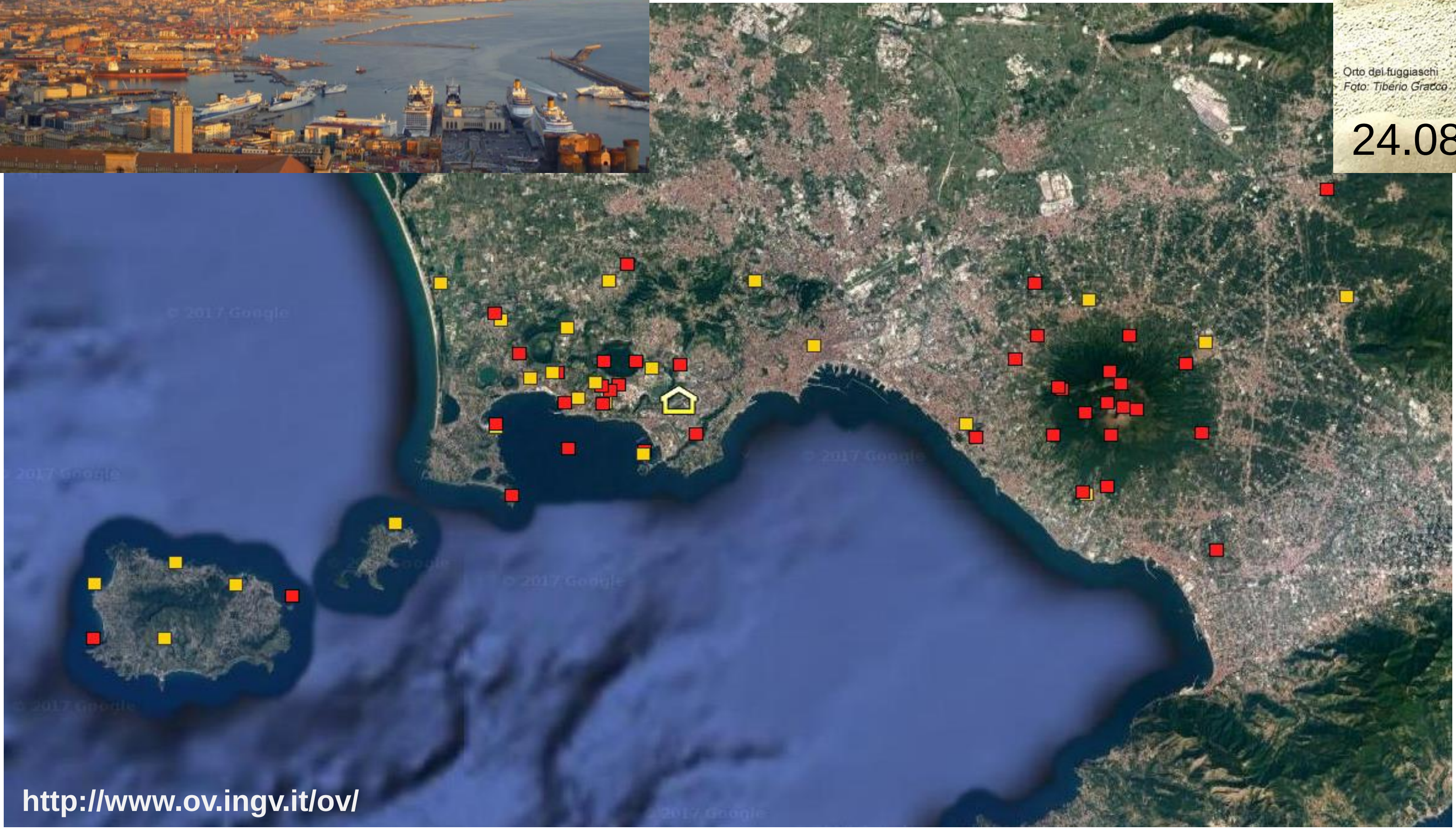
F Sigmundsson *et al. Nature* 468, 426-430 (2010)

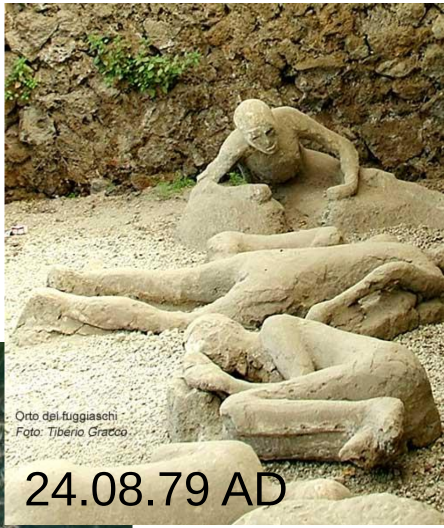
Emerging: Eyjafjallajökull, March-April 2010



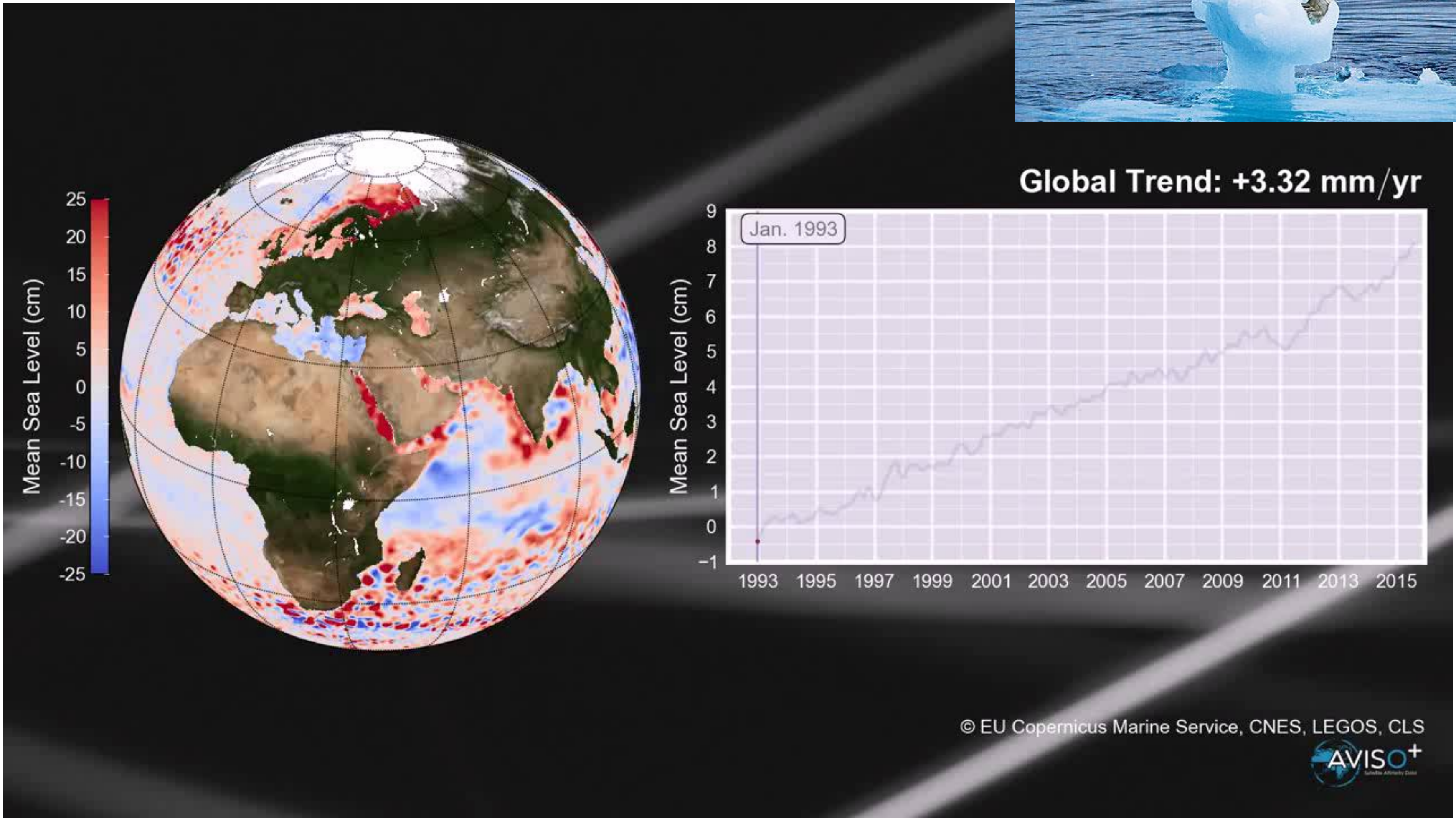
[NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC]

Emerging: Mount Vesuvius ?

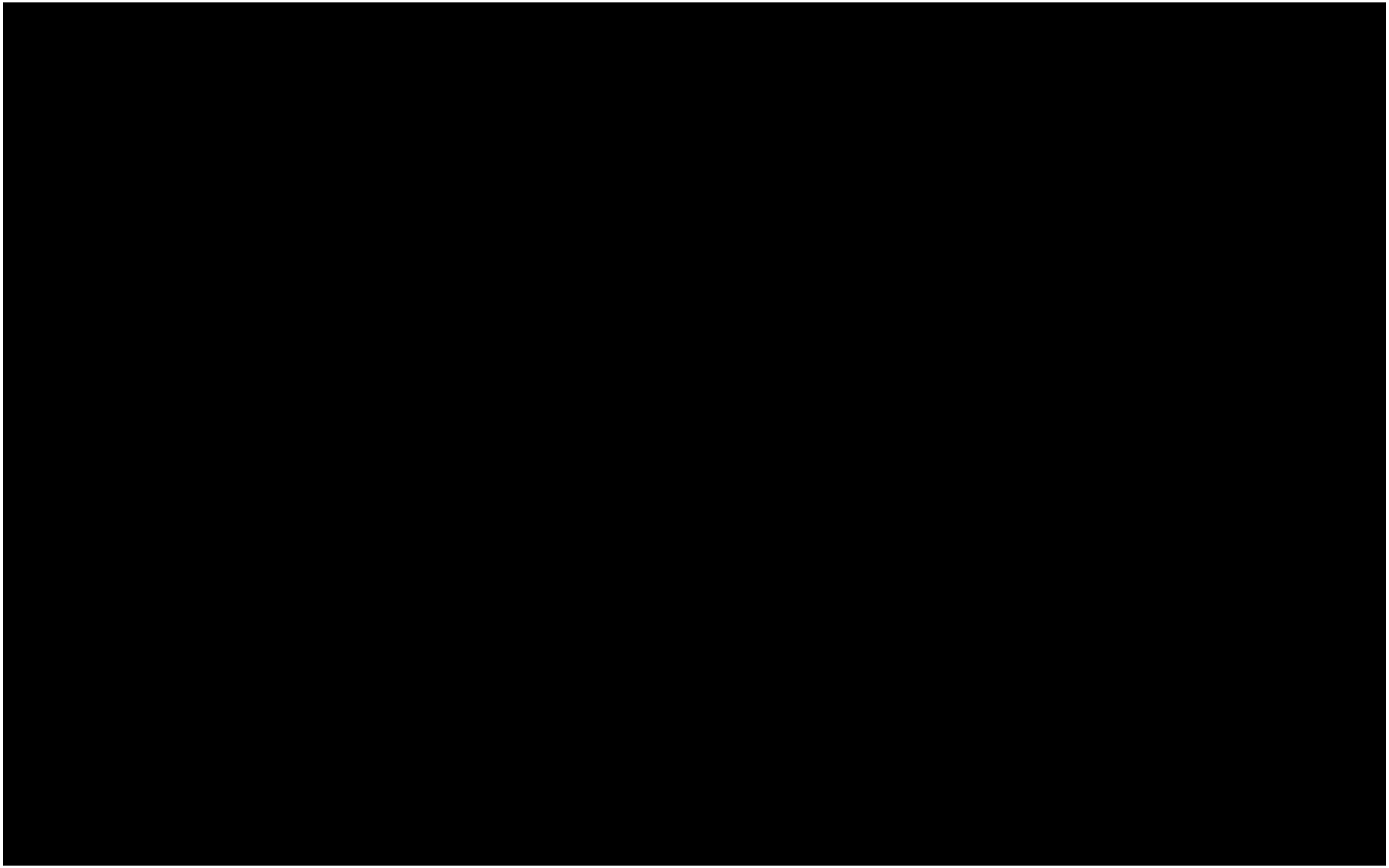




Long term: Sea level rise

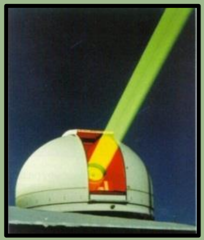
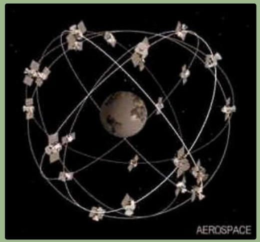


Why geodetic VLBI?



The role of VLBI for space geodesy

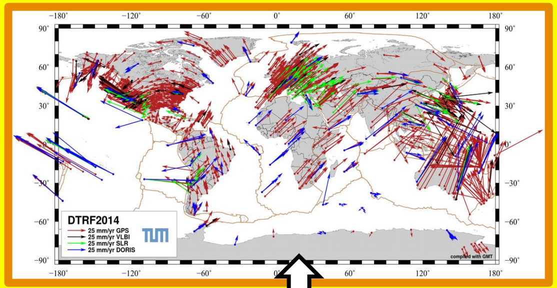
Geodetic observation techniques

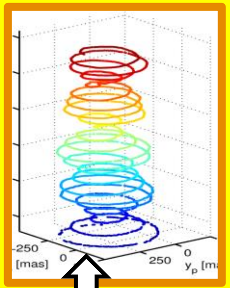




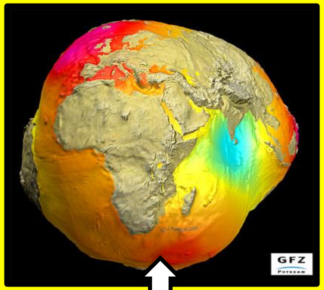


Standards and Models | Analysis Centres | Combination Centres

Geodetic products







Geodetic reference frames

IAG GGOS Bureau for Products and Standards (Angermann et al, 2016)

The role of VLBI for space geodesy

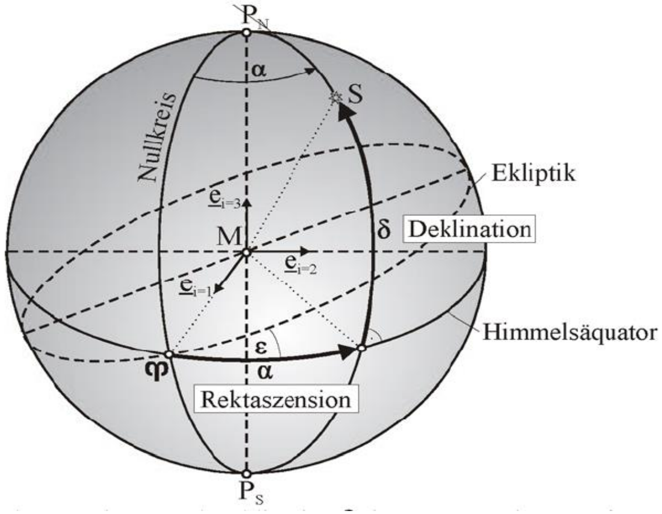
Parameter Type	VLBI	GNSS	DORIS	SLR	LLR	Altimetry
ICRF (Quasars)	X					
Nutation, Precession	X	(X)		(X)	X	
Polar Motion	X	X	X	X	X	
UT1	X					
Length of Day	(X)	X	X	X	X	
ITRF (Stations)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO Orbits		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time Freq./Clocks	(X)	X		(X)		

Fields involved

- astronomical objects, radio sources (astrophysics, radio astronomy),
- propagation of radio in space-time (gravitational physics) and in the atmosphere (atmosphere physics)
- the antenna- and receiver, mechanical and electronical components of the instrumentation (radio-frequency engineering),
- Earth as being the carrier of the interferometer baselines formed by antenna pairs (geodynamics),
- correlator (signal processing), and analysis of VLBI observations, application of physically motivated mathematical models through the software based on the objective and subjective decisions of the operator(s)
- (space geodesy)

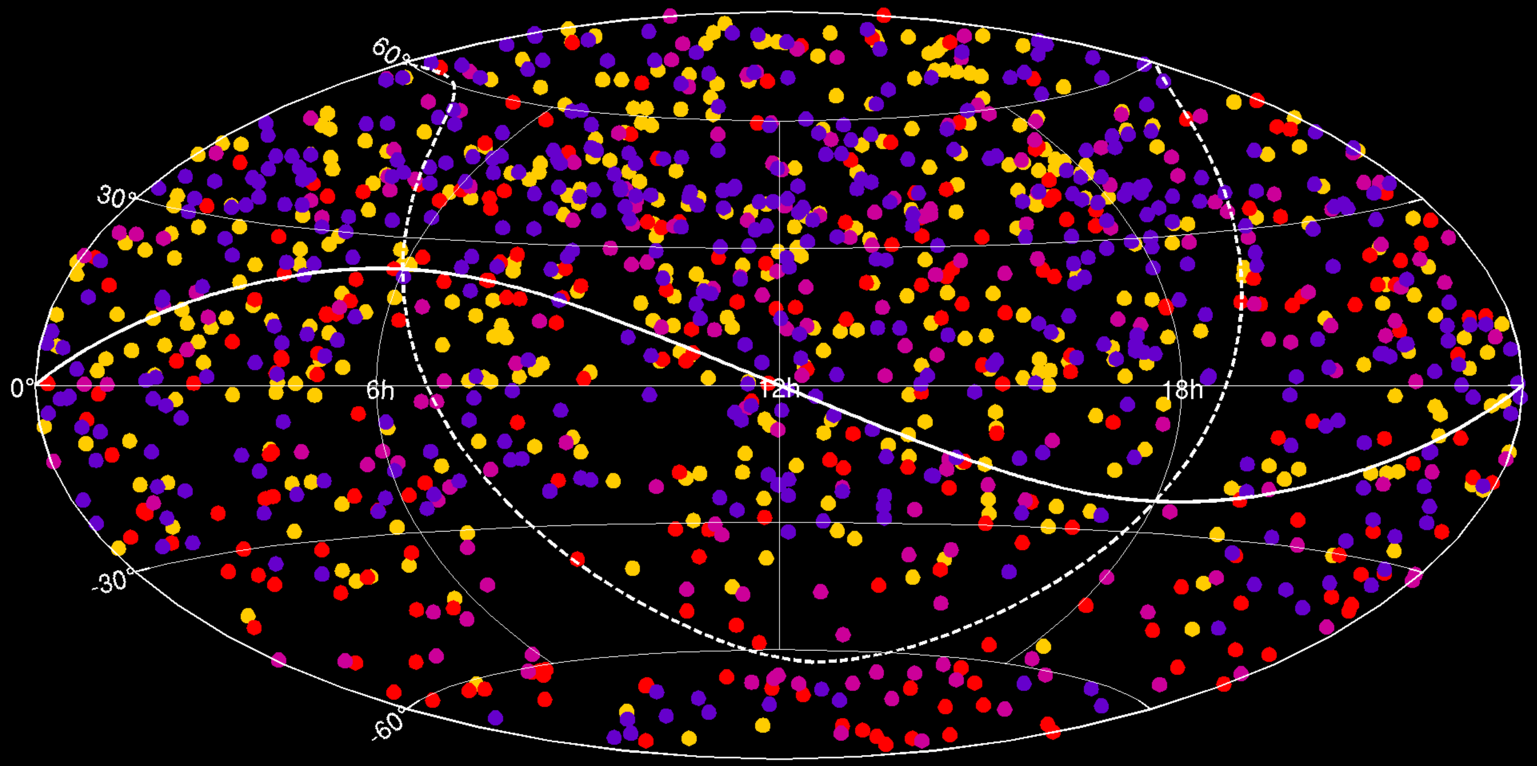
Quasi-inertial system realized by VLBI

- Orientational quasi-inertial system realized by VLBI
- Origin
  - Solar System Barycenter (SSB), i.e. the center of mass of the solar system bodies (solar system dynamics)
- Time scale, metric
  - Barycentric coordinate time (TCB), BCRS
- Orientation, principal plain
  - True celestial equator at J2000.0 defined by precession (Lieske et al, 1977) and nutation (Seidelmann et al., 1982) models
- Coordinates
  - Right ascension
    - Clockwise hour angle α, Zero = vernal equinox ♈ (intersection of the mean ecliptic with the true celestial equator at J2000.0 (solar system dynamics)
  - Declination
    - Angle w.r.t. the principal plane δ, positive towards celestial north pole P_N
- Orientation stability
  - The stability of the axes is given by the constant positions of the quasar coordinates (kinematically non-rotating)



(Arias, E.F., et al., Astron. Astrophys. 303, 604, 1995)

International Celestial Reference Frame



Why do we need the ICRF?

- For geodesy, the radio sources are the most stable remote targets.
- They provide the external orientation of Earth (Earth Orientation Parameters).

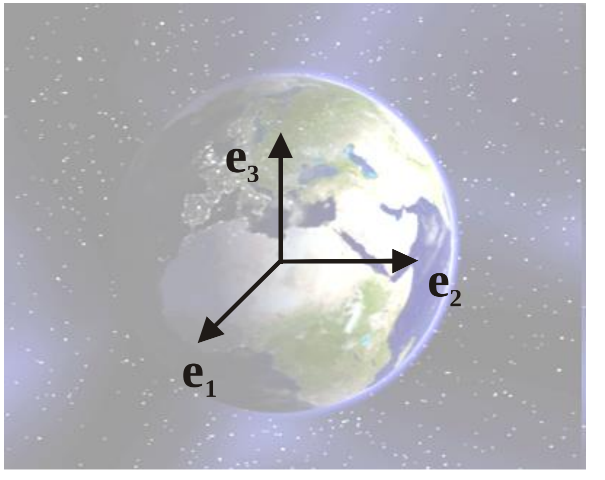
- ICRF2 (Fey et al., 2015) is the most precise and stable orientational frame available
- (IAU 2009, IUGG 2011). It is realized by VLBI observations of extragalactic radio sources.

- Other (celestial) reference frames, such as
  - the galactic reference frame (GalRF),
  - other radio reference frames (e.g. at other radio frequencies),
  - the optical star catalogs (FK5, Hipparcos, FK6, etc.),
  - the planetary ephemerides (JPL, IAA, etc.) and
  - the orbits of satellites

…are referred to ICRF.

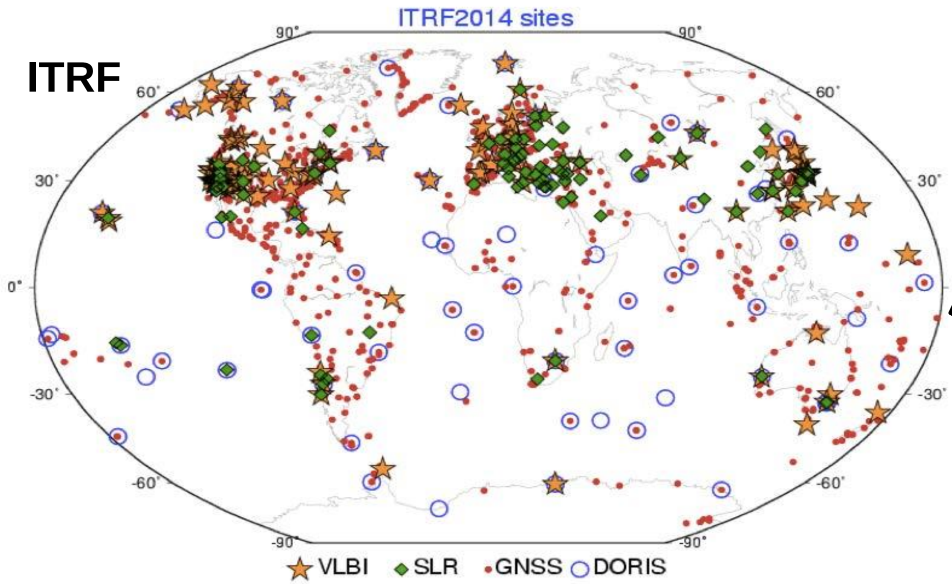
Geocentric co-rotationg body-fixed system

- Origin
  - Center of mass of system Earth, including solid Earth, oceans, atmosphere, cryosphere, …
- Time scale, metric
  - Geocentric coordinate time (TCG), GCRS
- Orientation, principal plane
  - BHI 1984.0 reference pole
  - Equatorial system: e_1 intersection of equator and Greenwich meridian, e_3 mean pole, e_2 orthogonal wrt. e_1/e_3
- Coordinates
  - Geocentric 3D-cartesian
- Orientation stability
  - NNR (kinematically non rotating) on Earth crust model

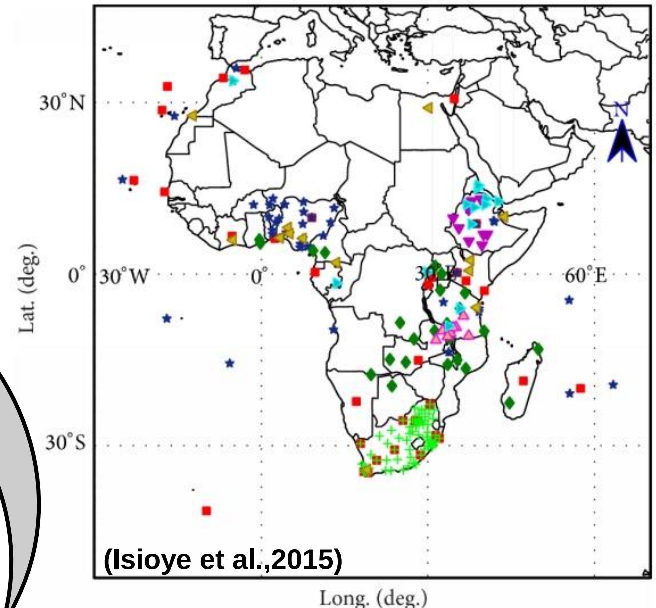


From large scale to the smallest detail

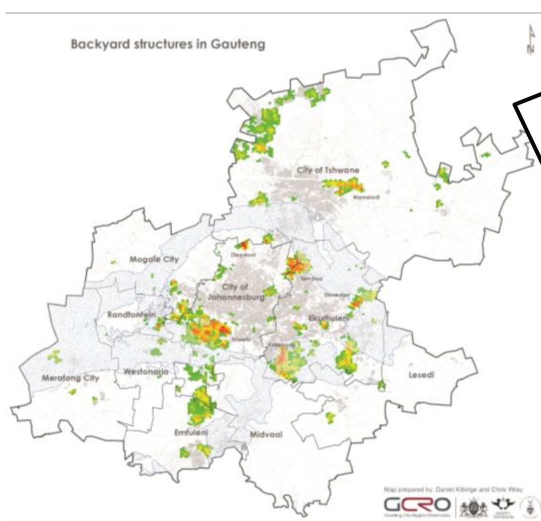
ITRF



AFREF

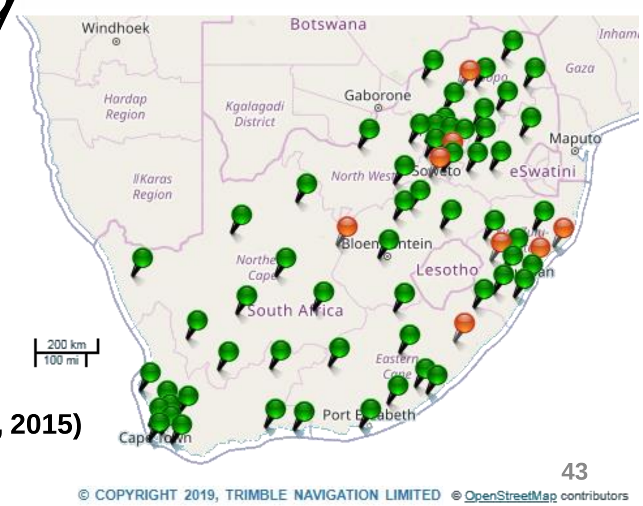


Local reference frame



TrigNet

(Combrinck, 2015)

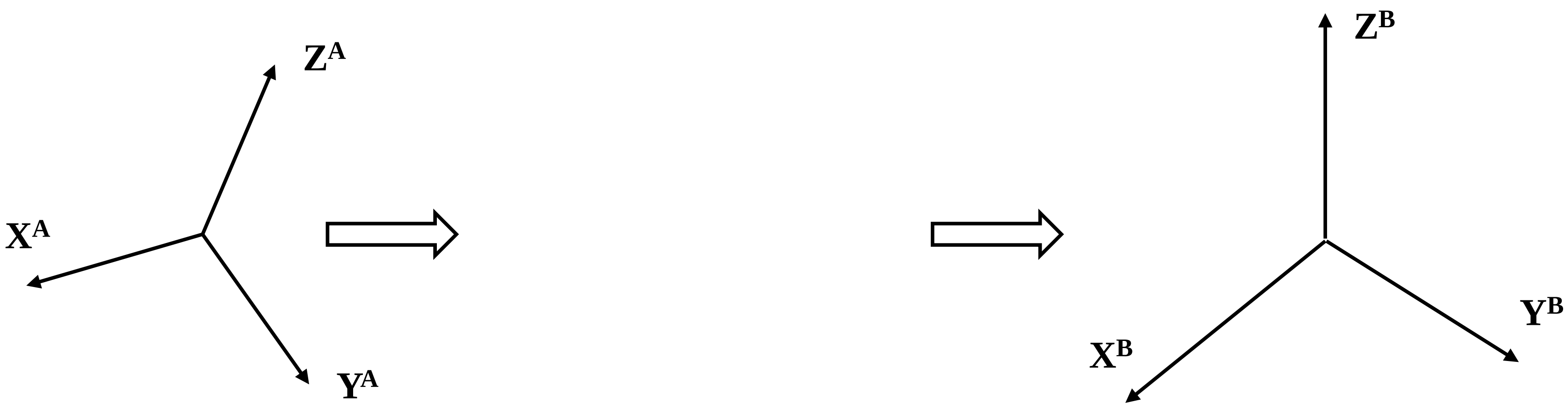


VLBI contribution to the ITRF: scale

Terrestrial Reference Frame

VLBI contribution to the ITRF: scale

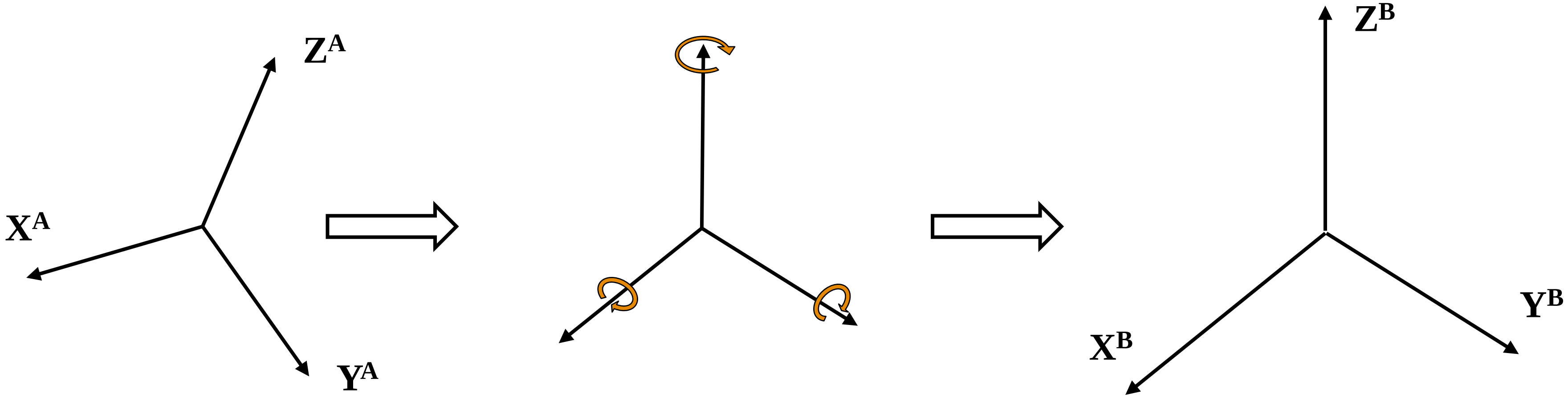
- HELMERT-transformation between two frames



VLBI contribution to the ITRF: scale

- HELMERT-transformation between two frames

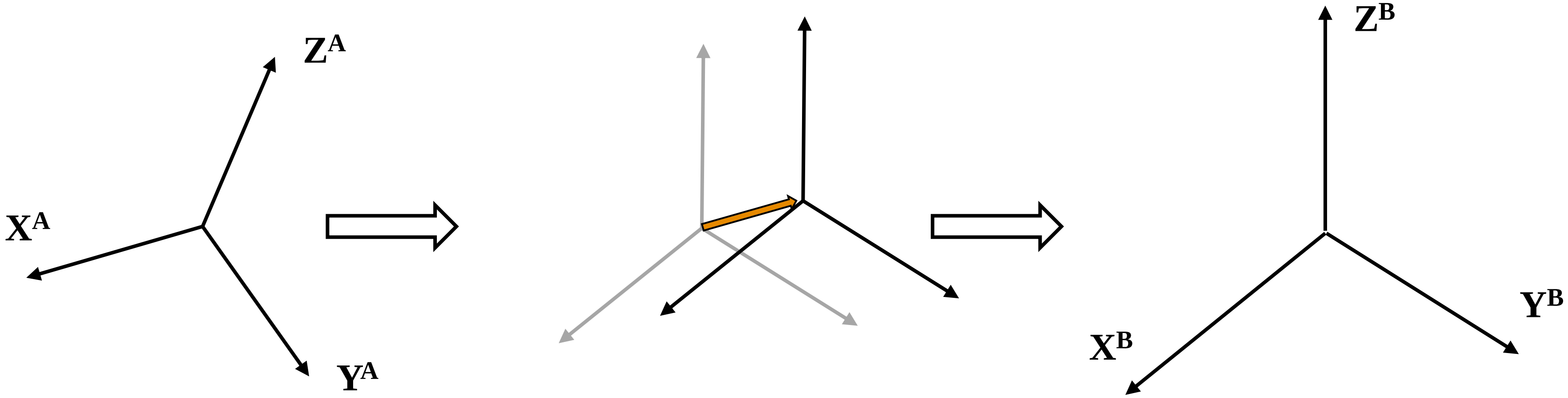
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^B = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} + (1 + s \times 10^{-6}) \cdot \begin{bmatrix} 1 & -r_z & r_y \\ r_z & 1 & -r_x \\ -r_y & r_x & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^A$$



VLBI contribution to the ITRF: scale

- HELMERT-transformation between two frames

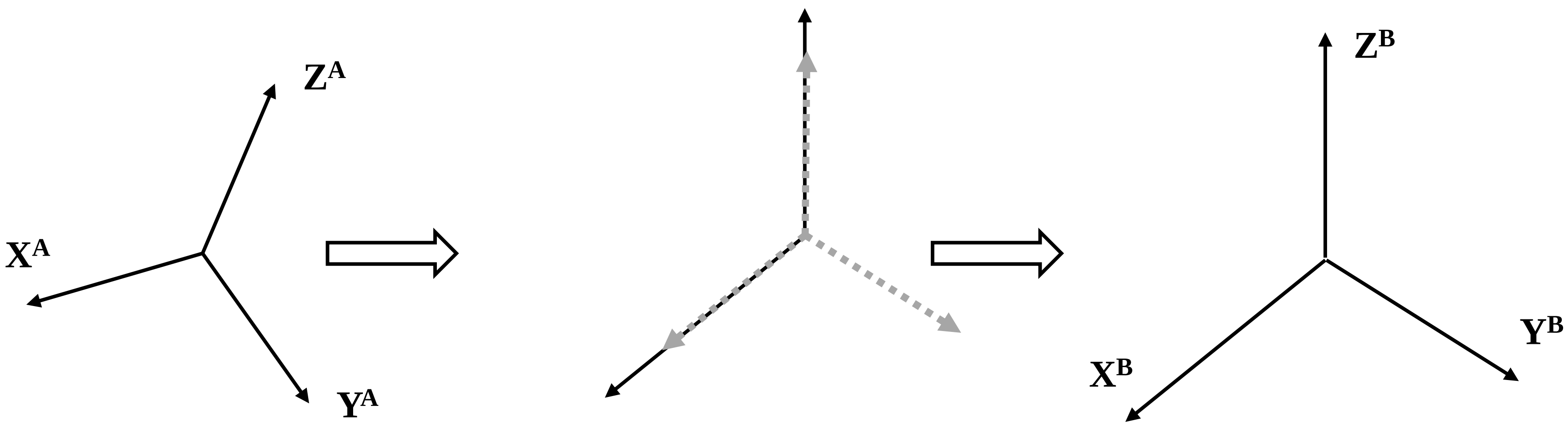
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^B = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} + (1 + s \times 10^{-6}) \cdot \begin{bmatrix} 1 & -r_z & r_y \\ r_z & 1 & -r_x \\ -r_y & r_x & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^A$$



VLBI contribution to the ITRF: scale

- HELMERT-transformation between two frames

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^B = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} + (1 + \boxed{s} \times 10^{-6}) \cdot \begin{bmatrix} 1 & -r_z & r_y \\ r_z & 1 & -r_x \\ -r_y & r_x & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^A$$



VLBI contribution to the ITRF: scale

- Definition
- The *geodetic datum* is the fixation of the degree of freedom of a reference frame. It relates the reference frame to the reference system through defining/specifying the external geometry.

- Scale
- The VLBI scale only depends on the speed of light (in vacuum) *c*, no other physical constant is involved. is the best known physical constant, a defining constant (no uncertainty).

- All observations obtained by the space geodetic techniques (DORIS, GNSS, SLR, VLBI) measure time differences. Together with the speed of light the observations realize a polyhedron of metric baselines that fully determines the inner geometry of the station networks. The lengths of the involved baselines realize the scale.

- The scale of ITRF is defined by VLBI and SLR.

The VLBI observable

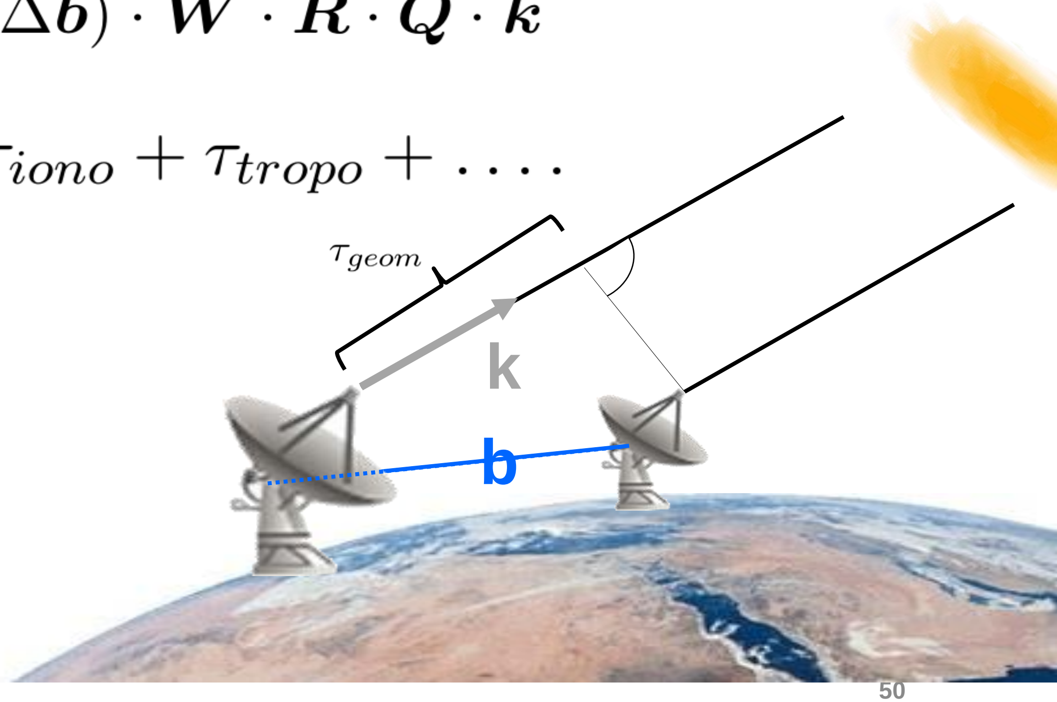
- **Geometrical delay**

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\boldsymbol{b}\cdot\boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,\boldsymbol{b}\cdot\boldsymbol{W}\cdot\boldsymbol{R}\cdot\boldsymbol{Q}\cdot\boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,(\boldsymbol{b}+\Delta\boldsymbol{b})\cdot\boldsymbol{W}\cdot\boldsymbol{R}\cdot\boldsymbol{Q}\cdot\boldsymbol{k}$$

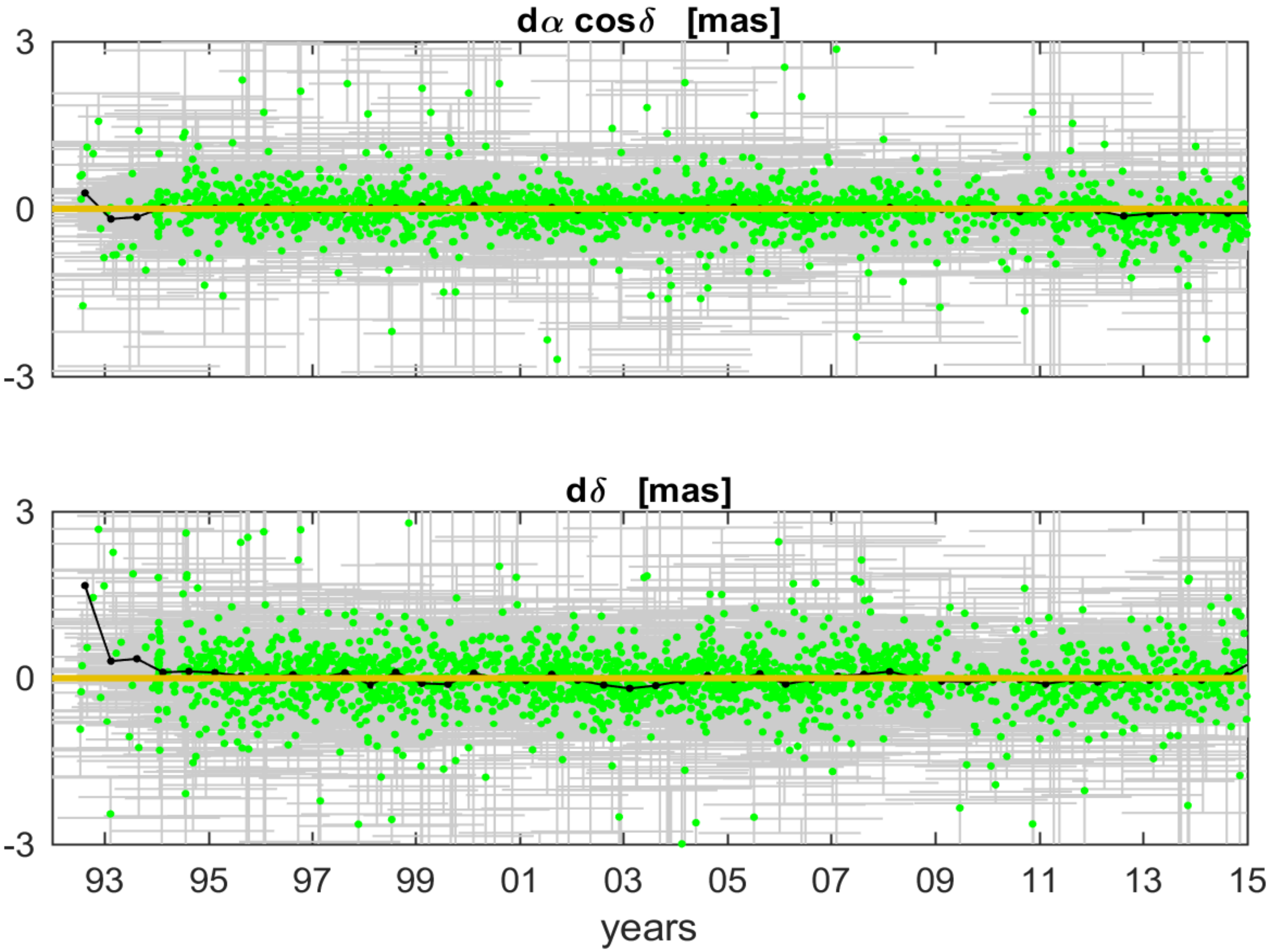
$$+\,\tau_{instr} + \tau_{clock} + \tau_{iono} + \tau_{tropo} + \ldots .$$



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

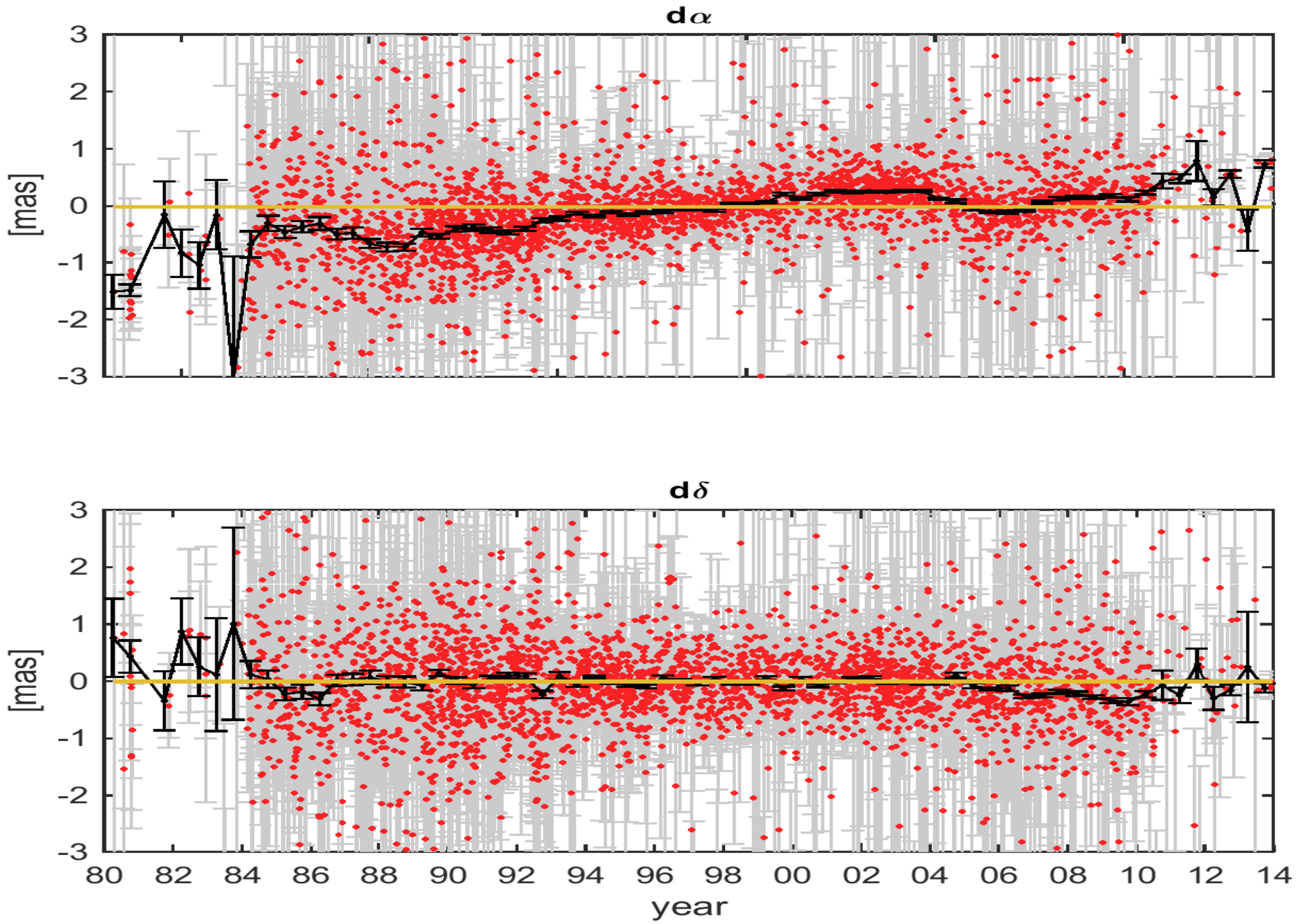
$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

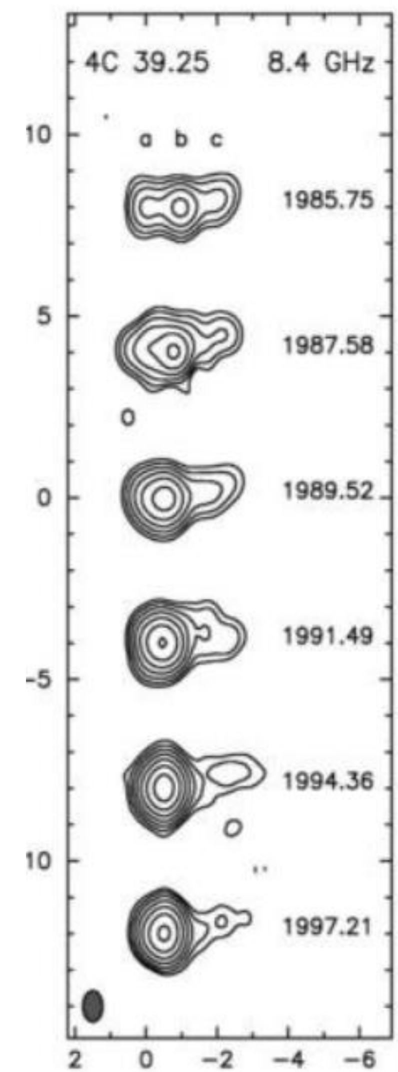
0059+581



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

4C39.25

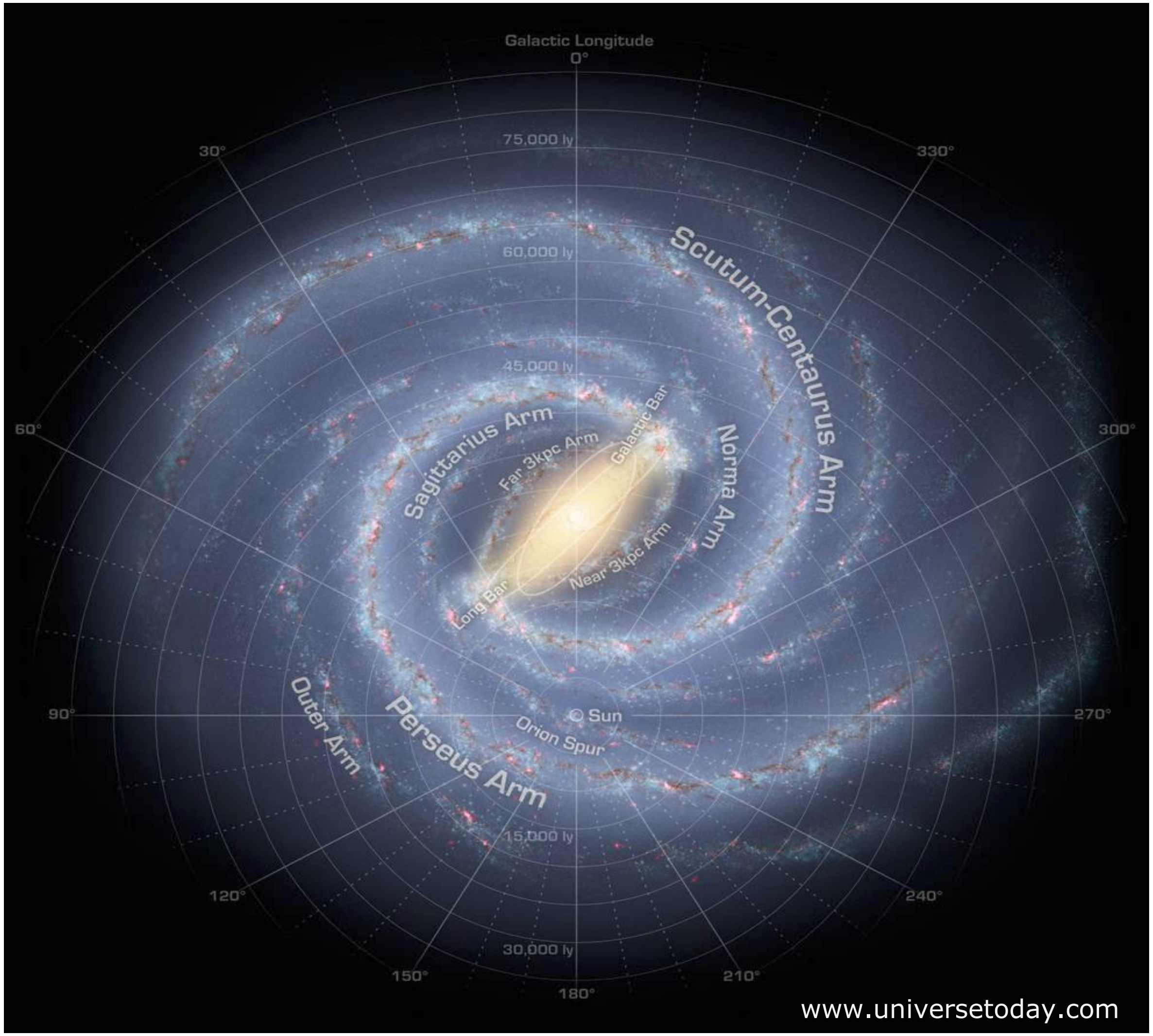




$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

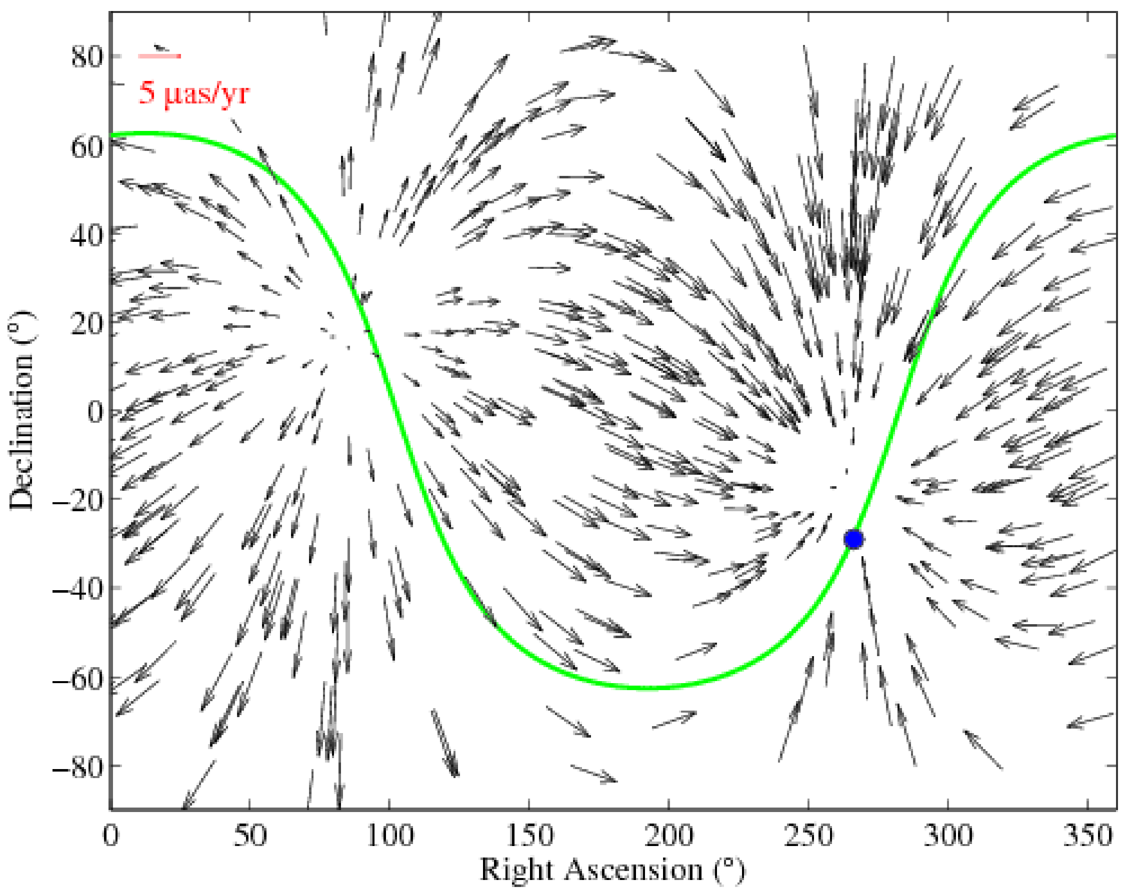
Secular abberation drift



- The gravitational attraction of the Galactic center leads to the **centrifugal acceleration** of the Solar system barycenter.
- It results in **secular aberration drift** which displaces the position of the distant radio sources.

$$\tau_{geom} = -{}^{1}/_{c} \cdot (\boldsymbol{b} - \Delta\boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

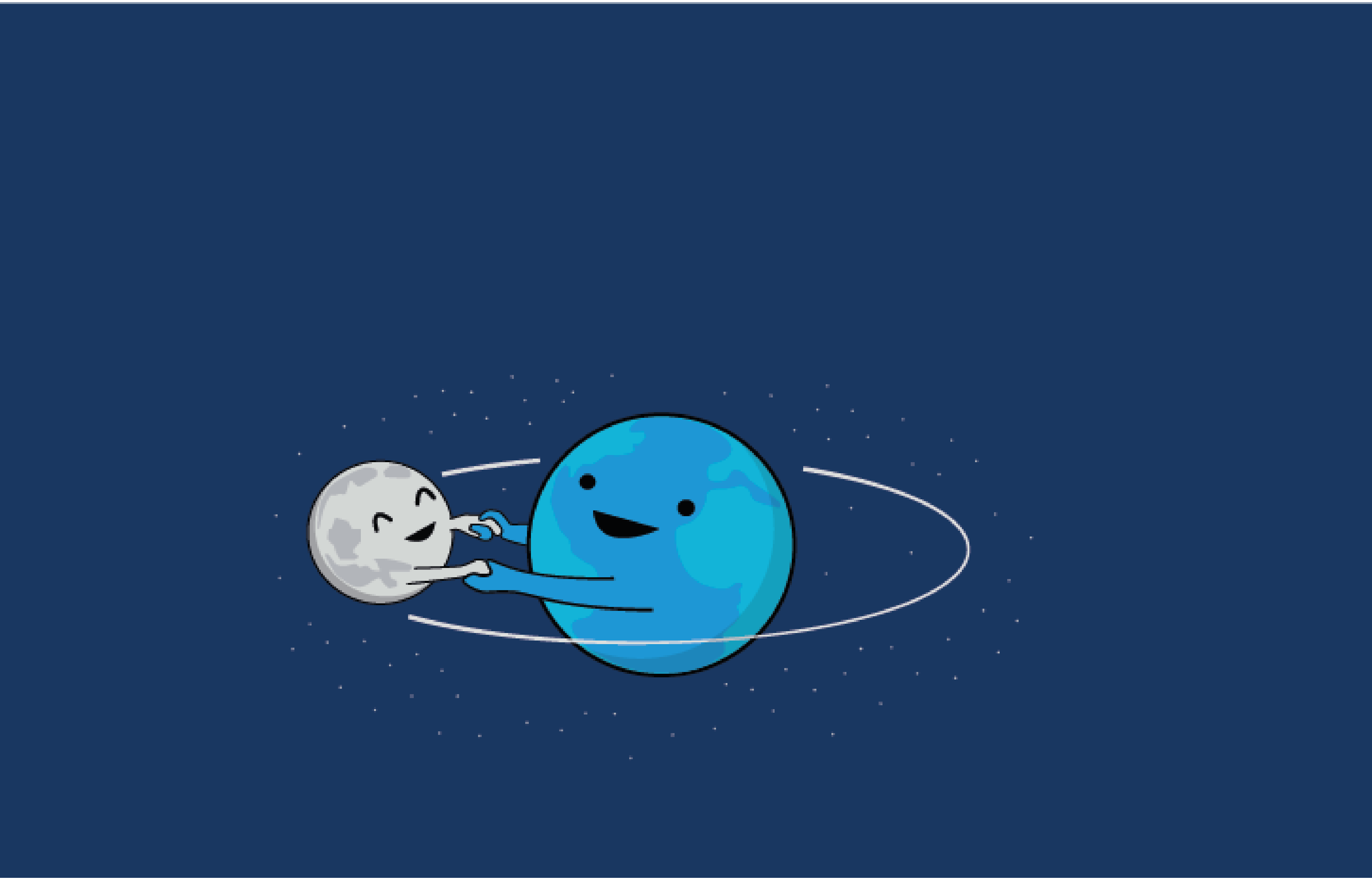
Secular abberation drift



[Titov 2011]

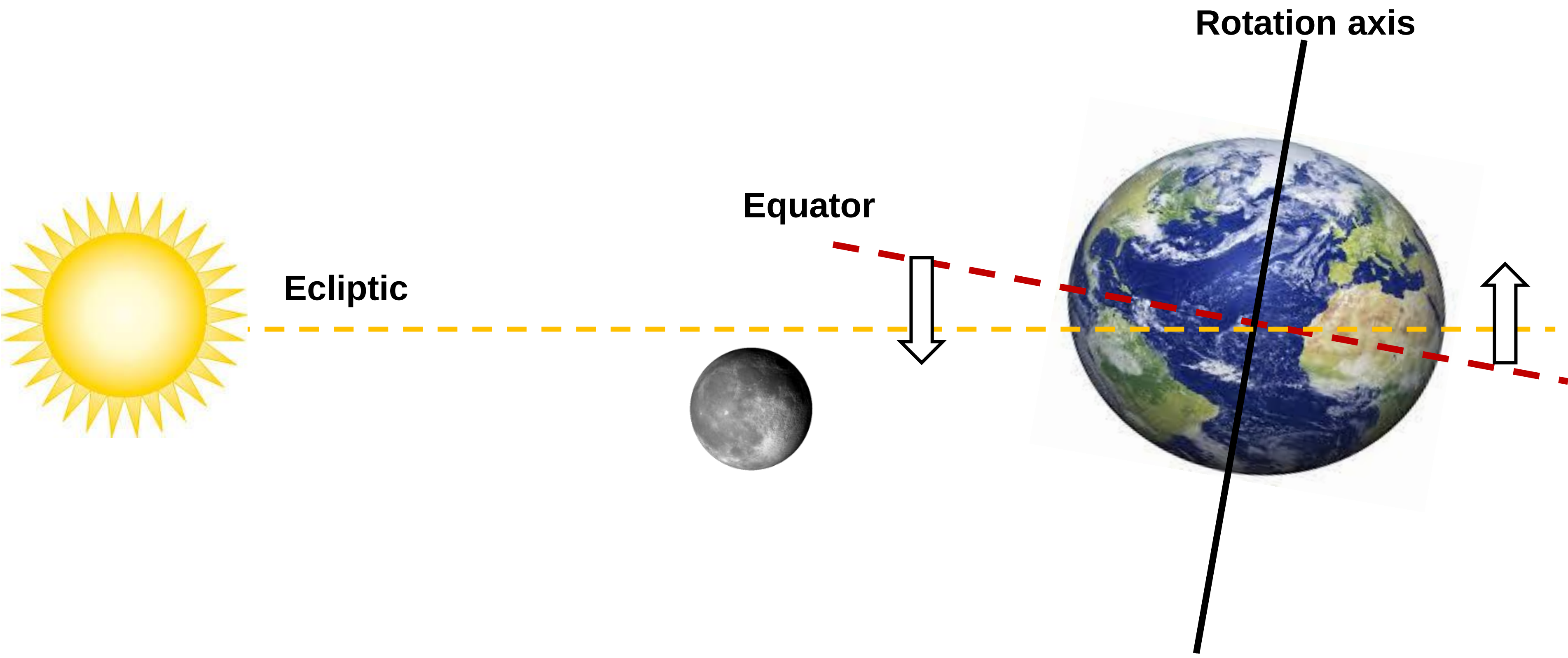
- The gravitational attraction of the Galactic center leads to the **centrifugal acceleration** of the Solar system barycenter.
- It results in **secular aberration drift** which displaces the position of the distant radio sources.

$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

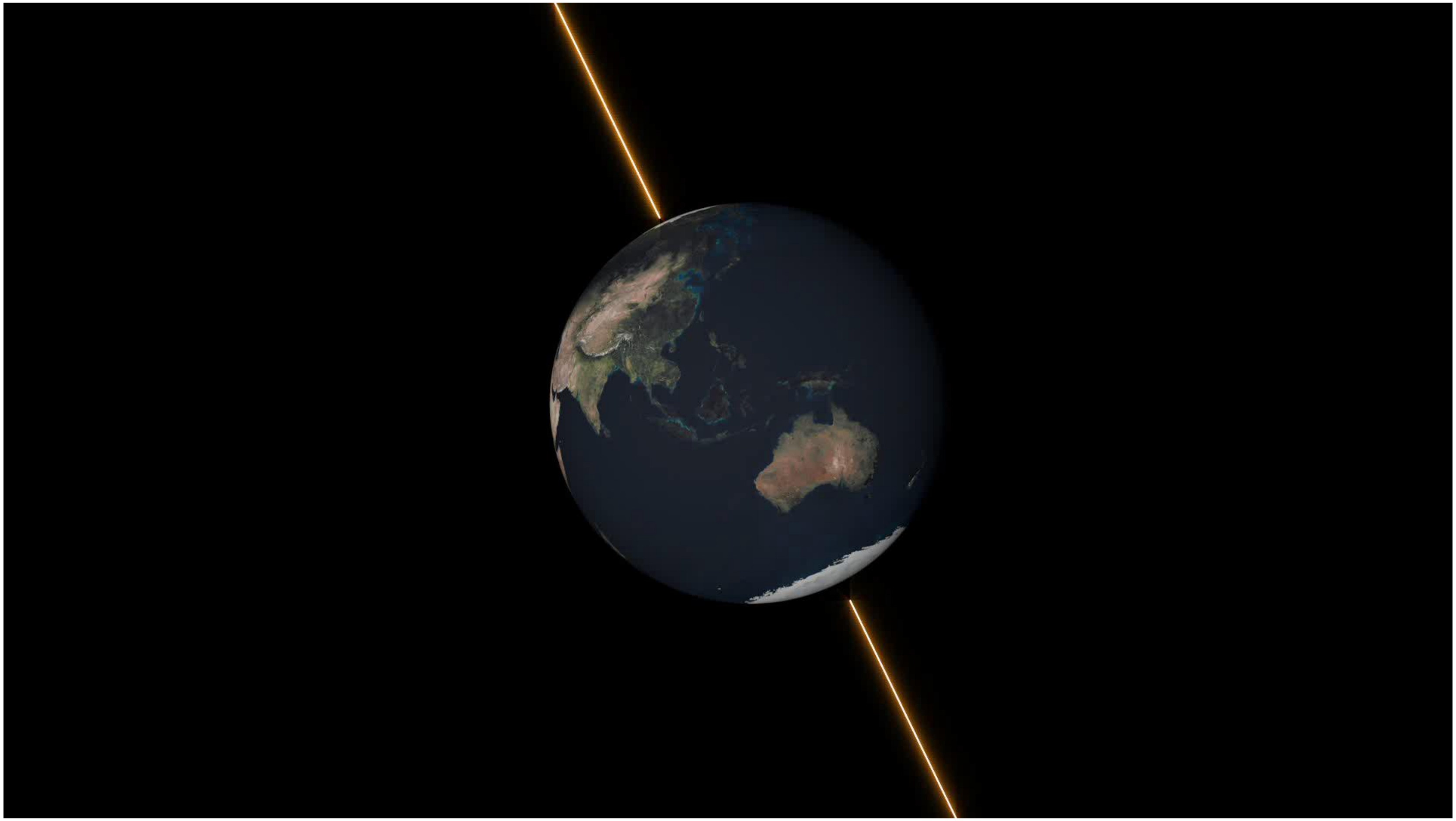
Precession & Nutation



$$\tau_{geom} = -{}^{1}\!/_{c} \cdot (\boldsymbol{b} - \Delta\boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

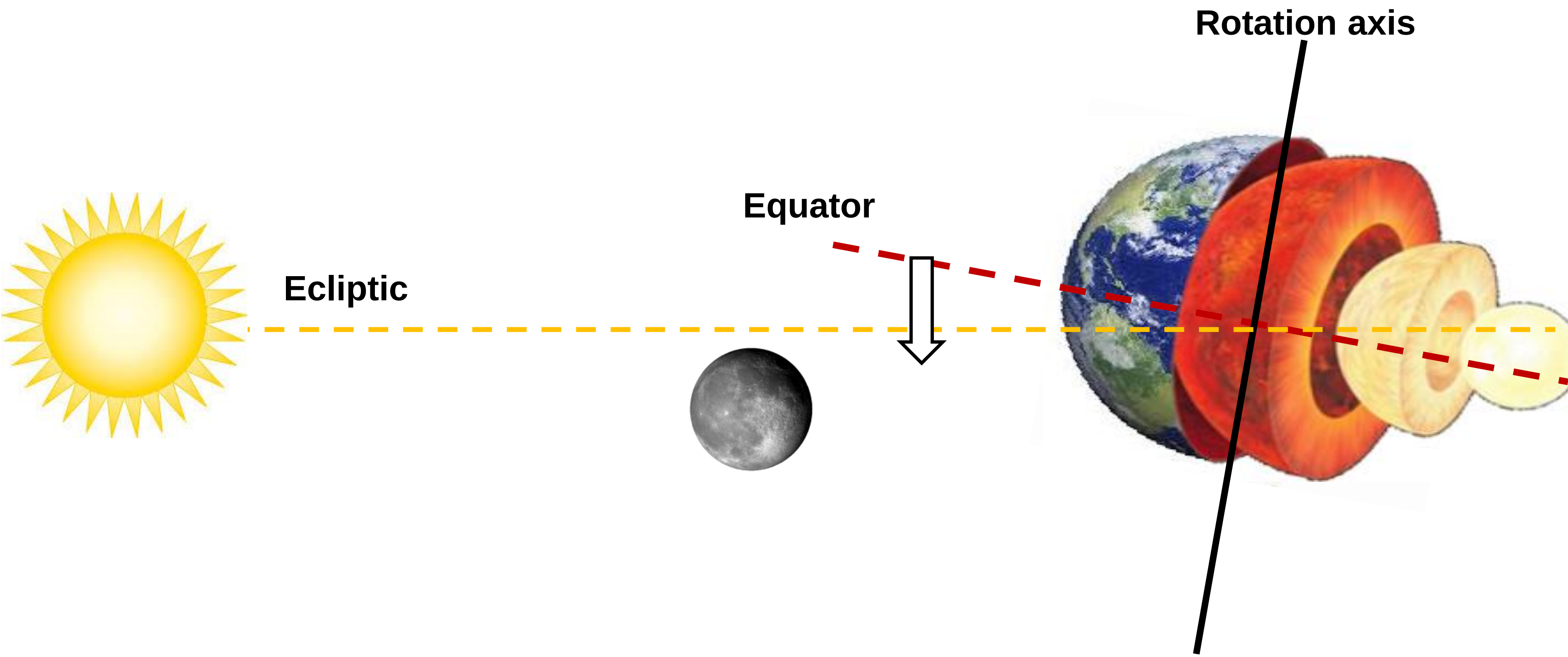
Precession & Nutation

NASA‘s GSFC Conceptual Image lab



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

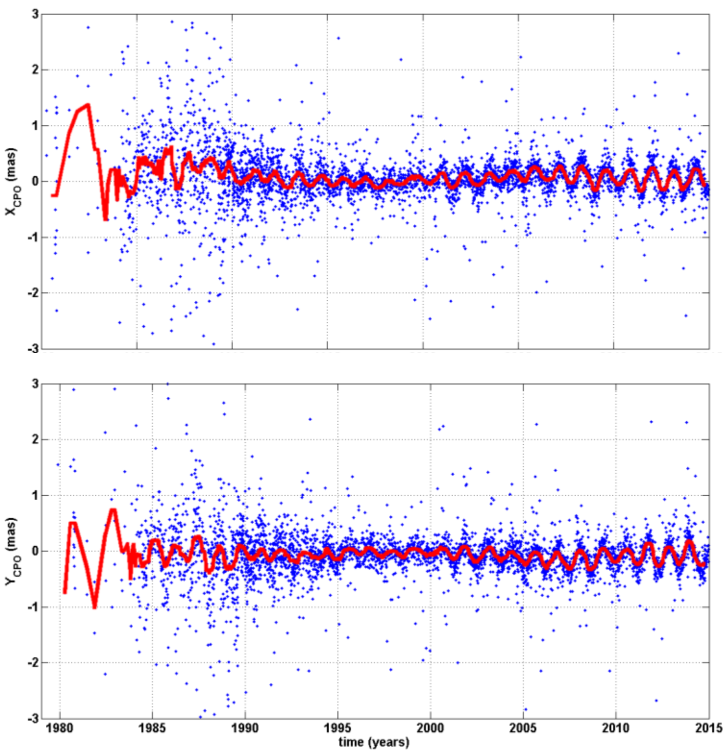
Precession & Nutation

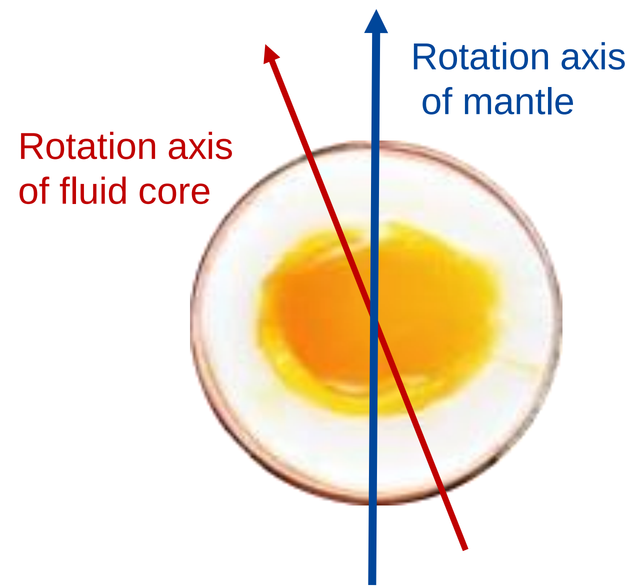


$$\tau_{geom} = -{}^{1}/_{c} \cdot (\boldsymbol{b} - \Delta \boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

Free Core Nutation

- Variations in free core nutation (FCN) are connected with various processes in the Earth's fluid core and core-mantle coupling, which are also largely responsible for the geomagnetic field variations, particularly the geomagnetic jerks. Period ~ 430 days

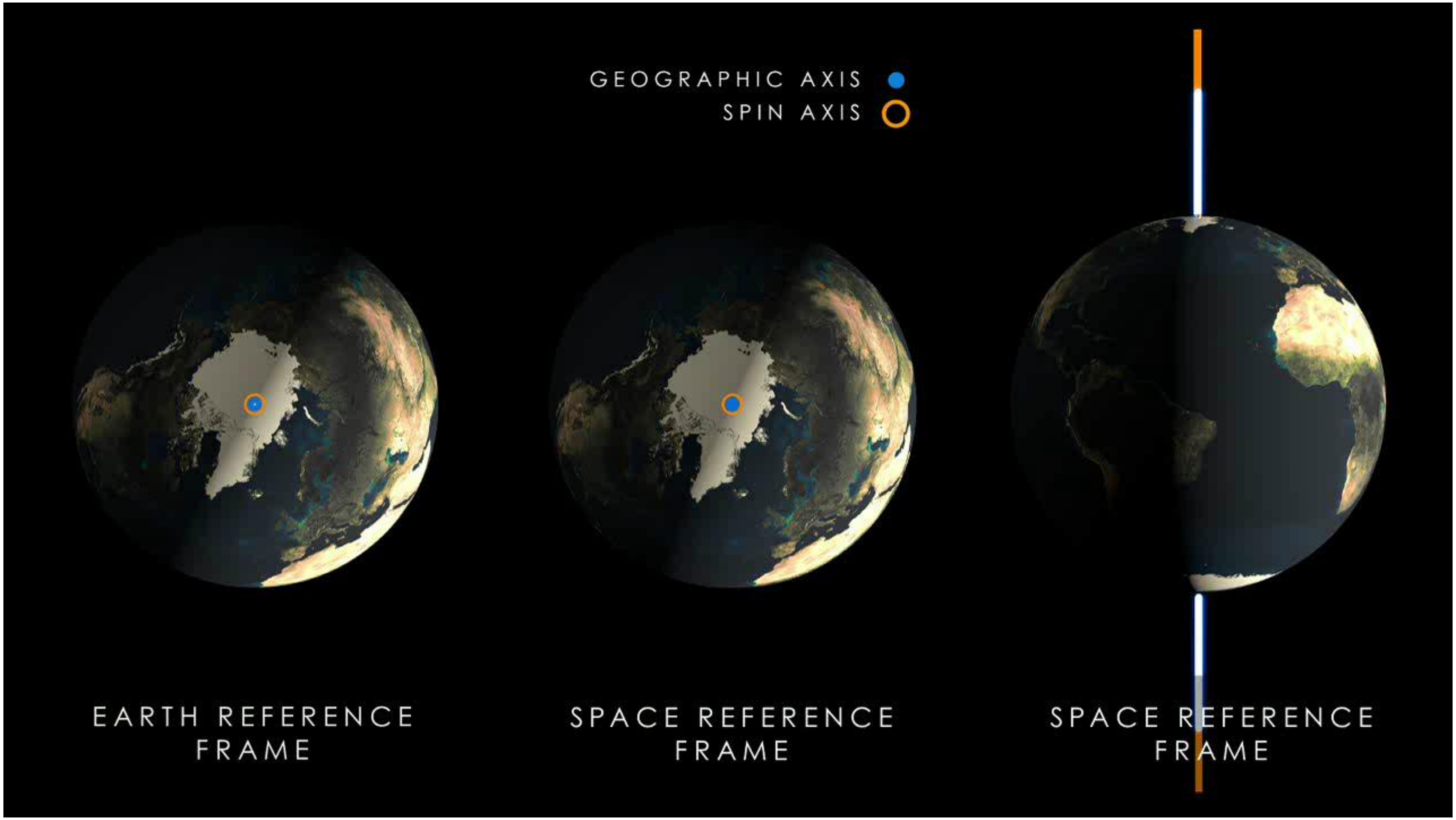




$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

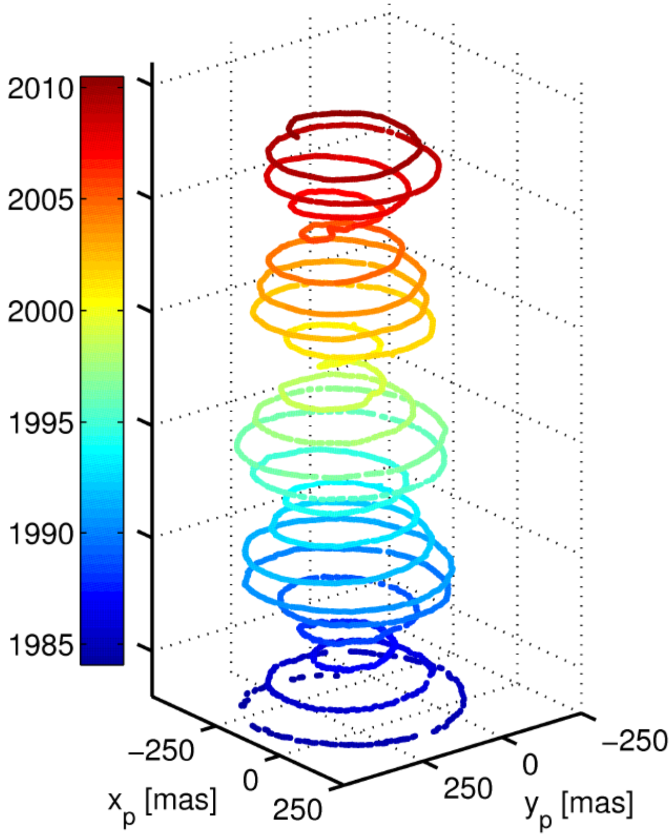
Polar motion

NASA‘s GSFC Conceptual Image lab

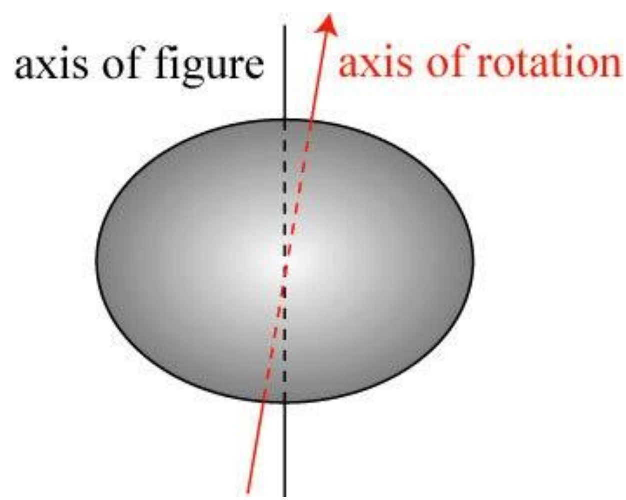


$$\tau_{geom} = -{}^{1}/_{c} \cdot (\boldsymbol{b} - \Delta\boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

Polar motion

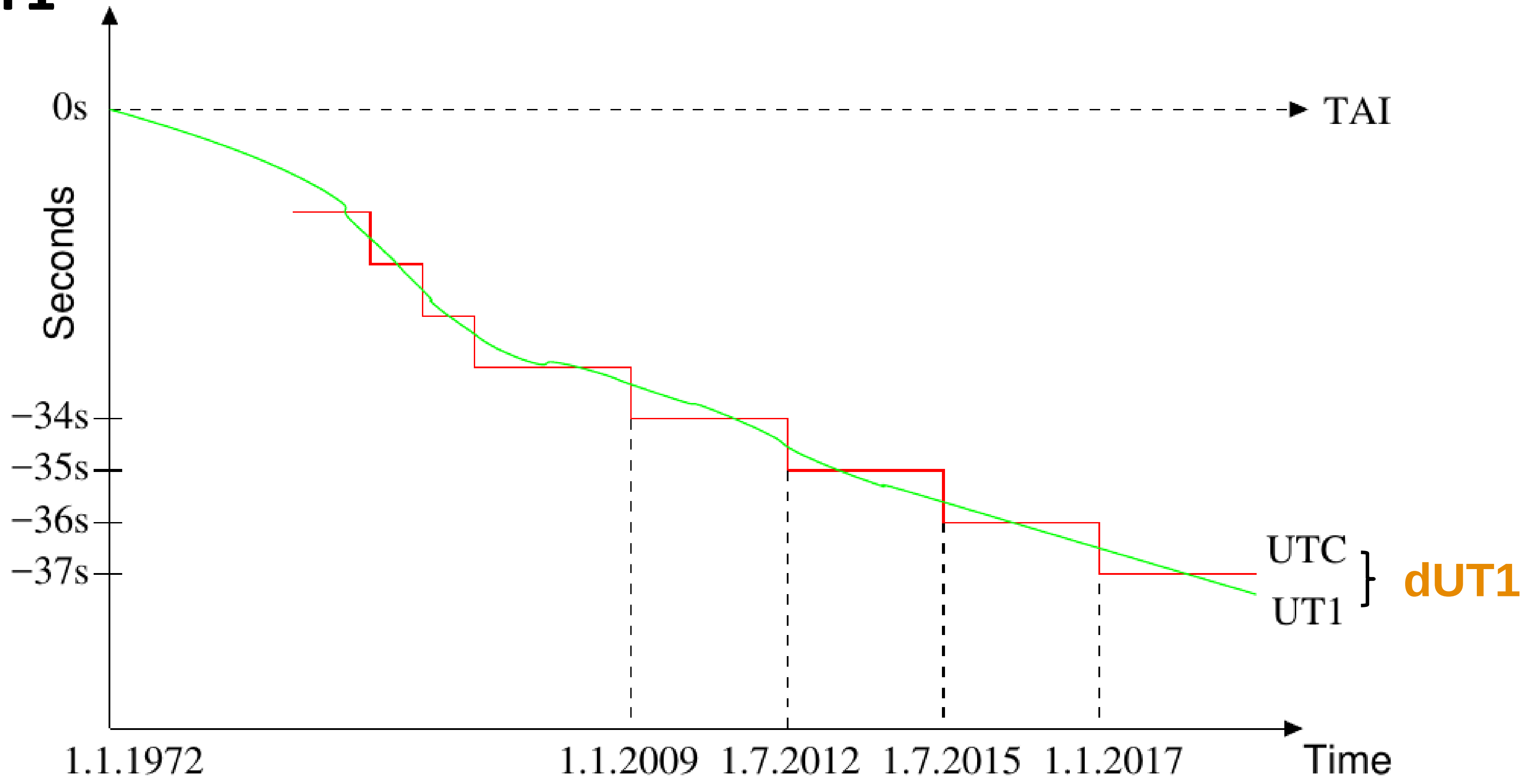


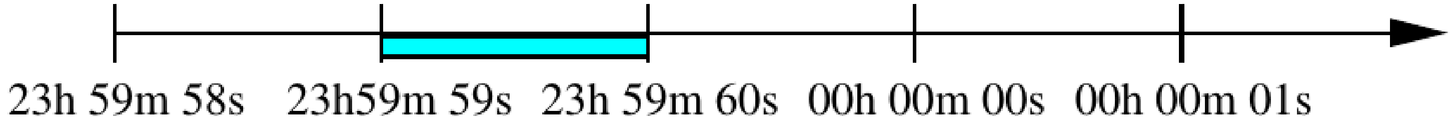
- Chandler wobble
  - Free oscillation
  - Amplitude ~6 m
  - Period ~430 d
- Yearly signal
  - forced oscillation (mainly atmosphere)
  - Amplitude ~3m
  - Pmeriod ~365 d



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

dUT1

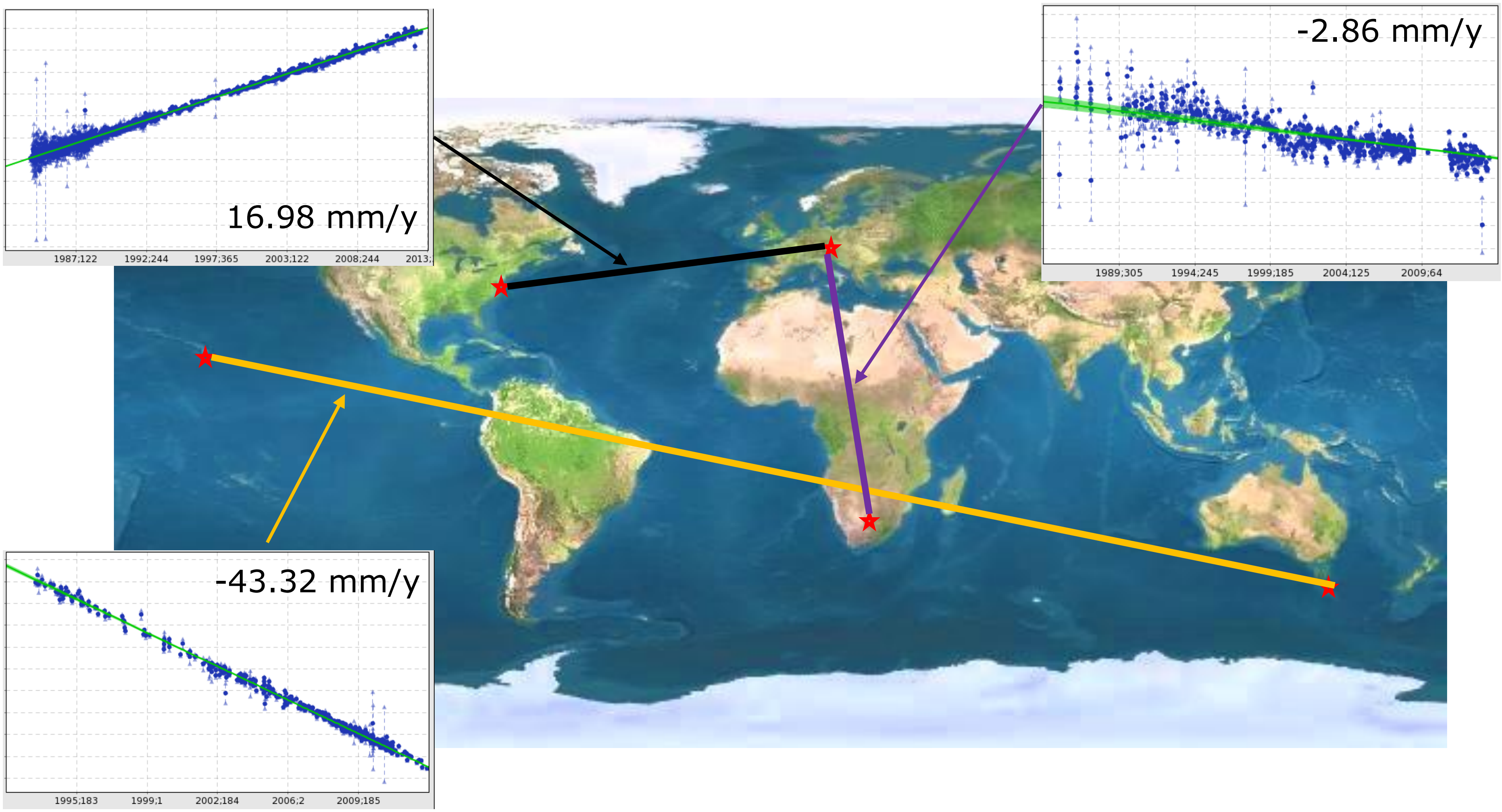




$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

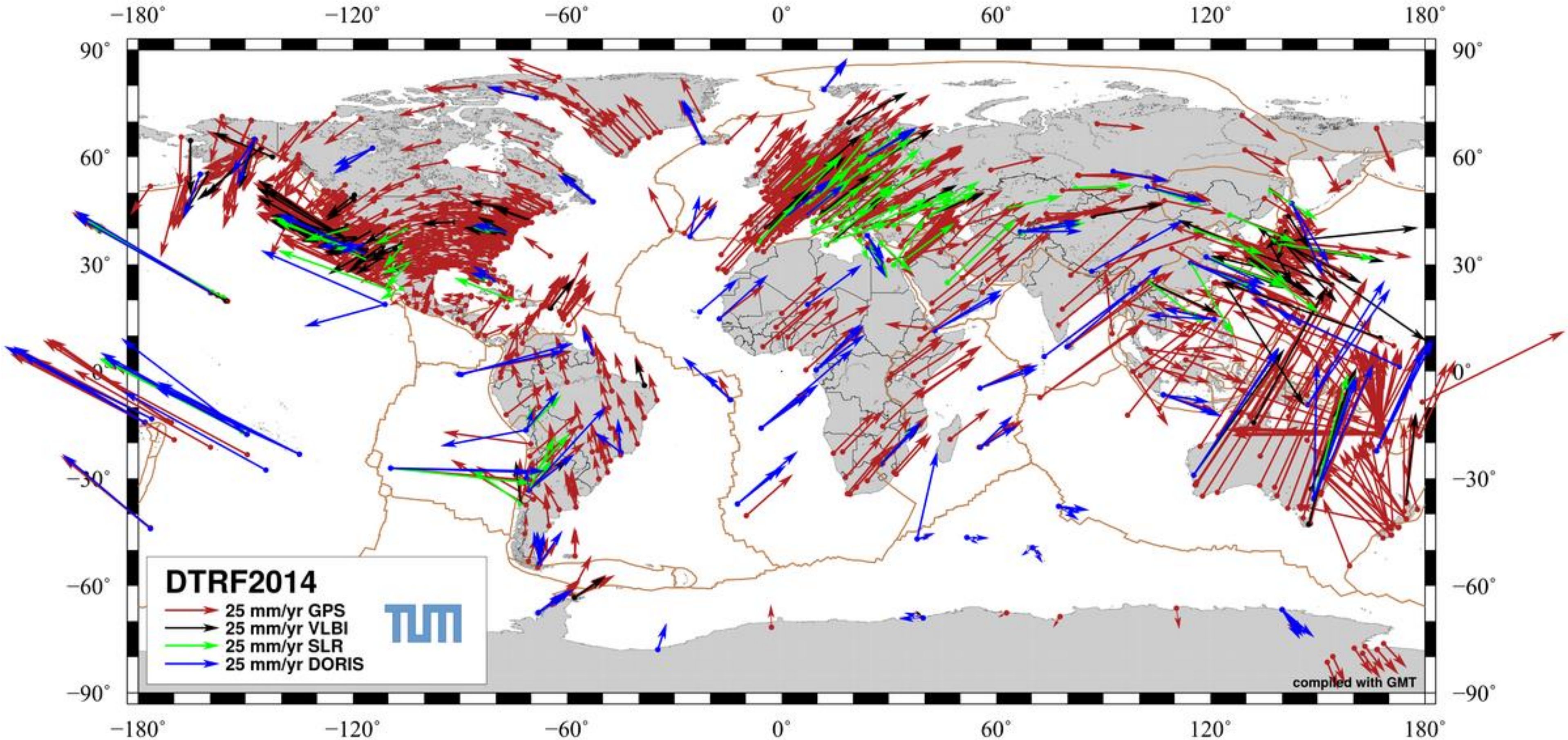
$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

Plate techtonics



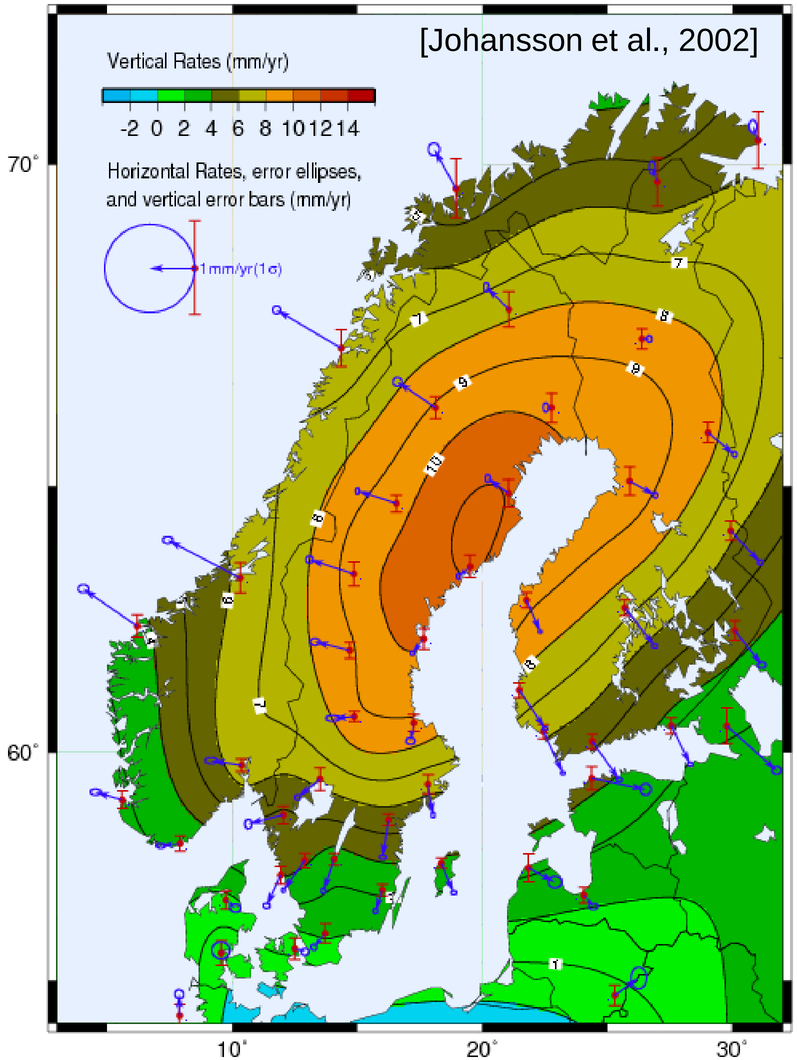
$$\tau_{geom} = -{}^{1}/_{c} \cdot (\boldsymbol{b} - \Delta \boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

TRF velocities



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

Post glacial rebound

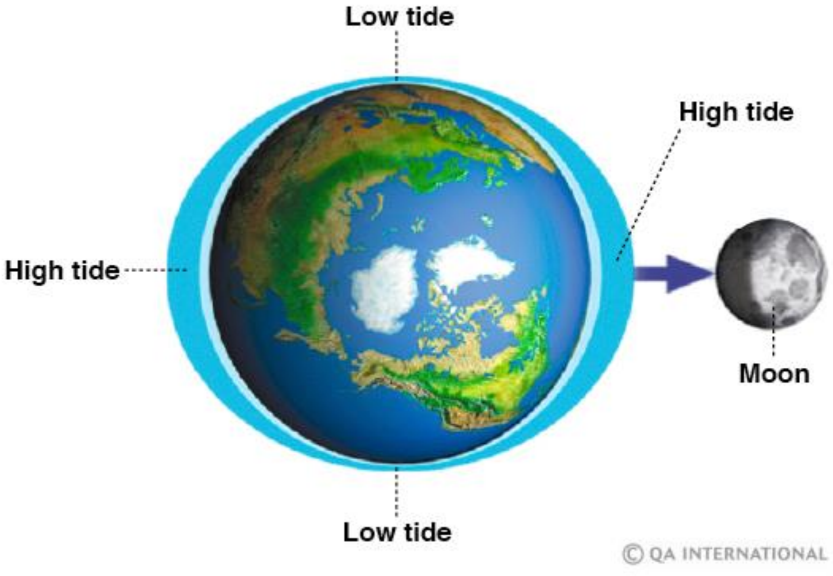


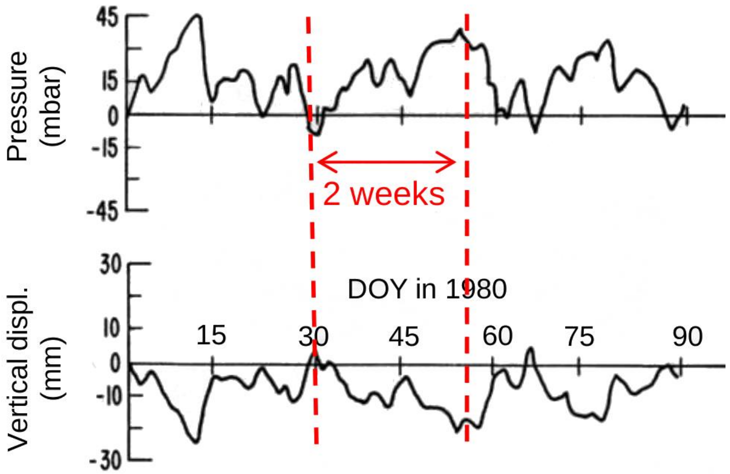
- Melting of ice sheets of last ice age:
  - Vertical up to 12 mm/y
  - Horizontal up to 3 mm/y

$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k$$

Tides

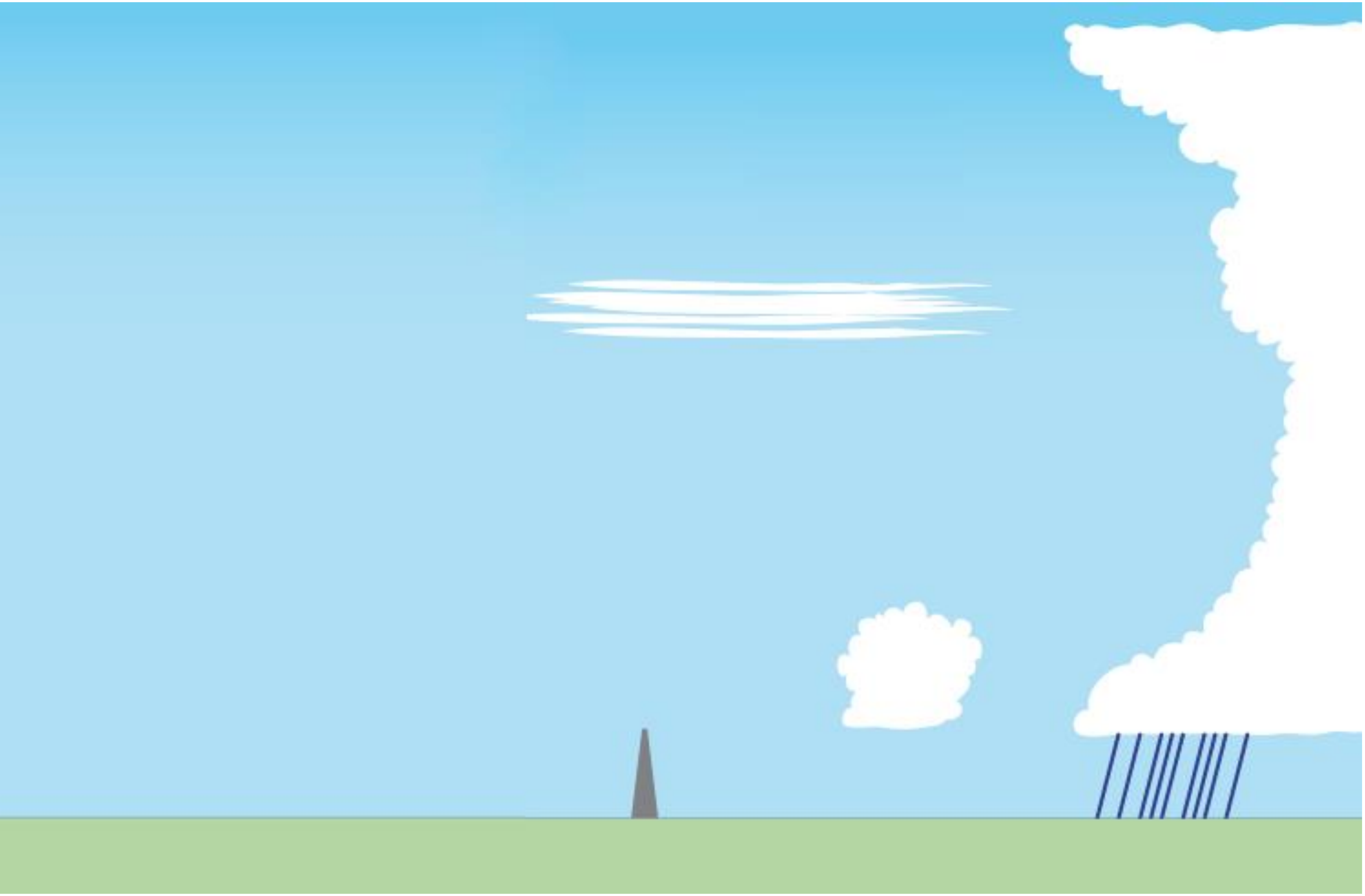
- Solid Earth tides +/- 30 cm
- Atmospheric loading:
  - tidal: 1-2mm
  - Non-tilal: up to 2 mm
- Ocean tidal loading:
  - Half of atmospheric effects
- Effect also Earth rotation!





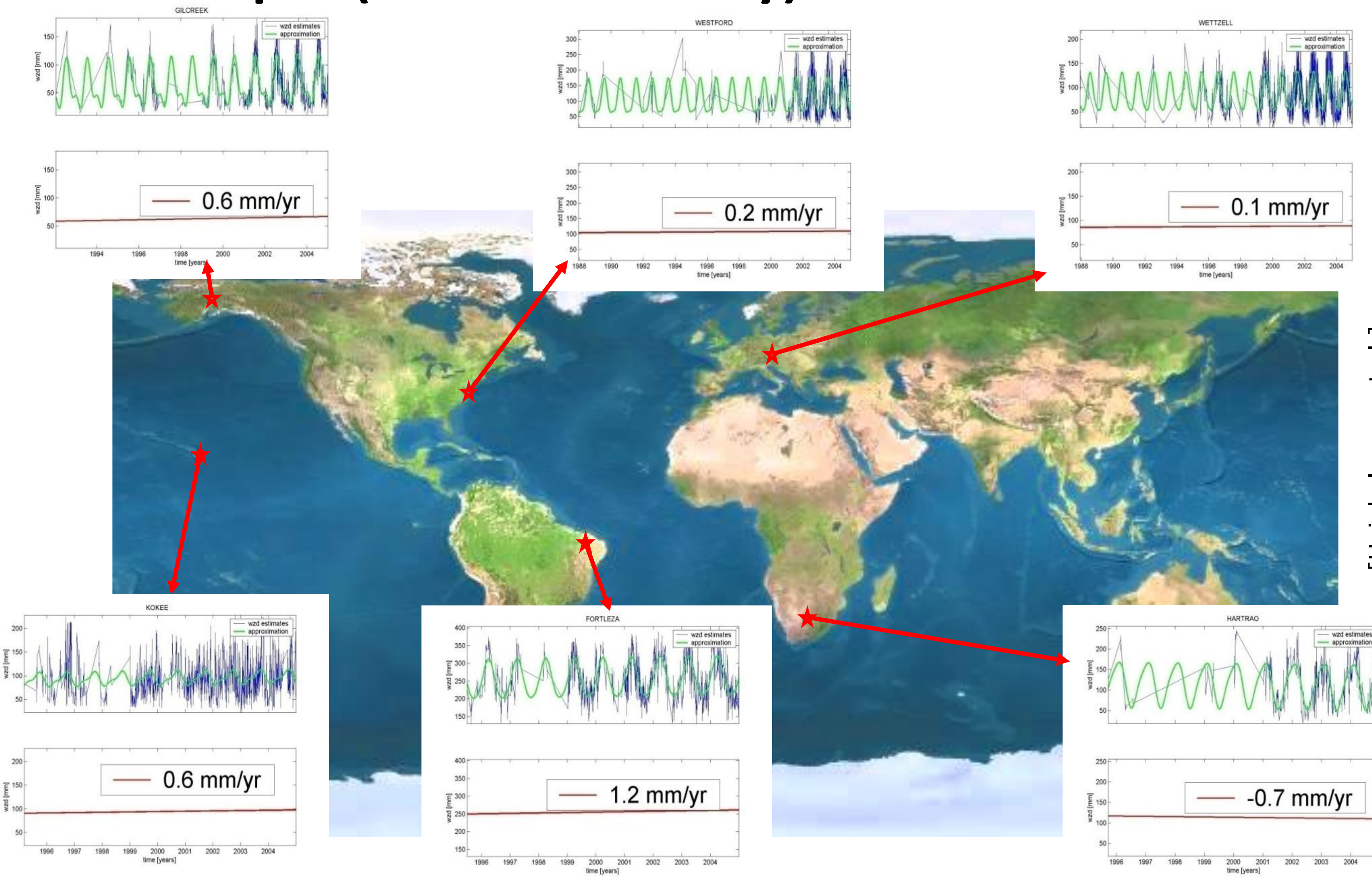
[VanDam & Wahr,1987]

$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k + \tau_{tropo}$$



$$\tau_{geom} = -{}^{1}/_{c} \cdot (b - \Delta b) \cdot W \cdot R \cdot Q \cdot k + \tau_{tropo}$$

Wather Vapor (zenith wet delay)



[Heinkelmann et al.]

What is geodetic VLBI good for?

- Realizes the conventional celestial reference system
- Is the only technique providing celestial pole offset estimates (precession/nutation) and the phase of Earth rotation: UT1
- This includes the free core nutation (FCN) signal
- Satellite techniques rely on the parameters provided by VLBI
- Provides the longest Earth-based baselines (up to 12,000 km) and thus direct measurement of tectonic plate motions, post glacial rebound, etc.
- Provides a long-term stable infrastructure that adds significant, precise, and robust information for the realization of the terrestrial reference system

Summary

Not shown here:

- Is capable of determining a number of other parameters
  - Clock parameters: Frequency transfer
  - Dispersive delays: Ionosphere, Solar corona
  - Relativistic effects: space-time curvature
  - Love & Shida numbers: geophysical Earth parameters

- Presents a second space-geodetic technique at radio wave-lengths and thus an optimal technique for comparison with or calibration of GNSS

- Colocation in space: observation of satellites with VLBI antennas.

Summary

Why di I like it?

- Covers a wide range of topics
  - From astrophysics down to the interior of the Earth
  - No chance to get bored
- Advent of VGOS
  - New & more data -> new results
- International community
  - …more like family

Thanks for your attention!