
The Importance of Time and Frequency in Space Geodesy

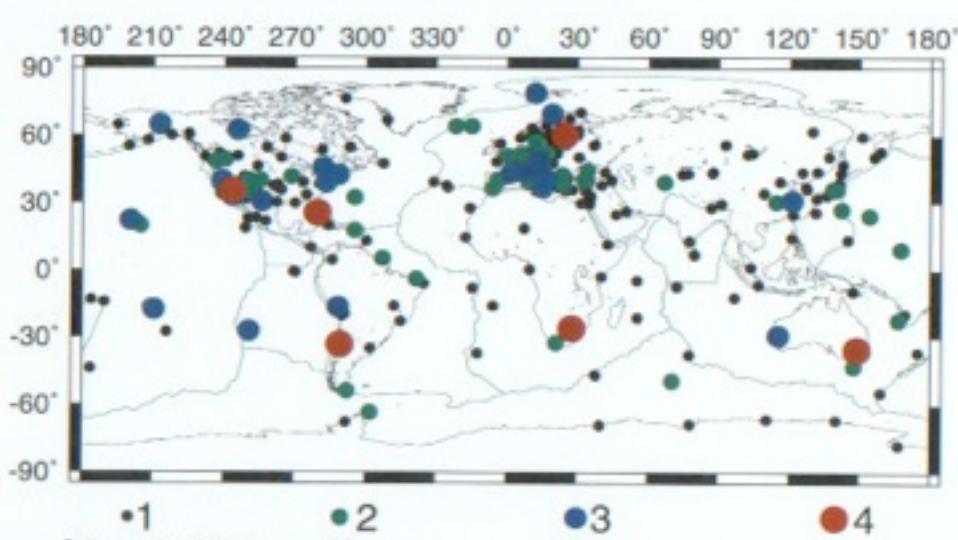
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Optical Networks for Accurate Time and Frequency Transfer

Space Geodesy

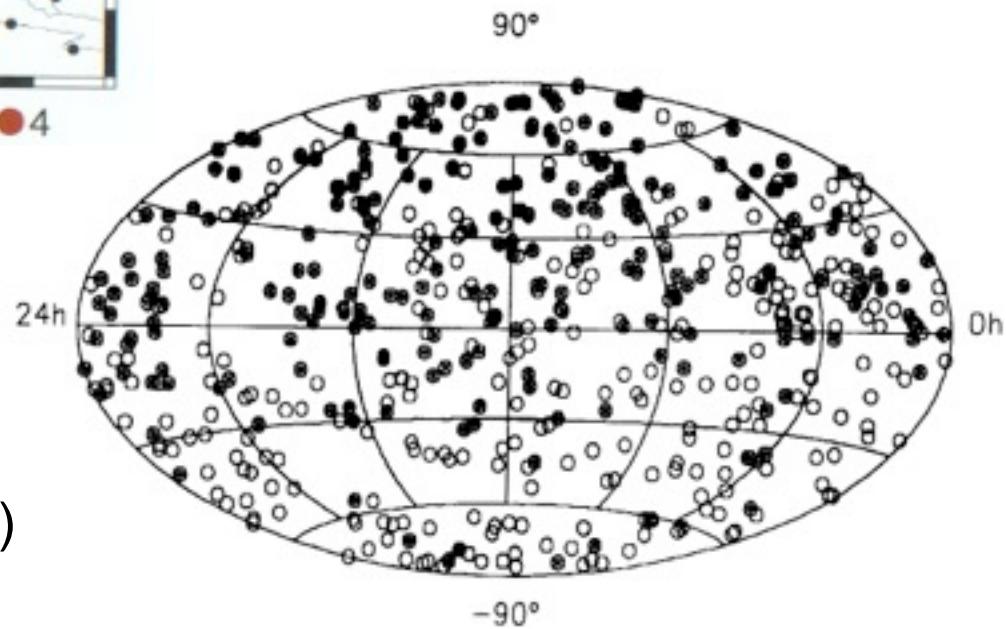
- Measurement of precise Coordinates for extra galactic Radio sources (Quasars) and their structure
- Determination of precise global, regional and local 3D-coordinates
- Determination of the Rotation rate of the Earth to allow the transformation between the two frames of reference
- Determination of the Earth gravity field and its variation over time

Reference Frames

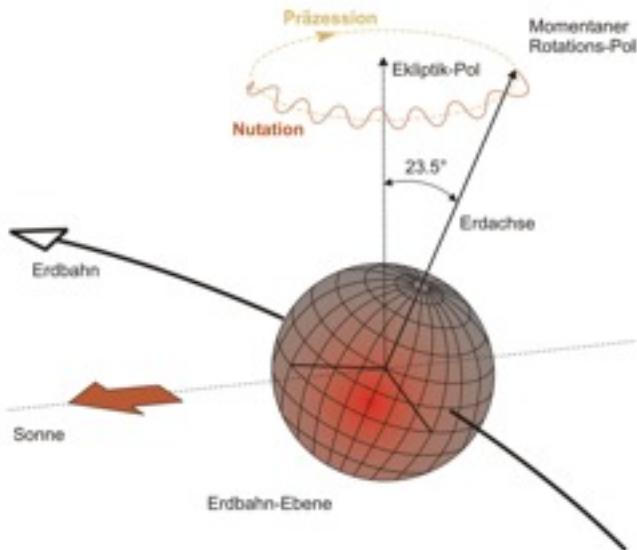


ITRF: International Terrestrial Reference Frame (Earth fixed)

ICRF: International Celestial Reference Frame (Space fixed)



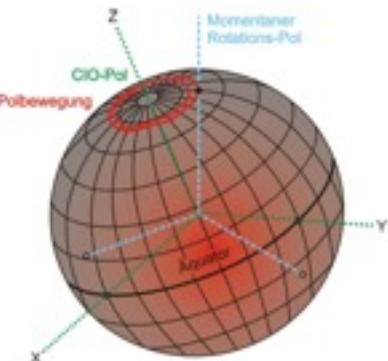
Earth Rotation links ITRF to ICRF



a) gravitational attraction of sun and moon on a near spherical object give rise to precession and nutation

b) the rotation rate of the Earth is not constant. Deceleration by dissipation and variation by momentum exchange. Free oscillations excited by ocean, atmosphere

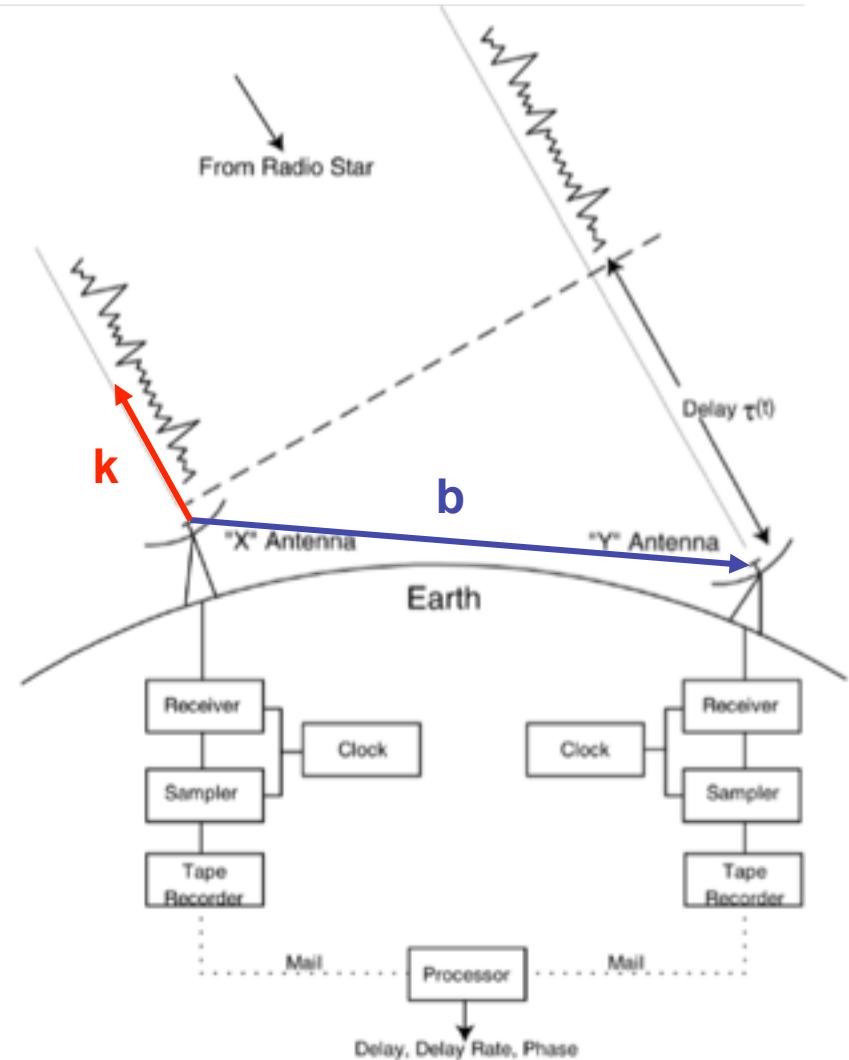
c) mass redistribution on Earth and the fact that the figure axis and the axis of Inertia are not coinciding, give rise to polar motion



Methods of Space Geodesy: VLBI

- Two or more telescopes observe the same extragalactic source
- Since the wavefront is flat, the signal reaches the telescopes at different times
- The observed signal delay $\Delta\tau$ is the prime observable

$$\Delta\tau = -\frac{1}{c} \mathbf{k} \times \mathbf{b}$$

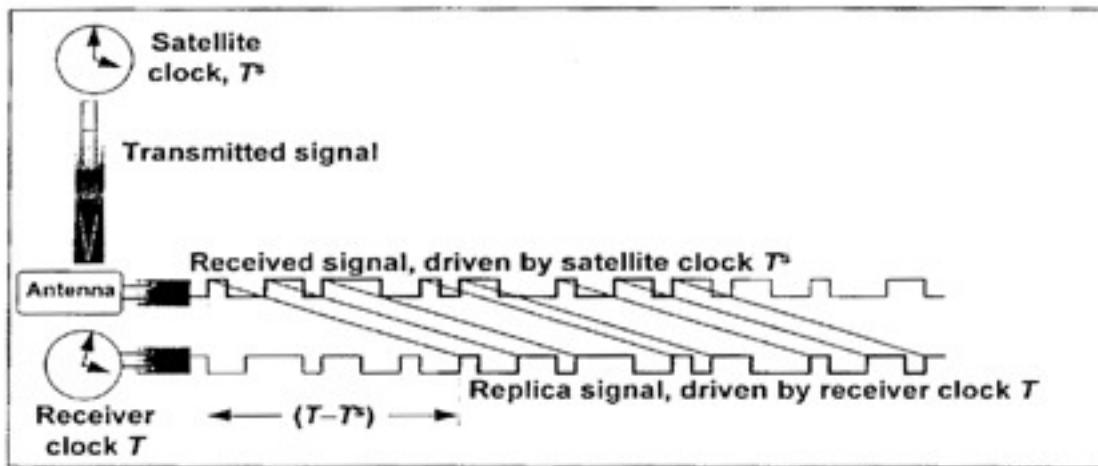


VLBI

- Station clocks are synchronized to at least 1 μ s to allow the detection of fringes in the correlation process.
- Station Clock offsets are estimated in the NLLSQ process
- 1 MHz frequency combs are used to align dispersion across the observation channels
- Shorter integration (VLBI2010) will require better clocks ($\Delta f/f < 2e-15$)
- Currently VLBI resolves 1 ps at best

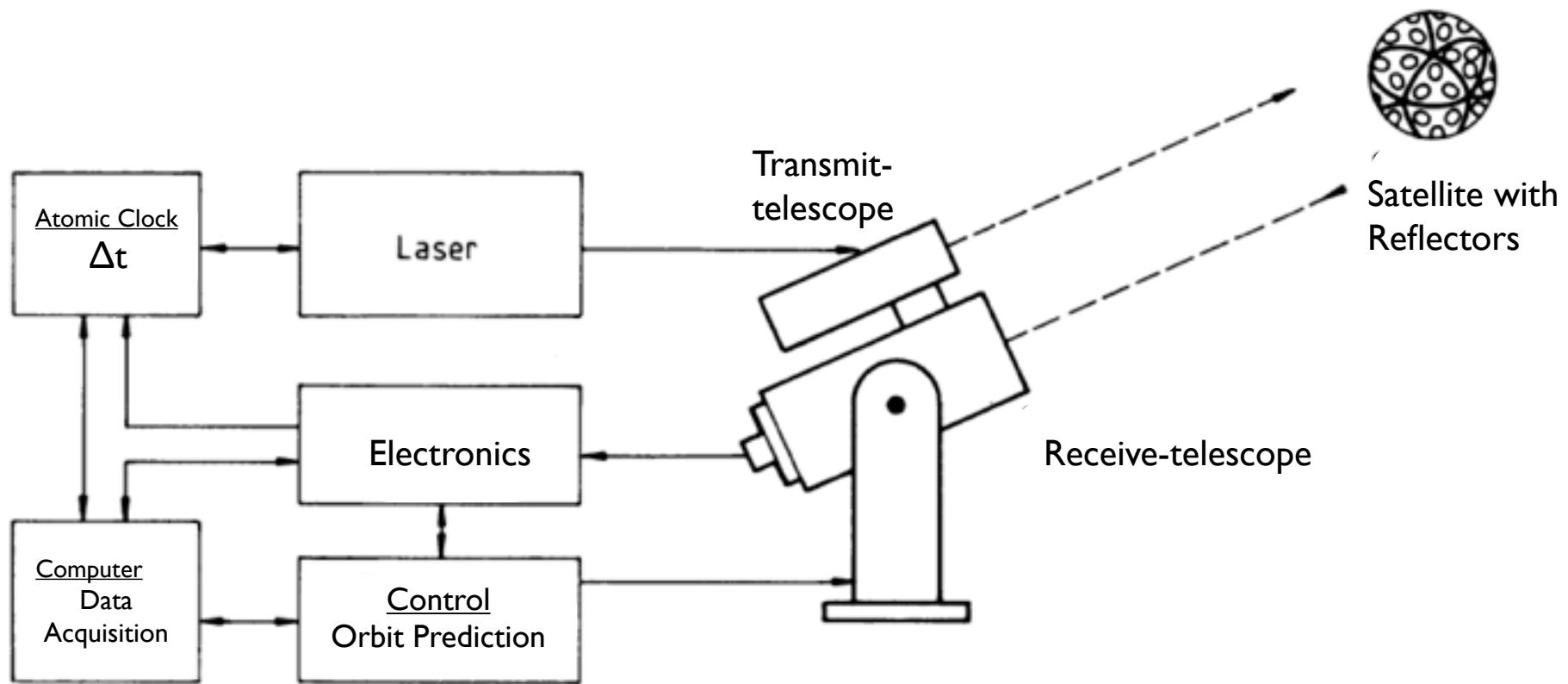
GNSS

- A pseudo random code is transmitted by the satellite at T^s
- The receiver correlates the detected code with an internal generated copy of the code, which yields T_r
- In order to obtain positions, satellite and receiver clocks must be synchronized. $\rho_r^s = c(T_r - T^s)$



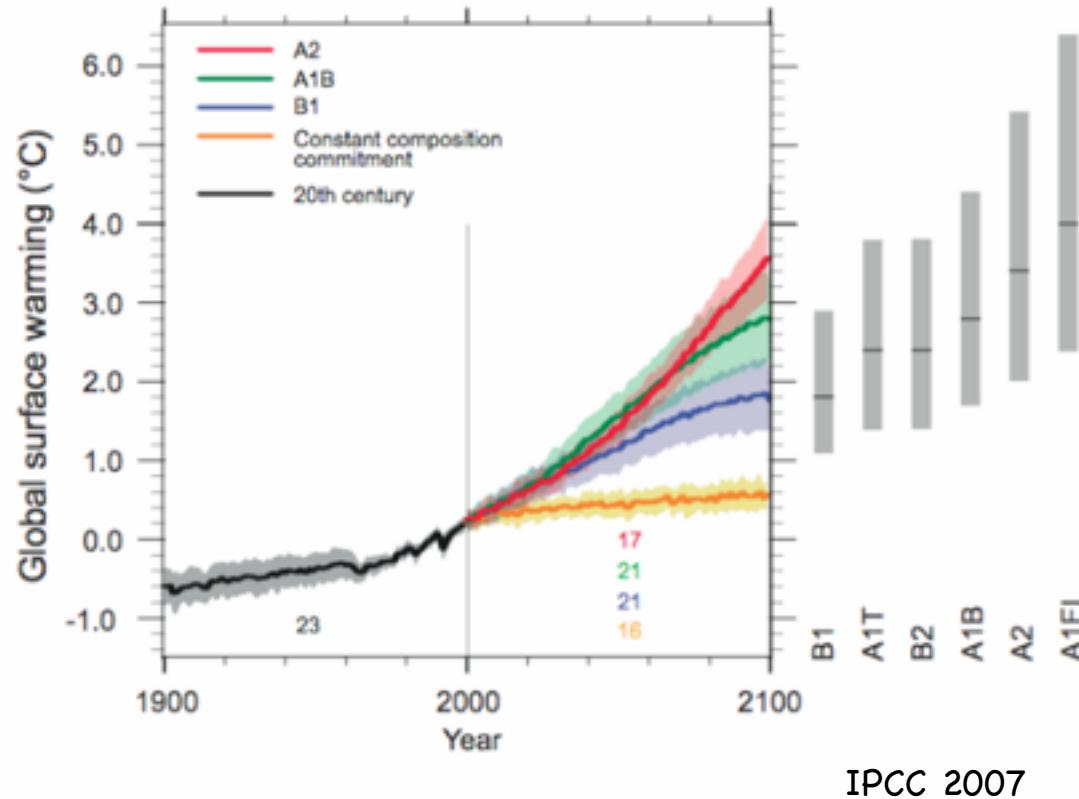
Blewitt, 1996

SLR

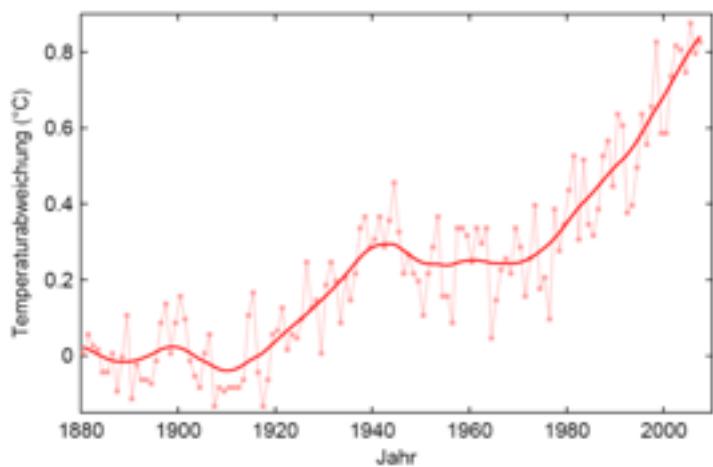


Application

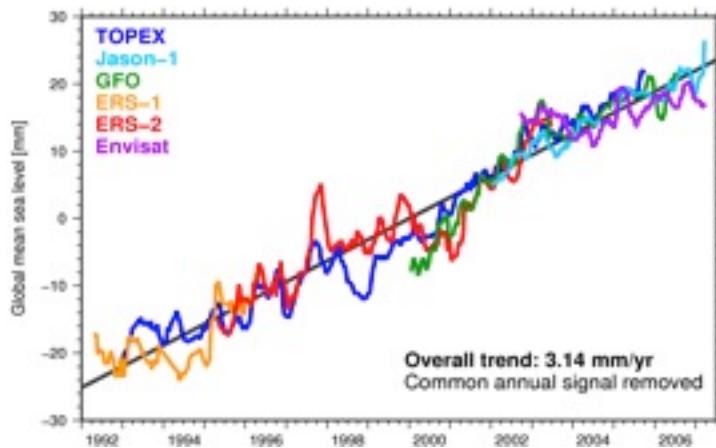
Intergovernmental Panel on Climate Change (IPCC)
modeled temperature scenarios



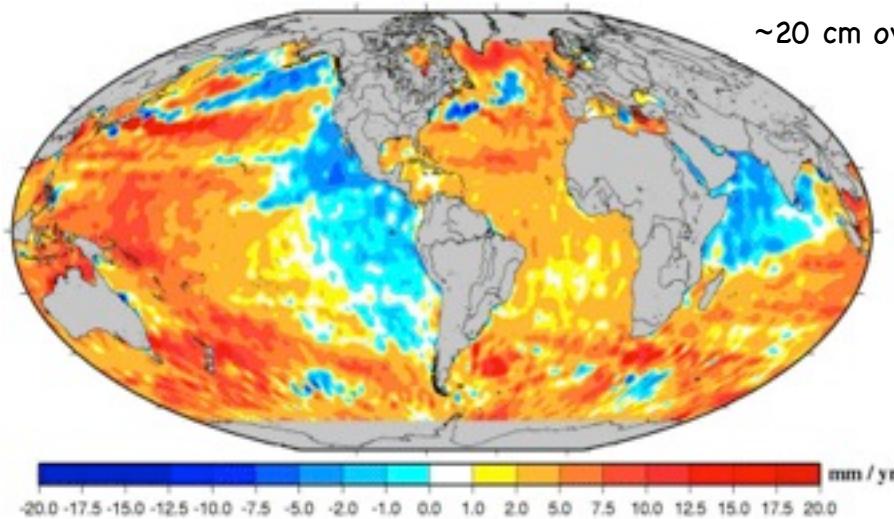
Increase in temperature → causes sea level rise



~0.8°C in the last century

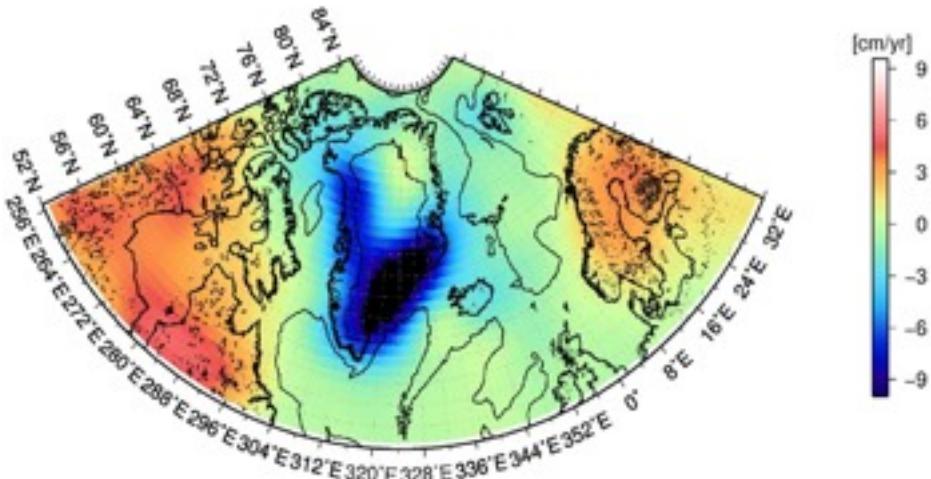


~20 cm over the last century



Loss of Ice Mass

GRACE – Results: Greenland



Variation (equivalent water height) in Greenland
(Feb. 2003 – Jan 2009) derived from GRACE

(Wouters et al., 2008)

→ approx. 180 Gt per year

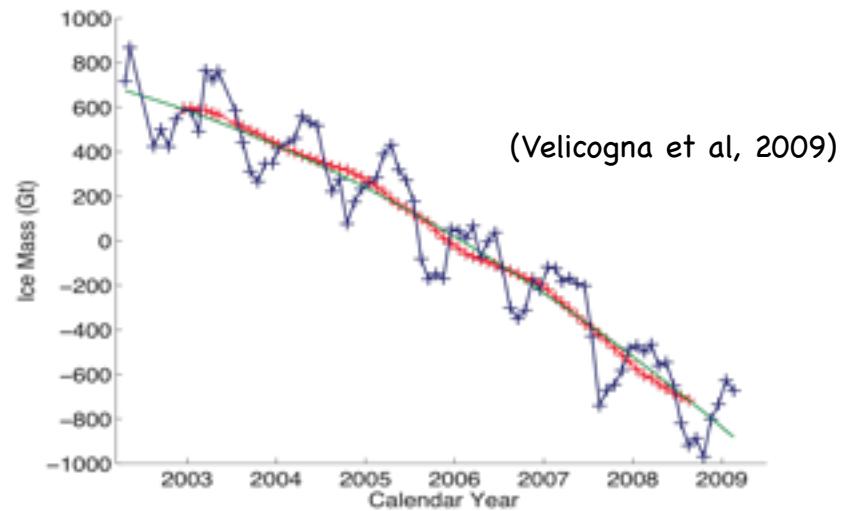
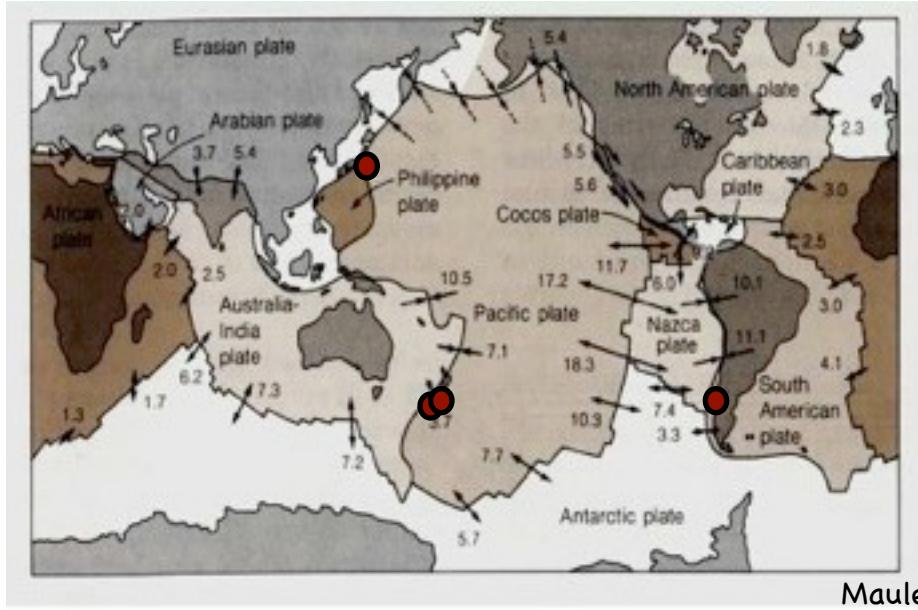


Plate Tectonics → Earthquakes



recent examples:

Maule: 27.2.2010 (mag. 8.8)

ChCh: 2.9.2010 (mag. 7.4)

ChCh: 22.2.2011 (mag. 6.3)

Japan, 11.3.2011 (mag. 9.0)

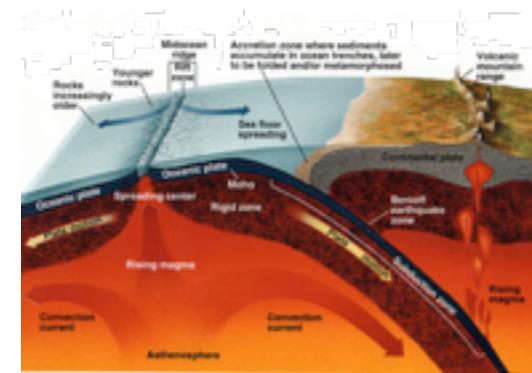


System Earth - Relevant Timescales

Lithosphere:

Plate Tectonics \leftrightarrow Earthquakes

Millions of Years \leftrightarrow several Seconds
cm/year \leftrightarrow km/s



Hydrosphere:

Sea Level Rise \leftrightarrow Tsunami

3 mm/year \leftrightarrow 300 m/s



Atmosphere:

Climate \leftrightarrow Weather

years - decades \leftrightarrow hours - days



→ Requirements

Measurement techniques of extremely high resolution and stability
Quantification of very small and slow processes vs. highly dynamic realtime

➤ „Internal“ Goal

Evolution of GGOS and the geodetic observation technologies to establish an Earth fixed reference frame with a relative accuracy of at least

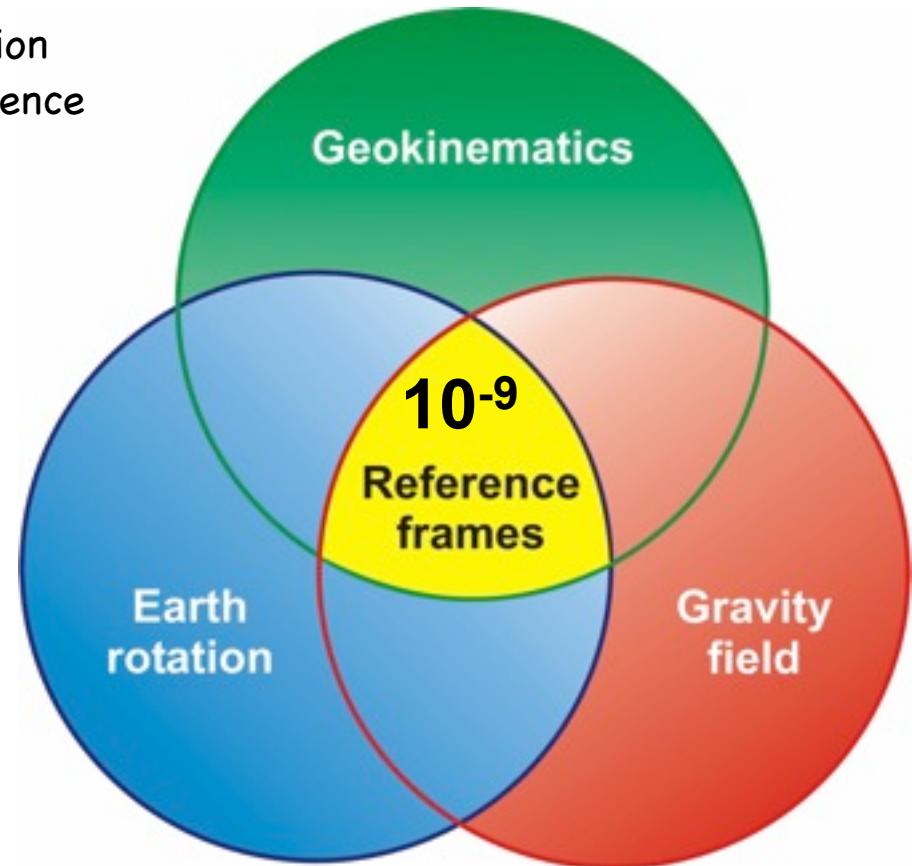
$$10^{-9} = 1 \text{ ppb}$$

with high spatial and temporal resolution.

➤ „External“ Goal

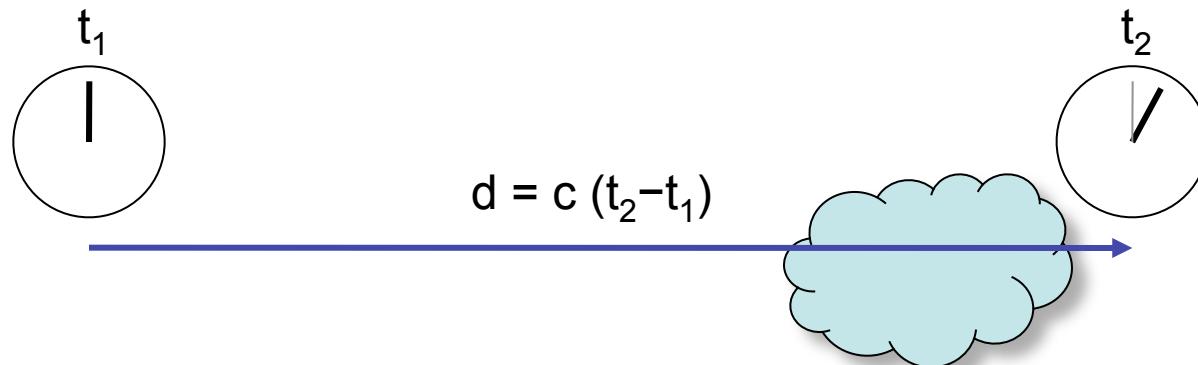
Integration of GGOS as an important contributor into **Earth System Research** (Modeling of physical, chemical and biological processes).

Contributions: Mass transport, dynamics, surface deformations.



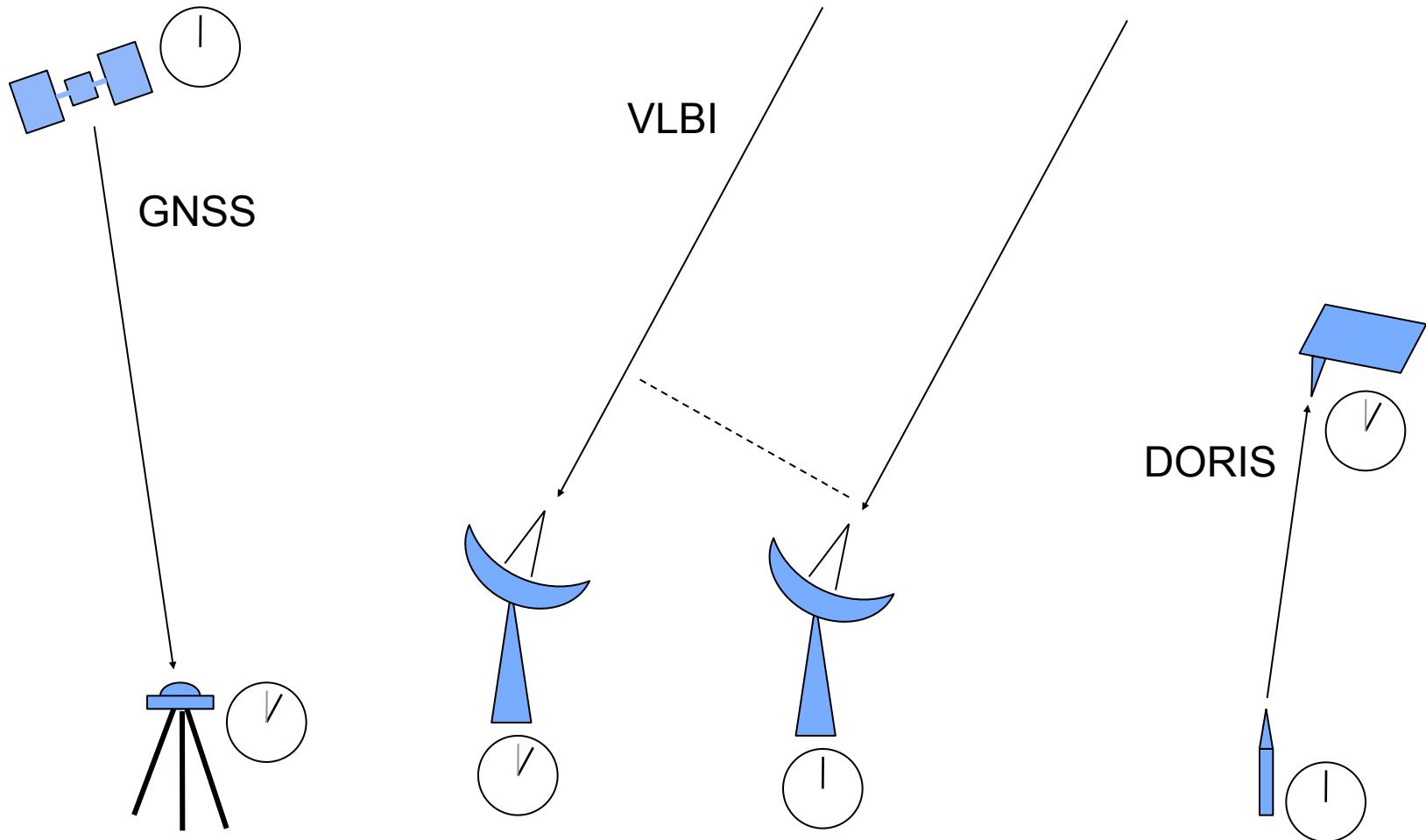
One-Way ranging techniques

- GNSS
- VLBI
- DORIS



- Clocks have to be *synchronized* always!
- The measurement always yields *pseudo ranges* (Range contaminated with synchronization errors)
- Synchronization of sensor clocks is elementary part of the data analysis in geodesy

One-Way ranging techniques



Time or Frequency?

- By concept all measurements in space geodesy are based on the transfer of electromagnetic signals
- Time or Frequency?
- Time transfer requires some sort of code measurements (group velocities). For GNSS this is about 100x less precise than phase.
- Time transfer requires calibrated and temperature stable cables and modules up to the clock.
- Time not yet used in geodesy as an observable

- Observation of phase: No time transfer possible because of ambiguities
- Frequency: Variation of the (biased) time intervals.

Time or Frequency

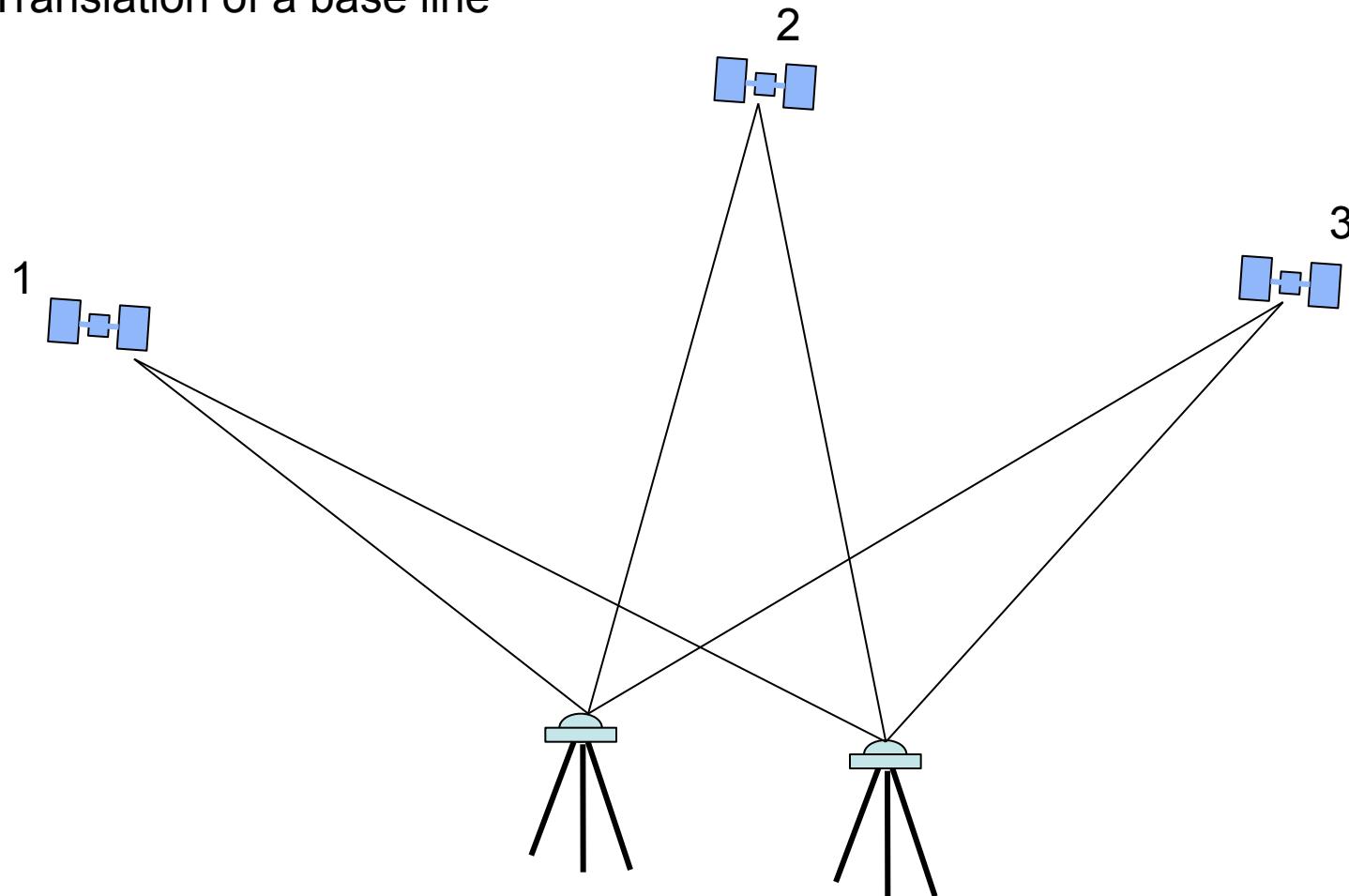
- What accuracy is required in geodesy?
 - precision for phase estimate: 1mm
 - granularity of the clocks $\Delta t_c = 1\text{mm}/c = 3\text{ ps}$
 - accuracy of applied timescale $\Delta t_v = 1\text{mm}/v_{\text{sat}} = 0.3\text{ }\mu\text{s}$
- Accurate time needs to be approximately 100'000x less precise than measured time intervals

Clock Synchronization in GNSS

- GNSS follows the basic measurement concept:
 - every receiver observes more than one satellite
 - every satellite is observed by more than one permanent station
- All clocks can be synchronized for every measurement epoch
- There are no stable clocks required within the network
- VLBI observes more than one quasar and there are a redundant number of telescopes involved
- Clock corrections are estimated for each system every 2 hours
- SLR observes time intervals and the requirements for the epoch are low

Clock Synchronization in GNSS

- Translation of a base line

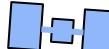


Clock Synchronization in GNSS

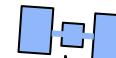
- Translation of a base line

possible by changing the correction of the satellite clock.

1



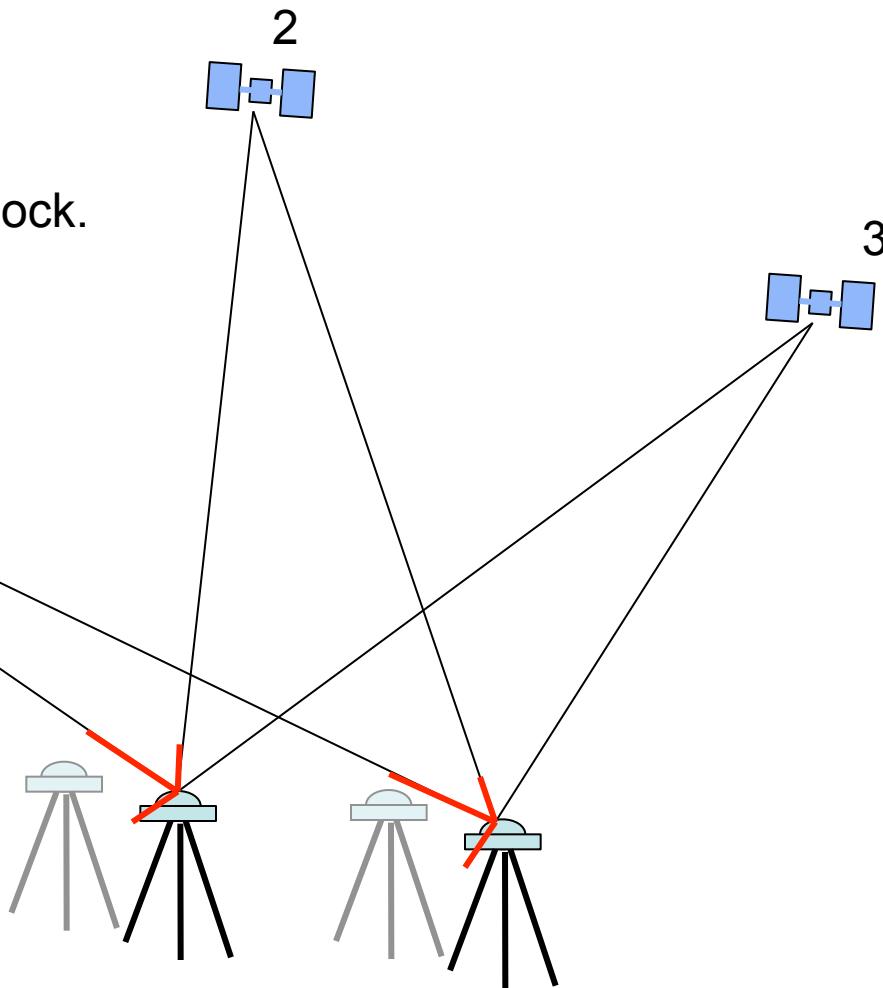
2



3

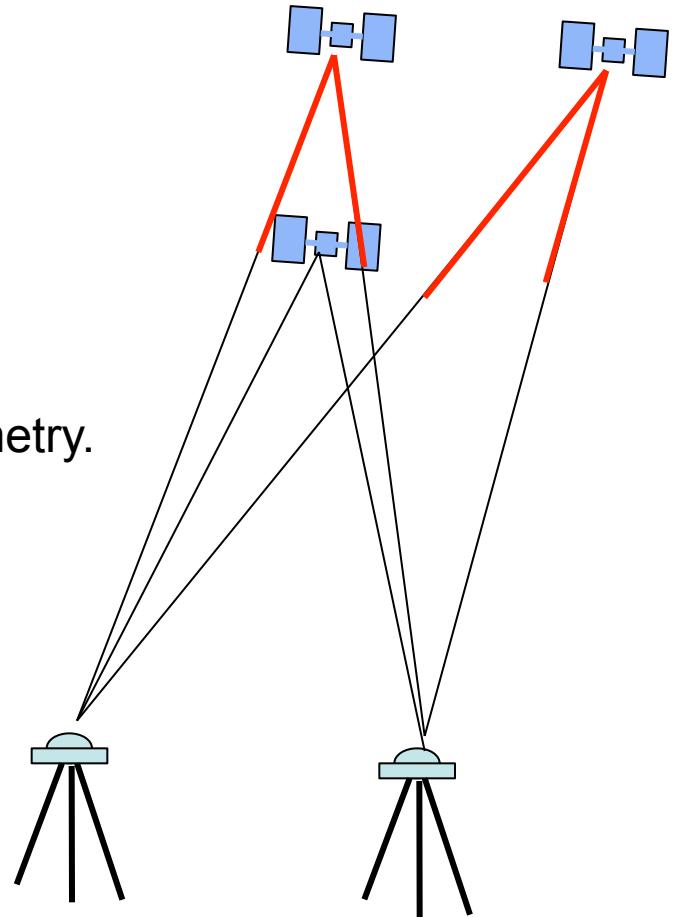


The geometry of the network is well established but not absolute positions



Clock Synchronization in GNSS

- Precise GNSS observations are angle measurements!
 - Radial displacements of the satellite can be compensated by shifting the clock.
 - Transversal satellite displacements can not be compensated by time.
- observation of phase is technically interferometry.
→ measurement of angle



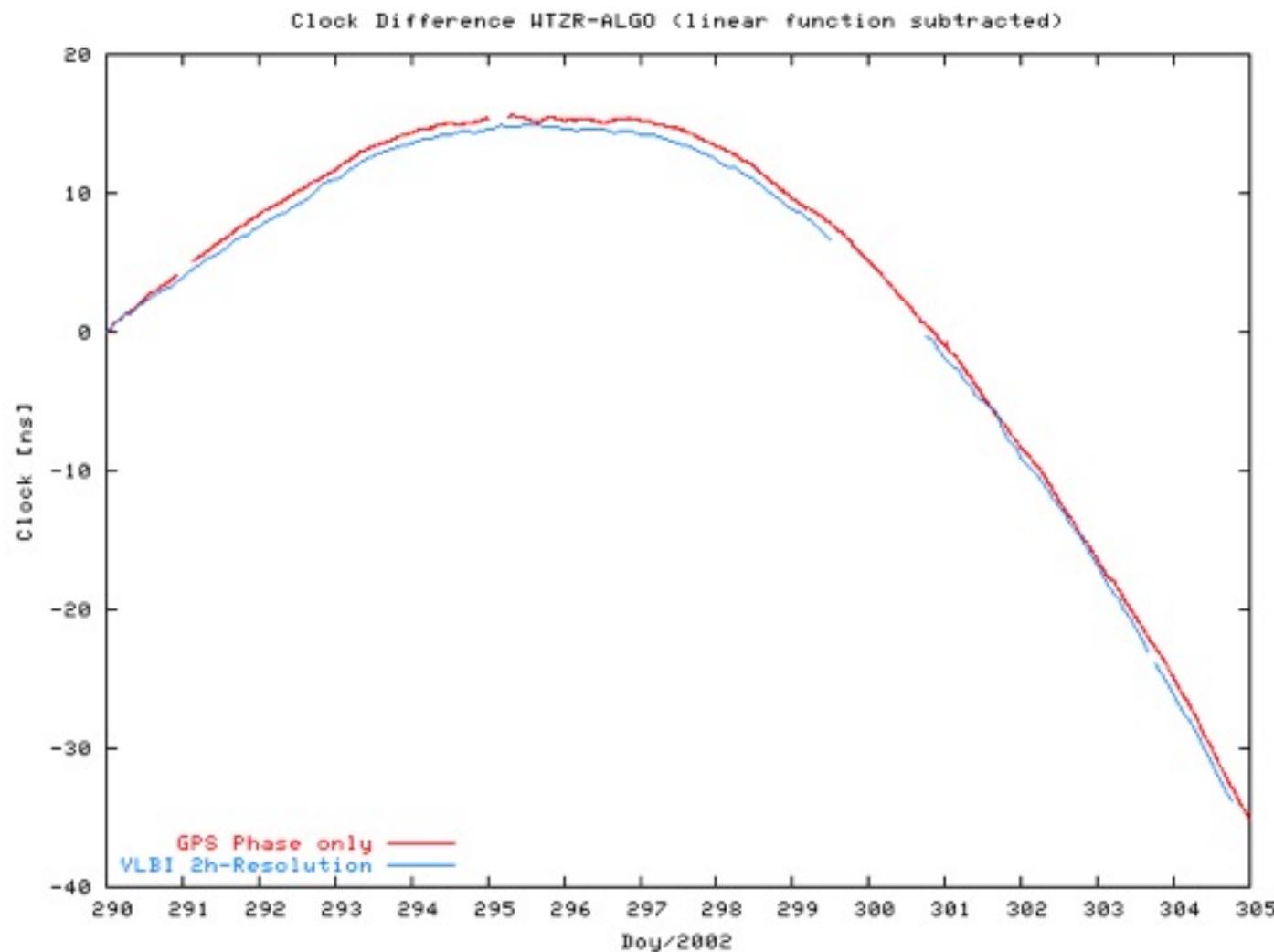
GNSS and VLBI

How does this compare to VLBI?

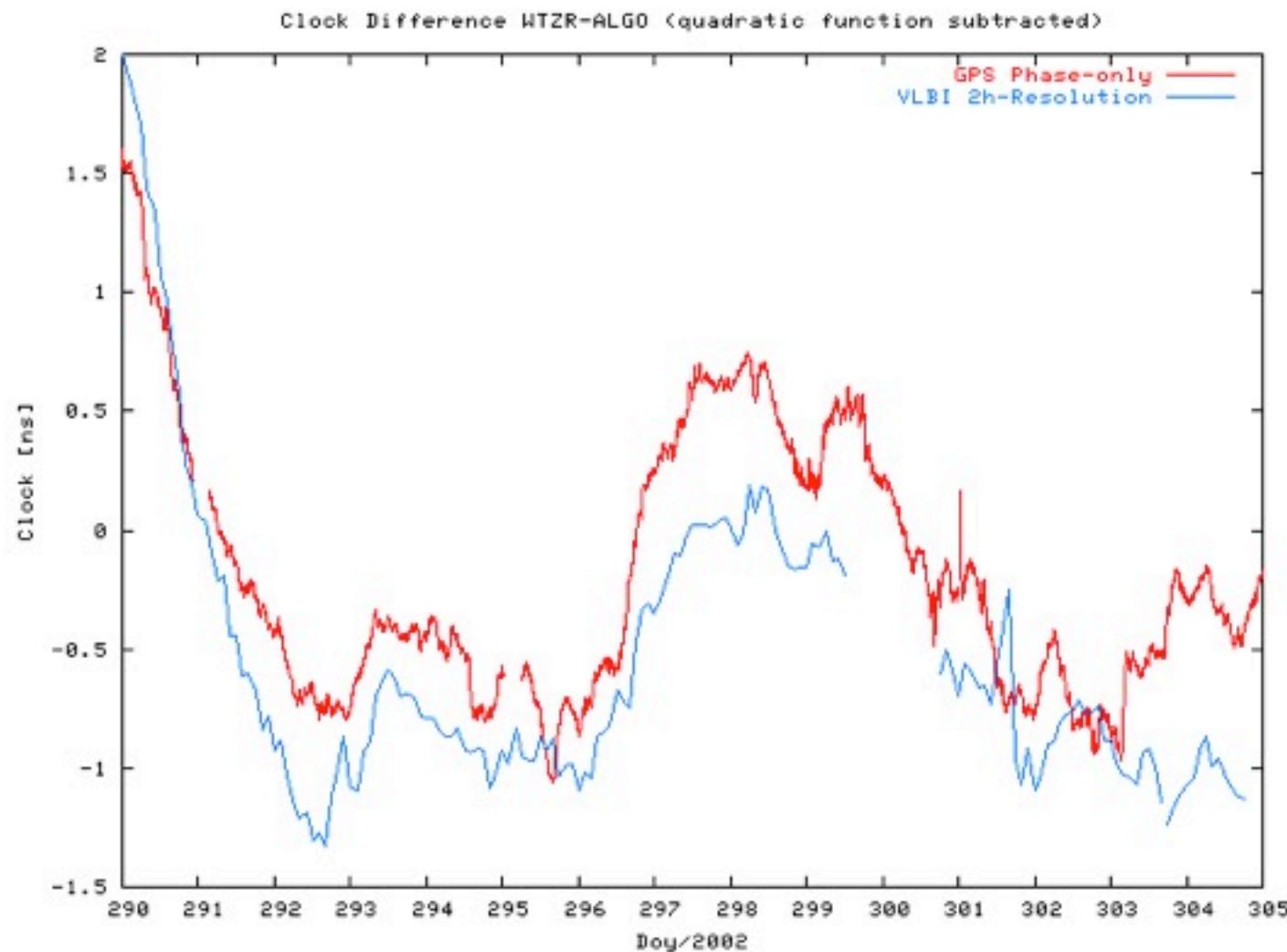
- one-way measurement
- observation of time delay (differences)
- somewhat larger antennas
- Orbit of sources can be modeled more precisely
- only *one* quasar observed per epoch!
- Clock behavior is modeled!



GNSS and VLBI

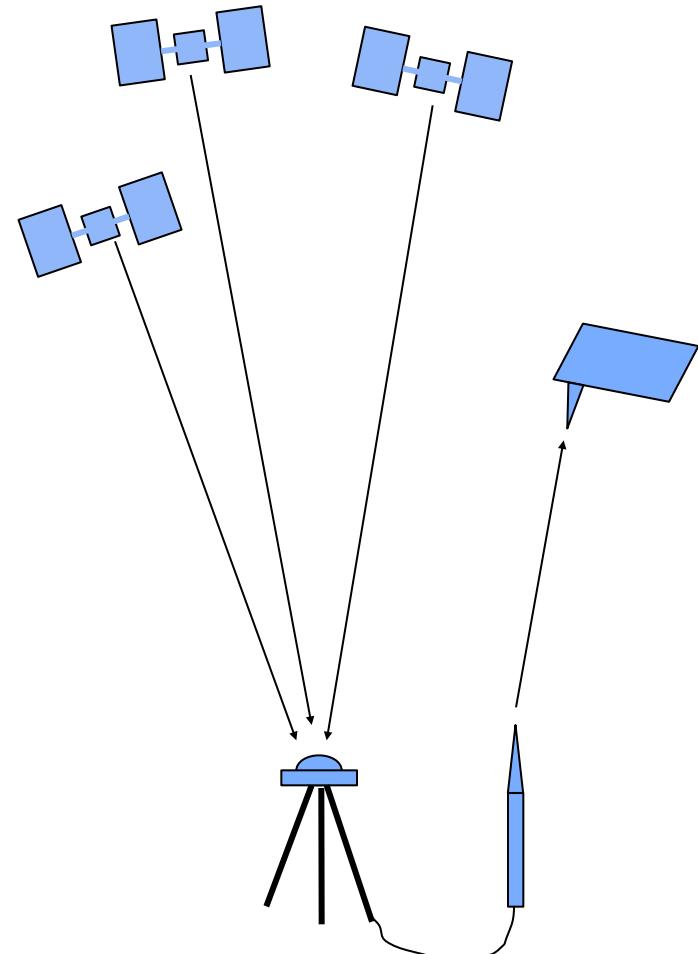


GNSS and VLBI



Combination of observations

- Goal: Improvement of error budget through combination of clock parameters
 - Clock parameter are contaminated by other error contributions (high correlation)
 - Common clock for all instrumentation on the observatory
-
- Common clock between observatories (VLBI)
 - 3D geodesy → 4D geodesy (space time)





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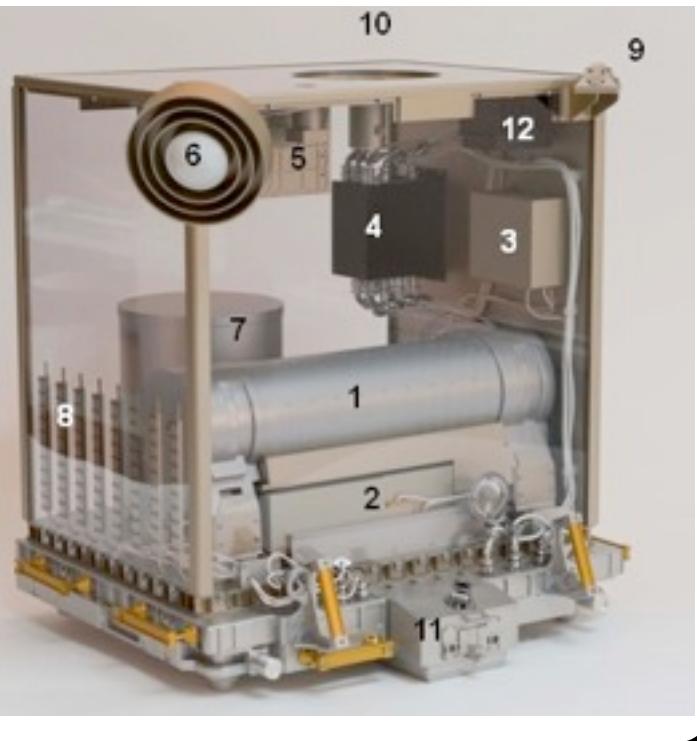
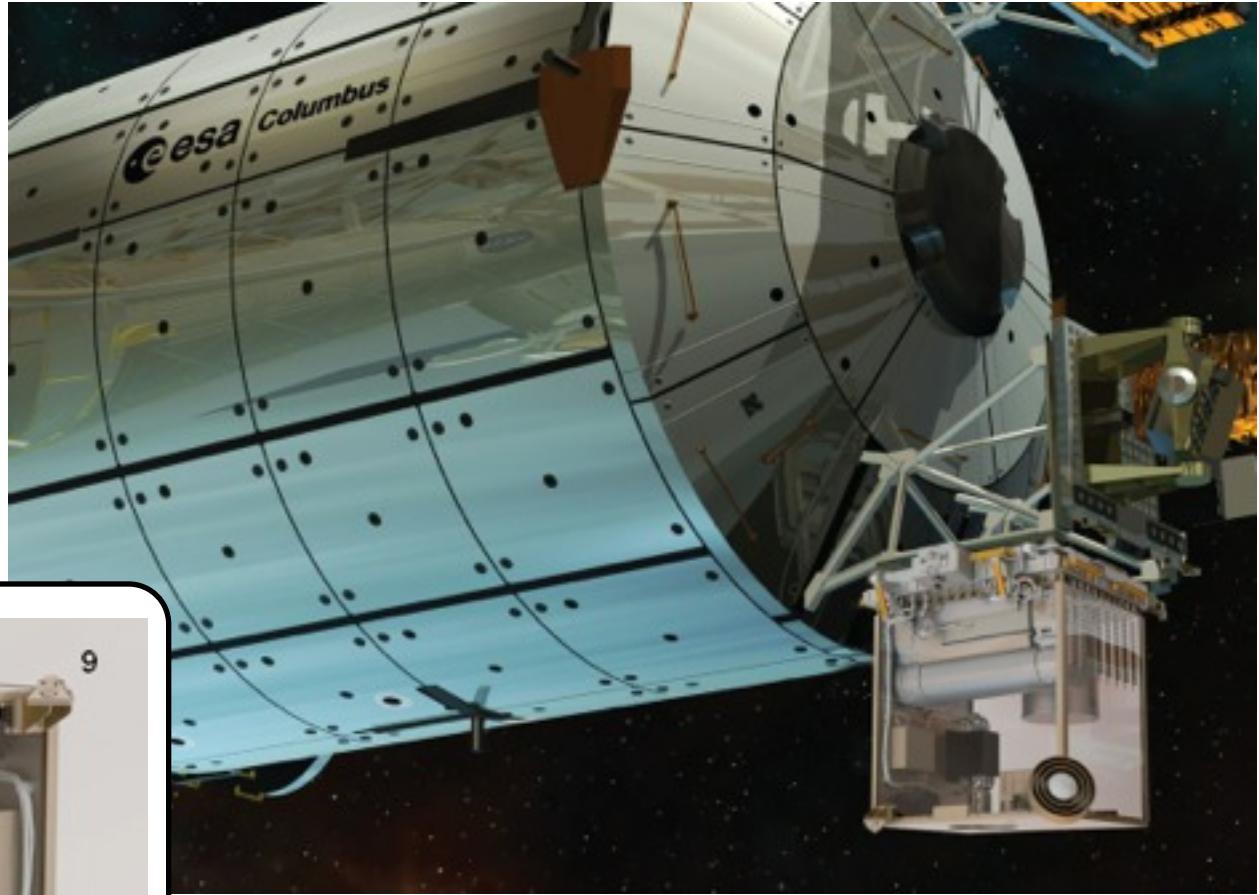


launch date: 2015

European Laser Time Transfer (ELT)

Two atomic clocks: a μg environment Cs fountain clock and a H-maser. Synchronization with the ground timescales are done by microwave and laser link, aiming at 25 ps and accuracy for the time comparison.





- | | |
|---|---|
| 1. PHARAO Cesium Tube
2. PHARAO Laser Source
3. PHARAO computer
4. XPLC
5. MWL
6. GNSS Antenna | 7. Space hydrogen Maser
8. Heat pipes
9. Laser corner cube reflector
10. MWL antennae
11. CEPA
12. ELT |
|---|---|

The payload has a volume of about 1m³ and a mass of ~362 kg.

Clock Comparison between WLRS and Jason 2

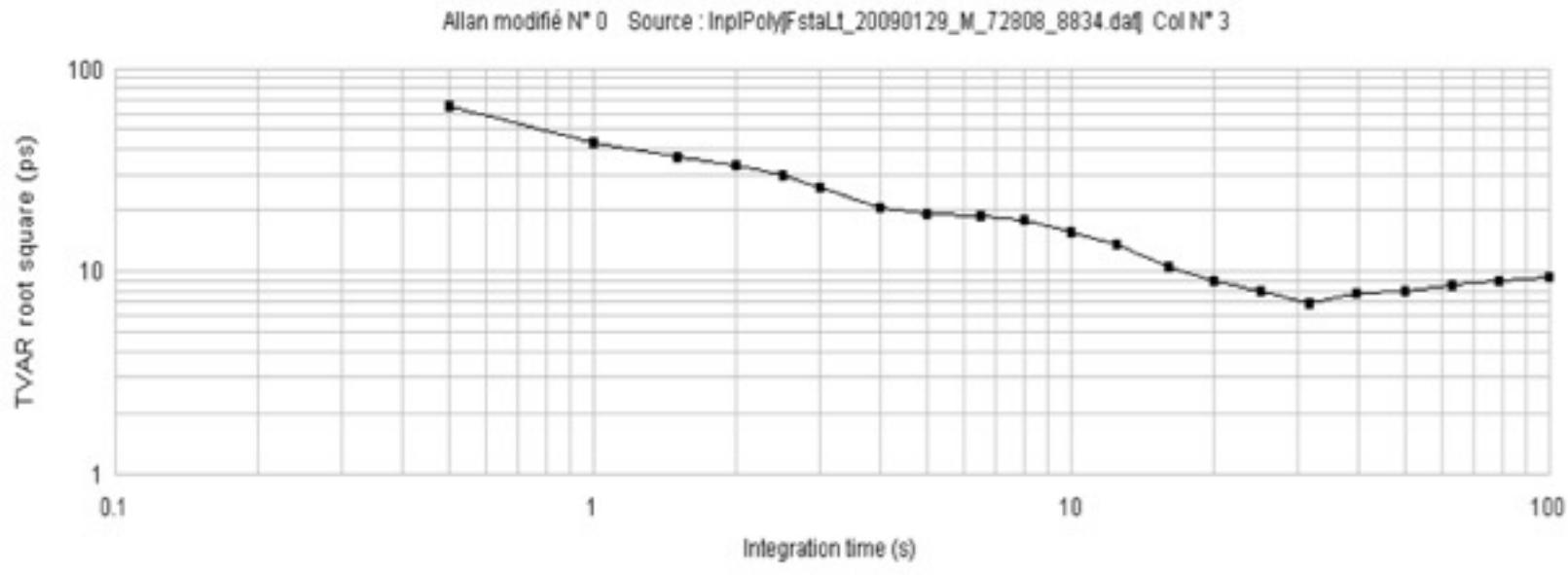


Figure 10: Time stability measured by T2L2 of the Wetzell's H-Maser compared to the T2L2's DORIS oscillator

DORIS USO (quartz) : 40 ps @ 1 s and 7 ps @ 30 s.

For integrated times >30 s : limit due to DORIS with : 5 ps @ 30 s and 10 ps @ 100 s

Source: Samain et al. „Time Transfer by Laser Link T2L2 first results“;
IEEE Xplore ID: 5168168 (2009)

