DORIS DAYS 2025

November, 3 and 5

DORIS observations

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Session 2 – Presentation 1

Setup of this class

First: What is DORIS observing? Define the main topics that you need to consider (~25 min)

Second: Use the Jupyter notebook, run a simulation and browse though a DORIS Rinex file (~60 min)

Jason-1 DORIS stations visibilities
Elevation 12°

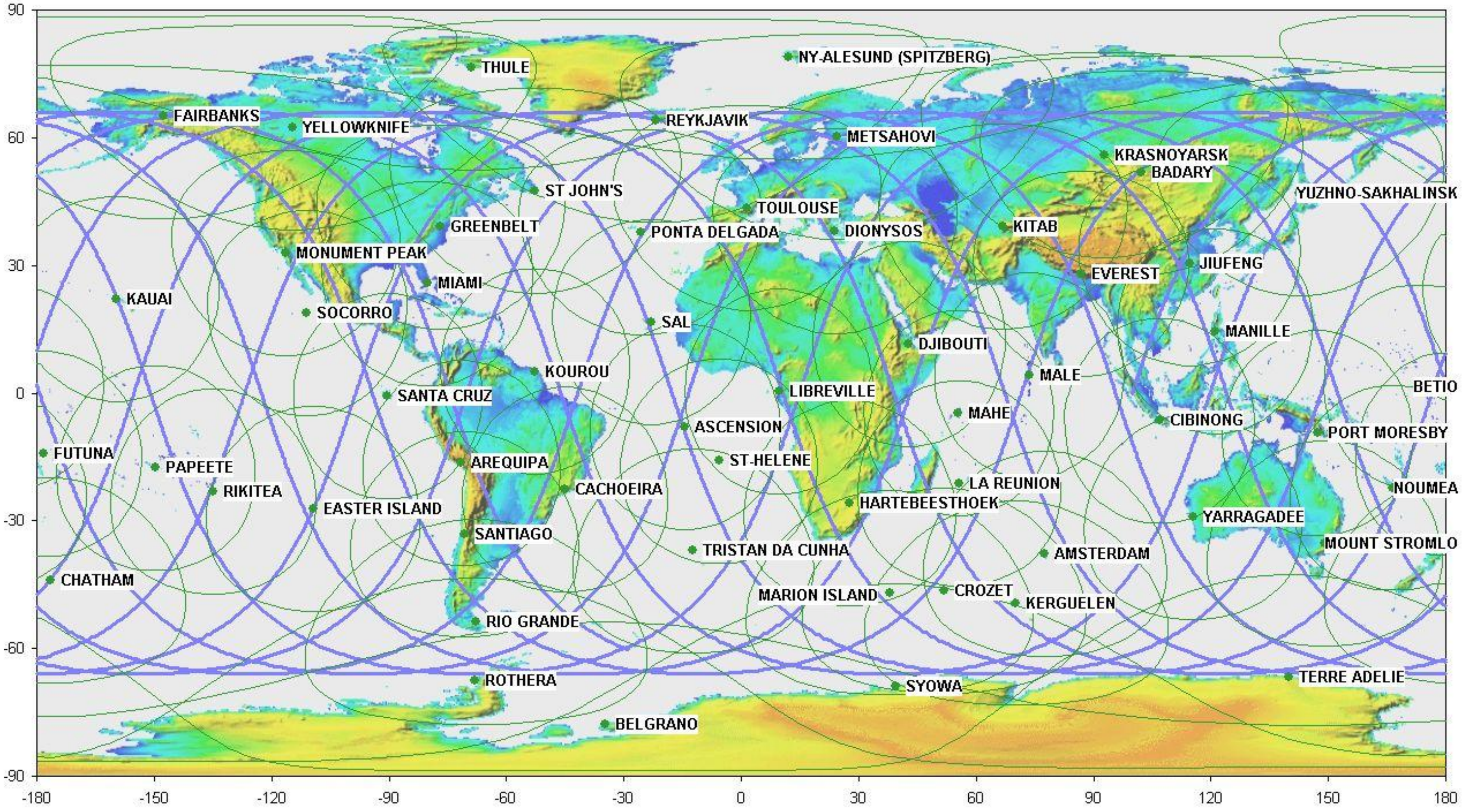
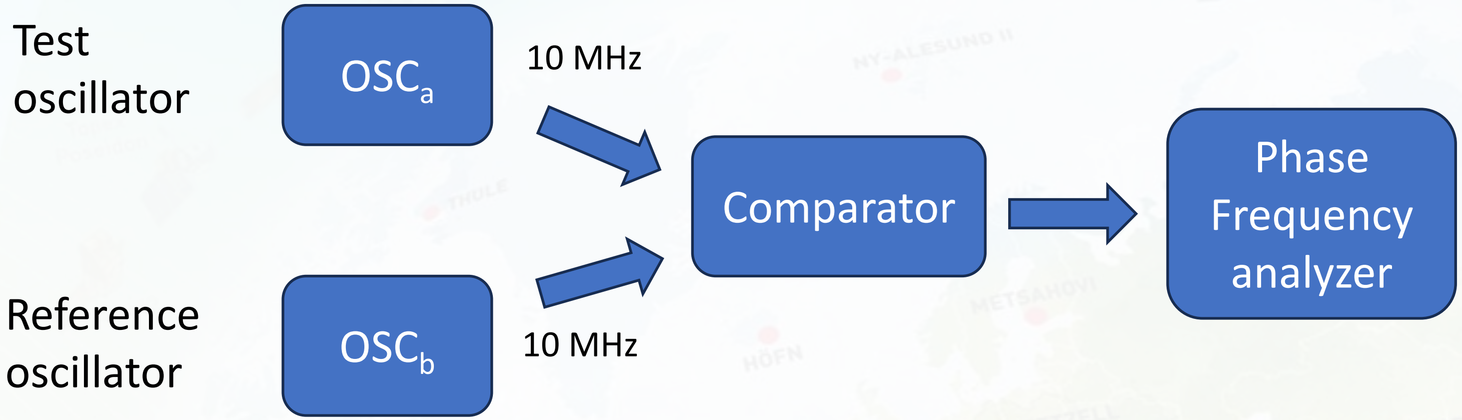


Image credits: IDS

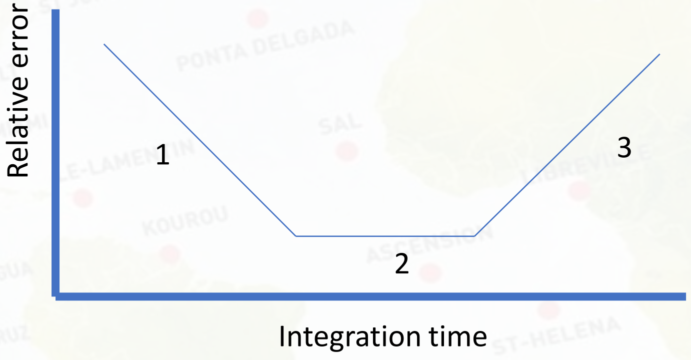
Content

- Twin oscillators
  - Experiment in the laboratory
  - Experiment in the field
- Conclusions from the field setup
  - Range and velocity
  - Time synchronization
  - Light time correction and relativity
  - Refraction
  - Antenna's
- Hands on
  - Differences between DORIS and GNSS
  - Argos simulator experiment (via Jupyter notebook)

Lab setup twin oscillators



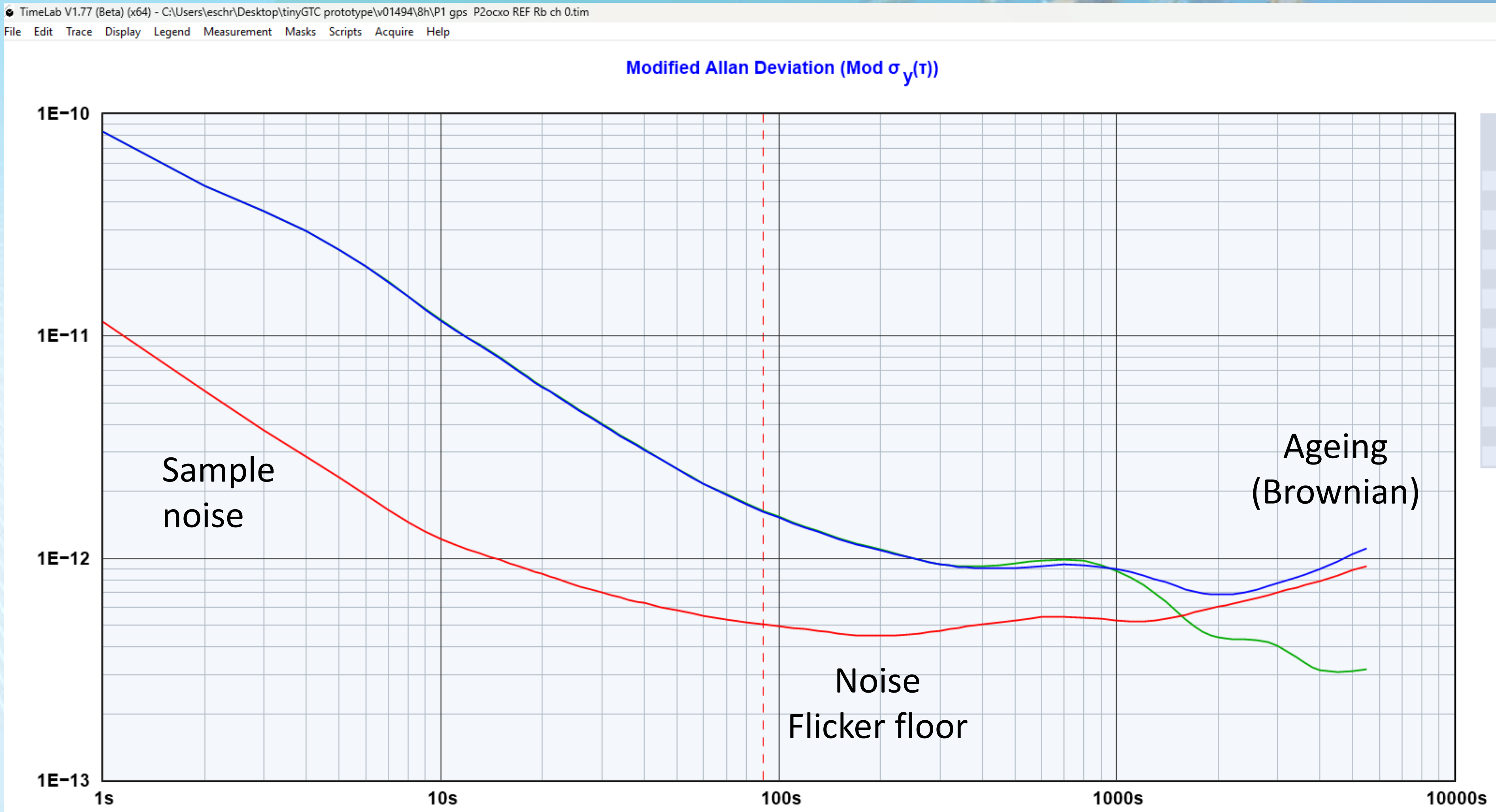
Allan deviation analysis



Oscillator model:

1: Sampling error
2: Noise flicker floor
3: Ageing effects

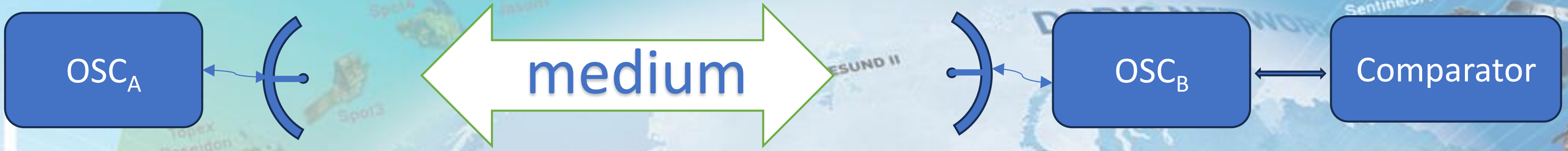
Result of the lab experiment



Tau	Sigma(Tau)
1s	8.34E−11
2s	4.74E−11
4s	2.96E−11
8s	1.51E−11
10s	1.18E−11
20s	5.95E−12
40s	3.09E−12
80s	1.77E−12
100s	1.54E−12
200s	1.10E−12
400s	9.21E−13
800s	9.74E−13
1000s	8.81E−13
2000s	4.41E−13
4000s	3.14E−13

Trace	Notes	Input Freq	Sample Interval	MDEV at 90s	Duration	Elapsed	Acquired	Trace Window	Channel
P1 gps P2ocxo REF Rb	tinyGTC FW V0.1494	10 MHz	1 s	1.64E−12	8h	8h	28800 pts	28800 pts	Ch 0
P1 gps P2ocxo REF Rb	tinyGTC FW V0.1494	10 MHz	1 s	5.04E−13	8h	8h	28800 pts	28800 pts	Ch 1
P1 gps P2ocxo REF Rb	tinyGTC FW V0.1494	10 MHz	1 s	1.63E−12	8h	8h	28800 pts	28800 pts	Ch 2

Field set-up



Elements in this experiment

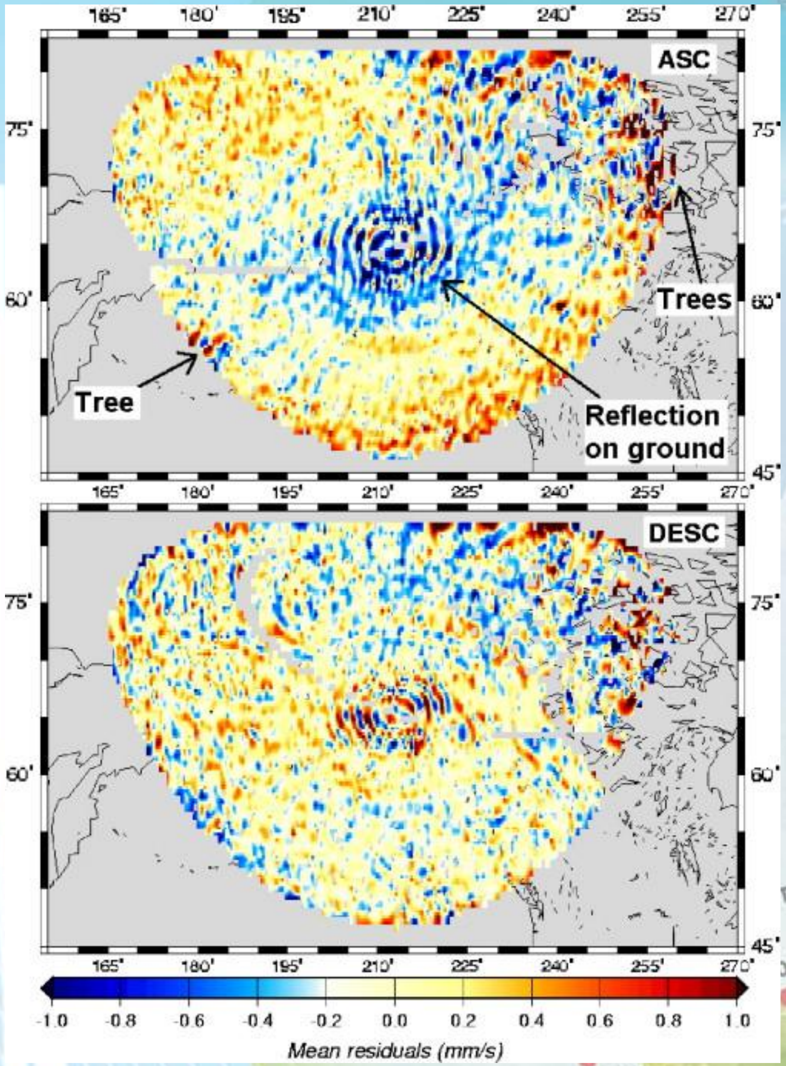
- OSC_A is a transmitting beacon
- OSC_B is a reference for a receiver
- Phase and frequency are transferred through a medium between A and B
- Phase definition is transferred by means of a modulation technique

Difference lab and field set-up

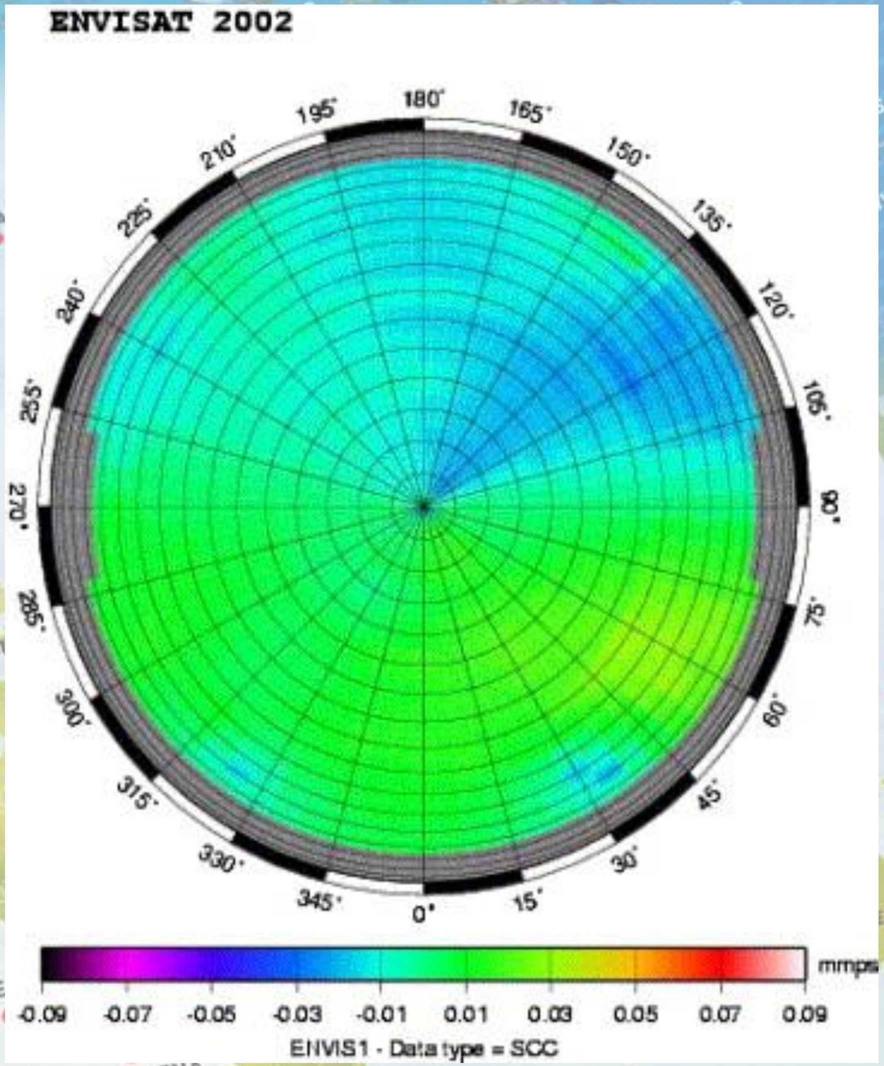
- Field set-up is affected by
  - Antenna's
  - Refraction
  - Geometry

- Antenna's:
  - Phase center definition depends on the design
  - Offset depending on topocentric azimuth and elevation
- Refraction
  - Wet and dry troposphere
  - Ionospheric delay
- Geometry
  - Relative velocity and distance
  - Light time effect
  - Time synchronization

Antenna phase center variations



POE orbit mean residuals of Fairbanks-SPOT-5 link from 2007/05/21 to 2007/08/28. P Yaya and C Tourain 2010 ASR



Willis, Desai, Bertiger, Haines and Auriol 2005 ASR

Refraction

- In its most general form:
  - $\Delta s = \int_A^B (n-1)ds$
  - Where the integral goes over the path A to B
  - Where ds is a small part along the path
  - Where n is an in-situ refractive index of the medium
- Troposphere : gasses between both antenna's
  - Non-dispersive effect so frequency independent
  - Wet toposphere : water vapor pressure (humidity)
  - Dry troposphere : dry gas content (air pressure)
  - With DORIS you estimate tropospheric parameters
- Ionosphere : free electrons cause the refraction

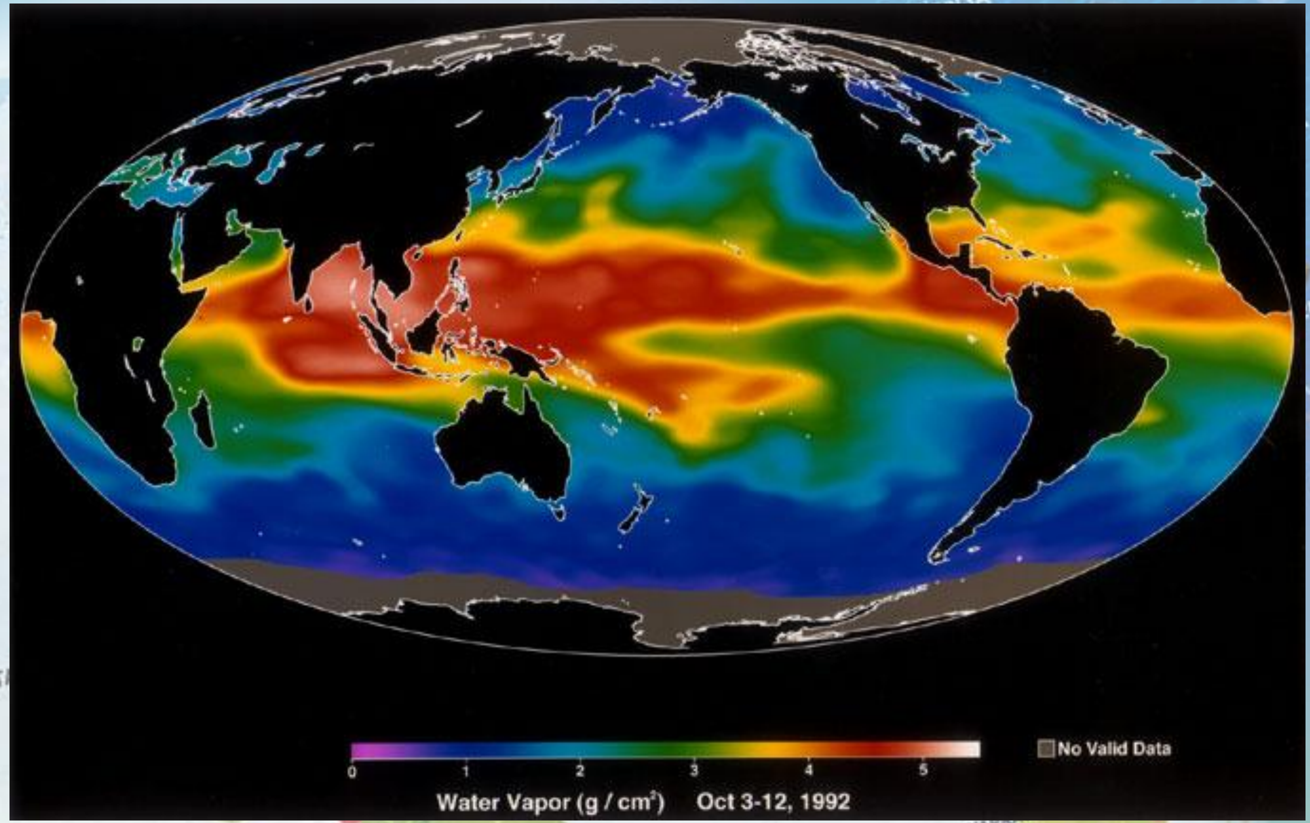
Wet troposphere mapped with a microwave radiometer

Since the non-ionizing atmosphere is non-dispersive you need to resort to more difficult techniques to measure it. Most people don't do this, but for satellite altimeter systems we do.

The atmosphere is opaque on certain frequencies due to water vapor and this is what you can measure at the water vapor absorption line (22 GHz) relative to a few neighboring frequencies.

A radiometer is a noise receiver, it measures the thermal noise of the object, and hence its blackbody temperature.

(Radiometer: it is >10 million USD instrument)



Ionospheric refraction

- Observe it with at least two frequencies (dispersive)

$$r(f_1) = r_o + \frac{\alpha}{f_1^2} \quad \text{and} \quad r(f_2) = r_o + \frac{\alpha}{f_2^2}$$

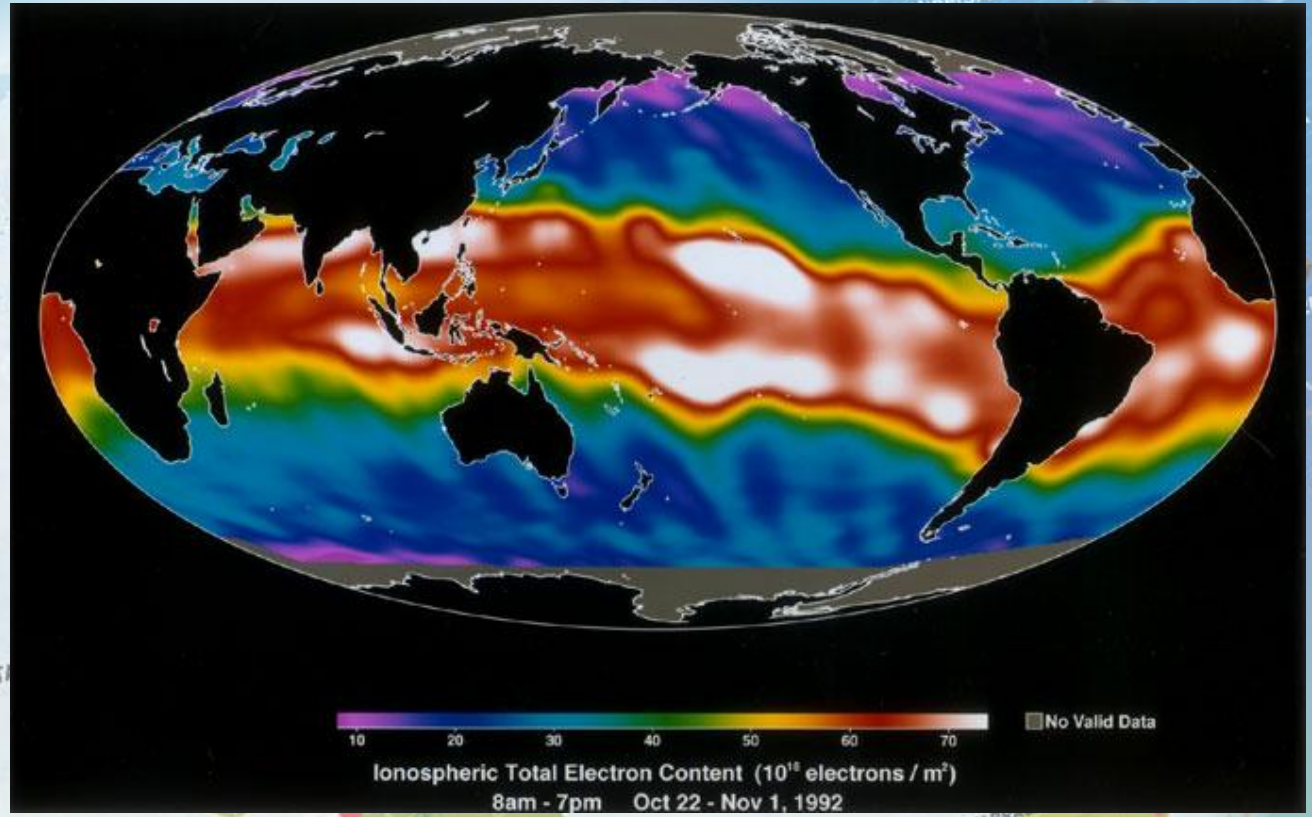
- Two equations with two unknowns, solve r_o and α
- The α parameter results in the free electron content along the path between A and B, converts to TEC
- And r_o is ofcourse what we want in further processing
- One problem: the phase centers for f_1 and f_2 do not match for any antenna, there is a phase offset.

Ionosphere mapped with dual frequency altimeter radar on C and Ku band

In this case you have a downward looking ocean sensing radar, it works on two microwave frequencies and you solve for the TEC which is downward to the sea surface.

The wavy red band coincides with the geomagnetic equator, this is where you can expect turbulence in the ionosphere.

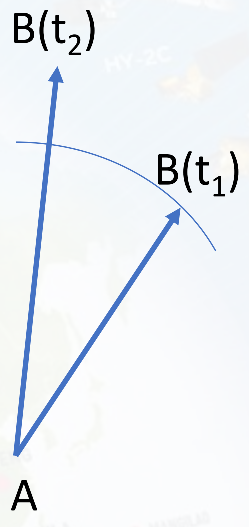
Locally the ionosphere is a smooth function of time and place, we correct it with the DORIS data.



Geometry: LOS velocity and distance

- Distance to phase relation OSC_A and OSC_B

$$d = c(t_B - t_A) = \varphi_B - \varphi_A$$



- Line of sight velocity OSC_A and OSC_B ➡ Doppler signal

$$f_o + \Delta f = 1 + \left(\frac{\boldsymbol{v}.\boldsymbol{n}}{c}\right) f_o$$: **v** velocity and **n** direction

- Integrate Δf over time and you get $\varphi(t_1,t_2)$ along **n**

$$\varphi(t_1,t_2) = \int_{t_1}^{t_2} \lambda \Delta f \, dt$$

- This is the phase difference between t_1 and t_2 when $c = \lambda f$ We also call it the observed carrier phase signal
- During POD $\varphi(t_1,t_2)$ is used to estimate $\varphi_B - \varphi_A$ for all defined epochs

Light time correction

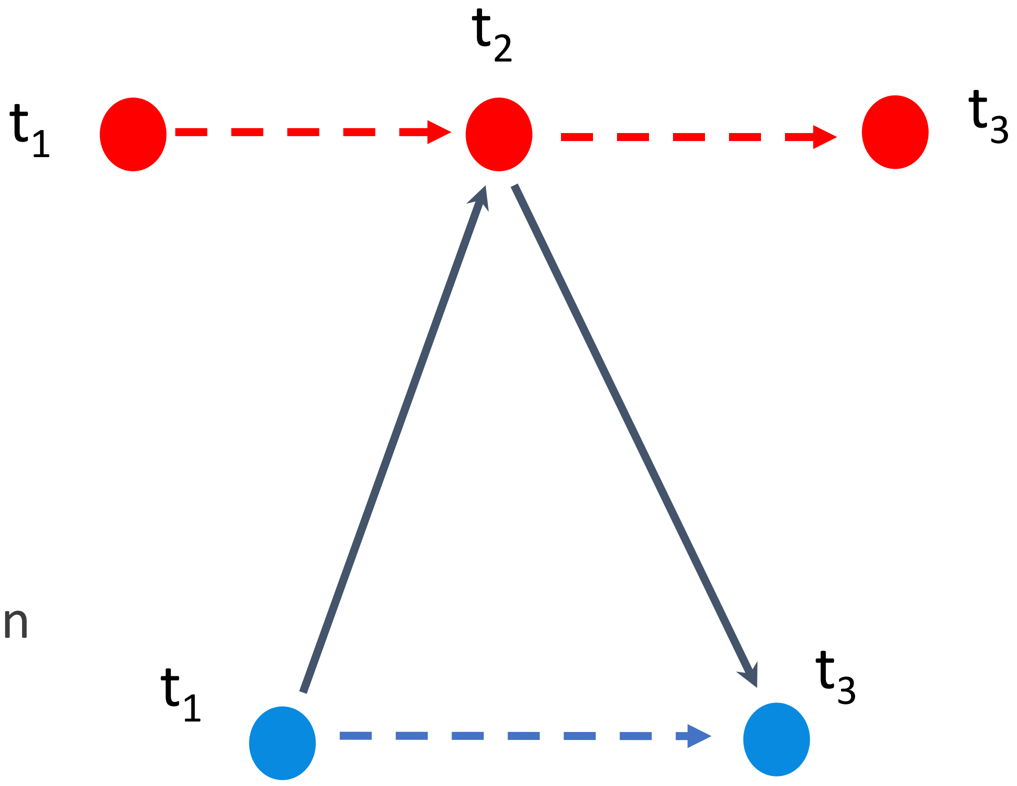
- The time-of-flight (or light-time) principle applies
  - To all measurements between the ground and the satellite
  - With two-way measurements we measure the round-trip time, thus a pulse leaves the laser, reaches the satellite where it reflects, and returns to a detector on the ground
  - With one-way measurements we measure the one-way trip from transmitter to receiver
- First and second order clock errors:
  - There is a first-order clock error $c \cdot dt$
  - There is a second-order clock error $v_{sat} \cdot dt$
- Both effects are significant
- Light time effect ≠ Relativity (not in this lecture)

Light-time effect illustrated with 2-way ranging

t_1 : laser sends the light pulse

t_2 : light bounces of satellite

t_3 : photons return in detector



- red is the satellite
- blue is the ground station
- black arrow is a light ray
- blue dashed arrow is motion ground station
- red dashed arrow is motion of the satellite

Light time effect

Transmitter	Altitude (km)	Milliseconds
GRACE	450	1.50
CryoSat-2	700	2.33
Jason-3	1330	4.46
Lageos	5893	19.6
GPS	20000	86.73
Geostationary	36000	140.10
Moon	384400	1281.3

Time synchronization

- On the satellite there is well behaved local oscillator (LO) with an ADEV like 5×10^{-13} at 1000s and 10^{-11} at 1s. The LO needs to be modelled relative to a ground beacon in DORIS where the timing pulses are synchronized to TAI
- Master beacons that are synchronized to TAI, they transmit synchronized C_1 and C_2 codes. So we have two tasks:
  - Task 1: Model the LO on the satellite with C_1 and C_2 which can only be done during orbit determination (OD)
  - Task 2: On non-master beacons you have an independent LO that needs to be modelled as well, also during OD either via beacon biases or more sophisticated techniques
- A part of the work is already done for you in the RINEX files where the epochs are in principle non-synchronized LO derived, but there is a correction field.

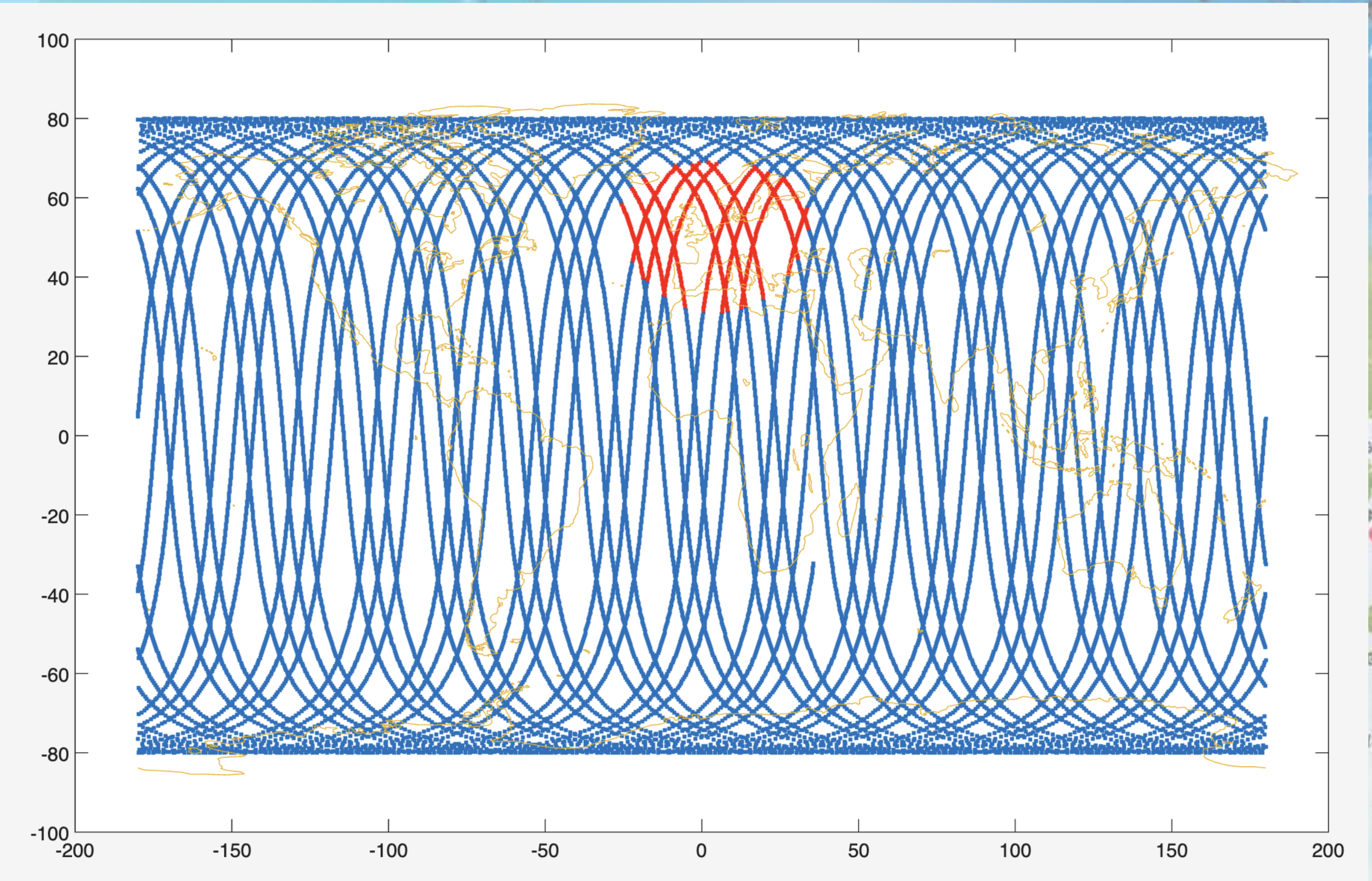
Differences to GNSS

- Similar : Pseudoranges and carrier phase on 2 frequencies
- DORIS frequencies are further apart: 400 MHz and 2 GHz
- No redundancy with pseudoranges, no easy navigation solution
- There is a DORIS navigator on the satellite, it is called DIODE
- DORIS receiver collects carrier phase integrated over 10 seconds from the beacons it encounters
- The data is downloaded and disemminated to the users.
- Modern way of transfer is the RINEX format.

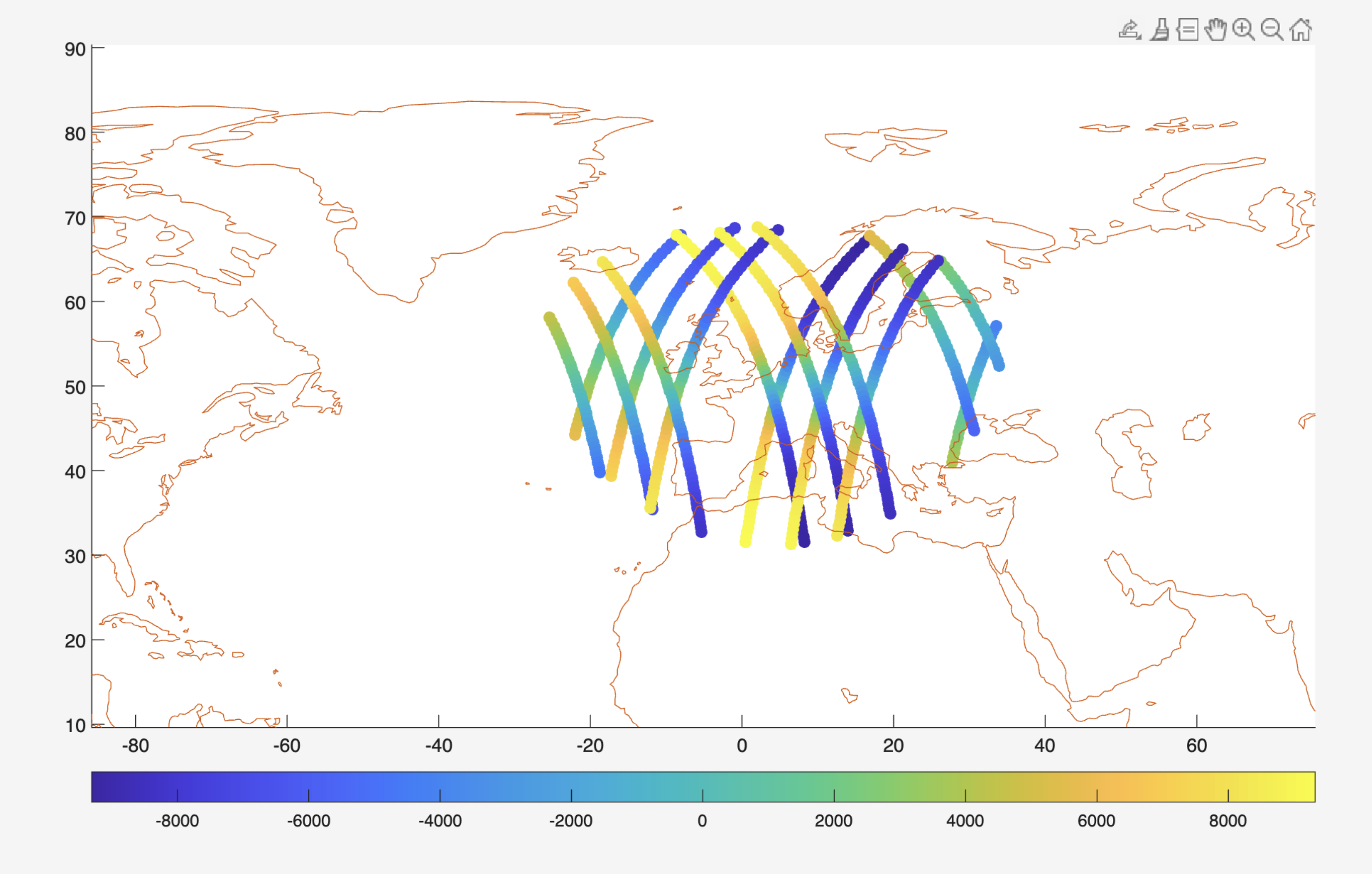
Demonstration of navigation with DORIS

- Assume for simplicity that the satellite's orbit is known and that the satellite carries a receiver
- There is one transmitting beacon in the field,
- Beacon: unknown position, small frequency offset
- Observe only the Doppler effect in space
- Now estimate the beacon position and the beacon frequency offset from the satellite data from a known orbit.
- Go to the argos simulator and your Jupyter notebook and play around with the program.

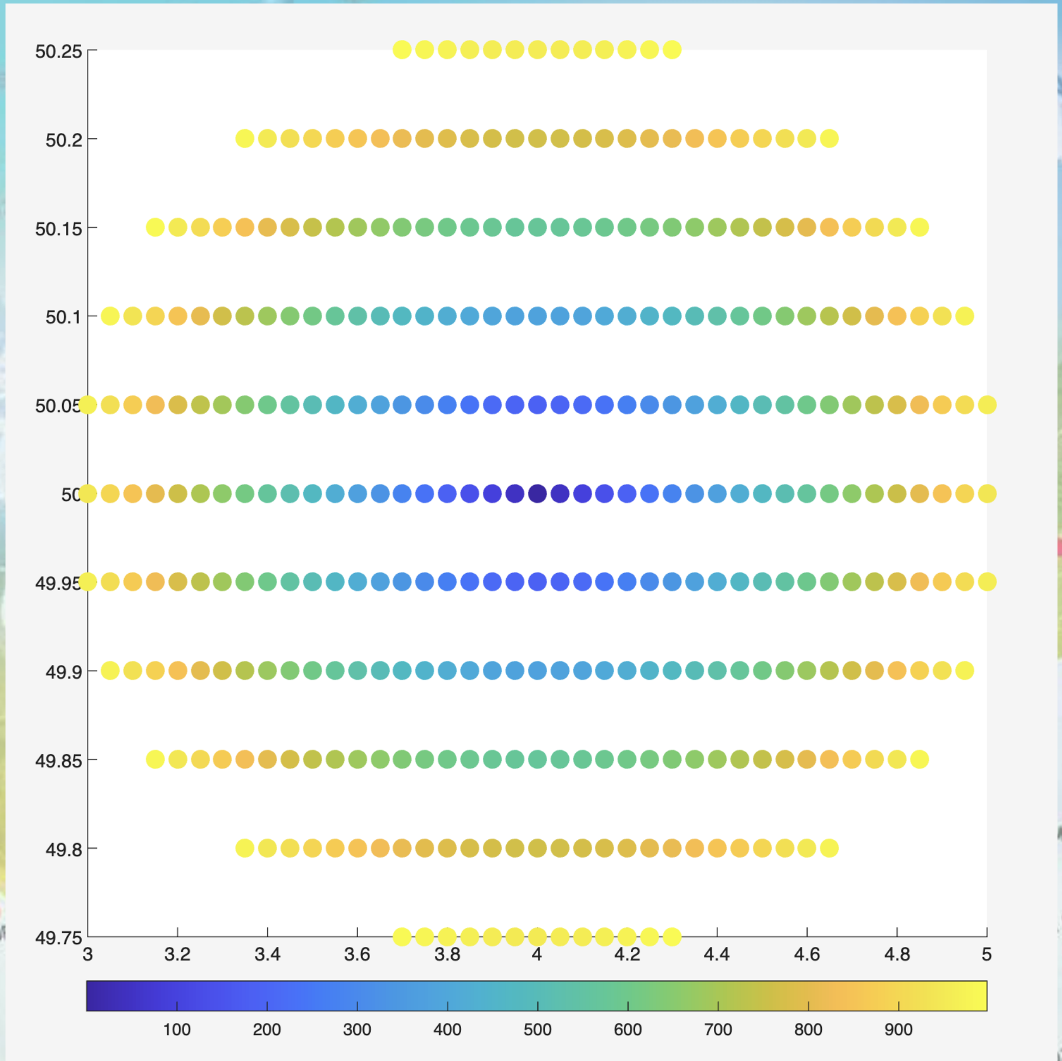
Beacon seen along tracks



Doppler seen by satellite



Residuals grid search method



Key points

- Point #1
  - The twin oscillator experiment in the laboratory results at best in an Allan deviation analysis
- Point #2
  - Field experiment differs from lab because of Antenna, Refraction and Geometry effects
- Point #3
  - Antenna: phase center offsets
  - Refraction: Wet/Dry troposphere and Ionosphere
- Point #4
  - We need to deal with a light time correction
- Point #5
  - We demonstrated the Doppler frequency to carrier phase relation
- Point #6
  - We explained time synchronization in DORIS and discussed the differences between GNSS and DORIS
- Point #7
  - Demonstration of a Doppler Navigation example by using a Jupyter notebook

Any questions so far?