SWOT ALTIMETRY (AND HYDRODYNAMIC MODELS) FOR GEODETIC APPLICATIONS

Aleksei Kupavõh, PhD student
Department of Civil Engineering and Architecture
Tallinn University of Technology

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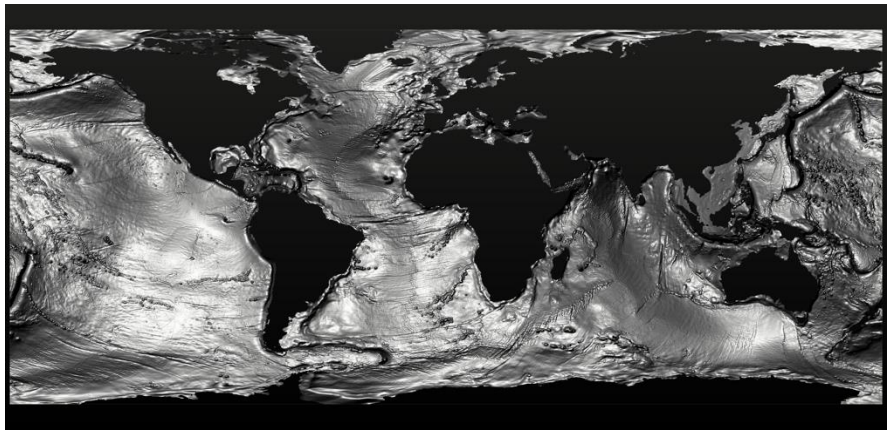
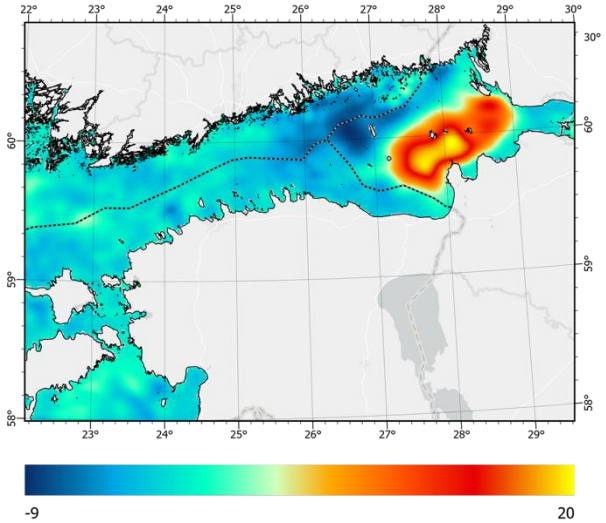
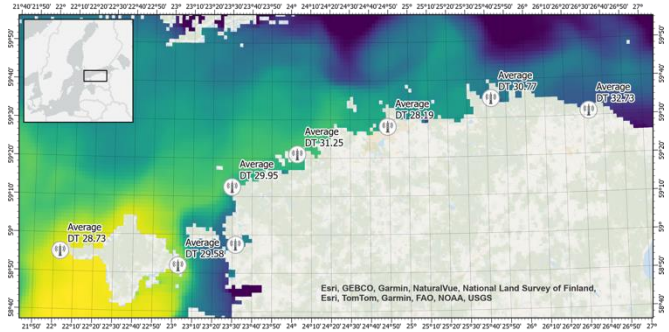
INTRODUCTION
WHO IS TALKING?

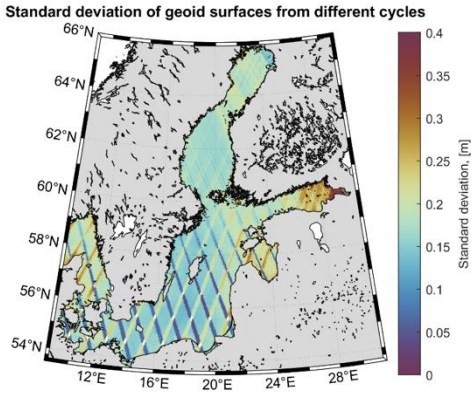
- Aleksei Kupavõh (Estonia)
  - Road Engineering and Geodesy specialising in Engineering Survey (MSc, 2024)
  - MSc Thesis - Performance and capabilities of SWOT satellite altimetry sea level data for exploring the coastal and offshore areas
  - Second year PhD student
  - Mostly deal with SWOT data
  - YPRA30, GGHS24, NKG WGHG meeting, EGU25, LPS25, IAG25

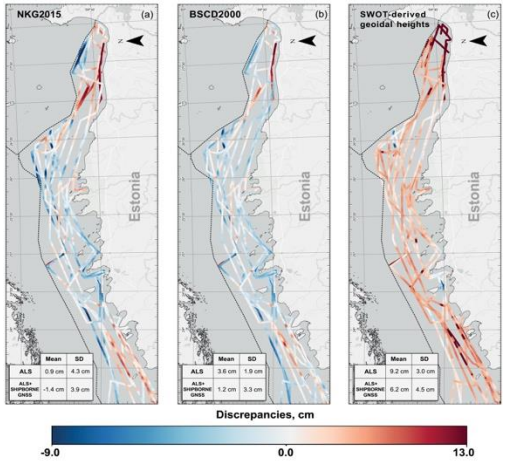
INTRODUCTION
WHO IS TALKING?

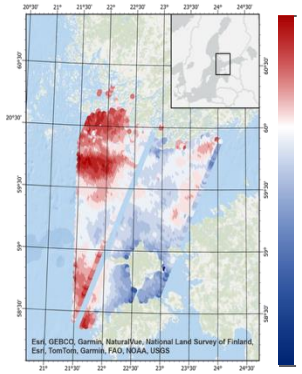


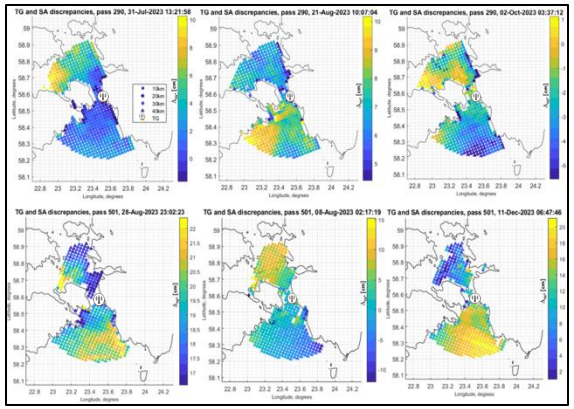


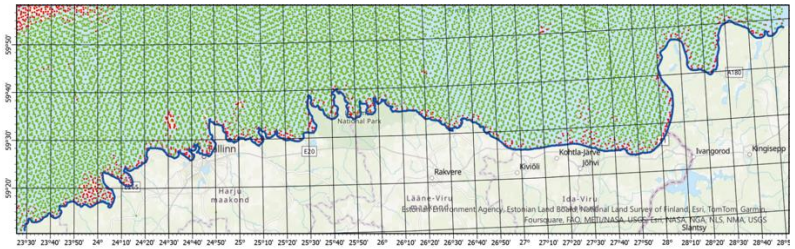












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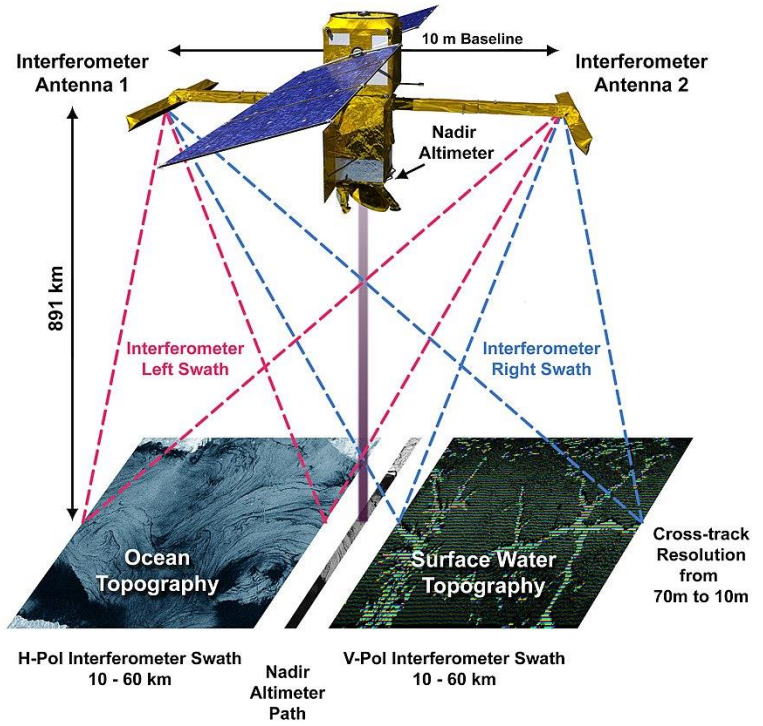
INTRODUCTION
SURFACE WATER AND OCEAN TOPOGRAPHY (SWOT)

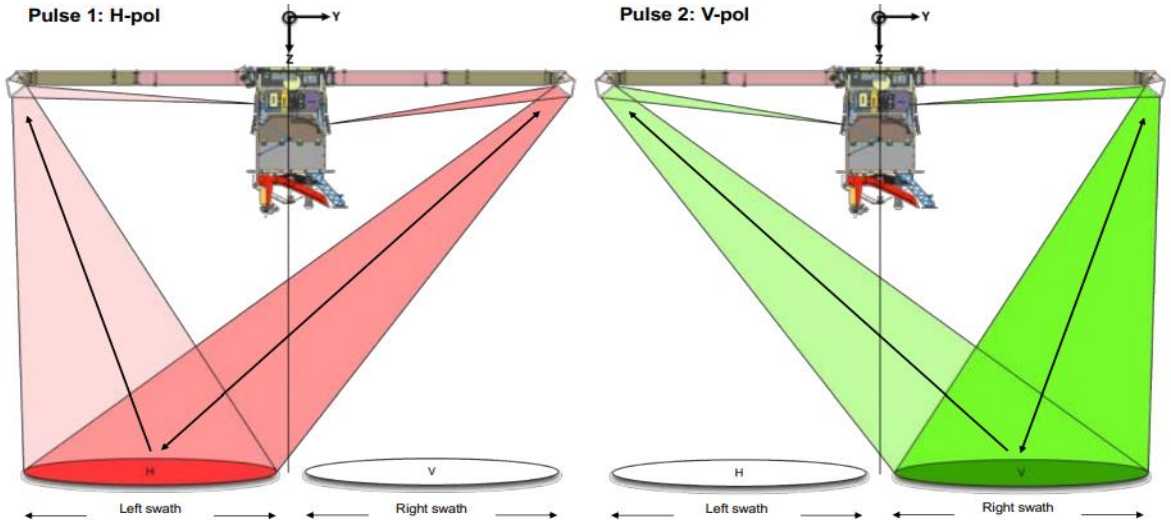
- NASA, CNES, CSA, UKSA
- Launched December 2022
- Until 2023.07 CalVal Phase
- After 2023.07 Scientific Phase
- Revisit 21 day
- Nadir altimeter (Poseidon 3C)
- **KaRIn:** Wide-swath altimeter in Ka-band

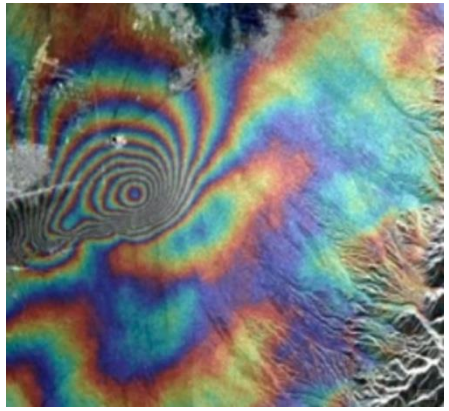


JPL/NASA

KA-BAND RADAR INTERFEROMETER KARIN

- Main concept of cross-track InSAR
- Alignment of 2 Single-Look complex images made simultaneously from different positions
- Phase shift determination
- Height determination from interferograms





SWOT - KARIN
DATA, TIPS, PERFORMANCE

SWOT KARIN – DATA OVERVIEW
VERSIONS OF WATER LEVEL DATA

- L2_LR_SSH - SWOT L2 KaRIn Low Rate Ocean products
- L2_HR_RiverSP; L2_HR_LakeSP and similar - SWOT L2 KaRIn High Rate - Land Basins

NASA, CNES

- All Level 3 (L3) products
- L3 data does not directly contain SSH (can be derived from SSHA)

CNES

SWOT KARIN – DATA OVERVIEW
PRODUCTS TYPES

Product (e.g. L2_LR_SSH, L3_LR_SSH)

Basic

- The most pertinent information for a basic utilisation of data
- 2x2 km, swath-aligned, geographically fixed grid
- Around 10 mb per file
- **Missing a lot of crucial corrections**

Expert

- Full set of information (also WindWave data)
- Enables additional analysis (custom recalculation)
- 2x2 km, swath-aligned, geographically fixed grid
- Around 33 mb per file
- **Well suited for most purposes**

Unsmoothed

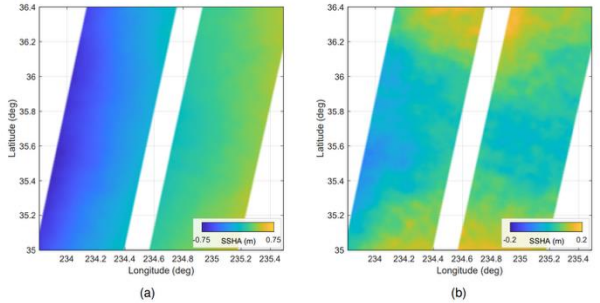
- Data provided at the native sampling and resolution of KaRIn (ca 250m sampling and 500m resolution)
- Average of all nine Doppler beams after beam combining
- Grid is non-regular, not geographically fixed, swaths are aligned approximately
- Around 660 mb per file
- **Provides finer resolution, but additional processing is needed**

SWOT KARIN – DATA OVERVIEW
WHAT IS INSIDE?

A lot of variables depending on data Level – will be looking at L2_LR_SSH_Expert

ancillary_surface_classification_flag	orbit_qual	swh_wind_speed_karin_source
cross_track_angle	phase_bias_ref_surface	swh_wind_speed_karin_source_2
cross_track_distance	polarization_karin	time
dac	pole_tide	time_tai
depth_or_elevation	rad_cloud_liquid_water	velocity_heading
distance_to_coast	rad_surface_type_flag	volumetric_correlation
doppler_centroid	rad_tmb_187	volumetric_correlation_uncert
dynamic_ice_flag	rad_tmb_238	wind_speed_karin
geoid	rad_tmb_340	wind_speed_karin_2
heading_to_coast	rad_water_vapor	wind_speed_karin_2_qual
height_cor_xover	rad_wet_tropo_cor	wind_speed_karin_qual
height_cor_xover_qual	rain_flag	wind_speed_model_u
ice_conc	rain_rate	wind_speed_model_v
internal_tide_hret	sc_altitude	wind_speed_rad
internal_tide_sol2	sc_pitch	wind_speed_ssb_cor_source
inv_bar_cor	sc_roll	wind_speed_ssb_cor_source_2
iono_cor_gim_ka	sc_yaw	x_factor
latitude	sea_state_bias_cor	
latitude_avg_ssh	sea_state_bias_cor_2	
latitude_nadir	sig0_cor_atmos_model	
load_tide_fes	sig0_cor_atmos_rad	
load_tide_got	sig0_karin	
longitude	sig0_karin_2	
longitude_avg_ssh	sig0_karin_2_qual	
longitude_nadir	sig0_karin_qual	
mean_dynamic_topography	sig0_karin_uncert	
mean_dynamic_topography_uncert	solid_earth_tide	
mean_sea_surface_cnescls	ssh_karin	
mean_sea_surface_cnescls_uncert	ssh_karin_2	
mean_sea_surface_dtu	ssh_karin_2_qual	
mean_sea_surface_dtu_uncert	ssh_karin_qual	
mean_wave_direction	ssh_karin_uncert	
mean_wave_period_t02	ssha_karin	
model_dry_tropo_cor	ssha_karin_2	
model_wet_tropo_cor	ssha_karin_2_qual	
num_pt_avg	ssha_karin_qual	
obp_ref_surface	swh_karin	
ocean_tide_eq	swh_karin_qual	
ocean_tide_fes	swh_karin_uncert	
ocean_tide_got	swh_model	
ocean_tide_non_eq	swh_nadir_altimeter	
orbit_alt_rate	swh_ssb_cor_source	
	swh_ssb_cor_source_2	

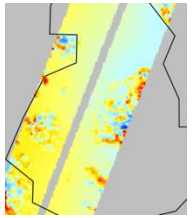
- Important to consider:
  - Height_cor_xover (crossover correction) is not applied by default.



  - ssh_karin – measured atmospheric corrections (Discontinuities may be present)

$$ssh\_karin = ssh\_karin\_2 + model\_wet\_tropo\_cor - rad\_wet\_tropo\_cor + sea\_state\_bias\_cor\_2 - sea\_state\_bias\_cor$$

  - ssh_karin_2 – model-based corrections



  - No additional corrections are applied to ssh_karin and ssh_karin_2. See ssha for „backward engineering“:

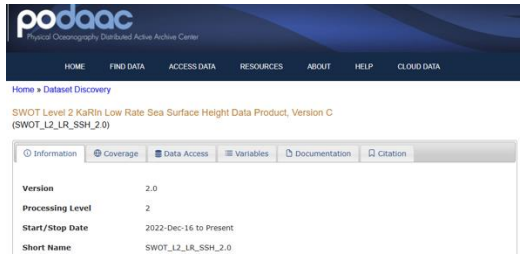
$$ssha\_karin = ssh\_karin - mean\_sea\_surface\_cnescls - solid\_earth\_tide - ocean\_tide\_fes - internal\_tide\_hret - pole\_tide - dac$$

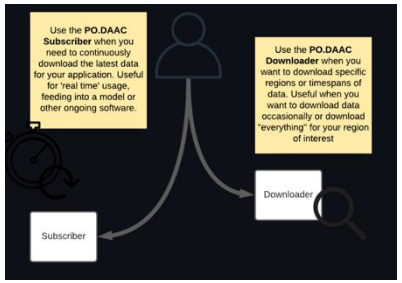
SWOT KARIN – DATA OVERVIEW

WHERE TO GET DATA?

L2 Data

NASA PO.DAAC
through API
PO.DAAC **Data Subscriber**

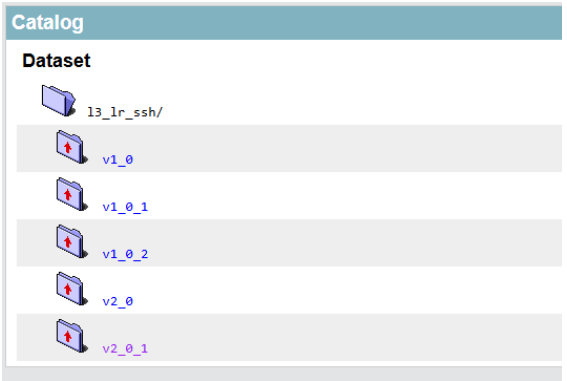




CNES Data Center Archive (AVISO+ required)

L3 Data

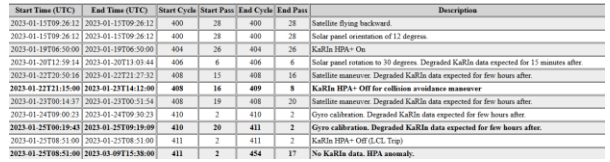
CNES AVISO THREDDS Data Server (AVISO+ required)



IMPORTANT

SWOT Significant Events

Table of significant events to double check data quality

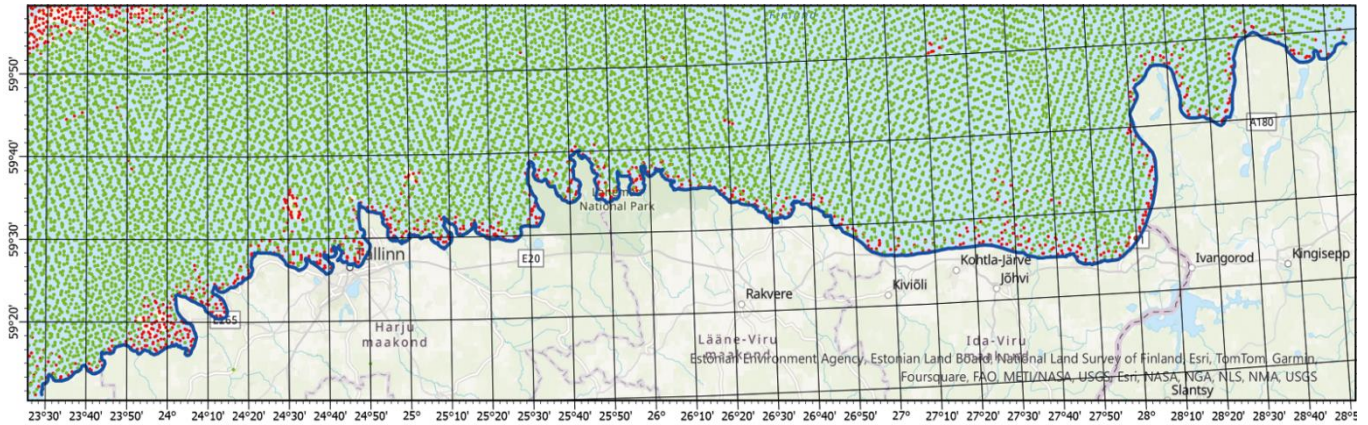


Start Time (UTC)	End Time (UTC)	Start Cycle	Start Pass	End Cycle	End Pass	Description
2023-01-15T09:26:12	2023-01-15T09:26:12	400	28	400	28	Satellite flying backward.
2023-01-15T09:26:12	2023-01-15T09:26:12	400	28	400	28	Solar panel orientation of 12 degrees.
2023-01-19T06:50:00	2023-01-19T06:50:00	404	26	404	26	KaRIn HPA+ On
2023-01-20T12:59:14	2023-01-20T13:03:44	406	6	406	6	Solar panel rotation to 30 degrees. Degraded KaRIn data expected for 15 minutes after.
2023-01-22T20:50:16	2023-01-22T21:27:32	408	15	408	16	Satellite maneuver. Degraded KaRIn data expected for few hours after.
2023-01-22T21:15:00	**2023-01-23T14:12:00**	**408**	**16**	**409**	**8**	**KaRIn HPA+ Off for collision avoidance maneuver**
2023-01-23T00:14:37	2023-01-23T00:51:54	408	19	408	20	Satellite maneuver. Degraded KaRIn data expected for few hours after.
2023-01-24T09:00:23	2023-01-24T09:30:23	410	2	410	2	Gyro calibration. Degraded KaRIn data expected for few hours after.
2023-01-25T00:19:43	**2023-01-25T09:19:09**	**410**	**20**	**411**	**2**	**Gyro calibration. Degraded KaRIn data expected for few hours after.**
2023-01-25T08:51:00	2023-01-25T08:51:00	411	2	411	2	KaRIn HPA+ Off (LCL Trip)
2023-01-25T08:51:00	**2023-03-09T15:38:00**	**411**	**2**	**454**	**17**	**No KaRIn data. HPA anomaly.**

SWOT KARIN
PERFORMANCE EXPECTATIONS?

- Some insigths into the performance – distance from coast

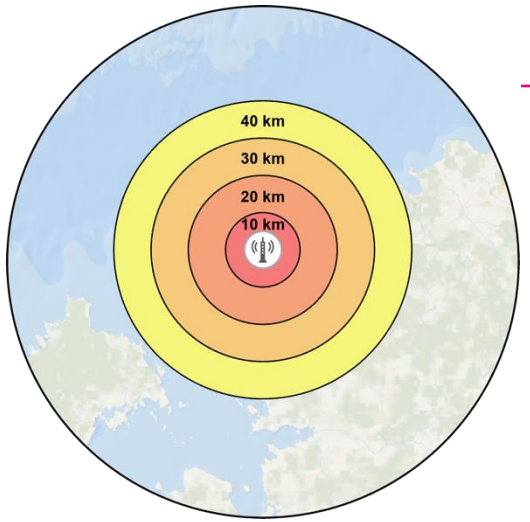
Coast length (Blue line) approximately 500 km							
Distance from the coast	**0-500 m**	**0-1000 m**	**0-2000 m**	**0-3000 m**	**0-5000 m**	**0-10000 m**	**0-40000 m**
Valid measurements	**43 (20%)**	**109 (22%)**	**376 (39%)**	**722 (52%)**	**1441 (65%)**	**3306 (82%)**	**13 664 (97%)**
All measurements	**220**	**477**	**952**	**1392**	**2207**	**4029**	**14050**

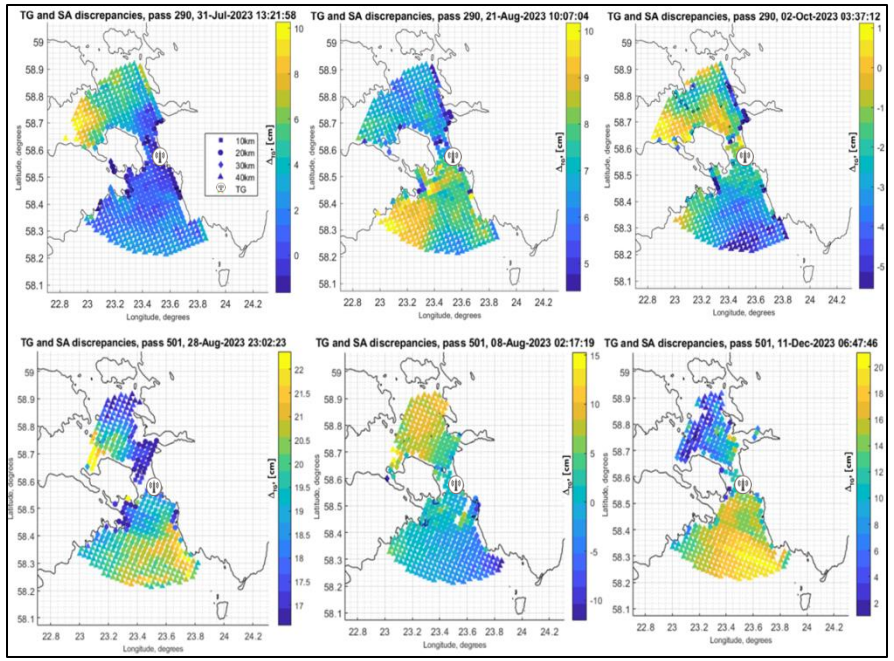


SWOT KARIN
PERFORMANCE EXPECTATIONS?

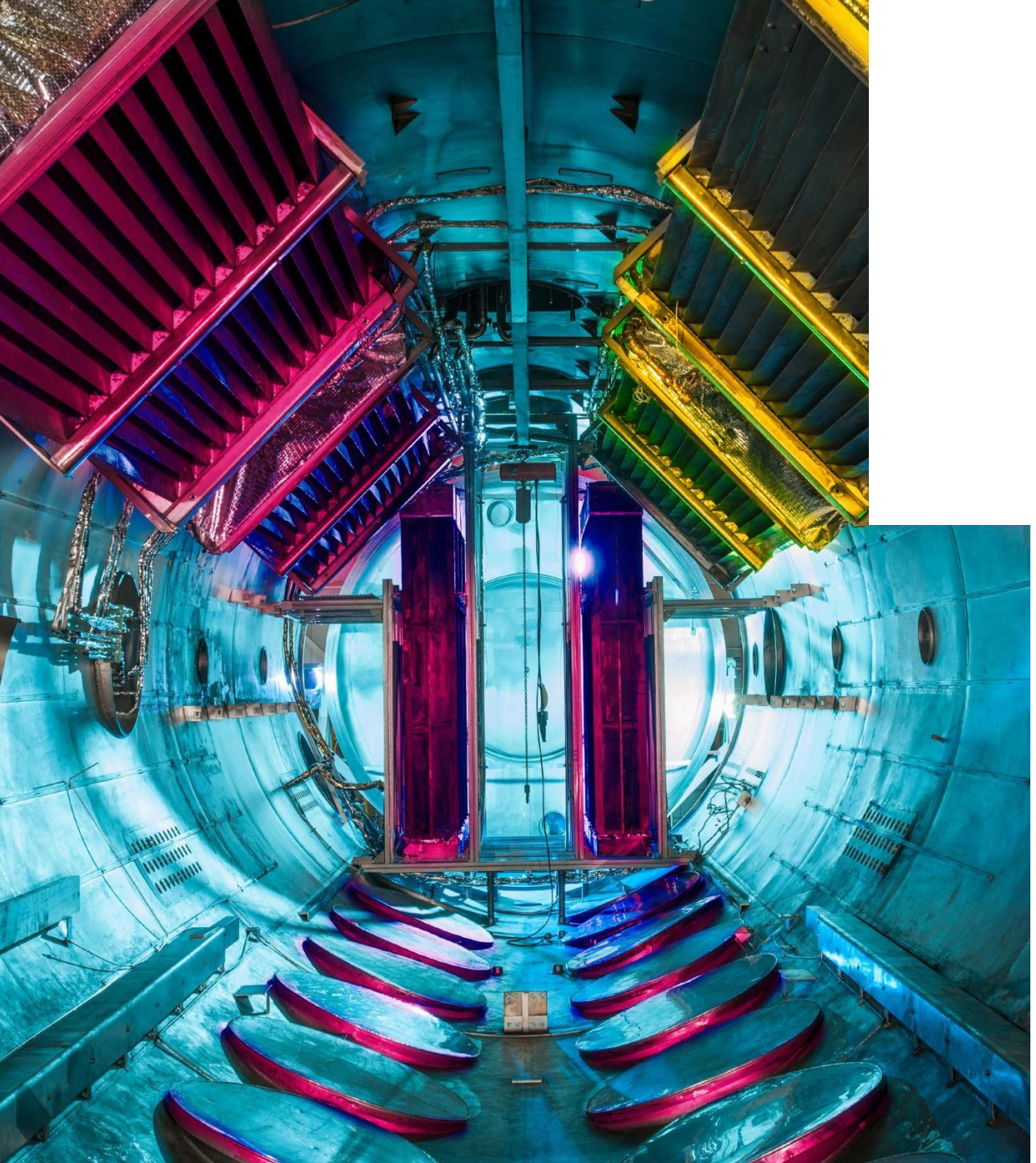
- Some insigths into the performance – comparison with TG

07.2023-12.2023
64 passes
15 TG





Range	Average RMSE [cm]
0-10 km	11.93
10-20 km	12.11
20-30 km	12.56
30-40 km	12.87



GEODETIC APPLICATION

GEOID GEOMETRIC SURFACE

GEODETIC APPLICATION

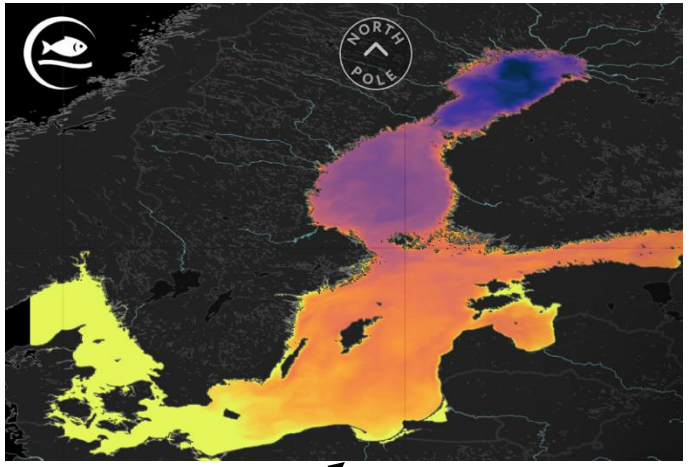
- On a **global scale MSS** calculated over a **long period** of observations can be **approximately equal to the geoid**.
- On **local scales**, however, this simplification is not always suitable:
  - Local scale solutions are expected to be **more reasonable** (compared to actual practices of gravity-based geoid models), have **higher resolution** and **accuracy**.
  - They usually depend on actual **height system**(s) of relevant countries.
  - Usually there is not enough data from just nadir altimeters to cover local region with required resolution.

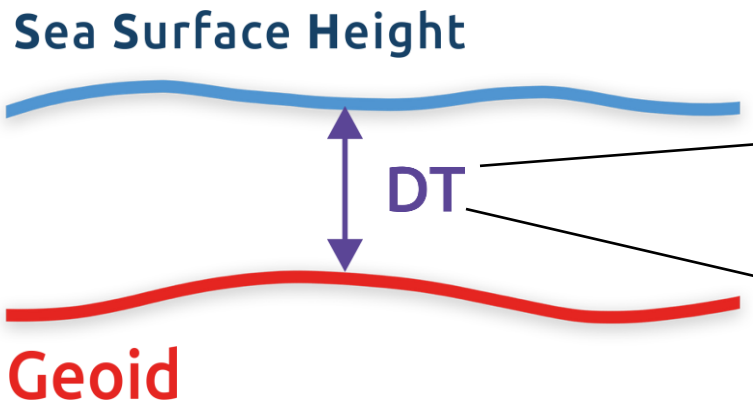
GEODETIC APPLICATION

Geoid cannot be derived purely geometrically and always needs a physical link

PHYSICAL LINK
DYNAMIC TOPOGRAPHY

- **Dynamic topography** (DT) represents the fluctuations of the sea level (SL) around the geoid
- Physically meaningful quantification of the sea level





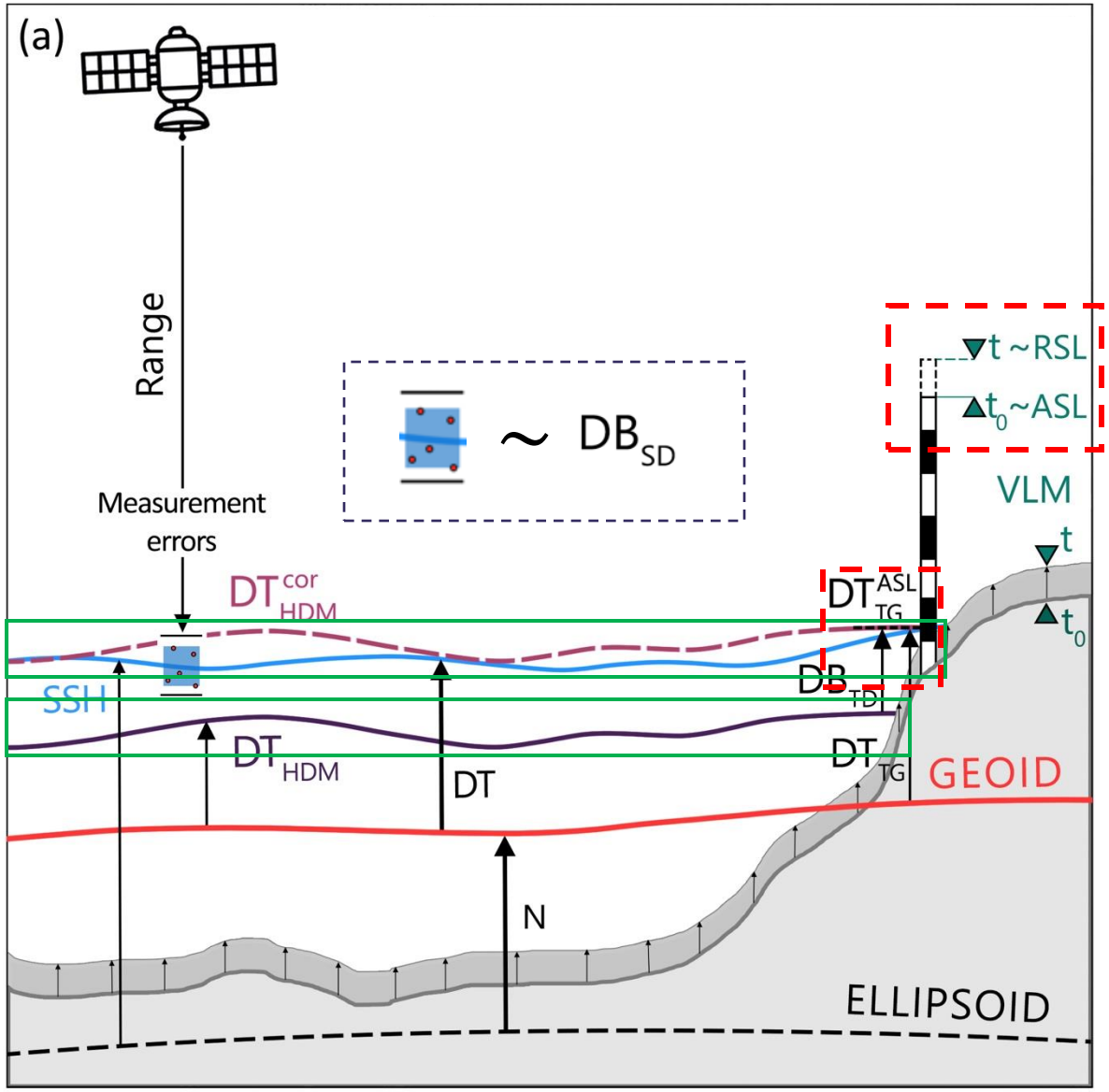
Offshore
Hydrodynamic model → ~~Geoid reffered~~

Coastal area
Tide gauge → Geoid reffered

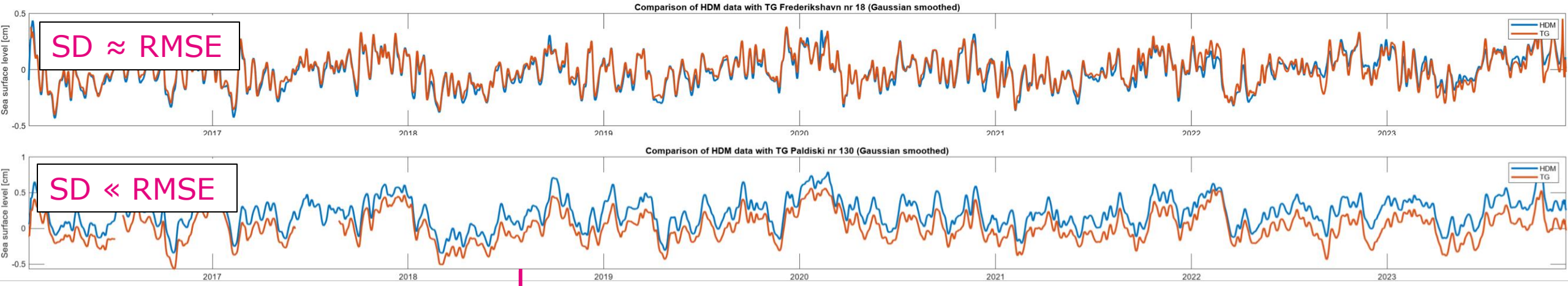
HYDRODYNAMIC MODEL (HDM)
AS A PHYSICAL LINK BETWEEN SSH AND GEOID

- HDMs are a vital source of simulated sea level data based on Navier-Stokes equations.
- Driven by meteorological and hydrological data that attempt to model reality.
- Consider great variety of geophysical fluid dynamic laws.

Main limitation is the **undisclosed vertical reference datum** of the model due to arbitrarily referenced open boundary conditions.

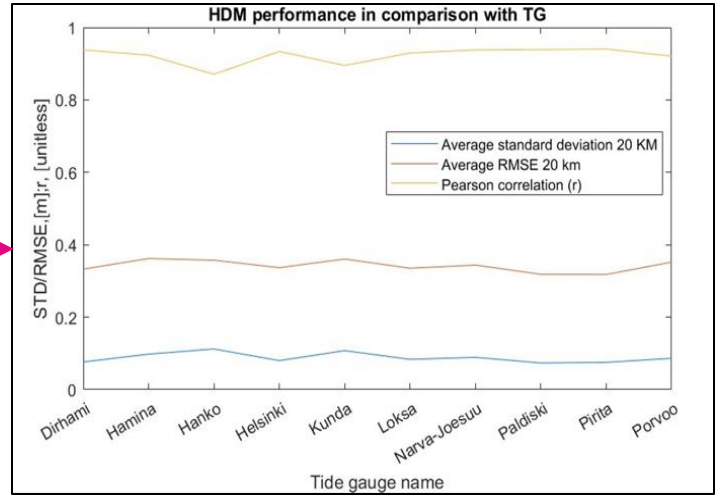


HYDRODYNAMIC MODEL
GOOD ENOUGH OR NOT?

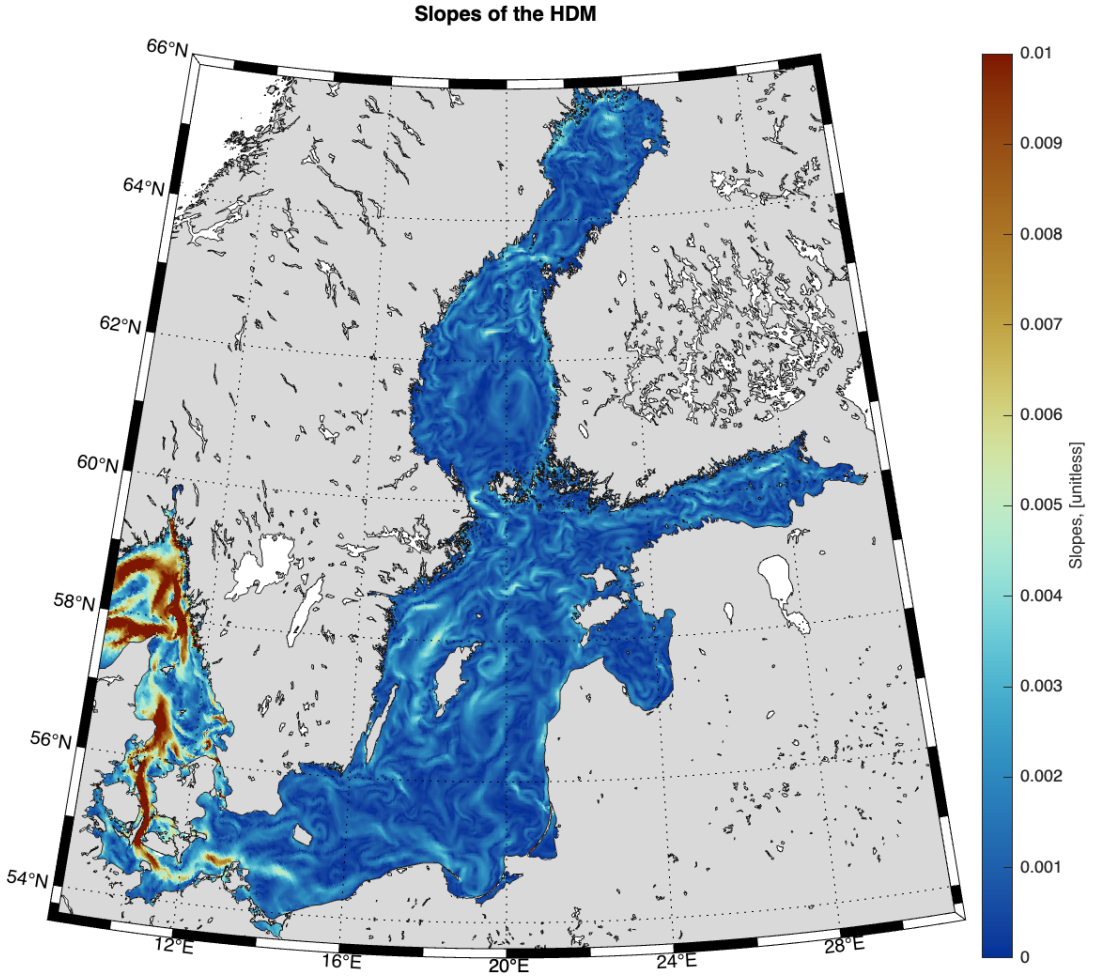


SD ≈ RMSE

SD « RMSE



HYDRODYNAMIC MODEL
WHY EVEN BOTHER?



SWOT MAKES THIS APPROACH POSSIBLE DUE TO HIGHER RESOLUTION AND COVERAGE

…But you know that already

LETS NOW THINK OF APPLICATIONS

LOCAL/REGIONAL SCALE

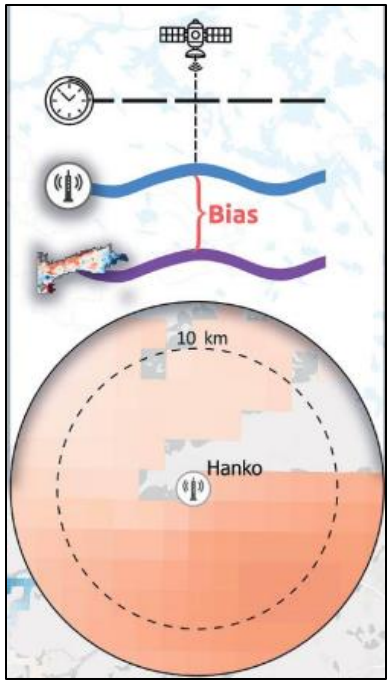
- **Evaluate** local geoid model in areas where errors are expected
- **Calculate** the geoid geometric surface and use it as chart datum (some parts of the world does not have such quality geoid models as we do)
- **Add** additional data to fill voids for new geoid calculation (from DoV to anomalies)

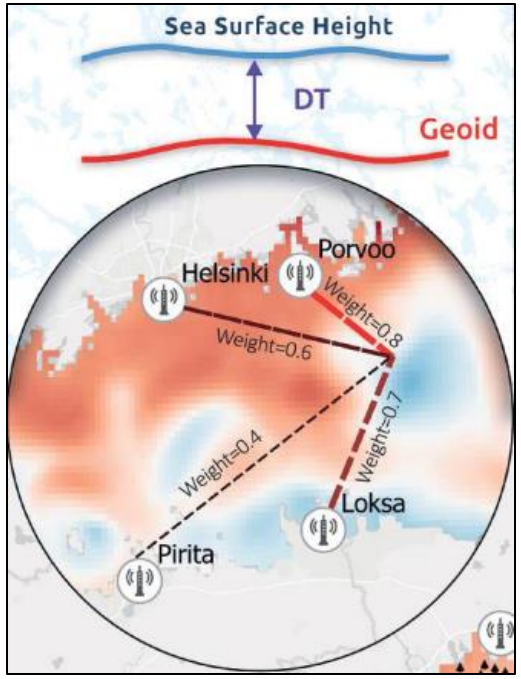
GLOBAL SCALE

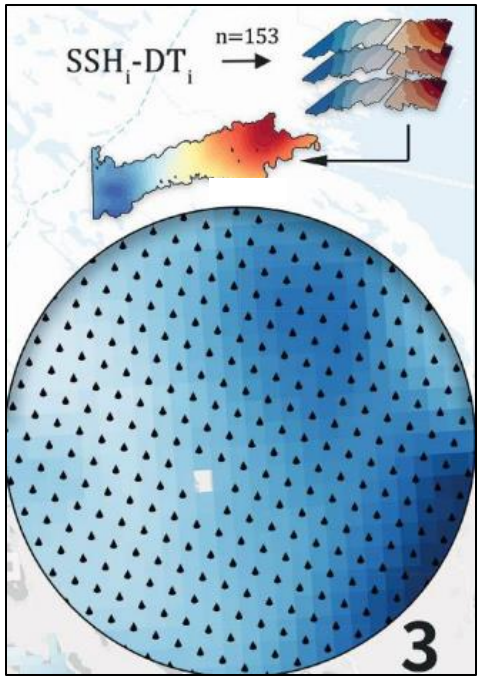
- **Mostly the same**, but it is possible to get better resolution (than in existing global models) in some areas.

CASE STUDY
BALTIC SEA

THE MAIN IDEA



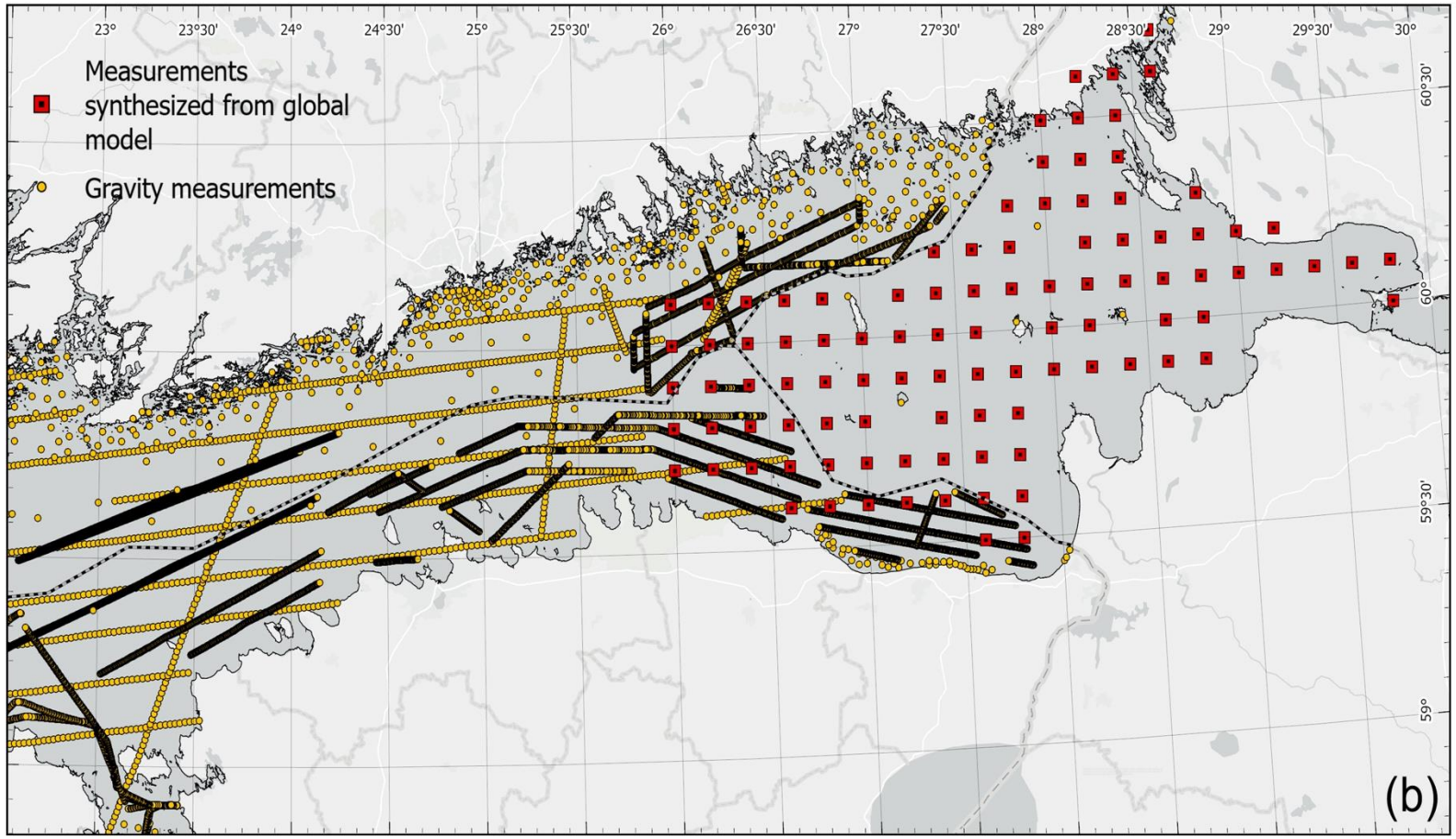




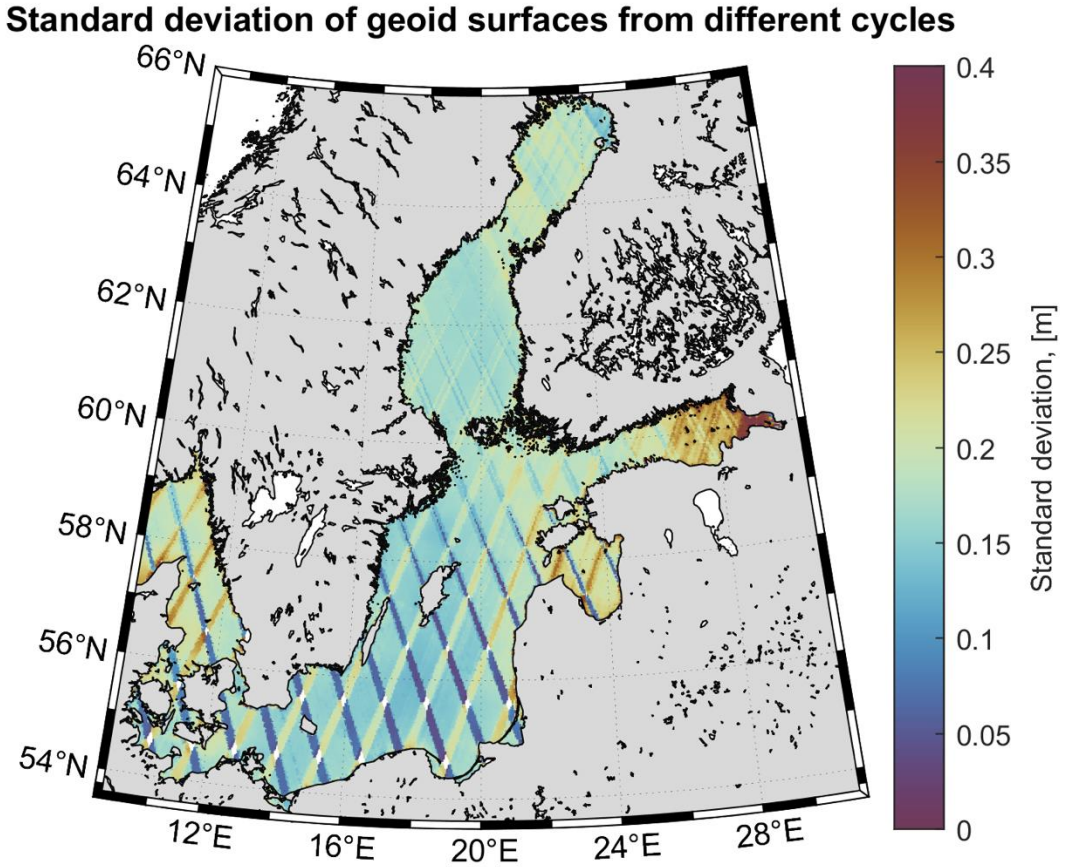
$$N_{SA}(\varphi_{SWOT}, \lambda_{SWOT}, t_{OF}) = SSH(\varphi_{SWOT}, \lambda_{SWOT}, t_{OF}) - DT^{cor}_{HDM}(\varphi_{SWOT}, \lambda_{SWOT}, t_{OF})$$

$$\overline{N_{SA}}(\varphi_{SWOT}, \lambda_{SWOT}) = \frac{1}{n}\sum_{i=1}^{n} N_{SA}(\varphi_{SWOT}, \lambda_{SWOT}, i)$$

LOCAL SCALE
EVALUATE THE PROBLEMATIC AREA

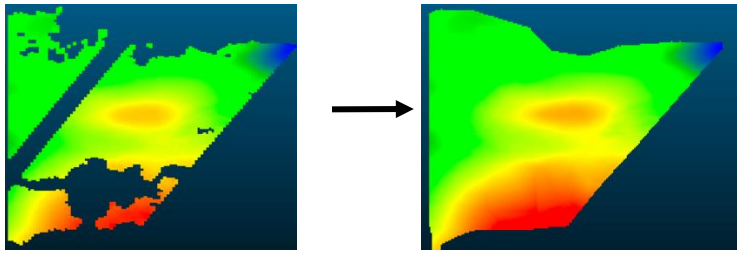


LOCAL SCALE
FILTERING IDEAS



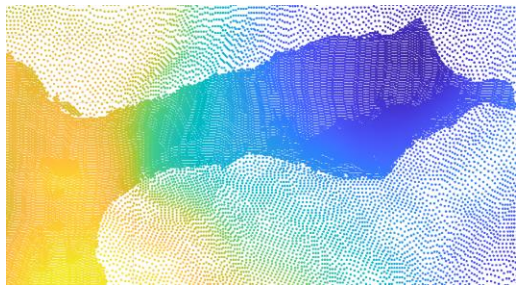
LOCAL SCALE
FILTERING IDEAS

Interpolate with limited edge distance enough to close the gap



Average

Choose control points from initial surface and geoid from mainland



Points from mainland just to enable further processing (matrix without voids)

Calculate Thin Plate Surface (TPS) (transform to cartesian before calculation)

NB! Just in case we do not want to use GGMs

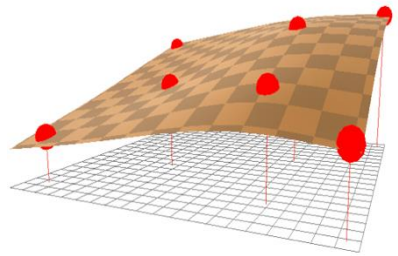
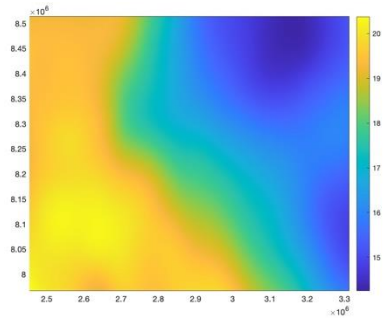
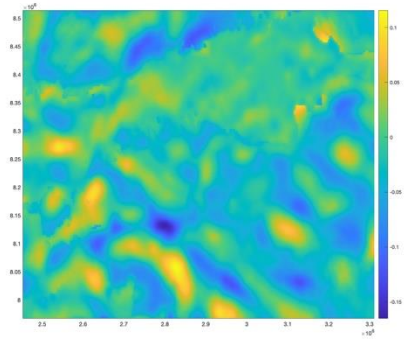


Figure from Lombaert, 2006



Mimic R-C-R

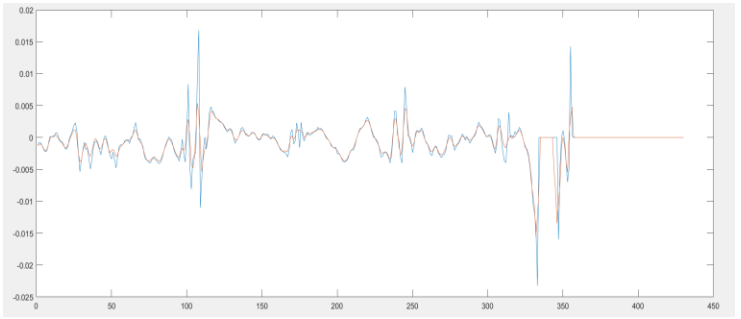
Subtract TPS from unified land geoid and SWOT-geoid



Apply Gaussian 2D smoothing

Subtract from previous step

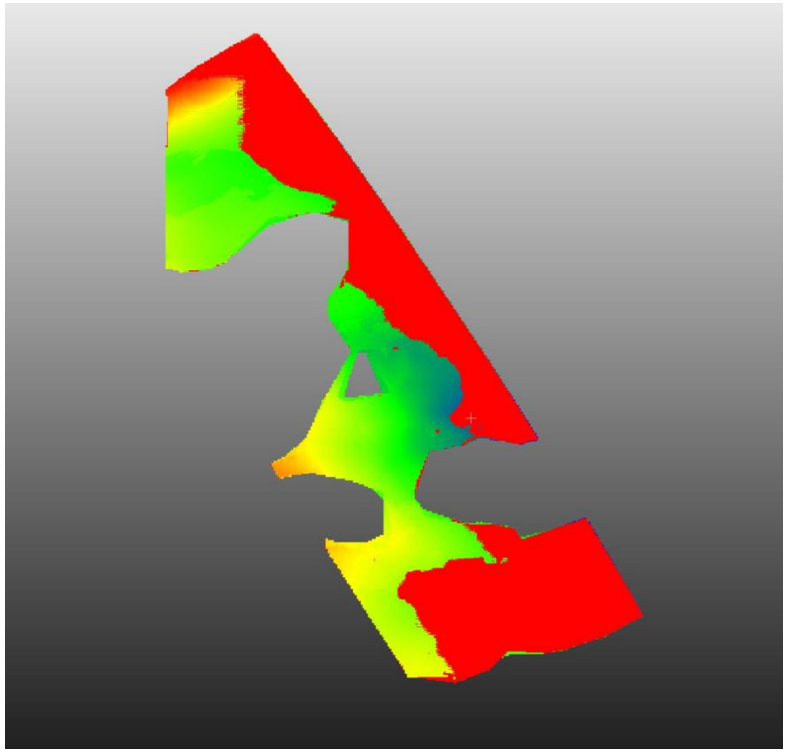
Apply any suitable smoothing method onto residuals

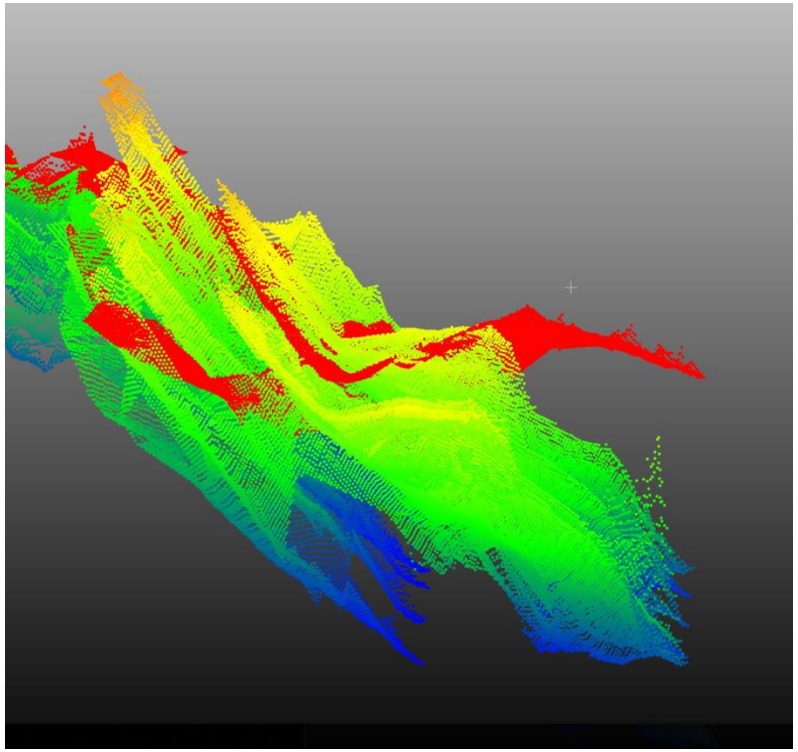


Substitute the residuals with smoothed ones and construct the whole chain backwards!

KEEP IN MIND

- **Even after crossover correction some tracks remain tilted**

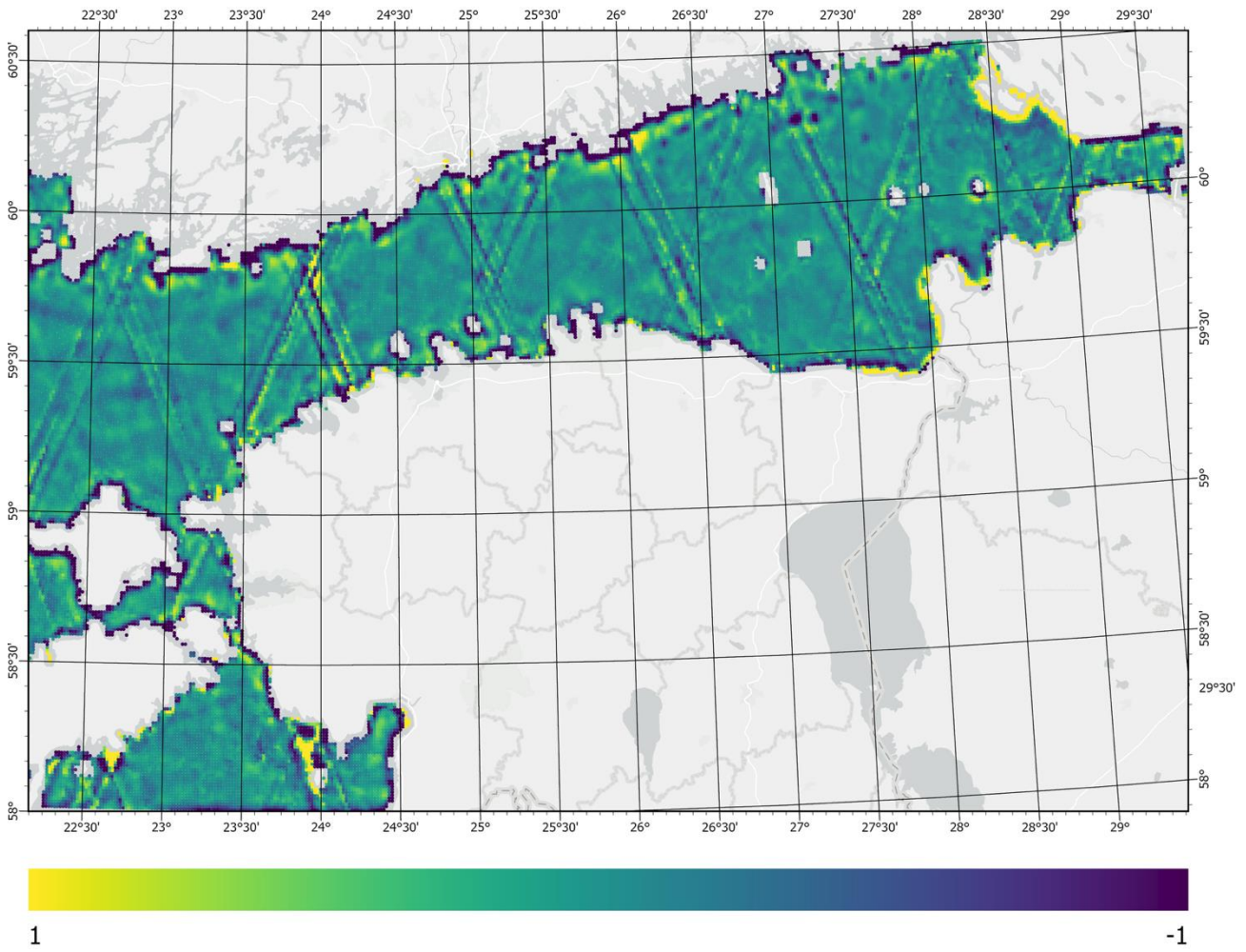




LOCAL SCALE
EVALUATE THE PROBLEMATIC AREA

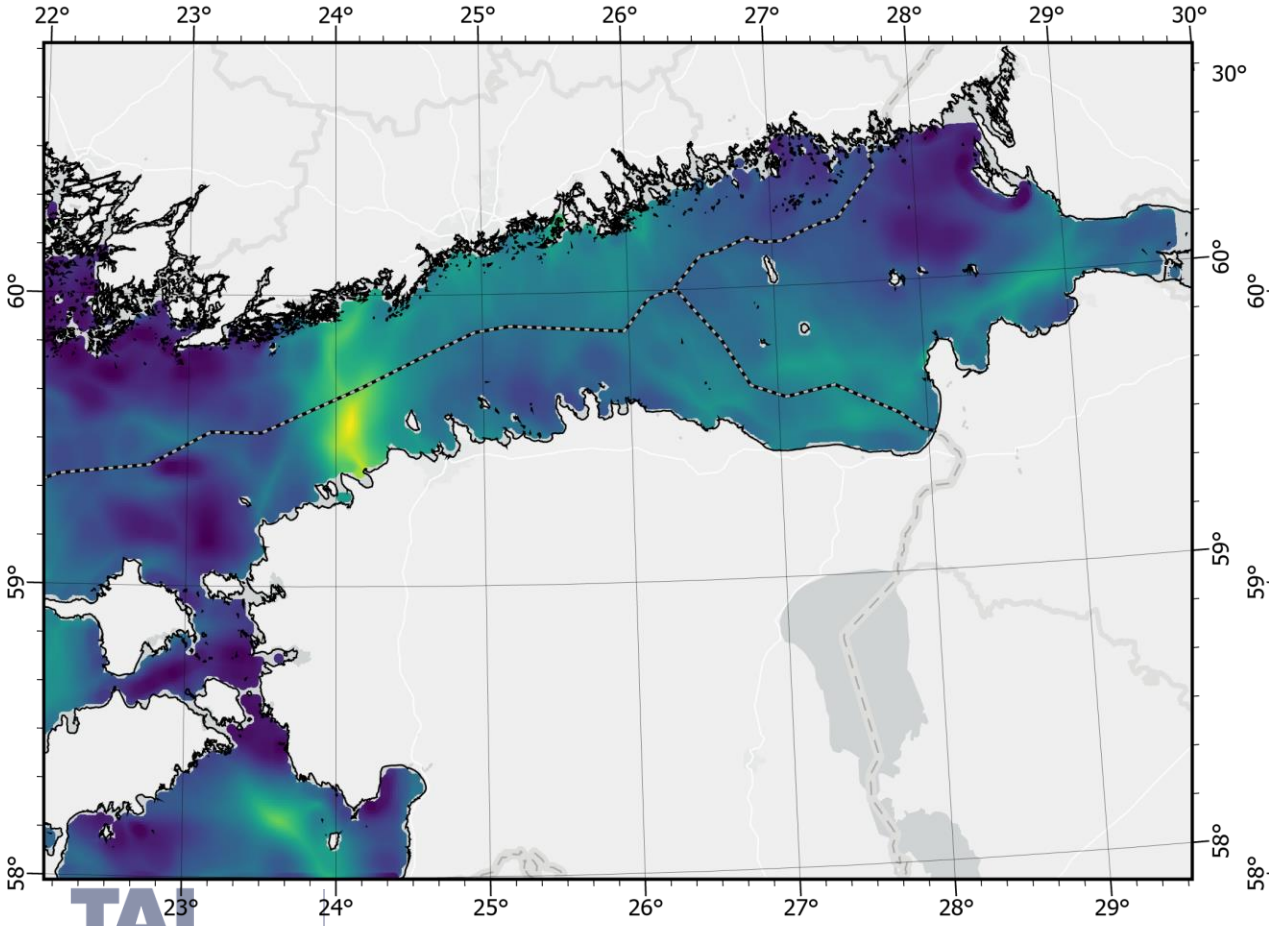
As a result, the **most significant component of SWOT artifacts is eliminated**, preserving other features as much as possible (with an offshore difference of ±1 cm).

Difference between RAW and smoothed surface

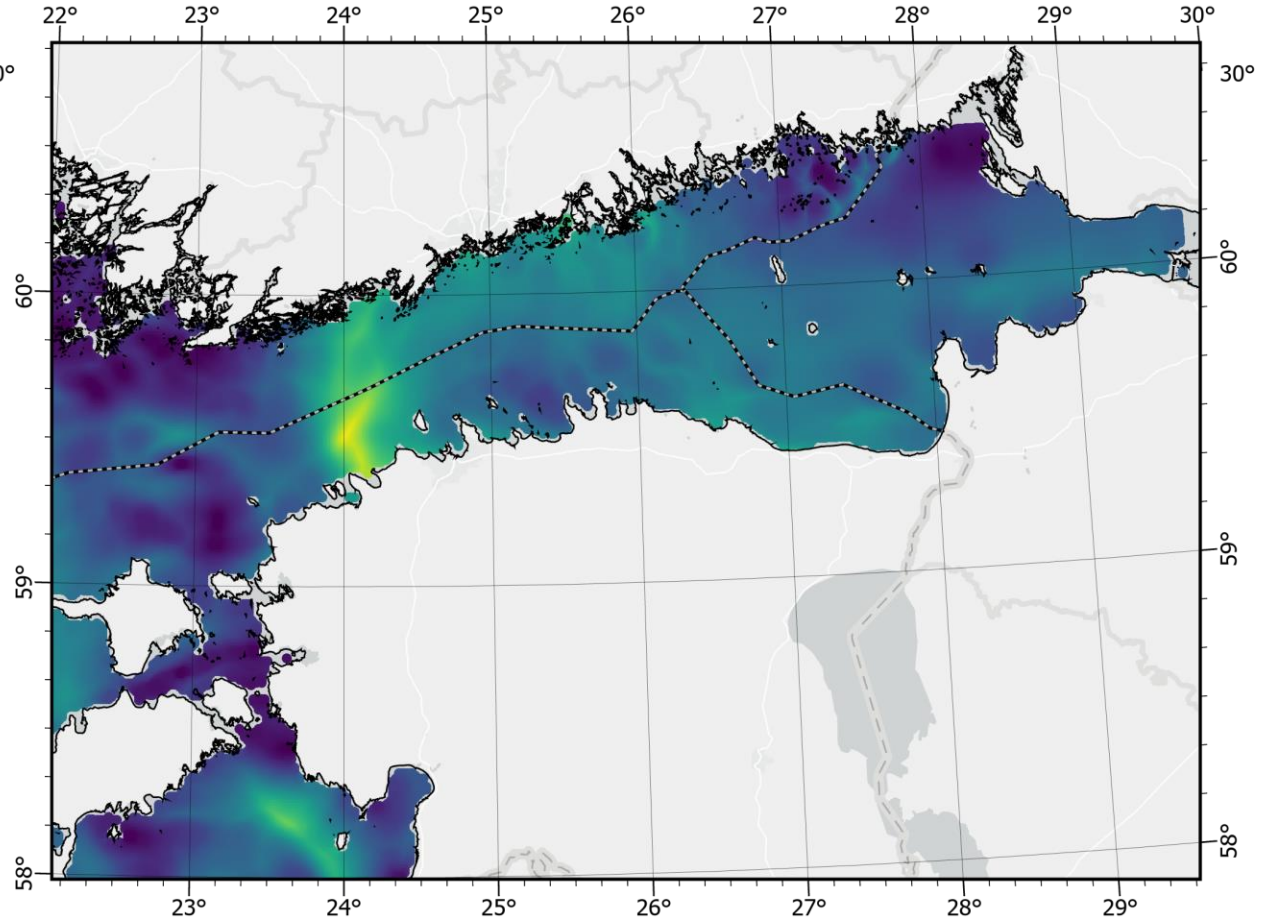


LOCAL SCALE
EVALUATE THE PROBLEMATIC AREA

SWOT-geoid slopes



BSCD2000 slopes



LOCAL SCALE

TIDE CONCEPT

The relation between the EVRS datum and its realization in EVRF 2000 is expressed by

$$\Delta W_{EVRS} = W_{NAP} - W_{NAP}^{REAL}$$
$$= W_{NAP} - U_{0\,GRS80}$$
$$= U_0 - U_{0\,GRS80} + \Delta W_{SST} + \Delta W_{TGO}$$

ΔW_{EVRS} is the offset to a world height system. The relation to a world height system with $W_0 = U_0$ needs the knowledge of the sea surface topography and the deviation in the NAP in connection with the normal potential at the mean Earth ellipsoid U_0 (at present $U_0 \sim 62636856\ m^2 \cdot s^{-2}$) at a cm-accuracy level.

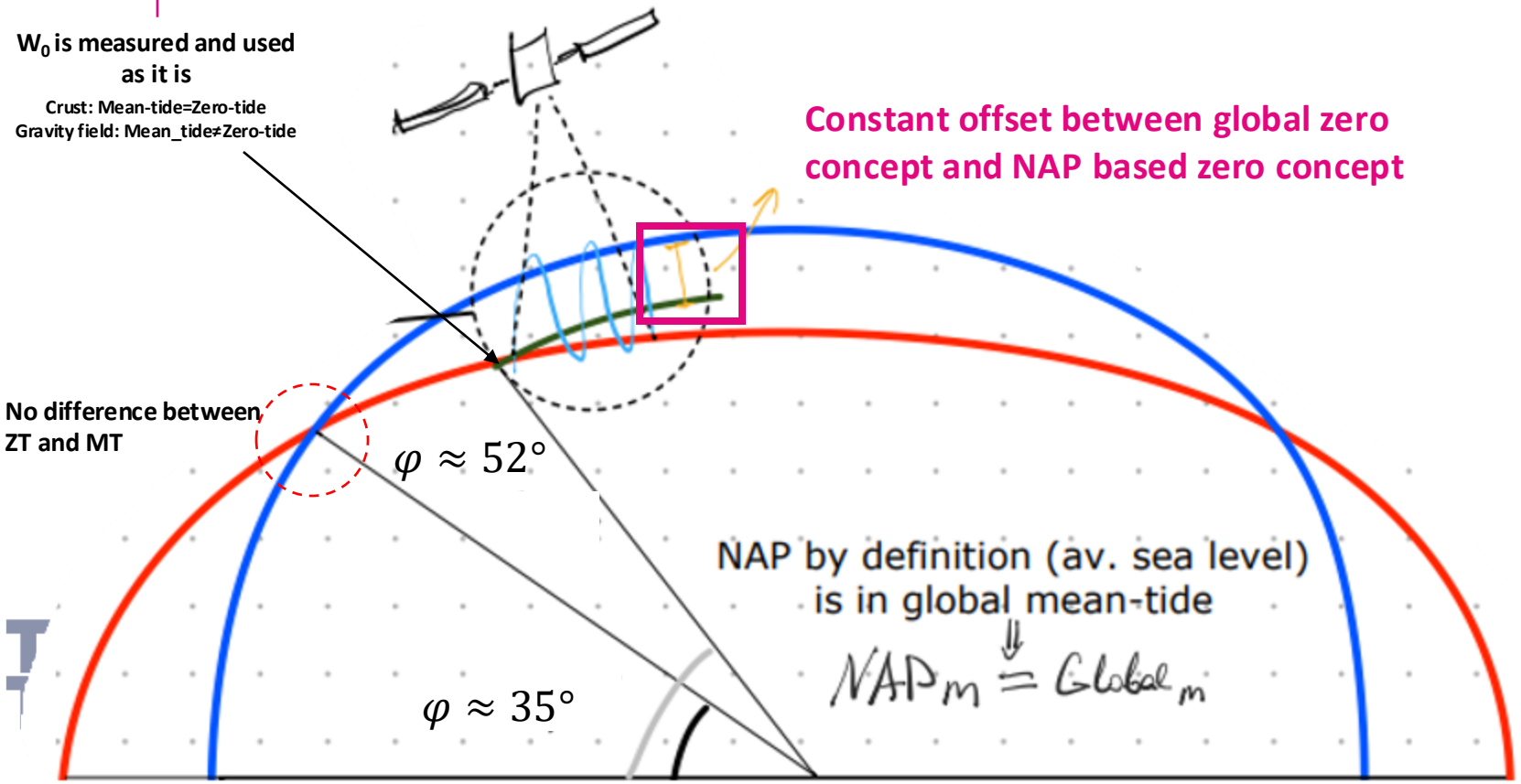
a) The vertical datum of the EVRS is realized by the zero level through the Normaal Amsterdams Peil (NAP). Following this the geopotential number in the NAP is zero:

$$c_{NAP} = 0.$$

W_0 is measured and used as it is

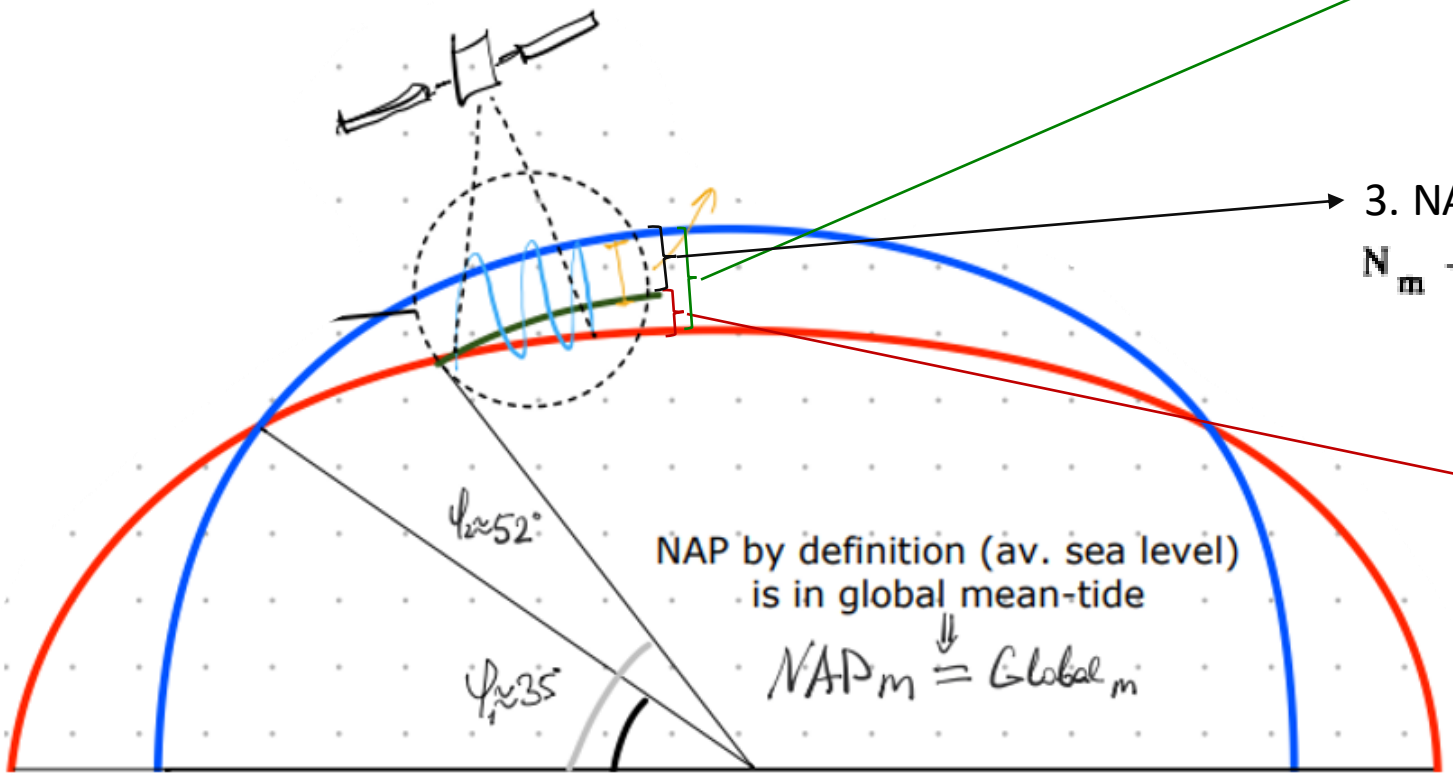
Crust: Mean-tide=Zero-tide
Gravity field: Mean_tide≠Zero-tide

Constant offset between global zero concept and NAP based zero concept



GLOBAL ZERO
GLOBAL MEAN
NAP BASED ZERO

LOCAL SCALE
TIDE CONCEPT



2. Transition from mean to zero (GLOBAL)

$$N_m - N_z = 9.9 - 29.6 \sin^2 \varphi \quad cm$$

3. NAP offset (in terms of gravity field)

$$N_m - N_z = 9.9 - 29.6 \sin^2 \varphi \quad cm$$

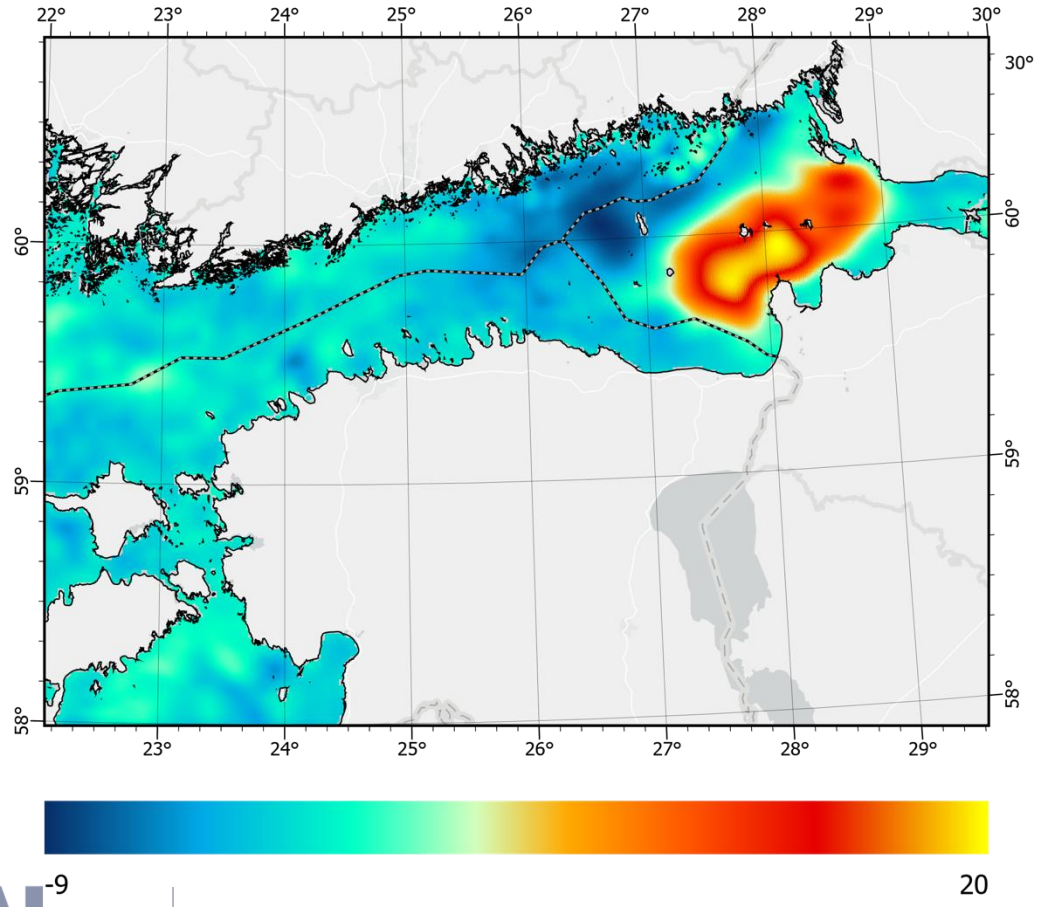
1. TG Relative to NAP (e.g. BSCD2000)

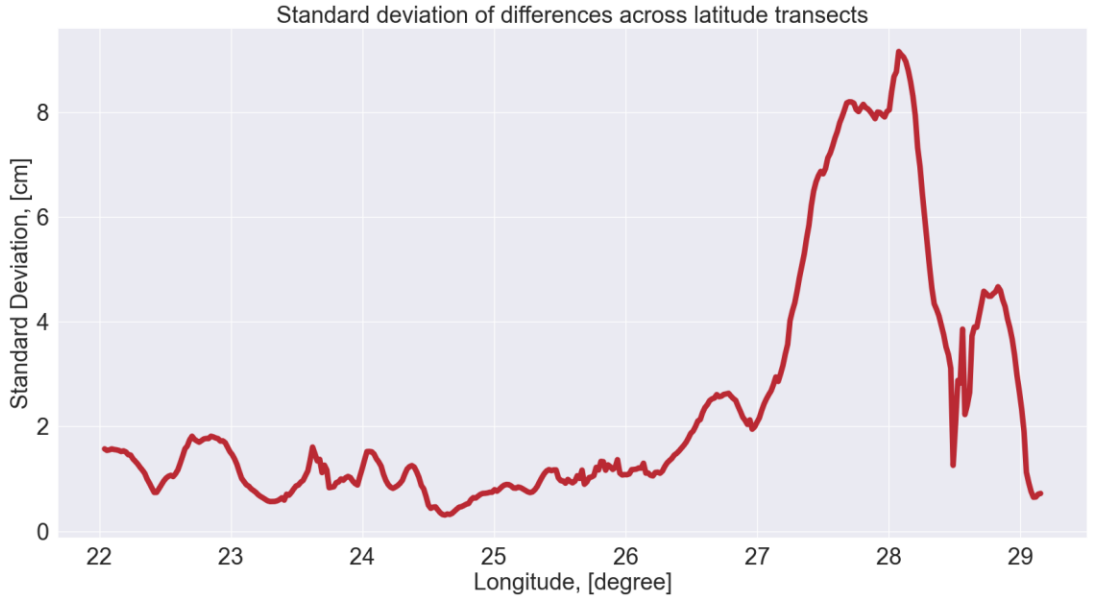
$$\Delta H_m - \Delta H_z = 29.6 \, (\sin^2 \varphi_N - \sin^2 \varphi_S) \quad cm$$

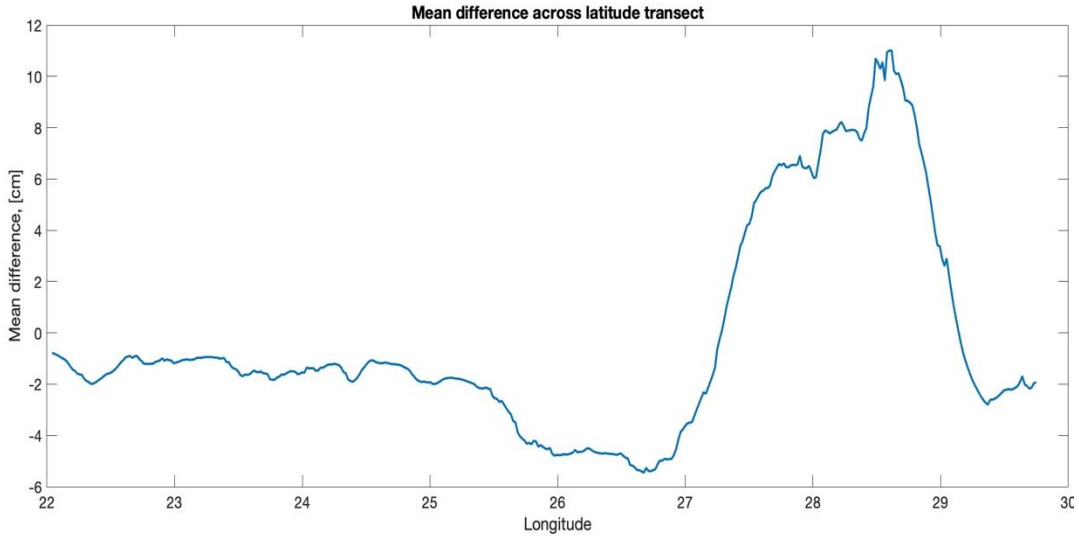
„The transformation between a height difference dH_z above the zero geoid, a height difference dH_m above the mean geoid“

LOCAL SCALE
EVALUATE THE PROBLEMATIC AREA

Difference between N_{SWOT} and $N_{BSCD2000}$



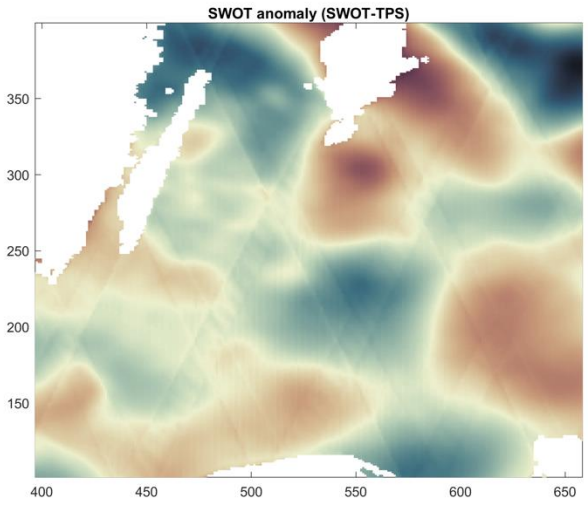


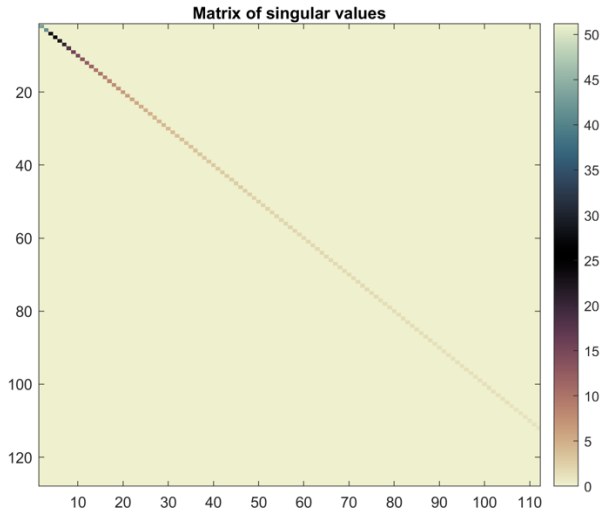


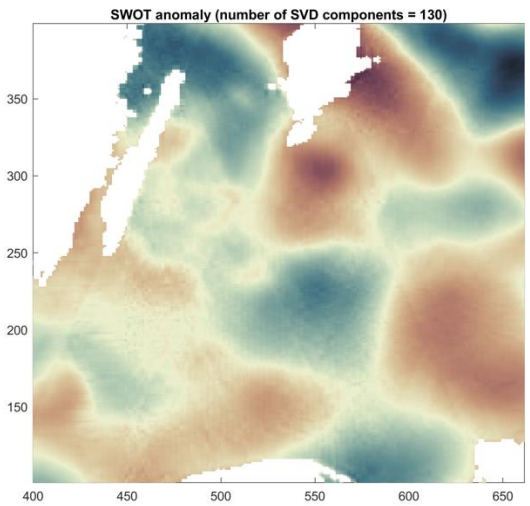
LOCAL SCALE

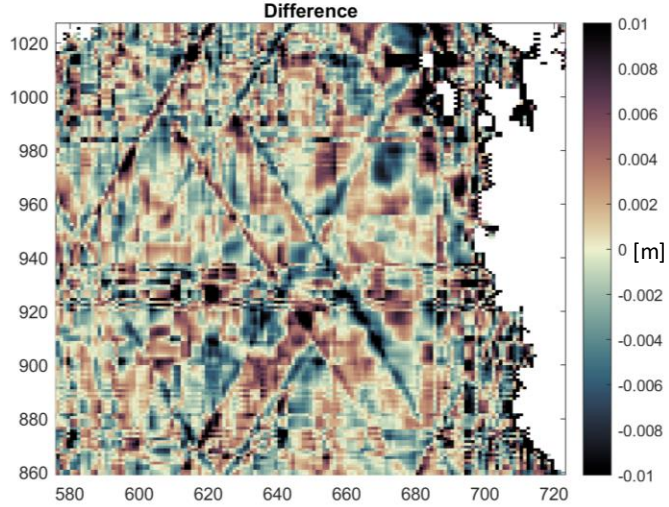
CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

- Reduce the influence of the edge artifacts
  - For example Singular Value Decomposition for ease?









LOCAL SCALE

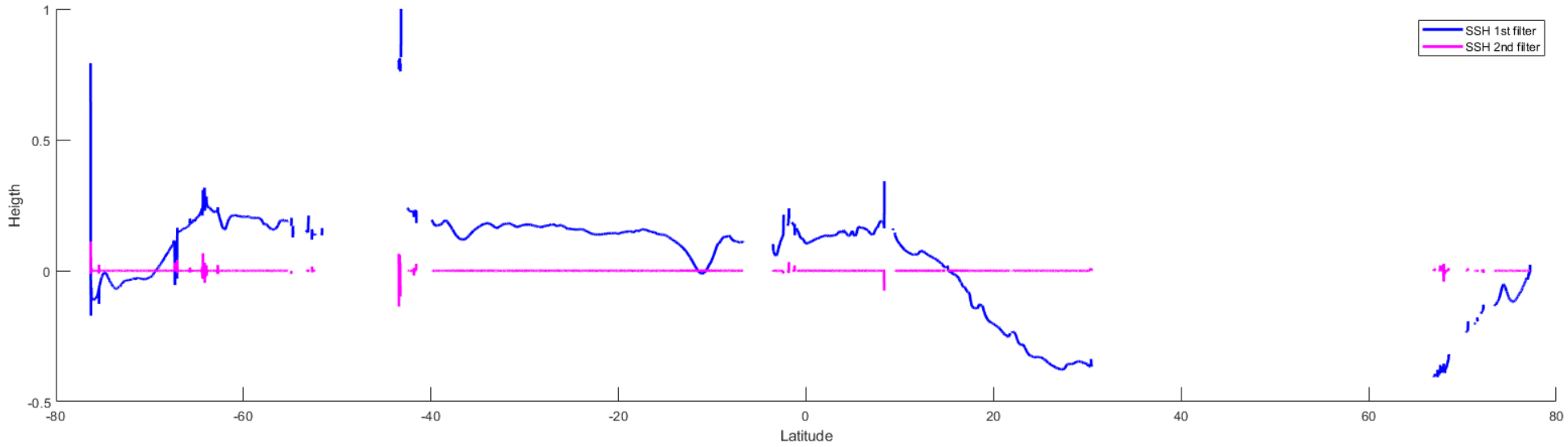
CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

- Or Teager-Kaiser Energy Operator filter

$$\Psi(x[n]) = x[n]^2 - x[n-1] \cdot x[n+1]$$

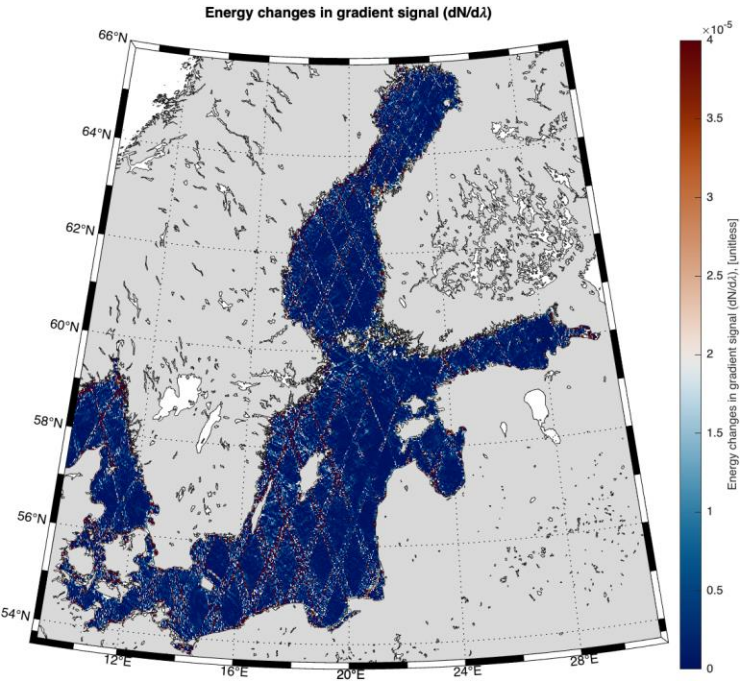
```
Nx_filt_T(2:end-1) = Nx(2:end-1).^2 - Nx(1:end-2).*Nx(3:end)
```

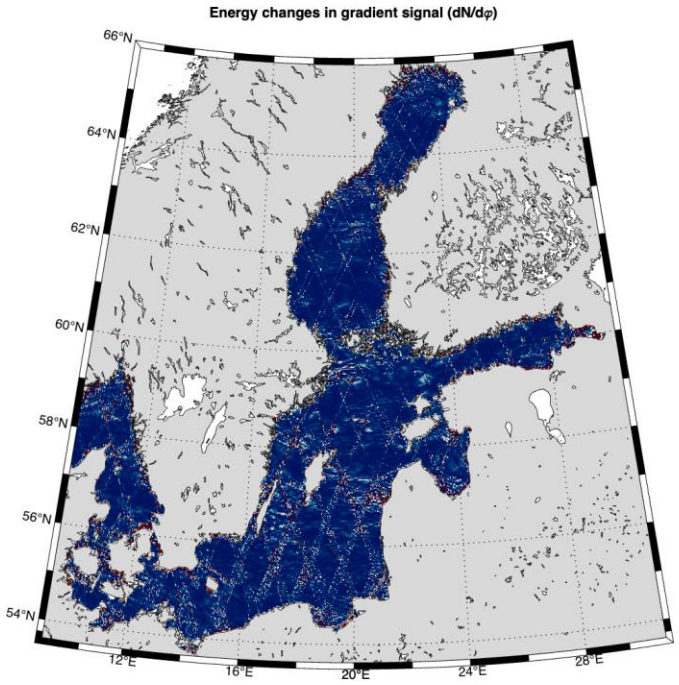
- And then normalized by dividing by max(Nx_filt_T)

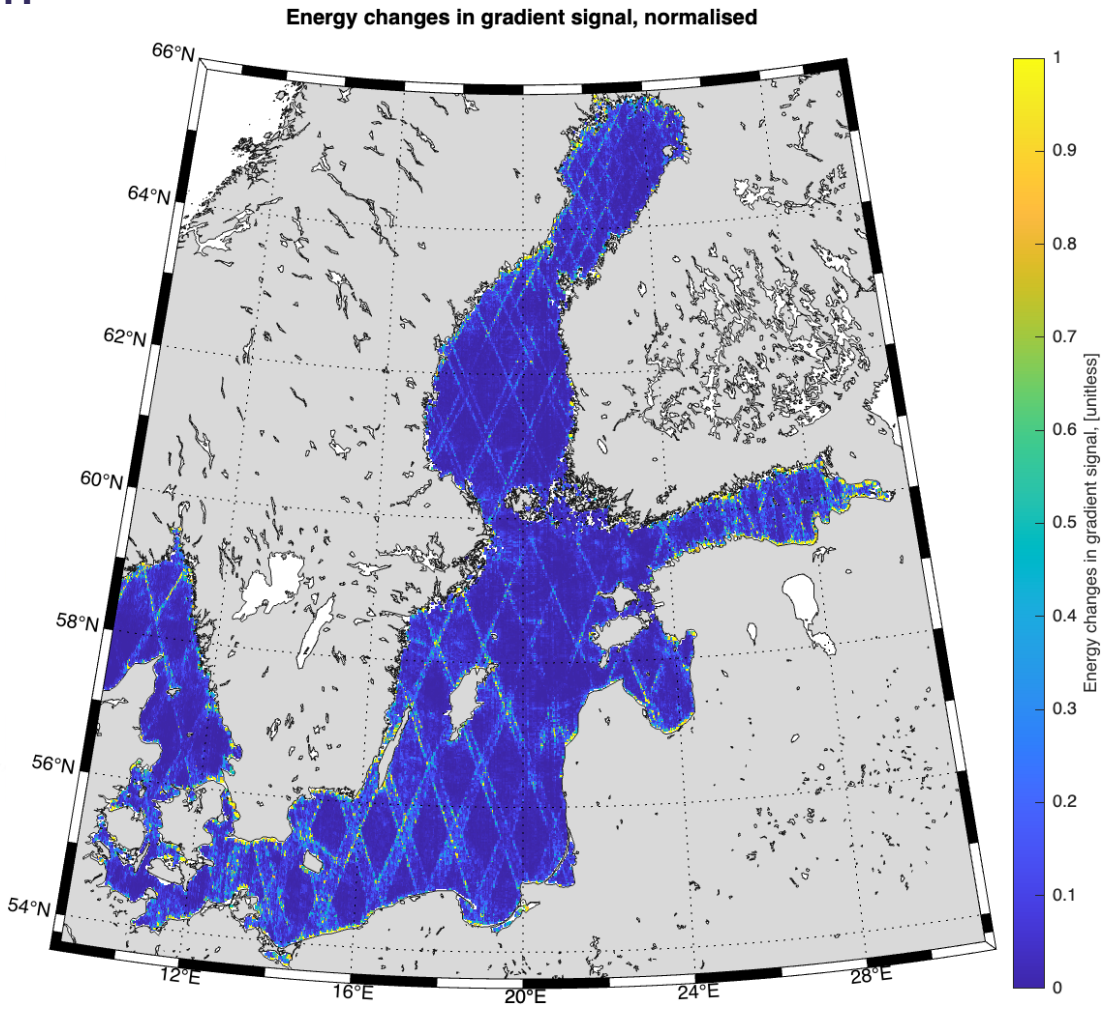


LOCAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM



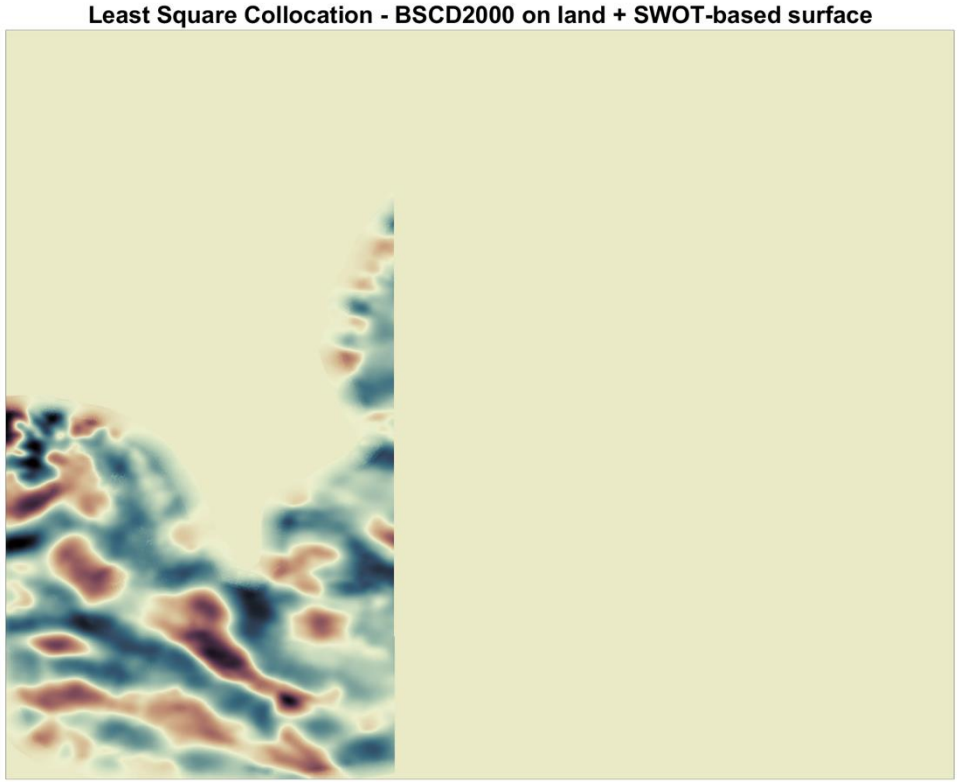




LOCAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

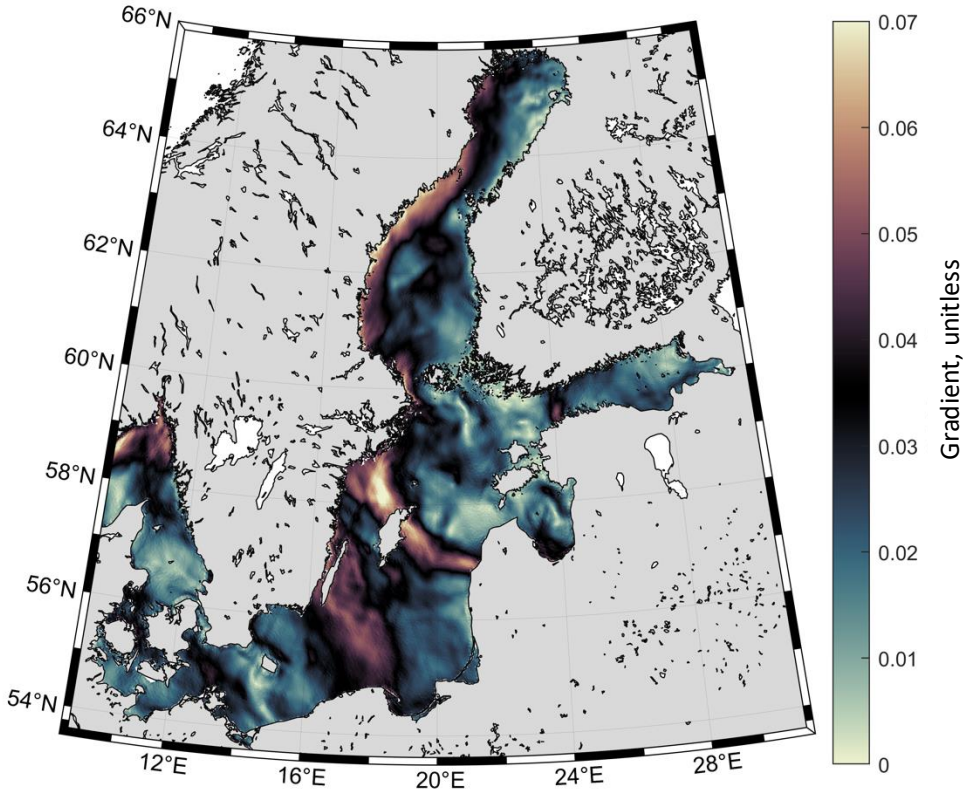
- **Would be good as is**, if forget about edge artifacts!
  - Next step – Least Square Collocation on what remained.



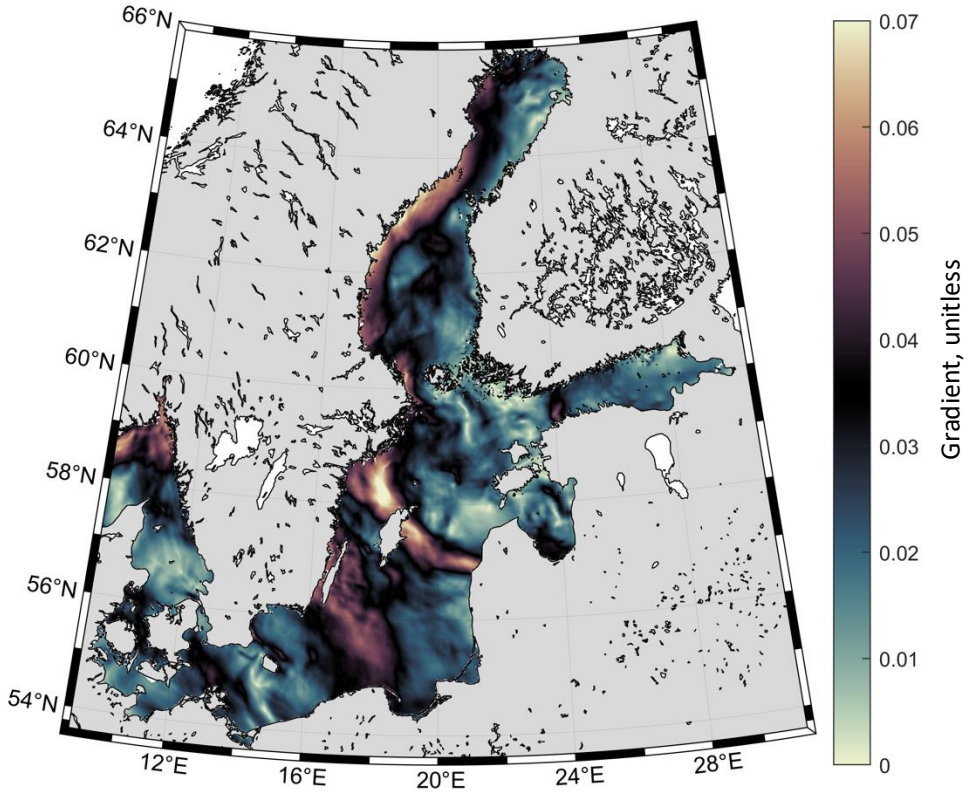
LOCAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

SWOT-based surface slopes



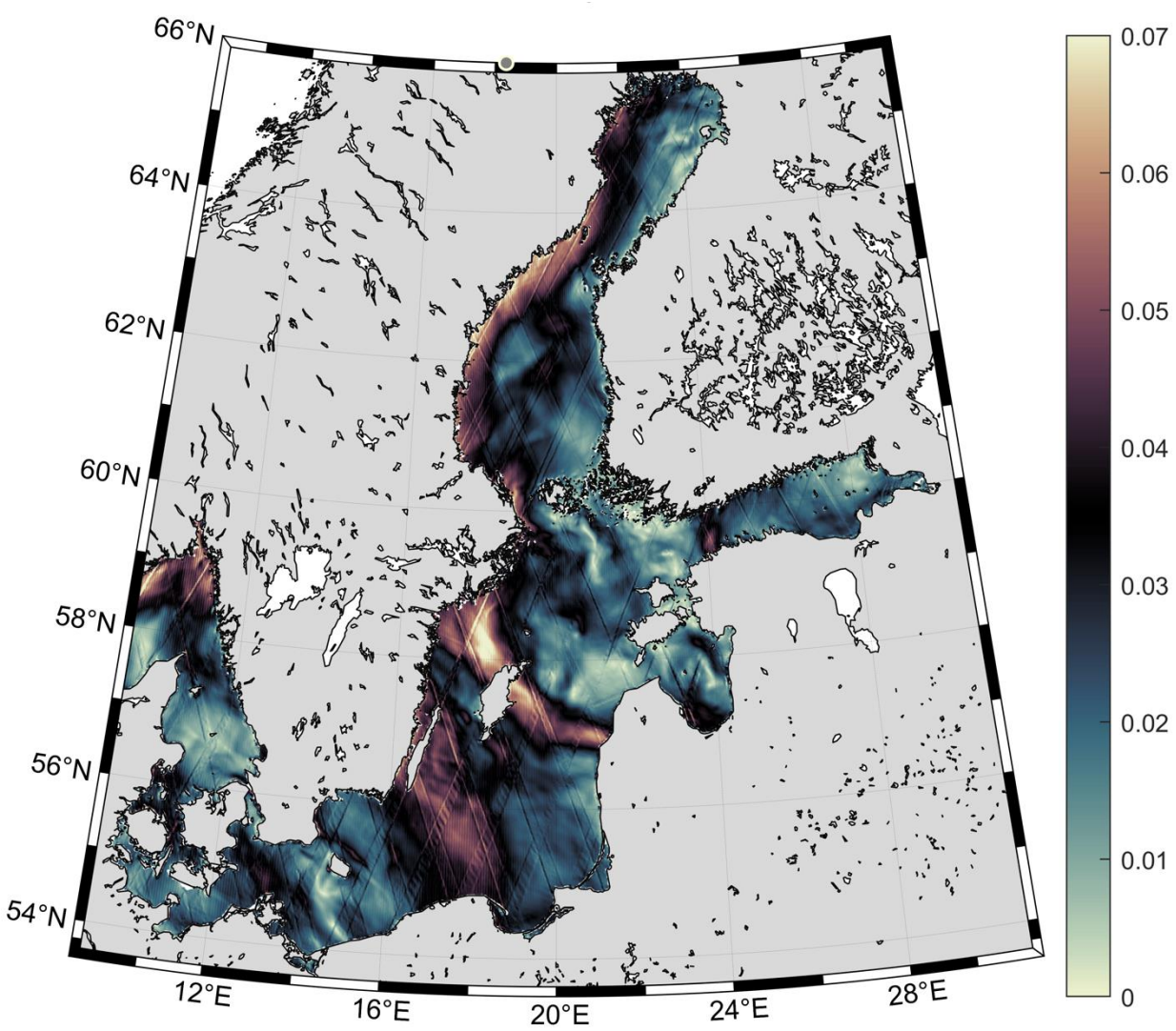
BSCD2000 slopes



LOCAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

Without previous steps looks like that!



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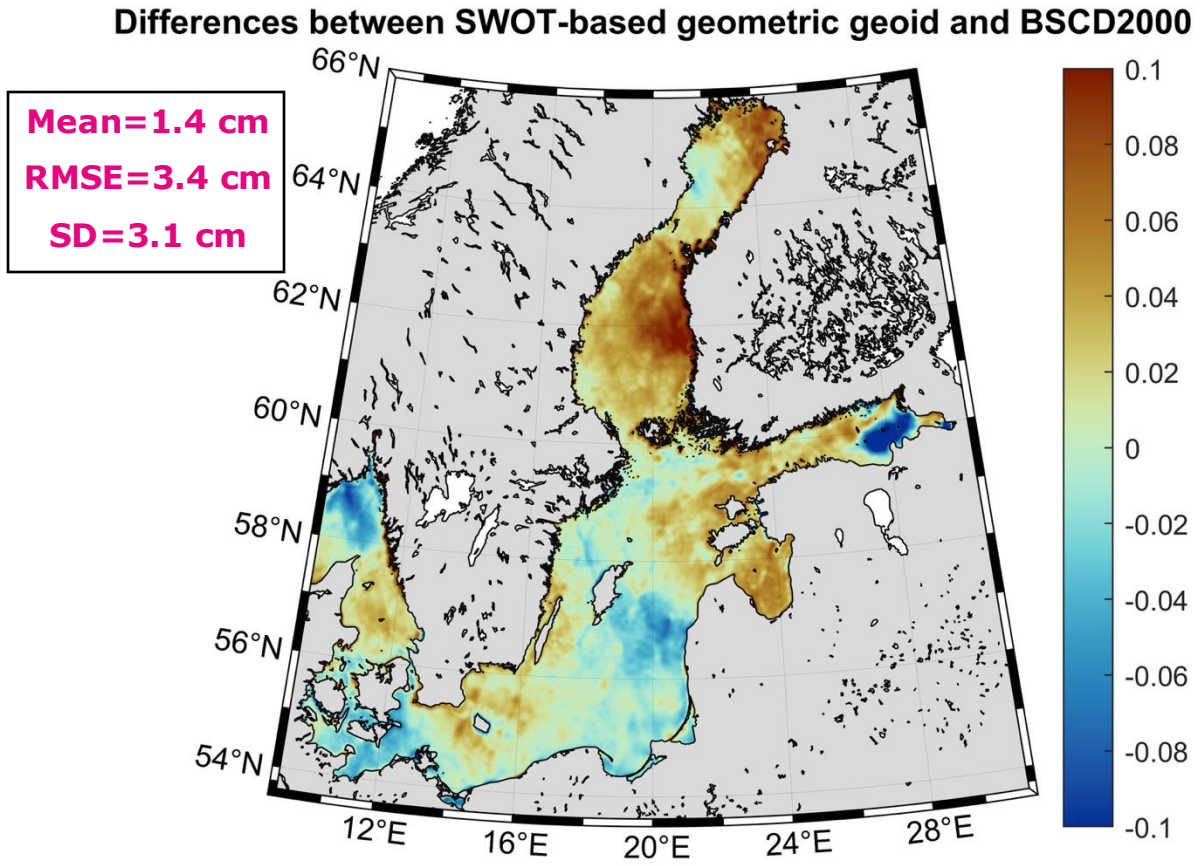
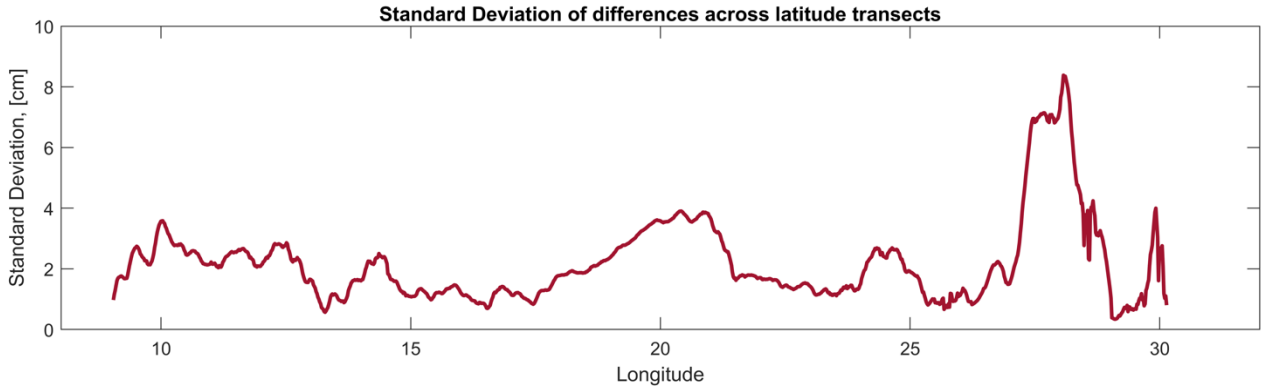
LOCAL SCALE

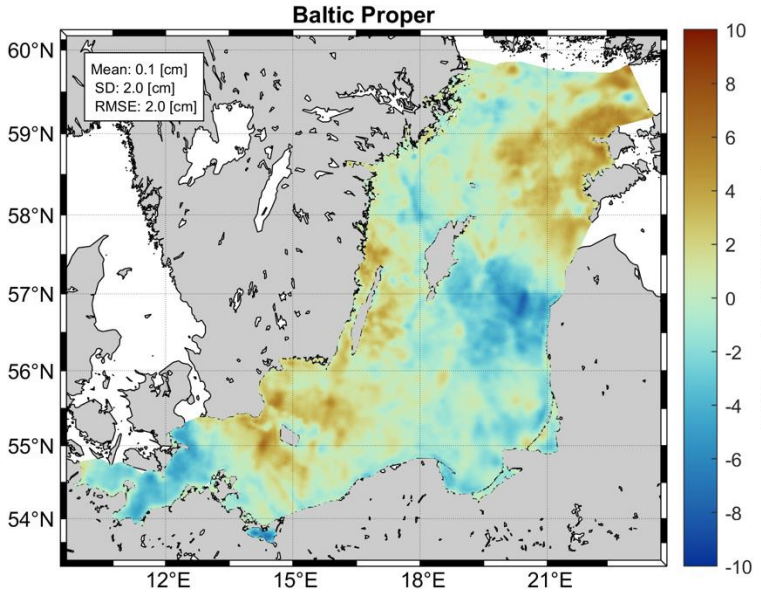
CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

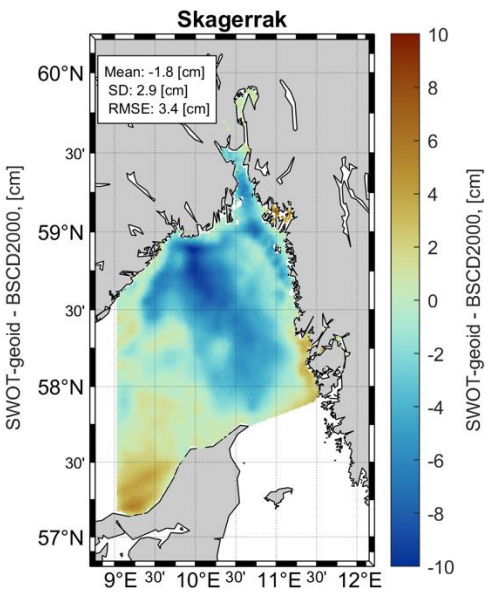


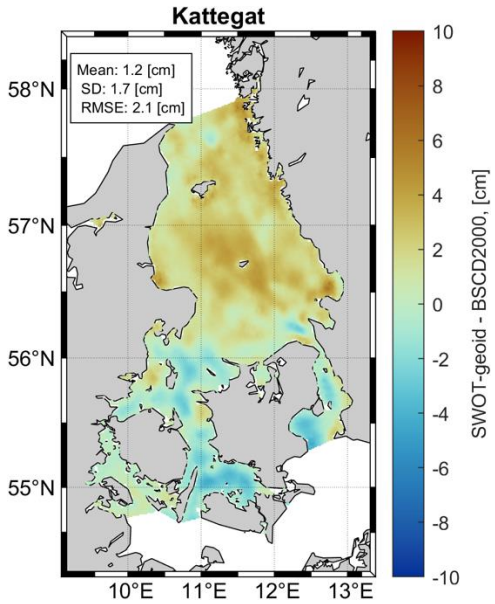


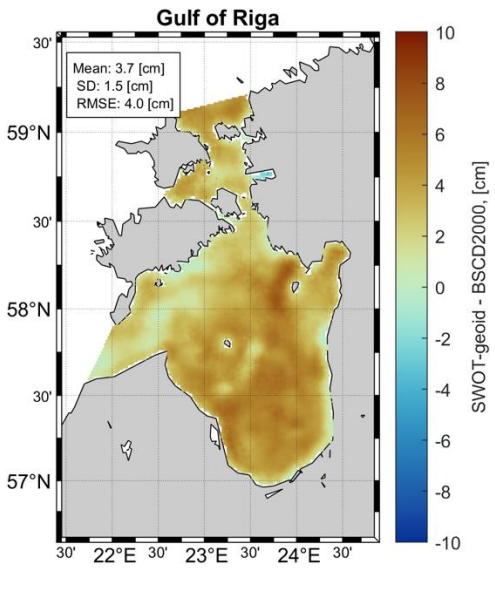
LOCAL SCALE

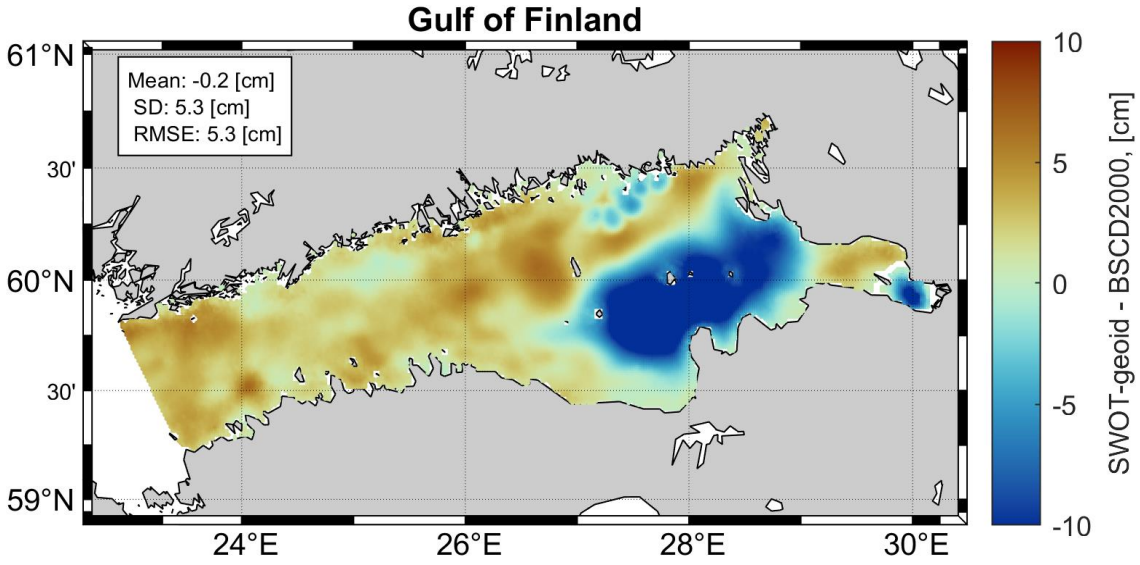
CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM

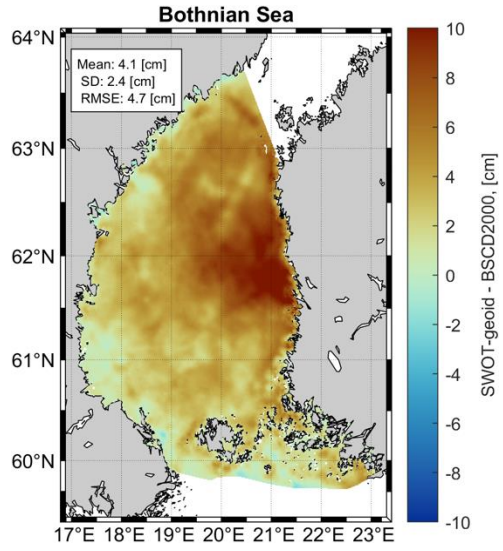


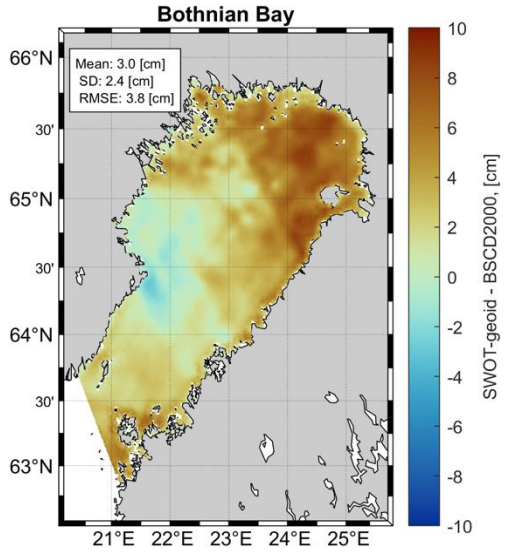






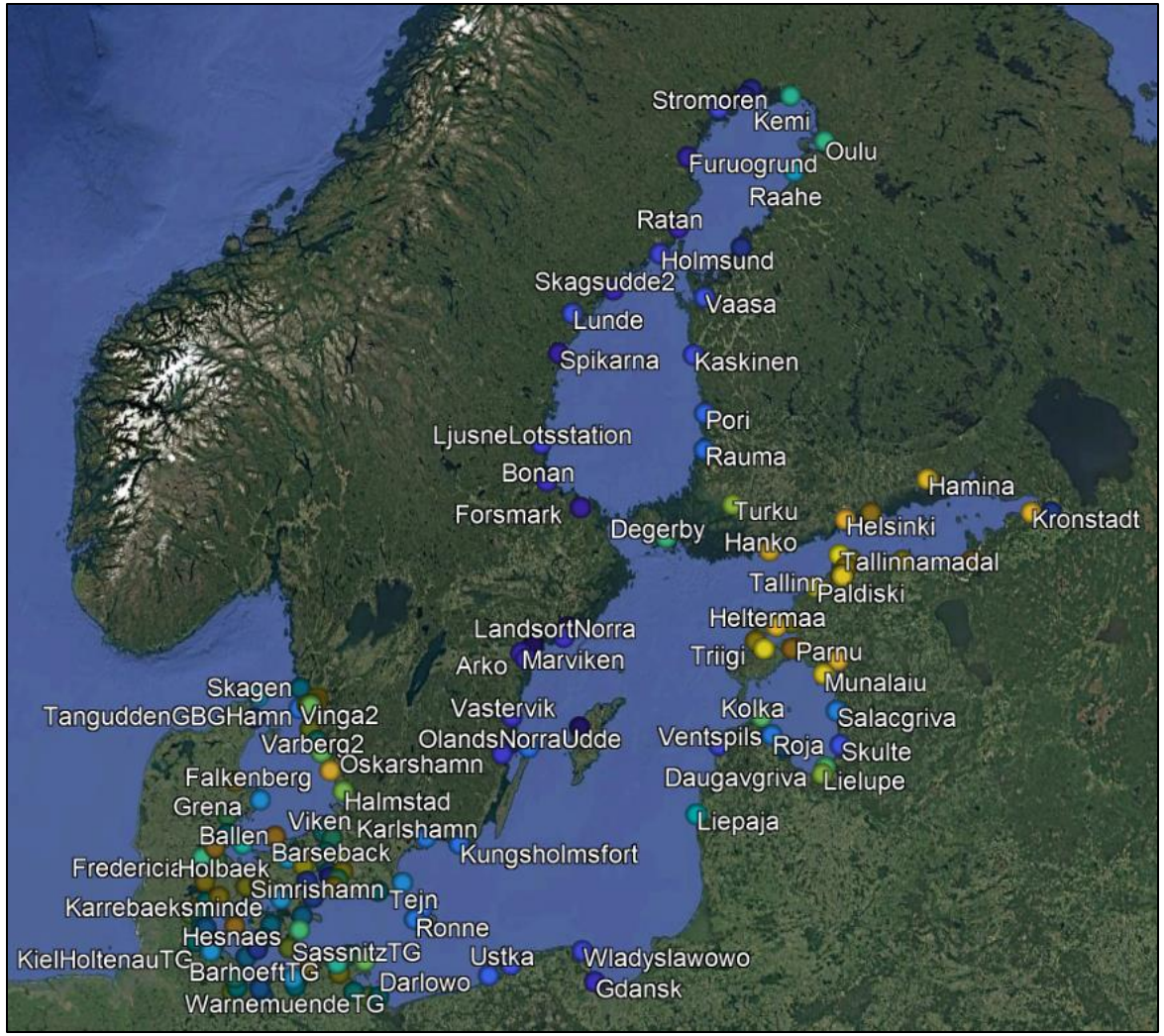






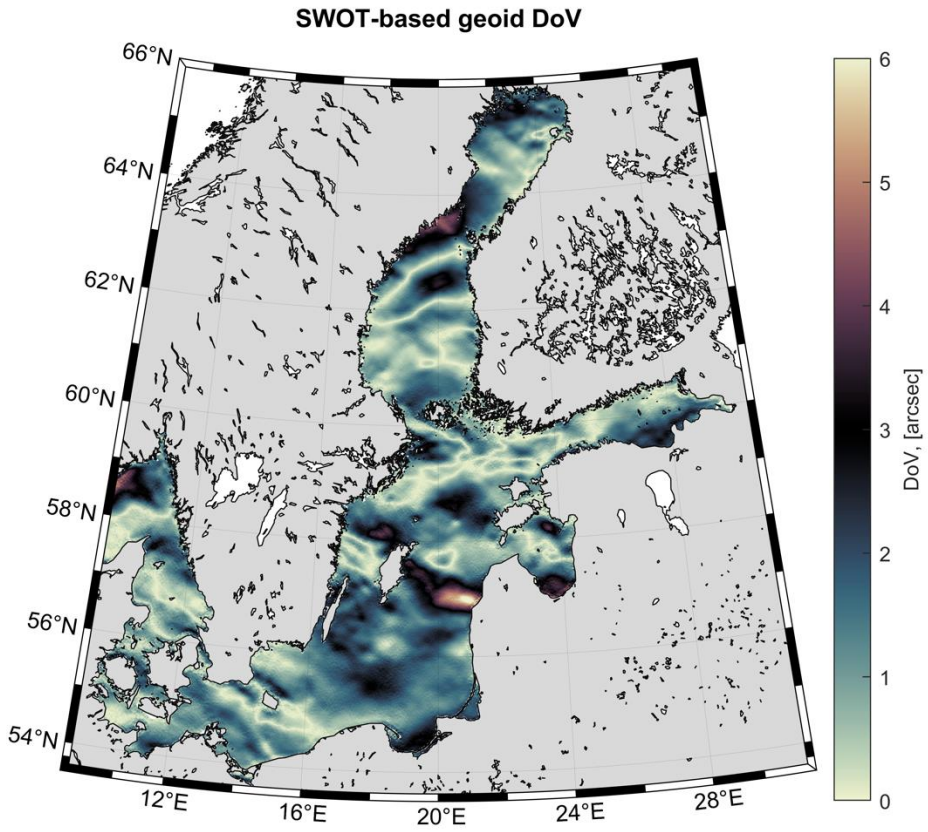
LOCAL SCALE

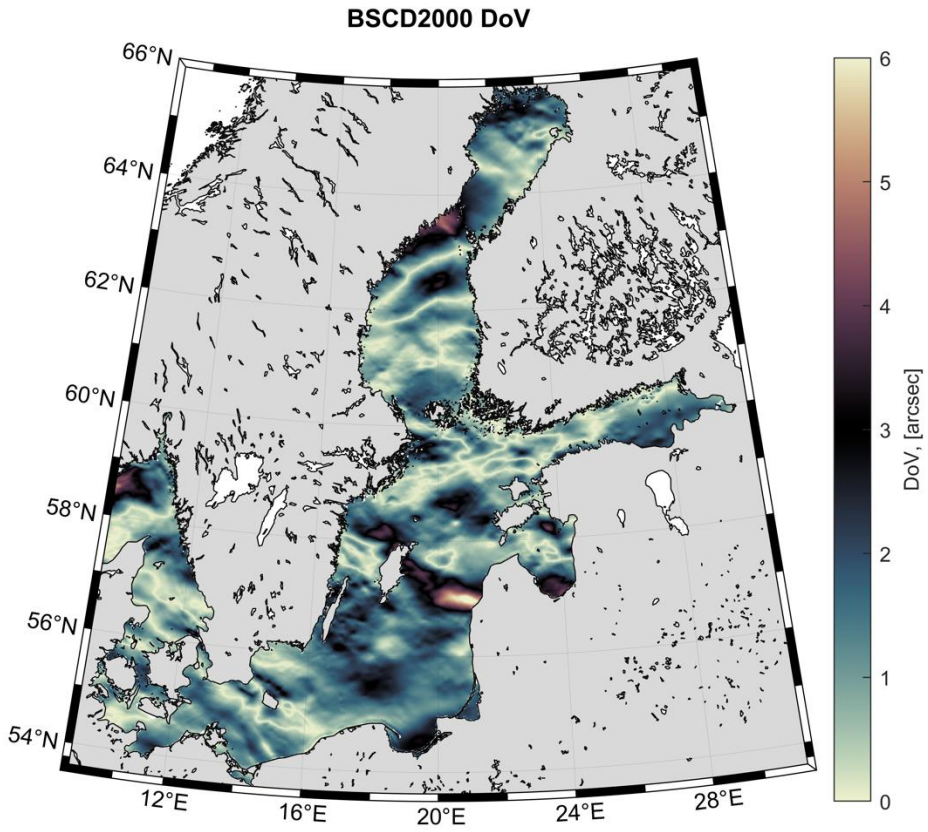
CALCULATE THE GEOID GEOMETRIC SURFACE AND USE IT AS CHART DATUM



LOCAL SCALE

GRAVITY ANOMALY FROM SWOT-BASED GEOID?

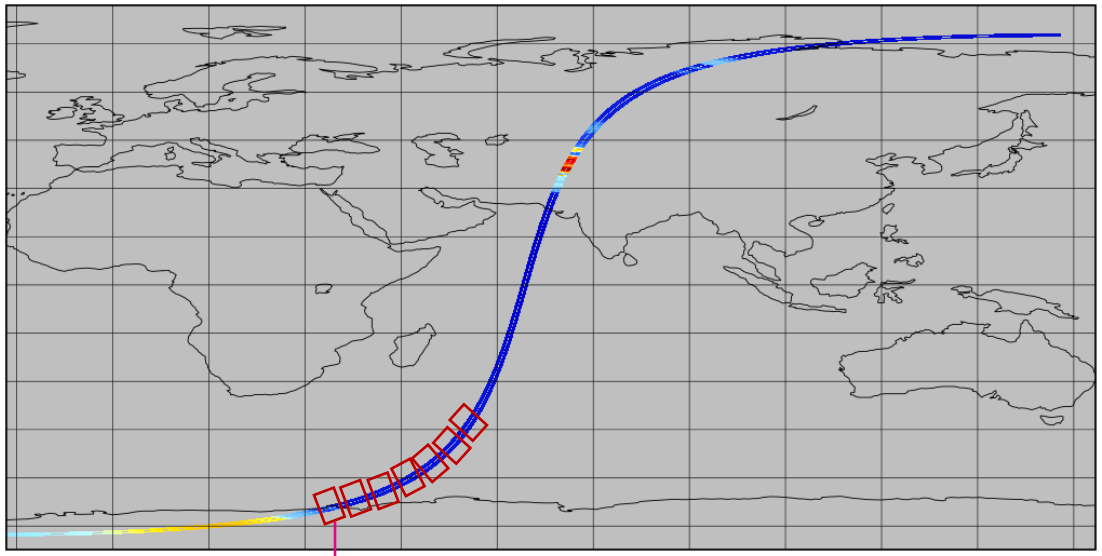


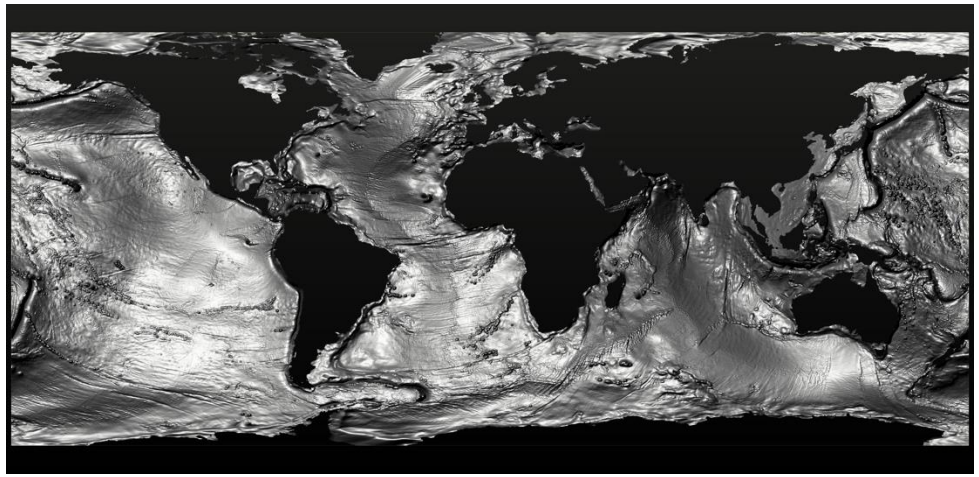


$$\begin{pmatrix} \xi \\ \eta \end{pmatrix} = -\begin{pmatrix} \frac{dN}{R \cdot d\varphi} \\ \frac{dN}{R \cdot cos\varphi \cdot d\lambda} \end{pmatrix}$$

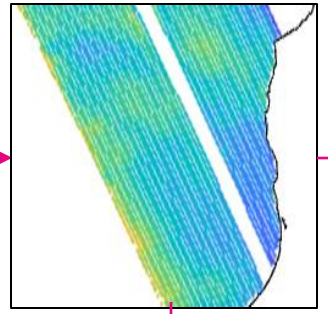
GLOBAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE

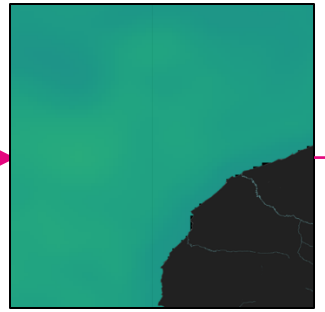




SWOT



HDM



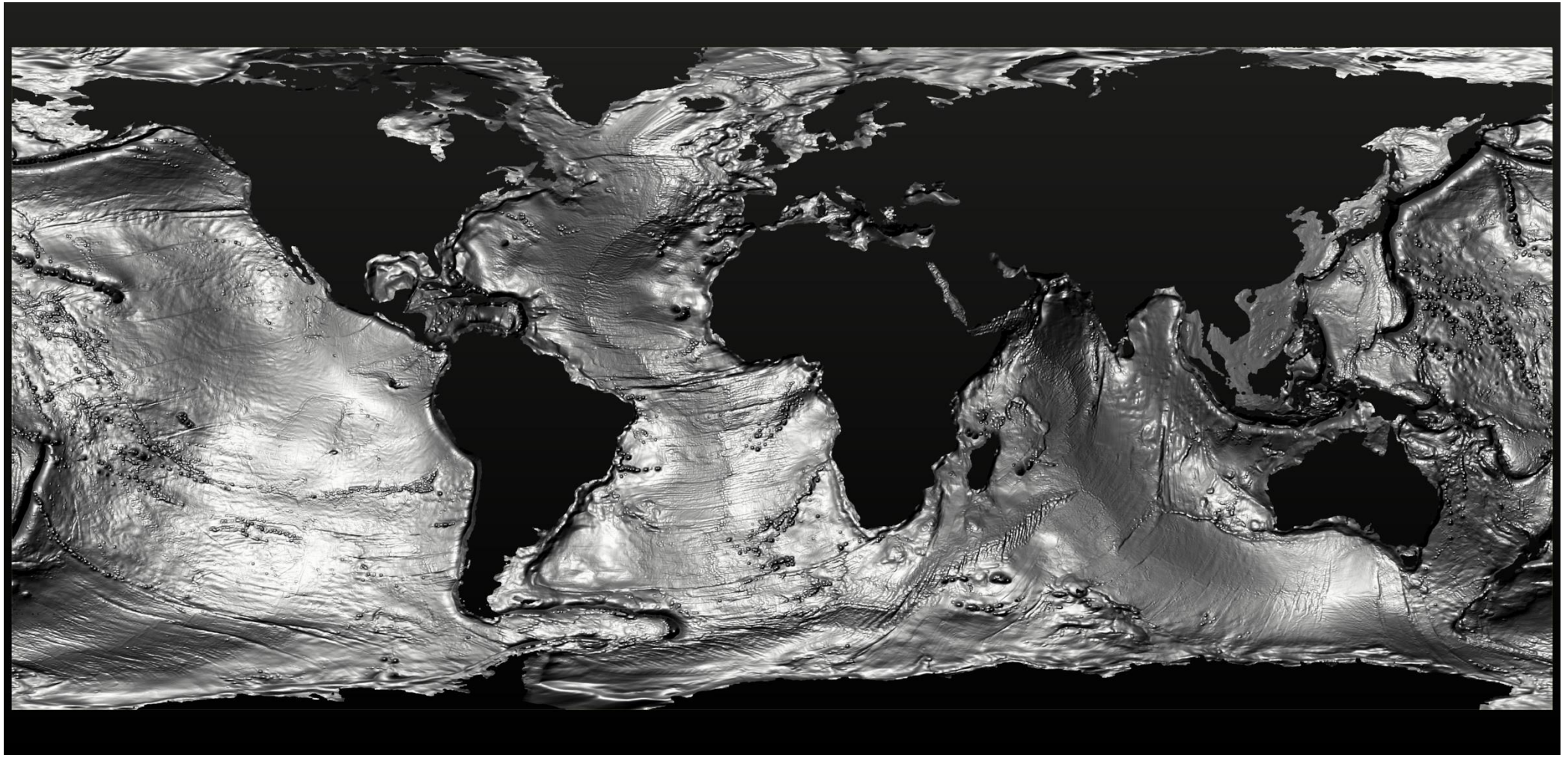
Time matches with mean tile time

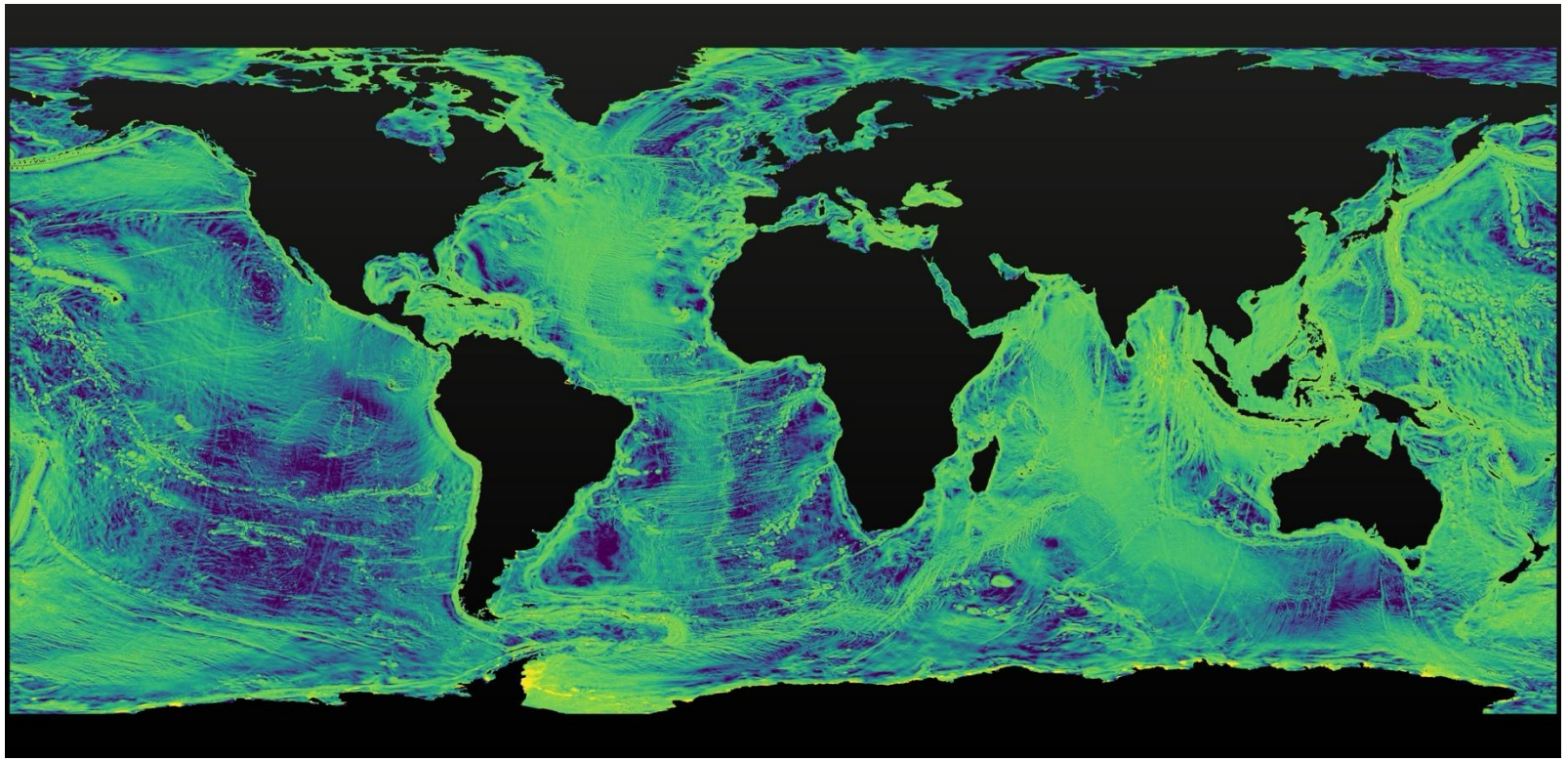
Mean tile time

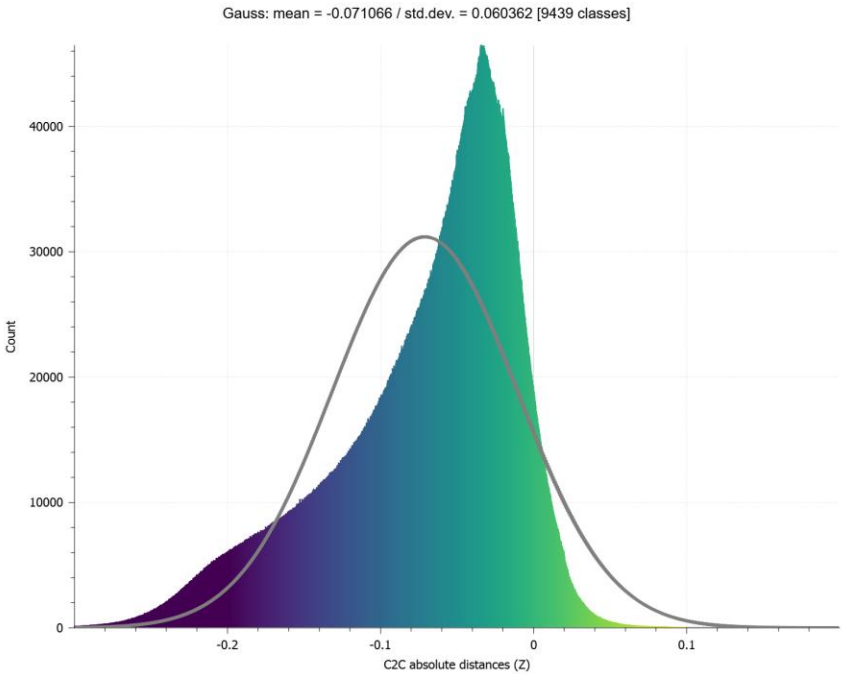
A lot of assumptions involved

GLOBAL SCALE

CALCULATE THE GEOID GEOMETRIC SURFACE






Gauss: mean = -0.071066 / std.dev. = 0.060362 [9439 classes]
Count
40000
30000
20000
10000
0
-0.2
-0.1
0
0.1
C2C absolute distances (Z)

WRAP-UP

WRAP-UP

- There’s a ton of data to dive into, and lots of different ways to analyze it.
- This or similar approach could be used in areas where there’s not much data or where the data is sparse.
- Each approach is trial and errors.
- Be aware of edge artifacts, tilted tracks, data voids etc.
- Be aware of new versions of data and avoid accidentely using diferent versions of the same data at the same time.

THANK YOU

TALLINN UNIVERSITY OF TECHNOLOGY

Aleksei Kupavõh
aleksei.kupavoh@taltech.ee