Baltic SEAL: Exploiting regional opportunities and a natural laboratory to advance processing algorithms for altimetry-derived Sea Surface Height estimation

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ESA-Baltic Earth Workshop on **Earth Observation in the Baltic Sea region**
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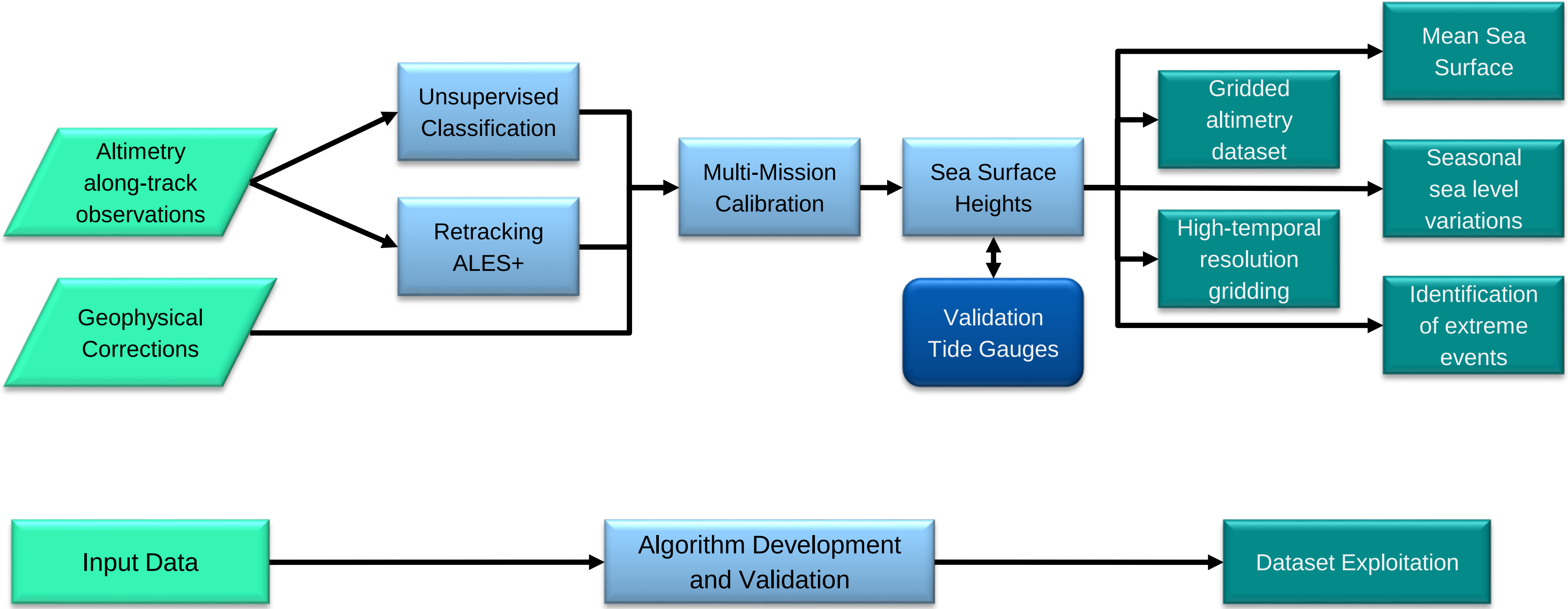
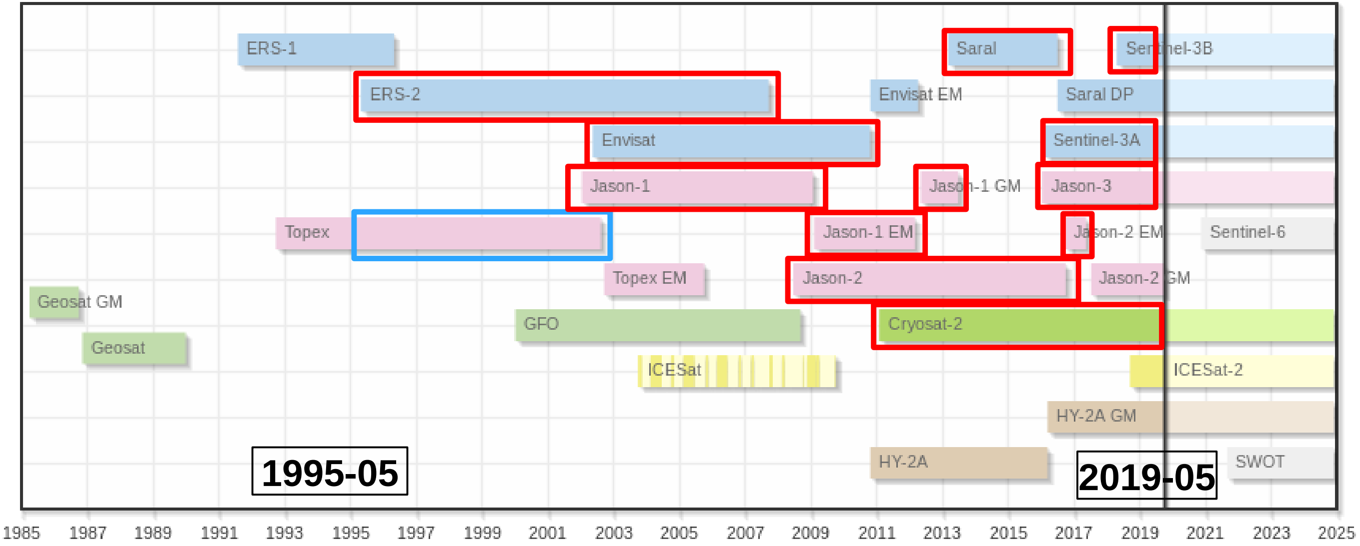
Workflow Baltic+ SEAL

18 months ESA Tender Project



Input Data: Altimetry dataset collection



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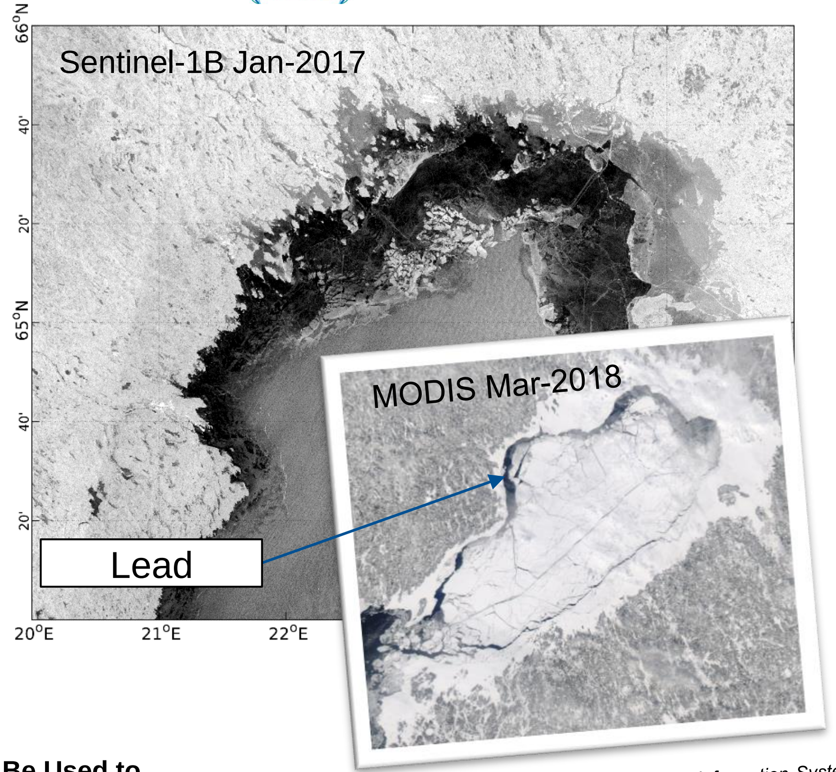
- 24 years Multi-mission altimetry data (Low-Resolution Mode (LRM) and Synthetic Aperture Radar (SAR))
- Usage of ALES+ retracked high-frequency along-track observations
- Multi-mission cross calibrated Sea Surface Heights
  - Regional cross calibration based on high-frequency along-track observations with respect to TOPEX/POSEIDON orbit

Algorithm Development and Validation - Unsupervised Classification

- ➢ Detection of open water observations within the sea ice area

- Classification to detect usable altimetry observations in order to estimate sea surface heights with multi-mission altimetry data within the sea ice area
- Unsupervised classification of waveforms without the use of selected training data for LRM and SAR altimetry data
- Comparison of classification with images from optical and side-looking SAR sensors



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More info: *Müller F.L et al.*: **Monitoring the Arctic Seas: How Satellite Altimetry Can Be Used to Detect Open Water in Sea-Ice Regions**. Remote Sensing, 9(6), 551, 10.3390/rs9060551, 2017c

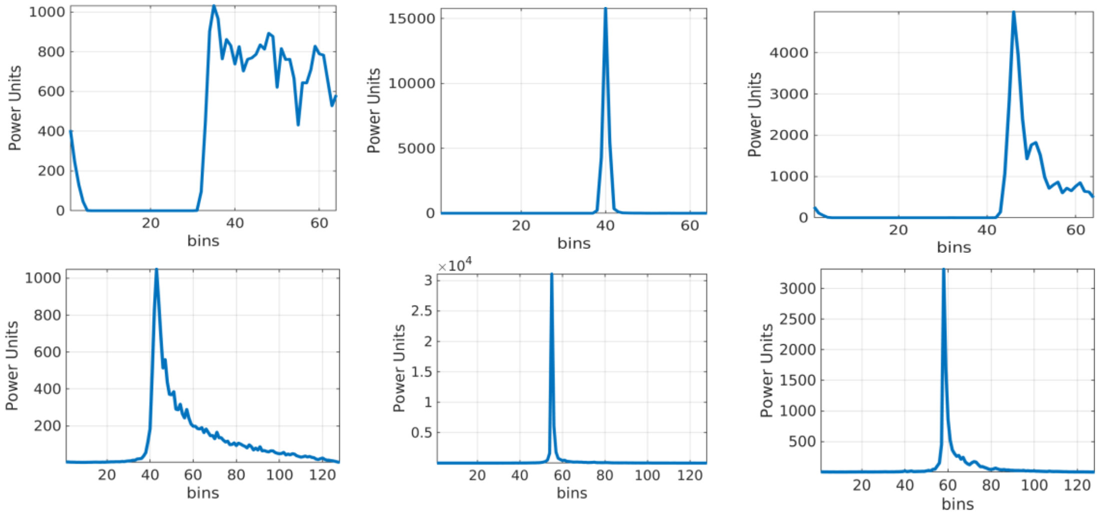
➢ Objective of classification to detect radar echoes from open water areas (lead, open ocean)

- Altimeter waveforms (i.e. radar echoes) are affected by surface conditions (e.g. roughness)
- Lead or calm water returns (no wind or waves): single-peak shape, specular behavior, strong backscatter
- Open Ocean waveforms: Brown-like shape, weak backscatter
- Sea-Ice returns: more random shape, backscatter depended on sea-ice surface, strong noise

OCEAN | LEAD | SEA ICE

ERS-2 — LRM

Sentinel-3 — SAR



Algorithm Development and Validation - Unsupervised Classification

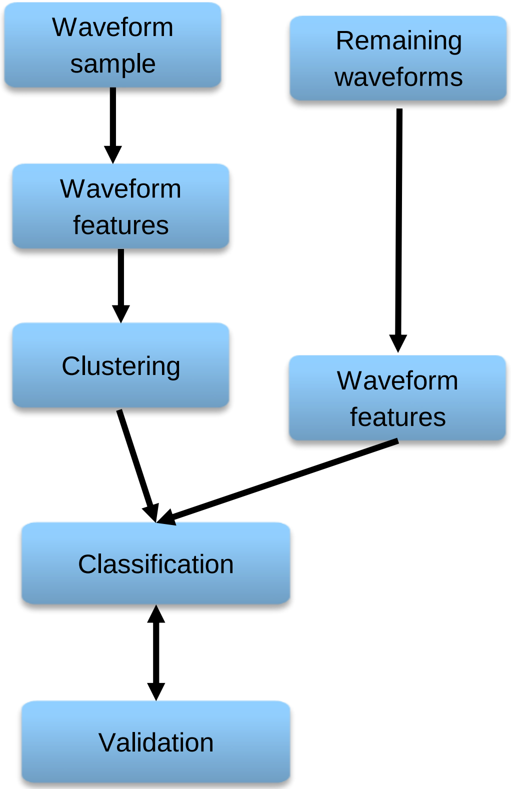
- Classification procedure for identifying water [1] and non-usable altimetry observations [0]

- Usage of <u>Artificial Intelligence Algorithms</u> (Data-Mining)
- Application of unsupervised classification

- **Input: Original waveform data**
- Definition and computation of waveform features
  - Maximum Power, waveform width, decay of trailing edge etc. (Parameters describe the waveform’s shape and its features)

- Clustering of waveforms in clusters applying K-medoids
  - Waveform reference model
- Assigning waveform clusters to surface conditions
  - 4 classes: calm water, ocean, sea-ice and undefined
- Classification of remaining waveforms using reference model and K-nearest neighbor (K-NN)
- **Classification output:** WATER [1] | ICE [0] | UNDEFINED [0] (per measurement)

- Same method for LRM and SAR missions, but slightly different feature space



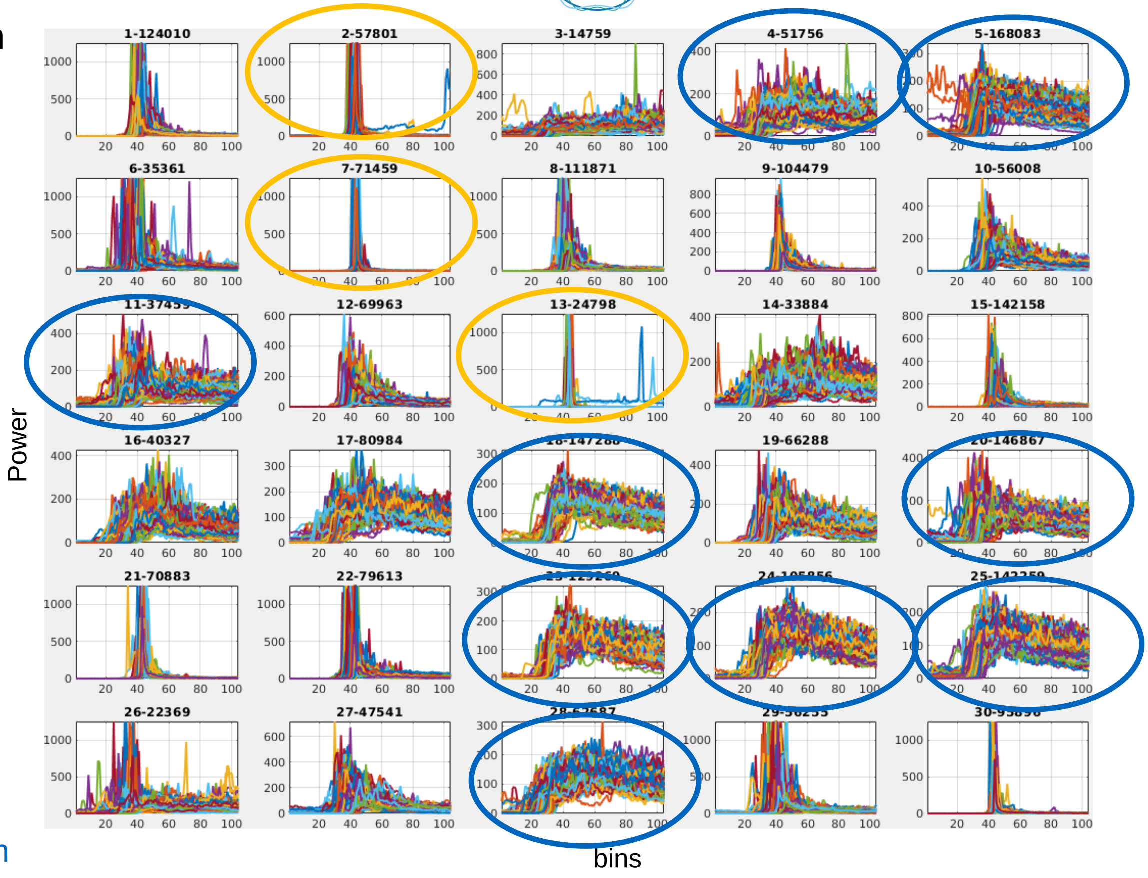
Algorithm Development and Validation - Unsupervised Classification

- ➢ Using characteristic differences between sea ice and open ocean measurements for clustering

- Generation of waveform reference model by using radar echoes during sea ice melting period

- Clustering LRM/SAR waveforms into 30/(25) Clusters using K-medoids

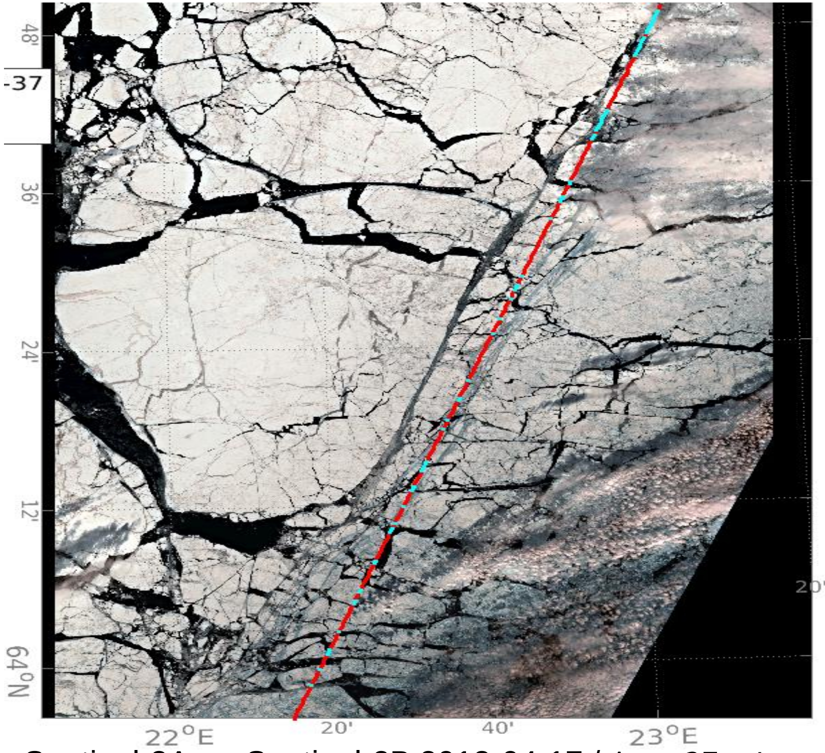
- Assignment of waveform clusters to ocean conditions by considering:
  - Features per Cluster
  - Waveform shape



- Lead return
- Open ocean return

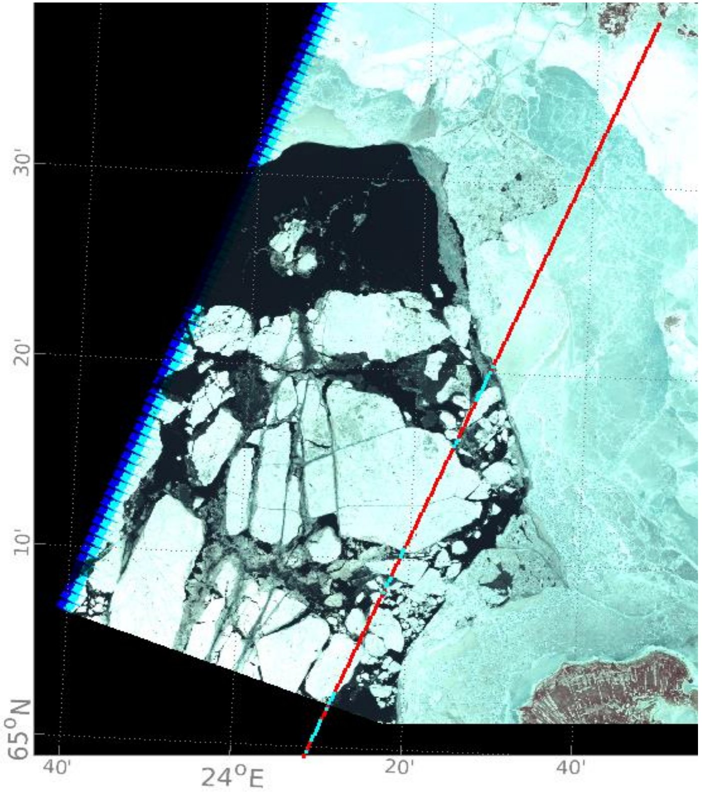
Example: Waveforms of Jason 1,2,3

Unsupervised Classification to detect, and exploit leads



Sentinel-3A vs. Sentinel-2B 2018-04-17 / $\Delta t = 37\ min$

- Water
- Ice



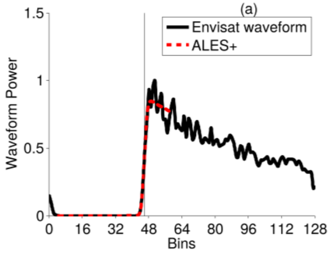
ERS-2 vs. Landsat-7 2001-04-22 / $\Delta t = 39\ min$

- Example: Classification for SAR (left) and LRM (right) altimetry data

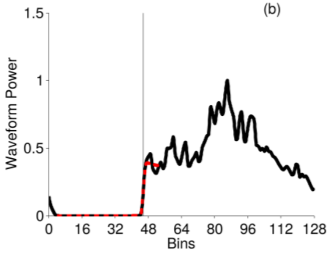
Algorithm Development and Validation (Retracking – ALES+)

➢ Getting the SL measurement from sea ice and coastal waveforms

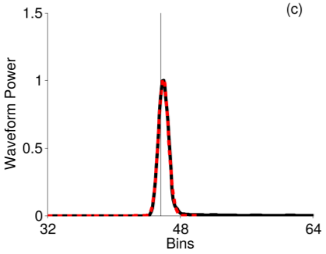
- Different water surfaces = different waveform shapes
- Different retrackers = varying performances and biases within retrackers
- **Objectives**: provide a homogenous solution for the Baltic Sea (without excluding coastal waters and leads!)



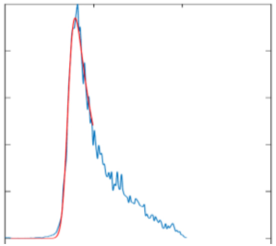
Ocean - LRM



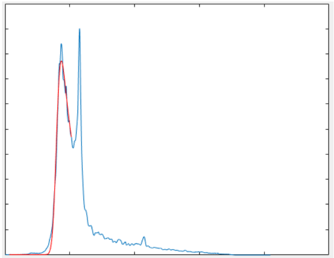
Coastal - LRM



Lead



Ocean - SAR



Coastal - SAR

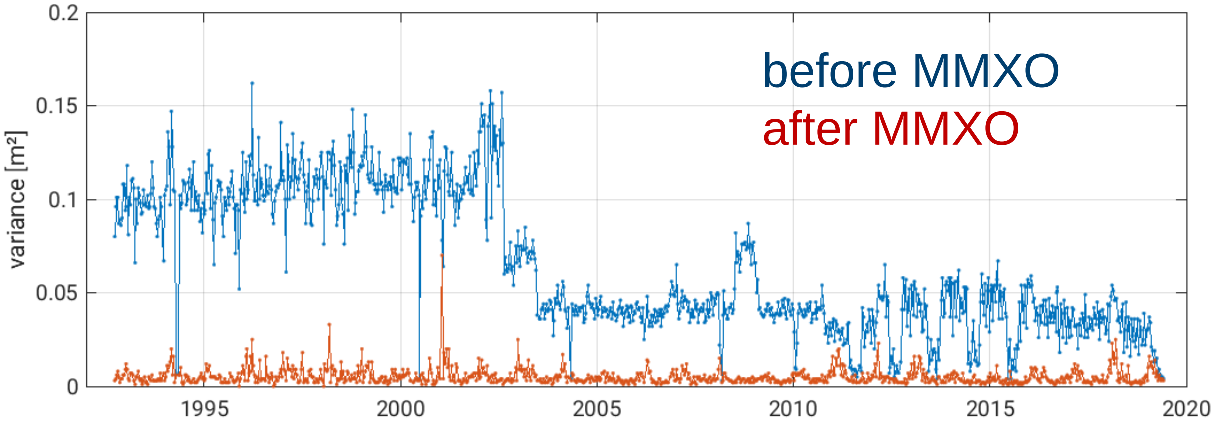
- **Sub-waveform retracker to avoid coastal contamination**
- Adaptive trailing edge decay to retrack peaky waveforms from leads
- Homogenous range estimation of lead/polynya, open ocean and coastal waveforms (avoids internal biases)

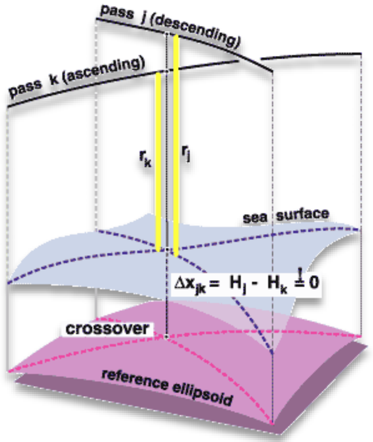
More Information: *Passaro M. et al.* (2017): **ALES+: Adapting a homogenous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters.**, *Remote Sensing of Environment*

Algorithm Development and Validation (Multi-Miss. Cross Calibration)

➢ Establishing a long-term multi-mission time series for the Baltic Sea

- Offset not always time-constant => drifts!
- Differences in sea level heights can have large-scale geographical pattern
- A location-dependent multi-mission cross-calibration (MMXO) between all missions is needed
- Output: time series of radial errors => applied as corrections to each measurement





More Information: *Bosch W. et al.*: **Multi-mission cross-calibration of satellite altimeters: constructing a long-term data record for global and regional sea level change studies.** Remote Sensing 6(3): 2255-2281, 10.3390/rs6032255, 2014

Algorithm Development and Validation (Multi-Miss. Cross Calibration)

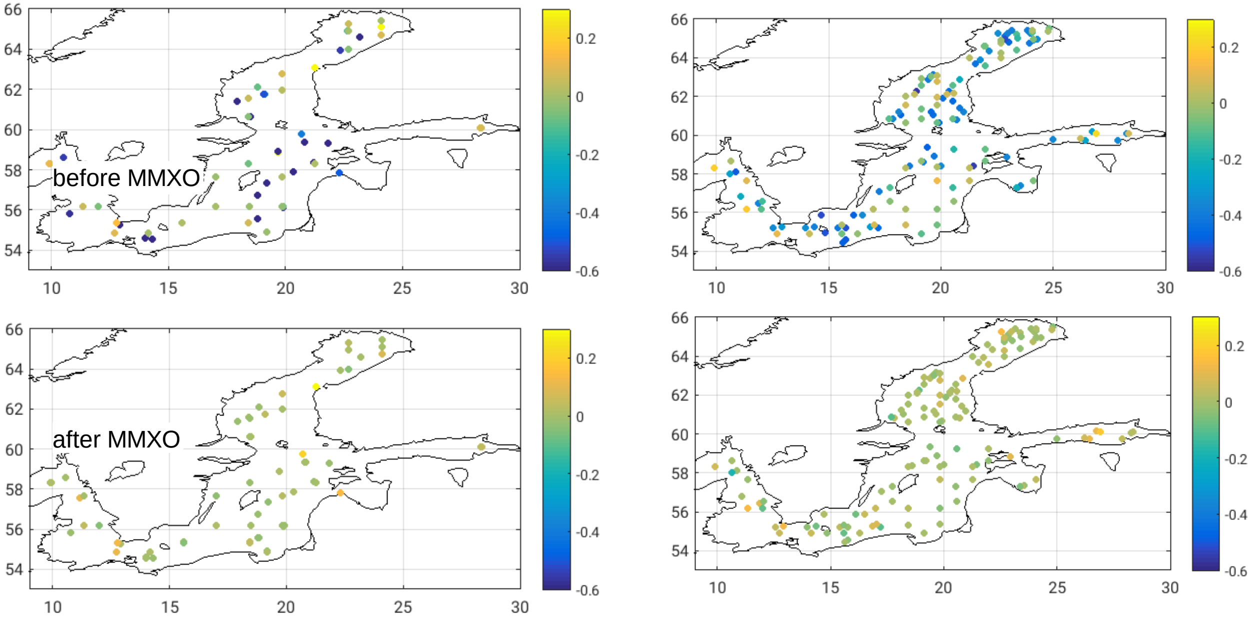
➢ Using altimeter track crossovers to inter-relate different altimetry measurements

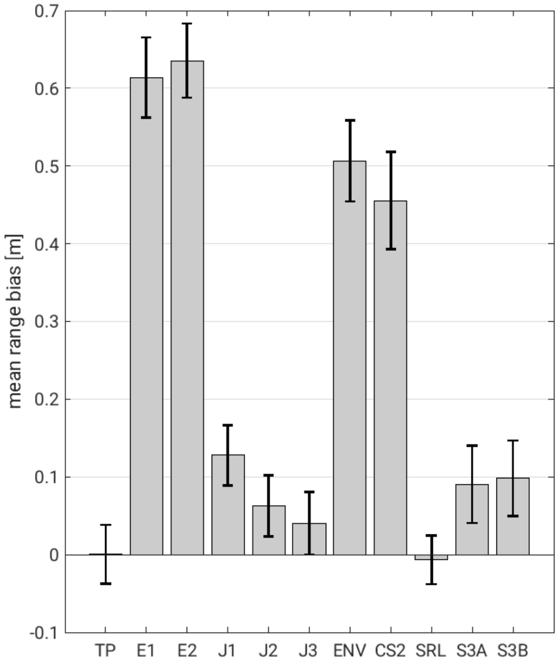
- Multi-mission crossover analysis: regional approach based on high-frequent SSH observations
  - Two – four missions per 10 day cycle / max. time differences = 3 days

Crossover Differences

TOPEX/ERS-2/Jason-1/Envisat

Jason-2/Jason-1 EM/Envisat/Cryosat





Mean range biases wrt TOPEX

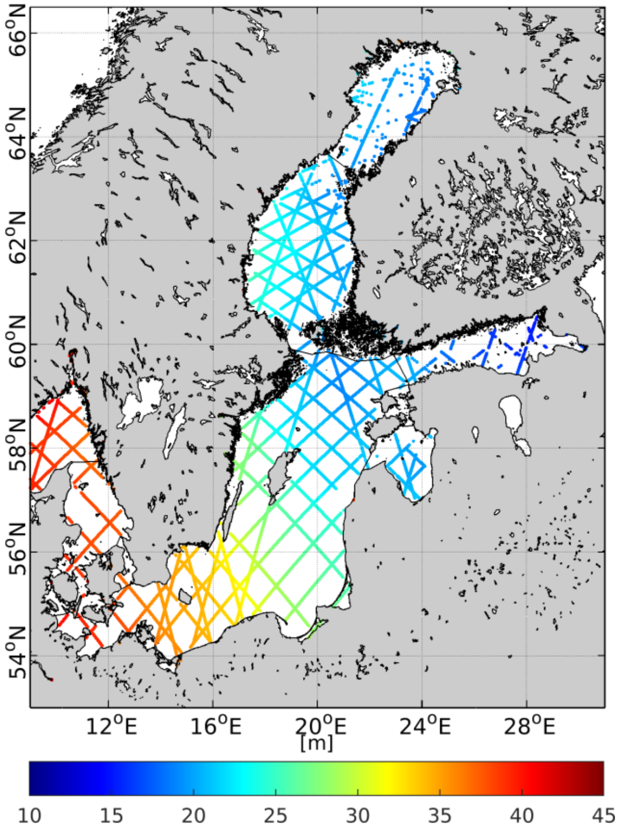
Algorithm Development and Validation (along-track outlier detection)

➢ Provision of quality flags for advanced applications

- Creation of along-track quality flag (qf) for indicating good and bad observations
- Generation of easy-to-use indicator (1-0)

- Application of along-track outlier flagging strategies:
  - Pre-defined flags (e.g. distance-to-coast (<3km), maximum deviation from the Mean Sea Surface (MSS), retrack flags)
  - Sea ice classification
  - etc.

- Possibility for individual use of quality flag (bad labelled observations are kept in dataset)

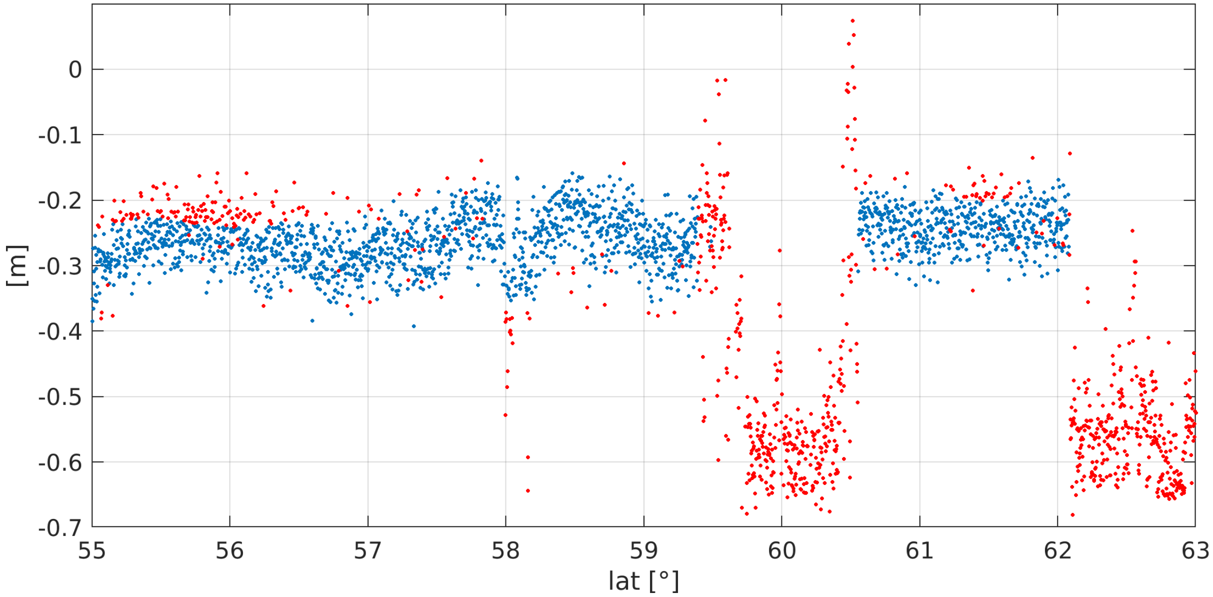


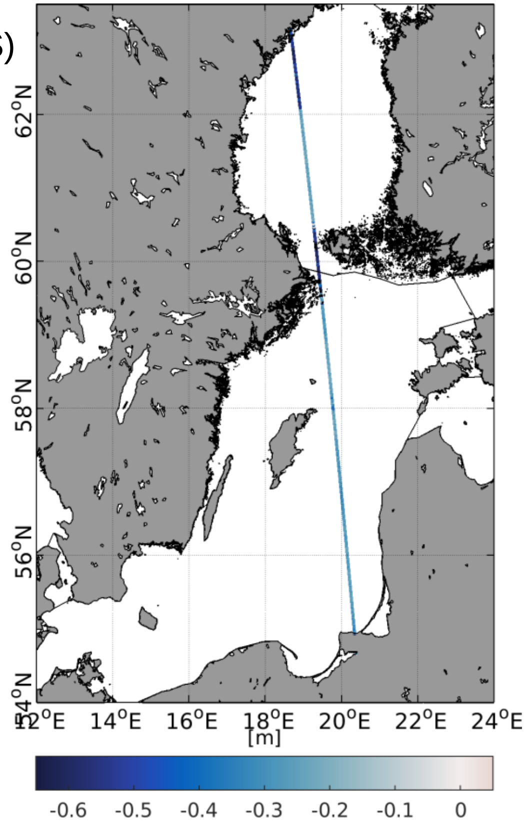
Example: 10 days Sea Surface Heights (2009-03-01 2009-03-10) qf applied

Algorithm Development and Validation (along-track outlier detection)

➢ Displaying suspect data for users to investigate (if needed)

- Example Sea Level Anomalies (SLA) of CryoSat-2 overflight (SLA: SSH-MSS)
- Labelling of good/bad observations





04-March-2018

- Good flagged observations
- Bad flagged observations

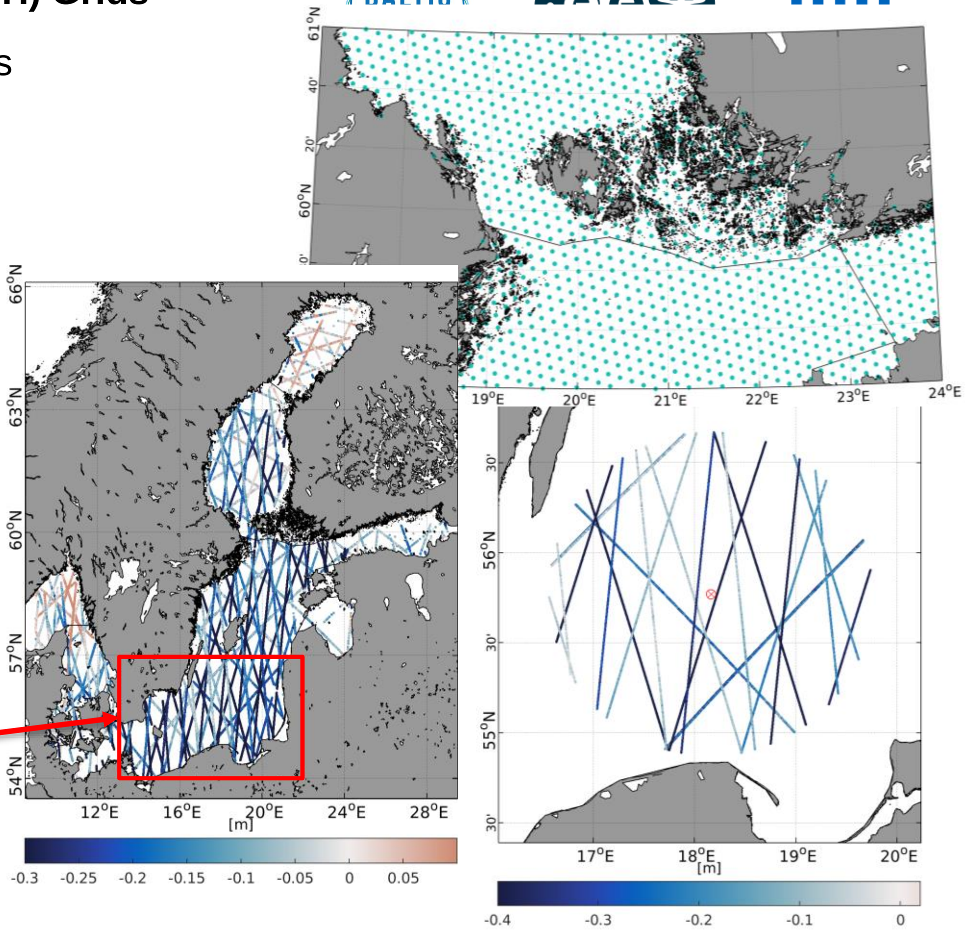
Data Exploitation: Monthly Sea Surface Height (SSH) Grids

➢ Development of gridded data from along-track inputs

- Gridding along-track SSH data (1995-05 → 2019-05) on a triangular, non-regular distributed grid (spatial resolution 7 km – 8 km)
- Least-squares estimation of inclined plane with mathematical equation:

$$\boldsymbol{h(x,y) = c_0 + c_1 x + c_2 y}$$

- Fitting a surface to observations within a certain cap-size (100km) around a grid node - estimation of 3-unknows (height $\boldsymbol{c_0}$, slope in x/y-direction $\boldsymbol{c_1}$, $\boldsymbol{c_2}$)
- Weighting:
  - Gaussian distance based weights (min. 50%)
  - Weights based on input uncertainties (along-track Median Absolute Deviation from uncomplex ocean region)
- Gridding is based on remove-restore strategy using Baltic dedicated Mean Sea Surface



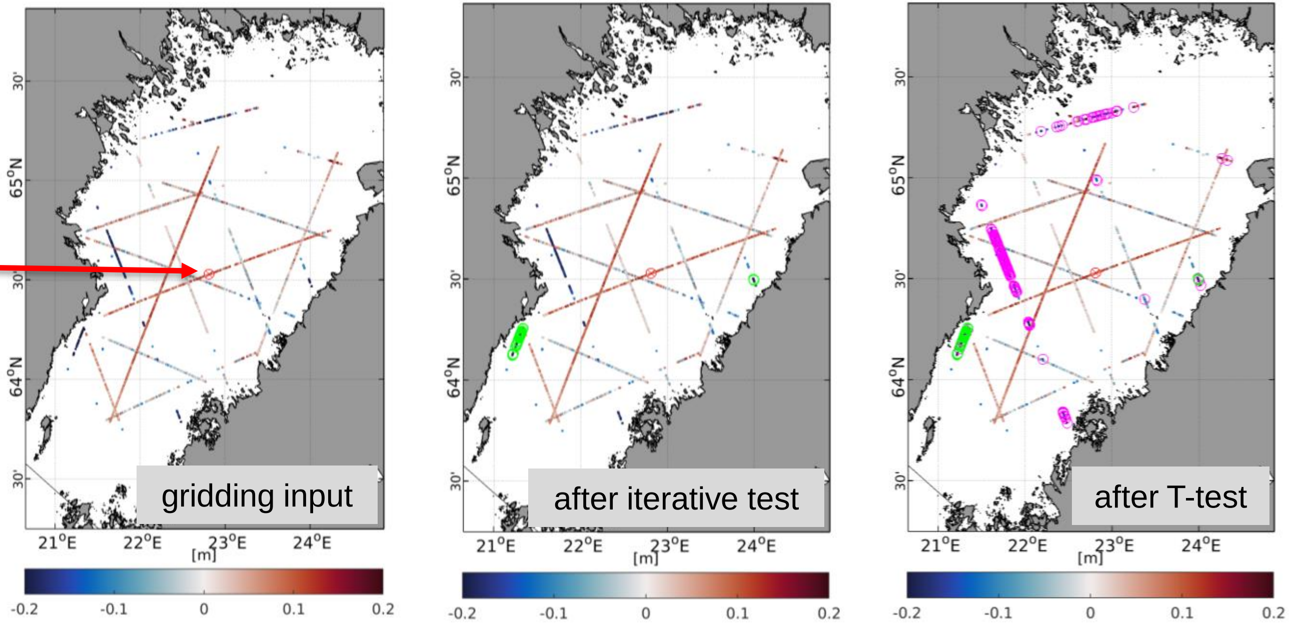
Data Exploitation: Monthly SSH Grids (Outlier-Flagging)

➢ Generation of outlier detection for a reliable gridding

- Gridding requires advanced outlier-flagging, which is dependent on the gridding location and used observations
- Baltic SEAL uses a 2-step outlier elimination strategy:
    1. Iterative Outlier Detection based on residuals until no outliers are detected (max. 30 iterations)
    2. Final statistical T-Test (99^{th} percentile significance level) based on standard deviation of the residuals

Example: Grid Node 390 Baltic Sea
2014-02 (Sea Level Anomalies)

grid node

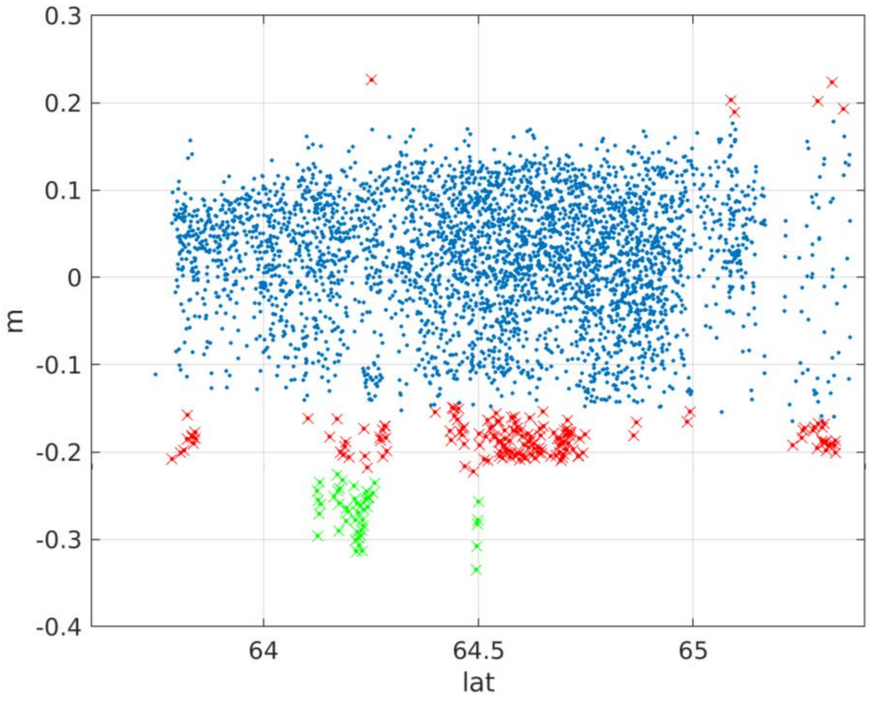


Detected outliers after:

- Iterative Test
- T-Test

Data Exploitation: Monthly SSH Grids (Outlier-Flagging)

- Example: Grid Node 390 Baltic Sea (sea ice region) 2014-02 (Sea Level Anomalies)



Detected outliers after:

- Iterative Test
- T-Test

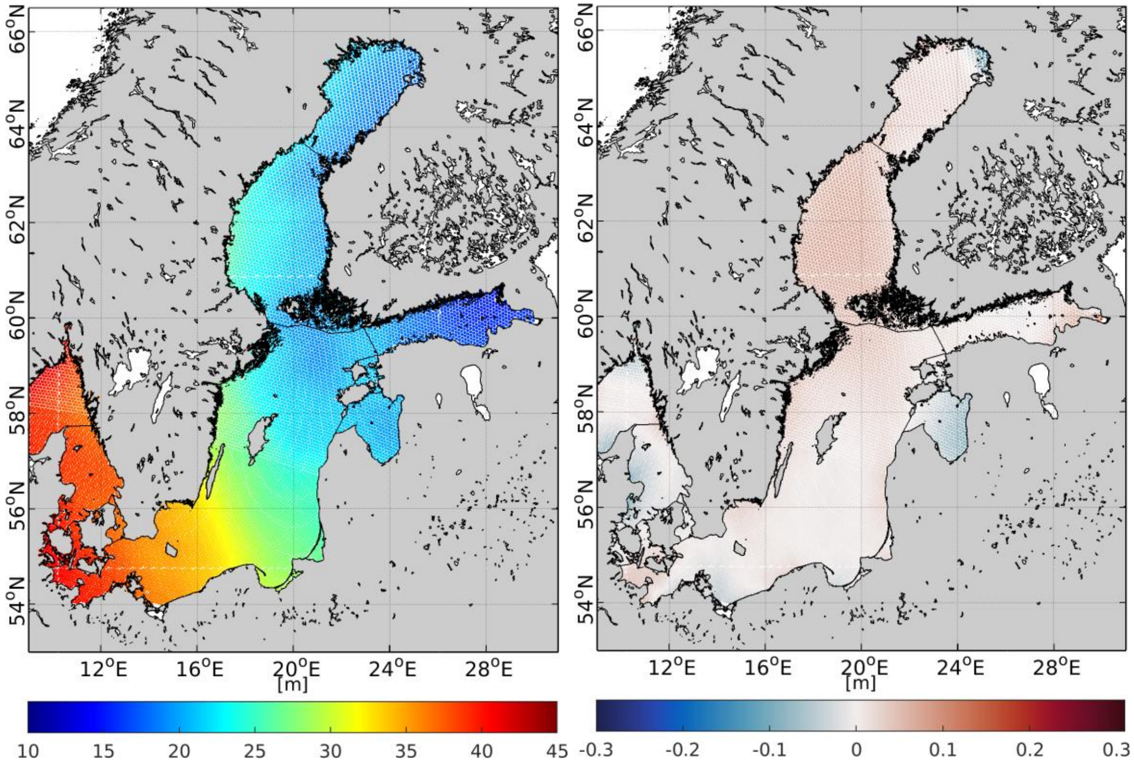
- Used observations

Results: Monthly Sea Surface Heights and visualization

- ➢ Visualization of along-track and gridded data in Python

- Release of simple stand-alone, open-source python code to convert:

- the grid data into GIS-compatible images (.tif)
- the along-track data into point .shp datasets for novices to explore using standard GIS software.



Example of gridded Sea Surface Heights (left) and Sea Level Anomalies (right) for March, 2017

Conclusion

- The **Baltic Sea** is used as a laboratory for high-frequency multi-mission satellite altimetry (LRM & SAR) data exploitation to produce improved sea level products (by end of 2020)
- **Development** of dedicated retracking algorithms and unsupervised classification techniques to derive sea surface heights in coastal and sea ice areas
- **Provision** of along-track and gridded datasets in NetCDF format and in various processing levels (standard and expert level)
- **Provision** of easy to apply source code to help novices using the data

<u>Outlook</u>:

- **Improvement** of algorithms, e.g. variable cap size
- **Transfer** of techniques developed in this framework to other regions
- **Exploit synergies** with other Baltic+ Themes