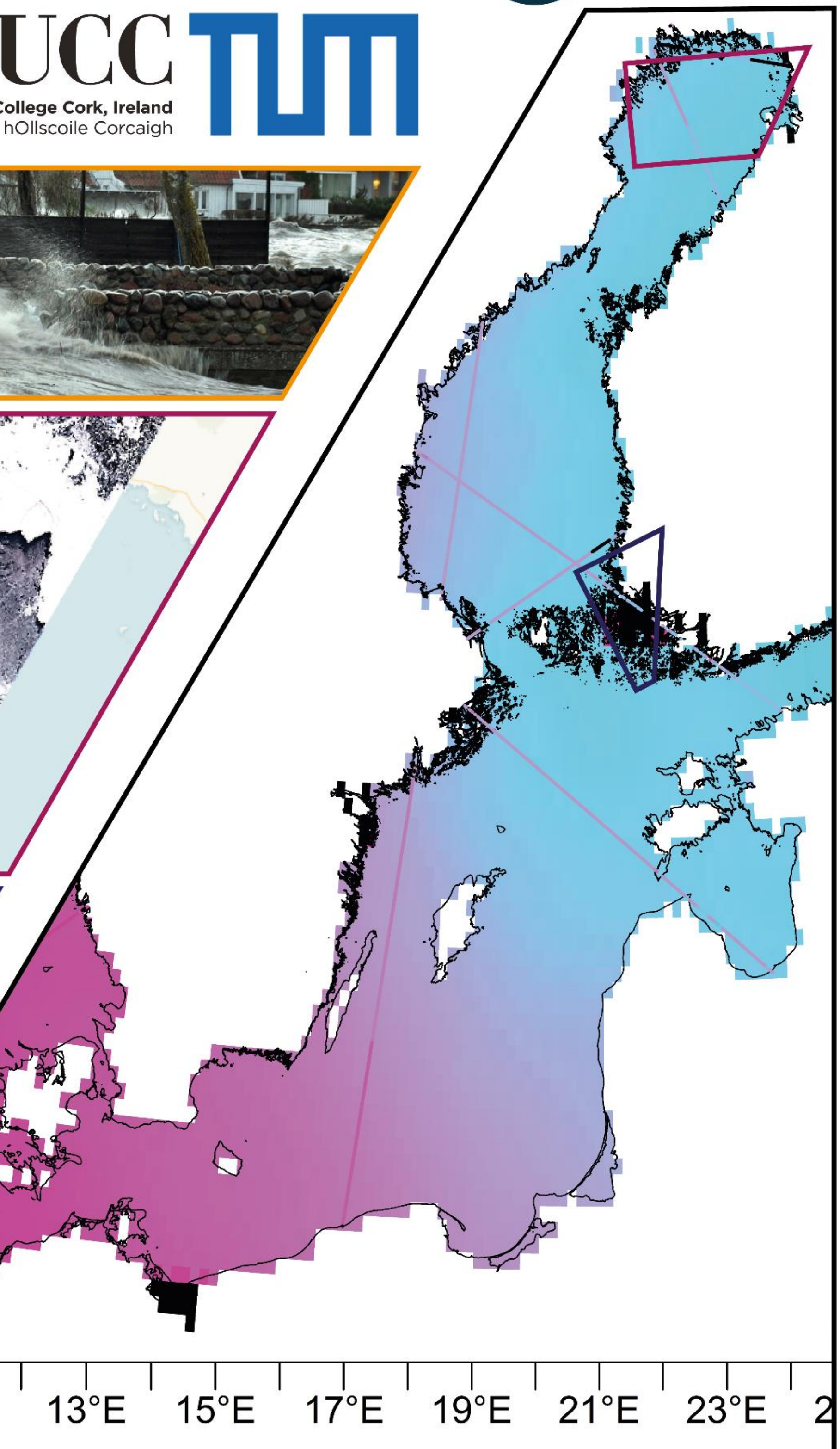

BALTIC+ Theme 3
Baltic+ SEAL (Sea Level)
Product Handbook

Document Details

ESA Contract: 4000126590/19/I/BG

BALTIC+ Theme 3
Baltic+ SEAL (Sea Level)
Product Handbook

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Contents

Summary

The European Space Agency funded Baltic SEAL[1] project has used the Baltic Sea as a testbed region to advance capabilities in Coastal Altimetry. It has produced a suite of two Sea Surface Height (SSH) products and two further ancillary datasets, derived from altimetry measurements across a range of altimetry missions spanning from May 1995 to November 2020. These SSH products are provided at two levels.

The first product consists of along-track datasets of Sea Surface Height (SSH) estimates. Each dataset is derived from a single path of an altimeter over the Baltic Sea region. In addition to the SSH value, flags are provided to advise users of measurements whose quality may be degraded. The second product type consists of gridded data products covering the Baltic Sea region at monthly temporal resolution. In addition to the along-track and gridded products, two further added value products are available - a new mean sea surface dataset for the Baltic Sea, as well as a sea level trend and annual cycle dataset. These are also provided as part of the Baltic SEAL product suite, downloadable from the data store, and are described in this handbook.

This handbook is designed to support both novice and more advanced users. It is a reference guide for users of the ESA Baltic SEAL suite of products. It provides fundamental information on the theory underpinning the products, and the technical specifications of the data you can access. It also provides links to the more in-depth literature and information on the theory and technical aspects of the product you are using.

Newcomers to satellite altimetry data can find basic information on altimetry, and how to interpret and understand the data files you have obtained. There are also helpful basic codes to display and explore your newly acquired data. For more expert users, the overview information is presented here, with more technical, and in-depth information available in the referenced literature.

Please note the team are also very interested in feedback concerning this product handbook. We very much welcome feedback and suggestions on content, structure, and language to shape data product handbooks for future versions, and new data products.[2] Furthermore, as a user of altimetry-derived products, it is strongly recommended you connect with the growing coastal altimetry community of practice. Ways to do so, and benefit from their extensive knowledge of this rapidly evolving field are also outlined in this handbook.

[1] The Baltic SEAL project is part of the Baltic+ Regional Initiative under the European Space Agency's Earth Observation Envelope Programme 5. Throughout this document the project is referred to as "Baltic SEAL" (e.g. the Baltic SEAL products). In other, more internal project documentation, the reader may encounter "Baltic+ SEAL", which is the same.

[2] To provide feedback, please use the contact us page on the Baltic SEAL website (www.balticseal.eu).

List of Abbreviations

ALES	A multi-mission adaptive subwaveform retracker for coastal & open ocean altimetry
ALES+	An enhancement of the ALES retracker
AVISO	The Archiving, Validation and Interpretation of Satellite Oceanographic data service
Baltic+	The European Space Agency's Baltic Plus regional programme
Baltic+ SEAL	The Baltic Plus SEA Level project, implemented under the Baltic+ Programme
Baltic SEAL	A simpler acronym for Baltic+ SEAL
BH	Brown-Hayne (model)
CCI	Associated with the European Space Agency's Climate Change Initiative
CNES	(FR) Centre National d'Études Spatiales
DAC	Dynamic Atmospheric Correction
DD	Delay-Doppler
DT	Dry Tropospheric correction
ECMWF	European Centre for Medium-range Weather Forecasts
EM	Electromagnetic
Envisat	The European Space Agency's "Environmental satellite" mission
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FTP	File Transfer Protocol
GIS	Geographical Information System/Sciences
GPD	GNSS-derived Path Delay - a methodology for computing wet tropospheric corrections for coastal altimetry
GPD+	GNSS-derived Path Delay Plus – an enhancement of the GPD methodology.
HDF	Hierarchical Data Format
IONO	Ionosphere correction
LRM	Low Resolution Mode
MAD	Median Absolute Deviation
MLE	Maximum Liklihood Estimation
MMXO	Multi-Mission crossover (X-Over)

MSS	Mean Sea Surface
netCDF	NETwork Common Data Format
NOAA	(U.S.) National Oceanic and Atmospheric Administration
NSIDC	(U.S.) National Snow and Ice Data Center
PP	Pulse Peakiness
PT	Pole Tide correction
ROC	Radial Orbit errors Correction
SAMOSA	A waveform retracker, developed specifically for SAR-derived waveforms
SAMOSA+	An enhanced version of the SAMOSA retracker
SAMOSA++	An enhanced version of the SAMOSA+ retracker
SAR	Synthetic Aperture Radar
SARAL	Satellite with Argos and ALtiKA (a joint satellite mission between the Indian Space Research Organisation, and CNES)
SET	Solid Earth Tide correction
SGDR	Sensor Geophysical Data Record
SLA	Sea Level Anomaly
SSB	Sea State Bias
SSH	Sea Surface Height
SWH	Significant Wave Height
TG	Tide Gauge
TWLE	Total Water Level Envelope
VCE	Variance Component Estimation
VFM	Vienna Mapping Function
WT	Wet Trophospheric correction

1 Introduction

The Baltic SEAL suite of products is the result of dedicated signal processing and corrections at different levels of complexity. These are implemented to extract sea level measurements from sea ice prone areas and jagged coasts. To understand the state of the art in this area, and exploit the information contained in the Baltic SEAL suite of products, there are some basic principles of satellite altimetry to understand, as well as the process whereby a measurement of a radar echo taken by a sensor, yields a value of sea level on the Earth's surface. This section outlines the basic principles of satellite radar altimetry. It introduces the key terminology, as well as highlighting informative documents, peer-reviewed publications, and online resources for altimetry novices or satellite-data experts new to the coastal altimetry arena.

1.1 Satellite Altimetry - the principles behind the data

Altimetry satellites essentially determine the distance from the satellite to a target surface by sending a radar pulse towards the surface, and measuring the time it takes to come back (Figure 1). If the satellites orbital position is known with a sufficient degree of precision (i.e. its orbital altitude with respect to reference surface, such as the ellipsoid), we can compute the height of the sea surface through difference analysis (for a detailed description of terms such as "range", "orbit", "altitude", see Figure 1). It is also worth noting that in addition to surface height, through looking at the shape and amplitude of the returned radar waveform, it is also possible to measure wave height and surface wind speed over the oceans' surface. For further information on these uses see the wide range of information on satellite altimetry and ocean sciences such as Cheney (2001), Stammer and Cazenave (2018), and most recently Cazenave (2019).

While the working principle of altimetry is simple, what makes the measurement complicated is the required precision, a few centimetres (the typical amplitude of sea level anomalies with respect to a mean state due for example to mesoscale features in the ocean). This must be achieved from a satellite orbiting at ~1000 km over the surface - a precision greater than one part in ten million. Envisioned as an everyday comparison, it is as if you went to the bakery to buy a standard loaf of bread (about 1 kg) and wanted to know its weight to an accuracy of less than 0.1 mg. This "one part in ten million" precision needs to be achieved and maintained, whilst the entire altimeter system (i.e. the instrument, but also the processing chain with the various corrections) is required to be stable in time, if we want to estimate long-term sea level rise. Currently, we can measure changes in global sea level with an accuracy of 0.5 mm/y (ESA, 2020).

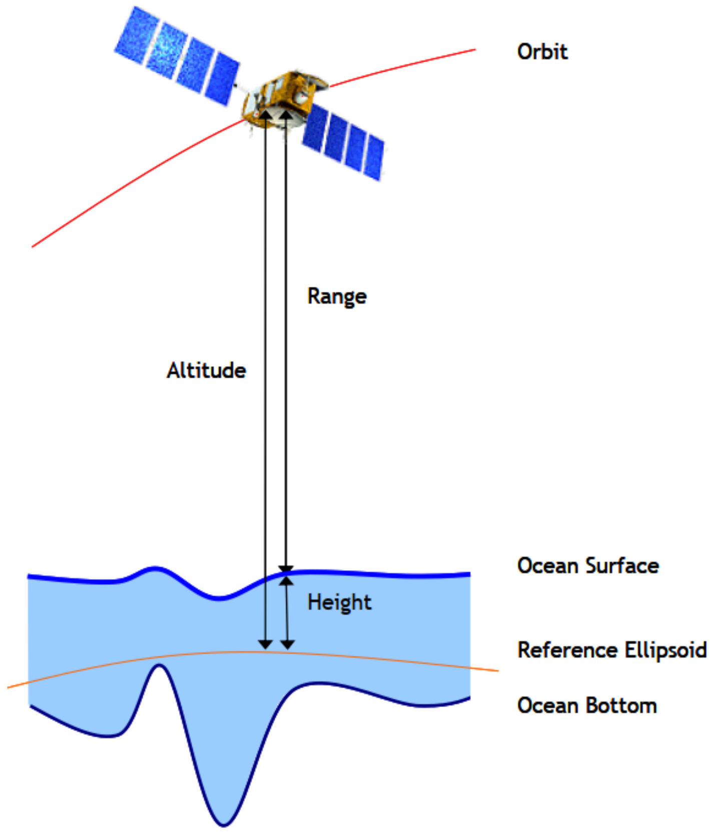

Figure 1: *Altimetric distances - the relationship between altitude, range, and height (Credit: Cipollini et al., 2014) reproduced with the kind permission of the authors).*

To obtain the desired accuracy we first need precise knowledge of the satellite's position, achieved through the use of several positioning systems on board. Secondly, we need to amend the measurement to account for the slowing down of the radar pulse due to electrons in the ionosphere ('ionospheric' correction) and to gases and water vapour in the troposphere ('dry tropospheric' and 'wet tropospheric' correction). All these can be corrected either through the use of ancillary measurements or the use of models. Thirdly, waves on the ocean's surface are not perfectly sinusoidal. The radar returns from troughs are typically stronger than those from crests. This can result in range overestimation due to sea state ('sea state bias'), which also needs to be adjusted for. This is normally achieved through the use of empirical models. Obtaining sea surface height estimates using altimetry thus requires a lot of factors to be taken into account, termed "corrections" or "adjustments". These are summed to yield the raw range estimate, in addition to more specialised processing, before the data can be deemed usable.

A final complication may arise depending on what component of the sea surface height we are interested in for our application. For example, if the signal due to currents is required, then we need to remove the contribution due to tides and to high-frequency atmospheric signals. This can be achieved through the use of models. However, here it is worth noting that for some applications, such as the study of storm surges, correcting for tidal and high-frequency atmospheric signals may not be required, as those signals are an integral part of the Total Water Level Envelope (TWLE), which is often the main quantity of interest for monitoring and assessing impacts.

1.1.1 The Altimetry Waveform - your key to understanding coastal altimetry

One key fundamental concept to understand when using coastal altimetry products, is that of the "waveform". This concept forms the bedrock on which coastal altimetry advances in signal processing are based. Radar altimeters operate on the basis of the satellite sensor instrument aiming a pulse of electromagnetic (EM) radiation towards an object (in this case the Earth's surface). This expanding arc of EM radiation is not flat, but curved, meaning the front of the arc interacts with the object before other areas of the arc (see Figure 2). Furthermore, the arc of EM radiation has a (minuscule) thickness, the transmitted pulse length (*tau*). This means that while one of the arc is in the final moments of interacting with the object, nearby areas can be beginning their interaction. Figure 2 shows how the circular arc of EM radiation, strikes and then interacts with the objects surface. In this case, the object is a perfectly smooth ocean surface, with the sensor at nadir, perfectly positioned to recapture any reflected radiation. The reflected EM radiation adopts the same arc form, however with differences following its interaction with the ocean surface, and a resulting differential in the power measured by the altimetry sensor upon the return of the arc to the sensor position.

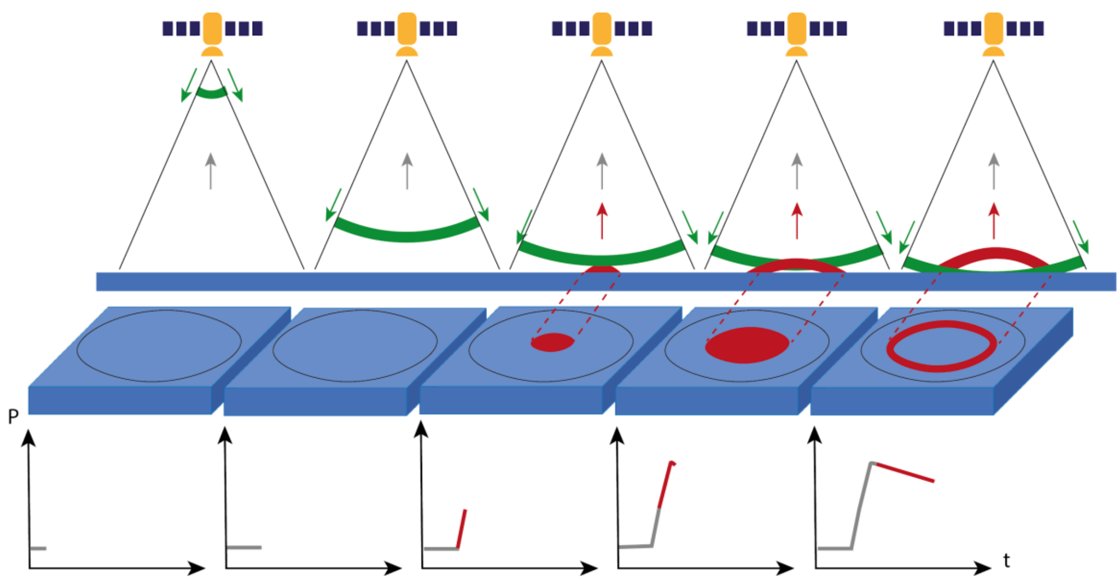

Figure 2: *Understanding how an altimetry waveform is obtained from a single radar pulse. From left to right is a timeline of a radar pulse from a nadir positioned radar sensor (top), its interaction footprint with the ocean surface (middle), and the resulting plot (waveform) of power versus time (bottom). The curved front of the radar pulse causes different parts of the pulse to interact, and bounce back from the ocean surface at different times. This gives the characteristic peak in the altimetry waveform, which is exploited by coastal altimetry processing (adapted from CNES, 2020). Note that the shape of the decline in the altimetry waveform is affected by the weighting operated by the antenna pattern (gain decreases from nadir to the border of the antenna).*

When we graph the power of the measured radiation against time from the generation of the radar pulse, we can see the power measured is not homogeneous (Figure 2). This graph (plot) is the pulses **waveform**. The interaction with the ocean's surface has produced a varying power reading over time, with the maximum reading produced when the largest volume of the EM arc was interacting with the ocean surface. If T_0 is the time of pulse generation, we can effectively identify the time at which the pulse struck the ocean surface using the peak of the plotted power over time. After this peak, the power measured features a characteristic decline (the trailing edge shown in Figure 3) which is influenced by the gain of the antenna.

When the pulse limited circle is fully established, the power received from the annuli (the expanding interaction circle) would remain constant if it were not for the reduction in power contributions at the borders due to the antenna itself, and its positioning. For each pulse generated, a resulting waveform is plotted from the returning signal measurements. Note that altimetry signals in Ku/Ka Band have a bandwidth (B) of 320-350MHz. This dictates a resolution of approximately 0.5 m in the direction of pulse propagation (known as range resolution). The example above is for a smooth ocean surface and a sensor positioned at nadir (which rarely exists as there is a high change due to antenna mis-pointing for example). A surface can be considered flat when its roughness is way below the range resolution (c*tau/2 or c/2*B, where 'c' is the speed of light) and all surface scatterers respond at the same time (i.e. in the same range resolution cell). The range resolution dictates the sampling of the waveform constructed at the receiver (i.e. the number of bins over which the waveform is constructed, see 'Bin Number' in Figure 3). The dimension of the footprint represented in Figure 2 is what is usually referred to as the resolution of an altimeter. The standard technology on which most of the radar altimeters are based (until recently) is characterised by a radius of the circular footprint (on the order of about 2-12 km). This radius changes depending on the wave conditions (the so-called "sea-state"). The newest altimeters, based on the Delay-Doppler technology, are instead characterised by a rectangular footprint with an along-track resolution of about 300m (which is also independent of the sea state), while the across-track footprint remains the same as the previous case. There are also subtle differences between altimetry waveforms collected from Low Resolution Mode (LRM) instruments, and those Doppler-based measurements gathered using Synthetic Aperture Radar (Figure 3).

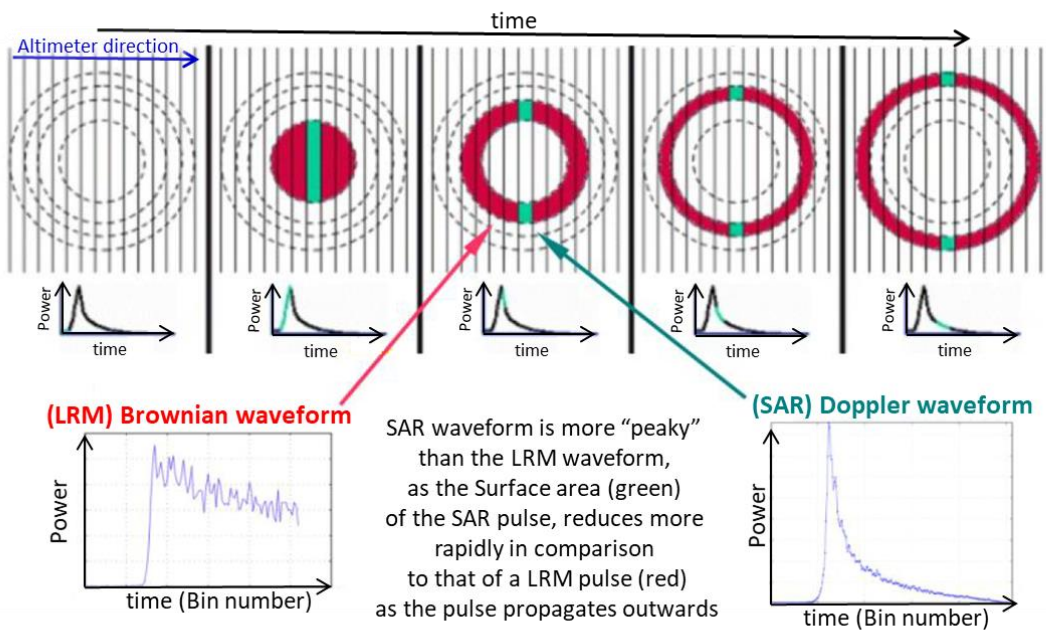

Figure 3: *Differences in waveform shape, between Brownian waveforms (acquired using LRM instruments), and Doppler waveforms (acquired using SAR instruments). The figure shows how the area of a SAR-based pulse interacting with the footprint area (green) gets smaller as it propagates outwards, while the footprint area remains constant with a more traditional LRM-based pulse (red). This results with a more "peaky" SAR-based waveform, characterised by a more consolidated, higher peak in power (i.e. increased signal-to-noise ratio) at the start of the waveform. Adapted with kind permission from Rosmorduc et al. (2011)[3].*

[3] An excellent and comprehensive introduction to radar altimetry can be found in Rosmorduc et al. (2011), available at: https://www.researchgate.net/publication/286440946_Radar_Altimetry_Tutorial [last accessed 25th January, 2021].

Understanding how the waveform is produced, through the nature of its interaction with surfaces, allows us to tease apart the waveform signal, using it to identify how rough the ocean surface is, or how high the waves on its surface area are. We achieve this by quantifying different aspects of the waveform which summarise the waveform's characteristics in numerical form for us to use (Figure 4). For more comprehensive instructional information on how the waveform characteristics are exploited for ocean sciences (and terrestrial sciences) see the AVISO website on Altimetry, operated by CNES (CNES, 2020), and the dedicated tutorial on Radar Altimetry produced by Rosmorduc et al. (2011).

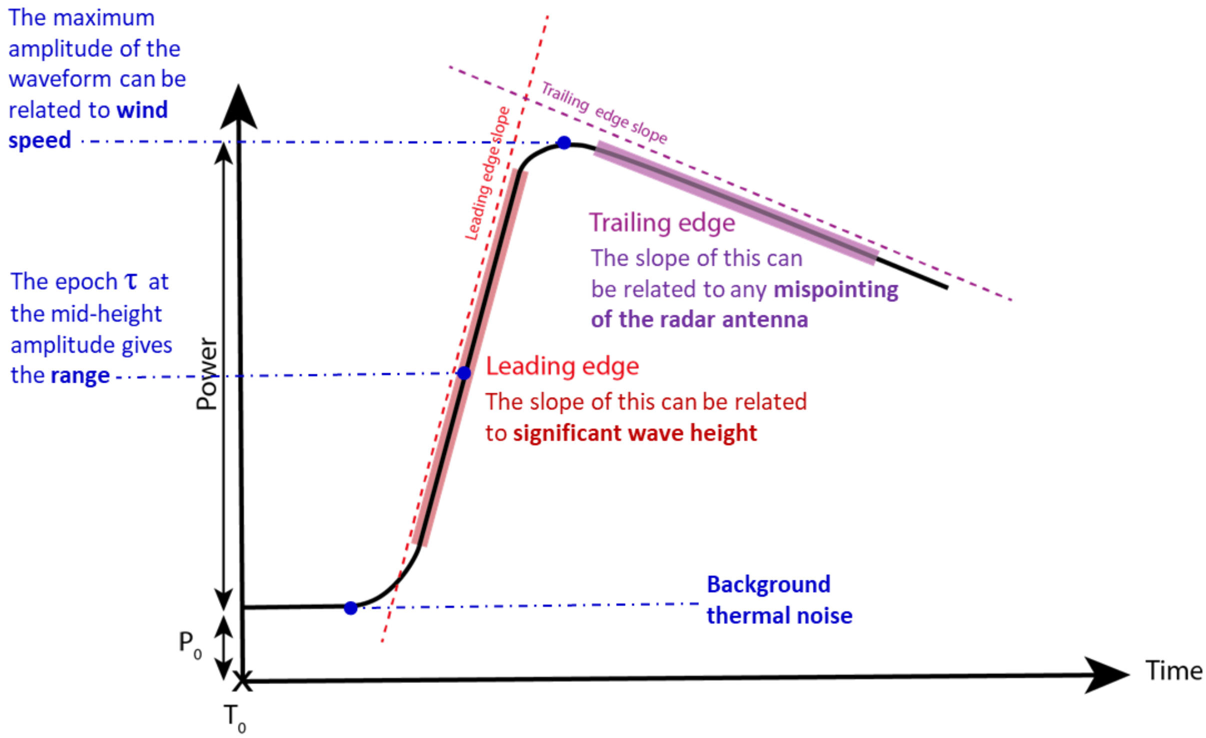

Figure 4: *An idealised waveform from a single radar pulse when plotted as power measured at the radar sensor over time. Key terminology is also included such as the leading edge and leading edge slope, two aspects which are essential for the field of coastal altimetry*[4]*. P_0 is the background noise received at the antennae, and T_0 is the time the pulse is emitted towards the Earth's surface. Note the time lag between T_0 and the increase in power. This is the time taken for the pulse generated at T_0 to travel to the surface, interact with it, and reach back to be measured at the sensor. The figure also shows the origins of other parameters from the waveform, which are applicable to altimetry, such as the range of the satellite sensor, the degree of antenna mis-pointing which should be accounted for, or to ocean sciences, such as significant wave heights in the pulse footprint, or wind speed estimates. An essential quantity to also know is the level of background thermal noise, which is also evident in the waveform.*

[4] *Adapted from information on* https://www.aviso.altimetry.fr/en/techniques/altimetry.html [accessed 21st December 2020]

1.1.2 “Along-track” and “Gridded” data

Two terms which often confuse new users of altimetry data, are ‘along-track’, and ‘gridded’. To understand this, remember that each pulse produces a waveform and sea-level estimate a single radar footprint. As the next pulse is produced along the satellites track, another waveform is produced, with another sea-level estimate along a track over the Earth’s surface. For delivery, these measurements are collated as a series of measurements, which when visualised (Figure 5) form a track, hence along-track data. The waveforms are typically delivered at a posting rate (the rate at which the waveforms are averaged and downlinked) of 20-Hz. As we estimate one sea level value for each waveform, a 20-Hz posting rate corresponds to obtaining a sea level measurement every ~300m along a satellite track. For certain users, these along-track data are the data of interest. However, for others, a more spatially comprehensive product is required. This is delivered as gridded data (Figure 6), integrating multiple altimeter tracks from the same sensor, or multiple sensors (in which case a multi-mission cross-calibration estimate is required) to produce a more spatially comprehensive gridded product to users. Note that while both SAR- and LRM-derived waveforms can be posted at 20Hz, this does not mean their data are available at the same spatial resolution. LRM-derived along-track data are available at spatial resolutions of between 2 and 12 km. Meanwhile SAR-derived along-track data can be processed to yield usable data at spatial resolutions of ~300m.

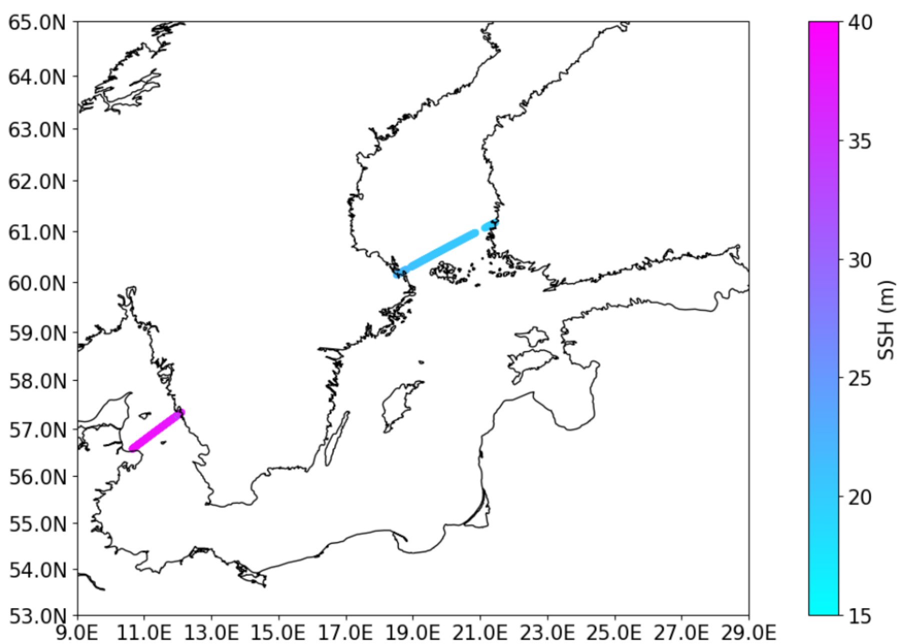

Figure 5: *A single along-track dataset of Sea Surface Height measurements from the Jason-1 sensor, over the Baltic Sea. The single line is composed of a series of point measurements arranged linearly along the path of the satellite’s transit. This visualisation was made using the python script provided in this product handbook.*

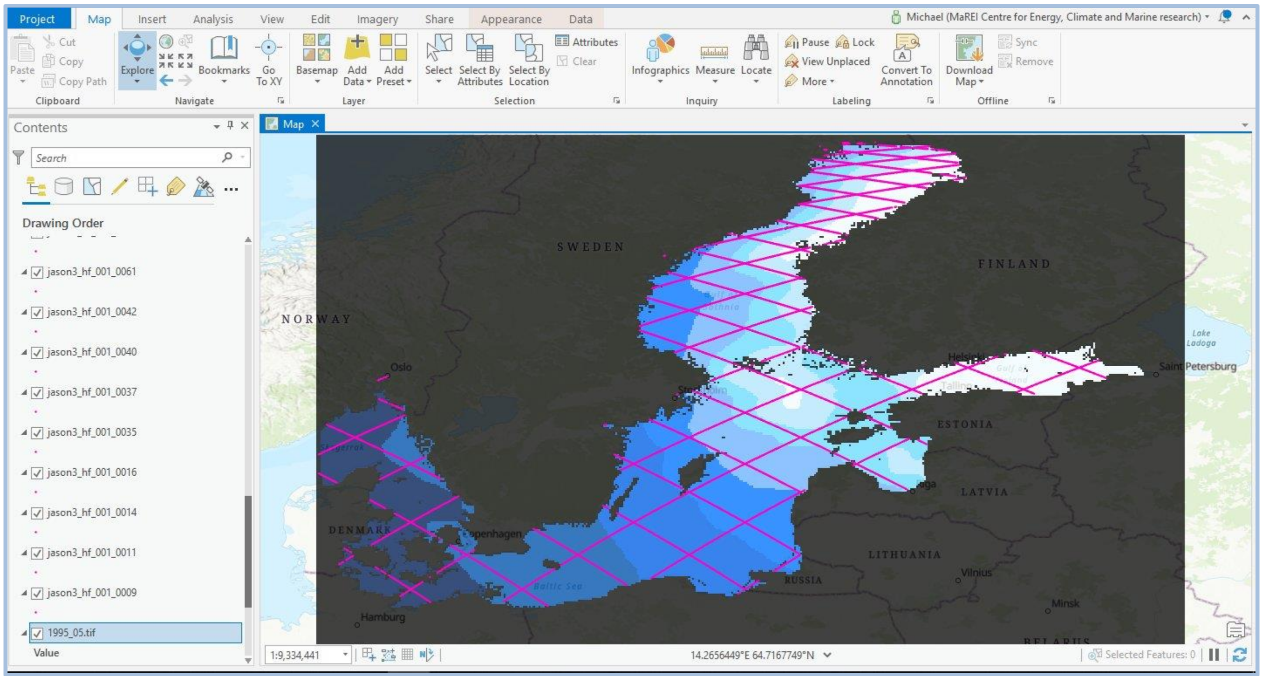

Figure 6: *Along-track versus gridded datasets, showing a GIS-workspace view of a number of along-track altimetry datasets over the Baltic Sea, overlying a gridded sea-level product produced using the Baltic SEAL gridding procedure. Visualisation done in ESRI ArcPro software.*

1.2 Issues and opportunities for altimetry in the Baltic Sea

Satellite altimeters have consistently been gathering measurements of the Earth's oceans for almost 30 years, with an excellent degree of accuracy (Figure 7). See Stammer and Cazenave (2018) for an interesting overview of the development of Altimetry, and some notable successes. In spite of these early successes, the use of satellite altimetry at high latitudes and coastal regions is limited by: (i) the presence of seasonal sea ice coverage, and (ii) the proximity of the measurement to the coast. Improvements in technology (such as the advent of Delay-Doppler, or SAR, altimetry), signal processing (retracking), sea-ice classification methods, and advances in geophysical corrections (wet tropospheric correction, sea state bias) have made regional-scale exploitation of satellite altimetry increasingly possible. However, exploring the advantages of these developments in a region such as the Baltic Sea, which strongly features these limiting conditions, was necessary to advance potential uses. These efforts could improve product quality, and in particular, product applicability to high latitude and coastal regions.

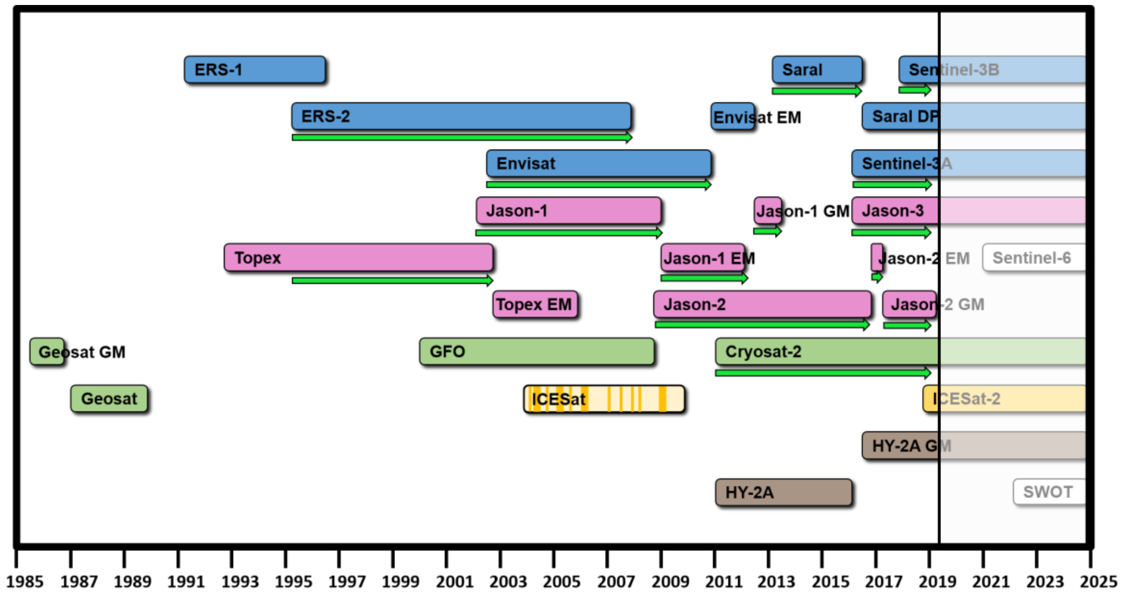

Figure 7: *Satellite missions featuring altimetry sensors, which have gathered measurements of the ocean's surface, and their operational timeframes. Satellite missions whose measurements have been incorporated into the products described in this handbook are highlighted with a green arrow.*

The semi-enclosed Baltic Sea features seasonal coverage of sea-ice in the northern and coastal regions, and complex jagged coastlines with a huge number of small islands. However, as a semi-enclosed sea with a considerable extent, the Baltic Sea features a much-reduced tidal signal, both open- and coastal- waters, and an extensive multi-national network of tide-gauges. These factors maximised opportunities to drive improvements in sea-level estimations from altimetry measurements, for coastal, and seasonal-ice regions. These improvements were explored under the remit of the ESA Baltic SEAL project, with the output products described in this document.

1.2.1 Opportunities to enhance altimetry use in areas with complex coastlines

The principle of radar altimetry, upon which the open ocean waveform models are based, implies that the illuminated area has homogenous backscatter characteristics. However, this is not often true in the coastal zone. First of all, land may fall within a radar footprint. Land can have a different elevation and a different backscatter with respect to the ocean. This results in the intrusion of land returns in the energy being reflected from the coastal waters back to the satellite sensor (Figure 8). A similar effect happens when land sheltering coastal waters from winds, or coastal upwelling fronts, produce areas of different sea roughness within the altimeter footprint. Processing specifications tuned for water surface measurements will exhibit excessive measurement values.

Before the advent of coastal altimetry, such measurements would be disregarded as poor data, effectively identified as useless. However, through the use of a process known as ***retracking***, and a clear understanding of the altimetry waveform, justifiable measurements from locations ever closer to the coast are increasingly possible. For less complex coastlines, this allows a measurement to be obtained closer to the mainland. Unfortunately, coastlines are rarely so simple, with the ocean often extending around islands, peninsulas, headlands, and into bays, harbours and lagoons. Understanding the impact of these features on the waveforms obtained using altimetry, is key to obtaining meaningful information from waveforms collected with land-contamination.

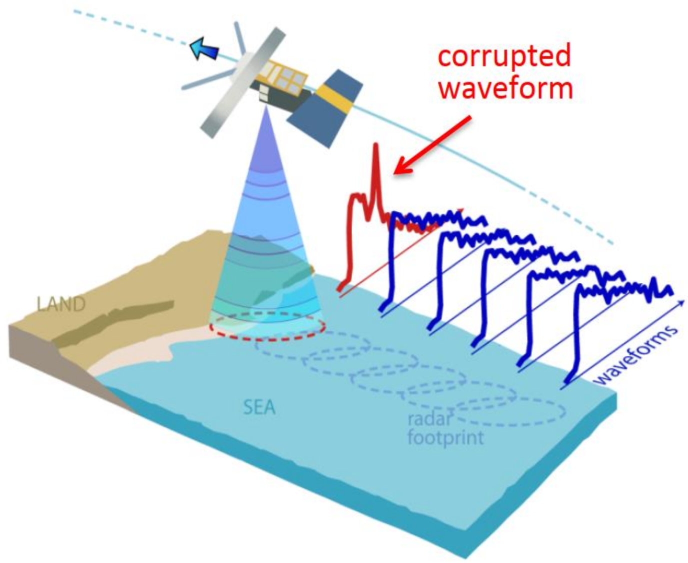

Figure 8: *An illustration of wave form corruption by land surfaces within the radar footprint, which occurs as the altimeter measures ever closer to the coast (Credit: Cipollini et al., 2014, reproduced with the kind permission of the authors).*

Such enhanced knowledge underpins the ALES+ retracker algorithm (Passaro et al., 2018b). For the Baltic SEAL products, there was an opportunity to test these novel retracker approaches, in areas with less tidal influence, and with a range of simpler and more complex coastlines. This led to improvements in the retracker tuning, which can now be applied to other regions of the globe.

1.2.2 Exploiting sea-ice leads to measure sea level in sea-ice areas

Sea-ice effectively prevents us from obtaining high quality measurements of sea level. The ice is in the way, extends below the ocean surface, and often does not have a smooth and level surface. However, where the sea ice splinters or fractures, the sea beneath can be exposed, and rises to fill the gap at a level equating to the area's sea level. This presents an opportunity to observe and measure the water level.

These splinters, or horizontal fracture lines, in the ice covering are known as leads, and can extend for kilometers across the sea-ice. However, they are bounded on either side by hard ice, and rarely are so wide as to allow for an uncontaminated radar footprint to be acquired, and yield an immediately usable sea level measurement. This provides an opportunity for the ALES+ algorithm (Passaro et al., 2018b) to contribute, building on its ability to use only a part of the waveform and to fit waveforms that are very peaky (since the leads often be considered as a mirror-like target), to extract a meaningful sea-level estimate. Such an opportunity can be only exploited if a dedicated algorithm is developed to spot the leads among the sea ice, an methodology for which has been developed by Müller et al. (2017). This advancement in processing is overviewed further below, but at this stage, it is important to note that sea level measurements can be obtained from sea-ice covered areas using altimeters, if there are sea-ice leads present, using the more advanced retracking algorithms and our increasing understanding of the waveform.

1.2.3 Enhancing retracking processes

Oceanographers are usually interested in subtracting a mean sea surface (MSS) from the SSH to obtain sea level anomalies. As recently as 2019, coastal altimetry studies still rely on MSS models computed using observations that are not optimised for the coast, rely heavily on interpolation with open ocean values, and are not consistent with the SSH dataset. Similarly, the majority of the newer retracking solutions do not provide a corresponding correction for the Sea State Bias (SSB). This is currently one of the largest sources of uncertainty linked with the altimetric signal (Andersen and Scharoo, 2010) and is linked with both the signal processing of the radar echo and the physics of the measurement.

The launch of the new Delay-Doppler (DD) instruments (Sentinel-3 and Cryosat-2) presents one of the most potentially impactful recent innovations for the field of coastal altimetry. SSH from DD instruments is generally more precise and reliable in the coastal zone, when compared to previous standard low resolution mode (LRM) altimetry missions (Passaro et al., 2016). This improvement exists even without any specific coastal retracker (see Figure 9; Passaro et al., 2016), of which the Adaptive Leading Edge Subwaveform retracker (ALES) is a key example of retrackers developed specifically to cater for coastal zone measurements. Figure 9 shows the noise of the altimeter estimations. This can be computed (as in the figure) by comparing many consecutive 20-Hz sea level measurements, since a change of sea level over only 300 m (if corrected for tides) cannot be considered physical. Note that the ***subwaveform*** term is used where only a part of the waveform is used and processed.

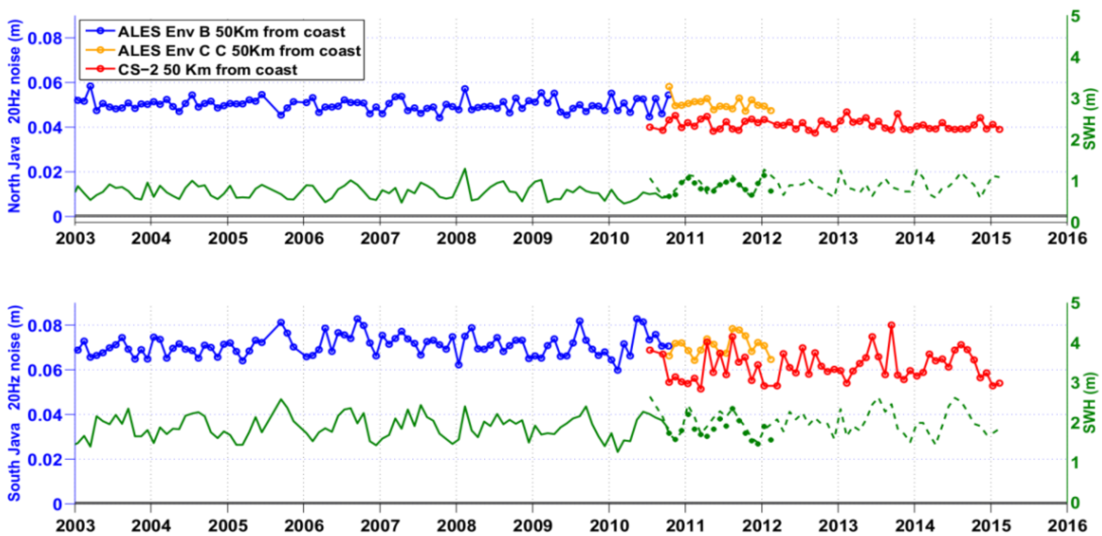

Figure 9: *Average 20-Hz noise of the Sea Level Anomaly (SLA) values South and North of the Java Island (Indonesian Throughflow region) within 50 km of the coast for the two missions phases of Envisat reprocessed with the ALES retracker (blue and orange) and the Delay-Doppler data of Cryosat-2 (red). Also shown is the average estimated significant wave height for each mission (green curves). Adapted from Passaro et al. (2016) with permission.*

ALES (Passaro et al., 2014) was designed to improve the detection of sea level in the coastal zone by overcoming the difficulties in retrieving the information from contaminated radar waveforms. This contamination typically arises from land existing in the radar footprint, or as a result of heterogeneity in sea state. ALES operates by fitting only that portion of the waveform where information about sea level is captured, i.e. the leading edge of the signal (Figure 4). The width of the subwaveform (a particularly useful subsection of the waveform) is adapted depending on the sea state, in order to produce estimations that have noise performances similar to those recorded in the Sensor Geophysical Data Records (SGDR) products for the open ocean.

Passaro et al. (2014) and Passaro et al. (2015) report on extensive investigations into the validity of the ALES approach, comparing ALES sea level measurements with tide gauge data. They report the ALES altimetry product has consistently increased the quality and the quantity of altimetry measurements in the coastal ocean. It has been validated with respect to in-situ data in several regions, showing constant improvements in terms of accuracy when compared to the standards. For example, comparing sea level measurements along a track from Jason-1 altimeter with the Trieste TG at the closest location (~7.5 km from the coast), the ALES time series had a correlation coefficient of 0.93 as opposed to 0.60 of the SGDR product.

More recently, ALES has been refined further, to produce the ALES+ algorithm (Passaro et al., 2018b), as a result of a polar oceans focus through the ESA Sea Level CCI initiative[5]. This refined algorithm was applied to data from ERS-2 and Envisat missions, and has expanded the retracking potential of the ALES algorithm by enabling more flexibility to trailing edge fitting of the signal (Figure 10). This refinement effectively makes ALES+ useful for extracting meaningful information from signals acquired over open-ocean, coastal zones, and also exposed water in sea ice leads.

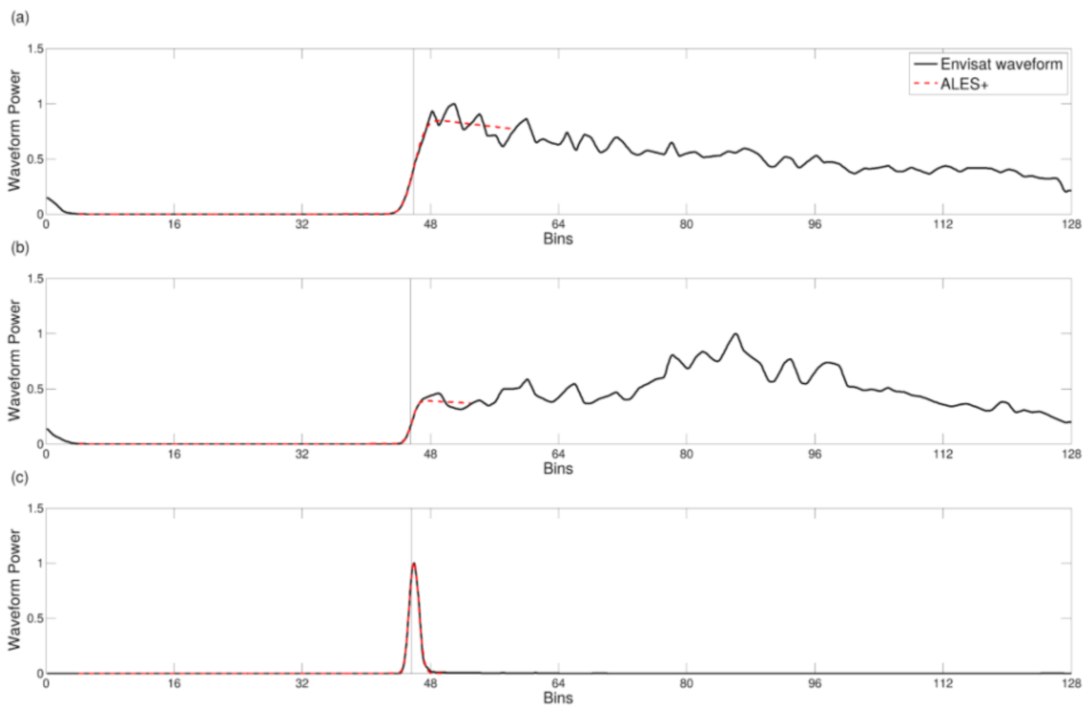

Figure 10: *Three examples of Envisat waveforms fitted using the ALES+ algorithm. Waveforms have been acquired from (a) the open ocean, (b) the coastal zone, and (c) from exposed water in a sea ice lead. Adapted with permission from Passaro et al., 2018b).*

The Baltic SEAL products outlined here contain an extension of the ALES+ algorithm, implemented on all LRM missions. Moreover, with the latest launches of Delay/Doppler (DD) altimeters under the Cryosat and Sentinel programmes, the datasets outlined in this manual expand the range of datasets processed using ALES+ SAR (a version of ALES+ dedicated to DD missions) which are available to the user.

[5] ESA Sea Level Climate Change initiative - http://www.esa-sealevel-cci.org

1.3 Altimetry missions now available through Baltic SEAL

The full range of mission data now processed using ALES+, and made available for the Baltic Sea region are shown in Table 1. Note that the products have been processed using ALES+ with the overall process enhancements detailed in the next section. The methodology applied to produce these is recorded in the project documentation, with overviews and reference links provided here. Furthermore, information on the product details and validation efforts are provided in this handbook, with more detailed documentation highlighted.

Table 1: *ALES+ processed Sea Level measurements available for users. Those products associated with a * were processed using ALES+ as part of the Baltic SEAL project.*

Altimetry Mission	**Timeframe**	**ALES+ processed Data available**
TOPEX/Poseidon	1995 - 2005	✗
ERS-2	1995 - 2010	✓
Envisat	2002 - 2012	✓
Jason-1	2001 - 2013	✓*
Jason-2	2008 - 2019	✓*
Alti-Ka	2013 - Present	✓*
CryoSat-2	2010 - Present	✓*
Sentinel-3A	2016 - Present	✓*
Sentinel-3B	2018 - Present	✓*
Jason-3	2016 - Present	✓*

2 Producing Sea Surface Height Products

The overall process from radar pulse to SSH estimate delivered as an along-track and/or a gridded product, is outlined in Figure 11. Also outlined are five enhancements which the Baltic SEAL project implemented to tailor the data produced to Baltic Sea regional stakeholders, and further develop best practice for coastal altimetry globally. These enhancements are presented here, and build on the overall pulse-to-SSH process (see Fu and Cazenave, 2001). Four of these enhancements relate to deriving the along-track dataset. The fifth specifically relates to producing the gridded product using the cross-calibrated along-track datasets.

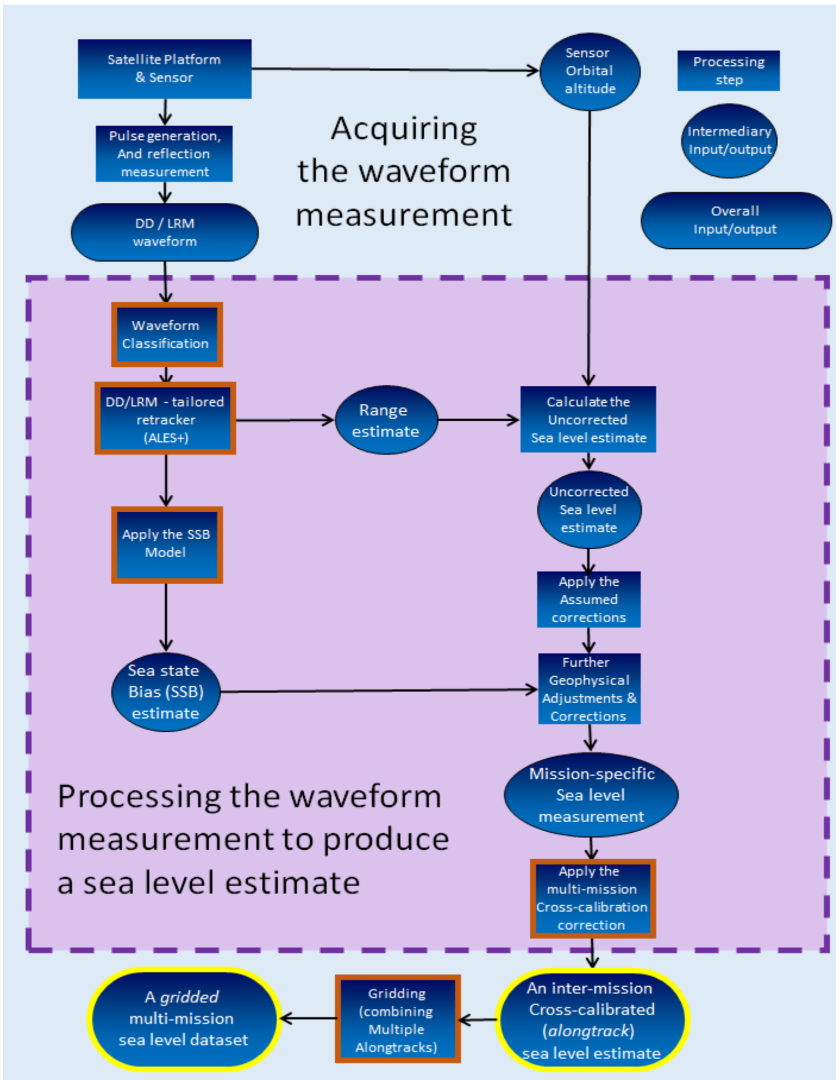

Figure 11: *From measurement to corrected sea level estimates delivered as along-track and gridded datasets. A simple flowchart of the origins of the waveform data, and how it has been processed to produce the Baltic SEAL estimate of sea level. Process steps which have been enhanced and tailored for use in Baltic Sea areas, are highlighted in orange. The two product options (individual along-track datasets, or composite gridded datasets), are outlined in yellow. Note that the sixth advance made in support of gridding (developing a new Mean Sea Surface model for the Baltic Sea for inclusion as a correction factor), is not depicted in this workflow.*

2.1 Enhancements to improve along-track sea level estimates

2.1.1 Unsupervised waveform classification to detect sea-ice, and sea-ice leads

Input	Output
Raw waveform dataset	Waveform with a classification tag (water, ice, unclassified), forming the basis of the sea-ice quality flags.

The shape of an altimeter radar waveform, is strongly affected by the reflecting surface (e.g. sea state). Very smooth and flat surfaces (leads, polynyas, calm water) produce single peaked waveforms. In contrast, rougher surface conditions lead to more noise and multi-peak waveforms (Figure 12). The unsupervised classification algorithm takes advantage of this and tries to find similarities or patterns among the waveforms related to the specific surface conditions. This is done without any pre-known or a-priori defined training datasets. Different waveform features (e.g. maximum power, waveform width, slope of the leading edge or noise of the radar echoes) are derived, and assigned to different surface types. The collection of features is also known by the feature space of the classification. Figure 11 shows examples of waveforms for Low-Resolution-Mode (LRM) and Delay-Doppler (DD) measurements, with respect to different surface conditions (open-ocean, sea-ice, and sea-ice leads) and scatterers. Major variability can be seen in the waveform power, width and noise level.

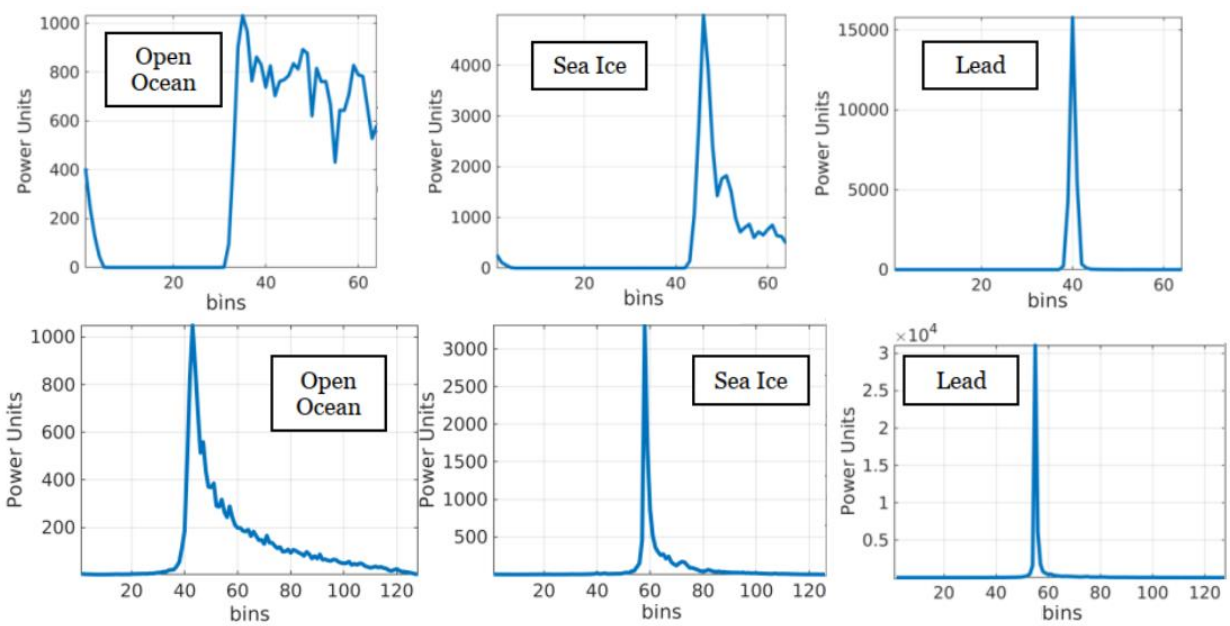

Figure 12: *Different waveform examples for ERS-2 (LRM altimeter, top row) and Sentinel-3A (DD-SAR Altimeter, bottom row) for three surface conditions (open ocean, sea-ice, and sea-ice leads).*

In general, the unsupervised classification consists of two principal stages. These are described in much greater detail in Müller et al. (2017) and Müller et al. (2020). Firstly, a reference library of waveforms for each sea-surface condition was established from a global training dataset. The majority of these waveforms are collected during the melting periods, to catch various ice types with strongly varying backscattering characteristics and shapes. An unsupervised (K-medoids) clustering algorithm was used to cluster the sample waveforms and set up a reference model. This was then followed by a manual classification (labelling) procedure to produce a defined, and clearly labelled reference set.

The second stage expanded this reference labelling to all remaining waveform data in the mission-specific collection of altimetry waveforms. Each one is labelled as water, ice, or undefined, before it enters the retracker stage. Note that this labelling forms the basis of the sea-ice quality flags (Figure 13). This allows the classified waveforms to be processed differently by the retracker step. It also enables each sea-level estimate to be delivered with an ice/water/undefined flag. This enables the user to remove retrievals corresponding to sea-ice reflections. Figure 13 demonstrates an example of this classification of points contained in an along-track, co-located with an image of sea ice and leads collected by an optical satellite.

Note that while the feature-based characterisations are applied to all input altimetry datasets from the range of satellite missions, slight differences in the computation, due to changed power adjustments, instrumental or specific dataset characteristics are possible. More information, regarding the feature computation can be found in Müller et al. (2017) should this be required.

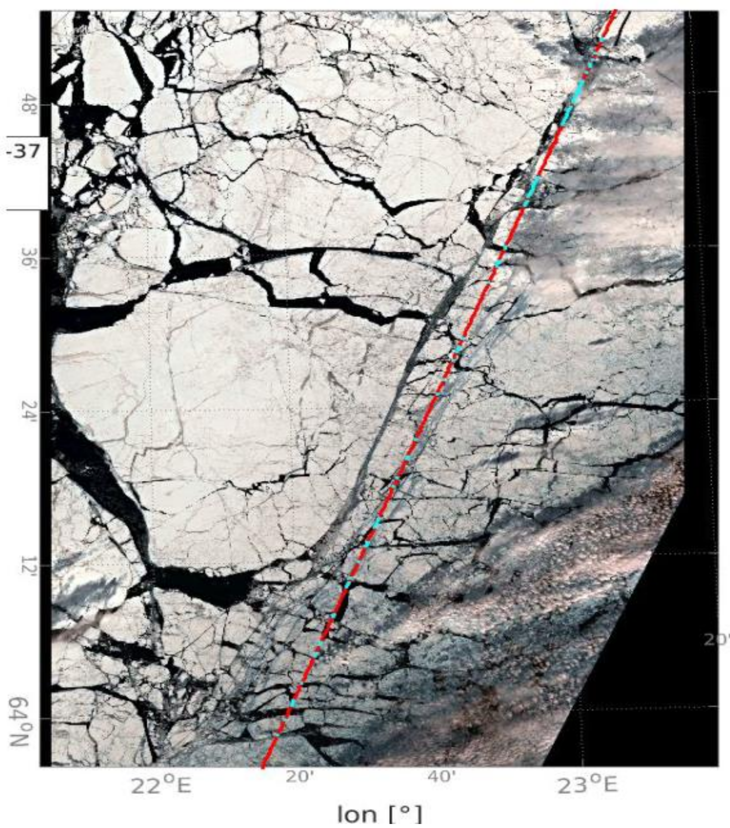

Figure 13: *A Sentinel-3A along-track of processed waveforms, tagged as ocean, and ice by the classification algorithm. The along-track overlays a Sentinel-2B optical image, with an acquisition time gap of 37 minutes. Sea-level estimates can be derived from waveforms identified as ocean, extending our capability to gather polar sea level estimates during the winter months.*

2.1.2 Retracking from LRM missions, and for DD altimetry.

Input	Output
Tagged waveform	Range estimate from the waveform

The Baltic SEAL project expanded the deployment of the ALES+ retracker onto a number of altimeter datasets acquired over the Baltic Sea. This retracker algorithm essentially derives an uncorrected estimate of the distance between the satellite and the sea surface (also known as a range estimate) from a raw altimetry waveform. When this quantity is subtracted from the satellite altitude, it corresponds to an uncorrected sea level estimate. ALES+ is based on the Brown-Hayne (BH) functional form (Brown, 1977; Hayne, 1980) that models the radar returns from the ocean to the satellite. It is important to remember that there are two primary types of altimeter - Delay Doppler (DD) and Low Resolution Mode (LRM) - each of which requires slightly different tailoring to the retracker algorithm, to obtain the most accurate estimates. In particular, a simplified version of the BH functional form is used by ALES+ in order to fit the DD waveforms. Since the full BH functional form is based on the principles behind the acquisition of an LRM waveforms, the use of ALES+ and the simplified BH to fit DD waveforms is purely empirical.

The ALES+ retracker extracts, and estimates a range estimate from, a subset of the entire altimetry waveform (known as a sub-waveform). A critical part of this sub-waveform is the leading edge, which contains the information on the range between satellite and reflecting surface. This leading edge must be correctly detected in all cases (sea-ice lead, and oceanic waveforms). See figure 14 for a visual overview of the difference in waveforms between the three classes. The second part of the sub-waveform consists of a segment of the trailing edge slope. Once extracted, the sub-waveform is retracked to obtain a range estimate.

Step 1: *Extracting the sub-waveform - the Leading Edge*

Firstly, the waveform is categorised as a (peaky) waveform, or a typical oceanic waveform. Note that waveforms can be peaky if the water surface is flat (e.g. over lakes), even if there is no sea-ice in the footprint, A Pulse Peakiness (PP) index is calculated from the waveform, and used to categorise the waveform as peaky, or oceanic. For LRM waveforms, those with a PP <1 are deemed to be oceanic in nature, whilst those with a PP> 1 are designated as "peaky". For DD waveforms, the thresholds are mission-dependent. For Cryosat-2, the oceanic threshold is also defined at PP<1. Meanwhile, Sentinel-3A and -3B have the oceanic threshold defined as PP<3.

The categorised (peaky/oceanic) waveform is then analysed to detect, and extract the leading edge segment. A more detailed description on the decision criteria for all four categories is described in the ESA Baltic SEAL Algorithm Theoretical Basis Document (Müller et al., 2020). Note that the only difference between LRM and DD cases are the checks done during the search for the leading edge. The subtle difference in processing is necessary because of the different signal-to-noise ratio of DD waveforms compared to LRM. Each leading edge is detected by identifying the "*Startgate*", where the power increases rapidly, and the "*Stopgate*" where the power plateaus before declining. These are then exploited in step 3.

Step 2: *Extracting the sub-waveform - the Trailing Edge*

The algorithm then defines the trailing edge of the waveform. This definition depends on two factors (i) the type of altimeter, and (ii) the Pulse Peakiness (PP) of the waveform, giving 4 options to calculate the trailing edge's slope (Table 2).

Table 2: *ALES+ Options for calculating the slope of the trailing edge.*

Altimeter/PP combination	Trailing edge slope ($c\xi$)
LRM altimeter Oceanic PP	$c\xi$ is already defined within the full Brown-Hayne model, as a function of the bandwidth and the antenna mispointing estimate.
LRM altimeter Peaky (non-standard) PP	$c\xi$ is externally estimated, fitting a full waveform using the simplified BH model to the entire waveform, and using the slope ($c\xi$) estimate for that model.
DD altimeter Oceanic PP	Here $c\xi$ cannot be physically defined by the full Brown-Hayne functional form and is assigned empirically as a fixed value.
DD altimeter Peaky (non-standard) PP	$c\xi$ is externally estimated, fitting a full waveform using the simplified BH model to the entire waveform, and using the slope ($c\xi$) estimate for that model.

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Step 3: *Sub-waveform retracking*

The final stage of retracking fits a model to the sub-waveform extracts (Figures 14 and 15), for which a tailored Stopgate formula is used.

The retracking for the LRM waveform consists of the the following steps:

1. A first retracking of the sub-waveform is implemented, restricted to the leading edge. This is essentially the first estimation of the First retracking of a sub-waveform restricted to the leading edge, i.e. first estimation of the Significant Wave Height (SWH).
2. The sub-waveform is extended, using a using a linear relationship between width of the sub-waveform and first estimation of the SWH
3. This extended sub-waveform is then retracked a second time, precisely estimating the Range, SWH, and sigma0.

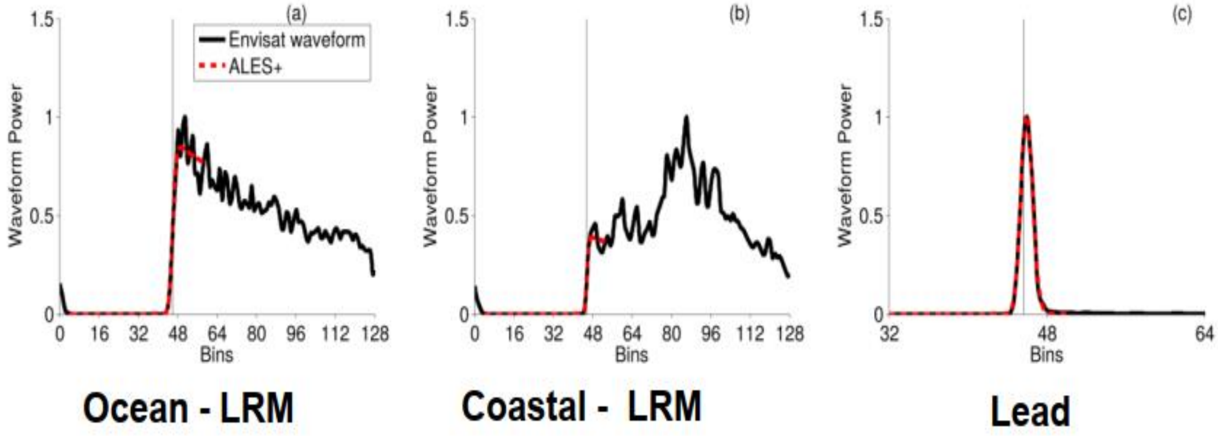

Figure 14: *Fitting the leading edge model (red) to LRM waveforms (black) acquired over areas of open-ocean, coastal waters, and a sea-ice leads.*

For DD waveforms, the sub-waveform is processed using a single retracking pass, precisely estimating the Range. In this case, no direct SWH estimation is possible; instead, the rising time of the leading edge, which is proportional to the SWH, is estimated.

For more information, see Passaro et al. (2018b).

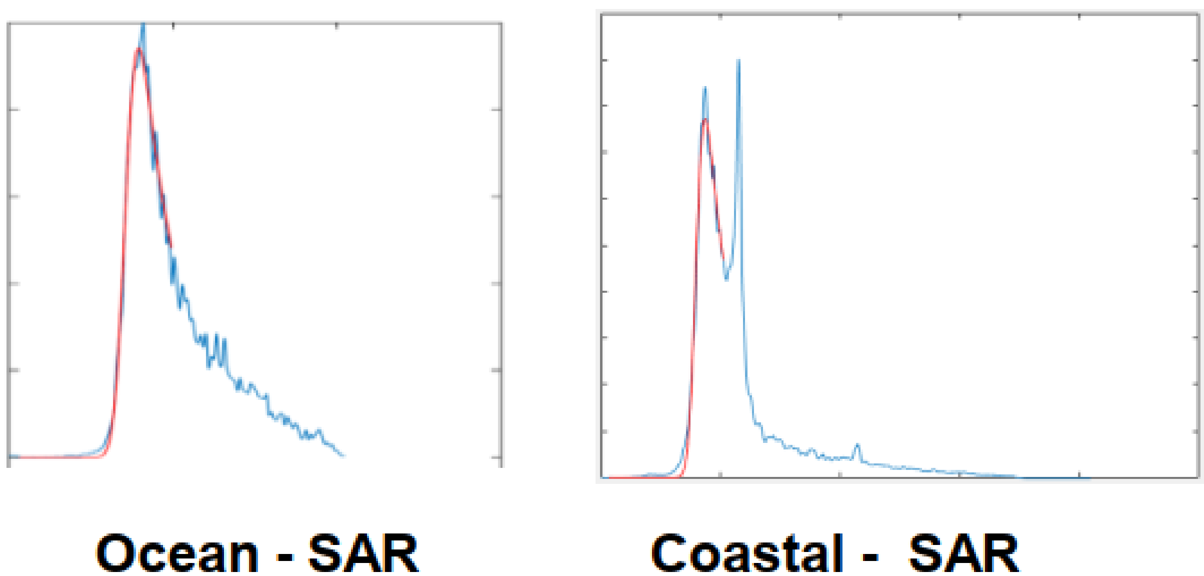

Figure 15: *Fitting the leading edge model (red) to DD waveforms (blue) acquired over areas of open-ocean, and coastal waters.*

2.1.3 Estimating Sea State Bias using a data-driven approach

Input	Output
Tagged waveform	Sea-State Bias Correction value for the waveform

Sea State Bias (SSB) is considered, the largest source of uncertainty linked with the altimetric signal (Pires et al., 2016). For Baltic SEAL products, the (SSB) correction, is estimated using the ALES+ retracked parameters. This correction is then applied to the along-track data being processed, as one of the range of geophysical corrections as shown in Figure 11.

The computation of the SSB model is based on an empirical relationship between residual errors in the sea level estimations, and parameters related to wave height and wind speed. Part of the correction is shaped by the physics of the waves, and will manifest itself in low frequency data averages, such as 1-Hz data (built by averaging 20 consecutive 20Hz sea level estimations). In addition, the SSB correction is affected by correlated errors between wave height, and sea level estimations. The procedure is described in detail in Passaro et al. (2018a). Two enhancements of this correction were implemented in the Baltic SEAL approach, which have demonstrably improved SSB estimations (Table 3). The first is the use of the estimated retracked parameters at high frequency (20Hz). This approach has proven more effective, as it reduces the correlated errors, and consequently reduces the noise of the sea level estimation. The second enhancement, applied for DD sensors, is the computation of a simple SSB model based on ALES+ SAR. For the details of the ALES+ SAR SSB model the reader is encouraged to refer to Müller et al. (2020).

The impact of the Baltic SEAL approach to deriving SSB from the data is shown in Table 3. The variance in SSH (as SSH has already been estimated) at the crossover before and after the application of the sea state bias correction is reported, together with the values reported by Gaspar et al. (1994), who estimated the coefficients of the Fu-Glazman model (a representation that depends on significant wave height and wind) on a global scale. The results of a high-rate sea state bias correction derived for the standard product of Jason-1 mission in the North Sea are also described by Passaro et al. (2018a). The variance explained by the sea state bias correction in ALES+ SAR is at the same level of the one explained by the high-rate sea state bias correction of Jason-1 and more than the one explained by Gaspar et al. (1994). This is expected, since Passaro et al. (2018a) demonstrated that the application of the SSB at high-rate is one way to reduce the correlated errors between the retracked parameters. Notably, the crossover variance from ALES+ SAR is lower than in Jason-1, which indicates the higher precision of SAR altimetry and of the ALES+ SAR retracking.

Table 3: *Assessing the impact of the Baltic SEAL approach to calculating SSB.*

Dataset	Crossover variance before SSB (cm^2)	Crossover variance after SSB (cm^2)	Variance explained
Gaspar et al. (1994) approach	127.7	120.4	6%
SGDR Jason-1 Mediterranean Sea	135.6	108.4	20%
ALES+ SAR Sentinel-3A	106.0	84.9	20%

2.1.4 Multi-mission Cross Calibration of altimetry-derived SSH estimates

Input	Output
Mission specific sea level estimate	Inter-mission-calibrated sea-level estimate, corrected to a common reference level

In order to ensure a consistent combination of all different altimetry missions could be made available, it was necessary to apply a cross-calibration correction. This enables users to be assured that their measurement of interest is corrected to a standard reference level, and they have a transparent value for that correction. Here, the global multi-mission crossover analysis (MMXO) approach (Bosch et al., 2014) was followed. This produced a harmonized dataset, and a consistent vertical reference for all the altimetry missions in the Baltic SEAL suite of products.

For all crossover locations (Figure 16), a radial correction for both involved observations were estimated by a least squares approach. This was based on SSH crossover differences without the application of any analytic error model. The corrections were later interpolated to all measurement points of all missions incorporated in the analysis. This method was first described by Bosch (2007) as discrete crossover analysis and later applied to different missions, among them Jason-2 (Dettmering and Bosch, 2010) and SARAL (Dettmering et al., 2015).

Müller et al. (2020) comprehensively describes the approach applied to the Baltic SEAL datasets. The approach relied on crossover points between altimeter tracks. A global dataset has been used to develop dual-satellite crossover differences in all combinations, with a crossover window (ΔT) < 2 days, using low frequency (1 Hz) data, and using only oceanic crossover points. This was inappropriate for deployment in the Baltic Sea, given the highly coastal nature of the basin, and the far smaller spatial extent (and likelihood of a crossover event occurring).

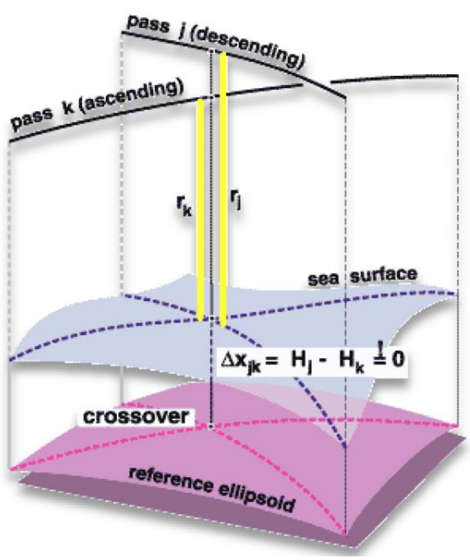

Figure 16: *An overview of the various aspects accounted for in extracting a MMXO value, using a crossover location to inter-calibrate altimetry-derived along-track SSH estimates.*

The approach developed for global calibration was therefore adapted for regional applications within this project. This comprises the following points:

1. The maximum acceptable time difference for the crossover computations was increased from two days to three days, in order to ensure enough crossover comparisons existed for the Baltic Sea region.
2. All crossover points used, including those from coastal areas.
3. High frequency (20 Hz) data are used instead of 1Hz data, for the computation of crossover differences. This was necessary in order to use retracked ALES ranges. This was achieved by changing the interpolation of along-track heights to crossover locations from point-wise to distance-wise.
4. All missions were equally weighted. No Variance Component Estimation (VCE) was performed as the number of observations was too small to generate viable results. The weighting between crossover differences and consecutive differences was adapted in order to account for the smaller region.

A snapshot of the results of the MMXO is shown in Figure 17 and table 4. The reader can see how newer missions such as Jason-2 and Cryosat are referenced back to the original TOPEX Poseidon mission. This provides data users with an ever-increasing timeline for monitoring and exploring sea-level.

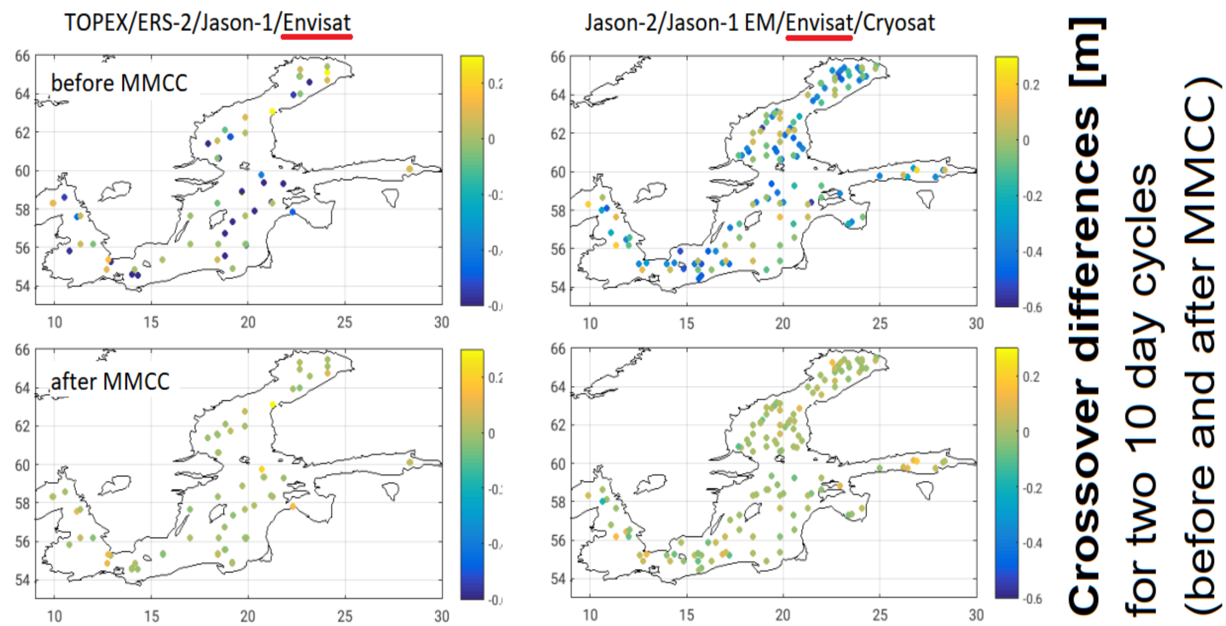

Figure 17: *The impact of overlaps in mission extents, and the application of a Multi-Mission Crossover Calibration (MMXO) exercise on altimetry data acquired over the Baltic Sea. Example of crossover differences for two 10-day periods (left and right) are shown giving an idea of the number and location of crossovers, and their height differences before and after the MMXO application.*

Table 4: *Mean Radial Errors estimated per mission. The ALES+ retracker was used in all cases except Topex and S3A SAMOSA (highlighted with an *).*

Mission	Mean Radial Errors (m)	Standard deviation in radial errors (m)	No. of crossover samples.
TOPEX (MGDR)*	0.000	0.37	14834
ERS-2	0.634	0.57	8745
Jason-1	0.125	0.38	22069
Jason-2	0.057	0.39	23986
Jason-3	0.034	0.39	12565
ENVISAT	0.500	0.071	10687
Cryosat-2 SAR	0.455	0.047	5769
Saral	-0.016	0.044	5641
Sentinel-3A	0.086	0.049	5769
Sentinel-3A SAMOSA*	0.035	0.035	4846
Sentinel-3B	0.091	0.050	1795

2.2 From along-track to gridded datasets

The Baltic SEAL along-track products were used to derive monthly gridded (raster) datasets of Sea Surface Height values. To enable this, a new Mean Sea Surface dataset, and an analysis of trends and annual cycles dataset, have been developed for the Baltic Sea region. This is in addition to a tailored gridding approach based upon an unstructured triangular mesh. These three aspects are described in detail here.

2.2.1 A new Mean Sea Surface for the Baltic Sea region.

A new Mean Sea Surface (MSS) for the Baltic Sea region has been developed using the along-track altimetry data processed under the Baltic SEAL project. It has been developed in the remove-compute-restore framework, a widely used technique in Geodesy. The **DTU15MSS** reference model (Andersen et al., 2016) was used to derive the Sea Level Anomaly (SLA) from Sea Surface Heights (SSH), containing ocean tide corrections by FES2014 (Lyard et al., 2020). Then, all the exact repeat track missions (from missions such as the Topex and Jason series, Sentinel series and others) are stacked to derive a mean profile along a specific pass. A new **long wavelength correction grid** for the DTU15MSS model was then developed by fitting harmonic regression curves, including a linear trending term. The long wavelength correction grid is subtracted from mean profiles. Following the crossover adjustment operation over the residual SLAs (i.e. the mean profiles), the data was gridded to derive the **short wavelength correction grid**. The final MSS was obtained by adding DTU15MSS, the long correction grid, and the short wavelength correction grid.

Note that the mean period of the new MSS for the Baltic Sea region is year 2003.0, which is identical to DTU15MSS and other global MSS models like CLS15MSS. It features a marked improvement with respect to the DTU15MSS model near complex coastal zones, the Danish Straits, the Gulf of Bothnia, and the Gulf of Riga. Coastal gaps do occur in the dataset, caused by a lack of altimetry data near the coast. This data absence is caused by land contamination or retracker failure. Using the ALES+ retracker has narrowed these coastal gaps, and enabled a more homogenous MSS of Baltic Sea to be derived.

In addition to the new MSS model, an associated interpolation error grid, and error grid mask are also distributed alongside the new MSS model. Note that the error grid map is not a measure of accuracy of the new MSS. It is simply an indicator of the data coverage around the computation grid node. For instance, the error grids tend to have larger values near the coastlines than open-ocean. The MSS dataset is distributed in NetCDF format, and is downloadable from the same ftp site as the along-track and gridded data described in this handbook. A full description of the global and variable attributes is available in the technical specifications section of this handbook. The sea level trends estimated from the Baltic Seal monthly gridded products are also provided along with the MSS model, both in the MSS dataset, and as a separate downloadable product. Users can therefore reference the MSS model to a particular year of interest by using the formula:

$$MSS_{Year} = MSS + ((Year - 2003.0) * Trend)$$

where *Trend* = Sea level trend at the grid node location

For example, a user who wants to reference the mean sea level to the year 2017.0, at a location where the trend is +0.00003 m/year (estimated from the Monthly grid products):

$$MSS_{2017} = MSS + ((2017.0 - 2003.0) * 0.00003)$$

2.2.2 A regional sea level trend and annual cycle dataset.

As part of developing the Mean Sea Surface model, a regional sea level trend and annual cycle product has been produced. This is downloadable as a netCDF file alongside the along-track, gridded, and Mean Sea Surface products.

Seasonal cycle, the linear trend and the parameter uncertainties have been estimated by fitting multi-year monthly averages (to approximate the seasonality), and a linear trend, to the data using a least squares approach. The annual cycle amplitude is defined as one-half of the difference of the largest and the lowest monthly average (the annual cycle uncertainty is thus based on the combined uncertainty of these individual averages). Trend uncertainties were derived while accounting for auto-correlated errors in the data using Maximum Likelihood Estimation (MLE). To identify the most appropriate noise model, fit of a variety of different stochastic noise model combinations was examined. Full details of these examinations are available in Abulaitijiang et al. (2021).

Figure 18 shows a sample of the information available in the *Sea Level Trend and Annual Cycle* dataset. The figure shows the map of sea level trends computed using this approach. Estimates of sea level trends derived from tide gauges (TG) are superimposed in circles along the coast. Further information on the analysis of these trends, including an examination of a number of sub-regions across the Baltic Sea region, are available in Abulaitijiang et al. (2021).

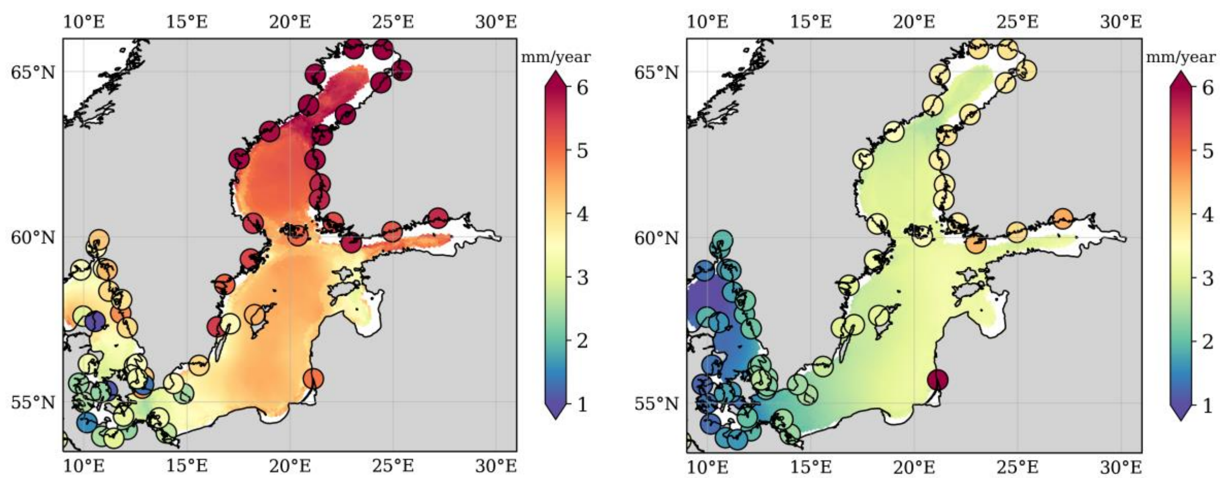

Figure 18: A sample of the information available in the Sea Level Trend and Annual Cycle product. (a) shows sea level trends from May 1995 to May 2018, computed using satellite-derived altimetry (grid points), while (b) shows corresponding uncertainties. Coastal circles show similar information extracted from tide gauge data covering the same period. Tide gauges data are corrected for the Glacial Isostatic Adjustment using the NKG2016 model. Uncertainties are reported as 95% confidence interval.

2.2.3 A monthly grid for the Baltic Sea region.

In order to generate monthly gridded sea surface heights, all along-track observations within a certain month, passing all along-track quality flagging criteria were input to a least-squares gridding approach (Koch, 1999). The basis of the gridding is an unstructured triangular mesh, characterized by near-equally spaced grid node distances (i.e. a geodesic polyhedron). The spatial resolution ranges from 7km to 8 km. Full details are available in Müller et al. (2020). The least-squares estimation is performed by fitting an inclined plane to observations located within a certain radius (i.e. cap-size) around each grid node. The following equation describes the inclined plane (h), which is defined as:

$$h(x, y) = c_0 + c_1 x + c_2 y$$

where c_0 defines the height, and
$c_{1,2}$ defines the slopes in the x- and y-direction respectively

The cap-size is set at 100 km. Each grid node spans a local Cartesian coordinate system (x, y), with the grid node as the origin. The least-squares fitting includes a Gaussian spatial weighting with a minimum weight of 50% at the cap-size edge (i.e. Grid_Gauss_Weighting_spatial_index = 1). Furthermore, in order to introduce *a-priori* uncertainty information into the least-square process, the Median Absolute Deviation (MAD) is computed per mission and month in a quiet Baltic Sea area (i.e. a region without known problematic topographic influences such as islands, complex coastlines etc.).

In order to obtain a more robust least-squares estimate, the along-track SSH observations undergo a flagging analysis, that highlights potentially untrustworthy data values. The along-track SSH observations are first reduced to sea level anomalies by subtracting the co-located Mean Sea Surface (MSS) value. Before fitting an inclined plane to the along-track observations, an iterative outlier analysis is performed. This highlights measurements which should be rejected on the basis of the least-squares adjustment, testing them against a 3-sigma criteria for statistical confidence. The iterative rejection analysis ceases, if no outliers can be detected. After the iterative analysis, a one-sided statistical T-Test is performed, based on the standardized residuals of the least-squares approach. It highlights any observations which exceed the boundary limit at the 99th percentile of the Student's t-distribution and should be rejected. Before saving the estimated monthly grids, the grid values are finally checked for coarse outliers against a 2m threshold. Again, identified values are highlighted as outliers for rejection. Highlighted outliers for rejection, are stored in memory, and factored into the quality flag determination. Afterwards, the MSS is re-added to restore the SLA values to SSH values (now accompanied by a quality flag).

2.3 Product Quality Flags, and their origins.

A set of quality flags are provided with each downloadable along-track and gridded dataset. They are are available in the netCDF file as Boolean (1/0) vectors, where 1 denotes a value of poor quality, and 0 denotes a value of good quality according to the quality flag analyses. Note that the quality flag values are saved as a double format, to enable the value "NAN" to be applied in the event of missing altimetry or correction data.

The **along-track quality flags** are generated by performing several outlier detection strategies. These can be broadly divided into a pre-gridding outlier detection analysis, and an outlier search within the gridding procedure itself. All identified outliers are kept in memory and integrated into the quality_flag (qf) NetCDF parameter per mission, and pass. An exception are the outliers detected during the gridding processing, which are additionally provided separately as a **gridded quality flag** (qf_grid). Note that the SSH value itself is not amended by the quality flagging procedures, only highlighted as potentially untrustworthy by an accompanying pair of quality flag values. Users can therefore identify and, if needs be, omit from their analysis, those along-track SSH values identified as untrustworthy by both the along-track quality flag analysis, and/or those highlighted as untrustworthy during the gridding process.

Along-track (pre-gridding) quality flags and outlier detection

Along-track observations are labeled as outliers, and accounted for in the quality flag as poor/bad quality values if:

- The Sea ice index detects sea-ice observations (Sea Ice Index is provided in the NetCDF),
- The value location is < 3km distance from the coast (Distance to coast value provided in the NetCDF),
- There is a >0.3 (LRM) and/or >0.1(SAR) retrack flag (retrack flag value provided in the NetCDF),
- There is a >2 meter difference between Mean Sea Surface and along-track sea surface heights,
- It has been flagged by the along-track filtering based on Median Absolute Deviation. *Description:* After removing already flagged data, by applying fixed defined thresholds, the along-track data are filtered using a moving median with 1 second window size. Each observation is tested against a 3 median absolute deviation (MAD) criteria (Sachs, 1984). New flagged observations are highlighted as poor quality, and incorporated into the quality flag vector. The moving median is applied to all passes, respectively.
- Enhanced sea-ice observation detection
  Description: In order to remove unrealistic Sea Surface Heights in the sea ice region, for example caused by thin ice, a second along-track outlier flagging only referring to sea ice conditions (>25% sea ice concentration) is implemented. Therefore, only sea level anomalies in the sea-ice area are tested against a 2-MAD (Sachs, 1984) criteria using the median of the entire pass as reference. Sea-ice areas are identified by using sea-ice concentration masks provided by the National Snow and Ice Data Center (NSIDC)[6].

[6] For more information on the NSIDC, see https://nsidc.org/ [last accessed 25th January, 2021]. To find out more about their work on sea-ice indices, see https://nsidc.org/data/seaice_index/ [last accessed 25th January, 2021]

Quality flags from gridding outlier detection

In addition to the along-track based outlier detection and quality flag determination, an additional outlier elimination is performed within the gridding process. In brief, the outlier flagging within the gridding process is composed of (i) an outlier detection based on a standard 3-sigma criteria, followed by (ii) an iterative outlier search based on standardized improvements and a T-Test environment. The gridding process returns flagged observations that are checked, by performing a standard Grubbs-Test (e.g. Grubbs, 1969) using already gridded sea level information in the vicinity of the observation. Further, more detailed information is available in Müller et al. (2020).

The grid flag (qf_grid) is saved separately for optional usage. It highlights whether or not the along-track estimate was considered good enough to be incorporated into the gridding process. However, the user must note that its value is also integrated into the overall quality flag (qf). qf_grid is effectively a subset of qf, enabling the user to isolate those SSH measurements which passed the along-track criteria, yet did not pass the pre-gridding screening. All quality flags consist of the value 1 (indicating poor/bad quality data), and 0 (indicating good quality data).

Post-gridding flag

Finally, in addition to the along-track and gridding outlier detections (and associated quality flags), the monthly gridded dataset contains an additional quality flag, provided in NetCDF attribute **qf_monthly_grid**. This flag is based on an analysis of the standard deviation of sea surface heights, which are combined to compute the value of an individual grid node. The value of a grid node is highlighted for rejection (i.e. considered as an outlier), when this standard deviation exceeds a specific threshold. Thus, the purpose of this procedure is to flag those values, which are derived from very noisy observations and potentially provide erroneous information of sea level. The threshold is set to the 90th percentile of all time-averages of ssh_std in the Baltic Sea, which is equal to ~4.252mm. An individual observation is highlighted as rejectable (flag=1), when the associated sea surface height standard deviation is larger than this threshold.

3 Product Validation

Validation efforts are comprehensively described in Rautiainen et al., (2020). This document presents a summary of the statistics produced to validate different stages of the algorithm development. These include:

- The results of the validation concerning the classification of the radar echoes in order to distinguish ice from open water;
- The main findings and statistics based on the comparison of the along-track raw high-rate dataset of sea level anomalies against tide gauge data, for each mission incorporated into the product suite, and
- The validation statistics for the multi-mission gridded dataset.

Users of the datasets are strongly encouraged to invest time in examining the validation results and approaches. A sample validation result for Sentinel-3A sea level data, extracted using the ALES+ processor is shown for the Rodvig validation site in Figure 19. The Sentinel-3A results across the range of validation sites is shown in Table 5. Note that these validation activities have been conducted for every mission integrated into the Baltic SEAL suite of products.

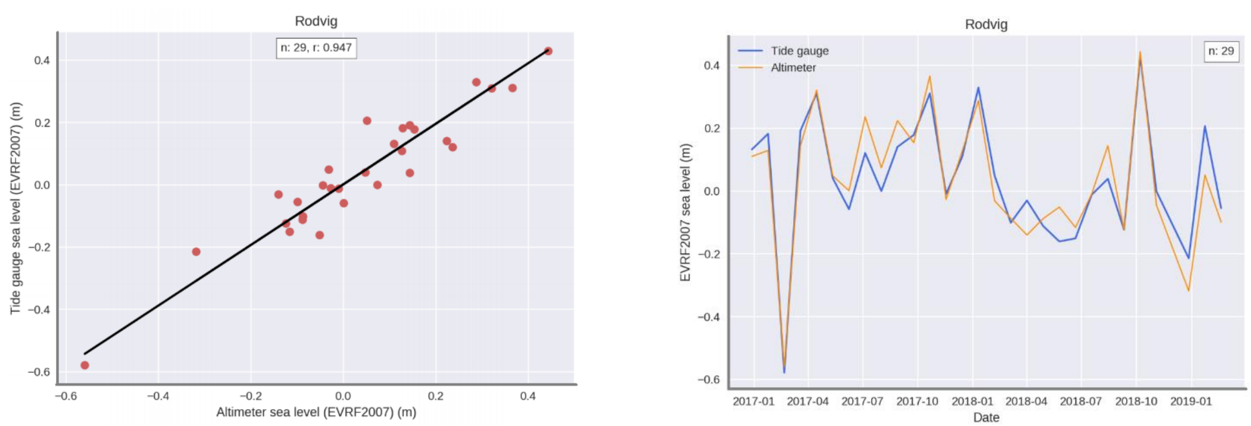

Figure 19: *Insights into the validation scatterplots (left) and time-series (right), derived for one of the Baltic Sea validation sites (Rodvig),when examining the Sentinel-3A-derived sea level estimates using the ALES+ processor. Extracted from Rautiainen et al. (2020).*

Table 5: *Along-track sea level validation results for the Sentinel-3A mission data processed using the ALES+ retracker. Matching tabulated validation detail is available for all Baltic SEAL processed missions, across a range of validation sites, in Rautiainen et al. (2020).*

Validation	Root Mean Square Error	r	No of samples
Bagenkop	0.05	0.95	28
Kalix-Storon	0.18	0.71	23
Rodvig	0.07	0.95	29

4 Technical Specifications

4.1 Along-track products

4.1.1 Format

The data are provided in NetCDF[7] format files. The file nomenclature is determined by the (i) altimetry mission, (ii) the satellite's repeat cycle, and (iii) the cycle's pass segment.

For example: X_hf_CCC_PPPP.nc ,where X substitutes the used high-frequent (hf) altimetry mission data (e.g. jason1_hf). CCC describes a 3-digit cycle number and PPPP designates the 4-digit pass number.

Please note: The order of cycles and passes might differ from the original files provided by the Agencies due to standardization and computational reasons.

4.1.2 Structure

The following list outlines all the included NetCDF attributes. Each attribute is associated with stored data, be it a measurement, a correction factor, a description etc.

Note that the same attribute structure exists for both the along-track and gridded datasets (due to them being from the same processing path). This has resulted in some of the along-track attributes being left blank, which may confuse the novice user.

Global Attributes

All files are provided with the following global attributes:

- The name of the file is provided.
  `product_name = "X_hf_CCC_PPPP.nc";`

- The project name and its website url are mentioned.
  ```
  institution = "ESA Baltic SEAL";
  creator_url = "http://balticseal.eu";
  ```

- The date and time of creation is specified.
  `creation_time = "DD-Mon-YYYY HH:MM:SS";`

- The name of the altimetry mission along with its cycle number and pass number are provided.
  ```
  mission = "X";
  cycle = "CCC";
  pass = "PPPP";
  ```

- The dataset version is specified.
  `version = "ESA Baltic SEAL Version 1"`

[7] For further information on NetCDF formats, there is an excellent introduction for beginners to NetCDF data use available at https://www.unidata.ucar.edu/software/netcdf/docs/netcdf_introduction.html **[last accessed 8th February, 2021]**

- Additional information about the product

```
summary = a short summary about the data attributes included in
the file
comment = additional information about the provided dataset
```

Variable Attributes

The variable attributes contained in an along-track dataset's netCDF file are outlined in Table 6.

Table 6: *Variable attributes contained in the along-track products. Aspects of the details columns are described in more detail in the next section (Metadata).*

Name	Details	Unit	Integrated into the given SSH Value calculation
lon*	Geographical longitude of high frequency observations	degrees	N/A
lat*	Geographical latitude of high frequency observations	degrees	N/A
time	Continuous time from 1985-01-01 00:00:00	days	N/A
ssh*	**Sea Surface height based on ALES+ retracker**	**meters**	**N/A**
ralt	Altimeter range retracked by ALES+	meters	Yes
ralterr	Fitting error on the leading edge of the normalised waveform	counts	Yes
eot11a	EOT11a ocean tide model correction	meters	No
got410	GOT4.10 ocean tide model correction	meters	No
fes2014	FES2014 ocean tide model correction	meters	No
tpxo8	TPXO8 ocean tide model correction	meters	No
sea_ice_index	Sea Ice Index by unsupervised open water detection	Water =[1] Non-Water=[0]	N/A
dac	Dynamic Atmosphere Correction	meters	Yes
distc	Distance to coast based on seavox_v16 coastlines	meters	N/A
qf	Quality Flag	bad=[1] good=[0]	N/A
qf_grid	Quality Flag based on gridding procedure (see	bad=[1] good=[0]	N/A

***** Geographical coordinates and sea surface heights refer to the TOPEX ellipsoid.

4.1.3 Metadata – a note on corrections

In order to provide sea surface heights (SSH) several corrections are applied:

$$SSH = H_{orbit} - (R + WT + DT + IONO + DAC + SET + PT + SSB + ROC)$$

H_{Orbit} is sensor-specific, reliant on the orbit height of its host satellite platform. Each of the others is defined in brief below, and the mission to which they are specifically applied is outlined in Table 7. A number of these are provided as variables in the provided along-track datasets, accompanying the SSH value.

Table 7: *Geophysical and atmospheric corrections integrated within the provided Sea Surface Height value, depending on the different missions.*

<table>
<tr><th>Corrections</th><th colspan="11">Missions</th></tr>
<tr><td></td><td>Topex Poseidon</td><td>Jason-1</td><td>Jason-2</td><td>Jason-3</td><td>ERS2</td><td>Envisat</td><td>SARAL</td><td>AltiKa</td><td>Cryosat 2</td><td>Sentinel 3A</td><td>Sentinel 3B</td></tr>
<tr><td>Altimeter range (R)</td><td>MGDR-B (TOPEX/Poseidon, 1993)</td><td colspan="10">ALES+ (Passaro et al., 2018b)</td></tr>
<tr><td>Wet Trop. (WT)</td><td colspan="3">GPD/GPD + (TOPEX/Poseidon, 1993)</td><td>VFM3 (Landskron and Böhm, 2018)</td><td colspan="2">GPD/GPD + (TOPEX/Poseidon, 1993)</td><td colspan="5">VFM3 (Landskron and Böhm, 2018)</td></tr>
<tr><td>Dry Trop. (DT)</td><td colspan="11">VMF3 (Landskron and Böhm, 2018)</td></tr>
<tr><td>Ionosphere (IONO)</td><td colspan="11">NOAA Ionosphere Climatology (NIC09) (Scharroo and Smith, 2010)</td></tr>
<tr><td>Dynamic Atmosphere Correction (DAC)</td><td colspan="11">DAC(inverse barometric(ECMWF),(MOG2D) HF) (Carrère and Lyard, 2003)</td></tr>
<tr><td>Solid Earth Tide (SET)</td><td colspan="11">IERS Conventions 2010 (Petit, G., Luzum, 2010)</td></tr>
<tr><td>Pole Tide (PT)</td><td colspan="11">IERS Conventions 2010 (Petit, G., Luzum, 2010)</td></tr>
<tr><td>Sea State Bias (SSB)</td><td>MGDR-B (TOPEX/Poseidon, 1993)</td><td colspan="10">ALES + (Passaro et al., 2018a)</td></tr>
<tr><td>Radial Orbit Errors (ROC)</td><td colspan="11">Multi-mission cross calibration (MMXO) Vers. 18 (Müller et al., 2020)</td></tr>
</table>

Altimeter range retracked by ALES+

TOPEX ranges are directly taken from MGDR-B data (TOPEX/Poseidon, 1993). All other missions ranges are retracted using the ALES+ processor.

Fitting error on the leading edge of the normalised waveform

An error estimate, given in counts, has been made by providing a fitting error on the leading edge. It is suggested to flag out observations with a fitting error higher than 0.3.

Sea State Bias (SSB) based on ALES+ processing

TOPEX sea state biases are directly taken from MGDR-B data (TOPEX/Poseidon, 1993). All other missions SSB are based on ALES+ processing (Passaro et al., 2018b).

GPD/GPD+ wet tropospheric correction (WTC)

Wet troposphere corrections are provided by GPD/GPD+ (Fernandes et al., 2015; Fernandes and Lázaro, 2016) and are used for sea surface height computation. In the event that there are entirely/or partly missing GPD data (e.g. as occurs with Jason-1 Geodetic Mission, Sentinel3-A/B, CryoSat-2, Jason-3, and SARAL/ALtiKa), the GPD correction is substituted using ERA-Interim based corrections obtained using the Vienna Mapping Functions Version 3 (Landskron and Böhm, 2018).

Ocean tide model correction

The correction values from four different Ocean Tide Models (Table 8) are included in the datasets. There is no separation between loading tide and ocean tide. Both loading and ocean tide corrections are summarised stored in a single value. No Ocean Tide correction is applied to the along-track SSH. The ESA Baltic SEAL team conducted an examination of the optimal tide models currently available to use. They recommend users use the FES2014 ocean and loading tide (Lyard et al., 2020)The others have been provided should the user wish to compare and contrast between the four.

Table 8: *Ocean tide models references*

Model	Reference
EOT11a	Savcenko et al. (2012); Savcenko and Bosch, (2012)
GOT4.10	Ray, (2013)
FES2014	Lyard et al. (2020)
TPXO8	Egbert and Erofeeva (2002)

Sea Ice Index by unsupervised open water detection

Sea-ice is flagged by an unsupervised classification algorithm described above. Open water areas are flagged to 1. Non-water regions are indicated by 0. The classification process is described in this handbook.

Dynamic Atmosphere Correction and inverse barometric correction

The Dynamic Atmosphere Correction is applied to all missions, which is a combination of low-frequency inverted barometric effects and the barotropic model MOG2D (Carrère and Lyard, 2003) including high-frequency changes of wind and pressure.

Distance to coast based on seavox_v16 coastlines

The SeaVoX Salt and Fresh Water Body Gazetteer[8] are used to provide distance to the coast.

Quality Flags in the along-track datasets

The along-track data product enables the usage of two quality flags. **qf** includes all outlier flagging (incl. gridding), which is applied to the along-track data. **qf_grid** includes only the outlier elimination performed in the gridding procedure. The quality flags include boolean values indicating good [0] and bad [1] measurements. Undefined values are possible, if a sea surface height computation is not possible.

[8] https://www.marineregions.org/gazetteer.php?p=details&id=23616 available at: https://repository.library.noaa.gov/view/noaa/10229 [last accessed 22nd Jan uary, 2021]

4.1.4 Introductory code for novices to explore along-track data

This code is a sample plot for users to plot a Baltic SEAL along-track dataset, using the Python programming language. It was developed Dr. M. Passaro and has been tested and annotated by Ms. E. Chalençon. Output plots (visualisations) are shown in Figures 20 and 21.

These codes were produced using python 3.8; The following packages have to be installed on your python: ***numpy***, ***scipy***, ***netCDF4***, ***matplotlib*** and ***cartopy***. You can install the packages using pip (for example "`pip install numpy`") or conda (for example "`conda install numpy`"). Note that in order to mask out points on land in the second code, the "***global-land-mask***" library is used and also has to be installed.

****Note: Cartopy** installation may be a bit complex as it has a lot of required dependencies. Using pre-built binaries can be a solution. They can be found at a variety of sources. Christoph Gohlke maintains unofficial Windows binaries (https://www.lfd.uci.edu/~gohlke/pythonlibs/). The correct version of the package of interest (ex: cp38 and win_amd64 is for Python 3.8 (64bits)) can be downloaded and installed by using "pip install" followed by the path of the .whl file which has just been downloaded (`pip install C:/some-dir/some-file.whl`).*

To obtain an easy to use copy of this code, go to www.balticseal.eu/outputs/ and download the suite of code packages.

CODE STARTS

```
# Importing the needed python library packages:
import netCDF4
import numpy as np
import cartopy as cart
from cartopy.mpl.ticker import LongitudeFormatter, LatitudeFormatter
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
from scipy.interpolate import griddata


 # Setting the inputs for your programme:
directory='C:/some-dir/' #The user should change the path to his .nc files' directory
filename='jason1_em_hf_262_0213.nc' #The user should change to the dataset file
S = netCDF4.Dataset(directory+filename)
lon = S.variables['lon'][:]
lat = S.variables['lat'][:]
ssh = S.variables['ssh'][:]
min_lat=53.0
max_lat=66.0
min_lon=9.0
max_lon=31.0

# Displaying the unstructured grid in a scatterplot:
```

```
fig = plt.plot()
plt.rcParams.update({'font.size': 15})
plt.plot
plt.rcParams["figure.figsize"] = (50,10) #Increase figure size
ax = plt.axes(projection=ccrs.Miller())
img=plt.scatter(lon, lat,
      c=ssh, s=20,
         cmap='cool', alpha=1,transform=ccrs.PlateCarree())
ax.coastlines(resolution='10m', color='black', linewidth=1)
ax.set_xticks(np.arange(min_lon,max_lon,2), crs=ccrs.PlateCarree())
ax.set_yticks(np.arange(min_lat,max_lat,1), crs=ccrs.PlateCarree())
lon_formatter = cart.mpl.ticker.LongitudeFormatter(number_format='.1f',
                                  degree_symbol='',
                                  dateline_direction_label=True)
lat_formatter = cart.mpl.ticker.LatitudeFormatter(number_format='.1f',
                                 degree_symbol='')
ax.xaxis.set_major_formatter(lon_formatter)
ax.yaxis.set_major_formatter(lat_formatter)
plt.colorbar(img,label=r'SSH (m)')
plt.clim(15, 40)
plt.show() #A window will show up, allowing the user to see and download the plot
```

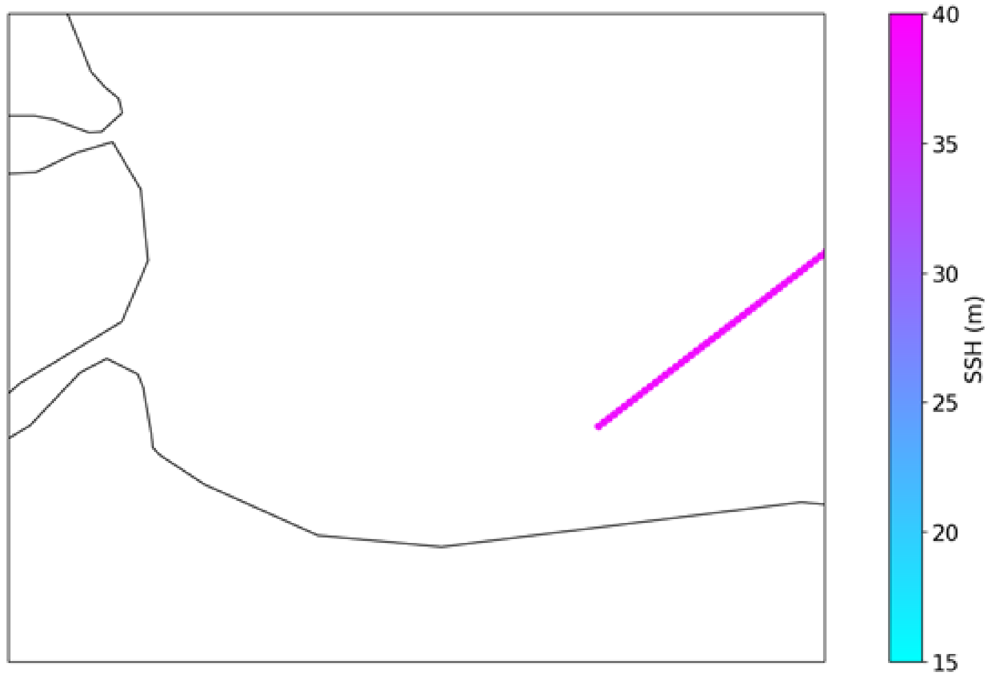

Figure 20: *Output of the along-track visualisation python code, zoomed in on the area of Treå Møllebugt (Denmark)*

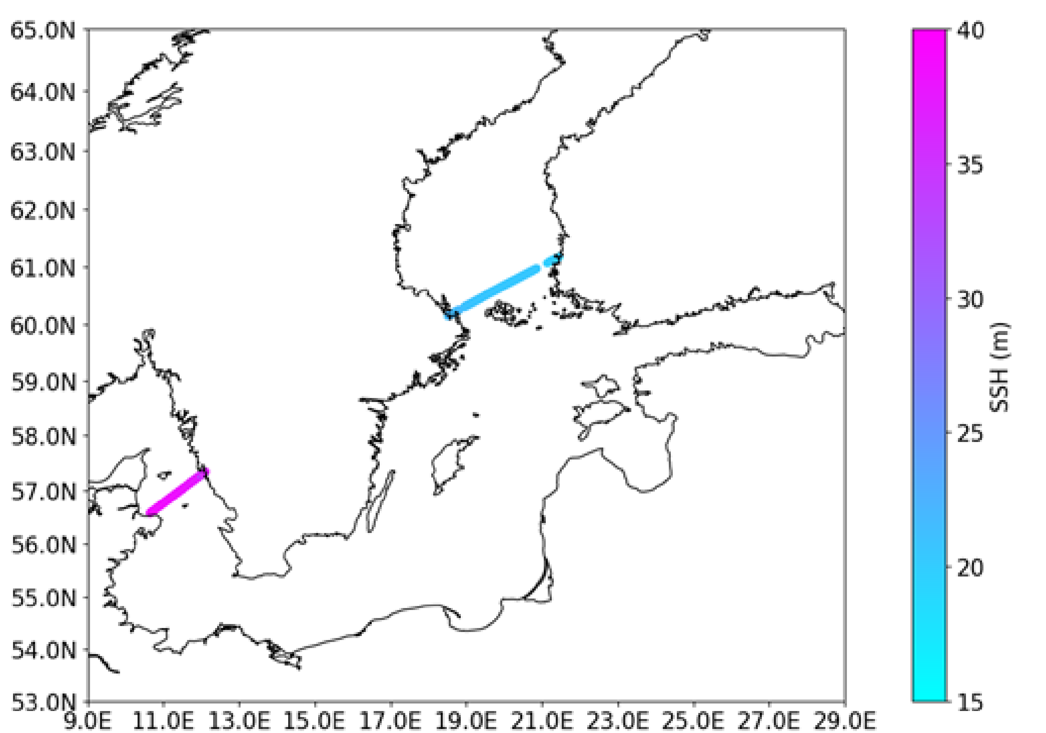

Figure 21: *Output of the along-track visualisation python code, showing a single Baltic SEAL along-track dataset of processed SSH measurements (Jason1_em_hf_262_0213.nc) across the Baltic Sea region.*

CODE ENDS

4.2 Monthly gridded products

4.2.1 Format

The data are provided in NetCDF[9] format files. The gridded datasets are provided covering the timeframe spanning 1995/05 → 2019/05 at monthly temporal resolution. The NetCDF files are organized in a year-month order.

For example: YYYY_MM.nc, where Y substitutes the year and M the month.

The gridding is based on an unstructured triangular mesh, characterized by nearly equally spaced grid node distances (i.e. a geodesic polyhedron). The spatial resolution ranges from 7 to 8 km. **Note that the SSH value and locations are related to the TOPEX ellipsoid (not the WGS1984 spheroid)**.

4.2.2 Structure

The following list outlines all the included NetCDF attributes. Each attribute is associated with stored data, be it a measurement, a correction factor, a description etc.

Note that the same attribute structure exists for both the along-track and gridded datasets (due to them being from the same processing path). This has resulted in some of the along-track attributes being left blank, which may confuse the novice user.

Global Attributes

All files are provided with the following global attributes:

- The name of the file is provided.
```
product_name = "YYYY_MM.nc";
```

- The project name and its respective url is mentioned.
```
project = "ESA Baltic SEAL";
creator_url = "http://balticseal.eu";
```

- The date and time of creation is specified.
```
creation_time = "DD-Mon-YYYY HH:MM:SS";
```

- The dataset version is specified.
```
version = "ESA Baltic SEAL Version 1"
```

- Additional information about the product
```
summary = a short summary about the data attributes in the dataset
comment = additional information about the provided dataset
```

[9] For further information on NetCDF formats, there is an excellent introduction for beginners to NetCDF data use available at https://www.unidata.ucar.edu/software/netcdf/docs/netcdf_introduction.html **[last accessed 8th February, 2021]**

- Extra global attributes define the grid. These are shown in Table 9.

Table 9: *Additional global attributes in the gridded data product.*

Name	Description
Grid_Name	Name of the grid ("YYYY_MM")
Grid_Type	Name of the underlying unstructured grid
Grid_cap-radius	Information about the cap-size radius around each grid node for identifying along-track observations (km)
Grid_Gauss_Weighting_spatial_index	Information about the strength of the spatial weighting (index).

Variable Attributes

The Variable attributes in a gridded dataset netCDF file are outlined in Table 10.

Table 10: *Grid products variable attributes*

Name	Long name	Unit
lon*	Geographical longitude of grid nodes	degrees
lat*	Geographical latitude of grid nodes	degrees
time	day since 1985-01-01 00:00:00 (continuous)	days
ssh*,**	Sea Surface Height (SSH)	meters
ssh_std_lsq	Uncertainty of the monthly SSH	meters
num_obs	Number of theoretical usable observations	index
num_used_obs	Number of used observations	index
qf_monthly_grid	Quality Flag based on the gridding process (Bad=1, Good=0)	index

* Geographical coordinates, orbital ranges and sea surface heights refer to the TOPEX ellipsoid.
** Please note, sea surface heights contain ocean tide corrections by FES2014 (Lyard et al., 2020).

4.2.3 Introductory code for novices to explore gridded data

This code is a sample plot for users to plot a Baltic SEAL gridded dataset, using the Python programming language. It was developed Dr. M. Passaro and has been tested and annotated by Ms. E. Chalençon.

It is important to note that Baltic SEAL is distributed using un-structured grids. Therefore, the points of the original grid need to first be displayed as a "scatter plot" (see the first python code section, and Figures 22-23). Since several ocean data are distributed as structured grids (your basic raster-type formats), it might be useful to interpolate a Baltic SEAL product on such a grid. The second section of code provides an example by defining a grid with a 1/10th-of-degree spacing in latitude and longitude. The outputs of the structured grid visualisation are shown in Figures 24-25. Note that these codes do not convert the data into a GIS-enabled raster format, merely visualise it. To convert along-track datasets into shapefiles, and gridded datasets into rasters, example codes are available on the Baltic SEAL website at www.balticseal.eu/outputs.

These codes were produced using python 3.8; The following packages have to be installed on your python: ***numpy***, ***scipy***, ***netCDF4***, ***matplotlib*** and ***cartopy****. You can install the packages using pip (for example "`pip install numpy`") or conda (for example "`conda install numpy`"). Note that in order to mask out points on land in the second code, the "***global-land-mask***" library is used and also has to be installed.

****Note: Cartopy*** *installation may be a bit complex as it has a lot of required dependencies. Using pre-built binaries can be a solution. They can be found at a variety of sources. Christoph Gohlke maintains unofficial Windows binaries (https://www.lfd.uci.edu/~gohlke/pythonlibs/). The correct version of the package of interest (ex: cp38 and win_amd64 is for Python 3.8 (64bits)) can be downloaded and installed by using "pip install" followed by the path of the .whl file which has just been downloaded (`pip install C:/some-dir/some-file.whl`).*

To obtain an easy to use copy of this code, go to www.balticseal.eu/outputs/ and download the suite of code packages.

*Plotting an **un-structured** grid of Baltic SEAL Gridded data*

CODE STARTS

```
# Import the needed packages:
import netCDF4
import numpy as np
import cartopy as cart
from cartopy.mpl.ticker import LongitudeFormatter, LatitudeFormatter
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
from scipy.interpolate import griddata

# Set up the file inputs and input variables:
```

```
directory='C:/some-dir/' #The user should change the path to his .nc
files' directory
filename='2002_06.nc' #The user should change to the file of his interest
S = netCDF4.Dataset(directory+filename)
lon = S.variables['lon'][:]
lat = S.variables['lat'][:]
ssh = S.variables['ssh'][:]
min_lat=53.0
max_lat=66.0
min_lon=9.0
max_lon=31.0

# Displaying the unstructured grid as a scatterplot:

fig = plt.plot()
plt.rcParams.update({'font.size': 15})
plt.plot
plt.rcParams["figure.figsize"] = (50,10) #Increase figure size
ax = plt.axes(projection=ccrs.Miller())
img=plt.scatter(lon, lat,
      c=ssh, s=20,
          cmap='cool', alpha=1,transform=ccrs.PlateCarree())
ax.coastlines(resolution='10m', color='black', linewidth=1)
ax.set_xticks(np.arange(min_lon,max_lon,2), crs=ccrs.PlateCarree())
ax.set_yticks(np.arange(min_lat,max_lat,1), crs=ccrs.PlateCarree())
lon_formatter = cart.mpl.ticker.LongitudeFormatter(number_format='.1f',
                                  degree_symbol='',
                                  dateline_direction_label=True)
lat_formatter = cart.mpl.ticker.LatitudeFormatter(number_format='.1f',
                                 degree_symbol='')
ax.xaxis.set_major_formatter(lon_formatter)
ax.yaxis.set_major_formatter(lat_formatter)
plt.colorbar(img,label=r'SSH (m)')
plt.clim(15, 40)
plt.show() #A window will show up, allowing the user to see and download
the plot
```

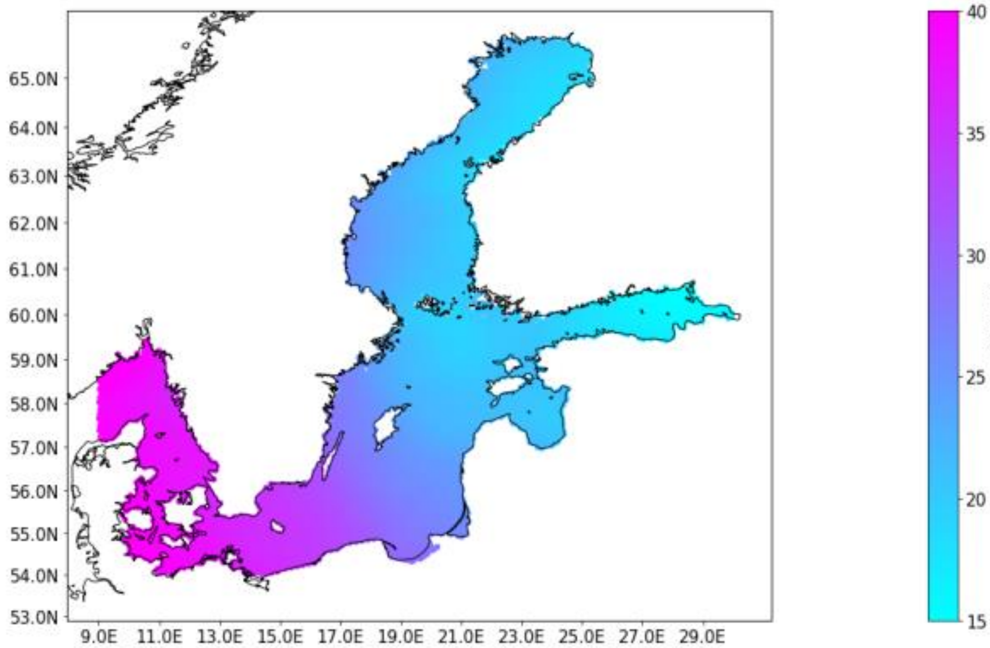

Figure 22: *A Baltic SEAL gridded dataset, available as an unstructured grid and visualised as a scatterplot.*

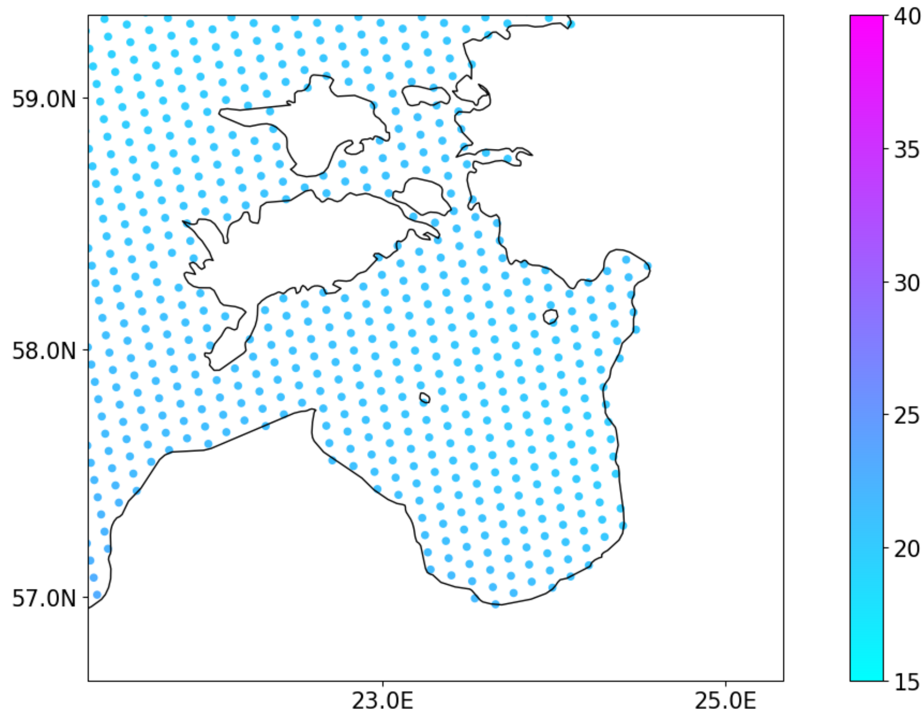

Figure 23: *Zooming in on the Gulf of Riga between Latvia and Estonia, so show how the unstructured grid data appear close-up.*

CODE ENDS

*Plotting a **structured** grid of Baltic SEAL Gridded data*

CODE STARTS

```
# Import the needed packages:
import netCDF4
import numpy as np
import cartopy as cart
from cartopy.mpl.ticker import LongitudeFormatter, LatitudeFormatter
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
from scipy.interpolate import griddata
from global_land_mask import globe

# Set up the file inputs and input variables:
directory='C:/some-dir/' #The user should change the path to his .nc files' directory
filename='2002_06.nc' #The user should change to the file of his interest
S = netCDF4.Dataset(directory+filename)
lon = S.variables['lon'][:]
lat = S.variables['lat'][:]
ssh = S.variables['ssh'][:]
min_lat=53.0
max_lat=66.0
min_lon=9.0
max_lon=31.0

grid_size=0.1
grid_x, grid_y = np.mgrid[max_lat:min_lat:-grid_size,min_lon:max_lon:grid_size]
points=np.column_stack((lon,lat))
grid_z0 = griddata(points, ssh, (grid_y, grid_x), method='linear')

# Displaying an interpolated Baltic SEAL product onto a structured grid:
fig = plt.plot()
plt.rcParams.update({'font.size': 15})
plt.plot
plt.rcParams["figure.figsize"] = (50,10) #Increase figure size
ax = plt.axes(projection=ccrs.Miller())
for i in np.arange(0,np.shape(grid_y)[0]) :
   for j in np.arange(0,np.shape(grid_y)[1]) :
       if globe.is_land( grid_x[i,j],grid_y[i,j]) :
             grid_z0[i,j] = np.nan
img=plt.pcolormesh(grid_y,grid_x,grid_z0,
          cmap='cool', alpha=1,transform=ccrs.PlateCarree())
ax.coastlines(resolution='10m', color='black', linewidth=1)
ax.set_xticks(np.arange(min_lon,max_lon,2), crs=ccrs.PlateCarree())
ax.set_yticks(np.arange(min_lat,max_lat,1), crs=ccrs.PlateCarree())
lon_formatter = cart.mpl.ticker.LongitudeFormatter(number_format='.1f',
                                  degree_symbol='',
                                  dateline_direction_label=True)
lat_formatter = cart.mpl.ticker.LatitudeFormatter(number_format='.1f',
                                 degree_symbol='')
ax.xaxis.set_major_formatter(lon_formatter)
ax.yaxis.set_major_formatter(lat_formatter)
plt.colorbar(img,label=r'SSH (m)')
plt.show()#A window will show up, allowing the user to see and download the plot
```

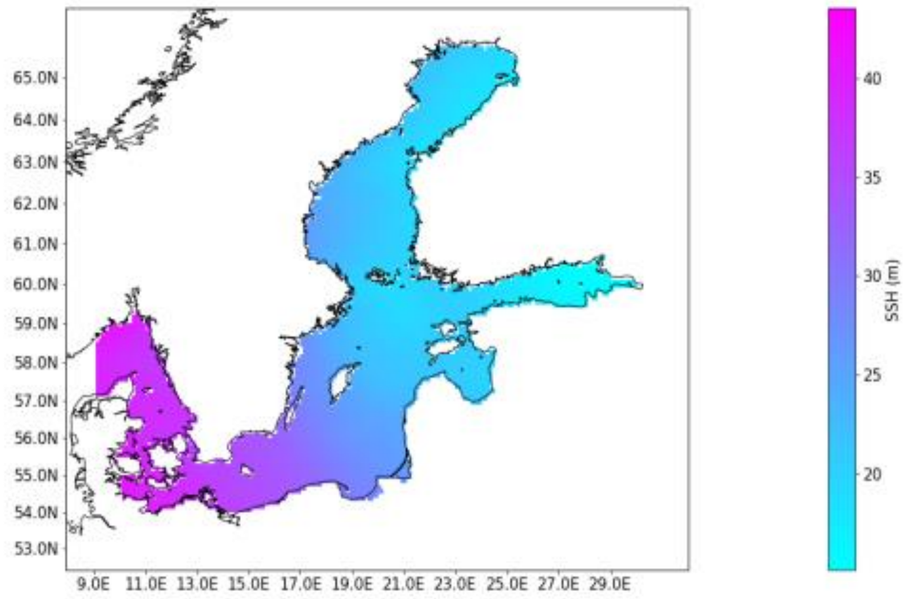

Figure 24: *A sample Baltic SEAL gridded dataset, available as an unstructured grid and visualised as an interpolated structured grid.*

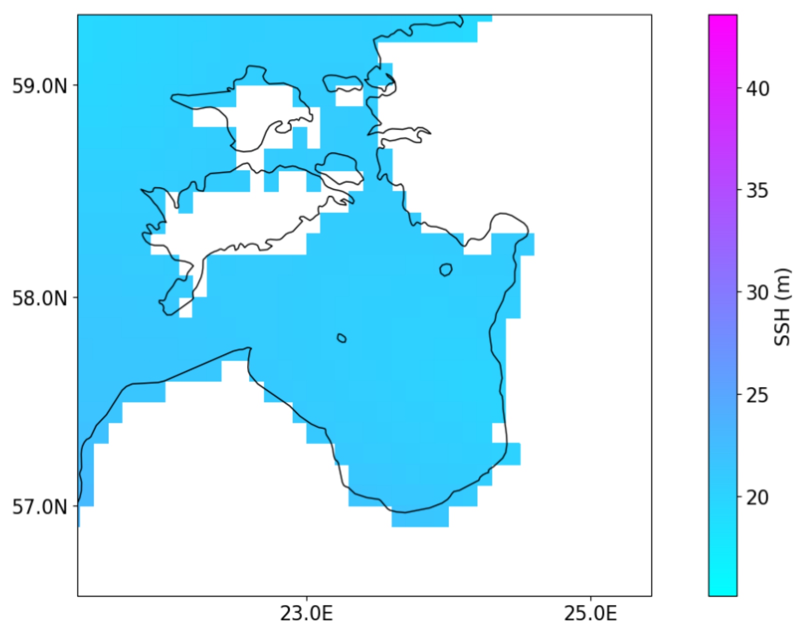

Figure 25: Zooming in on the Gulf of Riga between Latvia and Estonia, so show how the interpolated structured grid data appear close-up.

CODE ENDS

4.3 Regional sea level trend and annual cycle dataset

4.3.1 Format

The data are provided in NetCDF[10] format files. The file name is `"BalticSEAL_trend_and_annual_cycle.nc`".

4.3.2 Structure

The following list outlines all the included NetCDF attributes. Each attribute is associated with stored data, be it a measurement, a correction factor, a description etc.

Global Attributes

The dataset file contains a number of global attributes. The meaning of each attribute is shown in Table 11. The content and a brief outline of each attribute is as follows:

- The name of the file is provided.
  `product_name = "BalticSEAL_trend_and_annual_cycle.nc";`

- The project name and its respective url is mentioned.
  `project = "ESA Baltic SEAL";`
  `creator_url = "http://balticseal.eu";`

- The date and time of creation is specified.
  `creation_time = "09-Dec-2020 11:11:11";`

- The grid type is specified.
  `Grid Type = "Triangular Unstructured";`

- The radius of the area around each grid node, (within which observations are input to the least-squares estimation step of the gridding process) is provided.
  `Grid_cap-radius = "100";`

- The Gaussian spatial weighting included into the least-squares fitting step of the gridding process.
  `Grid_Gauss_Weighting_spatial_index = "1";`

- The dataset version is specified.
  `version = "ESA Baltic SEAL Version 1"`

- Additional information about the product
  `summary = a short summary about the data attributes in the dataset`
  `comment = additional information about the provided dataset`

---

[10] For further information on NetCDF formats, there is an excellent introduction for beginners to NetCDF data use available at https://www.unidata.ucar.edu/software/netcdf/docs/netcdf_introduction.html **[last accessed 8th February, 2021]**

- Detailed information on the netCDF and HDF versions which structure this file are indicated: `_NCProperties = "version=2, netcdf=4.7.6,df5=1.10.4";`

- The convention used to implement convention-specific parsing of the NetCDF file is highlighted. `_CoordSysBuilder = "ucar.nc2.dataset.conv.DefaultConvention";`

Table 11: *Global attributes in the Baltic SEAL trend analysis and annual cycle data product, and their meaning.*

Name	Description
product_name	The file name
project	The project under which this data product was generated
creator_url	Website where further information on the project is available
creation_time	Date and time at which this product was finalised
Grid_Type	Name of the underlying unstructured grid
Grid_cap-radius	Information about the cap-size radius around each grid node for identifying along-track observations (km)
Grid_Gauss_Weighting_spatial_index	Information about the strength of the spatial weighting (index).
Version	Version of the overall Baltic+ SEAL dataset suite.
summary	a short summary about the data attributes in the dataset
comment	additional information about the provided dataset
_NCProperties	The version of NetCDF (Network Common Data Format) interface used for the file, and version of the HDF5 (Hierarchical Data Format 5)[11] suite that makes it possible to manage the data collection.
_CoordSysBuilder	Specifies the convention used to implement convention-specific parsing of the NetCDF file. In this case, the MSS file uses Default Coordinate Convention.

[11] The HDF5 structure allows for very large datasets to be managed and explored. The NetCDF file structure exploits this. Further information on Hierarchical Data Formats, and the HDF5 suite can be found at https://portal.hdfgroup.org/display/support **[last accessed 8th February, 2021]**

Variable Attributes

The Variable attributes in a gridded dataset netCDF file are outlined in Table 12.

Table 12: *Variable attributes in the Baltic SEAL trend and annual cycle dataset, their meaning and associated units.*

Name	Long name	Unit
lon*	Geographical longitude of grid nodes	degrees
lat*	Geographical latitude of grid nodes	degrees
ssh_trend	**Sea level trend from May 1995 to May 2019. Note that trends and annual cycles are not computed for locations with < 250 months of good quality data.**	**Meters /year**
ssh_trend_unc	Statistical uncertainty regarding the Sea Level Trend from the sea level time series. Note that trends and annual cycles are not computed for locations with < 250 months of good quality data.	Meters /year
ssh_annual_ampl	Mean Annual Amplitude of the sea level time-series, from May 1995 to May 2019. Note that trends and annual cycles are not computed for locations with < 250 months of good quality data.	Meters
ssh_annual_ampl_unc	Statistical uncertainty regarding the Mean Annual Amplitude of the sea level time-series. Note that trends and annual cycles are not computed for locations with < 250 months of good quality data.	Meters
ssh_annual_ampl_max	Month with the maximum amplitude of the average annual cycle (1 = January, 12 = December).	N/A
ssh_annual_ampl_min	Month with the minimum amplitude of the average annual cycle (1 = January, 12 = December).	N/A

* Geographical coordinates refer to the TOPEX ellipsoid.

4.4 Regional Mean Sea Surface dataset

4.4.1 Format

The dataset is provided in a NetCDF format file. The file name is is "`ESA_Baltic_SEAL_MSS.nc`".

4.4.2 Structure

The following list outlines all the included NetCDF attributes.

Note that along with the MSS product, sea level trend grid is also provided at 1 arcminute resolution grid. The sea level trend grid matches sea level trend estimated from the monthly gridded products (TUM) included in ESA_Baltic_SEAL_trend_and_annual_cycle.nc (previous section). The sea level trend is obtained by interpolating/extrapolating the unstructured grid to regular grid nodes, and is included as an attribute in the MSS product (see Table 14).

Global Attributes

All files are provided with the following global attributes (explanations provided in table 13):

- The name of the file is provided.
  `product_name = "ESA_Baltic_SEAL.nc";`

- The project name and its respective url is mentioned.
  `project = "ESA Baltic SEAL";`
  `creator_url = "http://balticseal.eu";`

- The date and time of creation is specified.
  `creation_time = "22-Dec-2020 21:33:53";`

- The Grid name is outlined.
  `Grid_Name = "Baltic_Sea_Mean_Sea_Surface";`

- The grid type is specified.
  `Grid Type = Regular 1 minute x 1 minute spatial resolution;`

- The dataset version is specified.
  `version = "ESA Baltic SEAL Version 1";`

- Additional information about the product is provided
  `summary = "ESA Baltic SEAL multi-mission gridded dataset containing mean sea surface and additional parameters";`
  `comment = "More information can be found in the Product Handbook doi: 10.5270/esa.BalticSEAL.PH1.1".`

- The convention used to implement convention-specific parsing of the NetCDF file is highlighted.
  `_CoordSysBuilder = "ucar.nc2.dataset.conv.DefaultConvention"`

Table 13: *Global attributes in the Baltic SEAL Mean Sea Surface data product, and their meaning. The contents for these attributes in the MSS product are described above.*

Name	Description
Product_name	The file name
Project	The project under which this data product was generated
Creator_url	Website where further information on the project is available
Creation_time	Date and time at which this product was finalised
Grid_Name	Name of the grid data product ("Baltic_Sea_Mean_Sea_Surface")
Grid_Type	Name of the underlying unstructured grid
Version	Version of the overall Baltic+ SEAL dataset suite.
summary	a short summary about the data attributes in the dataset
comment	additional information about the provided dataset
_CoordSysBuilder	Specifies the convention used to implement convention-specific parsing of the NetCDF file. In this case, the MSS file uses Default Coordinate Convention.

Variable Attributes

The Variable attributes in a gridded dataset NetCDF file are outlined in Table 14.

Table 14: *Variable attributes in the Baltic SEAL Mean Sea Surface dataset, their meaning, and associated units.*

Name	**Long name**	**Unit**
lon*	Geographical longitude of grid nodes	degrees
lat*	Geographical latitude of grid nodes	degrees
MSS	**Mean Sea Surface (MSS)**	**meters**
interp_err	Gridding interpolation error	meters
qf_err	Quality flag based on a 0.04 meter threshold of gridding interpolation error	index
Sl_trend	**Sea level trend estimated from the monthly gridded products**. It matches the ssh_trend variable in ESA_Baltic_SEAL_trend_and_annual_cycle.nc (shown in Table 12)	Meters /year

* Geographical coordinates, orbital ranges and sea surface heights refer to the TOPEX ellipsoid.

5 Accessing the Baltic SEAL product range

Public access to the data products is via the Baltic SEAL web portal - http://balticseal.eu/data-access/.

Simply go to the webpage, and follow the link to request access. You will be supplied with a user name and access to the FTP site containing the products, which you are free to browse and download as needed.

Should you be using Baltic SEAL products, please let the team know how you find using them. The team would very much appreciate being made aware of how you are using the product, and any refinements you may wish to suggest to drive product improvement into the future.

The team are also very interested in feedback concerning this product handbook, and very much welcome feedback and suggestions on content, structure, and language to shape data product handbooks for future data products.

To provide feedback, please use the contact us page on the Baltic SEAL website (www.balticseal.eu).

5.1 Constraints on use

The Baltic SEAL suite of products are experimental, and provided primarily for research purposes to demonstrate their suitability for monitoring sea level, and enhancing sea level models for the Baltic Sea. The user must proceed with caution and explore the data and possible uses with due diligence.

Should the products be used in your research, please cite the dataset using the following:

Passaro, M., Müller, F., Dettmering, D., Schwatke, C., Oelsmann, J., Andersen, A., Abulaitjiang, A., Rautiainen, L., Tuomi, L., Särkkä, J., Ringgard, I., Høyer, J.L., Madsen, K., Scarrott, R.G., Chalençon, E., Seitz F., Restano, M., and Benveniste, J. (2021). *Baltic SEAL Sea Level dataset suite, Version 1.0*. Dataset produced under the Baltic SEAL project (ESA contract no. 000126590/19/I/BG). DOI: http://doi.org/10.5270/esa.BalticSEAL.PH1.1.

Note that this is an interim recommended citation, correct as of the publication of this handbook. In the event of a peer-review publication being released summarising the dataset product, the recommended citation will be amended.

Lastly, while this handbook tries to be correct and complete, note that nothing can replace the information to be gained at conferences and other meetings from those using these data. To this end, please get involved with the Coastal Altimetry community, by going to http://www.coastalt.eu/.

5.2 Further information and contacts

For queries regarding Baltic SEAL product data, please do not hesitate to contact:

Data coordinator: Felix L. Müller

Email: felix-lucian.mueller@tum.de

For queries regarding the Baltic SEAL Project, please do not hesitate to contact:

Project coordinator: Dr. Marcello Passaro

Website: http://balticseal.eu

Email address: info@balticseal.eu

For insights into the European Space Agency's (ESA) Science for Society Programme, see: https://eo4society.esa.int/

Note that the coastal altimetry community holds regular workshops where the science and techniques of coastal altimetry are reviewed and the various applications are showcased and discussed. See http://www.coastalt.eu/community for more detail.

6 Further Reading

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