TUM

DMI
Danish Meteorological Institute

DTU

FMI

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

ESA Contract: 4000126590/19/I/BG

BALTIC+ Theme 3

Baltic+ SEAL (Sea Level)

Scientific Roadmap

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J. Benveniste (ESA-ESRIN)	[signature]	04/02/2021

Executive summary

For sea level studies, coastal adaptation, and planning for future sea level scenarios, regional responses require regionally-tailored sea level information. Global sea level products from satellite altimeters are now available through the European Space Agency′s (ESA) Climate Change Initiative. However, these global datasets are not entirely appropriate for supporting regional actions. Particularly for the Baltic Sea region, complications such as coastal complexity and sea-ice restrain our ability to exploit altimetry data opportunities.

The Baltic+ SEAL project has been framed as a laboratory to test advances in altimetry data processing to estimate sea level. It has developed a complete, replicable chain, from the treatment and flagging of individual echoes to the production of added-value products. The project activities also demonstrated the use of these new regionalised products, by conducting an examination of Baltic Sea regional sea level trend, calculating a new mean sea level map, and producing an experimental high-temporal resolution grid. The Baltic+ SEAL project achieved the development of algorithms that can be applied to the entire constellation of altimetry missions, to significantly improve the quality and the quantity of sea level data available. Such techniques are easily exportable to other regions of interest.

The released dataset, described in a dedicated product handbook, consists of multi-mission along-track data, gridded monthly sea level and mean sea surface. The sea level trend analysis performed within the project has highlighted the role of the North Atlantic Oscillation phases in shaping absolute sea level trend differences at a sub-basin scale. Further possible exploitation of the dataset includes a wide range of opportunities from supporting local ocean circulation research, to storm surge monitoring.

As such, the project activities generated a wide range of new insights, products, best practices, scientific findings, and promotional material. These advances funded under the ESA Baltic+ programme represent the project foreground, which, if properly identified and managed, can maximise the impact of the project activities well beyond the end date of the project itself. This document outlines options for taking the scientific advances forward, in addition to a number of additional support activities which would maximise the impact of any future advances. The proposed suite of activities are framed by a context analysis, examining the sea level scene outside the Baltic+ SEAL project, in the coastal risk, and coastal altimetry arenas. The foreground generated by the Baltic+ SEAL project has also been mapped against this context. Finally the proposed scientific activities are proposed along with a first-estimate of costs, and mapped onto the context analysis to provide a measure of cost versus impact.

The advances under Baltic+ SEAL address a number of priority need areas identified by a context analysis using literature studies. These encompass the need to/for:

- Obtain measurements closer to the coast;
- Integrate more altimetry missions and cross-calibrate them;
- Customize approaches (highlighting the importance of regional and smaller scales);
- Differentiate the coastal approach from the open ocean one, with coastal-dedicated approaches;
- Explore new instruments, and processing techniques;
- Integrate stakeholder engagement into advance efforts;
- Outreach about coastal altimetry;
- Departitioning / multi-disciplinarity (synergy) approaches;
- Compare the outputs of the various altimetry products;
- Enhance uncertainty information available with the data products.

A number of future scientific avenues for further research activity were identified and are proposed. These are supplied with a non-binding, preliminary estimate of their costs and timeframes. In addition, a range of (non-costed) support activities have been identified to run in parallel/synergy with the scientific activities, to maximise impact. Alignment of these activities with the community need areas is detailed within the document.

Advancement proposed (where there are options, a range of costs are proposed)	Max. timeframe	Cost estimate
Develop regional hydrodynamic tide models to estimate tides, to optimise sea level measurements derived from altimetry sensors.	18	€318,000
Implement a regional case-study examination of sea level for the Baltic Sea.	18	€81,000 - €386,000
Implement a regional (Baltic+ style) study focused on examining combined sea-level, significant wave height and sea state extremes within a region.	15	€71,000 - €185,000
Implement studies to demonstrate synergies between altimetry and other data sources.	15	€84,000 - €257,000
Implement a range of regional demonstrations of altimetry-derived measurement use.	24	€99,000 - €740,000
Implement a focused study to optimise interpolation techniques for coastal-dedicated gridding.	12	€216,000
Implement a study into the power spectrum of noise in the altimetry data, towards developing a model to capture the spectral features detected.	6	€108,000
Implement studies to advance altimetry retrackers. Demonstrate the potential for synergy examinations of issues with altimetry data, using different sensor products (e.g. Sentinel-1 SAR, Sentinel-2 optical, Sentinel-6 products etc.).	21	€93,000 - €758,000
Implement a targeted study to improve Sea State Bias estimations.	15	€99,000 - €311,000
Demonstrate the potential of applying Baltic+ SEAL data and approaches.	30	€128,000 - €692,000
Implement targeted studies to enhance the existing Sea Level CCI suite of products.	21	€180,000 - €464,000
Support Action proposed		**Cost estimate**
Lobby, and if possible support, the expansion of Baltic Sea TG networks, to address the southern shoreline gap.	Not estimated	Not costed
Integrate the wide range of mission-specific Baltic+ SEAL processing chains into the ESA GPOD architecture.	Not estimated	Not costed
Raise awareness of the consolidated asset made available on the ESA GPOD platform.	Not estimated	Not costed
Examine the use of Baltic+ SEAL products for standardised educational purposes	Not estimated	Not costed
Explore the potential for sea-level-themed capacity-building activities	Not estimated	Not costed

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List of Abbreviations

ALES	A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry
ALES+	An enhancement of the ALES retracker
ARGO	A global array of autonomous floats or profilers, deployed across the world's oceans, reporting subsurface ocean water properties
ATBD	ESA Baltic+ SEAL Algorithm Theoretical Basis Document
Baltic+	The European Space Agency's Baltic Plus regional programme
Baltic+ SEAL	The Baltic Plus Sea Level project, implemented under the remit of the Baltic+ Programme.
CAWS	Coastal Altimetry Workshop
CCI-SL	ESA Climate Change Initiative's Sea Level project
CCI-SS	ESA Climate Change Initiative's Sea State project
CTD	Conductivity, Temperature & Depth (a widely-used approach to gathering vertical profiles of oceanographic measurements)
DD	Delay-Doppler
DIAS	The European Union's Data and Information Access Services
DMI	Danish Meteorological Institute
DTU	Technical University of Denmark
EGU	European Geophysical Union
EO	Earth Observation
ESA	European Space Agency
ESERO	European Space Education Resource Office
ESA GPOD	ESA's Grid Processing On Demand facility
FMI	Finnish Meteorological Institute
GIS	Geographical Information Systems
GNSS	Global Navigation Satellite System
IAR	ESA Baltic+ SEAL Impact Assessment Report
IEOS	Irish Earth Observation Symposium
IP	Intellectual Property
ITT	Invitation To Tender
LRM	Low Resolution Mode
MaREI	Irish Centre for Marine Energy and Climate

MMXO	Multi-mission cross calibration
OSTST	Ocean Surface Topography Science Team
SAMOSA	A waveform retracker, developed specifically for SAR-derived waveforms
SAMOSA+	An enhanced version of the SAMOSA retracker
SAMOSA++	An enhance version of the SAMOSA+ retracker
SAR	Synthetic Aperture Radar
SLA	Sea Level Anomaly
SoW	Statement of Work
SSB	Sea State Bias
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SWH	Significant Wave Height
SWOT	The French-U.S. Surface Water and Ocean Topography mission
TEP	Thematic Exploitation Platform
TUM	Technical University of Munich
UCC	University College Cork
VLM	Vertical Land Motion

Introduction

This document presents the Scientific Roadmap, arising from the range of scientific advances made under the Baltic+ SEAL project, and the recommended scientific avenues to be explored to take the research further.

Section 1 is a policy-maker-focused executive summary, a brief outlining the key points, actions to be taken, and preliminary cost estimates. Section 2 introduces the document, highlights how it is structured, and briefly outlines the analysis approach. Section 3 provides the results of the context analyses for the proposed future scientific activities. Section 4 presents the recommended scientific activities. Section 5 presents the recommended support activities to maximise impact. Section 6 presents the cost estimates for the range of proposed scientific activities.

Defining the way forward

Three key analyses were undertaken to roadmap options to take the scientific developments under Baltic+ SEAL forward. Firstly, a comprehensive foreground analysis was undertaken by the project consortium. This key effort identified all advances and items created under the remit of the Baltic+ SEAL project. These were then categorised, and the acceptable future use of each item clarified by its creator(s), and recorded. This mapping enabled detailed and comprehensive summaries of project advances to be compiled, which were firstly mapped to the objectives of both the Baltic+ programme, and the statement of work within which the Baltic+ SEAL project is framed. This provides a concise and clear demonstration of how the project has met the ESA-designated objectives.

In parallel, a second analysis was undertaken. This involved literature survey of the wider Sea Level community, examining workshop reports, white papers, and more formalised recommendations. Key contextual aspects were also examined in addition to these coastal risk and oceanographic aspects, and coastal altimetry community perspectives. These included:

- Existing and future European satellite missions, including Sentinel-6;
- Potential for the SWOT mission
- Potential for the existing ESA GPOD infrastructure to animate advances;
- Potential for increasing Copernicus data uptake and information product use;
- Potential for ESA Baltic+ SEAL advances to support ESA CCI Sea Level (CCI-SL) product suite;
- The next generation of altimetry users, and
- Potential project synergies.

From this pool of literature and perspectives, general community needs where coastal altimetry-derived sea level data could be applied, or enhanced, were identified. The project advances were then cross-referenced further against the wider community needs, indicating how exactly the scientific advances made by the Baltic+ SEAL team, have responded to a wide range of coastal needs. In this way, we are able to understand the steps forward that made Baltic+ SEAL an innovative laboratory for satellite altimetry, and at the same time identify and define remaining problems and remaining challenges.

The latter are then used to frame the way forward beyond Baltic+ SEAL, defining roadmap of discrete actions, framed within community needs. A third analysis was undertaken here. The project meeting minutes were first analysed for all references to research that could be done beyond the remit of the Baltic+ SEAL project. These references were rephrased into action statements, and then grouped into consolidated action areas. Further actions were derived from the context analysis, to ensure that a range of support actions also accompanied the scientific actions. These could serve to magnify the impact of future research if it is deemed appropriate. Finally these action areas were cross-referenced with the community needs identified through the literature review, and a first estimation of costs of the various action options was undertaken, an overview of which is presented in this report.

Note that the detailed foreground information, and the detailed cost estimates are available in the Annexes of this report, with summary information provided in the main body.

Analyses and outputs

Baltic+ SEAL generated a number of new insights, products and materials through its range of activities. This project foreground has been analysed and mapped against the original Baltic+ programme objectives and the Baltic+ SEAL Invitation to Tender (ITT) objectives. The foreground itself has been identified by the Baltic+ Team, and an overview is provided here grouped under four main headings: Algorithms and processes, datasets, project documentation, and outreach materials.

Advances in knowledge under Baltic+ SEAL

The advances achieved by Baltic+ SEAL were guided by the objectives outlined in the Statement of Work (SoW), to which the Baltic+ SEAL proposal responded. There are two primary groups of objectives. The first are the ESA tender (ITT) objectives, those spanning across all funded Baltic+ projects. The second group are within the Baltic+ theme itself - in this case theme 3 of the ITT (Baltic Sea Level Dynamics and trend). These objectives are outlined in table 1 (overall ITT) and table 2 (theme 3), along with the advances made by the Baltic+ SEAL project team which contribute to meeting them.

Table 1: *Baltic+ SEAL contributions to advancing progress towards the overall Baltic + ITT objectives.*

Objective	**Advancement made**
To foster the scientific exploitation of EO-based geo-information products to respond directly to the needs of the Baltic scientific community	We have improved the exploitation of Satellite Altimetry data in areas that were previously not considered for the generation of gridded sea level products in the area of study, in particular sea-ice covered areas and coastal waters.
To support existing international and national efforts to improve the observation, understanding and prediction of ocean-sea-ice-atmosphere processes at different spatial and time scales demonstrating the capability of EO and ESA data to respond to the needs of the Baltic research community;	We have shown scientific advances that can be applied to other EO and ESA efforts, such as the Sea Level Climate Change Initiative. We have applied our dataset to study the influence of atmospheric processes on the sub-regional differences in sea level trend estimates in the Baltic Sea during the altimetry era. We have also shown the potential benefits of multiple temporal resolution products through producing the monthly, and an experimental 3-day, resolution gridded products.
To support the establishment of a solid scientific basis for the development of potential future new applications for the Baltic;	The provision of a regional monthly gridded sea level product, and an experimental 3-day temporal resolution gridded product, can foster the development of studies that deal with interactions between different ocean variables distributed in a similar manner, for example Sea Surface Temperature, Sea Surface Salinity. The high quality of the along-track product can be of particular interest for future applications combining high resolution sea level and sea state data.
To develop a Scientific Roadmap as a basis for further ESA activities in support of the Baltic research and applications to be further developed and consolidated within future actions in the context of the ESA Baltic Initiative.	This roadmap developed for the theme 3 (Baltic Sea Level Dynamics and trend) aspects of the Baltic+ SoW, contains a set of transposable actions for further scientific advancement, and support activities to maximise societal and scientific impact. These are delivered in such a way as their origins are traceable to origins in the literature, and/or activities undertaken by the Baltic + SEAL team, and can be directly drawn into the overall Baltic+ Roadmap.

Table 2a: *Baltic+ SEAL successes in meeting the the Baltic + ITT Theme 3 objectives (part 1 of 2).*

Objective	**Advancement made**
Generate a new Baltic dedicated long-term multi-mission sea level product(s) that overcomes the current limitations of the CCI-SL global sea level products	We have generated the requested product, overcoming several of the main limitations characterising the CCI-SL global sea level product, in particular: The absence of cross-calibration between the along-track missions The systematic flagging of any altimetry data close to the coast and in the sea-ice zone The along-track filtering used to generate the global product, which results in a strong smoothing of the variability in the grids and is not tailored for regional applications
Examine the classification of altimetry echoes over ice-covered sea (both Low Resolution Mode and Delay-Doppler)	This task was fulfilled by the adoption and extension of the K-means unsupervised classification method
Examine the use of the retracking of high-rate waveforms in order to include sea level estimations from leads	This task was fulfilled by the adoption and extension of the ALES+ algorithm for LRM missions and by the development of the ALES+ SAR algorithm for Delay-Doppler missions
Develop a dedicated coastal re-tracking system both for Low Resolution Mode and Delay-Doppler	This task was also fulfilled by the adoption and extension of the ALES+ algorithm for Low Resolution Mode (LRM) missions and by the development of the ALES+ SAR algorithm for Delay-Doppler (DD) missions
Develop a dedicated Sea State Bias correction (derived from a local Sea State Bias model and/or a new Sea State Bias Correction for shallow waters.	A dedicated Sea State Bias correction was computed for LRM missions based on the ALES+ estimations of Significant Wave Height (SWH) and Wind. An Ad-Hoc Sea State Bias (SSB) model was designed for ALES+ SAR range estimations, by means of a crossover adjustment of the sea level differences in function of the estimated width of the leading edge.

Table 2b: *Baltic+ SEAL successes in meeting the Baltic + ITT Theme 3 objectives (part 2 of 2).*

Objective	**Advancement made**
Demonstrate cross calibration to exploit multi-mission data	The cross-calibration based on the MMXO technique (Bosch et al., 2014[1]) has been adopted and expanded and enabled a multi-mission use of the data, which is currently absent in other international efforts dedicated to the improvement of coastal along-track data (such as CCI-SL)
Develop a new Mean Sea Surface model	A new Mean Sea Surface model was computed and is described in the Impact Assessment Report (IAR). This Mean Sea Surface, based on the along-track dataset developed in Baltic+ SEAL, reduces the error in particular in the coastal zone.
Produce a map of the seasonal and annual sea level variability (derived from processing of altimetry and tide gauge data).	A map of trends and annual seasonality of the sea level has been produced and successfully compared against Tide Gauges, showing very good agreement and improvements compared to the global datasets. These dataset has been analysed in terms of sub-basin differences and connection to atmospheric variability. The analysis is described in the IAR and it is the subject of a draft that has been submitted to peer review.
Derive a set of Vertical Land Movement estimations	A derivation of VLM by Tide Gauges and Altimetry differentiations has been tested and described in the IAR. Remaining problems are the shortness of the along-track time series in the proximity of the tide gauges. Further studies and more time than what was planned within Baltic+ SEAL will be needed to improve this technique.

[1] Bosch, W., Dettmering, D., Schwatke, C. (2014) Multi-Mission Cross-Calibration of Satellite Altimeters: Constructing a Long-Term Data Record for Global and Regional Sea Level Change Studies. *Remote Sensing* **6**(3) 2255-2281. DOI: 10.3390/rs6032255.

ESA Baltic+ SEAL Foreground

Annex A contains a detailed map of the Baltic+ SEAL foreground, identified by the project team throughout the final year of the project activities. A summary is provided here, to demonstrate the wide variety of advances made, and the possible uses of this foreground beyond Baltic+ SEAL. These fall under four different categories - Algorithms & Processes, Datasets, Project documentation, Outreach materials & Branding.

Algorithms & Processes

These form the heart of advancements made under Baltic+ SEAL. They include enhancements to the ALES+ altimetry data processor to ingest new mission data, an improved bias correction for sea state; a regional multi-mission cross-calibration approach specifically tailored to the Baltic Sea region and adapted from a global approach; an altimetry waveform classification approach to enable exploitation of sea ice leads to estimate sea level, and a gridding approach to produce gridded sea level products from multiple along-track estimates of sea level. The foreground and envisioned path of the foreground is shown in table 3. All the algorithms are replicable, through the detailed freely available project documentation, and existing or future potential publications.

Datasets

The datasets produced by the various stages of Baltic+ SEAL development of the final released datasets, are all unique, identifiable elements of the researcher’s foreground. These are described in table 4 along with their envisioned usage beyond the Baltic+ SEAL project. Note that in the situation where they are not available openly, an interested party may contact the data owner, to discuss access. All queries should be directed to Felix Müller (felix-lucian.mueller@tum.de), who will endeavour to connect you to the appropriate research partner.

Project Documentation

All deliverables produced by the project team in developing the Baltic+ SEAL suite of data products, and advancing the algorithms, are made publically available, with a dedicated DOI. These deliverables are described in table 5, and are made available through the www.balticseal.eu website and the dedicated long term storage arranged by TUM.

Outreach materials

Part of the Baltic+ SEAL activities involved showcasing key project perspectives, learnings and advances. These were done through a variety of promotion avenues including briefings and information disseminated via the project website; oral and poster presentations given at workshops, symposia and conferences; news items and outreach material disseminated via the project team’s social media (Twitter) platform. Open source codes to enable novices and teachers to access and utilise the Baltic+ SEAL data products have also been produced as part of the outreach activities and integrated into the Baltic+ SEAL product handbook. All materials used for outreach are publicly available via the project’s website, with their categories and envisioned uses outlined in table 6.

Table 3: *Baltic_ SEAL's* ***Algorithms and Processing*** *foreground, and envisioned future path.*

Foreground item	Envisioned use
Enhancement to the ALES+ data processor, to enable ingestion of data from the Jason 1-3 missions, and the SARAL mission	Algorithm published, public release of the code is not foreseen.
Enhancement to the ALES+ data processor, to enable ingestion of SAR-altimetry data.	Algorithm described in the project documentation, and integrated onto the ESA GPOD platform, public release of the code is foreseen, if requested by other projects (such as ESA's HYDROCOASTAL[2])
A novel approach to producing a Sea State Bias Correction, for use as part of the ALES+ SAR processing chain.	Details of the parametric model used to estimate the SSB correction are freely available in the Baltic+ SEAL ATBD[3].
A novel approach to Regional Multi-Mission Cross Calibration, demonstrated on data acquired from the Baltic Sea region.	The approach is described in the Baltic+ SEAL ATBD[2]. Public release of the code is not foreseen.
A novel approach to altimetry waveform classification, tailored to identify viable sea-level estimates from altimetry tracks over sea ice.	Details of the approach used is freely available in the Baltic+ SEAL ATBD[2]. This is also the subject of a recently released publication.
A gridding approach to produce a gridded sea level image, from multiple available along-track estimates of sea level.	Details of the approach used is freely available in the Baltic+ SEAL ATBD [2].
An approach to generating a 3-day temporal resolution gridded product, using an adaptation of an SST-based interpolation technique used at DMI.	Details of the approach used is freely available in the Baltic+ SEAL IAR[4]. The approach is earmarked for further development research.

[2] https://www.satoc.eu/projects/hydrocoastal/ [last accessed 4th January, 2021]

[3] Passaro, M., Müller, F., Dettmering, D. (2020) Baltic+ SEAL: Algorithm Theoretical Baseline Document (ATBD), Version 2.1. Technical report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.ATB2DV2.1

[4] Abulaitijiang, A., Andersen, O.B., Ringgaard, I.M., Hoeyer, J.L., Oelsmann, J., Müller, F., Passaro, M., Rautiainen, L., Särkkä, J. (2020) **Baltic+ SEAL: Impact Assessment Report, Version 1.1**. Report delivered under the Baltic+ SEAL project. DOI: http://doi.org/1.5270/esa.BalticSEAL.IARV1.1

***Table 4: Datasets** produced during the course of the Baltic+ SEAL project, and access/usage restrictions.*

<table>
<tr><th>Foreground item</th><th>Envisioned use</th></tr>
<tr><td>Mean Sea Surface dataset (Version 1)</td><td rowspan="3">Access restricted, please contact the Baltic+ SEAL to discuss access and usage.</td></tr>
<tr><td>Mean Sea Surface dataset (Version 2)</td></tr>
<tr><td>Experimental set of along-track datasets used over the course of final dataset development</td></tr>
<tr><td>Mean Sea Surface dataset (final version)</td><td rowspan="4">No restrictions on access (freely available).
Use limitations and constraints applicable and available in the product metadata.</td></tr>
<tr><td>Along-track dataset(s) product for the Baltic Sea region</td></tr>
<tr><td>Gridded Sea Level dataset(s) product for the Baltic Sea region</td></tr>
<tr><td>The experimental high temporal resolution gridded product</td></tr>
</table>

***Table 5a: Reports and documents** delivered under the remit of ESA Balitc+ SEAL (part 1 of 2).*

Foreground item	**Envisioned use**
Requirements Baseline Document	Tuomi, L.; Rautiainen, L.; Passaro, M.; Müller, F. *et al.* (2019) Baltic+ SEAL: **Requirements Baseline Document, Version 3.1**. Technical report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.RBDV3.1 . Available at www.balticseal.eu/outputs
Datasets and dataset description	Ringgaard, I.M., Madsen, K.S., Müller, F., Tuomi, L.,Rautiainen, L., Passaro, M. (2020) Baltic+ SEAL: **Dataset Description, Version 1.1**. Technical report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.DDV1.1 Available at www.balticseal.eu/outputs
Algorithm Theoretical Baseline Document(s)	Passaro, M., Müller, F., Dettmering, D. (2020) Baltic+ SEAL: **Algorithm Theoretical Baseline Document (ATBD), Versions 1.1**. Technical report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.ATBDV1.1 . Available at www.balticseal.eu/outputs Passaro, M., Müller, F., Dettmering, D. (2020) Baltic+ SEAL: **Algorithm Theoretical Baseline Document (ATBD), Version 2.1**. Technical report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.ATBDV2.1 Available at www.balticseal.eu/outputs
Validation Report(s)	Rautiainen, L., Särkkä, J., Tuomi, L., Müller, F., Passaro, M. (2020) Baltic+ SEAL: **Validation Report, Version 1.1**. Technical report delivered under the Baltic+ SEAL project. DOI http://doi.org/10.5270/esa.BalticSEAL.VRV1.1 Available at www.balticseal.eu/outputs Rautiainen, L., Särkkä, J., Tuomi, L., Müller, F., Passaro, M. (2020) Baltic+ SEAL: **Validation Report, Version 1.1.** Technical report delivered under the Baltic+ SEAL project. DOI http://doi.org/10.5270/esa.BalticSEAL.VRV2.1 Available at www.balticseal.eu/outputs

***Table 5b: Reports and documents** delivered under the remit of ESA Balitc+ SEAL (part 2 of 2).*

Foreground item	**Envisioned use**
Baltic+ SEAL Product Handbook	Passaro, M., Müller, F., Dettmering, D., Abulaitijiang, A., Rautiainen, L., Scarrott, R., Chalençon, E., Sweeney, M. (2021) **Baltic+ SEAL: Product Handbook, Version 1.1**. Report delivered under the Baltic+ SEAL project. DOI: http://doi.org/10.5270/esa.BalticSEAL.PH1.1 Available at: www.balticseal.eu/outputs
Baltic+ SEAL Impact Assessment Report	Abulaitijiang, A., Andersen, O.B., Ringgaard, I.M., Hoeyer, J.L., Oelsmann, J., Müller, F., Passaro, M., Rautiainen, L., Särkkä, J. (2020) **Baltic+ SEAL: Impact Assessment Report, Version 1.1**. Report delivered under the Baltic+ SEAL project. DOI: http://doi.org/1.5270/esa.BalticSEAL.IARV1.1 Available at: www.balticseal.eu/outputs
Baltic+ SEAL Roadmap (this document)	Scarrott, R., Passaro, M., Chalençon, E., Müller, F., Dettmering, D., Oelsmann, J., Rautiainen, L., Tuomi, L., Särkkä, J., Abulaitijiang, A., Andersen, O., Høyer, J., Madsen, K., Ringgaard, I., Schwatke, C. (2021) **Baltic+ SEAL: Scientific Roadmap, Version 1.1**. Report delivered under the Baltic+ SEAL project DOI: http://doi.org/10.2570/esa.BalticSEAL.SRV1.1 Available at: www.balticseal.eu/outputs

***Table 6: Outreach and branding materials**, and envisioned usage beyond Baltic+ SEAL.*

Foreground item	**Envisioned usage beyond Baltic+ SEAL**
Posters presented at: • the 13th Irish Earth Observation Symposium (IEOS 2019) • 3rd Baltic Earth Conference: Earth System Changes and Baltic Sea Coasts • the 2020 MaREI Symposium for Marine, Climate and Energy	Abstracts and posters available for download at www.balticseal.eu/outputs Contact the main author if intending to use these materials or excerpts of them.
Oral presentations given at at: • 2019 Ocean Surface Topography Science Team Meeting (OSTST 2019) • the EGU General Assembly (EGU 2020) • the 12th Coastal Altimetry Workshop (CAWS2020) • 2020 ESA- Baltic Earth Workshop on "*Earth Observation in the Baltic Sea region*" (ESA BalticEarth 2020) • 2020 Ocean Surface Topography Science Team Meeting (OSTST 2020)	Abstracts and presentation available for download at www.balticseal.eu/outputs Contact the main author if intending to use these materials or excerpts of them.
Abstracts submitted to (as of January 4th, 2021): • ESA Dual-CRYO workshop on dual band altimetry of the cryosphere. Online, 13-14 January 2021	Abstracts and presentations will be available for download at www.balticseal.eu/outputs Contact the main author if intending to use these materials or excerpts of them.
Python code for novice programmers to visualise along-track and gridded data products.	Available in the product handbook and via the www.balticseal.eu website. Free to use. Please accredit the code authors if doing so.
Python code for intermediate programmers to convert along-track data into .shp file formats, and gridded data into .tif format. This was created to assist with converting the netcdf data into GIS-compatable formats, in support of 3rd-level teaching and learning	Available in the product handbook and via the www.balticseal.eu website. Free to use. Please accredit the code authors if doing so.
Baltic+ SEAL Brand including logos and design created by ESA, and outreach material templates developed by the project team.	The logo design and templates are intended for use by the project team beyond the timeframe of the Baltic+ SEAL project. Please contact the project manager if interested in discussing usage.

External considerations framing future progress

In order to properly frame the road-mapping recommendations arising from the Baltic+ SEAL project, a number of workshop reports and available literature concerning sea level, altimetry, coastal altimetry and coastal challenges were analysed. The details of the literature analysis are provided in Annex B. By way of a summary, it is possible to see a high level of relevance of advances under Baltic+ SEAL to a number of needed action areas (table 7). These include the following considerations which should frame future endeavours:

- Facilitate **data access**;
- Obtain measurements **closer to the coast**;
- Integrate **more altimetry missions** and cross-calibrate them;
- Customize approaches (highlighting the importance of **regional and smaller scales**);
- Differentiate the coastal approach from the open ocean one, with **coastal-dedicated approaches**;
- Explore **new instruments, and processing** techniques;
- Integrate **stakeholder engagement** into advance efforts;
- **Outreach** about coastal altimetry;
- **Departitioning / Multidisciplinarity**;
- **Compare the outputs** of the various altimetry products;
- **Enhance uncertainty information** available with the data products.

***Table 7a**: Alignment of Baltic+ SEAL achievements with identified actions from literature (part 1 of 2).*

Advancement made	**Data access**	**closer to the coast**	**more altimetry missions**	**regional and smaller scales**	**coastal-dedicated approaches**	**new instruments, and processing**	**stakeholder engagement**	**Outreach**	**Departitioning / Multidisciplinarity**	**Compare the outputs**	**Enhance uncertainty information**
We have improved the exploitation of Satellite Altimetry data in areas that were previously not considered for the generation of gridded sea level products in the area of study, in particular sea-ice covered areas and coastal waters.	✓	✓								✓	
We have shown scientific advances that can be applied to other EO and ESA efforts, such as the Sea Level Climate Change Initiative. We have applied our dataset to study the influence of atmospheric processes on the sub-regional differences in sea level trend estimates in the Baltic Sea during the altimetry era. We have also shown the potential benefits of multiple temporal resolution products through producing the monthly, and an experimental 3-day, resolution gridded products.		✓				✓					
The provision of a regional monthly gridded sea level product, and an experimental 3-day temporal resolution gridded product, can foster the development of studies that deal with interactions between different ocean variables distributed in a similar manner, for example Sea Surface Temperature, Sea Surface Salinity. The high quality of the along-track product can be of particular interest for future applications combining high resolution sea level and sea state data.		✓		✓					✓	✓	
This roadmapping approach delivers a set of transposable, and costable, actions, and suggested potential scientific studies. It has proven to be a practical, useful approach to aid researchers engage with the first stage of the IP process - identifying foreground, and align their achievements which needs as gathered from the wider scientific literature. There is a capacity building challenge which the approach needed to adapt to, to ensure the researchers understand and appreciate the value of their endeavours, and the investment of their time in identifying their foreground.							✓	✓			
We have generated the requested product, overcoming several of the main limitations characterising the CCI-SL global sea level product, in particular: 1) The absence of cross-calibration between the along-track missions 2) The systematic flagging of any altimetry data close to the coast and in the sea-ice zone 3) The along-track filtering used to generate the global product, which results in a strong smoothing of the variability in the grids and is not tailored for regional applications			✓			✓				✓	

***Table 7b**: Alignment of Baltic+ SEAL achievements with identified actions from literature (part 2 of 2).*

Advancement made	**Data access**	**closer to the coast**	**more altimetry missions**	**regional and smaller scales**	**coastal-dedicated approaches**	**new instruments, and processing**	**stakeholder engagement**	**Outreach**	**Departitioning / Multidisciplinarity**	**Compare the outputs**	**Enhance uncertainty information**
This task [“*examine…classification*”] was fulfilled by the adoption and extension of the K-means unsupervised classification method						✓					✓
This task [“*examine…retracking*”] was fulfilled by the adoption and extension of the ALES+ algorithm for LRM missions and by the development of the ALES+ SAR algorithm for Delay-Doppler missions		✓				✓					
A dedicated Sea State Bias correction was computed for LRM missions based on the ALES+ estimations of SWH and Wind. An Ad-Hoc Sea State Bias model was designed for ALES+ SAR range estimations, by means of a crossover adjustment of the sea level differences in function of the estimated width of the leading edge.						✓					✓
The cross-calibration based on the MMXO technique (Bosch et al., 2014) has been adopted and expanded and enabled a multi-mission use of the data, which is currently absent in other international efforts dedicated to the improvement of coastal along-track data (such as CCI-SL)			✓			✓				✓	✓
A new Mean Sea Surface model was computed and is described in the IAR. This Mean Sea Surface, based on the along-track dataset developed in Baltic+ SEAL, reduces the error in particular in the coastal zone.		✓		✓							✓
A map of trends and annual seasonality of the sea level has been produced and successfully compared against Tide Gauges, showing very good agreement and improvements compared to the global datasets. These dataset has been analysed in terms of sub-basin differences and connection to atmospheric variability. The analysis is described in the IAR and it is the subject of a draft that will be submitted to peer review.				✓							✓
A derivation of VLM by Tide Gauges and Altimetry differentiations has been tested and described in the IAR. Remaining problems are the shortness of the along-track time series in the proximity of the tide gauges. Further studies and more time than what is was planned within Baltic+ SEAL will be needed to improve this technique.				✓		✓					✓

The Coastal Risk and Oceanographic Landscape

Detailed in Annex B, is the analysis of a range of workshop reports examined. The key relevant points noted by stakeholders, and of relevance to altimetry-derived sea level measurements, are outlined here.

Firstly, there is an emphasis in the literature on the need for more coastal information. The range of reports highlight the need to implement new observations where necessary, making use of both remotely-sensed and in-situ observations. Special emphasis should be given to the monitoring of coastal regions worldwide where a variety of climate- and non-climate-related processes interact. These observations can provide early warnings of local sea-level rise acceleration. There was an interesting note regarding polar regions, where stakeholders reported on the use of radar-based sea level sensors in polar regions. They recognized that additional research and/or technological solutions are required in ice impacted seas, however it does provide a flavour of the multi-sensor and data source approaches required to generate this needed coastal information.

Secondly, there are needs concerning the satellite-derived sea level data itself. Here, there are 2 primary needs to be addressed. The first is the need to improve accuracy estimates, and provide estimates of the associated uncertainty with the data. The need to reduce systemic errors is specifically highlighted, with the suggestion that increasingly refined calibration/validation and quality control procedures would help here, particularly if the data are provided with comprehensive uncertainty estimates. This would allow users to properly assess what the data could be used for, and identify where improvements are needed to unlock further avenues of exploitation. The second primary need concerns the temporal extent of the available sea level information. Stakeholders have specifically highlighted the advantages of continuity in the satellite-derived sea-level record, and the essential advantage to having a set of highly accurate and stable reference mission such as the Topex/Jason series.

Such improvements in accuracy, availability of smaller spatial scale information (closer to the coast), and the availability of extended timeframes of regularly estimated sea level data, would allow advances such as improved sea level budgets to be estimated. This is the kind of actionable information coastal stakeholders ultimately need from satellite-derived sea level data. The literature highlights the need to develop an open climate model, ingesting information from a range of models. The role of observations to provide enhanced calibration is highlighted here, particularly as the information needed from such a model is improved, trustable, and actionable, coastal sea level information in the areas of storm surges and waves, at high spatial and temporal resolutions.

With the development of trust in mind, the literature also highlights the need for enhanced engagement with the information users. It highlights the need to develop a stakeholder forum that enables timely and effective exchange of vital information for mitigation of and adaptation to sea-level change including present states of and projected changes in mean and extreme sea levels, wave conditions, and potential impacts such as changes in coastal flooding events, coastal erosion, and saltwater intrusion. Here, it is recognised that all application-centred projects involve a measure of stakeholder engagement and community development. The key is to introduce an element of engagement coordination and community development across the range of different sea level projects. This would ensure that sea-level coastal stakeholders, engaged through either global and/or regional initiatives, are encouraged to consolidate their support in a coordinated, and rewarding, pan-project stakeholder forum.

Existing and future European satellite missions

We are currently in an unprecedented era for satellite altimetry. There have never been so many altimeters functioning in orbit at the same time. Furthermore, it is encouraging to note that 4 of them are ESA missions (Cryosat-2, Sentinel-3a, Sentinel-3b, Sentinel-6). This fleet of altimeters presents a great exploitation potential. In particular, it magnifies our capability to acquire and provide detailed snapshots of global and regional level, whilst at the same time, presents several challenges in terms of data handling. In the Baltic Sea for example, this wide availability markedly increases the potential to observe sea level dynamics before, during and after a storm surge event. This enhanced awareness can improve or verify regional models, and ultimately improve the resilience of coastal communities.

Aside from guaranteeing the continuity of service along the Jason tracks, the incoming Sentinel-6 measurements are of particular interest. Sentinel-6 will allow the experimental production of waveforms based on the so-called “Fully-Focused SAR” technique. This highlights the potential for the Baltic Sea region to be used to explore and understand the retracking of these waveforms. Such work will be necessary, given that the across-track dimension is still the same of traditional altimetry. Moreover, studies on the exploitation of these measurements can be undertaken in terms of noise reduction, sea level retrievals from sea-ice leads, and developing dedicated sea state bias correction.

While the future SWOT mission will hopefully contribute to insights into sea level variability at 15-200 km spatial scales, its 21-days repeat cycle does not exempt it from filtering and interpolation schemes. Moreover, given the new mission concept, a previous knowledge of the local variability will be needed to assess and validate SWOT′s new data, and derived sea level information. The success of this mission in the coastal and shelf seas will be highly dependent on (i) regional efforts such as Baltic+ SEAL, and (i) the capability to exploit the full altimetry constellation and auxiliary data, to unveil and interpret variations at high temporal and spatial resolutions. Both of these issues were examined by this project, which therefore aims at significantly contributing to this important milestone in the success of the next altimetry era.

Capitalising on the existing European Big Data infrastructure to animate advances

Europe is quickly advancing capacity in Big Data processing infrastructure. From the European Space Agency side, investment in the Thematic Exploitation Platforms (TEPs) has produced a suite of high-end federated computing platforms, designed to support information extraction from rapidly growing archives of satellite-derived measurements. Of note here, is the Coastal TEP[5], a virtual platform where EO data and in-situ coastal data may be accessed, processed, analysed and shared for the enhancement of our maritime management, research and development sectors. This facility has already integrated processing chains dedicated to satellite-derived altimetry data, namely to demonstrate the extraction of storm surge information from altimetry datasets. This available experience in integrating altimetry processing chains into Big Data facilities is also seen in another, European Commission-funded experimental platform – the Coastal Waters Research Synergy Framework (Co-ReSyF)[6], a more research-focused platform. The existence of both indicates there is expertise in Europe to integrate complex altimetry-processing chains into research and applications data processing facilities.

In parallel, the European Union has invested heavily in the Copernicus Programme. In addition to the more physical infrastructure such as the Sentinels operated by the ESA, the Programme has also established data archiving and access hubs. Both climate- and ocean-focused facilities, the Copernicus Marine Environment Monitoring Service[7], and the Copernicus Climate Change Service[8] host global data, however, regionalised datasets which exploit advanced coastal and sea-ice dedicated techniques (such as those produced under the

[5] www.coastal-tep.eu [last accessed 22nd December, 2020]

[6] www.co-resyf.eu [last accessed 22nd December, 2020]

[7] https://marine.copernicus.eu/ [last accessed 22nd December, 2020]

[8] https://cds.climate.copernicus.eu/ [last accessed 22nd December, 2020]

Baltic+ SEAL project) are not available in Copernicus data hubs. Furthermore they are only available as single-mission along-track data within the framework of the ESA CCI-SL. These data search and access points are now complemented by the European Commission's Data and Information Access Services (DIAS), five online cloud platforms which provide access to, and tools to analyse, Copernicus data (including Earth Observation data)[9].

While these TEPS, Copernicus data access facilities, and DIASs are rapidly establishing themselves at the heart of European Earth Observation processing, a third asset must be considered – the ESA Grid Processing on Demand (ESA GPOD) for Earth Observation Applications. The ESA GPOD is an asset of immense importance to advancing the application of processing algorithms devised under Baltic+ SEAL. It is a grid computing environment and provides online and on-demand data processing services. Using ESA GPOD, specific data handling applications can be integrated, and coupled with high-performance and sizeable computing resources, magnifying the data processing potential. Concerning altimetry data, the team have noted that the ALES+ SAR retracker has been integrated into the ESA GPOD architecture (for Sentinel-3 and Cryosat 2 data). Furthermore, the tools associated with the ESA GPOD/SARvatore family of services (SAR processors & retrackers) proved to be an essential element of tackling and examining difficult targets as highlighted by the outliers, and develop solutions and insights for future applications. As such, there is remarkable potential to animate interest in altimetry, should the other specific processing chains developed by the Baltic+ SEAL team (for the wide range of altimetry missions), be integrated into the ESA GPOD architecture. This interest would be maximised if coupled with coordinated awareness raising of the consolidated assets availability.

This third asset is already established, and has a proved track record in supporting high volume information extraction from Earth Observation, and research into understanding the complexities of altimetry waveforms. It also addresses an existing need to provide a space to experiment and further advance our understanding of altimetry waveform use. The case for such dedicated research-focused online processing platforms has been made by the user-needs assessment conducted under the H2020 Co-ReSyF project[10], which highlights their niche requirements in comparison to more commercially-focused wider-use platforms. Strategic use of the ESA G-POD facility should be an essential part of this Europe-wide infrastructure for Earth Observation data processing. Much like the Baltic Sea, the ESA G-POD facility is a potential testbed, where processing chains to extract good quality sea level information from altimetry data, are tried, tested and refined before being exported to the more publically available TEPs and Copernicus suit of data processing facilities.

The Next Generation of Altimetry-data users.

At its heart, Baltic+ SEAL had the mission of providing altimetry data that uses advanced processing to users that would like to exploit the information, but are not altimetry experts. Reinforcing this, the Coastal Altimetry Community has often lamented the lack of clarity for novice users, in the provision of dedicated sea level products. Altimetry-derived sea level products require comprehensive understanding of altimetry should a user wish to use them. Furthermore, they are typically distributed in efficient, NetCDF, formats, which are difficult to integrate into third level education practicals. These practicals focus less on programming, and more on teaching students to use the wide range of commercial and open source GIS software available to explore a scientific quandary (such as Climate Change and sea level), providing an opportunity for products delivered in easy-to-integrate formats. This requires programming skills the students are highly unlikely to possess, should they wish to begin exploring the data. The team also recognise the efforts of the Climate Change Initiative team in developing the CCI App., a downloadable visualisation tool which can be used by educators to teach the principals of Climate Change to a range of

[9] https://www.copernicus.eu/en/access-data/dias [last accessed 22nd December, 2020]

[10] Publically available at http://co-resyf.eu/wordpress/wp-content/uploads/2019/01/CORESYF-UCC-TEC-SRD03-E-R_User-Community-Requirements-Document_V2_1.1.pdf [last accessd 4th January, 2020], or via https://cordis.europa.eu/project/id/687289/results [last accessed 4th January, 2020]

primary and secondary level audiences[11] Finally the team recognise the expertise held in the European Space Education Resource Office (ESERO), whose national partnership teams have a tailored knowledge of member states primary and secondary level education systems, and the teaching practices which can benefit those seeking to expand EO data engagement in the third level system.

To address this opportunity in a small way, the Baltic+ SEAL team have developed a suite of simple, Python programming codes, to enable novice programmers to visualise the along-track and gridded data, and if they wish to, convert the datasets into GIS-enabled formats (along-track *.shp* files, and gridded *.tif* files). These freely available codes can also be used by educators themselves, to quickly convert a large volume of Baltic+ SEAL datasets into GIS-enabled formats for use in GIS practicals where the issue of sea level is explored by the next generation of sea level data users, and potential additions to the more specialised altimetry community.

Potential ESA project synergies

There are four primary ESA-funded initiatives which could synergise with activities arising from Baltic+ SEAL. The first set are the two complimentary projects in the ESA Baltic+ family. The Baltic+ Salinity, and the Baltic+ Reference Systems projects. The second set are under the more global ESA Climate Change Initiative Programme. These are the ESA CCI Sea Level project, and the ESA CCI Sea State project. Potential synergies are briefly outlined here per-project.

Synergy with Baltic+ Salinity

To be explored is the detection and monitoring of the Atlantic salinity inflow and its recirculation inside the basin by presenting a preliminary assessment of the consistency between structures detected in Baltic+ Salinity-produced Sea Surface Salinity (SSS) maps and circulation patterns derived from Baltic+ SEAL altimetry observations. As an example of application the following can be analysed: how SSS and Sea Surface Height (SSH) reflect the mean flow condition across the Danish strait and how they react by local wind conditions and larger atmospheric circulation patterns. Moreover, the synergy of SSS and sea level data can characterise the gradient in sea level trend that is observed in the last decades between S-W and N-E sub-basins and that is likely to be caused by interannual anomalies in the winter westerlies wind forcing. This can be also done in terms of a regional sea level budget, using SSS data in synergy with sea surface temperature and ARGO/CTD profilers to derive a steric sea level component.

Synergy with Baltic+ Geodetic SAR for Baltic Height System Unification (SAR-HSU)

To be explored is the comparison between Vertical Land Motion derived from the connection of tide gauge markers with the GNSS network geometrically by the geodetic SAR technique and the difference between Tide Gauges and Satellite Altimetry. This synergy would be a significant advance in the cross-validation of techniques to study Vertical Land Motion that can be exported to other areas of the world. Moreover, the height system unification and determination of the absolute sea level at tide gauges allow for the chance of an absolute validation of the altimeters and can be very effective in test the incoming new altimetry missions (Sentinel-6, SWOT)

Synergy with the CCI Sea Level project

The current phase of the Sea Level CCI project has several similarities with the Baltic+ SEAL project. In particular, both projects have similar primary objectives: to determine sea level trend; to exploit dedicated retracking strategies and corrections to maximise the uptake of data close to the coast; and to develop a regional focus. With this in mind, the Baltic+ SEAL project has provided advances in knowledge that can be exploited by Sea Level CCI. More specifically, the Sea Level CCI does not yet have a strategy to cross-calibrate the along-track data provided to users. Cross-calibration implementation is restricted to a gridding step for the global product. This restrains users from exploiting along-track mission data of different tracks in synergy, and restricts them from removing Geographic Correlated Errors. Baltic+ SEAL has developed a

[11] Scarrott, R., McSweeney, C. (2016) *Food for thought: Some observations from using the CCI Visualisation tool in teaching school groups and the public.* Presentation to the ESA CCI Collocation Meeting October 5th, 2016, ESA ESRIN.

technique based on multi-mission crossover comparisons, which solve this problem by providing an inter-mission correction for various locations across the Baltic Sea. Secondly, Baltic+ SEAL has demonstrated for the first time, an approach to producing a dedicated gridded product which exploits the information coming from areas close to the coast, and information from the sea-ice covered region. Should the Sea Level CCI advance the production of its dedicated gridded product to incorporate coastal and shelf seas (potentially using the Baltic+ SEAL methodologies), the pool of users that are able to exploit this innovative altimetry data can be magnified. This is particularly relevant given the identified need for more regionalised, and smaller scale applications of altimetry-derived sea level products, with more validity closer to coastlines.

Synergy with the CCI Sea State project

The Sea State CCI (CCI-SS) is about to release a new multi-mission significant wave height dataset that promises to significantly increase the data availability in the coastal zone. This would be a great chance to study trends and extremes in sea state climate in the Baltic Sea and the interconnections with trends and extremes in sea surface height. Stakeholders and modellers would be particularly interested in understanding more about events in which storm surges combine with high waves and this synergy would surely contribute to this effort.

Barriers and challenges to achieving potential for future progress

The following barriers and challenges must be considered when framing and charting the way forward:

Restrictions in reprocessing of TOPEX data.

For regional sea level studies, it is detrimental to produce high-spatial resolution gridded sea level products using data acquired using only a single altimeter. Therefore, the use of TOPEX data is required at a minimum from 1995 onwards (the date of launch of ERS-2 satellite). This enables the inclusion of 6 years of data where otherwise only ERS-2 would be available (given the issues encountered by ERS-1). The current Sensor Geophysical Data Records of TOPEX mission do not provide enough information and documentation to allow for a dedicated reprocessing exercise. This was shown to lead to a substantial decrease in data quality compared to the other missions reprocessed in the project (see Validation Report v1). Until new, improved TOPEX records are available (in a similar manner to that done by ESA with the REAPER project for ERS-1 and 2), it will be impossible to know whether the high-rate data (10-Hz) of TOPEX can be more optimally retracked and corrected.

Lack of knowledge in appropriate gridding approaches

Relative to the effort investment across the range of advances made under Baltic+ SEAL, the gridding of along-track data has received comparably less attention, in comparison to the algorithm development of along-track products for example. Nevertheless, significant challenges were noted, which restrain progress potential. In particular, advances in the following areas would overcome these encountered challenges:

- advances in data quality control,
- development of an adaptive search-radius when interpolating sea level measurements,
- integration of external data to better characterise the covariance matrix in the interpolation process and to provide an information about accuracy that goes beyond the pure statistical uncertainty.

Sub-optimal along-track quality control, and excessive data loss

The primary objective of this project was to provide a monthly sea level gridded product for sea level trend and variability studies at a basin scale. In order to achieve this, quality control was needed, to ensure the data provided to the general public are as free as possible from outliers. For this reason, as a first, safe approximation, a flag is raised for all measurements closer than 3 km from the coast. Given that the Baltic Sea is characterised by tens of thousands of small islands, this resulted in a significant amount of data that will be unexploited. Preliminary studies have confirmed that, especially in the case of Delay-Doppler altimeters, many of these measurements are actually of very good quality. The future challenge therefore is to refine the quality control approach. One option is to choose dedicated sub-basins characterised by small scale variability, such as the Gulf of Riga, where local tests to improve the quality control of along-track data and suppress the 3-km flag can be undertaken.

Recommended Priority Scientific Activities

Analysis of the above contextual information reveals a number of scientific activities which can be implemented. These can also be combined with scientific activities identified by the Baltic+ SEAL team over the course of the project (shown in Annex C) to produce the following recommendations, and cross-referenced with the literature actions to provide a perspective on potential impact (Table 8). Note that a number of the options provided may appear more than once, as they could be implemented under a number of different primary research activities (marked bulleted with an arrow), and themes (in bold).

Integrating Baltic+ SEAL data into use cases demonstrations

- ➢ Develop regional hydrodynamic tide models to estimate tides, to optimise sea level measurements derived from altimetry sensors.
- ➢ Implement a regional case-study examination of sea level for the Baltic Sea. Aspects to examine include:
  - comparing the mass versus steric Sea Level changes in the region;
  - clarifying the Baltic sea level budget, integrating altimetry data with data from Argo floats and cruise measurements, Sea Surface Salinity data, and Sea Surface Temperature data (for the steric component), and mass data from the GRACE and GRACE-FO missions;
  - examining regionally-external influences on trends in sea level;
  - examining sea level and sea state extremes in the Baltic Sea, in a similar manner to the North Sea under the past "ESA eSurge" project.
- ➢ Implement a regional (Baltic+ style) study focused on examining combined sea-level, significant wave height and sea state extremes within a region. Ensure the study:
  - improves the local dataset concerning wave climate;
  - quantifies local trends in wave height, sea state, and sea level.

Conducting synergy studies using Baltic+ SEAL data

- Implement studies to demonstrate synergies between altimetry and other data sources. Examples include studies to:
  - clarifying the Baltic sea level budget, integrating altimetry data with data from Argo floats and cruise measurements, Sea Surface Salinity data, and Sea Surface Temperature data (for the steric component), and mass data from the GRACE and GRACE-FO missions;
  - use the ESA GPOD/SARvatore family of services (SAR processors and retrackers), to examine difficult altimetry targets highlighted outliers, and develop solutions and insights for future applications.

Conducting regional studies using Baltic+ SEAL data and approaches

- Implement a range of regional demonstrations of altimetry-derived measurement use, including:
  - test the application of developments produced within the Baltic+ SEAL context to other regions. In particular, prioritise European areas of strategic interest (e.g. the Atlantic Coast of Ireland), and areas of the world with poor access to local in-situ data.
  - use the Northern Baltic as a test site to exploit improved SAR processing schemes (e.g. fully-focused SAR, FF-SAR), and exploiting the future availability of FF-SAR processors for Cryosat-2, Sentinel-3 and Sentinel-6 data on the ESA-GPOD platform.
  - examine sea ice thickness of the Baltic Sea using altimetry. This may involve mapping the outliers and clarifying the physical explanation behind it, perhaps cross-referencing with available optical data. Note that improvements could complement the future ESA CRISTAL Mission. Also note that (i) data from the Cryosat-2 mission would also help for this region – namely the utility of the Cryosat-SARIn products and those from the ICEsat mission, and (ii) further study of this issue could guide changes to the current sea-ice mask used within the Baltic+ SEAL project.
  - conduct targeted CCI-Sea Level studies with a regional perspective of use in mind, noting that this may require regional feedback to be gathered and analysed.

Advancing the field of altimetry science

- Implement a focused study to optimise interpolation techniques for coastal-dedicated gridding.
- Implement a study into the power spectrum of noise in the altimetry data, towards developing a model to capture the spectral features detected.
- Implement studies to advance altimetry retrackers. Studies are advised to include a selection from the following options:
    - compare and contrast the outputs of the ALES+ SAR and SAMOSA++ retracking processors;
    - enhance leading edge analyses to account for lessons learned from the ALES+SAR – SAMOSA comparison undertaken in coordination with Baltic+SEAL.;
    - examine the potential of using the variable sub-waveform width to improve the ALES+ SAR retracker;
    - explore possibilities to classify and retrack TOPEX measurements, should new re-processing and dedicated documentation become available;
    - develop dedicated retracking techniques for Fully Focused SAR data from the Sentinel-6 mission;
    - implement an inter-comparison of ALES+SAR and other retrackers developed for coastal zones, and sea-ice leads. The availability of multiple processors on the same platform (e.g. the ESA GPOD platform with both the SAMOSA+ and SAMOSA++ processors) would be beneficial here;
    - demonstrate the potential for synergy examinations of issues with altimetry data, using different sensor products (e.g. Sentinel-1 SAR, Sentinel-2 optical, Sentinel-6 products etc.).
- Implement a targeted study to improve Sea State Bias estimations. Studies should focus on:
    - examining the validity of the Sea State Bias correction in nearshore locations;
    - exploiting the decorrelation of SWH-SLA errors from retracking, in particular in LRM altimetry, to decrease the high-rate noise and subsequently recompute a SSB model;
    - exploiting as-yet-unidentified approaches to improve the Sea State Bias estimate.

Promoting scientific uptake of data and approaches beyond Baltic+ SEAL

- Demonstrate the potential of applying Baltic+ SEAL data and approaches. In particular:
    - examine the potential for the multi-mission cross-calibration approach from Baltic+ SEAL to be integrated into CCI Sea Level processing approaches;
    - develop a regional hydrodynamic tide model to estimate tides, which optimises sea level measurements derived from altimetry sensors;
    - examine regionally-external influences on trends in Sea level (as measured and processed under Baltic+ SEAL);
    - Optimise the 3-day gridded product approach, to make it suitable for testing as a storm surge preconditioning product.

Enhancing CCI products with Baltic+ SEAL insights

- Implement targeted studies to enhance the existing Sea Level CCI suite of products. In particular, focus on:
    - implementing regional CCI-SL studies and algorithm performance improvements (noting this will require regional feedback to be gathered and analysed);
    - examining the potential for the multi-mission cross-correlation approach from Baltic+ SEAL to be integrated into CCI Sea Level processing approaches.

***Table 8**: Alignment of consolidated potential scientific activities beyond Baltic+ SEAL to meet identified actions from literature*

Advancement proposed	**Relevance beyond Baltic+ SEAL**										
	Data access	**closer to the coast**	**more altimetry missions**	**regional and smaller scales**	**coastal-dedicated approaches**	**new instruments, and processing**	**stakeholder engagement**	**Outreach**	**Departitioning / Multidisciplinarity**	**Compare the outputs**	**Enhance uncertainty information**
Develop regional hydrodynamic tide models to estimate tides, to optimise sea level measurements derived from altimetry sensors.				✓		✓			✓		✓
Implement a regional case-study examination of sea level for the Baltic Sea.		✓		✓			✓	✓			
Implement a regional (Baltic+ style) study focused on examining combined sea-level, significant wave height and sea state extremes within a region.				✓			✓		✓		
Implement studies to demonstrate synergies between altimetry and other data sources.			✓			✓			✓		
Implement a range of regional demonstrations of altimetry-derived measurement use.				✓			✓				
Implement a focused study to optimise interpolation techniques for coastal-dedicated gridding.		✓		✓	✓	✓			✓		
Implement a study into the power spectrum of noise in the altimetry data, towards developing a model to capture the spectral features detected.						✓					
Implement studies to advance altimetry retrackers.			✓			✓			✓		✓
Implement a targeted study to improve Sea State Bias estimations.						✓					✓
Demonstrate the potential of applying Baltic+ SEAL data and approaches.		✓		✓	✓		✓	✓		✓	
Implement targeted studies to enhance the existing Sea Level CCI suite of products.		✓			✓					✓	

Recommended Priority support activities

Analysis of the contextual information and internal Baltic+ SEAL documentation also revealed a number of potentially impactful support activities (Actions), which could magnify the impact of existing Baltic+ SEAL advances, and the priority scientific activities outlined previously. These are outlined here and are cross-referenced with the literature actions to provide a perspective on potential impact in Table 9.

Enhancing the Baltic Sea region as a development site for altimetry research.

- Lobby, and if possible support, the expansion of Baltic Sea TG networks, to address the southern shoreline gap.

Expanding access to Baltic+ SEAL processing developments to maximise uptake of knowledge.

- Integrate the wide range of mission-specific Baltic+ SEAL processing chains into the ESA GPOD architecture. The availability of multiple processors on the same platform (e.g. the ESA GPOD platform with both the SAMOSA+ and SAMOSA++ processors) would be beneficial to a range of end users, and enhance the capacity for algorithm performance assessment in novel areas.
- Raise awareness of the consolidated asset made available on the ESA GPOD platform.

Engaging the next generation of potential altimetry data users

- Examine the use of Baltic+ SEAL products for standardised educational purposes considering:
    - the development of open access training courses/modules in altimetry, coastal altimetry, and altimetry over sea-ice areas;
    - the development of open access practicals in altimetry-derived sea level data use;
    - the development of validation practicals, using real data from the Baltic Sea tide gauge network, and the Baltic+ SEAL suite of sea level products;
    - the development of a suite of coastal altimetry training for novices, which connect with new generation of scientist and users using tools that are commonly used to teach (e.g. standard GIS software), as opposed to those requiring a high level of coding capability.
- Explore the potential for sea-level-themed capacity-building activities which:
    - specifically target third level undergrads and MSc's
    - bring students to altimetry data through sea level
    - are thematically focused on non-EO subject areas (e.g. sea level monitoring; storm surge modelling and measuring; coastal inundation trends and adaptation etc.)

***Table 9**: Alignment of consolidated support activities beyond Baltic+ SEAL to meet identified actions from literature*

Support Activity Proposed	Relevance beyond Baltic+ SEAL										
	Data access	**closer to the coast**	**more altimetry missions**	**regional and smaller scales**	**coastal-dedicated approaches**	**new instruments, and processing**	**stakeholder engagement**	**Outreach**	**Departitioning / Multidisciplinarity**	**Compare the outputs**	**Enhance uncertainty information**
Lobby, and if possible support, the expansion of Baltic Sea TG networks, to address the southern shoreline gap.		✓								✓	✓
Integrate the wide range of mission-specific Baltic+ SEAL processing chains into the ESA GPOD architecture.	✓					✓	✓			✓	
Raise awareness of the consolidated asset made available on the ESA GPOD platform.	✓						✓	✓		✓	
Examine the use of Baltic+ SEAL products for standardised educational purposes							✓	✓			
Explore the potential for sea-level-themed capacity-building activities							✓	✓			

Fuelling further advancement of ESA Baltic+ SEAL

The above range of actions (scientific and support activities), represent options for scientific advancement, and options to enhance the impact of these advances. Each option presents a cost of investment. To support decision making, a first estimate of costs for each **scientific activity** avenue is presented here (Table 10 and Annex D). Where a single activity is proposed within an action avenue, a single figure is presented. Where there are options within the single activity, a range of costs from lowest to highest is presented.

Costs have been calculated as follows:

- For each specific activity, and sub-option, a best case scenario (A), worst case scenario (C) with extensive costs, and a medium option scenario (B) are given a cost in terms of effort. The given cost of the activity is calculated as:

$$\frac{A + 3B + C}{5}$$

- For those activities without options, a baseline cost is added into the A, B, and C scenarios. For the monthly cost rate, the Baltic+ SEAL overall cost per month was used, increased by adding 2% (the European Central Bank's target inflation rate). Full details and formulas are in Annex D.
- For those activities with options:
    - the baseline cost is separated out. It is then added to the lowest cost option, and the highest cost option to provide the range of costs. For the baseline cost of an activity, the team have used the cost of Baltic+ SEAL Work package 6 per month, and increased this by adding 2% (the European Central Bank's target inflation rate). Full details and formulas are in Annex D.
    - the cost of each option per month is the (Baltic+SEAL total – Baltic+ SEAL WP6) per month, with an additional 2% (the European Central Banks target inflation rate). Full details and formulas are in Annex D.

This approach is considered a first estimate of potential costs. These estimates are preliminary, non-binding, and open to revision. The approach takes into account the risk associated with scientific advancement, where significant challenges are unexpectedly encountered (the C scenario). Averaging thus weights the estimates towards the higher figures should the activity be deemed of exceedingly high risk potential, particularly where the activity progresses fundamental scientific advancement.

A detailed breakdown of the estimates per activity and per options is available in Annex D of this report. Annex D also contains the formulas used, and the assumptions used in estimating the costs.

***Table 10**: Alignment of consolidated potential scientific activities beyond Baltic+ SEAL to meet identified actions from literature. A more detailed breakdown of costs per activity and per option is available in Annex D, supplied with this roadmap report.*

Advancement proposed	**Max. timeframe (months)**	**Cost estimate**
Develop regional hydrodynamic tide models to estimate tides, to optimise sea level measurements derived from altimetry sensors.	18	€318,000
Implement a regional case-study examination of sea level for the Baltic Sea.	18	€81,000 - €386,000
Implement a regional (Baltic+ style) study focused on examining combined sea-level, significant wave height and sea state extremes within a region.	15	€71,000 - €185,000
Implement studies to demonstrate synergies between altimetry and other data sources.	15	€84,000 - €257,000
Implement a range of regional demonstrations of altimetry-derived measurement use.	24	€99,000 - €740,000
Implement a focused study to optimise interpolation techniques for coastal-dedicated gridding.	12	€216,000
Implement a study into the power spectrum of noise in the altimetry data, towards developing a model to capture the spectral features detected.	6	€108,000
Implement studies to advance altimetry retrackers.	21	€93,000 - €758,000
Implement a targeted study to improve Sea State Bias estimations.	15	€99,000 - €311,000
Demonstrate the potential of applying Baltic+ SEAL data and approaches.	30	€128,000 - €692,000
Implement targeted studies to enhance the existing Sea Level CCI suite of products.	21	€180,000 - €464,000
Support Action proposed		**Cost estimate**
Lobby, and if possible support, the expansion of Baltic Sea TG networks, to address the southern shoreline gap.	Not estimated	Not costed
Integrate the wide range of mission-specific Baltic+ SEAL processing chains into the ESA GPOD architecture.	Not estimated	Not costed
Raise awareness of the consolidated asset made available on the ESA GPOD platform.	Not estimated	Not costed
Examine the use of Baltic+ SEAL products for standardised educational purposes	Not estimated	Not costed
Explore the potential for sea-level-themed capacity-building activities	Not estimated	Not costed

Annex A

To discuss access to the detailed foreground information, please contact the project manager Dr. Marcello Passaro at Marcello.passaro@tum.de

Annex B

For access to the detailed excel spreadsheet containing the literature review analysis, contact the project manager Dr. Marcello Passaro at Marcello.passaro@tum.de

Annex C

For access to the detailed excel spreadsheet containing the activity analysis, contact the project manager Dr. Marcello Passaro at Marcello.passaro@tum.de

Annex D

For access to the detailed costs, please contact the project manager Dr. Marcello Passaro at Marcello.passaro@tum.de

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