Final Report

LOTUS - Preparing Land and Ocean Take Up from Sentinel-3

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SEVENTH FRAMEWORK PROGRAMME

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1 Executive summary

Continuous monitoring of the Earth is important in relation to understanding climate change and to maintain value adding services. Satellite altimetry has been applied since the late 70s to monitor the ocean surface elevation. The technique has later proven to be successful for other surfaces such as, continental ice, sea ice and continental water. The launch of CryoSat-2 (and the upcoming Sentinel-3) has marked a new era of satellite altimetry with the revolutionary SAR altimeter on-board, which provides an along-track resolution of 300m.

The main objectives of the LOTUS project have been to develop new methodologies to handle the data from the SAR altimeter, provide prototype data sets, and develop new and innovative applications of the SAR altimetry products.

For the ocean the SAR data and the methodologies developed in the project have resulted in products with a generally higher resolution and accuracy. At coastal regions more accurate estimates of sea surface height, wave height and wind speed can now be obtained much closer to the coast. For the Polar Ocean a significantly larger amount of useful data is now available, since the higher along-track resolution makes it possible to obtain better estimates of sea surface height from leads in the sea ice.

Over land the higher along-track resolution has implied a more precise estimation of the water level for continental water. The higher resolution has made it possible to study much smaller water bodies and the improved precision has made it possible to detect water levels changes below the decimetre level in favourable conditions. The LOTUS project has furthermore investigated two newer and innovative applications of satellite altimetry over land; soil moisture and snow depth. Soil moisture has successfully been derived from CryoSat-2 low-resolution data in selected deserts. During the project it was demonstrated that deriving snow depth from satellite altimetry shows great potential.

The derived prototype data sets for the ocean were applied in coastal scale hydrodynamics and provided essential information regarding both sea surface elevations and for significant wave heights to coastal processes

The derived prototype data for continental water, river levels over the Brahmaputra River, were incorporated into a hydrological model of the basin, where these proved to be useful.

In conclusion the LOTUS project has successfully demonstrated the usefulness and importance of SAR mode satellite altimetry. The developed methodologies and the experience gained in the project will be of great use to others in upcoming projects related to e.g. Sentinel-3.

2 Project context and objectives

The LOTUS project was established in order to prepare a basis for the development of innovative new Copernicus products or applications based on operational space data availability from European Sentinel-3 satellites. LOTUS was initiated to utilise the new capabilities of the Sentinel-3 SRAL instruments and develop new products with increased resolution for both marine and land Copernicus services.

Unfortunately, Sentinel-3 is still not launched (expected within spring 2016) which means that this document will only be able to describe the potential impact of the Sentinel-3 data based on modelling and studies using the predecessor altimeter on-board the Cryosat-2 satellite. This instrument, however, differs in several significant points with respect to the upcoming Sentinel-3 SRAL sensor. Consequently it is important to bear these differences in mind when fully evaluating the future impact of the upcoming operational Sentinel-3 data. Sentinel-3 data will be of higher quality and lower latency compared to Cryosat-2 data used in LOTUS, which will increase user-uptake and impact significantly and even beyond what could been found in LOTUS. Particularly:

- Sentinel-3 will be an operational satellite. Cryosat-2 is an Earth Explorer satellite with no guarantee on data quality and continuity. Typical delivery time of low level Cryosat-2 data from ESA is one – two months. Hence, in LOTUS we performed data processing and quality enhancement of these data in order to use these data for various demonstration studies.

- For Sentinel-3 Near-Real Time data is expected to be delivered to the users within 3 hours for observations taken on-board Sentinel-3 enabling far better use for i.e. search and rescue and flooding/surges. In the LOTUS project it was necessary to design and rely on hind-cast modelling as data delivery time from Cryosat-2 is several months.

- Sentinel-3 will carry a radiometer to increase the accuracy of the data. Cryosat-2 does not carry an on-board radiometer, which means that the quality of the Cryosat-2 data used in the LOTUS project will not meet the quality of the Setinel-3 data.

- Sentinel-3 will operate in an exact repeat orbit providing observations every 27 days along predefined ground tracks. Cryosat-2 is in an experimental mission which is only able to provide data at fixed locations on the ground with one-year intervals.

Regarding the SRAL instrument, numerous studies in LOTUS confirms that the Cryosat-2 dataset have shown the very good performance of SAR altimetry, compared to the classical Low Resolution Mode (LRM) for retrieving higher resolution, higher accuracy along-track sea level anomaly (SLA). Most notably, SAR altimeter data from Cryosat-2 show much reduced noise at scales between 20 and 50 km compared to traditional altimetry (Envisat and/or Jason-2).

Hence, the LOTUS project has been able to develop new and improved coastal oceanographic services by utilizing the new data. Also, the LOTUS project has been able to develop new and improved land services by utilizing the Cryosat-2 data and find these to be even more prosperous with Sentinel-3. Several of these services will be described in Section 3.

2.1 Main purpose of the LOTUS project

The objective of the LOTUS project was to support the development of Copernicus by developing applications of Sentinel-3 to complete the space observation infrastructure that are designed for land and ocean monitoring for Copernicus (previously called Copernicus). Sentinel-3 is the space component for monitoring the oceans. The SRAL instrument on-board Sentinel-3 is a radar altimeter that provides observations of sea-surface and land-ice topography, in continuation of altimeter missions such as Envisat, Jason-1, and Jason-2. Furthermore, the SRAL instrument will operate in a Synthetic Aperture Radar (SAR) mode and provide along-track high-resolution heights globally. Up until the beginning of the LOTUS project the SAR capabilities were relatively unexplored and no data products based on SAR mode were provided or used operationally. Therefore, new methodologies as well as data processing chains needed to be developed to prepare the take-up of the Copernicus Sentinel-3 data. As Sentinel-3 has not yet been launched at the time of writing this final report of the LOTUS project, the primary dataset has been Cryosat-2, which is the first satellite mission to carry a SAR altimeter.

Within the LOTUS project, new methodologies, data processing chains, and applications for SAR mode data were developed, which will contribute to high-resolution sea surface heights, wave heights, and wind speeds in the open oceans, coastal seas, as well as in sea ice covered regions for operational marine services. In the same manner, the LOTUS project has contributed to operational land services with SAR mode data for inland water levels in river and lakes, soil moisture, and snow depth. With these data, the LOTUS project can support operational services for emergency response and security in the events of, e.g., storm surges and flooding. The new land products provide valuable information about the hydrological cycle and supports services on monitoring hydrological parameters for climate change. Through a strong involvement of innovative companies and SMEs the LOTUS project will stimulate new commercial activities in the value-adding sector.

2.2 Objectives of work packages

The scientific part of the LOTUS project was divided into 7 work packages, with a total of 37 tasks. The objective of each work package can be seen below.

2.2.1 Objectives of WP 1: Processing of SRAL SAR mode waveforms over ocean

The objective for the first work package in the LOTUS project was to develop a processing scheme for extracting high-resolution sea surface heights, wave heights, and wind speeds from SAR mode data. In addition, LOTUS has applied the RDSAR (Reduced SAR) technique to convert SAR mode data into Low Resolution Mode (LRM) data, which complement the open ocean LRM data sets in coastal areas and secure a seamless transition between converted SAR mode data and open ocean and open ocean LRM products. The work package was subdivided into three themes: open ocean, polar ocean, and coastal zone.

2.2.2 Objectives of WP 2: Processing of SRAL SAR mode waveforms over land

The second work package aimed at developing processing schemes for extracting high-resolution river and lake heights, soil moisture, and snow depths. Detailed reviews of existing relevant algorithms for LRM and SAR mode data for each of these purposes were performed, and new methods were subsequently developed.

2.2.3 Objectives of WP 3: Definition of new data products and processing chains

Based on the specification and development of processing chains for SAR mode data in WP1 and WP2, higher-level products were designed. In work package 3, several kinds of data products and processing chains were defined and designed, addressing different surface targets of the Sentinel-3 topography measurement:

- Sea surface heights, wave heights, and wind speeds
- River and lake levels
- Soil moisture
- Snow water equivalent

2.2.4 Objectives of WP 4: Production of demo data and assessment

The objective of the LOTUS project has been to prepare prototype Sentinel-3 data sets to support the development of new value-adding applications for ocean and land services, respectively. As Sentinel-3 has not yet been launched at the time of writing this final report of the LOTUS project, the primary dataset has been Cryosat-2. However, the methods have been developed so that when Sentinel-3 data become available, adaption will be straightforward. Cryosat-2 SAR data has been processed in specific targeted test areas to prepare prototype data sets for the surface targets specified in Section 2.2.3 above.

2.2.5 Objectives of WP 5: Applications of new Copernicus data in value-adding ocean services

The objective of this work package has been to develop new and improved coastal oceanographic services by utilizing the data features emerging with Sentinel-3. The services will primarily utilize the increased resolution of SAR and place emphasis on value adding integration with complementary data such as ocean modelling, in situ data and multiple sensors. The services were developed to have a global applicability.

2.2.6 Objectives of WP 6: Applications of new Copernicus data in value-adding land services

The objective of work package 6 was to develop new and improved land services by utilizing the data features emerging with Sentinel-3. The services will be integrating different sources of information such as Earth Observation data (from different sensors and satellites), land in situ data and also model data hydrological modelling. The services will be developed to have a global applicability and will be demonstrated in selected case study regions and targeting the following applications: monitoring of river and lake levels, monitoring soil moisture, monitoring of snow water equivalent, and contributions to climate monitoring.

2.2.7 Objectives of WP 7: Dissemination and exploitation

Finally, the LOTUS project disseminated the results obtained in the project on the use of SAR mode data as well as derived new products for Copernicus land and marine services. During the project the results have been presented to European SMEs, European services and projects contributing to climate change monitoring as well as to Copernicus services for security and emergency management.

3 Main scientific and technical results

This section contains the main scientific and technical results. It is organised according to the individual WPs.

3.1 WP 1: Processing of SRAL SAR mode waveforms over ocean.

A thorough state of the art review on ocean applications for SAR mode altimetry was undertaken studying available literature on CryoSat-2 as well as other missions. The literature review touched the subjects of data processing, such as waveform retracking and contamination from off-nadir targets, over open ocean, coastal zones, and polar ocean.

As Sentinel-3 was not launched within the project timeframe, only SAR data from the CryoSat-2 SIRAL altimeter were analysed, and the limitations and drawbacks of the data were identified and discussed. The available techniques and methods were analysed and potential alternatives to these were suggested for the preparation of the take-up of the Copernicus Sentinel-3 Surface Topography Mission SRAL L2 data.

3.1.1 Open Ocean

During the LOTUS project a complete processing chain (level 1 and 2) of the SAR and RDSAR data was defined and developed. The processing chain is inherited from the CNES Cryosat Processing Prototype (CPP) processing chain [Boy et al., 2012], for SAR and LRM mode data. For open ocean it was decided to retrack LRM and RDSAR waveforms using the MLE-4 retracker [Thibaut et al., 2010]. The MLE-4 retracker is a conventional Brown ocean retracker based on unweighted least square estimations. The MLE-4 algorithm estimates four parameters: range, significant wave height (SWH), power, and slope of the trailing edge). In SAR mode, a 3-parameter ocean retracker was used to fit the numerical multi-looked waveform model to a 20 Hz level 1B SAR waveform using the least squares estimator (LSE) method. In this way the range, significant wave height, backscattering coefficient, and fitting quality information were retrieved.

A list of test areas were defined for Open Ocean as presented in Table 1.

Table 1: Geographical and temporal extent of open ocean datasets.

Area	NE Atlantic Ocean	Bay of Singapore	Adriatic Sea
Geographical coverage	13W – 15E, 48N 59N	98E – 121E, 4S -25N	12E – 20E, 40N - 46N
Temporal coverage	1 May 2012 – 30 April 2014	1 May 2012 – 30 April 2014	1 May 2012 – 30 April 2014

3.1.2 Polar Ocean

The are many major challenges in obtaining sea surface height estimates in the polar ocean; the limited amount of sea-ice leads, areas with sea-ice mélange, retracking of extremely peaky waveforms, and off- nadir returns.

For the reasons mentioned above it was decided to work with three retrackers depending on the state of the ocean as defined by the shape of the waveform.

In order to process the data in the Polar Ocean, the first step is to perform a classification of the waveform (ocean, lead or sea-ice floe/mélange) and to select the appropriate retracker. The classification is primarily based on a set of parameters describing the morphology of the waveform and the power distribution in the individual looks in the stack. After classification, the waveforms are retracked using one of the following retrackers:

1. SAMOSA-3 retracker for open ocean waveforms [Dinardo, 2013].
2. SAMOSA-3 adapted retracker for specular waveforms retrieved over leads [Jain, 2014].
3. Primary Peak empirical threshold retracker for remaining waveforms primarily retrieved over sea-ice floes or mélange.

The use of the Primary Peak empirical threshold retracker is performed for all waveforms that cannot be retracked by the SAMOSA-3 ocean or adapted retracker. This included sea-ice floes/mélange or even unclassifiable waveforms with multiple peaks. Further information on the retracking methods can be found in [D1.3] of the LOTUS project.

The test areas for Polar Ocean were defined as tracks crossing the North Pole, and as a region covering the Norwegian archipelago, Svalbard in the Arctic Ocean.

Table 2: Geographical and temporal extent of polar ocean datasets.

Area	North Pole tracks	Svalbard
Geographical coverage	Individual tracks crossing the North Pole (see Figure 1)	0E – 40E, 75N – 85N
Temporal coverage	2011-2013	2012

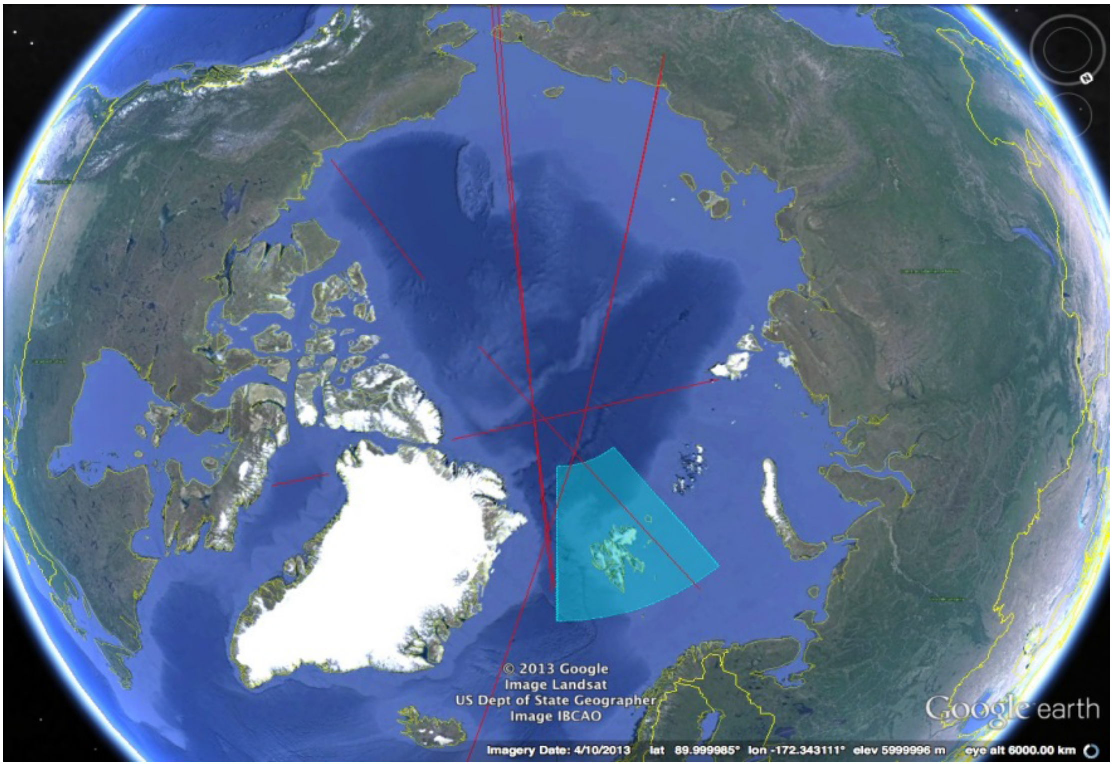

Figure 1: Polar Ocean datasets covering North Pole track (red) and the Svalbard region (blue).

3.1.3 Coastal zones

The increasing interest of SAR mode altimetry, especially in coastal areas, is linked to the higher resolving measurement capability in the direction of the platform velocity, i.e. along-track direction. The improved resolution is a consequence of the delay-Doppler processing of the radar echoes. The along-track resolution reaches values typically around 250 to 300 meters [Raney, 2005], which represents a remarkable improvement in comparison to the several kilometres currently achieved with conventional altimetry. However, the resolution improvement occurs only on the along-track direction, while the across-track direction remains pulse-limited. This implies that the Delay-Doppler altimeter's (DDA) response in coastal regions depends on the relative orientation between the coastline and the spacecraft orbital plane. The 250 m dimension prevails when the coastlines are perpendicular to the flight direction, whereas the longer pulse-limited direction dominates when the altimeter is passing parallel to the shore. In [Dinardo et al., 2011] the authors provided examples of CryoSat-2 SAR mode waveforms in these situations. Figure 2, shows an example where the track is perpendicular to the coast. In this case the waveform is uncorrupted just a few hundred meters from the coast. Figure 3 shows an example where the track is parallel to the coast. Despite the fact that the distance to the coast is almost 5 km, SAR waveform #56 is corrupted by a land effects in its tail, which prevents the use of this data for oceanographic applications.

Within the LOTUS project there has been developed an algorithm to disregard the range bins of the SAR waveform, which are likely to be affected by land contamination. This is achieved by geo-locating the delay and Doppler pairs of the SAR Altimeter stack, i.e. the

2-dimensional array for the range cell migrated Doppler looks aligned with respect to the nadir position. The SAR waveform retracker is then fed with this information and neglects the range bins subjected to land contamination from the geophysical parameter estimation process.

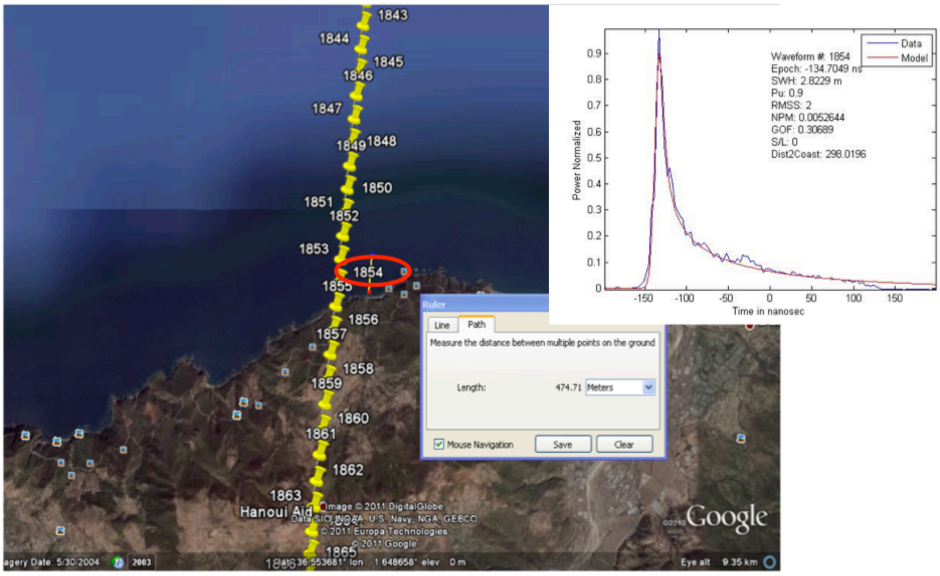

Figure 2: Example of SAR altimetry waveform for a track perpendicular to the coast

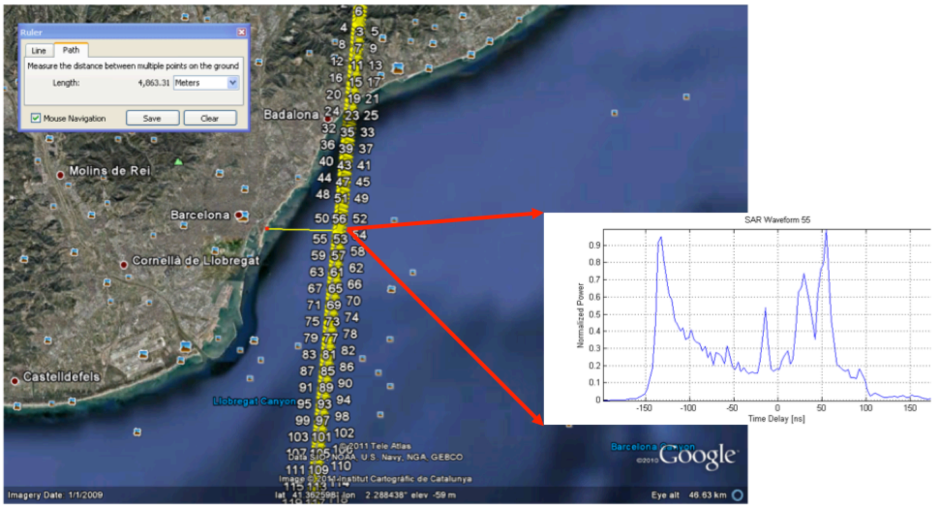

Figure 3: Example of SAR altimetry waveform for a track parallel to the coast

As for the open ocean, prototype data sets were planned for the areas defined in Table 3. As for open ocean, two of the test areas cover parts of the Atlantic Ocean and the Adriatic Sea.

Table 3: Geographical and temporal extent of coastal ocean datasets.

Area	NE Atlantic ocean + North Sea	Adriatic Sea
Geographical coverage	15W – 17E, 46N – 61N	10E – 22E, 38N – 48N
Temporal coverage	1 May 2012 – 30 April 2013	1 May 2012 – 30 April 2013

3.2 WP 2: Processing of SRAL SAR mode waveforms over land

When the LOTUS project was initiated in the beginning of 2013, the literature on SAR altimetry processing over land was limited, only a few preliminary results existed for studies related to continental water. For the newer applications of satellite altimetry; Soil moisture, Snow water equivalent and snow depth, the literature was even more limited. The state-of-the art of the land sub themes; River and lake, Soil moisture and snow depth was collected in [D2.1]. Furthermore, this deliverable contains a thorough description of SAR altimetry, retracking algorithms developed both for SAR (ocean) and conventional low-resolution altimetry, and corrections.

3.2.1 Scientific and user requirements for SAR mode data over land

In order to secure the transition of altimetry data products between the data processing teams and the users e.g. hydrologists, some user requirements have been proposed for the different sub themes. Water level obtained from Satellite altimetry is an important input parameter in hydrological modelling. For satellite altimetry to be useful, the following constraints; temporal and spatial resolution and the accuracy of the level measurements must be taken into account. For most hydrological applications the requirements are; a temporal resolution of tens of days, a spatial resolution of tens to hundreds of km, and an accuracy of ten to fifty cm. The advantage of altimetry compared to in-situ data is its global coverage. Hence, altimetry based levels are important contributions to hydrological models in poorly gauged river basins. Another advantage is the continuous observation period that spans more than 20 years, which makes satellite altimetry ideal to derive the long-term water level trends from lakes and reservoirs.

Sentinel-3 will have a repeat period of 27 days and an across track spacing of approximately 104 km at the Equator. When considering both ascending and descending tracks a temporal coverage of approximately 13.5 days is achieved, which almost fulfill the constraint defined above. The spatial coverage depends on the latitude, and the size and orientation of the underlying water body. Hence, due to the orientation of the tracks, east-west directional lakes and rivers will be visited more often compared to those oriented in the north-south direction. The precision of SAR altimetry is high due to the smaller antenna footprint, which ensures that Sentinel-3 meets the constraint that is required in hydrological modelling.

Derivation of surface soil moisture from satellite radar altimetry is a novel application [Berry et al., 2013; Berry and Carter, 2011]. The surface penetration at these wavelengths (Ku band 12-18 GHz; 2.5-1.67 cm) is restricted to a few cm for desert surfaces, and so this technique measures surface soil moisture within the top 5 cm (ibid). This technique relies on deriving DRy EArth ModelS (DREAMS) from multi-mission satellite radar altimetry in Ku band. In order to create a DREAM, the surface must be dry for at least 2 months of the year. This requirement restricts the primary application areas to desert and semi-arid terrain. As these are regions where in-situ data are extremely sparse, and where the various remote sensing techniques do not perform well [de Jeu et. al., 2008]. This technique provides a measurement capability not otherwise available, e.g. over the climate sensitive desert margins. The user requirements for small desert regions are; temporal resolution of tens of days, spatial resolution of hundreds of meters, and an accuracy of 1% of soil moisture contents.

Over most desert regions, it is clear that very good waveform acquisition is achieved; however, even with the four times wider range window utilized over land by the altimeter, the instrument loses lock over mountainous terrain. In principal, Cryosat-2 LRM data may be utilized to augment ERS1 GM data in desert regions where this instrument is able to maintain lock. This application is thus driven and constrained by the altimeter data availability and model availability, and also by the surface overflown. In rough terrain, echoes may not be acquired and even if some echoes are retrieved, stable backscatter values may not be derived to form a model. There is some potential to extend this technique to wetter regions by using third party data (in-situ measurements or soil moisture models) co-temporal with an altimeter dataset from ERS2, Envisat or Cryosat-2, to allow regression of models over wetter areas to dry earth conditions. However, this would produce less precise estimates of soil moisture.

Currently there is no satellite mission able to perform direct measurements of the snow water equivalent (SWE). However, it has been demonstrated that it is possible to obtain information on snow depth from altimeter data [Papa et al., 2006]. A step forward towards estimation of SWE could be represented by the estimation of snow depth by altimeter data, and used in combination with measurements of snow density from other sources (e.g. numerical models, SAR). Even if the temporal resolution is coarser than daily, snow depth estimation from radar altimeter could be of great interest for the scientific and users' communities, as it can provide measurements over areas which are difficult to reach and thus not yet monitored. The user requirements for snow depth monitoring from satellite altimetry in low topography and mountainous areas are; a temporal resolution of tens of days, a spatial resolution of hundreds of meters, and an accuracy of 0.1 meter. For further details regarding user requirements see [D2.2].

3.2.2 Test areas

The chosen test areas for the different sub-themes are presented in the table below.

Table 4: Test areas for land

Theme	Name	Geographical coverage	Temporal coverage
River and Lake	Denmark	8E – 13E, 54.5N – 58N	16th July 2010 – 10th July 2014
River and Lake	Thailand Chao Phraya River	99E-101.5E, 13.25N-17N	16th July 2010 – 8th July 2014
River and Lake	Brahmaputra River	89.5E-91.5E, 21.75N -24.25N	13rd October 2012 – 3rd July 2014
River and Lake	Amazon River	-61E, -47E; -5S, 3N	1st October 2012 – 9th July 2014
Soil moisture	Simpson Desert	99E-101.5E, 13.25N-17N	16 July 2010 – 8 July 2014

Soil moisture	Tenere Desert	89.5E-91.5E, 21.75N-24.25N	13 October 2012 – 3 July 2014
Soil moisture	Kalahari Desert	8E – 13E, 54.5N – 58N	16 July 2010 – 10 July 2014
Snow depth	Northern Great plain	93W-99W, 44N – 99N	January 2005 – December 2009

3.2.3 Processing of level 1 SAR mode data for river and lake

Radar reflections from inland water bodies show a large diversity in the shape of the waveform (Figure 4). Very still standing water is an efficient reflector and therefore produces a specular waveform, while a more rough water surface produces an ocean like waveform. Waveforms from inland water are typically also contaminated with signals that originate from the surrounding land; hence these waveforms will often contain multiple peaks. It is therefore a great challenge to derive the actual water level from such waveforms.

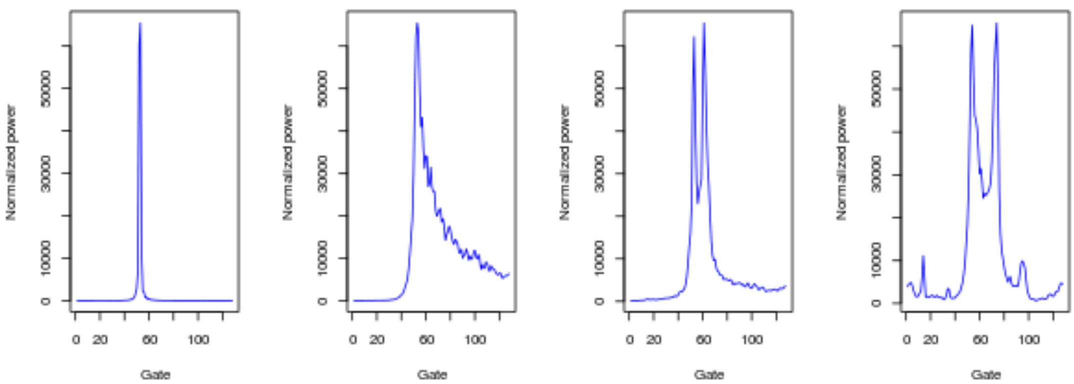

Figure 4: Examples of inland water waveforms

To handle these challenging waveforms a multiple peak threshold retracker was developed in the project. This retracker basically estimates the height related to the first ten peaks in the waveform, and in a sub sequent post-processing the most likely water level is determined. However, in a later evaluation this retracker was in some cases more unstable compared to a sub-waveform threshold retracker. Hence, it was decided to apply the Narrow Primary Peak Threshold retracker (NPPTR) [Jain et al., 2015] instead. The algorithm flowchart is displayed in Figure 5. For each waveform a sub-waveform is extracted based on start and stop thresholds. These thresholds are found from the standard deviation of the power differences in consecutive bins. Once the sub-waveform is extracted, the retracking bin is found by applying a threshold retracker (80 %) on the sub-waveform. In a post-processing procedure the MODIS mask is used to identify measurements over a given in-land water body. For each track that contains more than 5 measurements a robust mean (Nielsen et al., 2015) water level is estimated in addition to the retracked water levels. For details see [D2.3].

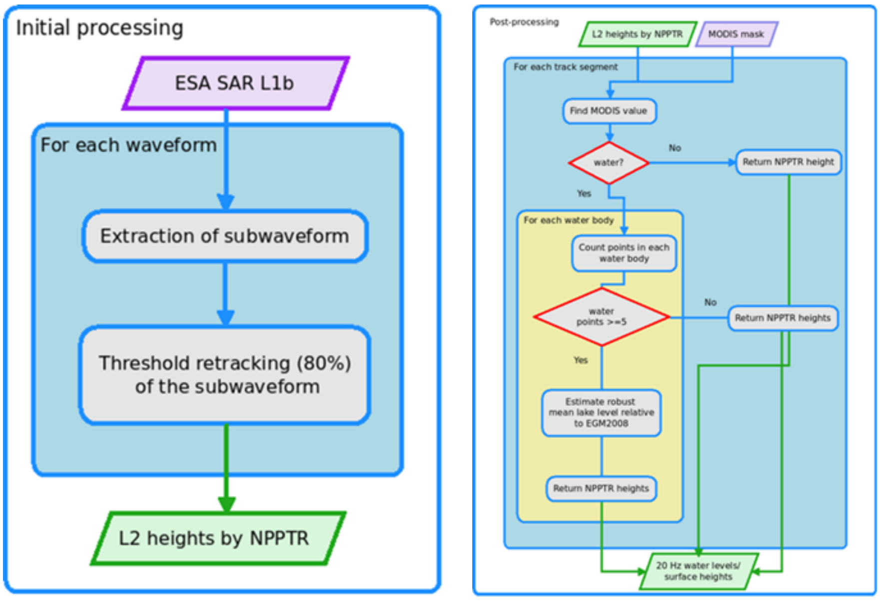

Figure 5: Flow chart of the processing algorithm for the sub theme river and lake

3.2.4 Processing of CryoSat-2 LRM data for derivation of soil moisture

Surface soil moisture estimates are derived over desert and semi-arid terrain by analysing each 20Hz waveform and computing the altimeter backscatter, applying all required corrections and scaling factors. These values are then compared with a DRy EArth Model (DREAM) which encodes the detailed variation in this parameter expected over the surface in dry earth conditions. The requirement for DREAM creation presently constrains this application to deserts and semi-arid terrain. From a comparison of the measurement with the model it is then possible to calculate the surface soil moisture. Because the highest spatial frequency variations in this parameter (resulting from changes in small-scale roughness and surface composition) are not captured in the DREAMS, some filtering and averaging of the values is essential.

The algorithm developed in the LOTUS project is called the Cryosat2 Soil Surface Moisture Estimator (CSSME): it is appropriate for estimating soil surface moisture content from Cryosat2 L1B LRM data, and has been developed using Cryosat2 LRM data. Analysis of the Cryosat2 L1B SAR/LRM transition zone in South Africa indicates that Cryosat2 L1B SAR data should also be appropriate for processing by this algorithm.

The processing chain for the internal soil moisture product SM_L2_Proc fromCryosat2 L1B input data is shown in Figure 6. Note that this processing chain is designed to work for each desert region separately: thus the Internal Product output by this processing chain contains data only over one DREAM file. However, the external data files, both the DREAM file and the CSME data file, may contain parameters for all desert regions: in this event, separate internal products SM_L2_Proc data files must be produced for each DREAM region. A full description of the processing algorithm is presented in [D2.4]

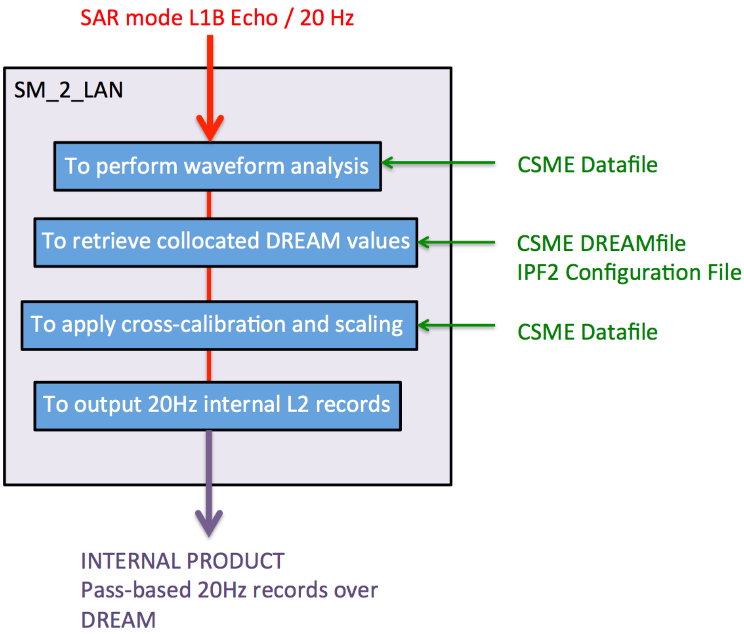

Figure 6: Flow chart for soil moisture processing

3.2.5 Processing algorithm to estimate snow depth

The snow depth is expected to be sensitive to the backscatter coefficient; hence the proposed methodology is built on the analysis of this parameter. The challenge is to be able to obtain a consistent measurement of the waveform power in order to relate it to the transmitted power and the rest of the system parameters. This will ultimately allow obtaining the Normalized Radar Cross Section, or sigma nough ($\sigma 0$), of the surface. The first step is to convert the altimeter waveform in absolute power. Once the waveforms have been re-scaled, absolute calibrated σ0 measurements can be obtained out of the waveform power value at the waveform retracking stage, as shown in [Dinardo, 2013]. The waveform power P_u, can be estimated by retracking techniques. The retracker used to estimate the total waveform power within the LOTUS projects is the offset-centre-of-gravity (OCOG) retracker [Wingham et al., 1986]. The algorithm flow chart is displayed on Figure 7. For a detailed description of the algorithm see [D2.5]

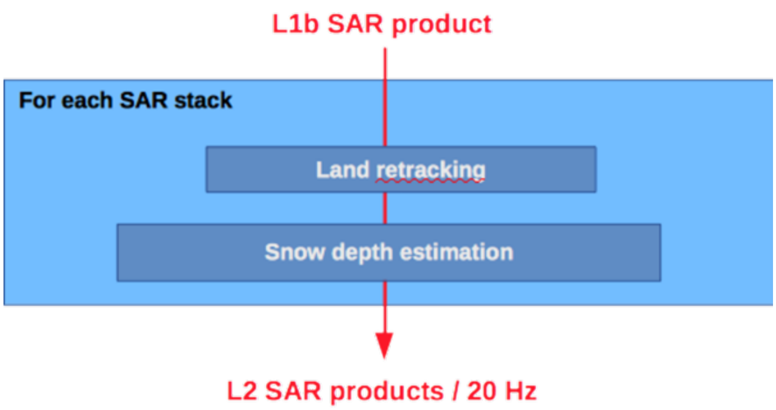

Figure 7: Flow chart for snow depth processing

3.3 WP 3: Definition of new data products and processing chains

Within the LOTUS project processing chains were set up to produce new data products for end users. Several kinds of demonstration products were defined and designed according to the different applications they were meant for (operational marine or land services) and the possibly different backgrounds of the end users.

All these products address the different surface targets of the Sentinel-3 topography measurements:

- Sea surface heights, wave heights and wind speeds in the open oceans, coastal seas as well as in sea ice covered regions.
- In-land water in rivers and lakes.
- Soil moisture.
- Snow water equivalent.

These products are designed to meet the needs of the different users:

- New Level-2 data products, complementing the ESA Sentinel-3 L2 data products.
- Higher level data products (Level-3 and Level-4), so that end users get an easy access to the specific higher-level information they need.

In the frame of the LOTUS project, data were processed to Levels 1, 2, 3, and 4 over the different targeted test areas, but only Levels 2, 3, and 4 data products were distributed for end-users. Level-1 products were used internally to the project as inputs to Level-2 processing and were as such not made available to the user community. The sketch in Figure 8 shows the different types of user products that were generated for each application (ocean or land topography measurements, and water surface target) and processing level [D3.1].

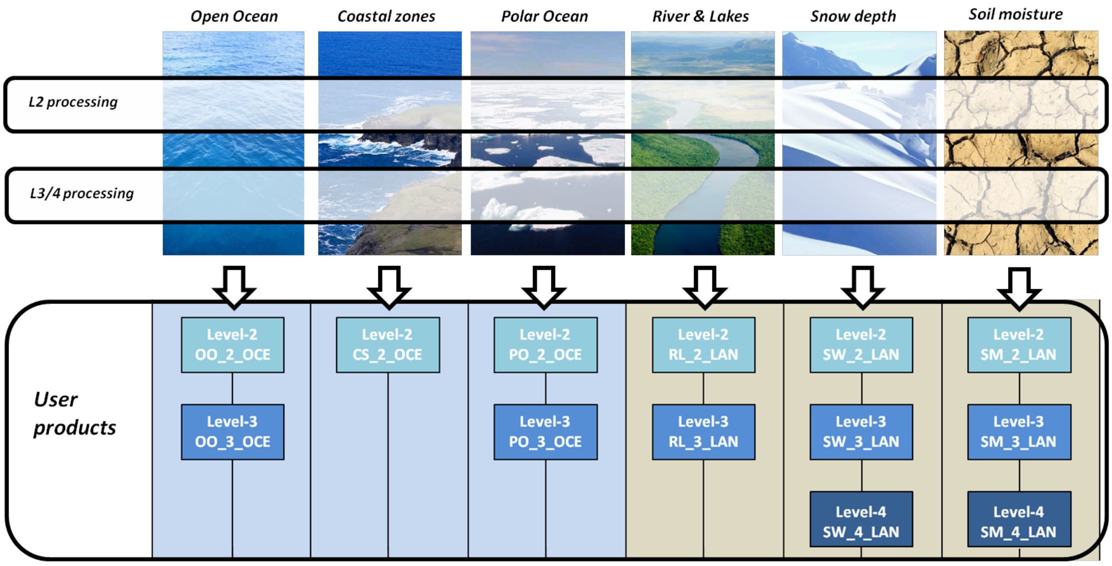

Figure 8: Overall view of the LOTUS prototype datasets.

The data flow diagram in Figure 9 shows the principal segments of the LOTUS processing chain. The LOTUS processing chains consist of refined scientific algorithms that have been designed and developed for the different surface types of interest for the Sentinel-3 mission over both the ocean and land. A complete ground processing chain has been defined and developed in the frame of the LOTUS project. All processing chains have been split in different levels (from 1 to 4), which correspond to the following standard definitions:

- **L1**: Holds geo-located and calibrated radar echoes with ancillary information (such as tracker range, latitude and longitude coordinates, altitude, surface type, geophysical corrections) at a sampling rate of 20-Hz. L1 data are not distributed to the end users.
- **L2**: Includes high-resolution along-track geophysical quantities (such as altimeter range, geophysical corrections, SWH and wind-speed information for ocean) derived from the processing of the measurements data provided into the Level-1 product, then time-tagged, precisely located and corrected for geophysical effects. For the most part, only scientists or engineers that already work in the field use L2 data.
- **L3**: Intended to ease the use of the altimetric measurements for the end users. Along-track data are ready for immediate use in applications, as they have been validated, corrected and/or inter- calibrated.
- **L4**: Only available for land data products. Includes products such as time series of water levels and discharge rates, which could be directly used by hydrologists.

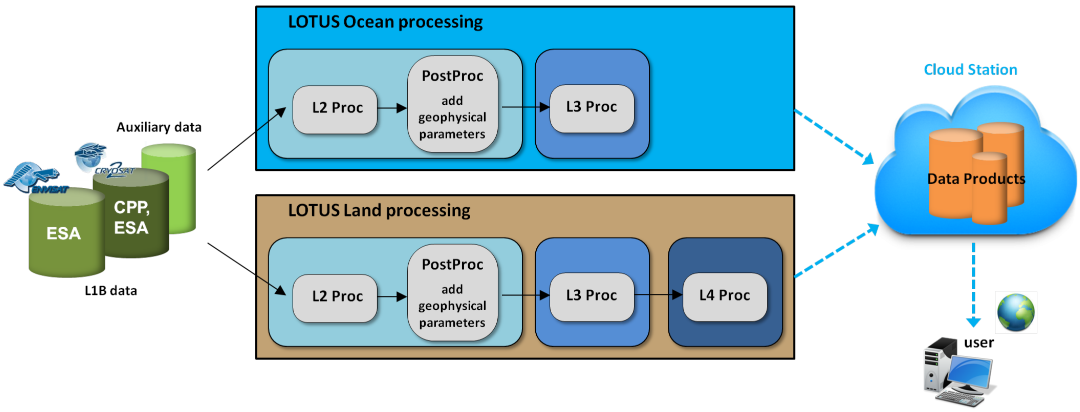

Figure 9: Flow chart describing the LOTUS data product generation.

As the LOTUS project progressed, it was decided to supply only L2 data for all purposes apart from soil moisture, for which L3 and L4 products are available. For all the test areas defined in WP1 and WP2, the data products from CryoSat-2 are available for download through the CLS cloud server (linked to the LOTUS project website http://www.fp7-lotus.eu/Publications/Prototype-data). The L3 and L4 data from soil moisture purposes can be found via the same link. A detailed explanation of algorithms and methods behind the different dataset levels can be found in the Algorithm Theoretical Baseline Document (ATBD) [D.3.3].

3.4 WP 4: Production of demo data and assessment

The section contains an evaluation of the various demo data sets for both Ocean and Land (Table 1-Table 4). These data sets have been processed according to the algorithms described in 3.1 and 3.2.3 to 3.2.5.

The prototype data sets have been assessed using a variety of validation data sets including multi-mission altimetry data, in-situ observations and model output. The validation data is available from ftp://ftp.spacecenter.dk/pub/EU-LOTUS/ReferenceDataSets/

3.4.1 Assessment of Open and Coastal Ocean

To evaluate the quality of the Cryosat-2 Open Ocean and Coastal Ocean prototype data sets of SWH (H_s) and wind speed (U_{10}) provided by CLS and STARLAB, these products have been validated against in-situ data and low-resolution mode altimetry data. The data sets included SAR and PLRM (Pseudo Low resolution mode) processed altimeter data with 1 and 20Hz resolution covering the North East Atlantic (NE Atlantic) during a 2-year period (2012-05-01 – 2014-04-30).

The assessment was carried out using independent data sets including low-resolution mode (LRM) altimeter data (Jason-2), wave model data (Mike21), atmospheric model data (CFSR) (Climate Forecast System Reanalysis) and in-situ data from Ekofisk (offshore site in the central North Sea) and Schiermonnikoog/Huibergat (near-shore site located 10 km from the Dutch coast).

Statistics regarding significant wave height H_s at Ekofisk

The statistics regarding evaluation of the significant wave height is summarized in the table below.

Data set vs in-situ data	Bias [m]	RMSE [m]	QQ Slope
Modelled (wave rider)	0.12	0.37	1.04
Jason-2 1 Hz LRM	0	0.24	1.08
Starlab 20 Hz SAR	0.68	0.98	0.87
CLS 20 Hz SAR	0.06	0.43	1.23
CLS 1 Hz SAR	0.15	0.24	1.06
CLS 20 Hz PLRM	-0.1	0.85	1.07
CLS 1 Hz PLRM	0.04	0.32	0.94

In conclusion, the CryoSat-2 (SAR, 1Hz) by CLS prototype data set agreed very well with in-situ Hs at Ekofisk. The accuracy of this data set was similar to the accuracy of the Jason-2 (LRM, 1Hz) data set at this station.

Statistics regarding wind speed U_{10} at Ekofisk

The statistics regarding the evaluation of the wind speed is summarized in the table below

Data set vs in-situ data	Bias [m/s]	RMSE [m/s]	QQ Slope
Modelled (CSFR)	0.73	1.75	1.00
Jason-2 1 Hz LRM	0.53	2.04	0.9
Starlab 20 Hz SAR	NA	NA	NA
CLS 20 Hz SAR	1.74	2.79	1.05
CLS 1 Hz SAR	1.60	2.54	1.06
CLS 20 Hz PLRM	2.05	2.90	1.06
CLS 1 Hz PLRM	1.86	2.76	1.06

In conclusion, for U_{10} the agreement between in-situ and Jason-2 was similar to the agreement between in-situ and CFSR model data at Ekofisk. For the CryoSat-2 prototype data the BIAS and
RMSE was slightly higher compared to Jason-2 and CFSR at this station. Possibly additional quality screening procedures and/or smoothing/filtering of the data may reduce these differences.

At Schiermonnikoog (costal) the data basis was too limited for any robust assessment. Possibly additional quality screening procedures and/or smoothing/filtering of the CryoSat-2 data may reduce some of the identified differences

3.4.2 Assessment of Polar Ocean

For the Svalbard region, the CryoSat-2 based sea surface height was evaluated against the Ny Alesund tide gauge (Figure 10). Fitting the monthly tide gauge data using a superimposed fit with a sinusoidal signal with a frequency of 1 year, gives an amplitude of 9 cm and a peak in the annual signal in early October (month 10.1).

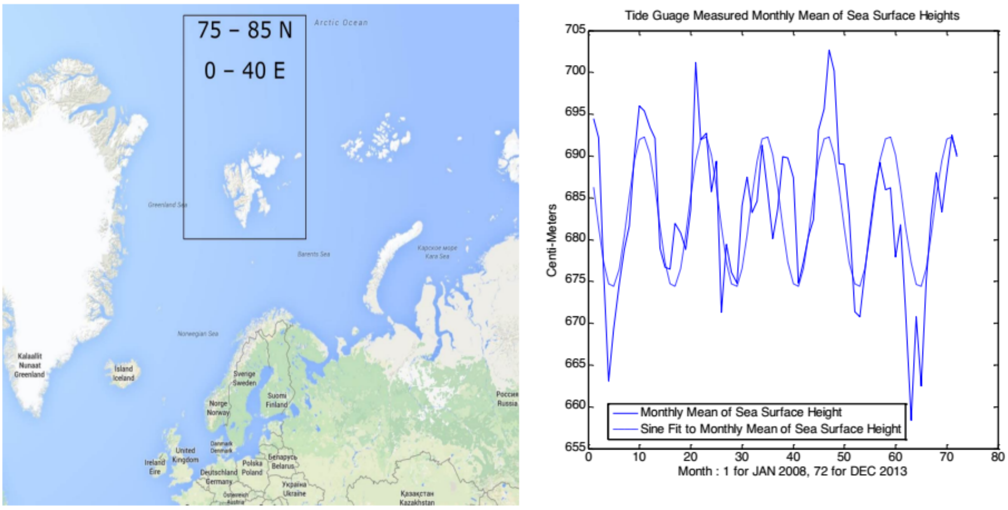

Figure 10: The Test region around Svalbard and the tide gauge measurements and fitted annual signal shown in the right figure. An offset of 7 meters (inherent in the PSMSL data) must be accounted for.

Sea surface height obtained with the primary peak retrackers show similar annual variation patterns to tide gauge data in terms of months of peak and magnitude of variation. The primary peak retrackers also show good correlation between the annual variation and the sinusoidal fit to the annual variation (>75 %). Hence they are acceptably accurate.

3.4.3 Assessment of water levels from river and lakes

The water levels based on the prototype data at the four test areas; Denmark (lakes), Amazon River, Brahmaputra River, and Chao Phraya River, was evaluated against in-situ and Saral/Altika and Envisat altimetry data.

Lakes

For the Danish area three lakes; Arresø, Skanderborg sø and Mossø ranging from 9-40 km^2 were evaluated for precision and Arresø was further compared with in-situ data. The precision, which here is defined as the standard deviation of the along-track mean water level, was found to be just a few cm for CryoSat-2 compared to 7-9 cm for Saral/Altika and 10-20 cm for Envisat.

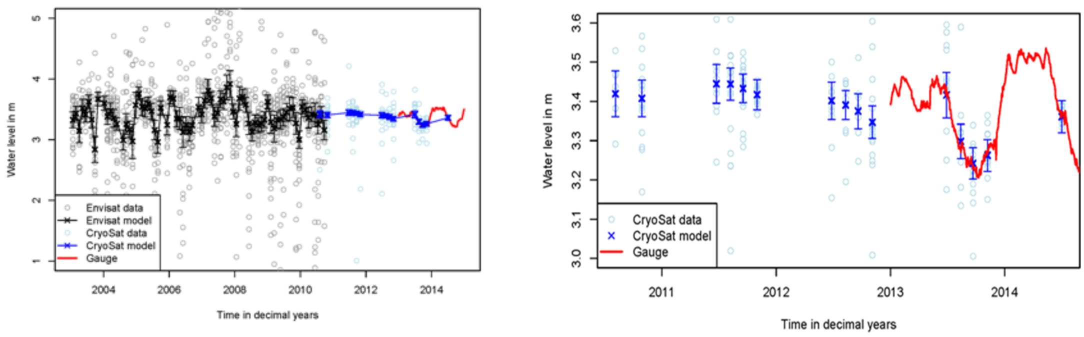

Figure 11: Time series of water level for Arresø.

Figure 11 shows altimetry based water levels together with gauge data (red). This example shows the remarkable improvements that SAR altimetry has resulted in. With SAR altimetry we are able to detect signals below the decimeter level. After a bias correction the CryoSat-2 and gauge data agrees within a few cms [Nielsen et al., 2015].

Rivers

Time series for rivers are more challenging to derive due to the drifting track pattern of CryoSat-2. This can to a large degree be accounted for by applying a slope correction if the topography is not too complex.

For the Amazon River the CryoSat-2 water levels was compared with Saral/altika data and a gauge near Obidos. The precision was estimated to a few cm for CryoSat-2 and approximately 7 cm for Saral/Altika. CryoSat-2 data approximately 40 km on each side of the Obidos gauge was slope corrected in order to construct a time series. The agreement is generally good, with a RMSE of 25cm.

Processed water levels for the Brahmaputra and Ganges Rivers were compared with Envisat data. From the obtained time series the amplitudes and phases reveal the ability of CryoSat-2 to provide time series with corresponding annual signals despite its orbit (Figure 12), which was not expected to facilitate time series derivation [Villadsen et al., 2015].

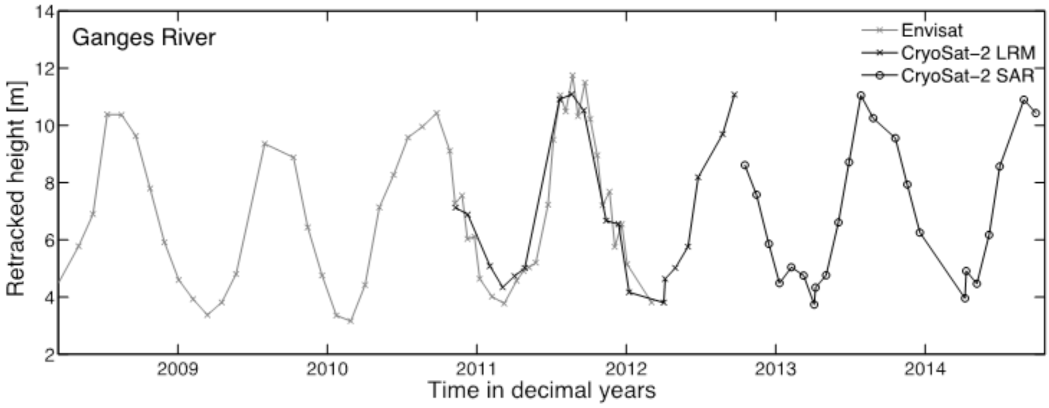

Figure 12: Water level time series at a virtual station on the Ganges River

Water levels based on CryoSat-2 over the Chao Phraya River in Thailand was compared with both in-situ data and SARAL/AltiKa and Envisat data. But due to the orientation (primarily North-South) of this river and its width it was not possible to obtain a valuable assessment.

3.4.4 Assessment of soil moisture

The validation of CSME (CryoSat-2 derived surface soil moisture estimates) soil moisture estimates with in-situ data was constrained by the extremely limited availability of in-situ data. Qualitative agreement was obtained over both the Tenere and Kalahari deserts with local precipitation data. The primary validation has thus been performed with soil surface moisture estimates derived from Jason2 re-calculated and

cross calibrated backscatter measurements. Track based
estimates were used, to minimise the effects of residual paleo-hydrology in the DREAMs. It is noted that the enhanced DREAMS and the new waveform discrimination protocols utilised for the Cryosat2 CSME data production were of significant assistance in deriving soil moisture estimates from Jason2 over all three deserts.

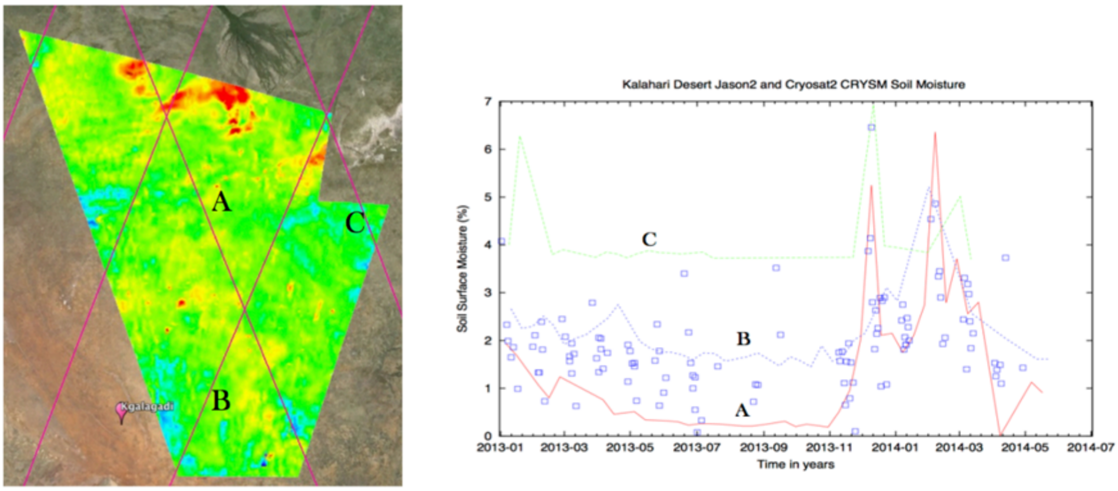

Figure 13: Left; Jason2 track locations with annotation of selected tracks on Kalahari DREAM. Right; Jason2 soil moisture estimates and Kalahari CSME estimates for validation period.

The outcome of this validation was extremely good for the CSME data over both the Kalahari (see Figure 13) and Tenere deserts, with identification of soil moisture seasonal signatures, which agreed in both phase and value with the Jason2 estimates. A more detailed analysis utilising less spatial averaging is now being undertaken. For the Simpson desert, the extremely sparse and aperiodic precipitation, together with the lack of surface drainage, meant that insufficient signals were detected in both datasets to demonstrate correlation. Whilst the lack of surface drainage minimised the chance of residual paleo-hydrology contamination in the Simpson DREAM, this was outweighed by the requirement to detect signals. It was concluded that a much longer time series would be required for CSME validation over this desert.Taken together with the outcome of the SAR-LRM mode study [Berry & Balmbra, 2015a; 2015b] it was concluded that this technique for soil moisture derivation would work effectively for Sentinel3 LRM and SAR mode data

3.4.5 Assessment of snow depth

Following the study done with Cryosat-2 data and presented in [D2.6], a further analysis was done using ENVISAT RA-2 data to assess the potential of using sentinel-3 altimeter data for snow-depth retrieval. The area chosen for the investigation was located in U.S. over the Northern Great plain. The choice was mainly guided by the flat topography, abundance of snow in winter, and presence of ground truth data. Over the areas of interest have been found ENVISAT RA-2 data covering the period between January 2005 and December 2009. About 16500 measurements have been selected over the Area of study.
Results showed a clear attenuation as the depth increases (see Figure 14), however it looks like there is a big spread of the measurements corresponding to a given snow-depth. This could be due to the large footprint of ENVISAT RA due to the fact that the

snow condition can vary within the illuminated area. We believe this could be different in the case of Sentinel-3, as in this case the satellite will have a higher resolution that could potentially allow a better filtering of the waveforms.

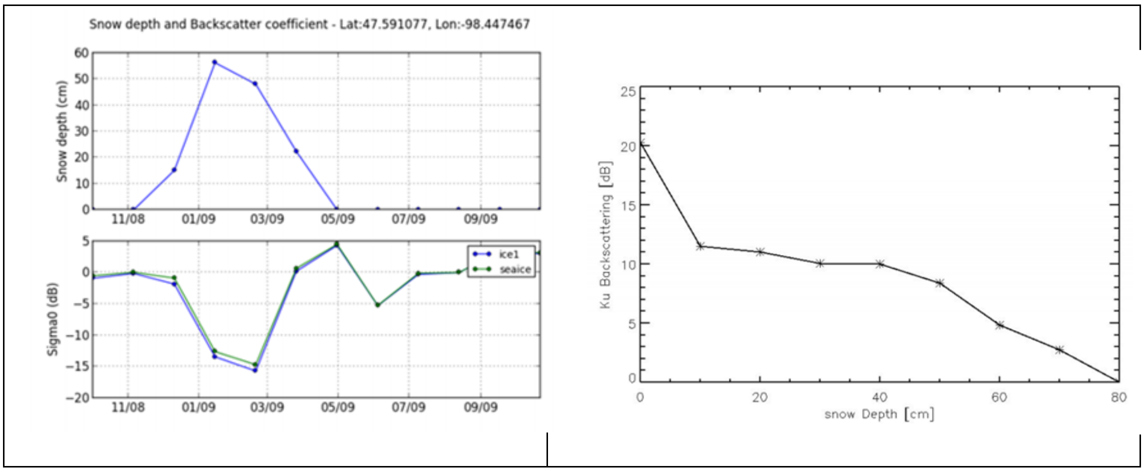

Figure 14: Left; Snow depth (up) vs backscatter values (down) for a measurement point over the period Oct. 2008 – Oct. 2009. Right; Snow-depth vs backscatter values at Ku-band for the whole dataset.

3.5 WP 5: Applications of new Copernicus data in value-adding ocean services

For this work package it was investigated how SAR altimetry contributes to various ocean service products. SAR data are especially a valuable source of information in coastal areas, where limited other information is available. Potential applications of such data could e.g. be for offshore wind farms, oil/gas platforms or marine infrastructure projects, in particular when located in remote areas.

3.5.1 Improved wave and wind design data

Improved wave and wind design data were demonstrated in terms of fast assessment of wind and wave conditions and in terms of improved validation of numerical models at a spatial scale including assessment of along-track distributions of extreme waves. The data basis included CryoSat-2 SAR data with 1 and 20Hz resolution covering the North East Atlantic (NE Atlantic) during a 2-year period (2012-05-01 – 2014-04-30). The basis further included LRM (low resolution mode) altimeter data (Jason-2), wave model data (from DHI), and atmospheric model data (from CFSR). The track patterns and resolution of the three datasets can be seen in Figure 15 below. Altimetric data were compared to modelled wind speeds adopted from CFSR (Climate Forecast System Reanalysis), a global atmospheric modelling system provided by NOAA NCEP, and to modelled SWH adopted from the DHI hindcast database. The SWH data were based on a calibrated MIKE Powered by DHI Spectral Wave Model (MIKE 21 SW) forced by CFSR wind data.

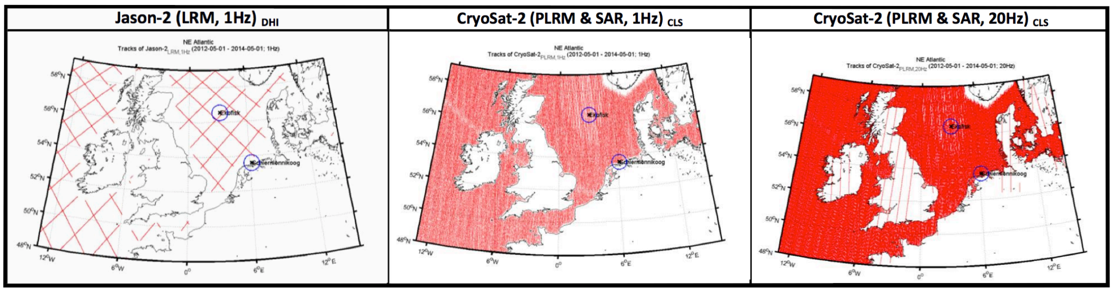

Figure 15: Altimeter coverage in NE Atlantic.

A comparison between a model and CryoSat-2 SAR 1Hz data SWH is presented in Figure 16. During the studies it was seen that the bias and root mean square errors (RMSE) for the 1Hz SAR data were very similar to the 20Hz SAR data offshore, but significantly lower in the nearshore areas. At this stage, the SAR 1Hz data set may be more appropriate for model validation nearshore compared to the 20Hz data.

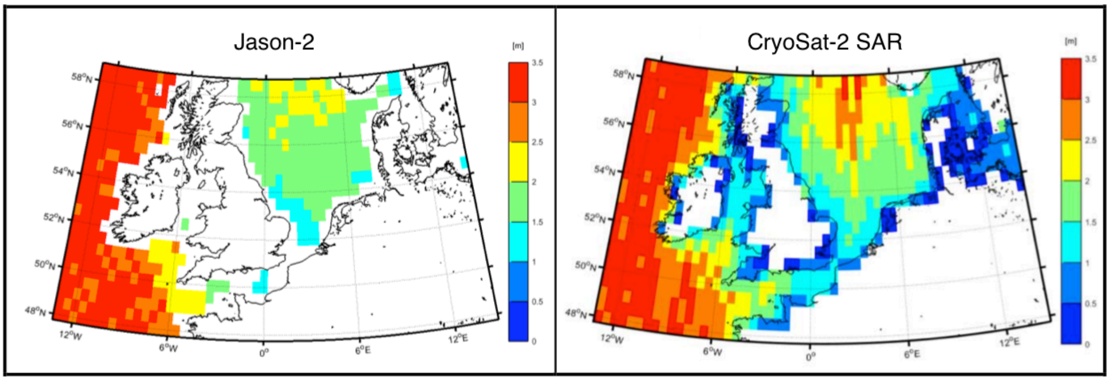

Figure 16: Mean of SWH in NE Atlantic (model - altimetric data). Jason-2 (right) and CryoSat-2 20Hz SAR (left) data from 2012-05-01 to 2014-05-01.

The findings for wind speeds at 10 m height, U_{10}, were similar to those for SWH. There was generally a good agreement for U_{10} (low bias and RMSE) between the model and the SAR 20Hz data offshore, but somewhat increased discrepancies nearshore. The bias of Jason-2 was on average 0.7m/s higher compared to CryoSat-2 (SAR, 20Hz). More about SWH and U_{10} can be found in [D.5.1].

3.5.2 Characterization of coastal scale hydrodynamics using SRAL SAR

The LOTUS project has considered new use of high-resolution SAR elevations and wave height data within coastal Copernicus services, mainly for identification of coastal processes as surge and waves.

As an example, CryoSat-2 data were compared to numerical wave and flow models of Hanstholm Harbour (an exposed North Sea port in Denmark). A comparison of SWH can be seen in Figure 17.

The general conclusion regarding coastal scale hydrodynamics is that high-resolution SAR data, both for sea surface elevations and for significant wave heights, do provide essential information for coastal processes. However, the time resolution does not allow resolution of most coastal processes, as these in most places occur on a timescale roughly of hours. Therefore, the fusion of satellite-based observations with numerical models is a way to utilize the synergies between the two. The satellite-based observations provide valuable ground truth at high spatial resolution, while the models are continuous in space and time and can provide the supporting framework for the observations and a physically based interpolation between the observations.

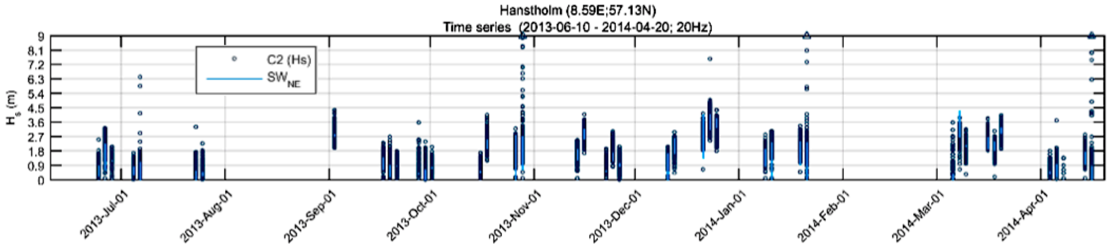

Figure 17: Time series of SWH along CryoSat-2 tracks in Hanstholm Harbour, Denmark. Points (black) from CryoSat-2 and line (blue) from MIKE 21 SW.

3.5.3 Improved surface current design data

The skills of new developments to the MIKE FM data assimilation module carried out under the LOTUS project has been assessed in [D.5.3]. For a case study, data from CryoSat-2, JASON-2 and AltiKa missions provided by CLS were used for a data assimilation model of the Adriatic Sea.

Unfortunately, data assimilation in this Adriatic Sea case with the provided data did not work well. There could be several explanations for this including too little data (not enough overpasses a day), and erroneous data (maybe close to the coast).

3.5.4 Identification and tracking of eddies for climate change services

Different algorithms exist for the processing of eddy identification and tracking. These algorithms are sensitive to preprocessing (filtering) of the input SSH maps, and their imperfections might cause identification and tracking problems when using altimetric datasets.

The sampling frequency and resolution of course plays a major role in the ability to detect and track eddies. Identifying eddies becomes easier with better scale sampling. Eddy tracking requires a high sampling frequency to provide a better coherence between two consecutive maps – otherwise the algorithms will "lose track" of the eddy.

3.6 WP 6: Applications of new Copernicus data in value-adding land services

3.6.1 Value adding land services

In the following sub sections land services regarding river and lake, soil moisture and snow depth are outlined.

3.6.1.1 River and lake levels

Altimetry for inland water (AltWater) is a new open service that provides altimetry based time series for inland water. Currently, the service only contains data from cryoSat-2, but other missions are planned to be included in future versions.

The service is available at http://altwater.dtu.space/. The web page contains a google map with the available inland water bodies and the user can access the data by clicking on the specific target of interest (see Figure 18). For each target the following files can be downloaded:

- lakename_levels_mode.dat
- lakename_ts_mode.dat
- lakename_mode.pdf
- README.txt

Here the mode indicates the measuring mode of CryoSat-2 (SAR, SARIn, and LRM), “lakename_levels_mode.dat” contains along-track water levels and “lakename_ts_mode.dat” contains the estimated water level time series. The “README.txt” contains further information regarding the files.

Figure 18: Locations of targets that are available from AltWater

3.6.1.2 Snow depth

Based on the results, regarding the estimation of snow depth from satellite altimetry, that were obtained in WP2 and WP4 a value adding service has been defined. The architecture of the service is displayed on Figure 19. A description of the final product is given in Table 5, which is based on the user and scientific requirements. The service will be located on a server, and the final product will be freely accessible on an ftp server after registration.

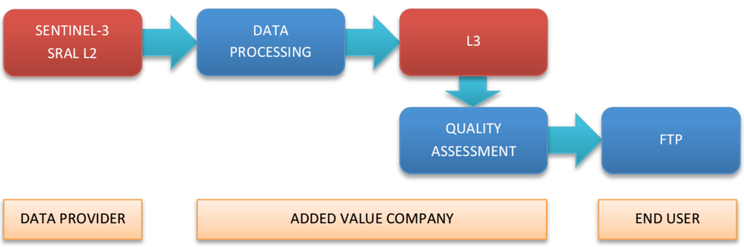

Figure 19: Service architecture

Table 5: Final product definition

Product	Snow depth
Type of information	Snow depth over tracks
Delivery format	Network Common Data Format – Climate and Forecast metadata conventions (NetCDF CF 1.6)
Inputs needed to elaborate the product	Sentinel-3 – SRAL Level 2 Enhanced – 20 Hz Ku band SAR mode
Geographical coverage	Global coverage, -81.5N – 81.5N
Time coverage	Daily product
Geographic projection - Coordinate reference system	Along-track product - Latitude/Longitude coordinates
Frequency	27-day repeat cycle, with a 4-day sub-cycle

3.6.1.3 Soil Moisture

Soil moisture product users have been identified from various communities: water resource, weather and climate, agriculture, and disasters/floods and hazards. From the requirements of each category, global user requirements have been defined in [D2.2]

An altimeter soil surface moisture service will follow the general form of the ESA Soil Moisture from ALTimetry (SMALT) project (ESA SMALT, 2013), with measurements made directly underneath the altimeter track and individual measurements averaged to overcome the high noise on individual estimates.

The retrieval of surface soil moisture from Sentinel3 SAR mode data is expected to be enhanced significantly w.r.t Cryosat2 because of the availability of repeat arcs of SAR mode data. This will allow detailed analysis and enhancement of the DREAMs, by analysis of repeat arc behavior. Crucially, the range of desert models considered can be extended to all those used in SMALT and then to semi-arid regions. The overall processing architecture of the S3 processing [D2.4] is illustrated in Figure 20.

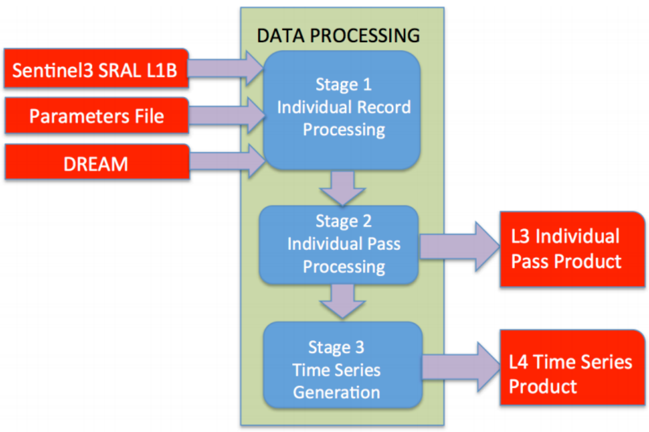

Figure 20: Data Processing Diagram for S3 Soil Moisture Product Generation.

The available output products will be the "L3 individual product" and the "L4 Time series products", which will be freely available in a user friendly file format. The level 3 product contains along-track filtered and averaged mean soil moisture estimates (SMMEs) for each pass; the level 4 product contains time series for each SSME.

3.6.2 Hydrological modelling and data assimilation

A catchment-scale hydrological-hydrodynamic modelling and data assimilation approach has been developed for assimilation of river water level measurements obtained from satellite altimetry data. The approach developed is based on the MIKE 11 hydrological-hydrodynamic modelling system and the general-purpose DHI Data Assimilation library. The data assimilation implementation has been tailored to assimilation of drifting-orbit altimetry data such as Cryosat-2.

For verification and demonstration of the data assimilation procedure implemented in MIKE 11 different tests have been performed, considering (i) assimilation of water level measurements in the hydrodynamic model using synthetic satellite track data (CryoSat-2 like), and (ii) assimilation of discharge measurements in the NAM rainfall-runoff model for one of the catchments in the Brahmaputra basin.

Case (i)

The results of the test run are shown in Figure 21. Discharge at the outlet of the model is shown for the base run, synthetic truth run, and all ensemble members. It can be seen that, in general, the assimilation main run is closer to the synthetic truth than the base run. Furthermore, each update reduces the ensemble spread, which represents the model prediction uncertainty.

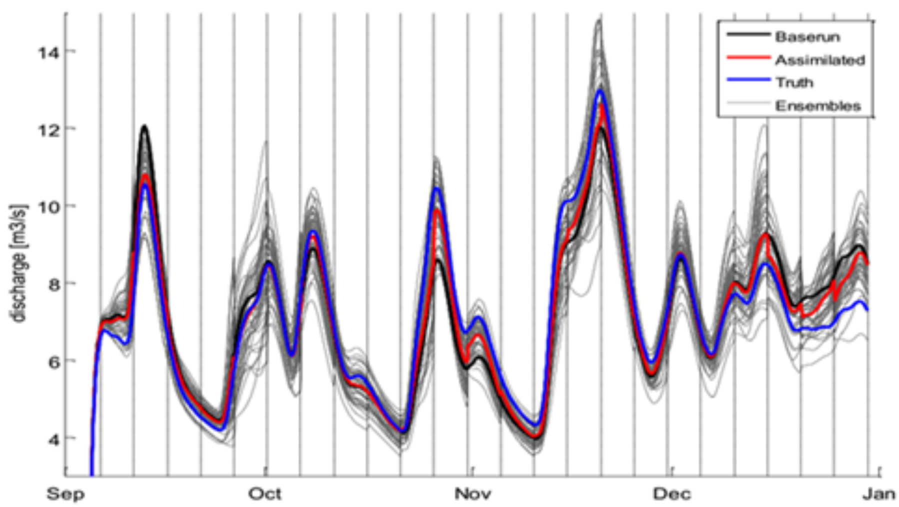

Figure 21: Results of the altimetry assimilation synthetic test run. Observation times are indicated by the vertical dashed lines.

Case (ii)

Figure 22 shows the results of the data assimilation over a 5-year period. The model states of the NAM model are shown with red and black lines for simulations with and without data assimilation (Open loop), respectively. It is clear that the DA in these examples most of the time improves the rainfall-runoff simulation after the state update by being closer to the observed runoff.

Both tests successfully verified the data assimilation system implemented in MIKE 11 and demonstrated its value for improving hydrological-hydrodynamic model predictions.

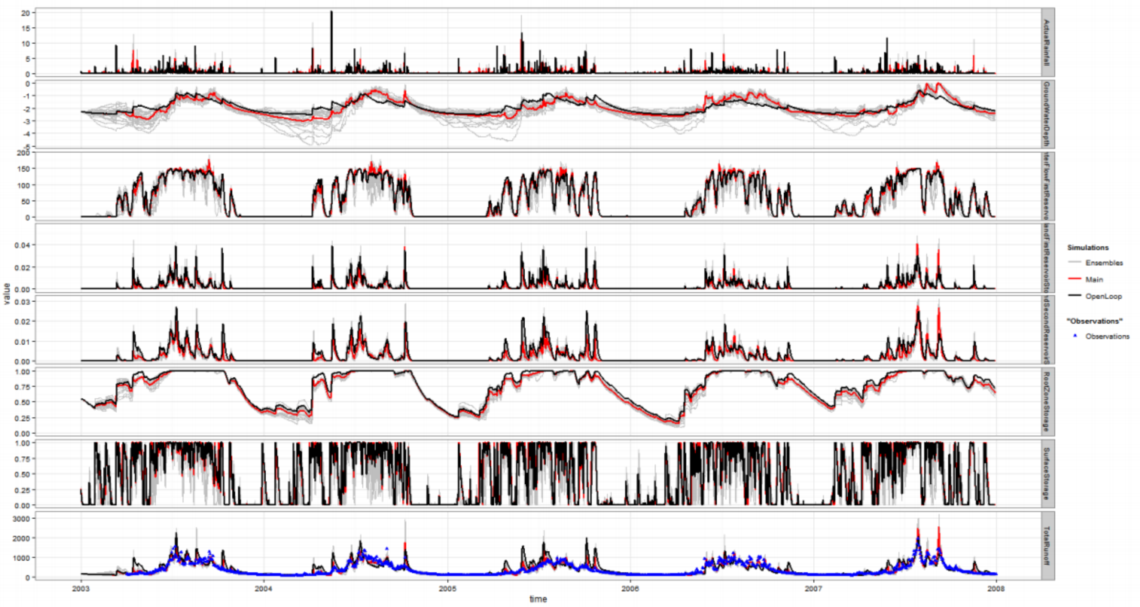

Figure 22: Data assimilation result. From top to bottom: Precipitation, Groundwater depth, First overland flow reservoir storage, Second overland flow reservoir storage, First interflow reservoir storage, Root Zone Storage, Surface storage, and Rainfall runoff. Grey: Ensemble, Red; Main model, Black: Open loop model, Blue: observations.

3.7 WP 7: Dissemination and exploitation

WP 7 addresses dissemination and exploitation. The activities and achievements of this workpackage will be summarised in Section 4.

4 Impact, dissemination and exploitation of results

4.1 Copernicus land and ocean services

The LOTUS project has developed new and improved coastal oceanographic services by utilizing the new SAR data from CryoSat-2. Also, the LOTUS project has been able to develop new and improved land services by utilizing the CryoSat-2 data and find that these products can be even more prosperous when Sentinel-3 data becomes available.

Several improvements beyond the state of the art were done during the LOTUS project, especially on L1BS/L2 pre-processing and L2 processing algorithms. New L2 products were subsequently generated as prototype products.

It was found that SAR altimeter by itself can significantly improve the estimation of the ocean parameters (SSH, SWH…) in the coastal areas. The along-track resolution reaches values typically around 250 to 300 meters, which represents a remarkable improvement in comparison to the several kilometres currently achieved with conventional altimetry. The coastal processing of SAR waveform developed in the LOTUS project shows that SAR waveform retracking can also be improved in the across track direction using a pre-processing step that clean the waveforms from land contamination.

LOTUS found that SAR altimetry is a huge step forward for Polar Ocean sea level products. This is particularly due to the enhancement in along track resolution (300 meters), the smaller footprint in the SAR processing, and the improved capabilities using the SAR stack information in determining the leads in the sea ice and to discriminate lead and contaminated returns.

It was found that in order to deliver operational services in the ocean and provide useful SAR-mode products for the end-users, a structured process has to be established which consists in:

- developing a level-2P production system (including editing, filtering, geophysical correction, orbit error correction and subsampling) to prepare the generation of the level-3 along-track products for the Copernicus Marine Service (CMS)
- generating level-3 products for data assimilation systems of the CMS
- generating level-4 products for various applications (currents, Search and Rescue, and climate)

LOTUS also demonstrated the great potential of SAR altimetry for inland water and how new improved products and services can be established.

The use of satellite altimetry for inland water services is a new topic which becomes operational with Sentinel-3. Hence, in LOTUS we have also focus on validation and quality assurance of inland water products as this is crucial to convince the users of Earth observation data for utilization of the Sentinel-3 products on inland waters.

Inland water, soil moisture and snow depth retrieval with SAR altimetry is under development, but compared to conventional altimetry it was found that i.e., the derived water levels for the individual crossings are significantly more stable than conventional altimetry from i.e. Envisat.

For Soil moisture products the ESA SMALT project has already demonstrated generation of soil moisture products from satellite radar altimetry. As this methodology continues to mature and the DREAMS become more precise and encompass larger areas, operational products are foreseen. The automated processing is already well defined and it is probable that products could be operationally generated within 1-2 years of data acquisition from Sentinel-3. This allows time to rebuild the DREAMS incorporating assessment from repeat cycles of Sentinel-3 SRAL altimetry.

LOTUS found that snow depth products from SAR altimeter is not yet mature enough to develop operational products with results based on CryoSat-2. However, this was in-part due to the annual repeat track pattern of that satellite. Similar investigations using conventional repeat track data from ENVISAT did not yield conclusive results due to the much larger footprint compared with SAR altimetry.

For Value adding services for marine products the general conclusion from the two case studies is that high-resolution SAR data, both for sea surface elevations and for significant wave heights, provide important information for coastal processes. However, the temporal resolution of the SAR data does not, in general, allow resolving coastal processes, which in most places occur on a timescale of hours. Therefore, the fusion of satellite-based observations with numerical models is a way to utilize the synergies between the two for value adding services. The satellite-based observations provide valuable ground truth at high spatial resolution, while the numerical models are continuous in space and time and provide a supporting framework for the observations and a physically-based interpolation between the observations.

For land applications it was found that particularly data assimilation results showed only marginal improvements in model performance from the use of Cryosat-2. One of the most important reasons for this might be the one-year repeat of the ground-tracks for Cryosat-2. Another important reason for this may be the assumption of uniform observation error for all CryoSat-2 water level data.

The investigation found that CryoSat-2 data and particularly the upcoming Sentinel-3 data may provide key data source for water managers. The impact of the altimetry data will increase with enhanced spatio-temporal resolution available from the combination of multiple missions and with a better understanding of the error statistics of the data. The modelling and data assimilation approach developed is scalable and can be extended to other basins and to continental/global coverage for establishing operational hydrological-hydrodynamic forecast systems

4.2 Exploitation

To date, no data products based on SAR mode data are provided or used operationally. They are neither considered nor implemented in the Copernicus services yet. To utilize the full potential of SRAL data and optimize the retrieval of the geophysical parameters, new algorithms and enhanced corrections need to be developed and also fully tested using CryoSat-2 SAR mode data to ensure that any unforeseen but undesirable impacts of SAR altimetry are fully characterized prior to the launch of Sentinel-3. Initial CryoSat-2 SAR mode ocean performances, metrics and algorithms have already shown significant progress, offering exciting new perspectives for oceanography, and providing significant experiences to maximize the possible achievements of the Sentinel-3 topography mission. Nevertheless, many scientists expressed the need to further consolidate these results, by collecting more CryoSat-2 data and undertaking further evolutions and improvements in our scientific understanding and technical capability for processing SAR mode altimeter data. Equally important, the geophysical parameters resulting from the upgraded service chains must within reasonable limits be designed to enable delivery the LOTUS WP5 applications of new Copernicus data in value-adding ocean services.

The LOTUS products are built for demonstration purposes to first prepare prototype Sentinel-3 data sets but also support the development of new potential Copernicus products and value-adding downstream applications for ocean and land services. But in order to utilize the full potential of its new data source, new processing schemes with innovative algorithms need to be developed and implemented. The primary objective of the LOTUS project is aimed precisely at defining and developing new products and processing chains to encourage and promote the take-up of data from Sentinel-3.

LOTUS products and characteristics has been found to be used or fused to retrieve actionable intelligence in the following challenge areas.

- **Science & Climate**
  - Marine geo-hazards: Tsunamis, marine earthquakes
  - Properties at risks: Storm surge, sea state, and swell
- **Safe activities at sea**
  - Detection and monitoring for safety: icebergs
  - Production of electronic marine charts: big tides, strong currents, eddy detection
- **Marine environment protection**
  - Human disaster: Oil Spill, marine pollution
  - Local surveillance: to reconstruct a ship route, and any route of a mobile target.

One particular result we would like to highlight which clearly shows the importance of SAR altimetry was recorded during the Storm Surge Xavier which hit Denmark and Germany during 5-6 December 2013 breaking a 1000-year sea level record in Kattegat and causing severe damage in several countries (Figure 23). The huge storm surge was recorded in the southern part of Kattegat at 55N by Kystdirektoratet and DMI (Danish Meteorological Institute) to peak at 1.9 meters above mean sea level during the storm.

This particular surge was the first storm surge to be observed with SAR altimetry on-board Cryosat-2. The data were processed by DTU using the ESA GPOD service using the SAMOSA-3 SAR processor which is identical to the processor to be used on Sentinel-3. Furthermore, the RADS (Radar Atlimetry Database System, rads.tu.delft) processed the identical Cryosat-2 SAR data as if they were conventional altimetry like ENVISAT (through RDSAR processing). This way it was possible to compare SAR altimetry and conventional altimetry during a storm surge. The SAR processing of Cryosat-2 recording performed significantly better and saw sea level heights of nearly 1.9 meters (exactly that of the DMI) in the southern part of Kattegat at 55N. (Figure 23)

This clearly demonstrates the huge potential of SAR altimetry from Cryosat-2 and Sentinel-3.

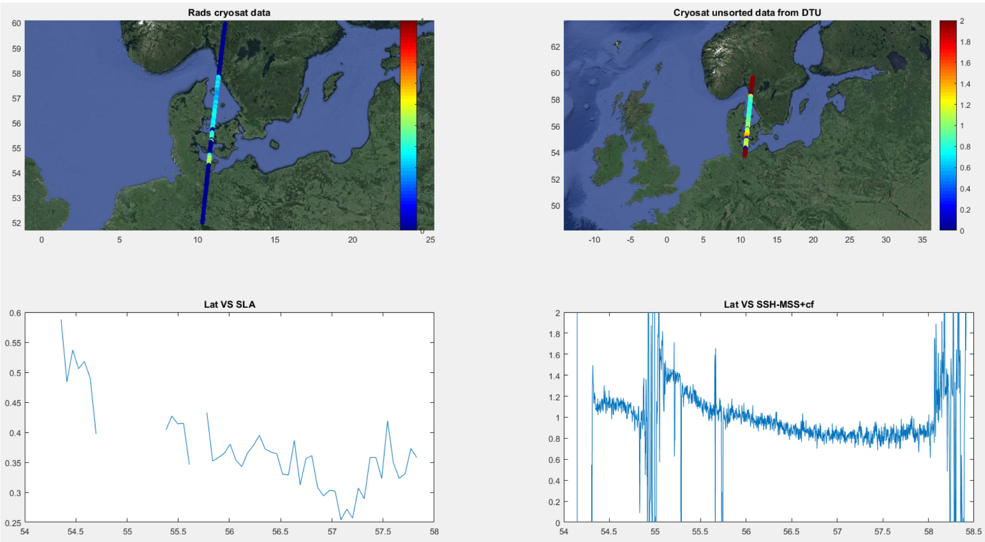

Figure 23: Storm Surge Xavier observed by Cryosat-2 along the track down through Kattegat and Storebælt in Denmark relative to mean sea level. Extraction of RADS 1-Hz Cryosat-2 data and right is 20 Hz Cryosat-2 SAR altimetry processed using SAMOSA-3

4.3 Climate change

To ensure knowledge of the climate and its monitoring, the Global Climate Observing System (GCOS) program has developed the concept of "essential climate variables" (ECVs) (GCOS 2010). These 50 variables cover the various components the atmosphere, the oceans, and land. Several of the parameters estimated in the LOTUS projects are climate essential variable such as; sea level, lake level, and soil moisture. The results obtained in the LOTUS project is therefore of great importance to the community that is involved in climate research.

4.3.1 Sea level

The Sea level evolution constitutes one of the most important monitoring of the climate change. It is used by the intergovernmental panel on Climate Change (IPCC) in addition to the surface temperature evolution, the greenhouse gas concentration evolution and the CO_2 emissions (see Figure 24).

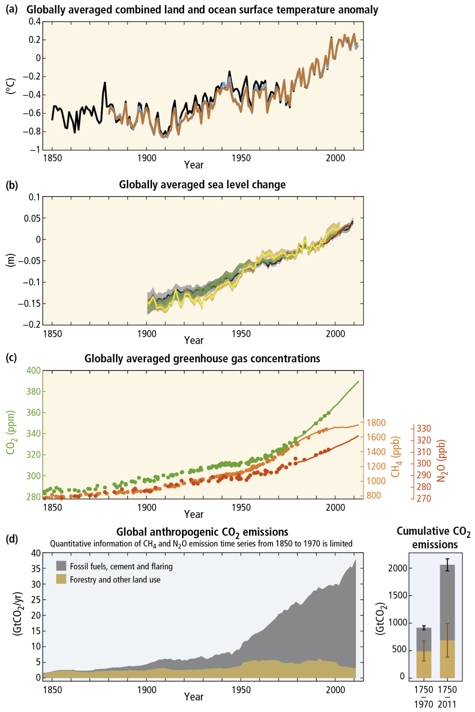

Figure 24: Adapted from the IPCC report

The smaller antenna footprint of the SIRAL altimeter in SAR mode makes it possible to obtain more accurate estimates of the sea level closer to the coast – especially when the track is perpendicular to the coastline. Although the effect of land contamination in the waveform is greatly reduced it is not removed completely. Hence novel processing algorithms have been developed in order to further reduce the effect of land contamination in the waveform to obtain more accurate water level estimates closer to the coast. A detailed description of these algorithms is found in [D1.3].

The increasing interest of SAR mode altimetry, especially in coastal areas, is linked to the higher resolving measurement capability in the direction of the platform velocity, i.e. along-track direction. The improved resolution is a consequence of the delay-Doppler processing of the radar echoes. The along-track resolution reaches values typically around 250 to 300 meters [Raney, 2005], which represents a remarkable improvement in comparison to the several kilometres currently achieved with conventional altimetry.

Two major consequences of such improvements are first, the sea level monitoring at global scale is significantly improved, and therefore the estimation of sea level rise can be better estimated, and secondly, the sea level estimation close to coastal areas has been improved and provide interesting results for coastal monitoring where the effect of climate change is the most visible. The improvement of sea level estimation near the coasts can clearly contribute to provide better estimates of sea level change.

SAR altimetry is furthermore a huge step forward for Polar Ocean sea level research. This is particularly due to the enhancement in along-track resolution, as well as the smaller footprint in the SAR processing, and the improved capabilities using the SAR stack information in determining the leads in the sea ice.

With the use of SAR altimetry it is for the first time possible to provide a sea level estimate within the leads of the sea ice. The accurate information on sea level can directly be used to determine information about the free-board of the ice and hence the amount of sea ice and the thickness of the sea ice. SAR altimetry can capture and measure sea level in small leads in the sea ice and hence provide a much better spatial pattern of sea level variations. Figure 25 shows the sea level change in the Arctic Ocean as a function of time including the data that was derived in the LOTUS project.

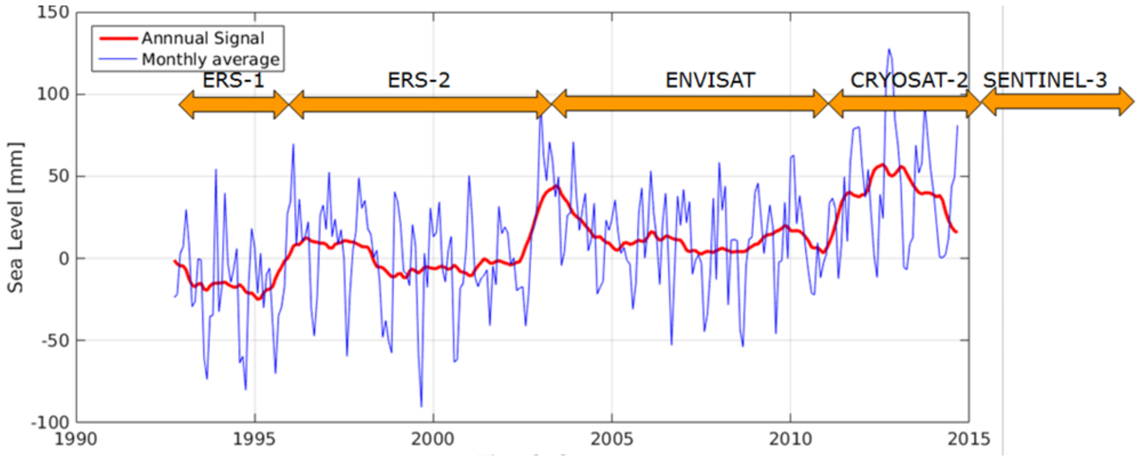

Figure 25: The 25 years sea level time series (65N to 82N) of the Arctic Ocean from the European satellites ERS-1, ERS-2, ENVISAT, Cryosat-2 and SENTINEL-3 in the future.

4.3.2 Continental water levels

The water level of rivers and lakes is an important climatic parameter in the sense that it represents the hydrological balance (precipitation and evaporation) of the surrounding area. Especially closed-basin lakes are sensitive to the changes in the relationship between precipitation and evaporation, and therefore serve as markers of the regional climate. GCOS has constructed a prioritized list of lakes that need to be monitored in order to assess the state of the climate. Ideally the lake level should be measured on a daily or at least on a monthly basis with a vertical resolution of 10 cm [GCOS 2010].

Water levels of inland water bodies from radar satellite altimetry have been derived for more than 20 years, and have proven to be a valuable supplement to in-situ station data, which are declining in number on a global scale. Hence, satellite altimetry can provide continuous time series of the world's rivers and lakes, which is invaluable in terms of climate monitoring.

In the LOTUS project the primary focus has been on SAR altimetry, for which four test areas have been selected: Denmark, Thailand, Brahmaputra River and Amazon River. Due to the relatively long repeat period of CryoSat-2, a significantly larger amount of water bodies are monitored. The number of crossings depends on the size of the water body in the east-west direction and the latitude. Hence, small lakes may only be visited a few times per year.

In the scope of the LOTUS project an open service "Altimetry for inland Water" (AltWater), see Figure 18, that provides water level time series, was established. This service in combination with other similar services are important sources of information regarding the global water budget, since time series of water level is available on a global scale.

4.3.3 Soil moisture

Soil surface moisture is a key climate variable, vital for a range of applications, including numerical weather predictions, flood and drought prediction and monitoring, water resource management, agriculture and epidemiological forecasting. In-situ data availability is sporadic and localised in spatial extent [Dorigo et al., 2013]: thus remote sensing techniques have a key role in global and regional monitoring of this parameter. Both active and passive sensors are used to derive soil moisture e.g. [Liu et al., 2011]. The key importance of this variable is underlined by the first two dedicated satellite missions, both currently operational; the ESA SMOS mission [Mecklenburg et.al., 2012] and the NASA SWOT mission [Panciera et al., 2014] .

One constraint on existing global remote sensing datasets is the pixel size, typically 0.25 degrees [Dorigo, 2013]. Soil moisture from satellite altimetry offers finer spatial sampling along-track and a more precise measurement capability in arid and semi-arid terrain, where other techniques encounter difficulties. The new enhanced DRy EArth ModelS (DREAMS) developed in the LOTUS project now allow detailed estimates from prior altimeter missions to be made; these data are now being processed to yield time series. In parallel with this activity, DREAM creation is being trialled over wetter areas to extend the remit of this new technique. The role of altimeter-derived soil moisture is seen as complementary to other remote sensing datasets, and as a bridge between the detailed local scale in-situ measurements and the generalised (0.25 degree) scale global remote sensed datasets.

4.3.4 Snow depth

The estimation of snow depth using altimeter is not mature enough yet to develop operational products. But, through the investigation, interesting results show a trend in the data that could allow snow depth estimation. However, such improvements can provide snow coverage information that could show the evolution of snowfall in mountain areas and others. This evolution is very representative of the current changes in the climate. Additionally, the products developed could be used into models for different purpose in combination with auxiliary parameters, in particular, to estimate the water content in (natural and artificial) storage areas.

4.4 Security and emergency management

In order to evaluate the impact on safety, security and emergency management, the LOTUS project performed risk analysis activities (ie. mitigation - intervention - recovery - preparedness) according to four challenges to tackle, namely:

- Natural disaster assessment: Copernicus Emergency Management Service
- Enhanced maritime security: Copernicus Maritime Security Service
- Safety of response of Maritime Search & Rescue: Special Meteo-Ocean Services

- Risk assessment for maritime environment: MEDESS-4MS (Mediterranean Decision Support System for Marine Safety)

4.5 Dissemination.

The following dissemination activities have been undertaken as part of LOTUS in order to perform dedicated dissemination to both broad users and to the specific users/groups and experts:

Particularly a public project web site where general information as well as results, demonstration products and press related communications have been developed and will be available also after the project ends.

Developed information material describing results obtained in the LOTUS project on the use of Sentinel-3 SRAL SAR mode data as well as derived new products for Copernicus land and marine services.

Prepared information directed towards European SMEs to facilitate the exploitation of the new products in value adding applications for both ocean and land

The main lines of disseminations have been

- Presentations at conferences, workshops and user meetings
- Presentation of results to other EU projects, international agencies and programmes related to Copernicus such as MyOcean, Geoland-2, SAFER, and G-MOSAIC.
- Publication of results in refereed journals

An advisory board was established early in the process to ensure that the developments in the LOTUS project progress consistently with the developments of the Sentinel-3 mission including data processing and data into which ESA and EUMETSAT representatives.

The following persons participated on the LOTUS advisory board.

> Jerome Benveniste (ESA, ESRIN); Remko Scharroo (EUMETSAT); Joel Dorandeau (EU My-Ocean project leader); Giovanni Cecconi (THETIS)
> These member of the advisory board participated actively in several of the LOTUS project meetings.

Throughout the project a total of 3 Review meetings where hosted in the LOTUS project to ensure a good communication and progress in the project. During these meetings project officers from REA; the advisory board and representatives from servies. One example was that in order to liaise with the EU project GMES **MyOcean Sea Level TAC:** Claire Dufau (CLS, France) participated during the LOTUS RV3 meeting.

Members of the LOTUS consortium have simultaneous been participating in other ongoing EU projects such as the GMES FTS projects (i.e. MyOcean/MyOcean2 and GEOLAND). This will ensure adequate links to these relevant projects. Similarly links to ongoing ESA projects including i.e., SAMOSA, Cryosat-Plus CP40, ESA Sea level CCI, ESA

GOCE user toolbox Project, CoastAlt, SAM, FreshWater, MarCoast etc was established early in the process and these projects have been informed about the LOTUS activities throughout the LOTUS project lifetime.

5 Addresses and links

Description	Link
The official project webpage	http://www.fp7-lotus.eu/
Deliverables	http://www.fp7-lotus.eu/Publications/Deliverables
Cloud service, hosted by CLS, that contains the prototype and reference data sets	https://nas-ext.cls.fr:443/fbsharing/PRPt1Kuc
Prototype data for the selected test areas	ftp://ftp.spacecenter.dk/pub/EU-LOTUS/
Relevant reference data including multi satellite altimetry data, model output and in-situ data	ftp://ftp.spacecenter.dk/pub/EU-LOTUS/ReferenceDataSets/
AltWater, on open service providing water level time series on a global scale	http://altwater.dtu.space/

6 References

[Berry & Balmbra, 2015a]: Berry, P.A.M. & Balmbra, R., 2015a. Surface Soil Moisture from Satellite Altimetry - from Cryosat2 to Sentinel3. Proceedings ESA Sentinel3 Workshop, in press.

[Berry & Balmbra, 2015b]: Berry, P.A.M. & Balmbra, R., 2015b. Surface Soil Moisture from SRAL Satellite Radar Altimetry. Proceedings
ESA Third Space for Hydrology Workshop, in press.

[Berry et al., 2013]: Berry, P.A.M. , Carter, J.O., Dowson, M., 2013, Surface soil moisture from multi-mission satellite radar altimetry, Proceedings of ESA LP2013, In press.

[Berry and Carter, 2011]: Berry, P.A.M., Carter, J.O., 2011, Altimeter derived soil moisture determination - global scope and validation, IAHS-AISH Publication 343, 92-97.

[Boy et al., 2012]: F. Boy, T. Moreau, J-D. Desjonquères, S. Labroue, N. Picot, J-C. Poisson and P. Thibaut, *"Cryosat Processing Prototype, LRM and SAR Processing"*, presented at the 2012 Ocean Surface Topography Science Team Meeting. Available online: http://www.aviso.oceanobs.com/fileadmin/documents/OSTST/2012/oral/02_friday_28/02_instr_processing_II/02_IP2_Boy.pdf

[Dinardo, S., B. Lucas, and J. Benveniste, 2011]: *SAR Altimetry in Coastal Zone: Performances, Limits, Perspectives.* San Diego: 5th Coastal Altimetry Workshop, 2011.

[Dinardo, 2013]: Dinardo, S., B. Lucas, C. Gommenginger, C. Martin-Puig, M. Srokosz, M. Caparrini, and J. Benveniste (2013), Detailed Processing Model of the Sentinel-3 SRAL SAR altimeter ocean waveform retracker – v2.3.0.

[Dorigo et al., 2013]: Dorigo, W.A., Xaver, A. Vreugdenhil, M. Gruber, A., Hegyiová, A. Sanchis-Dufau, A.D., Zamojski, D. , Cordes, C., Wagner, W., and Drusch, M. (2013). Global Automated Quality Control of In situ Soil Moisture data from the International Soil Moisture Network. *Vadose Zone Journal, Volume 12, No.3.*

[Jain et al., 2015]: Jain, M. , Andersen O.B., Dall, J. and, Stenseng,L., Sea surface height determination in the Arctic using Cryosat-2 SAR data from primary peak empirical retrackers, Advances in Space Research, Volume 55, Issue 1, 1 January 2015, Pages 40-50, ISSN 0273-1177, http://dx.doi.org/10.1016/j.asr.2014.09.006.

[Jain,2014]: Jain, M., C. Martin-Puig, O. Baltazar Andersen, J. Dall, and L. Stenseng (2014), Determination of sea surface heights in the Arctic using SAMOSA3 Adapted retracker on Cryosat-2 SAR data, in *EGU General Assembly Conference Abstracts*, *EGU General Assembly Conference Abstracts*, vol. 16.

[de Jeu et al., 2008]: de Jeu, R.A.M., Wagner, W., Holmes, T.R.H., Dolman, A.J., van de Geeson, N.C., Friesen, J., 2008, Global soil moisture patterns observed by spaceborne microwave radiometers and scatterometers, Surv. Geophys., 29, 399-420.

[GCOS 2010]: Mason, Paul J., and Kajfež-Bogataj Lučka (2010). Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC: (2010 Update). *Geneva: World Meteorological Organization, 2010. Print.*

[Liu et al., 2011]: Liu, Y. Y., Parinussa, R. M., Dorigo, W. A., De Jeu, R. A. M., Wagner, W., van Dijk, A. I. J. M., McCabe, M. F., Evans, J. P. (2011). Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals. *Hydrology and Earth System Sciences, 15, 425-436,* doi:10.5194/hess-15-425-2011

[Mecklenburg et al., 2012]: Mecklenburg,S., Drusch,M., Kerr,Y.H., Ford, J., Martin-Nrira,M., Delwart,S., Buenadicha,G.,Reul,N., Daganzo-Eusabio,E., Olivia,R. and Crapolicchio,R. (2012). ESA's Soil Moisture and Ocean Salinity Mission: Mission Performance and Operations. *IEEE Trans. Geoscience and Remote Sensing, Volume 50, Issue 5.*

[Nielsen et al., 2015]: Nielsen, Karina et al. (2015), Validation Of CryoSat-2 SAR Mode Based Lake Levels. Remote Sensing of Environment, 171 (2015): 162–170.

[Panciera et al., 2014]: Panciera, R., Walker, J. , Jackson, T. J., Ryu, D. , Gray, D. , Monerris, A. , Yardley, H. , Tanese, M. , Rudiger, C., Wu, X. , Gao, Y. , and Hacker, J. (2014).

The Soil Moisture Active Passive Experiments (SMAPEx): Towards soil moisture retrieval from the SMAP mission. *IEEE Journal of Selected Topics in Earth Observations and Remote Sensing, 51, no. 1, pp. 490–507, 2014.*

[Papa et al., 2006]: Papa, F., Legresy, B., Mognard, N.M., Josberger, E.G., Remy, F., 2006, Estimating terrestrial snow depth with the TOPEX-Poseidon altimeter and radiometer. IEEE Trans Geosci. and Remote Sens. 40(10), 2162-2169.

[Raney, 2005]: R.K. Raney, "*Resolution and Precision of a Delay-Doppler Radar Altimeter".* Vol. 3. OCEANS, 2005. Proceedings of MTS/IEEE , 2005.

[Thibaut et al., 2010]: P. Thibaut, J. C. Poisson, E. Bronner, N. Picot "Relative Performance of the MLE3 and MLE4 Retracking Algorithms on Jason-2 Altimeter Waveforms", Marine Geodesy, 33: 1, 317 — 335

[Villadsen et al., 2015]: Villadsen, Heidi et al. (2015), CryoSat-2 Altimetry for River Level Monitoring — Evaluation in the Ganges–Brahmaputra River Basin. *Remote Sensing of Environment 168 (2015): 80–89.*

[Wingham et al., 1986]: Wingham, D.J., Rapley, C.G., Griths, H., New techniques in satellite tracking system, *Proc. IEEE IGARSS, Zurich, 1986.*

6.1 LOTUS deliverables

[D1.1]: LOTUS report, "*SAR mode for Ocean State of the art review*", Version 1.0, 12 Jan. 2016.

[D1.2]: LOTUS report, "*SAR mode for Ocean Scientific Requirements*", Version 1.0, 18 Jun. 2013.

[D1.3]: LOTUS report, "*Algorithm Theoretical Baseline Document for SAR mode processing over ocean*", D1.3, Version 1.0, 11st Jun. 2014.

[D2.1]: LOTUS report, "*State of the art review of SAR mode data over land*", Version 3.0, May 2014

[D2.2]: LOTUS report, "*Scientific requirements for SAR mode*", Version 1.0, Aug. 2014

[D2.3]: LOTUS report, "*Theoretical Basis Document for river and lake levels algorithms*", D2.3, May 2014.

[D2.4]: LOTUS report, "*Cryosat2 Soil Surface Moisture Algorithm Theoretical Basis Document*", D2.4, June 2014.

[D2.5]: LOTUS report, "*Snow depth Theoretical Basis Document*", D2.5, August 2014.

[D2.6]: LOTUS report, "*Develop processing for snow depth*", D2.6, August 2014.

[D3.1]: LOTUS report, "*Data Product Definition Document*", D3.1, November 2014.

[D3.2]: LOTUS report, *"Data Product User Manual (DPUM)",* D3.2, May 2015.

[D3.3]: LOTUS report, "*Algorithm Theoretical Baseline Document detailing the high level specification of the process*", D3.3, April 2015.

[D3.4]: LOTUS report, "*SAR Mode for Ocean Corrections Theoretical Basis Document*", D3.4, July 2014.

[D4.1]: LOTUS product, "*Processed ocean SAR data*", D4.1, May 2015.

[D4.2]: LOTUS product, "*Processed land SAR data*", D4.2, May 2015.

[D4.3]: LOTUS product, *"Prototype data sets for ocean and land applications",* Version 1.0, May 2015

[D4.4]: LOTUS product, "*Data sets for validation and long term referencing*", Version 2.1, Sep. 2015

[D4.5]: LOTUS report, "*Report describing results from the assessment of the prototype data sets*", Version 3.4, Oct. 2015

[D5.1]: LOTUS report, "*Improved wave and wind design data*", D5.1, June 2015.

[D5.2]: LOTUS report, "*Characterization of coastal scale hydrodynamics using SRAL SAR*", Version 1.0, Jan. 2016

[D5.3]: LOTUS report, "*End-to-end demonstration of improved surface current design data*", D5.3, December 2015.

[D5.5]: LOTUS report, "*Surface current, eddy and front detection climate change services*", Version 1.0, Jan 2016

[D6.1]: LOTUS report, "*Lake and river level monitoring service*", Version 2.3, Nov. 2015

[D6.2]: LOTUS report, "*SWE monitoring service*", Version 1.0, Mar. 2015

[D6.3]: LOTUS report, "*Multi sensor soil moisture product*", Version 2.2, Nov. 2015

[D6.4]: LOTUS report, "*Prototype modelling and data assimilation system*", Version 1.0, Jan. 2016

[D6.5]: LOTUS report, "*Demonstration of water resources management services for selected basins*", Version 1.0, Jan 2015

[D7.1]: LOTUS report, "*Report describing the web site*"

[D7.2]: LOTUS report, "*Report describing Sentinel-3 SRAL SAR mode data and new products for Copernicus land and marine services*". Version 2.1, Dec. 2015

[D7.3]: LOTUS report, "*New LOTUS products and their potential use in value adding applications described in report*", Version 1.0, Jan 2016

[D7.4]: LOTUS report, "*Report describing the results to European services and projects contributing to climate change monitoring*", Version 1.0, Jan 2016

[D7.5]: LOTUS report, "*LOTUS results to Copernicus services for security and emergency*

management described in report", Version 1.0, Dec 2015

7 List of abbreviations

AltWater	Altimetry for inland Water
CSME	Cryosat2 derived surface soil moisture estimates
CSSME	Cryosat2 Soil Surface Moisture Estimator
CNES	Centre National d'Études Spatiales
CPP	CNES Processing Prototype
DREAMS	DRy EArth ModelS
ECV	Essential Climate Variable
GCOS	Global Climate Observing System
GM	Geodetic Mission
GMES	Global Monitoring for Environment and Security
LOTUS	Land and Ocean Take-Up from Sentinel-3
LRM	Low Resolution Mode
LSE	Least Squares Estimator
OCOG	Offset-Centre-Of-Gravity
RDSAR	Reduced SAR
SAR	Synthetic Aperture Radar
SIRAL	SAR Interferometric Radar Altimeter
SMALT	Soil Moisture from ALTimetry
SRAL	Sentinel-3 Ku/C Radar Altimeter
SWE	Snow Water Equivalent
SWH	Significant Wave Height
WP	Work Package