D2.2: Scientific and user requirements for SAR mode data over land

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Acronyms

ADCP Acoustic Doppler Current Profiling

DEM Digital Elevation Model

DREAM Dry earth models

ECMWF European Centre for Medium-Range Weather Forecasting

ESA European Space Agency

FBR Full Bit Rate

LRM Low Resolution Mode

RCS Radar Cross Section

SAR Synthetic Aperture Radar

SIRAL Synthetic Interferometric Radar ALtimeter

SRAL SAR Radar Altimeter

SWE Snow water equivalent

SWOT Surface Water and Ocean Topography mission

Contents

1 Summary

This report has been prepared as part of the project 'Preparing Land and Ocean Take Up from Sentinel-3 (LOTUS)' Work Package 2 'Processing of SRAL SAR mode waveforms over land', Deliverable 2.2.

The report describes user requirements for a number of use cases and corresponding scientific requirements for application of SAR radar altimetry for three land products:

1. Water levels of inland water bodies (rivers and lakes)
2. Snow depth
3. Soil moisture

User requirements in terms of temporal resolution, spatial resolution, accuracy and coverage are listed for the different use cases.

For water level, user requirements are assessed for four use cases within the area of large-scale river basin modelling and management, and one use case on combination of high-resolution hydrodynamic models and radar altimetry data. Since there is not yet any definitely determined ground track location for Sentinel-3, statistical analysis has been performed for water bodies of various sizes and shapes for analysing the user requirements. The probability for detecting a water body of a given size at a random location and corresponding accuracy and temporal resolution of the mapping are evaluated for future scenarios of having one or two Sentinel-3 satellites in orbit. It is shown that, in general, for the use cases related to large-scale river basin modelling and management the minimum user requirements can be met. For the use case related with high-resolution hydrodynamic modelling, the spatial resolution requirement can only be met along-track. The satellite has a better detection probability for water bodies elongated east-west, which allows mapping of smaller water bodies; however, at the cost of a decrease in accuracy. Within the foreseen future it will be possible to combine altimetry data from Sentnel-3 with other satellites (e.g. Jason-2, Jason-3, AltiKa, Hy-2 and Cryosat-2), which will improve significantly the spatio-temporal resolution and accuracy for mapping of inland water bodies. The range and geophysical corrections on Cryosat-2 are evaluated, and it is suggested how corrections should be derived for the upcoming Sentinel-3 satellite relevant for the retrieval of land geophysical parameters.

Snow water equivalent (SWE) is typically used for mapping of snow storage. However, currently there is no satellite mission able to perform direct measurements of SWE. In the LOTUS project mapping of snow depth using SAR is investigated, which in combination with measurements of snow density from other sources can be used for estimation of SWE. To evaluate the performance of the Sentinel-3 altimeter for snow depth monitoring and its limitations with respect to orography two use cases are considered for monitoring over low topography and mountainous areas. The derivation of snow depth from altimeter data is mainly related to the power of the returned radar echoes penetrating the snow and vegetation media. The penetration capabilities of the wave into the snow pack depend on the dielectric properties of the snow area, which in turn depends mainly on its liquid water content. Different instrumental requirements and geophysical corrections that address this issue are discussed.

Derivation of surface soil moisture from satellite radar altimetry is a relatively new application. In the LOTUS project a technique that relies on deriving DRy EArth ModelS (DREAMS) from multi-mission satellite radar altimetry is investigated. In order to create a DREAM, the surface must be dry for at least 2 months of the year to allow the solution to be regressed to dry earth conditions. This requirement restricts the primary applications to desert and semi-arid areas. The prior application of DREAMS has been optimized for ERS2 and Envisat altimetry, and hence considerable further enhancement is possible, utilizing the Sentinel-3 and Cryosat-2 SAR data. In addition, there is some potential to extend the technique to wetter regions, which would extend the geographic scope of the soil moisture product significantly. This will be investigated in the LOTUS project.

2 Use cases and user requirement

2.1 Water levels in inland water bodies

2.1.1 Review of applications

Two principal approaches to inform inland water models with radar altimetry data have been reported in the literature. The first is assimilation of altimetric water level data into high-resolution hydrodynamic models for flood protection and management. Because this approach requires high spatial resolution, most studies have used either synthetic datasets with characteristics similar to what is expected from the Surface Water and Ocean Topography (SWOT) mission (e.g. Andreadis et al., 2007; Biancamaria et al., 2011; Durand et al., 2008) or spatially distributed water level data obtained from merging high-resolution digital elevation models (DEMs) with flood extent images obtained from synthetic aperture radar, SAR (e.g. Hostache et al., 2010; Mason et al., 2009; Neal et al., 2009; Schumann et al., 2008).

The second principal approach is to use nadir altimetry data sets for calibrating, validating and updating river-basin models for large and poorly gauged basins. In such approaches altimetric water level time series at virtual stations (crossings between the satellite ground track and a river) are either used directly to inform the models or are first transformed into river discharge using rating curves. Recent studies include Getirana (2010), Getirana (2011), Getirana et al. (2010), Getirana et al. (2012a), Getirana et al. (2012b), Getirana and Peters-Lidard (2013), Pereira-Cardenal et al. (2011), Getirana et al. (2013), Milzow et al. (2011). Recent studies by Michailovsky et al. (2013) and Michailovsky and Bauer-Gottwein (2013) have explored the potential of radar altimetry for real-time operational river-basin modelling and have assimilated nadir altimetry data over the Brahmaputra and Zambezi rivers into Muskingum-type river routing schemes.

2.1.2 Comparison of monitoring capabilities based on traditional in-situ networks and radar altimetry

Traditional observation data for surface water monitoring consist of water level data and river discharge data. Water level data is typically recorded with pressure transducers or automatic water level recorders. In developed countries, such stations are installed and maintained at regular intervals (typically 10s of kilometers) along all significant rivers. Data are transferred in real-time via the mobile network and are archived and processed by relevant agencies. Many countries provide free and web-based access to such datasets, while in other countries, this information is classified and hard to obtain. Typically, the accuracy of the equipment is better than one centimeter and the temporal resolution is a few minutes or less. In developing countries, the density and quality of the in-situ station network is much worse and there are many indications that the in-situ monitoring capability for surface waters has been declining at the global scale over the past 1-2 decades (Fekete and Vorosmarty, 2007).

Direct measurements of river discharge data are obtained from cross-sectional measurements of water velocity or from Acoustic Doppler Current Profiling (ADCP), see Figure 2-1. ADCP uses Doppler reflection of ultrasound waves on suspended particles in the river current to obtain current velocity, and bottom reflections to obtain depth. River discharge is obtained as the integral of current velocity over the entire river cross section. ADCP is an efficient technology and the accuracy is around 10% (Muste et al., 2004). ADCP field work does not require a tagline, as the exact transect of the boat can be taken into account when processing the data.

The river cross section method is more tedious and time consuming. First, a tagline has to be installed across the river. Then, water velocity is measured at regular intervals and depth across the river, using propeller current meters. Again, total discharge is computed as the integral of current velocity over the entire section. At permanent discharge stations, the tagline is typically a permanent installation, and current profiling is done automatically from a control station on the shore.

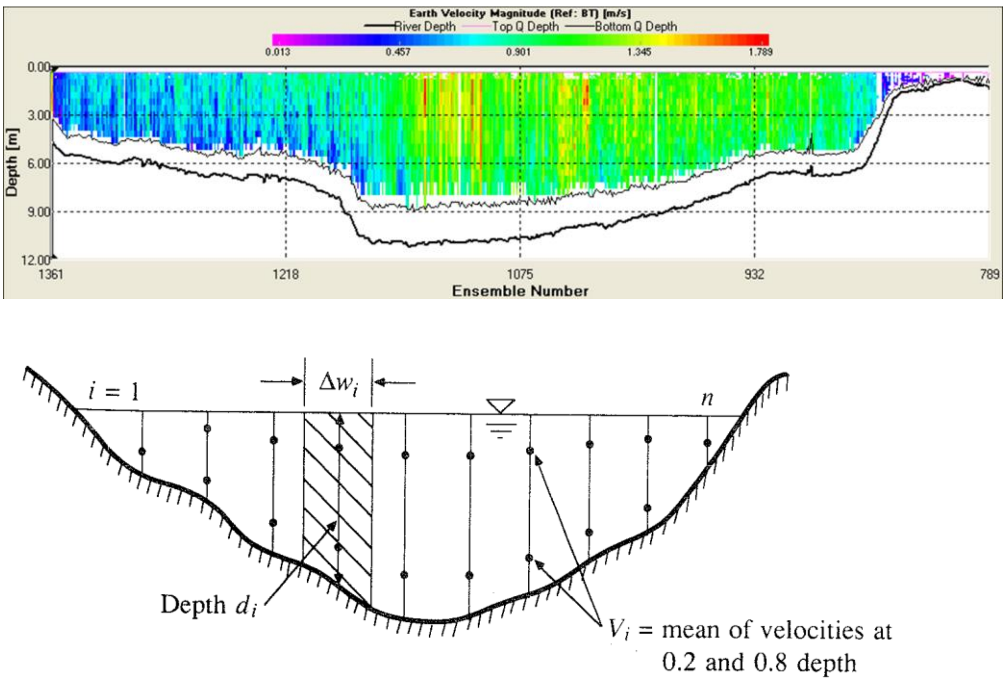

Figure 2-1: Above: ADCP cross section of the Zambezi River. Below: Cross-section method to measure river discharge (from Chow et al., 1988).

As direct river discharge monitoring is tedious and costly, discharge is often inferred from water level using rating curves. A rating curve is a relationship between water level and discharge based on a number of co-incident measurements of water level and discharge (Figure 2-2). Typically a polynomial relationship or power-law is fitted through the data points and is used to estimate discharge from level. A major issue is the stability of rating curves over time. In natural rivers, bank erosion and sediment transport will change the rating curve and the relationship should therefore be updated at regular intervals.

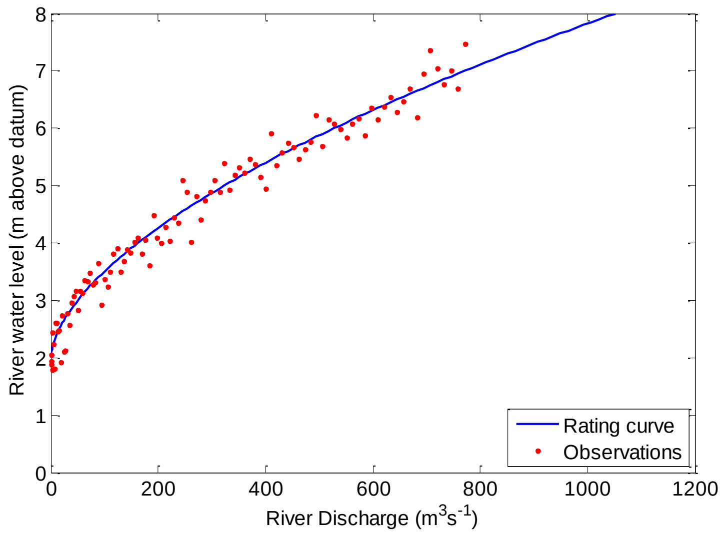

Figure 2-2: Example of a rating curve describing the relationship between water level and discharge.

Radar altimetry has primarily been used to measure water level in inland water bodies such as rivers and lakes. Water level can then be translated to river discharge with rating curves, using similar approaches as for in-situ levels. The main constraints for the use of radar altimetry data in hydrology are

- Temporal resolution
- Spatial resolution
- Accuracy of the level measurement

In the future, if sufficiently high spatio-temporal resolution and accuracy can be achieved, secondary characteristics such as spatial and temporal derivatives of water level can be extracted from the radar altimetry dataset, which are of major interest in hydrology. Moreover, the high along-track resolution of the SAR altimeter onboard Sentinel-3 may enable the measurement of high-resolution water level transects across rivers and river-floodplain systems. Such dataset will provide new insights into the hydrological processes and phenomena occurring in such systems.

Table 2-1 summarizes the main characteristics of traditional and radar altimetry data for hydrological applications, as relevant for the LOTUS project.

Table 2-1: Main characteristics of in-situ datasets and hydrological datasets derived from radar altimetry.

	In-situ water level	In-situ discharge	Water level from radar altimetry
Temporal resolution	From seconds to months	Daily	Tens of days
Spatial resolution	Tens of kilometers	Tens of kilometers	Tens to hundreds of km for virtual stations, hundreds of m for transects
Accuracy	Sub-cm	10%	0.5 m
Coverage	Dense in some regions, zero elsewhere	Dense in some regions, zero elsewhere	Distributed evenly over areas of the same latitude. Increasing density towards the poles.

It is clear that, for the foreseeable future, radar altimetry will not be able to compete with in-situ datasets in terms of accuracy and temporal resolution. However, radar altimetry has some significant advantages over in-situ datasets and offers an attractive monitoring capability for a number of use cases. Below is given an overview of use cases in hydrology. Use cases 1-4 fall into the area of large-scale river basin modelling and management, while use case 5 explores the combination of high-resolution hydrodynamic models and radar altimetry data.

2.1.3 Use case 1: Large and poorly-gauged river basins

Many of the planets major river basins (e.g. in the Arctic, in Africa) are poorly gauged or ungauged. In such river basins, radar altimetry represents a significant monitoring capability. Many studies have investigated the use of radar altimetry in this context using data from previous missions such as Topex-Poseidon, Jason, ERS1-2 and Envisat (e.g. Birkinshaw et al., 2010; Coe and Birkett, 2004; Getirana et al., 2009; Michailovsky et al., 2013).

Figure 2-3 shows a map of the major river basins of the world. For most of these river basins, hydrological models have been developed. Modeling approaches and implementations vary widely and range from conceptual lumped-parameter models to fully distributed, physically-based models. The map also shows in which basins altimetry has been used to date. Due to its size and importance, the Amazon River basin has been the showcase application case study for inland water monitoring using radar altimetry. However, over recent years, several much smaller rivers have also been monitored successfully (e.g. Zambezi, Mekong). Rivers as narrow as 100 m could be detected and monitored using nadir altimetry from the Envisat platform.

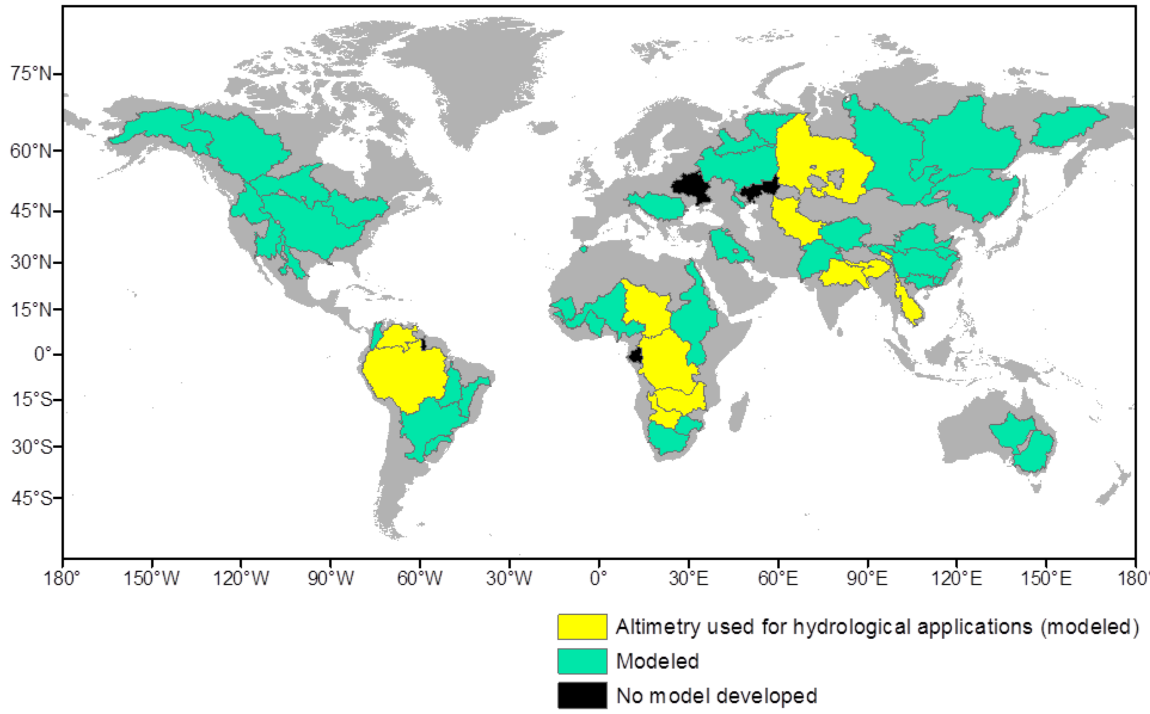

Figure 2-3: Major river basins of the world. Hydrological model development and use of radar altimetry (adapted from Bauer-Gottwein et al., 2013).

For this use case, heights as a function of space and time are the preferred delivery format, because the hydrologist will typically want to decide flexibly, which height measurements can be interpreted as belonging to an inland water body of interest. Beyond height product delivery, Doppler beam steering for known locations with open water also has potential.

The user requirements for this use case are listed in Table 2-2.

Table 2-2: User requirements for the large and poorly-gauged river basins use case.

	Minimum requirement for radar altimetry water level product
Temporal resolution	Tens of days
Spatial resolution	Tens to hundreds of km
Accuracy	0.5 m
Coverage	Large river basin scale

2.1.4 Use case 2: Continental-scale water balance monitoring

One clear advantage of radar altimetry over traditional in-situ monitoring datasets is the global coverage. To fully exploit this advantage, radar altimetry should be used jointly with global inland water simulators to produce consistent estimates of continental-scale water budgets and inland water dynamics. To our knowledge, no global operational hydrological model has been informed with radar altimetry data to date. However, several authors have published preliminary studies and results to support this research direction (Yamazaki et al., 2011; Yamazaki et al., 2012). For this use case, time series at virtual stations are the preferred data delivery format.

The user requirements for this use case are listed in Table 2-3.

Table 2-3: User requirements for continental-scale water balance monitoring use case.

	Minimum requirement for radar altimetry water level product
Temporal resolution	Tens of days
Spatial resolution	Tens to hundreds of km
Accuracy	0.5 m
Coverage	Continental scale/global

2.1.5 Use case 3: Long-term water level trends

Radar altimetry from ERS and Envisat has been collected consistently for the past almost 20 years at the global scale (Gao et al., 2012; Ricko et al., 2012). The availability of consistent long-term records provides an opportunity to quantify effects of global change on the global water budget. Continental freshwater storage in lakes and reservoirs may become a similarly important climate change indicator as for instance global sea level rise and ice mass loss. For this use case, time series at virtual stations are the preferred data delivery format.

The user requirements for this use case are listed in Table 2-4.

Table 2-4: User requirements for the long-term water level trends use case.

	Minimum requirement for radar altimetry water level product
Temporal resolution	Tens of days
Spatial resolution	Tens to hundreds of km
Accuracy	0.1 m
Coverage	Global
Temporal consistency	Decades

2.1.6 Use case 4: Large ensembles of small water bodies

Some hydrological systems on the planet are characterized by large numbers of small water bodies, which, due to their large number and remote location, are difficult to monitor in-situ. Examples include ephemeral water bodies in the Sahel, lake ensembles in the Arctic and ensembles of sinkholes, e.g. in the Yucatán karst aquifer, Mexico. Radar altimetry offers a unique monitoring capability for such systems (Smith and Pavelsky, 2009). For this use case, heights as a function of space and time are the preferred delivery format. Doppler beam steering for known locations with open water also has potential.

The user requirements for this use case are listed in Table 2-5.

Table 2-5: User requirements for the large ensembles of small water bodies use case.

	Minimum requirement for radar altimetry water level product
Temporal resolution	Tens of days
Spatial resolution	Tens of km
Accuracy	0.5 m
Coverage	Regional/catchment scale

2.1.7 Use case 5: Flood dynamics and river-floodplain interactions

One of the advantages of new SAR-altimetry technology is the high along-track resolution. Potentially, this can be used to resolve small-scale water level variations in river and wetland systems and may provide new insights in floodplain-channel interactions and water budgets. To our knowledge, such results have not been reported in the literature. Findings may have a direct impact on the exploitation of the upcoming SWOT mission. For this use case Doppler beam steering for known locations with open water is preferable.

The user requirements for this use case are listed in Table 2-6.

Table 2-6: User requirements for river-floodplain interaction use case.

	Minimum requirement for radar altimetry water level product
Temporal resolution	Tens of days
Spatial resolution	Hundreds of meters
Accuracy	0.1 m
Coverage	Local scale

2.2 Snow depth

In many regions snow represents an important component of the hydrological cycle. Snow storage is typically measured in terms of Snow Water Equivalent (SWE), which represents the amount of water contained in the snow pack per unit area, usually measured in mm. Despite the increasing interest of SWE in the scientific community, its estimation with remote sensing techniques still remains a major challenge. By definition, SWE is the product of two other snow parameters: snow depth and snow density. Currently there is no satellite mission able to perform direct measurements of 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). Information of snow depth is also important due to its influence on surface radiative exchange and heat transfer, affecting frozen ground and permafrost distribution and moisture recharge (Armstrong et al., 2009). Within the frame of the LOTUS project the product to be derived from the SRAL instrument is snow depth.

Conventionally, snow depth is measured at single points on the surface using snow rulers or ultrasonic ranging sensors within a centimeter accuracy (Armstrong et al., 2009). These measurements are interpolated and extrapolated spatially in order to cover wider areas. In Table 2-7 is reported the general requirements for in-situ snow depth measurements.

Table 2-7: General user requirements for in-situ snow depth measurements.

	Requirements for in-situ snow depth measurements
Temporal resolution	Daily
Spatial resolution	In-situ
Accuracy	0.01 m
Coverage	Local scale

However, the spatial representation of point measurements at basin or larger scale is uncertain. Space-borne sensors, which can cover a wide swath and can provide rapid repeat global coverage, are ideally suited to augment the snow information on a regional and global scale. 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. To evaluate the performance of the Sentinel-3 altimeter for snow depth monitoring and its limitations with respect to orography two use cases are envisioned, considering, respectively, low topography and mountainous areas.

2.2.1 Use case 1: Monitoring over low topography areas

Large areas of the northern hemisphere covered by snow are characterized by flat areas with low topography (e.g. Northern Great Plains, east Europe plain of Russia). These areas are often difficult to reach during winter for in-situ measurements, and only sparse stations are available. Thus, remote sensing techniques are the only feasible method of acquiring information about snow-pack at regional scale.

To assess the performances of Sentinel-3 altimeter for the estimation of snow depth an area located in the Northern Great Plains will be selected. The Northern Great Plains study region covers a geographical area from 42° to 49°N and 91° to 104°W. The test area is about 800,000 km^2. This encompasses the states of North Dakota, South Dakota, and Minnesota. The geomorphology of this area is rather homogeneous. For example, the Roseau River in Minnesota and Manitoba, Canada, is a typically small basin that flows into the Red River. The Roseau basin has relatively low relief (< 500 m) with a mixture of cropland and forests (hardwoods and conifers). Josberger and Mognard (1998) reported a comparison of satellite and aircraft remote sensing SWE estimates in this region. They found that in this prairie ecosystem passive microwave observations could be used to derive SWE. This area, therefore, is ideal for studying the characteristics of ground snow depth measurements and microwave-derived snow depths.

The Northern Great Plains is currently not included in the SAR processing mask of Cryosat-2. A formal request will be made to ESA in order to request for the addition of a SAR patch for the area. In the case this requirement cannot be met by ESA, another test area (to be defined) will be used for this purpose.

The user requirements for this use case are listed in Table 2-8.

Table 2-8: User requirements for low topography snow depth monitoring.

	Minimum requirement for radar altimetry snow depth product
Temporal resolution	Tens of days
Spatial resolution	Hundreds of meters
Accuracy	0.1 m
Coverage	Local scale

2.2.2 Use case 2: Monitoring over mountainous areas

Snow monitoring in mountainous areas are more interesting for the user community at local scale since snow accumulation and melting are major sources for social and commercial applications. Satellite remote sensing observations in such areas are often difficult to obtain due to distortions introduced by the topography. In a previous study aiming at estimating snow depth using altimeter measurements over mountainous areas it was determined that due to the complicated topography, the radar echoes were corrupted, and therefore a reliable estimation of the radar back-scatter could not be achieved (Reppucci et al., 2011). However, it has to be pointed out that the area used for the study was characterized by a very steep slope (in the middle of the Pyrenees) and heterogeneous vegetation cover.

In this study, an area characterized by varying topography will be used to assess the capabilities of the altimeter for snow depth retrieval with respect to the terrain topography. This will allow determining the applicability bounds of SRAL data over mountainous regions and the applicability of derived products with hydrological modelling for water resources management applications.

The user requirements for this use case are listed in Table 2-9.

Table 2-9: User requirements for snow depth monitoring in mountainous areas.

	Minimum requirement for radar altimetry snow depth product
Temporal resolution	Tens of days
Spatial resolution	Hundreds of meters
Accuracy	0.1 m
Coverage	Local scale

2.3 Soil moisture

Derivation of surface soil moisture from satellite radar altimetry is a novel application (Berry et al., 2013; Berry and Carter, 2011) and the scope of this application is increasing as the research advances. The surface penetration at these wavelengths (Ku band 12-18 GHz; 2.5-1.67 cm) is restricted to a few cms for desert surfaces, and so this technique measures surface soil moisture within the top 5 cm (ibid). The presence of significant water within the soil structure increases reflection from closer to the surface; mitigating against this is the faster drying time of the surface layers.

This technique relies on deriving DRy EArth ModelS (DREAMS) from multi-mission satellite radar altimetry in Ku band; the key data source is the ERS1 Geodetic Mission dataset, because of its close spatial sampling (average track separation 4km). An example of DREAM for the Simpson desert is shown in Figure 2-4.

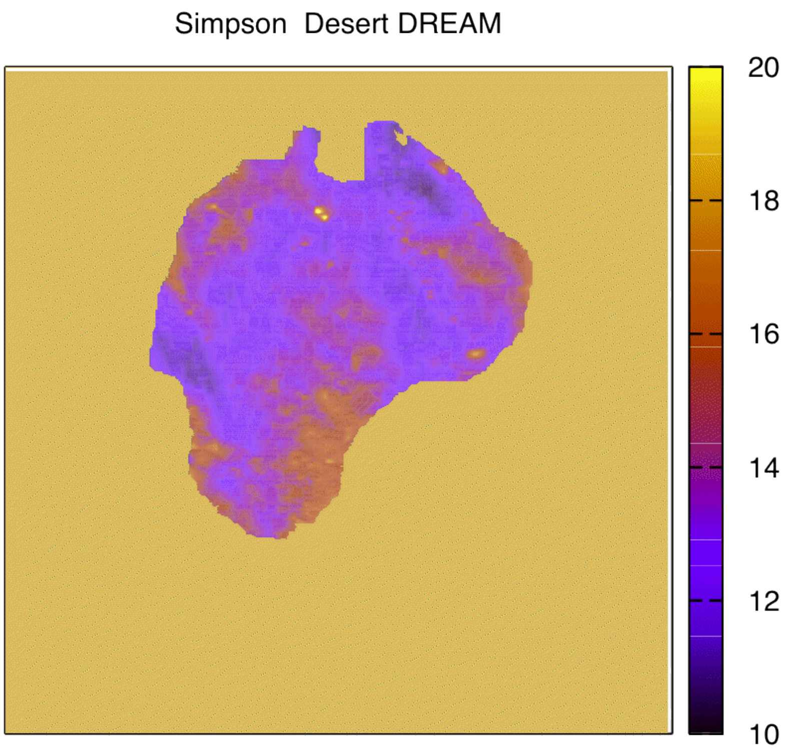

Figure 2-4: Dry Earth Model (DREAM) for the Simpson desert from multi-mission satellite radar altimetry (scale in dB).

In order to create a DREAM, the surface must be dry for at least 2 months of the year. This allows the solution to be regressed to dry earth conditions in a complicated four-stage process requiring manual intervention at each stage. These DREAMS are thus difficult and time-consuming to craft; however, because the complexity of the surface response is vested in the model, they then allow a direct calculation of surface soil moisture with no reliance on external information on surface composition or roughness, a critical limitation on other active sensor techniques (Barrett et al., 2009; Bartalis et. al., 2007). 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. Spatially, data are provided under the satellite tracks and thus generate profiles of surface soil moisture at spatial locations and at temporal spacing determined by the satellite orbit. A pilot scheme for a small number of desert regions has been funded by ESA and results from this work are being made available online (SMALT, 2013).

The user requirements for this use case are listed in Table 2-10.

Table 2-10: User requirements for soil moisture product.

	Minimum requirement for soil moisture product
Temporal resolution	Tens of days
Spatial resolution	Hundreds of meters
Accuracy	1% on soil moisture content
Coverage	Local scale

3 Scientific requirements

3.1 Water levels in inland water bodies

Section 2.1.3 - 2.1.7 pointed out that the important parameters for the application of SAR altimetry in hydrological modelling are the spatial and temporal resolution of the data and the precision of data. Below an outline of these parameters is presented for future scenarios of having one or two Sentinel-3 satellites in orbit.

In this section we have adapted the requirement and constraints for the various use cases and adapted these to the Sentinel-3 and identified how the scientific constraints on size and accuracy and temporal resolution are and can be met with Sentinel-3. In section 3.1.4 we have re-investigated the range and geophysical corrections on Cryosat-2 and suggest how corrections should be derived for the upcoming Sentinel-3 satellite relevant for the retrieval of land geophysical parameters.

For all use of satellite altimetry for retrieval of land geophysical parameters it is crucial that the water body studied will be measured by the satellite. However, orbit restrictions will limit where the altimeter observations will be available.

There is not yet any definitely determined ground track location. This means that in the following we have based the study on water bodies of various sizes and shapes representing the different hydrological use cases presented in section 2.1.3 - 2.1.7. We decided to use statistical measures trying to answer the question: What is the probability that a random water body of a given size and random location will be measured by the Sentinel-3 and to what accuracy and temporal resolution will it be mapped? This is done in order to investigate and answer how satellite altimetry from Sentinel-3 matches and fulfil the minimum requirements set out by the hydrological use cases.

3.1.1 Temporal resolution

Sentinel-3 will have a repeat period of 27 days. However, within a given region, there will be both ascending tracks and descending tracks, which in many locations double the sampling period to 13.5 days. Basically, such a temporal sampling will fulfil the requirements of the different use cases for the use of satellite altimetry over inland water bodies.

3.1.2 Precision

The SRAL data product over land will largely resemble the SIRAL data that are obtained from Cryosat-2 (see the Deliverable D2.1 report). Hence, the precision of Cryosat-2 data has been taken as a proxy for the Sentinel-3 SRAL SAR data precision.

A 20Hz Cryosat-2 measurements has a precision of 11 cm. This number is based on various presentations from the Cryosat-2 SAR altimeter workshop in Southampton, June 2013 (http://www.satoc.eu/projects/CP4O/docs).

In order to determine the precision, we assume that it is dominated by white noise. Consequently, the precision of the estimation of the height of a water body will be determined by the number of observations when the satellite crosses the water body. For each 300 meters one observation with a precision of 11 cm is taken. A water body with a size of 1 km by 1 km will typically contain 3 height measurements. This gives a precision of the mean height of the water body of $11/\sqrt{3}$ = 6.3 cm. The height of larger water bodies will be more accurately determined.

3.1.3 Spatial resolution

The along-track resolution of the SRAL SAR altimeter on board Sentinel-3 is approximately 300 meters for 20 Hz observations. The across-track spacing for Sentinel-3 varies from 104 km at the Equator decreasing with latitude until it reaches 0 km at 82 north and south. The temporal sampling is 27 days.

With the across-track spacing being a consequence of the orbit inclination decrease as the latitude increases, we have chosen 45 latitude as a typical latitude for our investigation. At this latitude the across-track distance is roughly 70 km.

Table 3-1 - Table 3-3 and Figure 3-2 - Figure 3-4 illustrate the probability of capturing water bodies of different sizes and shapes. At 45 latitude only water bodies with a width larger than 50 km will be observed with 100 percent certainty, i.e. it will always be captured by the altimeter data. Smaller water bodies might also be captured, depending on the exact track location. Hence, given the spatial resolution of Sentinel-3, the user requirements regarding the spatial resolution can be met in use case 1-3.

In use case 4 the spatial resolution requirement can be met at higher latitudes or by combining data from different satellites, e.g. another Sentinel satellite. The spatial resolution in use case 5 can only be met along-track.

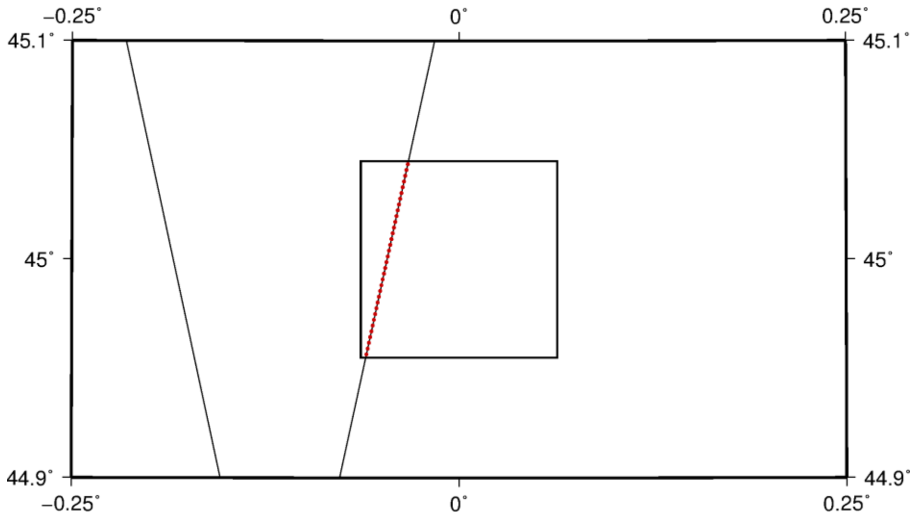

Figure 3-1: Example of a 10 km by 10 km water body with a satellite tracks crossing it. The figure illustrates the individual 20Hz altimetric water height observations along the chosen track being taken within the few seconds of crossing of the water body.

Figure 3-1 illustrates all observations that are used to compute the height of the water body at the time of crossing. The size of the water body along with its shape determines the probability and accuracy the water body can be measured from satellite. Consequently, we have investigated typical squared and elongated water bodies in the following as the satellite naturally favours water bodies elongated east-west due to the fact that the satellite flies nearly north-south.

3.1.3.1 Squared water bodies

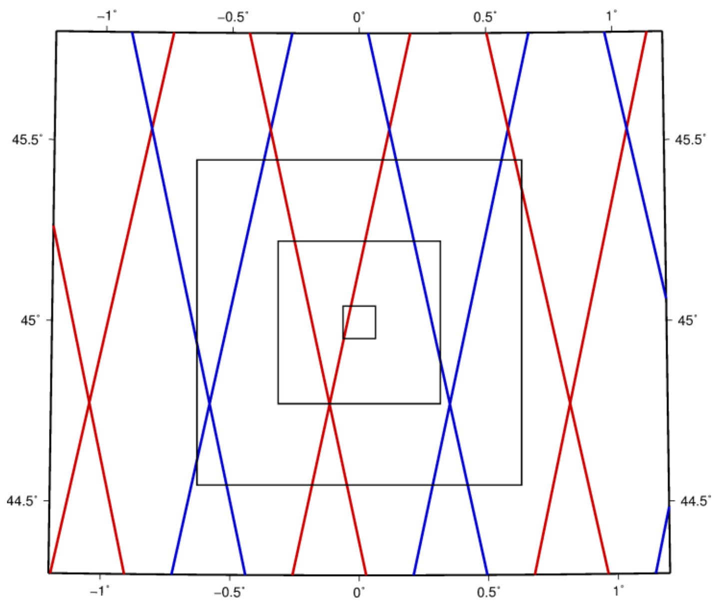

Figure 3-2: Illustration of squared water-bodies located at 45N and with Sentinel-3A tracks shown in red and Sentinel-3B tracks shown in blue. The 10x10 km, 50x50 km and 100x100km water body is outlined.

Table 3-1: The probability, precision and temporal resolution of squared water bodies of various sizes representing the different use cases.

Box size	Probability of mapping		Precision of mean height		Temporal resolution	
	S3A	S3A+S3B	S3A	S3A+S3B	S3A	S3A+S3B
0.1km x 0.1km	0.3 %	0.6 %	11.5 cm	11.5 cm	27 days	13.5 days
0.5km x 0.5km	1.4 %	2.8 %	8.1 cm	8.1 cm	27 days	13.5 days
1km x 1km	2.7 %	5.5 %	6.6 cm	6.6 cm	27 days	13.5 days
10km x 10km	>99.9%	54.8 %	2.1 cm	2.1 cm	27 days	13.5 days
50km x 50km	>99.9%	>99.9%	1.0 cm	1.0 cm	13.5 days	6.8 days
100kmx100km	>99.9%	>99.9%	0.7 cm	0.7 cm	9 days	4.5 days

Table 3-1 illustrates the probability of mapping a water body of a given size from Sentinel-3 altimetry and from a possible scenario with Sentinel-3A and Sentinel-3B being launched simultaneously. Within the foreseen future, in addition to the Sentinel-3 satellites both Jason-2, Jason-3, AltiKa, Hy-2 and Cryosat-2 will be flying simultaneously. If these data are being included in the investigation of land hydrology, the probability of mapping will be much larger than what is stated in Table 3-1. Basically, there is a linear relationship with the number of satellites and the chance of mapping a water body.

3.1.3.2 East-west elongated water bodies

For this investigation we took the same water bodies as shown in Figure 3-2 and presented in Table 3-1 and elongated these by a factor of 4 in the east-west direction and similarly decreasing the size in the north-south direction by a factor of four, see Figure 3-3. The increase in east-west direction means that significantly smaller water bodies can be mapped. However, the accuracy that they can be mapped with decreases.

Table 3-2 illustrates the probability of mapping an east-west four times elongated water body of a given size from Sentinel-3 altimetry and from a possible scenario with Sentinel-3A and Sentinel-3B being launched simultaneously.

Table 3-2: The probability, precision and temporal resolution of east-west elongated water bodies of various sizes representing the different use cases.

Box size	Probability of mapping		Precision of mean height		Temporal resolution	
	S3A	S3A+S3B	S3A	S3A+S3B	S3A	S3A+S3B
0.25km x 4km	11.0 %	21.9 %	11.5 cm	11.5 cm	27 days	13.5 days
1.25km x 20km	54.8 %	>99.9%	5.75 cm	5.75 cm	27 days	13.5 days
2.5 km x 40	>99.9%	>99.9%	4.1 cm	4.1 cm	13.5 days	6.8 days
12.5km x 200km	>99.9%	>99.9%	1.9 cm	1.9 cm	4.5 days	2.5 days

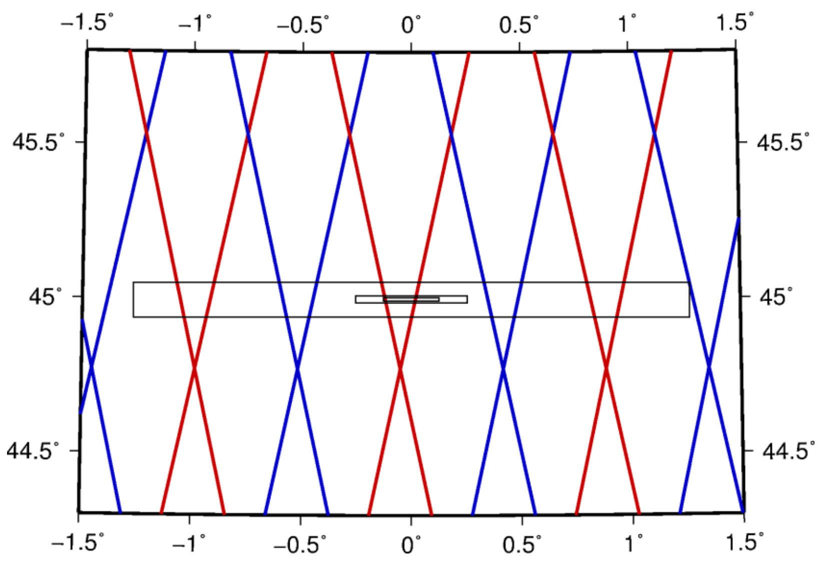

Figure 3-3: Illustration of east-west elongated water bodies. All water bodies have the same area as the water bodies illustrated in Figure 3-2. The chance of mapping these are shown in Table 3-2.

3.1.3.3 North-south elongated water bodies

For this investigation we took the same water bodies as shown in Figure 3-1 and presented in Table 3-1 and elongated these by a factor of 4 in the north-south direction as in the investigation above, see Figure 3-4. At low latitudes where the satellite flies most north-south this will result in smaller probability of mapping the water body from satellite. Fortunately, a large fraction of water bodies and river systems at low latitudes runs east-west, or vice versa (i.e., Ganges, Amazonas, Congo, etc.).

Table 3-3: The probability, precision and temporal resolution of 4 times north-south elongated water bodies of various sizes representing the different use cases.

Box size	Probability of mapping		Precision of mean height		Temporal resolution	
	S3A	S3A+S3B	S3A	S3A+S3B	S3A	S3A+S3B
4km x 0.25km	0.7 %	1.4 %	5.1 cm	5.1 cm	27 days	13.5 days
20 km x 1.25	3.4 %	6.8 %	2.3 cm	2.3 cm	27 days	13.3 days
40km x 2.5km	6.8 %	13.7 %	1.6 cm	1.6 cm	27 days	13.5 days
200km x 12.5km	34.2 %	68.5 %	0.7 cm	0.7 cm	27 days	13.3 days

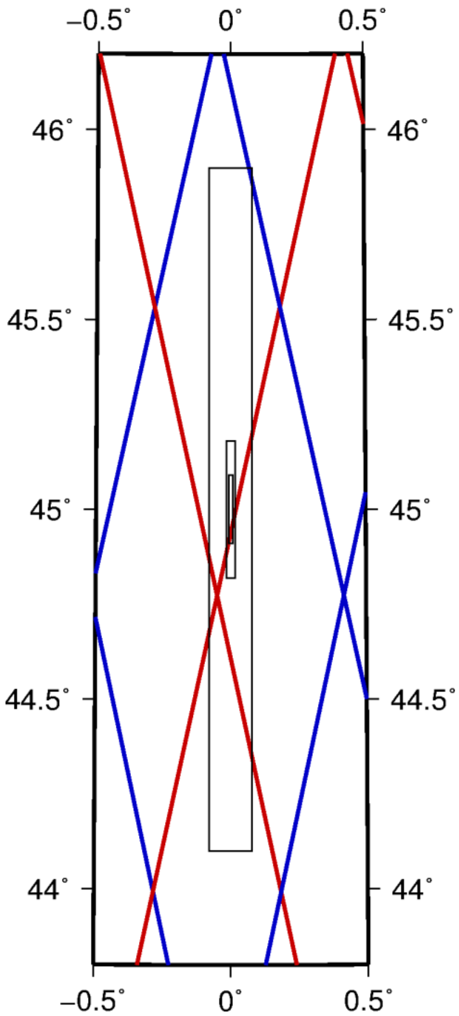

Figure 3-4: Illustration of north-south elongated water bodies. All water bodies have the same area as the water bodies illustrated in Figure 3-2 and Figure 3-3. However, the chance of mapping these is significantly smaller than for east-west elongated water bodies.

Table 3-3 illustrates the spatial probability of mapping a north south elongated water body of a given size from Sentinel-3 altimetry and from a possible scenario with Sentinel-3A and Sentinel-3B being launched simultaneously. The increase in the north-south direction means that the water bodies are more accurately mapped. However, the chance of mapping a water body is significantly lower than for both squared and east-west elongated water bodies.

3.1.4 Corrections

This section briefly outlines the main findings for the various range and geophysical corrections applied for observations on land. The section presents the most recent developments and experiences based on the description in the Deliverable D2.1 report, focusing on recommendations for the upcoming Sentinel-3 satellite.

A major conclusion is the importance of making model-based corrections available for wet and dry troposphere and ionosphere corrections, and ensuring that editing of the data is not performed on the basis of the quality of the satellite derived corrections. Model-based range corrections might not be as accurate as corrections for the wet troposphere based on the radiometer and corrections for the ionosphere based on dual frequency satellite altimeter observations (Andersen and Scharroo, 2011). However, the advantages of the model-based corrections are that they are not contaminated by land, and they are generally available everywhere, which is essential.

Furthermore, it is important to take into account the thickness of the atmosphere, which is normally estimated based on a crude topographic grid (0.25^{o} x 0.25^{o}) equivalent to the resolution of the ECMWF model. However, with this approach small-scale topography is not well represented, and we suggest upgrading the wet troposphere correction using the altimetric range observations itself. The altimetric range observations could be used to estimate topography, and this could then be used to derive a more precise estimate of the atmosphere thickness, especially in areas with small-scale topographic changes.

Further research is suggested to investigate the accuracy of the wet troposphere correction over continental water bodies as well as deriving better corrections for future altimeter products.

3.2 Snow depth

The derivation of snow depth over land surfaces is mainly related to the power of the returned radar echoes penetrating the snow and vegetation media. The penetration capabilities of the wave into the snow pack depend on the dielectric properties of the snow area under observation, which in turn depends mainly on its liquid water content. The backscattered signal is thus the joint contribution of the echoes from the ground, vegetation and snow-pack layers. Reliable estimation of snow depth represents in itself an important advancement in the retrieval of SWE. Once this is solved, the snow density should be estimated with radar polarimetry or other remote sensing techniques.

At this stage there are several scientific requirements that can be defined in order to be able to estimate snow depth with the required precision by the users. The scientific requirements can be classified into instrumental requirements, and geophysical corrections.

Instrumental requirements

- **Radar Power Normalization:** In order to be able to obtain an absolute backscatter measurement from the observed target, i.e. the so-called Radar Cross Section (RCS), or sigma0, the instrumental system parameters need to be normalized from the echo power measurements. Those include: antenna gain, receiving chain characterization, system noise, etc.
- **Radar Calibration:** External and internal calibration of the radar electronics shall be performed in order to monitor possible drifts of the radar electronics, or antenna frame. Calibration targets of stable backscattering, such as the rain forest, shall be defined in order to perform an external calibration of the instrument. At the same time, the electronics shall be verified routinely in order to account for possible gain variations along the orbit. Special care shall be taken at eclipse and full illumination situations.
- **Platform Miss-Pointing:** The platform miss-pointing angle shall be continuously monitored in order to account for different rocking angles of the antenna frame, which would lead to different sigma0 measurements.

Geophysical corrections and requirements:

- **Atmospheric corrections:** Variations in the dry and wet troposphere can lead to variable signal attenuation that could potentially bias the RCS estimation. For that reason, microwave radiometer water vapour measurements shall also be available over land.
- **Soil surface condition variations:** Snow depth measurements will be affected by the soil surface conditions. Therefore soil moisture and freeze/thaw state are parameters that will need to be closely monitored for the final estimation of snow depth.
- **Surface Topography Conditions:** The SAR altimeter provides an enhanced along-track resolution. However, the across-track resolution is equivalent to that of the conventional altimeter. For this reason, an extended flat area will need to be used for the development and validation of the snow depth algorithms. Other areas will also be analysed in order to consider the application of the SAR altimeter snow depth retrieval in mountainous areas or zones with more complicated topography.

CryoSat-2 radar altimeter waveforms will also be analysed to determine whether range measurements, and/or difference in range from different echoes can be used to derive snow depth. Therefore, the same type of corrections as the ones used to derive altimetry information of the oceans will need to be applied. Those include atmospheric corrections, i.e. dry and wet troposphere, ionospheric delay, orbital corrections, and also the effect of surface topography.

3.3 Soil moisture

The DREAMS utilized for prior soil moisture estimations (Berry et al., 2013; Berry and Carter, 2011; SMALT, 2013) were in initial development stages and considerable further enhancement is possible. This is required as the DREAMS were optimized for ERS2 and Envisat altimetry by merging into the models repeat passes of data from these satellites to over-populate the models beneath the satellite tracks (ibid), and Sentinel-3 is in a different orbit. The effect of this is that Sentinel-3 soil moisture estimates from current DREAMS will be primarily reliant on the ERS1 GM dataset. It is noted that, whilst Geosat waveform data are available for the Geosat Geodetic Mission, this instrument was affected by severe offpointing, rendering that dataset unusable for this application. The 10 day orbit repeat patterns of TOPEX, Jason1 and Jason2 are too coarse to provide significant model enhancements; additionally, whilst the long-running TOPEX satellite acquired a considerable volume of waveforms over relatively benign terrain including desert regions, an onboard instrument problem caused shifts in calculated surface backscatter. This was corrected using global averaged derived wind speed over ocean (Callagham, pers. comm.) but over land, unpredictable shifts remain.

There is thus a requirement for ERS-1 Geodetic Mission data to be available for each desert modelled (one desert critically affected by this requirement is the Takla Makan, where an ESA calibration zone for the ERS1 altimeter, together with the loss of data over the Himalayas, resulted in critical data loss). The global distribution of successfully acquired echoes from the ERS1 Geodetic Mission is shown in Figure 3-5. 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, and this possibility will be investigated. It is noted that analysis to date of Cryosat SAR data show that snagging on bright targets remains a significant complicating factor in waveform analysis and interpretation, as for prior altimeters, affecting both inland water and soil moisture applications (soil moisture estimates can be affected by snagging on both inland water bodies and salars).

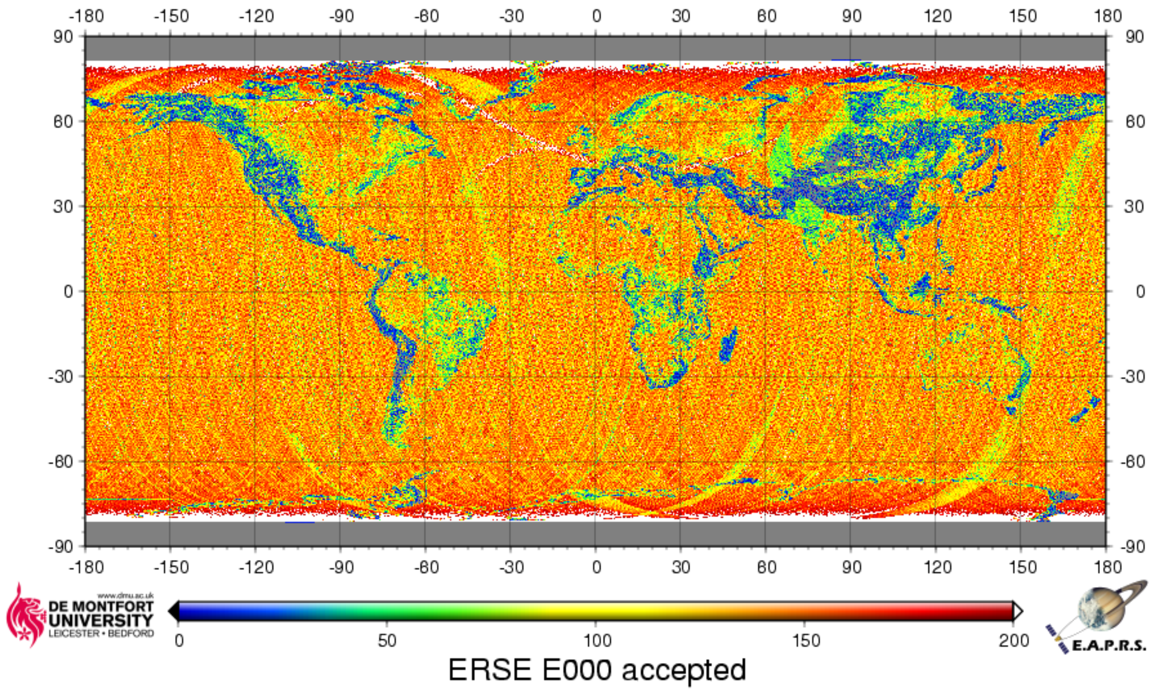

Figure 3-5: Global distribution of accepted echoes from the ERS1 Geodetic Mission.

However, preliminary analysis of Cryosat-2 SAR FBR waveforms suggests that FBR data may overcome this constraint. It is also noted that the Sentinel-3 altimeter may not retain lock over rough topography, the key limitation on altimeter measurements from prior altimeters over land and inland water. Analysis of Cryosat-2 data shows loss of lock over moderate terrain, and the proposed DEM controlled tracker for the Sentinel-3 SRAL can only be utilized over a small number of large water bodies.

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. Over salars, soil moisture cannot be measured by this technique, as the dielectric constant of surface salts does not change sufficiently with moisture content to affect reflectance to Ku band nadir illumination.

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. Whilst this would produce less precise estimates of soil moisture, it could extend the geographic scope of a soil moisture product very significantly, and this will be investigated.

Before this technique can be utilized with the Sentinel-3 SRAL instrument, the effects of the novel instrument design must be evaluated using Cryosat-2 SAR mode data. In principle, the surface area contributing significantly to each echo (and thus to the calculated backscatter for each waveform) should be reduced in the along-track direction, although remaining similar in across-track return to that of prior altimeters. However because surface roughness and composition can change on a short spatial scale, the availability of SAR FBR waveforms has potential to increase the actual measurement spatial resolution, as evidenced by prior work with Envisat Burst Echoes (Berry et. al., 2011), providing more precise data but also requiring more high frequency information to be incorporated into the DREAMS to interpret this information in terms of surface soil moisture.

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