Development of SAR Altimetry Mode Studies and Applications over Ocean, Coastal Zones and Inland Water (SAMOSA)

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WP-3 Technical Note

Recovery of short wavelength geophysical signals and short spatial scale sea surface height/slope signals

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1 Introduction

A number of phenomena in the open ocean are yet unresolved by conventional 1 Hz altimetry, but could be observed through the potential improvements offered by SAR, or Delay-Doppler (DD), altimetry.
As stated in (Cotton et al., 2008), the DD altimeter offers the following benefits with respect to conventional satellite altimetry:

- Factor of 20 improvements in along track resolution.
- Along-track footprint length that does not vary with wave height (sea state).
- Improved Precision ratio allowing for more precise sea surface height measurements / sea surface slope measurements.

The specific aim of the work described in this technical note was to: *investigate how the higher resolution following from the higher Pulse Repetition Frequency (PRF) of SAR mode altimeter may enhance the capability to provide information on short spatial scale geophysical sea surface height/slope signals (especially in areas of high waves).*

There were two aspects to this work:

(i) Theoretical modeling to characterize the expected gain between high PRF reduced SAR mode data and low PRF classical LRM data in terms of improved performance in measuring ocean surface geophysical parameters

(ii) Processing and analysis of simulated data to assess the expected gain between high PRF reduced SAR mode data and low PRF classical LRM data.

These requirements were addressed in an experiment which simulated geophysical data representing small scale (5-20 km) sea-mounts and trench or abyssal hill structures on the sea bottom. The expected sea-surface signatures of these features were modeled and the consequent “visibility” of these features under different sampling frequencies was investigated. A digital sea-surface elevation model containing these sea-surface signatures was then created and used as input to CRYMPS to produce simulated CRYOSAT data. These simulated data were then investigated.

2 High Resolution Mapping of Geophysical Signals

The sea surface height or sea surface slope (i.e. the difference between two consecutive sea surface height observations) are direct measures of the changes in geoid and consequently are also a direct measure of changes in the local gravity field. Altimeter observations of sea surface height offer a fundamentally different way to measure the local gravity than that provided by space gravity missions such as GRACE, CHAMP or GOCE. Space gravity missions measure the gravity field directly at an altitude of 400-700 km. However, diminution of the signal through the inverse square law affects these observations, which means that only long wavelength features can be obtained from such space missions. In terms of space-borne instrumentation only altimeters can measure the high resolution gravity field (in the range of 5-100 km) because this approach measures the geoid height variations at the sea-surface.

Of course marine gravity can be directly measured by dedicated airborne or marine surveys but, as documented by Sandwell (2005), this approach is many times more expensive than measuring it from satellite. Another virtue of satellite observations is that they provide near global uniform coverage of observations independent of territorial restrictions and weather conditions.

The effectiveness of the retrieval of short wavelength geophysical signals from space is limited by the inverse square law, as the strength of the gravity field falls off as the square of the distance between the source and the observer. Indeed, the shorter the wavelength of the (geophysical) signal, the stronger is the effective attenuation. Consequently there will be a scale dependent attenuation of the gravity anomalies from geophysical signatures on the sea floor. A rule of thumb is that gravity anomalies related to geophysical structures with long wavelength compared with the mean depth will suffer little attenuation, while anomalies with short wavelength compared with the water depth will be strongly attenuated. This effect is investigated in more detail in Section 4.3

The morphology of the seafloor is composed of a variety of features at a range of spatial scales. Most structures are related to sea floor spreading and undersea volcanoes, both the result of plate tectonics. Horizontal fracture zones and abyssal hills are effectively 2-Dimensional elongated structures, similar to trenches, and are mainly seen associated with spreading zones where they form ribbon like signals in a pattern away from the zones. Sea-mounts on the other hand are isolated structures mainly seen in the western Pacific Ocean. Examples of these kinds of structures as seen in the gravity anomaly map are shown in Figure 1, where the left panel shows the mid-Atlantic spreading zone in the southern Atlantic Ocean, and the right panel shows the trenches in the western Pacific Ocean and the large number of sea-mounts in between.

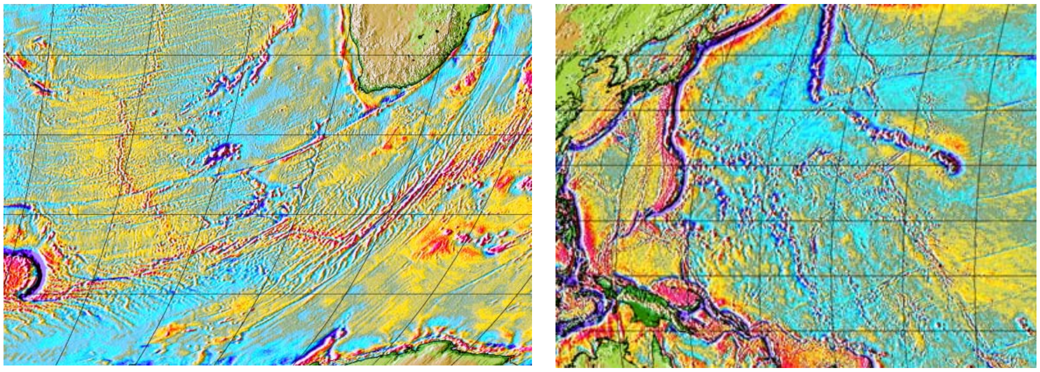

Figure 1. Illustration of the two dominant types of geophysical features on the sea floor that can be seen from satellite altimetry. Derived from the DNSC08 global free air gravity field. Left Panel: the mid-Atlantic spreading zone. Right Panel: the western Pacific Ocean showing the trenches close to the Japan and the Philippines, and the Hawaiian undersea mountain chain.

Geophysical structures with spatial signatures greater than 20 km have already been mapped on global scale through a combination of ship-borne surveys and satellite altimetry. In the simulations and investigations described in this technical note we will focus on retrieval of geophysical signals in the 5 – 20 km range. Features in this spatial scale are not currently retrievable from satellite altimetry due to a combination of restrictions imposed by the size of the altimeter footprint and the noise on the observations. However signals in the 10-20 range are in-frequent mapped along track when the 1 –Hz data support it.

The dominant source of geophysical signals at these spatial scales will be smaller sea mounts and abyssal hills. The abyssal hills are very important to a number of physical oceanographic disciplines due to their critical role in ocean circulation and mixing. Here we focus on the possible mapping of these features using a DD altimeter.

The total number of sea-mounts mapped from conventional satellite altimetry and ship-borne observations in the global ocean is plotted against the sea-mount height (logarithmic scale) on Figure 2. The figure illustrates that sea-mounts with heights of less than ~2 km (and a corresponding horizontal spatial signature smaller than 15-20 km) become too small to be mapped by conventional satellite altimetry. The interesting feature is the vast number of these smaller sea-mounts. If the logarithmic relationship between the number of seamount and their heights that is seen for sea-mounts with heights in the range 2-8 km continues below 2km, then it follows that of the order of 40-50,000 sea-mounts with heights greater than 1 km are still unknown / uncharted. This is ten times the total number of sea-mounts currently charted.

The DD instrument may offer the only realistic method for mapping these seamounts, to use conventional ship-borne survey techniques would be prohibitively expensive. Furthermore, the mapping of the morphology of geophysical structures in the 10-20 km spatial range is of vital importance to a number of geophysical and oceanographic disciplines, including tsunami warning, ocean current steering, ship safety and mineral exploration.

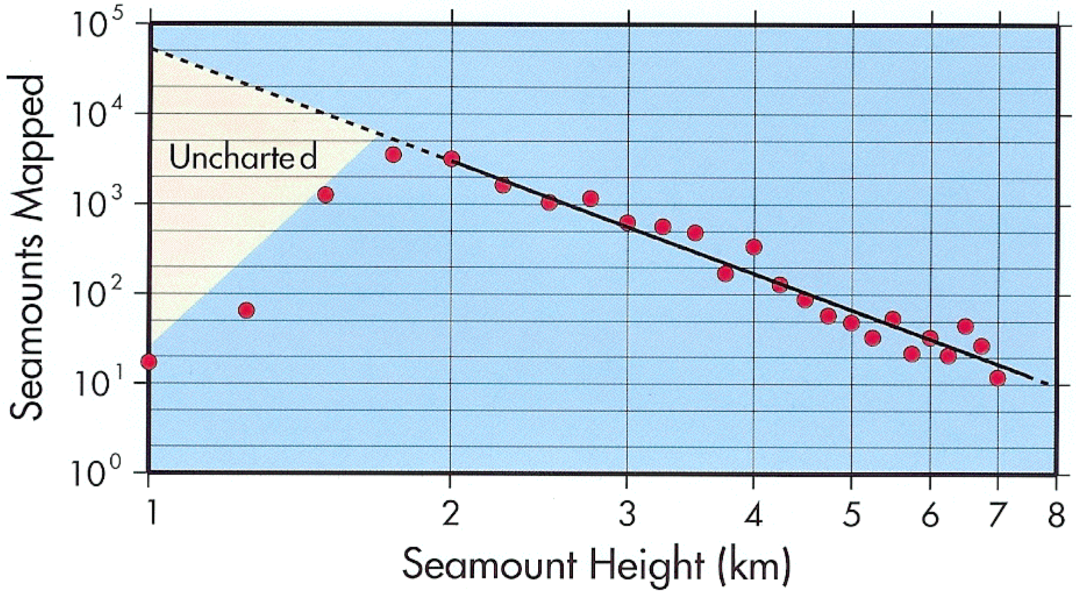

Figure 2. The number of mapped sea mounts surveyed from satellite and ship mapped as a function of the sea mount height (Smith et al., 2005), plotted on logarithmic axes.

Gravity anomalies are to a large extent associated with sea floor topography. However, one should be aware than in some regions there are limitations to the gravity-bathymetry correlation because of sub-surface geology (variations in sediment thickness and density can also have a gravity signal). Fortunately, in most parts of the open ocean the spatial correlation between the sea floor topography and the gravity field is larger than 80%, and consequently in most cases the gravity field is highly correlated with the sea floor topography and geophysical features.

3 Advantages of the Delay-Doppler Altimeter

The preceding section has outlined the major limitations of current techniques in deriving accurate marine gravity fields and sea floor bathymetry.

The specific limitations of conventional satellite altimetry in this respect are the spatial resolution (determined along-track by the altimeter footprint), the accuracy of individual SSH observations, and the degradation of sea-surface height measurements with increasing proximity to the coast.

The Delay-Doppler (DD) altimeter provides key improvements to each of these limitations. More specifically, the DD altimeter has the following significant advantages over conventional satellite altimetry.

These are

- The along track length of footprint is constant and does not depend on the significant wave height.
- The along track resolution is around 300 meter versus 6 km for 1-Hz conventional satellite altimetry.
- The Signal to Noise (SNR) or precision is a factor of two better than that of "conventional" current-day altimeters.

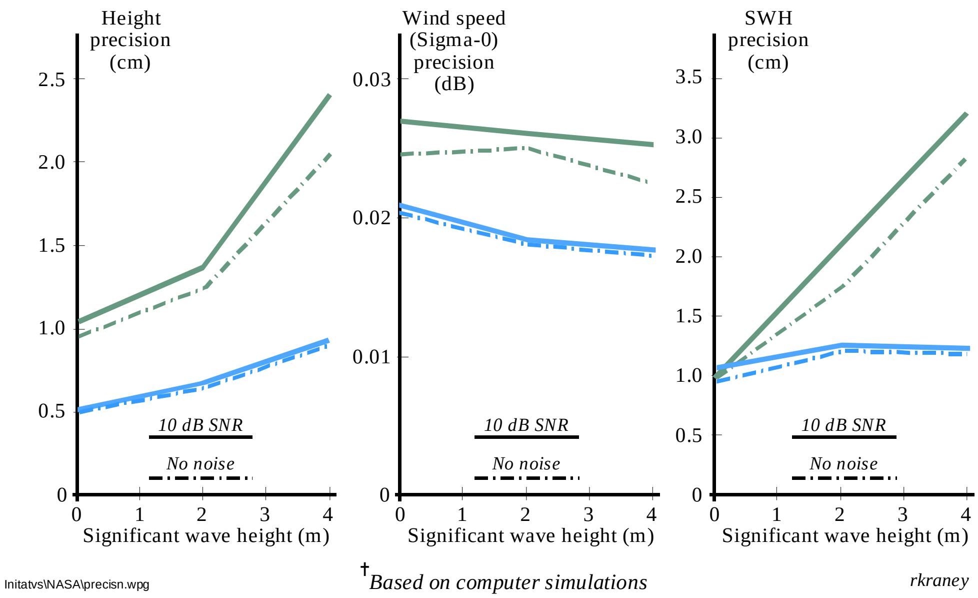

Figure 3. The simulated height precision, wind speed precision and SWH precision of 1 Hz observations derived with a DD instrument (bright blue curve) compared with a conventional satellite altimeter (green curve) (Jensen and Raney, 1998)

Also, as demonstrated in Figure 3, the DD altimeter offers a significant improvement in the precision of the sea-surface height measurements

It is important to be aware of the fact that existing geophysical exploration maps have been derived from geodetic mission altimetry from GEOSAT (1985-1986) and ERS-1 (1994). Current day altimeters are more accurate and the potential improvement in the Precision of the DD altimeter compared with these “old” instruments is most likely to be even higher than the factor of two to three indicated in Figure 3.

The DD altimeter has the potential with respect to SNR and spatial resolution to provide a “quantum leap” forward in the mapping of marine gravity and sea floor topography as will be investigated using the simulation below, but it must be stressed that the choice of orbit is as fundamental as the instrument itself in the design of the mission. A suggestion for the use of a Near Exact Repeat orbit is made in Section 5.

4 Simulations of Sea-Surface Geophysical Signals from Sea-Floor Features

4.1 *Introducing the Scenario*

To support this investigation of DD altimeter observations of geophysical signals, a scenario was introduced in which the sea surface topography/height response from "real" geophysical structures on the sea floor with 5-20 km spatial wavelength and various heights (depths) was considered. Features at these wavelengths cannot in principle be recovered fully using conventional 1 Hz satellite altimetry (e.g. ENVISAT), so any signals which could be recovered using DD altimetry would represent improvements over the capability of currently operational altimeters.

The potential of DD altimetry to recover details of these sea-floor features (through the signal at the sea surface) was investigated in two ways:

- by considering possible sampling rates and anticipated Precision ratios on the height signal.
- by analyzing modeled CRYOSAT echo waveforms from this sea-surface, the waveforms produced by the UCL CRYMPS simulator.

For the input file to CRYMPS an 8 second simulated digital elevation and backscatter model of the sea surface, corresponding to 54 km along track and 8 km across track, with a spatial resolution of 10 meters, was needed. The file contained a sea-surface height model (geoid height) which represented the surface signature of four circular sea-mounts and two trenches of variable sizes located at a base depth of 2000 meters. The scene was patched out with zeros to cover a larger region (60km), in an attempt to avoid "edge effects". The details are discussed in more detail below. Additional scenarios with varying swell amplitude had been considered but resources available to the project limited the team to one scenario only for this aspect of the study.

The bathymetry model, the gravimetric response and the geoid or sea surface height model are shown in Figure 4. The bathymetric features range up to 1.5 km in height which brings them to within 0.5 km of the sea surface. The sea surface height signal, given in the right-hand panel of the figure, ranges from -14 cm to +15 cm. Thus the signals observed by the satellite are very small, placing a requirement for improved accuracy on sea surface height observations to be retrieved from the DD altimeter. In Figure 4 the 54 km of geophysical signal starts at y=6 km and ends at y=60 km. The centre of the scene in the x-direction, representing the along-track nadir point of the satellite, is at x = 22 km. The central profiles along this track for the bathymetry model, the gravimetric response and the geoid or sea surface height model are shown in Figure 5. The forward gravimetric response was computed in 2D using a combination of the prism formula, the McMillan formula and the point mass formula as described in Forsberg, (1984). The integration of gravity anomalies to calculate the geoid height anomalies was performed using the Stokes integration over the simulated area. Due to the fact that the scene is both small and not quadratic, truncation error will be present in this simulation, and the geoid amplitudes will be too low. These degraded amplitudes were compensated for by increasing the amplitudes slightly in the simulated sea-surface height field.

The four sea mounts are the first four features in the scene. Two identical 1.2 km high sea mounts were placed at 9 and 14 km, each being circular and 5 km wide at the bottom and consequently touching each other at the sea bottom. This arrangement was selected so that the capability of the DD altimeter to distinguish between the surface signals of closely separated sea floor features could be investigated. The third sea mount is 1 km tall but offset by 5 km from the center of the scene (x=22 km) and has a center at y=23 km. The fourth and largest sea mount is 1.5 km tall and has it center at 35 km and is circular with radius of 7 km at the sea bottom.

Finally two “trench” features were introduced. Both trenches are perpendicular to the flight direction, and will consequently appear as two-dimensional features. The first trench is centered at 46 km and has a depth of 1000 meters. The second trench has a depth of 1500 meters and is centered at 56 km.

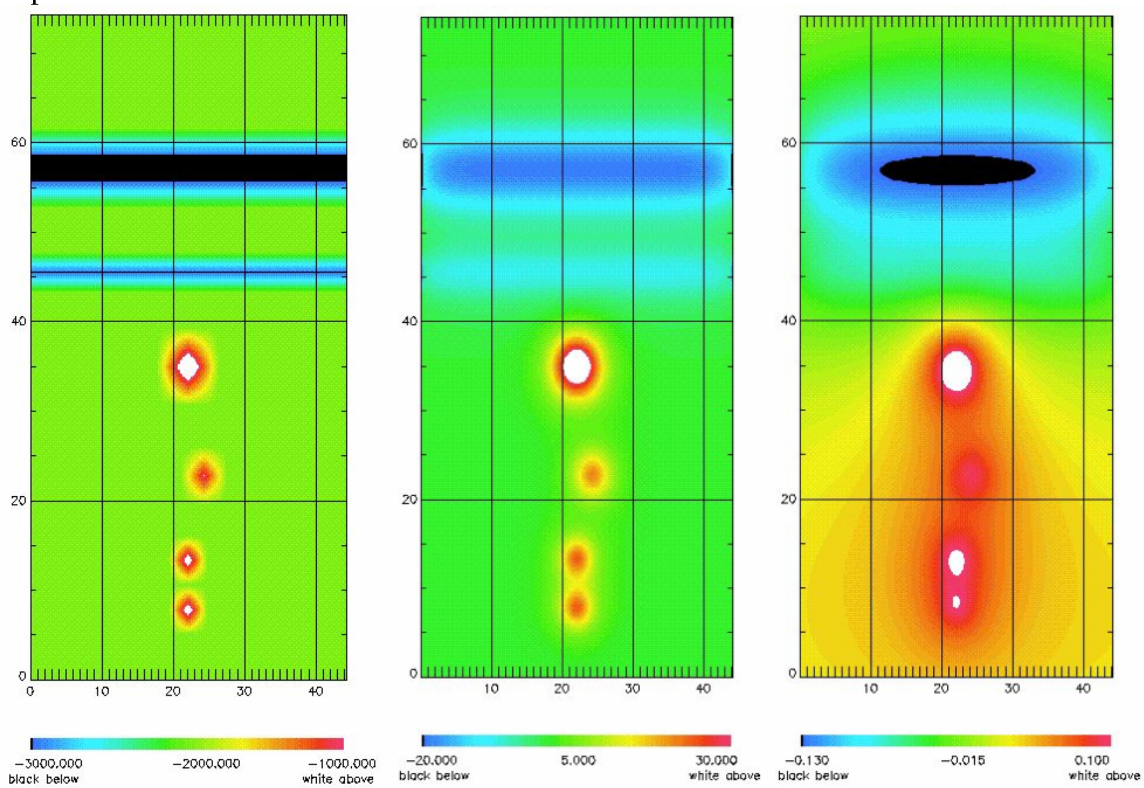

Figure 4. Left Panel: The geophysical or bathymetric signal. The range is between 4000 1000 meters. Centre Panel: The surface gravimetric response of the bathymetric signal, ranging between -20 mGal and 47 mGal. Right Panel: The geoid response of the bathymetric signal and hence the sea surface signal that will be seen by the DD altimeter. This signal ranges between -14 cm and +15 cm. These amplitudes are slightly too low

because of truncation errors as the scene is both small and not quadratic. The degraded amplitudes were compensated for in the simulation by increasing the amplitudes slightly.

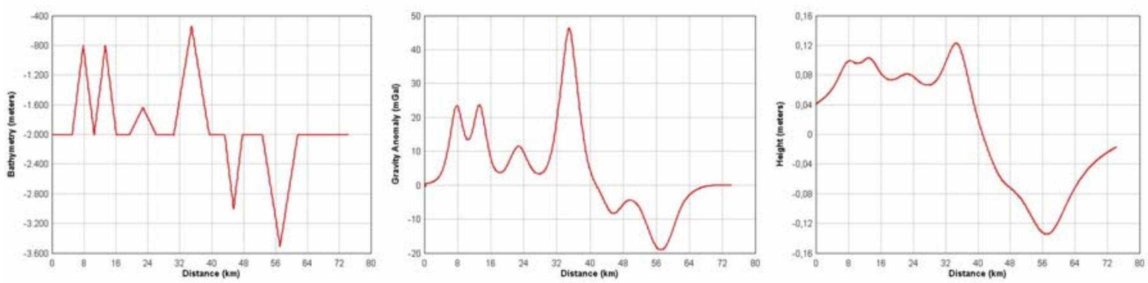

Figure 5. Centre along-track profiles at x = 22 km. Left Panel: The bathymetric signal. Centre Panel: The surface gravimetric response of the bathymetry, ranging between -20 mGal and 47 mGal. Right Panel: The geoid response of the bathymetric signal and hence the sea surface signal that will be seen by the DD altimeter. This signal ranges between -14 cm and +15 cm.

4.2 *Attenuation due to "Upward Continuation"*

The retrieval of short wavelength geophysical signals is limited because the strength of the gravity field decays as the square of the distance between the source and the observer.

The process by which potential fields data are projected from one datum or height surfaces to another datum or height are called upward or downward continuation. In upward continuation used here, the situation is mathematically simpler as this is done outside the sources of gravity investigated.

Signals from shorter wavelength features will be attenuated more strongly than those of longer wavelength features. Consequently, this effect is particularly significant when considering the retrieval of geophysical signals with spatial scales of 5-20 km range, which will suffer greater attenuation as the depth of the ocean increases.

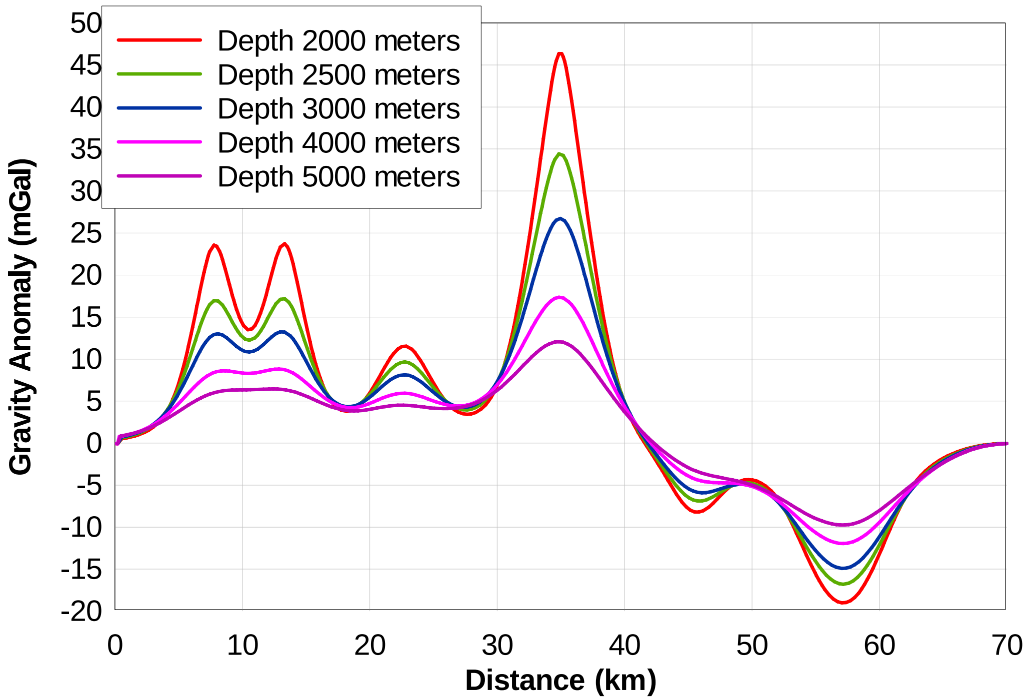

Figure 6. Result from forward gravity simulations using the bathymetry scenario in Figure 4 at different base depths. At a depth of 5000 metres the largest sea-mount will rise to 3.5 km and the trench will dip to 6.5 km.

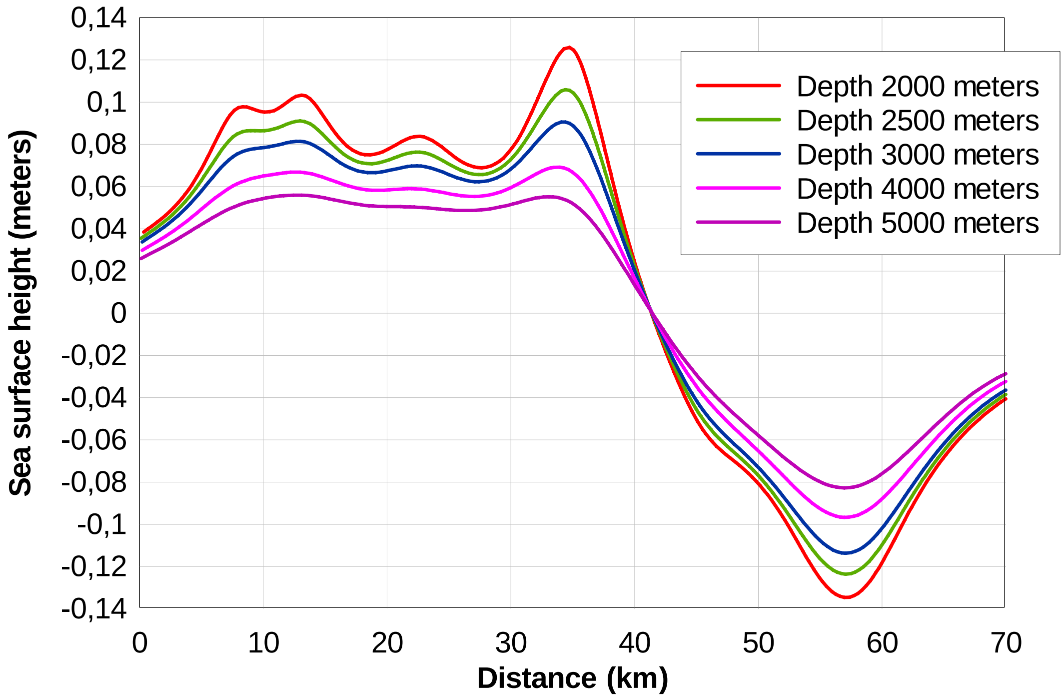

Figure 7. Result from forward sea surface height simulations using the bathymetry scenario in Figure 4 at different base depths. At a depth of 5000 meters the largest sea mount will rise to 3.5 km and the trench will dip to 6.5 km.

The investigation of the upward continuation is performed by lowering the Sea bottom bathymetry by steps of 500 meters. The bathymetry is seen in Figure 5 to have a base at 2000 meters. This base is suqsequently put to greater and greater depth with maintaining the seamount and trench structures.
Results from the gravity and sea surface height simulations for various ocean depths are presented in Figures 6 and 7. It is obvious that direct gravity field observations (i.e. as performed by ships) will suffer less attenuation due to upward continuation attenuation than the geoid signal (the latter is reduced with respect to the former due to Stokes integration of the gravity anomalies).

The two twin sea mounts at x=8 km and x=13 km were included to allow an investigation into the ability of the DD altimeter to separate signals from 2 closely separated sea-floor features. The upward continuation attenuation affect also limits the ability to distinguish between the separate signatures of these two features. It is seen that in terms of gravity anomalies the two 1.2 km height sea mounts can be separated when the base ocean depth is 5000 meters or less (equal to the horizontal separation between the two features). For greater depths the two signals are blurred into one anomaly. This result corresponds to the result by Sandwell and Smith, 2004.

For the geoid height signal and consequently the sea surface height /sea surface slope signal it is found that the situation is slightly worse. In this case the two signals can be separated until the ocean base depth increases from 3000 to 4000 meters. Hereafter they blur into one signal. For greater depths it is important that the combined signal can still be measured even though geophysicists will interpret the geoid/gravity signal as one common bathymetric seamount.

The signals of the ocean floor trenches are significantly more difficult to recover as these geophysical signals range “downwards”, away from the observer, as opposed to the sea-mounts which lift upwards to the sea surface making them standing clearer in the gravity signal. The simulation results reveal that when the ocean base depth is 3000 meters or more the signals from the two trenches cannot be separated from each other.

The simulation shows that the ability to recover geophysical signals is strongly dependent on depth. It also shows that the gravity signal and the sea surface height signal will appear as a band pass filtered version of the underlying bathymetry. Also the signal strength spectrum and in particular the Precision ratio are important parameters for the ability to resolve geophysical features using altimetric observations. This aspect will be investigated in the following section

4.3 ***Precision***

In the simulations above it was demonstrated how the signal is attenuated as the depth of the ocean increases. In this investigation no noise was added to the observations. Key improvements anticipated from DD altimetry are an improvement in the precision by a factor of two compared with current-day altimeters and the independence of this precision with respect to sea state (conventional altimetry is known to degrade at high sea states).

In theory, the precision ratio from DD altimetry should be a factor of 2.5 better than that from the geodetic mission altimetry from ERS-1 and GEOSAT. These are missions (1985-6, 1994) from which the current "state of the art" geophysical maps have been derived.

An uncorrelated or white noise spectrum added to the gravity field values will result in a somewhat "blue" noise field on the geoid height anomalies which is actually what the DD instrument measures. A blue noise field has increasing power at decreasing wavelength.
The investigation was carried out by simulating the noise using a random generator which subsequently adds noise to the observations.

From Figure 3 the expected precision for a typical significant wave height in the open ocean of 2 meters will be around 0.7 cm for a 1 Hz DD observation, compared with 1.4 cm for state of the art satellite altimeters (Keith Raney – personal communication). Assuming that for white and blue spectra the noise on a sum of observations falls off with the square-root of the number of the observations it can be estimated that for 2 Hz observations the noise will be roughly 1 cm for DD observations and 2 cm for a conventional altimeter. Therefore, for CRYOSAT 18 Hz SAR the noise can be estimated to be 3 cm whereas this would be 6 cm for a conventional altimeter.

In Table 1 the along track averaging values and corresponding noise are shown for three altimeters types: Delay-Doppler, State of the Art conventional altimeter (2000's), and Geodetic mission (Geosat, ERS-1: < 1995) altimetry. Along track spacing between the individual observations of the averaged sea surface height observations assuming a roughly 800 km orbit is also given

	DD altimeter (cm)	State of the art Conventional altimeter (cm)	Geodetic mission altimetry (ERS-1/GEOSAT) (cm)	Along Track Spacing (km)
1 Hz	0.7	1.4	1.8	6.5
2 Hz	1.0	2.0	2.6	3.25
5 Hz	1.5	3.0	3.6	1.25
18 Hz	3.0	6.5	8.0	0.36

Table 1. Noise on averaged sea surface height / slope observations for various altimeters. Along track spacing between the individual observations assuming an 800 km orbit is given in the final column

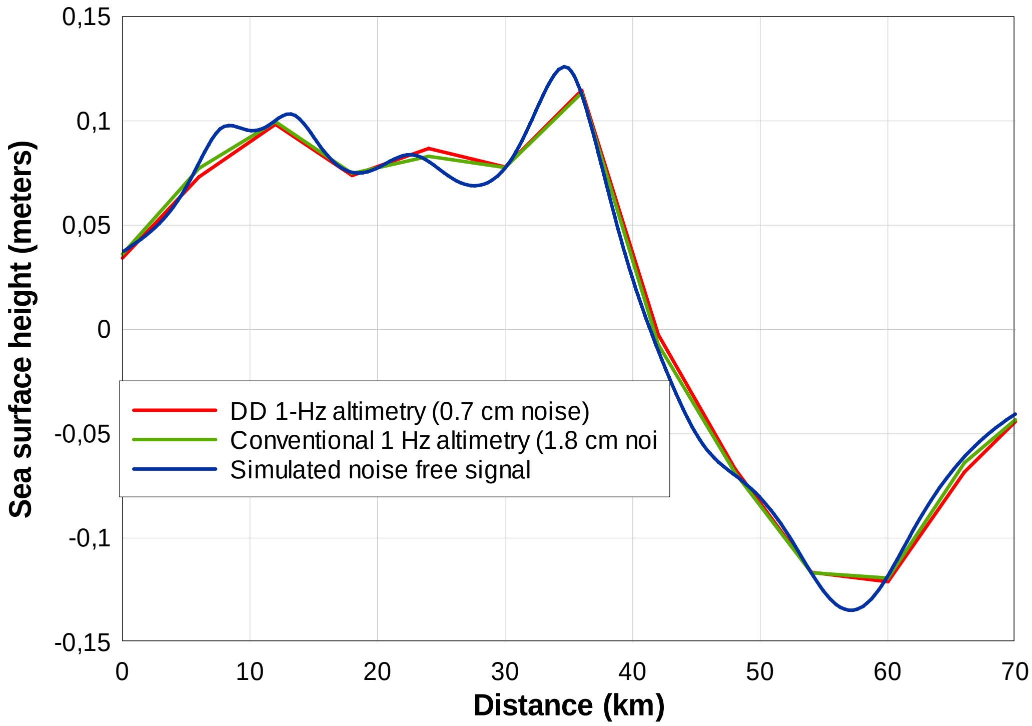

Figure 8. Simulation with 1Hz DD observations and corresponding 1 Hz geodetic mission altimeter. These conventional data are the typical data used to derive existing geophysical maps of the world's bathymetry.

Figure 8 shows the full simulated noise free sea surface height signal from the bathymetric features in Figure 4 along the profile indicated in Figure 5, together with simulated DD and conventional altimeter data sub-sampled at 1 Hz (6 km along track). It is clear that a large proportion of the maximum anomalies are not captured at this sampling which leads to severe underestimation of the height of the sea-mounts and the depth of the trenches. Also notice that the two trenches are nearly blurred into one trench.

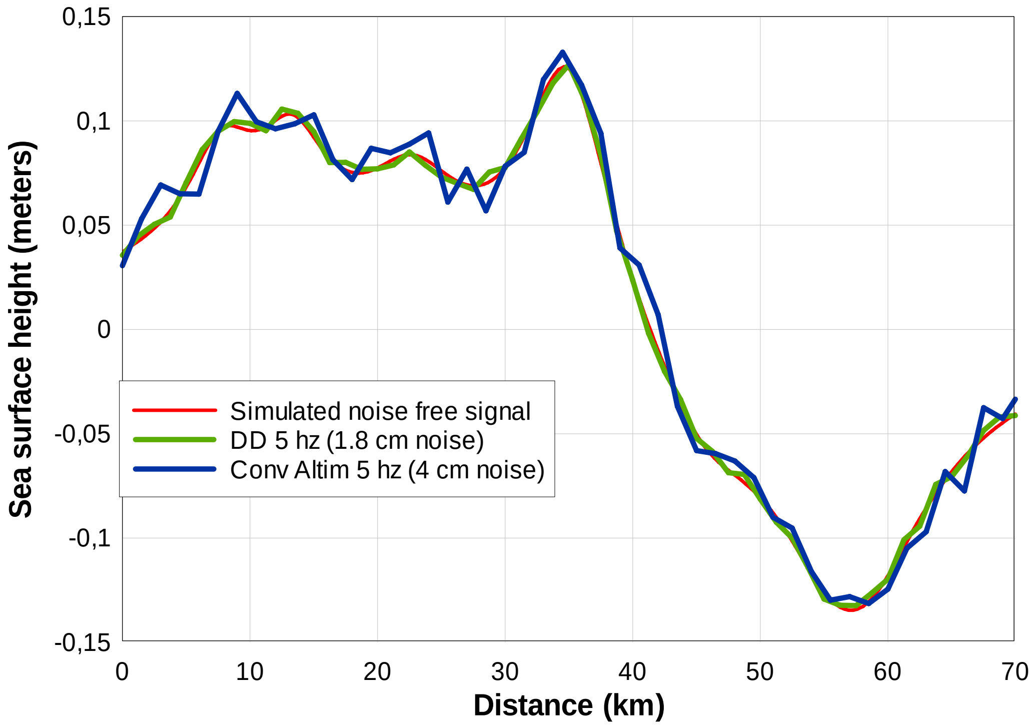

Figure 9. Simulation with 5 Hz DD observations and corresponding 5 Hz geodetic mission altimeter.

Figure 9 shows the full simulated noise free sea surface height signal from the bathymetric features in Figure 4 along the profile indicated in Figure 5, together with simulated DD and conventional altimeter data, sub-sampled at 5 Hz (corresponding to 1.2 km along track).

The noise on conventional altimetry is roughly 4 cm at this sampling. This noise level limits the ability of the altimeter to map anything but the largest sea mount and one of the trenches.
In contrast, the lower noise level on DD altimetry (1.8 cm) permits the separate resolution of all four sea mounts. Similarly nearly all of the anomalies are captured at this 1.2km along track sampling which will give very accurate estimation of the geophysical signals below.

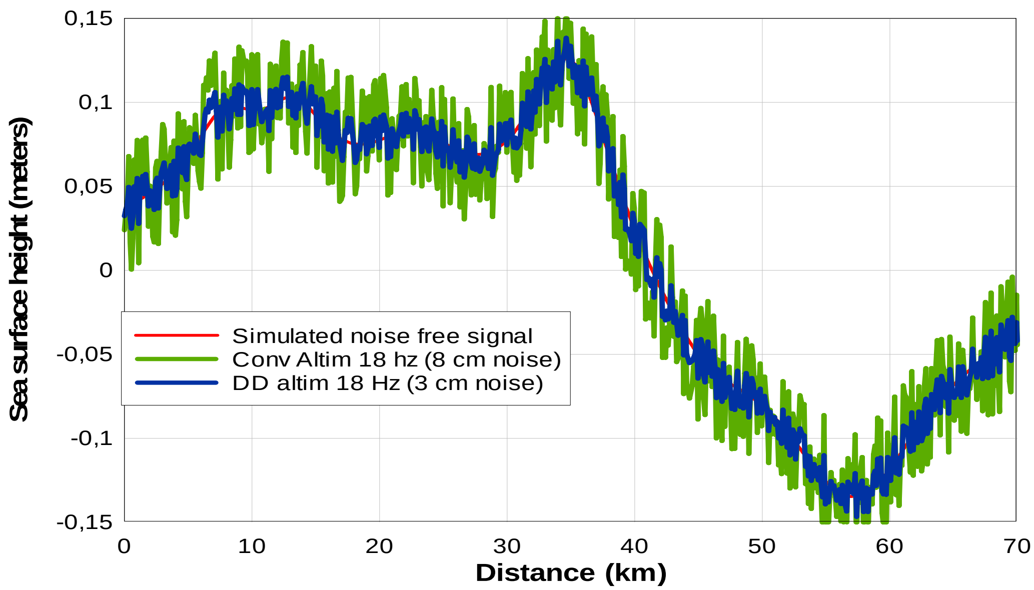

Figure 10. Simulation with the full 18 LRM DD observations and corresponding 18 Hz geodetic mission altimeter.

18 Hz DD observations and "conventional" altimetry observations with an along track sampling of 0.3 km are shown in Figure 10.

Conventional altimetry only resolves the largest sea mount and one trench at this precision level and sampling rate and is nearly worthless for mapping the other small seamounts. DD altimetry also has problems as the signal from the two first seamounts blurs into one, whilst the second seamount is just about resolvable.

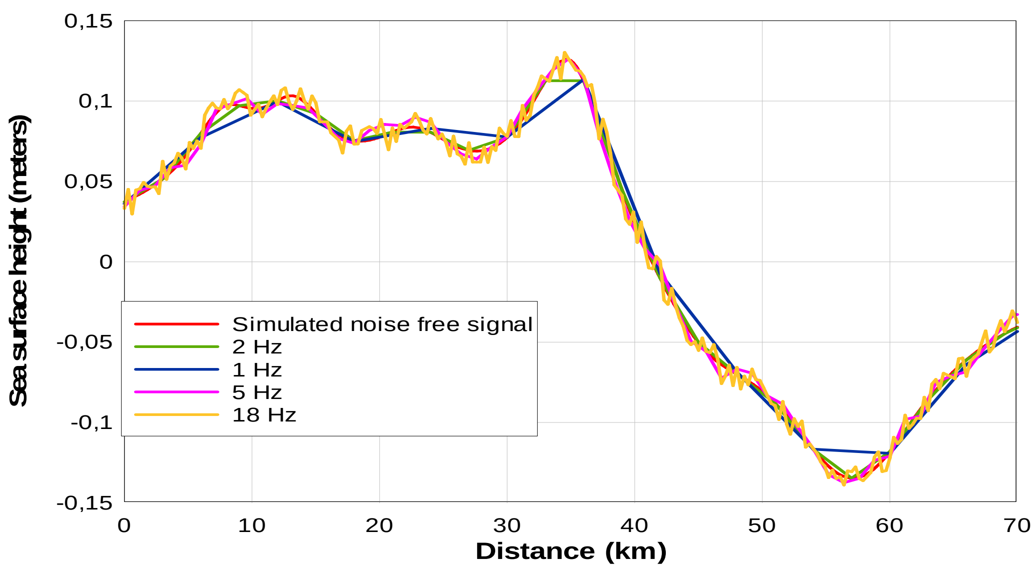

Figure 11 Simulation of various along-track averaging frequencies (1, 2, 5 and 18 Hz) versus the noise on the averaged observations.

Figure 11 shows a simulation of the noise free signal and various noisy sub-samples at 1, 2, 5 and 18 Hz sampling along track. It is seen that 5 Hz is the optimum choice in order to achieve the best compromise between spatial resolution / sampling and precision ratio for a DD instrument with respect to resolving the geophysical signals in the range of 5 – 20 km which are currently more or less un-resolvable from conventional satellite altimetry.

4.4 *Preliminary Results from CRYMPS Simulations*

A Digital Elevation Model, with topography as defined in Figure 4 (right hand panel) was used as the basis for a scenario to be input to CRYMPS. To the base topography a wave field of 1m amplitude, 100m wavelength and a standard deviation with a PDF of 4 cm was then added to produce the final CRYMPS input file.

This scenario was then run on CRYMPS to provide a modeled response of the CRYOSAT SAR mode altimeter to this input field. The simulator provides SAR mode and Low Resolution Mode (LRM) outputs.

Data from the "Version 1 results" (See Gommenginger et al., 2008, P18) are discussed here. That is to say the sensitive "ice-tracker" was applied in within the CRYMPS simulation. This is known to have consequences in terms of the stability of the epoch measurement, unless a correction is applied.

The following presentation of LRM output includes all waveforms present in the CRYMPS LRM product. The waveforms are displayed as scaled intensity (z-axis) plotted against along-track sample number (x-axis) and waveform gate number (y-axis).

In the case of the LRM products, there are 260 samples in each product, which, assuming these correspond to 18Hz averages, correspond to 14.4 seconds along-track (out of the 16 second DEM provided). Since no information was available on how to scale the waveform intensity into power, the analyses were performed on digital numbers scaled by 10^6. These waveforms are shown in Figure 12.

NOCs "re-tracked" the LRM waveforms using the NOCS ocean re-tracker, to extract Significant Wave Height, Sigma0 (backscatter), epoch, and thermal noise. These extracted parameters are shown in Figure 13.

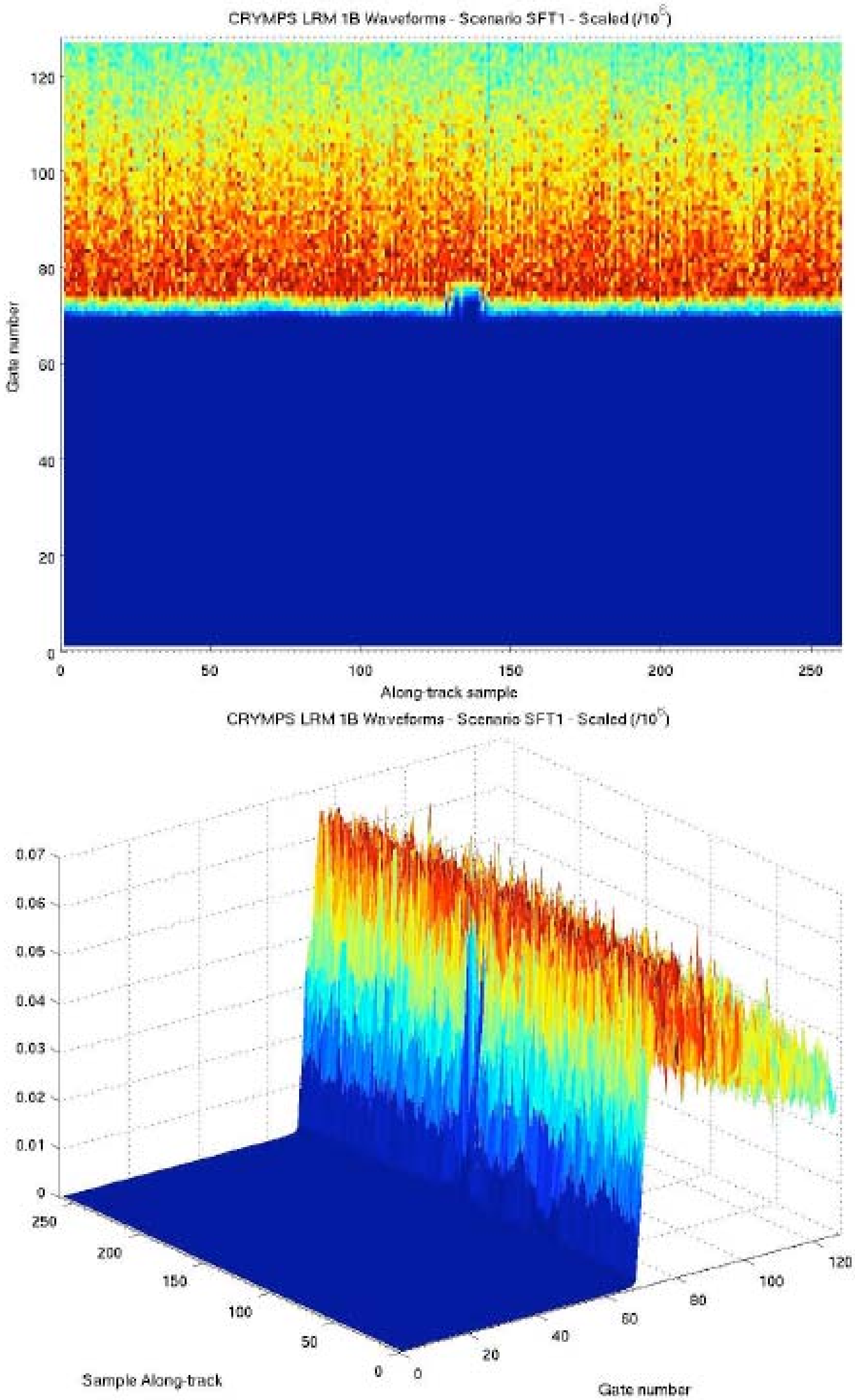

Figure 12 CRYMPS Low Resolution Mode waveforms for ocean with the bathymetric features shown in Figure 4 along the profile in Figure 5

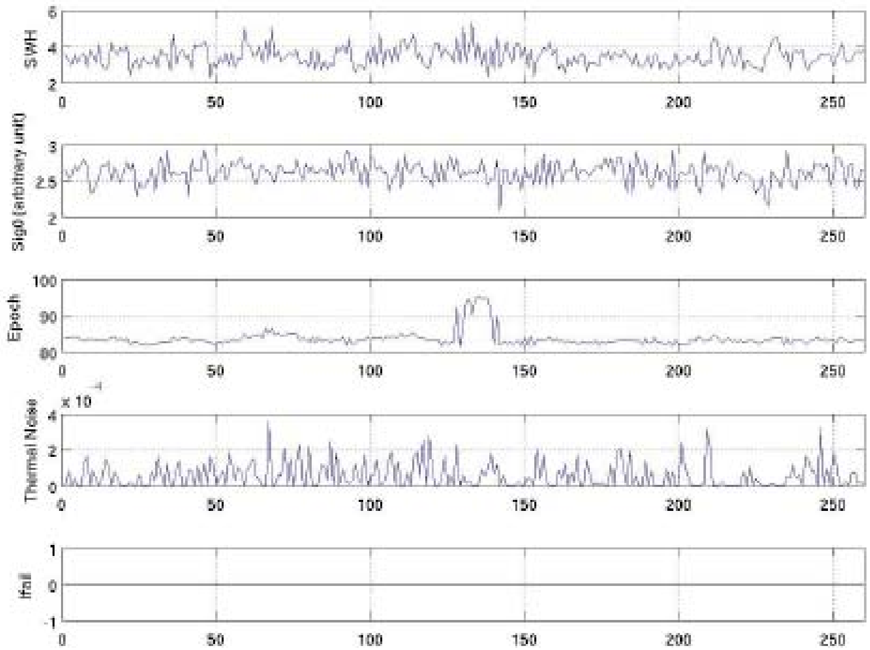

Figure 13.Output from the NOCS ocean re-tracker run on the CRYMPS LRM waveforms (scaled by 106) for scenario SFT1 (RV1). Top to bottom: retrieved SWH, Sigma0, epoch, thermal noise and retrieval quality flag). The bathymetric features shown in Figure 4 along the profile shown in Figure 5 are mapped.

The CRYMPS LRM simulations presented in Figures 12 and 13 are somewhat difficult to interpret. The epoch, which should correspond to a scaled version of the sea surface height has a predominant feature close to X = 130, near the location of the largest sea mount in Figures 4 and 5 (centered at 35 km out of 60 km).

This suggests the possible presence of some interesting information in the LRM simulations. Also it could be argued that there is some indication of upraised features in the first half of the epoch profile which could be correlated with the first sea-mounts (in Figures 4 and 5 these centered on 9 km and 13 km out of 60 km). There is no evidence of any signature of the trench features. However, we should note that there are known problems in extracting a reliable epoch from the CRYMPS output when the sensitive ice-tracker has been applied.

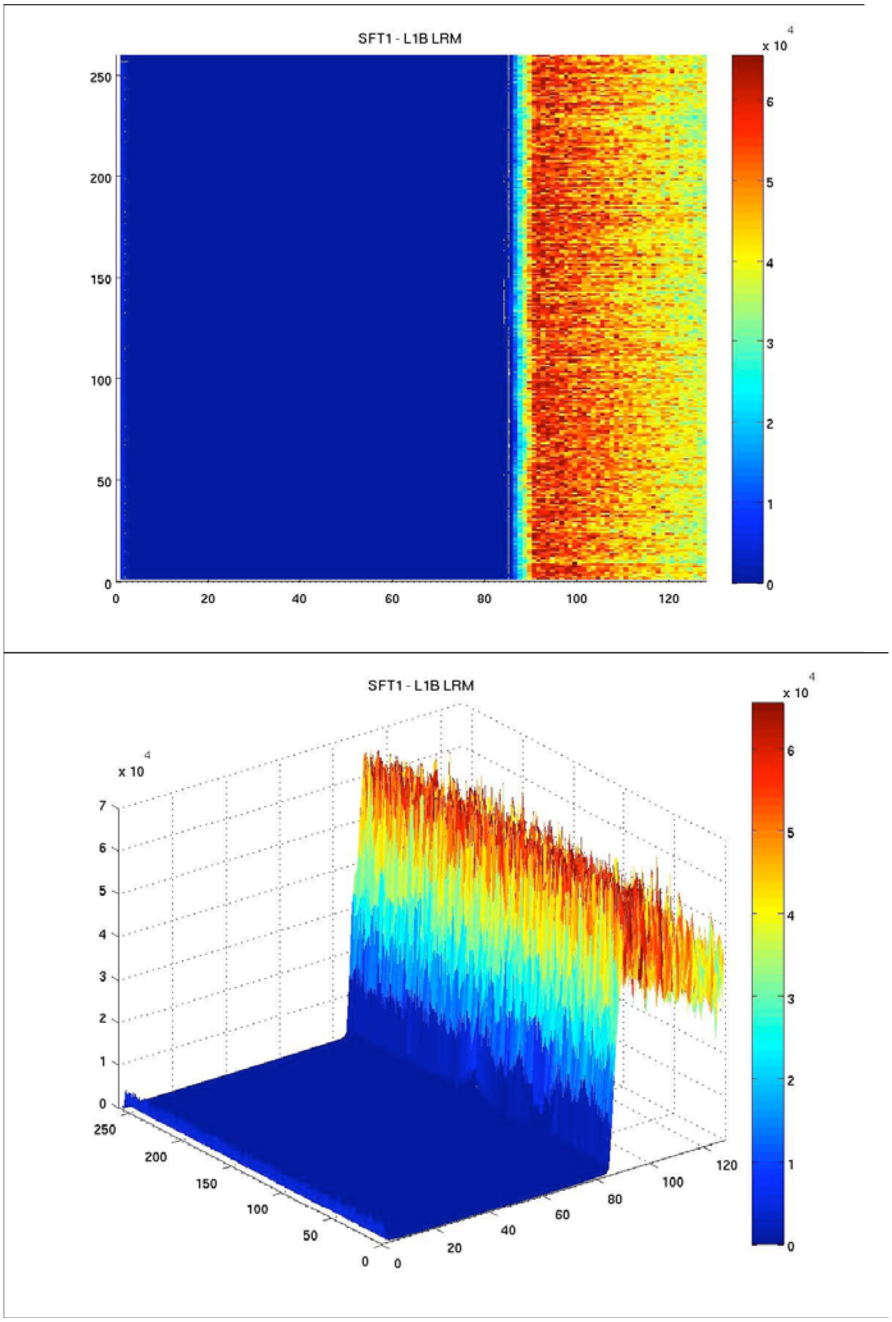

Figure 14 CRYMPS Low Resolution Mode waveforms for ocean with the bathymetric features shown in Figure 4 along the profile in Figure 5(SFT1, RV2)

A second version of the retracking (RV2) of CRYMPS runs were performed to improve the results and the result from this is shown in Figure 14. (fixed tracker and using Version 3 of the RDSAR software, Gommenginger et al., 2008 Section 5).Due to limited effort remaining to complete this work, the RDSAR and ocean retracking analyses were not repeated so we are still uncertain of the outcome with respect to retrieval of geophysical features from CRYMPS.

This analysis with this improved retracker shows that the predominant feature close to X=130 in Figure 12 and 13 dissapears when the tracker is set fixed, and as such the predominant feature seen in these figures are an artifact originating from a not corrected tracker shift.

This leads to the conclusion that there is apparently no sign of geophysical features in the simulated DD data related to sea floor topography. This might be due to the relativelylarge swell signal (1 meter) that it added to the observations in the simulations. In processing of conventional altimetry careful processing is normally carried out in order to remove oceanographical signal (crossover analysis). Otherwise, the oceanographic related signal clearly dominates the geophysical signal, and it can be suspected that the same can have happened for the CRYMPS simulations. It is therefore essential to try to use data from a CRYMPS simulation study without the added oceanographic noise to conclude how the added oceanographic signal influences the retrieval of geophysical signal and to prove numerically that with SAR mode it is possible to map each short scale geophysical featured in the scenario which has been generated from real geophysical ocean bottom topography signals.

The difficulty in carrying out a full and satisfactory analysis of these data mirrors the experience in Work Package 2. Further work is required in the analysis of these simulated data to allow a more complete assessment.

This further work includes:

- Defining precisely the along track location of the echoes in the LRM data
- Running a simulation without adding 100m swell wavelength and investigate how accurate the input DTM signal can be recovered.
- Running a simulation without adding 4 cm PDF signal and investigate how accurate the input DTM signal can be recovered.
- Establishing and applying the correct scaling to the waveform power
- Establishing and applying the correction for the tracker window location and hence producing an accurate and consistent range/epoch along the track of the simulation.
- Analysis of the data from the run with the fixed tracker
- Analysis of the SAR waveforms

5 Choice of Orbit – The Near ERM Orbit

Although DD altimetry offers a potentially significant improvement in the along-track mapping of global marine gravity and sea floor topography, the major drawback remains in that the across-track resolution is not improved and still remains between 2 and 6 km. CRYOSAT-2 will be flown in a roughly 320-day repeat orbit which will give an 8 km cross-track distance. This orbit configuration is chosen for optimum mapping of the cryosphere and ice-sheets where the interferometric capabilities of the instrument, provides uniform along-track and across-track coverage with this configuration.

Without lowering the cross-track distance to a few kilometers the unique possibility of mapping approximately 50,000 currently un-charted sea-mounts will not be achievable, and with the current choice of orbit and repeat the number might in its worst-case scenario be limited to a few thousand. The cross-track distance can be lowered by flying the satellite in a geodetic mission mode where the satellite at random covers the Earth with denser and denser ground-tracks as times goes by (the configuration applied to GEOSAT in its geodetic mission).

However a far better choice would be to choice a near-exact repeat mission, hereinafter called N-ERM. The advantage of such a mission would be that the cryospheric and oceanographic observations would suffer nearly no degradation.

In the N-ERM orbit, the spacecraft is allowed a small but constant east of westward drift of a few kilometers in longitude for each repeat. This way the ground tracks will not be repeated, but the earth will gradually be covered with denser and denser ground-tracks throughout the duration of the mission. Currently conventional satellites repeat within accuracy in the cross track direction of around 1 km. If such a measure should be maintained on a mission carrying a DD altimeter on board an N-ERM drift of 1 km per repeat would gradually increase the density of tracks and result in 2 km cross-track distance after 4 years and 1 km track distance after 8 years. For most oceanographic and cryospheric studies the data can be considered as repeating but for geodetic and geophysical studies this opportunity for increased track density would make a world of difference.

The choice of orbit is basically as important as the choice of instrument because the spatial coverage is the key to mapping unknown tectonic features. If the DD altimeter is not flown in an N-ERM the potential for a quantum leap improvement in coverage and accuracy will not be achieved. This does not mean that the DD will not provide a significant improvement over conventional altimeters, but it would limit the impact to the identification of perhaps a few thousand new seamounts

A choice of a N-ERM seems to be the best possible choice to satisfy both the needs of cryospheric science, geodesists/geophysical science and oceanographic science. For oceanography and cryospheric science the analysis of near-repeated observations should be investigated in more detail for possible drawbacks.

6 Conclusions

In this workpackage an investigation was performed into, how the higher resolution following from the higher Pulse Repetition Frequency (PRF) of SAR mode altimeter may enhance the capability to provide information on short spatial scale geophysical sea surface height/slope signals (especially in areas of high waves)

Theoretical modeling was performed in order characterize the expected gain between high PRF reduced SAR mode data and subsequently input DTM were designed for a theoretical scenario with sea mounts and trenches for the CRYMPS simulation.

The theoretical analysis of upward continuation in combination with the smoothness of the gravity field signal from geophysical structures on the sea bottom quickly revealed that the expected gain between high PRF reduced SAR mode data and low PRF classical LRM data in terms of improved performance in measuring ocean surface geophysical parameters is not the critical issue as the signal is too smooth.

The difficulty in carrying out a full and satisfactory analysis of the simulated CRYMPS data mirrors the experience in Work Package 2. Further work is required in the analysis of these simulated data to allow a more complete assessment.

This further work includes:

- Defining precisely the along track location of the echoes in the LRM data
- Running a simulation without adding 100m swell wavelength and investigate how accurate the input DTM signal can be recovered.
- Running a simulation without adding 4 cm PDF signal and swell signal and investigate how accurate the input DTM signal can be recovered.
- Establishing and applying the correct scaling to the waveform power
- Establishing and applying the correction for the tracker window location and hence producing an accurate and consistent range/epoch along the track of the simulation.
- Analysis of the data from the run with the fixed tracker
- Analysis of the SAR waveforms

In order to access the full potential capability of DD altimetry it is also important to carry out an investigation in which existing “real” bathymetry derived from conventional 1 Hz altimetry close to an existing track is being feed into the CRYMPS. This should be done in order to investigate output from a simulation in which you have well known 18 Hz along track to gain experience with.
Once these are completed simulation with other parameters simulating surface conditions should be completed.

The analysis also revealed that significant improvement in global bathymetry mapping from CRYOSAT 2 is AS DEPENDENT ON THE ACCURACY OF THE DD INSTRUMENT AS THE CHOICE OF ORBIT.

If CRYOSAT is launched in a Near ERM orbit resulting in 1 km cross-track distance after 8 years or it would result in mapping of ten of thousands of new uncharted sea mounts and tons of other sea bottom features.
If CRYOSAT is launched in the suggested 320 days repeating orbit this number might be reduces to below 1000. However even in this case significant improvement in the accuracy of the altimetry derived bathymetric model will be gained along the tracks due to the improved precision ratio of the DD instrument.

Which ever orbit (8 km 320 days ERM or 1 km N-ERM) is chosen it was demonstrated that 5Hz sub-sampling (corresponding to roughly 1.2 km along track averaging) offers the optimum approach in terms of precision and resolution in order to resolve geophysical signals of ocean floor features in the 5-20 km spatial range which are the range that bears significant commercial interests and which is currently unmapped from conventional 1 Hz altimetry observations from i.e. ENVISAT and JASON).

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