SCOOP

Study for Swell and Sea State Bias

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Table of Contents

1 Introduction

1.1 Purpose of this document

This is a technical note to summarise present knowledge on the impact of swell on SAR mode altimetry, and based on this knowledge to provide recommendations for the development of Sea State Bias corrections for SAR mode altimeter data. This document represents deliverable D2.7 of the SCOOP project.

1.2 Background

The much higher along-track resolution offered by SAR Mode altimetry introduces the possibility that long wavelength swell impacts the retrieval of the altimeter ocean surface parameters, viz. sea surface height, significant wave height, and radar backscatter that relates to wind speed. Here we investigate to what extent this expected (and demonstrated) dependency represents an issue that has to be dealt with during processing and analysis. Also, there is a clear need for a dedicated model or parameterization of the sea state bias (SSB), the correction to be applied to the SAR retrieved sea surface height. The approach developed for conventional Low Rate Mode (LRM) altimetry is not appropriate, because a big difference exists between the re-trackers applied in SAR and LRM altimeter data processing, despite similar physical background. These issues should lead to proposals for reliable SSB and SSB_{swell} corrections. Additionally, the impact of using these models on the climate record should be investigated.

The sensitivity of the unfocused SAR altimeter measurements to long ocean surface waves have been largely addressed in last five years. Different studies conducted by different groups of the altimetry community converged to say that long ocean surface waves do impact SAR-mode altimetry [Moreau et al., 2013; Aouf et Phalippou, 2015; Abdalla and Dinardo, 2016; Moreau et al., 2018], degrading the precision of SAR-mode measurements and biasing estimates of SWH. Nonetheless, further studies have still to be done in order to gain a better understanding of this sea-state effect at global scales. No less importantly, it is necessary to assess whether such effect could introduce spurious trends in the altimeter climate record as current and planned altimeter missions increasingly migrate from operating in LRM to SAR mode. This issue has to be carefully examined especially regarding the continuity with measurements obtained by conventional missions in the optic of deriving long term climatic time series.

The observed effects are very likely due to the shorter along-track effective sampling window of the SAR altimeter (300 m against a few km in conventional altimetry) that can no longer fully image long period waves, but only a portion of them [Moreau et al., 2018]. Consequently, the assumed Gaussian statistics of heights and slopes in the range/Doppler resolution cells are not satisfied. As a result, the measured distribution is not predictable and difficult to model, and also depends on which portion of the long-wavelength wave is imaged. This cause distorted echo shapes and subsequent impacts on parameter retrievals, especially in SWH estimates due to the use of inappropriate processing schemes (standard MLE re-trackers based on Gaussian assumptions) for retracking these non-traditional waveforms.

In this report we provide the state-of-the-art knowledge in this field. We summarise key results from a study carried out as part of SCOOP [RD-1], together with recent studies carried out by SCOOP partners and others, we highlight key findings, and make recommendations for further study.

1.3 Reference Documents

RD-1 Bellingham, C., 2018 Technical Note for SCOOP, Study into the Impact of Swell on SAR Altimeter Data, SCOOP_ESA_TN_SS.

2 Impact of Swell on SAR mode altimetry Retrievals

2.1 EUMETSAT Study by NOC

Bellingham, Srokosz, and Gommenginger (2016) presents results of a study for EUMETSAT to derive recommendations on Sea State Bias corrections to be applied to SAR mode altimeter data. This study is largely based around theory presented by Meric Srokosz, which states that scattering will occur from peaks and troughs of the swell, above and below the mean sea surface respectively, and, under certain conditions, the signature of this scattering will be seen in the SAR altimeter waveform as two peaks on either side of the leading edge. This theory suggests that, due to the SAR altimeter bin width at 20 Hz of around 3 nanoseconds, the time taken for the signal to travel to the surface and back, and allowing for noise and sea waves, double peaks would not be detectable for conditions where swell was less than around 1.9 m.

Key findings from this study were:

- No consolidated evidence was found of specific ***swell*** effects on waveform shapes, SSH biases or precisions.
- For a given SWH no dependency of SSH precision on swell height was found – *but SSH precision is worse (SD greater) for greater SWH*
- Empirical SSB estimation recommended as only viable approach for SAR mode altimetry.
- Development of SAR mode SSB corrections should include dependence on sea state development, but *no basis currently for including parameterised swell information*

2.2 SCOOP study by NOC / SatOC

[RD-1] reports on a study carried out for the SCOOP project, on the impact of swell on Cryosat-2 SAR mode data. The study looked at Cryosat-2 SAR mode data for the Agulhas region, for the period July 2010 to May 2012, and used ENVISAT ASAR data to identify and categorize swell conditions. PLRM data from RADS were used as the reference, to look for effects on the SAR mode data.

The key findings were:

- Within this data set limited data were found for cases with high swell, high SWH, long wavelength AND swell parallel to satellite ground track. These are the conditions for which the theory indicates the SAR mode processing could be most sensitive to swell (Bellingham et al, 2016).
- For a given SWH, no dependency of SSH precision was found on swell height.
- An increasing bias in SWH (SAR mode minus RADS) was found for increasing SWH.
- No clear directional dependency has been demonstrated, but there is a caveat that there are few examples in the data set of parallel swell and satellite ground track.
- An analysis of (non-averaged) waveforms indicated “noisier” SAR waveforms for longer wavelength swell and larger SWH. There was no evidence of double peaks in the waveforms themselves, but a suggestion of a variation in the position of the leading edge and main peak from the plots of waveform standard deviation.

The results did not provide any evidence to support the inclusion of parameterized swell information in SSB estimation for SAR mode altimetry, indicating that an empirical SSB estimation remains the recommended approach.

This study was hampered because of the small number of examples of data where the swell conditions met those where the theory indicates the impact on SAR mode altimetry to be the strongest: Swell Hs > 4m, and swell direction parallel to satellite ground track. *Thus, to provide a sufficient data base it is recommended any subsequent study should be carried out with Sentinel-3 data which provides global SAR mode coverage. Sentinel-1 can then be used for ocean swell spectra.*

2.3 Swell Impact studies by CLS

The sensitivity of the unfocused SAR altimeter measurements to long ocean surface waves including the distortion of echo shapes and hampered parameter retrieval has been studied in detail by Moreau et al (2017) and Raynal et al. (2018) using Cryosat-2 and Sentinel-3 SAR-mode data, and collocated WW3 wave model (Tolman, H. L.; 2009). This wave model allows for the characterization of swell conditions at the altimeter ground track locations. We summarize the main findings from these studies below:

- In terms of bias, SWH differences between PLRM and SAR mode seem to depend on the values of significant wave height (SWH) and mean wave period (T02) of the WW3 wave model, suggesting inaccuracies in the SWH retrieval for SAR-mode in comparison with PLRM.
- Also, the 20-Hz SAR SWH noise appeared to be highly dependent on both SWH and T02 and exhibits a distinct wave direction related signal with respect to the satellite ground track direction: a higher measurement standard deviation (SD) is observed when the waves propagate parallel to the satellite ground track.
- Preliminary results from comparing directly the ranges from both PLRM and SAR mode indicates that the range differences do not depend on T02, suggesting that the challenges to compute SAR mode sea state bias (SSB) correction for SAR-altimeter ranges are the same (parametrization) as for conventional LRM-altimetry. Which means that standard empirical approaches to develop a SAR dedicated SSB model could be applicable and seem to offer the best way forward. This is a promising outcome.
- An investigation of the long-wave effects, based on simulated data, confirms the different behaviour in PLRM and SAR products. The assumption of a Gaussian distribution of the sea surface elevations used within the ocean re-tracker model is not always appropriate to describe the statistical properties of the measured scatterer elevations within the SAR-altimeter ground cells. This divergence from Gaussian behaviour increases with increasing T02. The related altimeter waveforms have distorted shapes that are incorrectly handled by the ocean re-tracker model, which in turn leads to non-negligible errors in the estimation of the different parameters, increasing the SD of the 20-Hz estimates. In other words: the goodness of fit of (current) SAR altimeter models worsens when T02 increases.

These studies provide the first evidence of a sea-state effect on altimeter SAR-mode SWH estimations. This then raises concern about the possible impact of these wave effects on the long-term sea level time-series, currently based on conventional LRM altimetry, when data from SAR-mode radar altimeter are incorporated. There is a clear and urgent need to extend the analysis to a much larger set of data than is available from CryoSat-2 SAR, which has limited geographic distribution (only at the SAR mode patches). Sentinel-3A and Sentinel-3B provide a good new means for further detailed study, especially in their formation flying calibration mission phase. Based on the observed limitations in the SAR-altimeter processing to cope with measurements of long ocean waves, concerns are raised about the ocean wave sensitivity of other innovative measure techniques, such as the upcoming Surface Water and Ocean Topography (SWOT) mission carrying a high-resolution altimeter (KaRin) or other innovative processing methodologies capable of providing higher spatial resolution.

More recently Tran et al. (2017) provided further characterization of errors on sea level in high T02 conditions, showing that SWH bias impacts SLA as these errors will feed through in the SSB computation (also raising concern about potential impact of such ocean wave conditions on the sea level time-series).

Spectral analysis of along-track sea level anomaly also reveals a continuous slope from 30 km to smaller scales, also called "red noise", linked to swell events [Labroue et al., 2017]. There is no detailed explanation yet on the source of such a slope in the SAR-mode spectrum, but observations have suggested that the slope is perfectly correlated with the mean wave period and the propagation angle of waves in swell-dominated regimes [Raynal et al., 2018; Faugère et al., 2018].

We also note an interesting study from Reale et al. [2018] explaining theoretically that the aliased-swell effect contributes to the increase of the SAR mode SLA noise level. Unfortunately, the data analysis conducted over low-swell regime does not allow a complete characterisation of this effect.

Some studies are currently undertaken to determine a dedicated processing scheme with SAR capabilities which can effectively account for swell impacts on retrieval performances [Boy et al., 2017].

2.4 Other related studies

Abdalla and Dinardo (2016) and recently Abdalla et al (2018) studied SWH and wind speed (WS) products from CryoSat-2 SAR data and validated them against operational atmospheric and wave model results from the ECMWF Integrated Forecasting System and against available observations from buoys, platforms and from the Sentinel-3 SAR and Jason-2 LRM altimeters. The CryoSat-2 SAR Mode data were processed from Level 1A (Full Bit Rate) to 1B applying the standard Delay-Doppler algorithm, and then to Level 2, i.e. retracked using the SAMOSA SAR return waveform model, as implemented in the SARvatore SAR toolkit available through ESA's (G-POD) service. The CryoSat-2 data cover two geographic SAR patches, one in the northeast Atlantic Ocean (6 September 2010 to 30 June 2014), and the other one in the eastern Pacific Ocean (7 May 2012 to 30 June 2014). The coverage and amount of data is therefore limited but still sufficiently large to assume robustness and significance of the results.

The Cryosat-2 SAR mode wave height tends to be slightly higher than the model, the in-situ and Jason-2 values, by less than 5%. SAR Mode SWH data are highly correlated with the model and in-situ measurements (0.98 in the NE Atlantic and 0.95 in the Pacific). The SD between SAR Mode and model and in-situ data is about 30 cm in the NE Atlantic and about 18 cm in the Pacific which are similar to the values obtained from Jason-2 for scales in excess of 75 km. The SAR Mode random error can be estimated by assuming equal model and altimeter errors as 21 and 13 cm for the NE Atlantic and the Pacific Boxes, respectively. These are much lower than the typical error requirements of previous conventional altimetry missions (e.g. 40 cm for Jason-3 global data). The CryoSat-2 SAR Mode wind speed also agrees very well with the other sources with very small bias (less than 0.3 m/s). The correlation between SAR Mode and the model is as high as 0.95 and between SAR Mode and the in-situ measurements is about 0.93. The wind speed SD is less than 1.2 m/s and about 1.3 m/s with respect to the model and the in-situ data, respectively. These values, although they include contributions of the model and in-situ errors, are better than typical altimeter mission requirements of 1.5 m/s or higher. Both SWH and WS are similar to their counterparts from Jason-2 (used as a reference "conventional" LRM mission).

There is evidence that ocean swell has adverse impact on wind and wave data from SAR altimetry: A "higher error" is seen in Cryosat-2 SAR mode SWH in NE Atlantic in summer, than in Jason-2 or in the ECMWF operational model. Standard Deviation for Cryosat-2 SWH is ~0.2m, for Jason-2 and the ECMWF model it is 0.18m. This could be related to dominance of swell in NE Atlantic in summer.

The paper also considered the variation of the standard deviation of wave model minus altimeter data against ratio of swell energy. For data where the ratio is 0.5 -1 (i.e. swell dominated seas), the SD of Sentinel-3 SWH is ~0.28m, where for Jason-2 SWH the SD is ~0.22m. This hints to swell having a negative impact on SWH from SAR altimetry (results in a higher standard deviation in retrieved SWH). Due to the limited data set and its coverage, this impact does require further investigation. The results presented in the paper are based on scales in excess of 75 km, due to the super-observation technique applied at ECMWF for data assimilation operational model. The analysis for scales below 75 km should be the subject of a future study. This work shows that altimeter SAR Mode products are suited as replacement for the conventional pulse-limited altimetry products in ocean data assimilation in numerical operational models. All in all, the results show that the quality of both CryoSat-2 SAR SWH and WS products is in line with Jason-2 performances and satisfies the typical altimetry mission requirements.

Indirect evidence for the need of a proper SSB model comes from Naeije and Bouffard (2019). This study comprises detailed analyses of the quality and stability of the CryoSat-2 GOP data products, such as sea level, wave height, wind speed, sigma0 and sea state bias. Though this study is targeted on LRM and PLRM data, it is shown that certain processing choices do affect the wave height estimates and by that (through the application of a sea state model) the sea level estimates. Based on collinear pass analyses taking point for point differences between CryoSat-2 GOP data and RADS Cryosat-2 data they found jumps in the sea level differences of a few mm and in the SWH differences of a few cm at the LRM-SAR-LRM transitions (the SAR data being processed into PLRM data, an equivalent of LRM data). Also, an average bias in SWH between GOP and RADS CryoSat-2 of 13 cm emerged. Observing that the GOP has significant wave height and sea state bias close to that of the reference missions Jason-2 and Jason-3, and from close inspection of the geographical plots for mean crossover differences with Jason-2 and Jason-3 and collinear differences with RADS, they conclude that GOP has more reliable (unbiased) SWH and better handles the LRM-SAR transitions than RADS. This observation would never have been made when only RADS sea level was compared with either Jason-2 or Jason-3. The few mm sea level bias drowns in the physical sea level signal. Apparently the RADS CryoSat-2 SSB model was tuned such that it corrected the off-setted SWH, so still providing a good estimate of (corrected) sea level. The bias in SSB between CryoSat-2 GOP and CryoSat-2 RADS appears to be 4 cm, quite high, whereas between GOP and the Jasons the difference is negligible. This seems to hint to the empirical SSB model for CryoSat-2 RADS absorbing, or better, accounting for the off-setted SWH. By that it is doing its job but it is farther away from the (physical) reality and is sub-optimal because the remaining (SSB corrected) SLA is still slightly biased and not smoothly transiting from LRM to SAR and vice versa. So, going for a purely empirical solution does not give the best results. The actual difference in SWH partly comes from the fact that the Gaussian approximation of the point target response used in the RADS re-tracker is not corrected for small SWHs and the fact that RADS CryoSat-2 employs MLE3 retracking and by that is too much dependent on the accuracy of the onboard attitude information that comes from the star trackers. From the collinear pass analysis, it became clear that by relying too much on the star-trackers a 480-days platform temperature cycle is introduced mainly in the estimated SWH. Thus, either the star trackers should be calibrated and corrected for this temperature cycle or an MLE4 retracking should be chosen in which the platform mis-pointing is estimated directly in the retracking of the data. Important conclusion is that for different altimeter systems dedicated SSB models should be developed but that they should not be purely empirical-based.

2.5 Summary / Conclusions

The different studies agree that there is evidence of increased variability, and increased bias in retrieved SWH for larger wave heights, and longer wavelengths. Whether or not this is specifically swell dependent is a point for discussion. The evidence in terms of the effect of larger SWH and longer wavelength on range retrieval is inconsistent, though there is evidence that the SAR waveforms become noisier and hence more difficult to fit for larger SWH and longer wavelength. Hence it could be expected there would be more variability in the retrieved SSH.

It is also well established that there remain problems in accurately retrieving SWH in SAR mode for low wave heights, due to steepness of leading edge in SAR echo. This will have an impact on the nature of the error in retrieving SWH, as SWH increases.

While there is an obvious attraction to use modelled wave data, we believe that the observational data will provide more accurate evidence. A "climatology" of how frequently and where parallel swell of high SWH occur would be beneficial to infer if the problem arises frequently. This would allow future studies to identify and focus on regions where SAR altimetry would be most likely to experience a bias due to parallel swell. Further studies could make use of SAR data from the Sentinel-1 mission, or indeed other SAR missions.

With regard to the approach for developing new SSB models. It is recommended that purely (tuned) empirical models should be avoided, and that physics, or at least calibration with in situ (buoy data), should be incorporated. Also, an extra correction for swell sea state SSB_{swell} is needed, again with sufficient physical foundation. Clearly, the impact of using these dedicated models to the climate record should be investigated.

3 Recommendations for Sea State Bias Corrections for SAR Mode Altimetry

All studies agree that for larger and longer wave heights both variability (noise) and bias increase for SAR altimetry inferred SWH. It is though not certain yet whether this has directly to do with the presence of (increased) swell. In theory there should be a dependency, so we are still in the process of trying to quantify this dependency both for swell magnitude, period and direction. If SAR waveforms are noisier (for larger SWH, and for longer wave period) then this not only poses a problem for SWH retrieval, but also increases the noise in the SSH retrieval. In addition, problems with SWH will enter the sea level estimate through the use of an SSB model. All studies also agree that greater global spatial coverage is needed for analyses (for CryoSat we have only a few SAR patches scattered around the globe) together with a much longer time series. A good way forward would be to work on an SSB_swell correction or an SSB correction with swell incorporated, based on studies comparing Sentinel-1 imaging SAR and Sentinel-3 SAR altimeter data. A comparison with real wave data (as opposed to simulated model data) is recommended. It is also well established that there remain problems in accurately retrieving SWH in SAR mode for low wave heights, due to steepness of leading edge in SAR echo. This will have an impact on the nature of the error in retrieving SWH, as SWH increases.

Based on the observed limitations in the SAR-altimeter processing to cope with measurements of long ocean waves, concerns are raised about the ocean wave sensitivity of other innovative measure techniques like the upcoming Surface Water and Ocean Topography (SWOT) mission carrying a high-resolution altimeter (KaRin) or other innovative processing methodologies capable of providing higher spatial resolution. This indicates an urgent need for more detailed studies. A constructive approach would be to compute a SSB correction accounting for not only the wave height but also the mean wave period, as already developed by Tran et al. (2010) for LRM missions. Some researchers recommend an empirical approach to develop the SSB model using wave period information from a wave model, whereas others are concerned that the use of information from models could propagate possible errors from models into the satellite products, and prefer to develop an SSB model based only on altimeter derived information. This remains a point for discussion.

We propose/recommend two types of investigations:

- A focussed case study on some individual examples of clearly defined long wavelength swell in selected orientations to the altimeter track. This could investigate in detail the impact on altimeter SAR waveform shapes, and the impact on the parameters retrieved from re-tracking

- A larger scale study using a data base of co-located SAR and SAR altimeter data. This could make use of Sentinel-1 SAR wave mode data. Otherwise some form of routine processing of other SAR missions' data to extract swell characteristics would be needed.

The final answer will come when sufficient Sentinel-6/Jason-CS data have been gathered. This will provide the first opportunity to directly compare LRM, PLRM, and SAR at the same time and at the same locations (approximately). This mission is currently scheduled for launch in November 2020.

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5 List of acronyms

ASAR	Advanced Synthetic Aperture Radar (instrument on Envisat mission)
CLS	Collect Localisation Satellites, Toulouse
Cryosat-2 (C2)	ESA altimeter cryosphere mission. The first space mission to operate SAR mode altimeter
ECMWF	European Centre for Medium Range Weather Forecasting
Envisat	SA Remote Sensing Mission (2002-2012), instruments included an altimeter and the ASAR
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GOP	Cryosat-2 Geophysical Ocean Product
GPOD	"Grid Processing on Demand" https://gpod.eo.esa.int - ESA online processing platform
Hz	Hertz (cycles per second)
KaRin	KA band Radar Interferometer. Main instrument on SWOT mission.
Jason-1, 2,3	Series of successive US/French satellite altimeter missions.
L0	Level 0
L1	Level 1
L1B	Level 1B
L2	Level 2
LRM	Low Rate Mode
MLE	Maximum Likelihood Estimator
NOC	National Oceanography Centre, Southampton (UK)
PLRM	Pseudo Low Rate Mode
RADS	Radar Altimeter Database System (http://rads.tudelft.nl/rads/rads.shtml)
SAMOSA	SAR mode radar altimeter Echo Model
SAR	Synthetic Aperture Radar
SARvatore	Online SAR altimeter processing utility
SD	Standard Deviation
Sentinel 3A, 3B	Copernicus ocean monitoring missions
Sigma0 ($\sigma 0$)	Nadir incidence surface backscatter
SSB	Sea State Bias
SSB_{swell}	Sea State Bias due to swell waves in SAR altimetry
SSH	Sea Surface Height
SWH	Significant Wave Height (swell plus wind sea)
SWOT	Surface Water and Ocean Topography mission
T02	Mean Wave Period
TOPEX	US/ French Satellite Altimeter mission, 1992-2006
WS	Wind Speed
WW3	WaveWatch 3 – wave forecasting model at National Oceanic and Atmospheric Administration (NOAA), USA.