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Coastal and Open Ocean Surface Currents Mission Study: Wavemill Product Assessment: WaPA

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Final Report

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Acronyms and Abbreviations

Abbreviation	Meaning
AD	Azimuthal Diversity
ADCP	Acoustic Doppler Current Profiler
APS	Atmospheric Phase Screen
ASAR	Advanced Synthetic Aperture Radar (as operated on Envisat)
ATI	Along Track Interferometry
CCN	Contract Change Notice
CDOP	C-Band Doppler Shift model
CFSR	Climate Forecast System Reanalysis
DPCA	Displaced Phase Centre Antenna
ECMWF	European Centre for Medium Range Weather Forecasting
Envisat	ESA Earth Observation satellite, carried a suite of EO instrumentation including a Radar Altimeter and a C-band ASAR, 2002-2012
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre, Noordwijk
FR	Faraday Rotation
GMF	Geophysical Model Function
GSP	General Studies Programme
HF	High Frequency
KuDOP	Ku Band Doppler Shift model
MSS	Mean Square Slope
NCEP	National Centers for Environmental Prediction (US)
NOC	National Oceanography Centre
NRCS	Normalised Radar Cross Section
NSCAT	Microwave Radar Scatterometer mission, for measuring ocean surface wind
NWP	Numerical Weather Prediction
PRF	Pulse Repetation Frequency
Quikscat	Microwave Radar Scatterometer mission, for measuring ocean surface wind
Radarsat-2	Canadian commercial C-Band SAR satellite
SAR	Synthetic Aperture Radar
SatOC	Satellite Oceanographic Consultants
SMOS	Soil Moisture Ocean Salinity – ESA Earth Explorer mission, launched 2009
SNR	Signal to Noise Ration
SRTM	Shuttle Radar Topography Mission
TerraSAR-X	X-Band satellite borne radar mission, partnership between DLR and EADS Astrium
TRMM	Tropical Rainfall Measuring Mission
WaPA	Wavemill Product Assessment
VV	Vertical transmitted polarisation, and vertical received polarisation
WP	Work Package
XTI	Across Track Interferometry

1 PROJECT OVERVIEW

Ocean Surface Current is one of the most important ocean properties for oceanographers and operators in the maritime domain. Improved monitoring of ocean currents is systematically the number one requirement that emerges from any science or end user requirement surveys.

Information on ocean dynamics on fine spatial scales is required also to advance our scientific understanding about fundamental surface mixing processes and, most importantly, how this affects interactions between physical and biological components of the ocean system, which is key to improving future climate predictions.

In the shelf seas and coastal zones, where ocean dynamics are typically high, there is huge demand for ocean current observations to inform, assist and/or protect the wealth of human activities in these regions.

Wavemill is a new radar instrument concept that could deliver much of what is needed. Wavemill is a novel hybrid interferometric SAR system first proposed by ESA/ESTEC [Buck, 2005]. It offers the possibility of generating two-dimensional wide swath, high resolution, high precision maps of surface current vectors and ocean topography [Buck et al., 2009]. Based on a single spacecraft, it avoids the difficulties of synchronisation and baseline estimation associated with other interferometric SAR systems based on two or more satellites (e.g. the "cartwheel" or "helix" concept).

The Wavemill concept has developed steadily since its first inception in 2005. A number of Wavemill studies in recent years have gradually put together facts and figures to support the case for Wavemill as a possible space-borne mission. This project builds on past studies to address some key aspects relating to the expected performances and limitations of a space-borne Wavemill instrument. This study is a critical step on the path towards establishing Wavemill as a convincing candidate core mission for ESA's Earth Explorer 9 series.

To achieve this, the Wavemill Product Assessment (WaPA) consortium brought together a uniquely strong team of European academics, scientists and engineers with complementary capabilities and expertise in all key aspects needed to drive the Wavemill instrument towards a well-defined mission concept.

WaPA was an essential step in defining the scientific capabilities and limitations of a space-borne Wavemill instrument in preparation for a possible submission of the Wavemill concept as a candidate Earth Explorer Core mission.

The role of the WaPA Mission Study was to formulate:

- A strong and justifiable scientific argument in regard to the scientific usefulness and uniqueness of the proposed Wavemill products.
- A high level of confidence in the ability of the proposed system design to generate the proposed data sets with useful levels of accuracy for scientific applications
- Technical rationale, which demonstrates that the implementation of the system is feasible.
- A set of study outputs which can be used to validate and enhance the Wavemill mission requirements.

The project approach included:

- An exhaustive literature review of SAR imaging of ocean currents in along-track interferometric mode to learn from previous experiments and modelling what key phenomena need to be accounted for to determine the true performance of a spaceborne Wavemill system. This Work Package was led by NOC.
- A significant validation effort based on Wavemill airborne proof-of-concept data and numerical simulations to determine the capabilities and limitations of a spaceborne Wavemill instrument for ocean current vector and sea surface height mapping, including quantified estimates of magnitude of errors linked to unwanted effects linked wind, wave conditions or tropospheric disturbances.This Work Package was led by Starlab.

- An analysis of the potential for ocean wind vector retrieval from a space-borne Wavemill instrument. This Work Package was led by IFREMER.
- An investigation of possible secondary products from Wavemill relating to rivers, ocean/atmosphere interactions, ocean swell and cryospheric applications. This Work Package was led by Starlab.
- An assessment of the synergy between Wavemill and ocean surface current products derived from other remote sensing techniques, accounting for the nature and variability of the measured properties, to identify any additional requirements on a future Wavemill mission. This Work Package was led by NOC.
- The overall project management was provided by SatOC.

2 SAR ATI MEASUREMENTS OF SURFACE CURRENTS

2.1 Introduction and Approach

The first activity of WaPA, undertaken out by NOC, was to carry out a review of SAR ATI measurements of surface current measurements, and to identify and summarise key issues relevant to the Wavemill concept. The specific objectives were to:

- perform an in-depth literature review of past experimental and theoretical modelling studies relating to Along-Track Interferometric (ATI) SAR for the retrieval of ocean current products and other parameters.
- identify key geophysical phenomena affecting ATI SAR surface current retrieval, review theoretical models proposed to represent the microwave scattering and determine the capability of these models to reproduce experimental results.
- document past experimental results in terms of the environmental conditions in which the measurements took place, what ground-truth was available for validation and the basic parameters of the radar systems.
- elaborate the implications of previous ATI SAR studies for a spaceborne Wavemill mission and the Wavemill scientific product requirements, accounting for the way performance may be affected when transferring from a 1D ATI to a Wavemill 2D system.

This review was focused primarily on the literature pertaining to the retrieval of ocean currents with ATI SAR. However, some relevant findings were also to be found elsewhere, for example regarding the effects of ocean waves and wind in other microwave techniques.

Thus, there exists for example an extensive literature on the retrieval of wind, waves and currents from “conventional” SAR (i.e. single-antenna systems), within which some publications provide interesting insight about the scattering responsible for the signals contributing to SAR, and indeed ATI SAR, measurements. But, since it was not possible within the scope of this task to include also an extensive review of the large body of work on SAR over oceans, we were able to consider only a few of these key references in this activity.

2.2 Overview of Previous Interferometric SAR Systems and Experiments

Overview of Systems Used

Most previously flown Interferometric SAR systems have been airborne, with some Across Track Interformetry (XTI) experiments on the Space Shuttle Radar Topography Mission (SRTM) and Along Track Interferometry (ATI) on a Low Earth Orbit satellite (TerraSAR-X).

The operating radar frequency evolved from low frequency L-band in early ATI systems to high frequency (X and Ku-band). Note that modelling predicts better performance at high frequencies

Except for Siegmund et al., [2004], the chosen polarisation was VV (vertically polarised for transmitted and received signals) to provide improved signal to noise ratio at far ranges in the swath.

Airborne systems generally operate with large incidence angles, for example:

- 20°-70°[Goldstein & Zebker, 1987; Anderson et al., 2003]
- 60° [Kumagae et al., 2011]
- 70° [Toporkov et al., 2005]

TerraSAR-X: Operated with a limited azimuth sampling rate (PRF) and short effective ATI baseline the consequence of which was increased phase noise and ghost echoes of nearby land by aliasing [Romeiser et al., 2010]

SRTM: Found that the sensitivity of the phase to height of surrounding land severely hindered current retrieval in rivers [Romeiser et al., 2007].

Squinted SAR systems were used to measure both current components in a single pass but the literature found there were inherent errors for systems where hybrid baseline is achieved with squinted beams, because

- A bias is found in the retrieved velocity linked to a mis-registration in the azimuth of moving surfaces in the fore and aft look of squinted systems.
- A gradient-induced distortion of ATI surface velocity maps is caused by the displacement in azimuth of moving targets, a typical feature of SAR imaging.

Oceanographic conditions and validation findings.

The experiments were carried out in a range of oceanographic settings, but mostly in areas with strong tidal regime (max current > 1 m/s).

The experiment sites were mainly close to land, possibly determined by limits of the aircraft range and availability of validation data (e.g. HF radar data is limited to 45km from land)

Unfortunately the means of validation of the ATI currents were, on the whole, disappointing. Often comparisons were made with models, but no information was provided on forcing and validity. There were three notable exceptions:

- Graber et al., [1996]: who used HF radar, weather buoys, directional wave buoys, current-meters and coincident ship campaigns
- Goldstein et al., [1989]; Kumagae et al., [2011]: Who validated against near-surface drifters

Wind & wave information were in general limited to whatever data available from a weather station in the vicinity. In many cases no wave information at all is available.

Only Perkovic et al., [2004] attempted to derive wind from ATI scenes to interpret ATI currents.

2.3 Errors and Mitigation Strategies

Attitude and navigation errors

There is a critical need for accurate platform attitude and navigation data during processing to avoid fluctuations and biases in the phase and resulting velocity fields. Even after correcting these effects, low frequency fluctuations can remain and contribute 0.1-0.2 m/s bias. Most studies mitigate these residual errors by calibrating the interferograms over land, setting retrieved velocity over land to zero.

Toporkov et al., [2011), explore the use of ships as targets of known velocity to calibrate the ATI phase in open ocean where land is not imaged, but they found that the smearing of the ships in the SAR images (due to SAR imaging of moving targets) introduced estimated uncertainty in the ship velocity of the order of 0.2 m/s, which makes this approach of limited use.

Long swell waves

Typically, if swell waves are not visible in the high-resolution ATI images, no swell correction is applied. Otherwise, the effect of long swell waves is mitigated by degrading the spatial resolution of the current maps to grid scale greater than the swell wavelength averaging, smoothing and filtering down to 100 x 100 metres or coarser.

If fine spatial resolution needs to be retained [e.g. Toporkov et al., 2005], there is no reported strategy to mitigate the effect of swell on ATI currents.

Wind

The contribution to surface motion by wind drift is also recognised, and is typically estimated as 3-5% of the wind speed at 10 metres in the direction of the wind. This wind drift is a legitimate constituent of the surface current one wants to measure, and it should be noted that this contribution by wind to surface displacement is separate from, and in addition to, the unwanted surface motion related to the phase velocity of the wind-generated Bragg scatterers.

Theoretical Models for wind and wave effects

The unwanted contributions to ATI signals by ocean surface wind and waves are the most important cause of errors in ATI retrieved currents. The surface wave contribution is usually quantified and removed using a theoretical scattering model, amongst those models available are:

- Thompson et al., [1989,1991]
- Romeiser & Thompson [2000]
- DopRIM [e.g. Hansen et al., 2012]

It should also be noted that there is much to learn from the SAR Doppler centroid & SAR wind literature, which was outside the scope of this review.

2.4 Implications for a Future Space-borne Wavemill Mission

The analysis of the literature has brought to light a number of points, which will need to be considered as part of the design of a space-borne Wavemill mission, as follows:

1. Ensure the availability of precise attitude and navigation data at high rate and their use during processing of the interferograms. Unfortunately, the required level of accuracy and update rate cannot be precisely determined from the literature review, since insufficient details are given in the reviewed papers about the sensitivity of the retrieved current (or measured phase) to platform attitude and height error. Further dedicated activities will be needed to properly quantify these requirements in terms of their impact on current retrieval performance.
2. Establish a strategy to calibrate the interferometric phase to remove residual attitude and navigation errors. Even after correction, all investigators report residual variations in phase, which can translate into large fluctuations in retrieved currents. For example, Romeiser et al. [2005] reports that antenna oscillations measured onboard SRTM with accuracy of 3mm, still resulted, after compensation, to residual "motion" errors with phase variations of the order of 0.1 rad, equivalent to horizontal velocity of 0.6 m/s. Issues to consider are how frequently the phase should be calibrated, whether the calibration strategy has to rely on imaging of land in all scenes (which would limit ATI acquisitions to within 100 km or so of land) or if the phase over ocean-only scenes can be calibrated using other means.
3. Optimise radar parameters to avoid aliasing. This includes choosing an effective along-track baseline, but also a careful choice of PRF to ensure adequate azimuth sampling and thus avoid aliasing, which produces ghost echoes of land over water that are difficult to remove [see Romeiser et al., 2010; Suchandt et al., 2010]
4. Quantify the impact on current retrieval performance of the choice of squint angle, incidence angles and platform altitude/velocity, given:
    a. biases in current retrieval due to azimuth mis-registration in squinted beams;
    b. reduced signal to noise ratio due to polarisation mixing, and thus with secondary implications for the power and mass budget, swath width, coverage, revisit time and mission lifetime.

    Dual-polarisation would mitigate the latter to some extent, and is also scientifically highly desirable by providing useful information about wind and wave breaking effects. However, full dual-pol capability would strongly impact the design of the instrument and the mission. Dual-polarisation on receive channels only may offer a useful compromise, but only if high-enough SNR can be achieved.

2.5 Implications for Wavemill Ocean Current Products

The literature review highlighted several outstanding scientific issues, some of which have implications for the Wavemill scientific products:

1. With ocean penetration depths at Ku-band typically less than 1 mm, Wavemill will sense all phenomena that impart velocity to the top layer of the ocean surface. These include:
    a. unwanted velocities that are sensed by radars but do not contribute to water mass transport i.e. the phase velocity of the Bragg waves and the orbital motion of longer

ocean waves. Their impact can be quantified and removed if wind and wave conditions are known.

b. All currents affecting the surface, including wind-induced currents (Ekman), Stokes drift, tidal currents, geostrophic currents, surface divergence and convergence flows, Langmuir circulation, etc.

These current components all vary on different temporal and horizontal scales, as well as with depth, making it a challenge to validation (see below). Wavemill will measure the “total current”, consisting of the sum of these various components as they are expressed at the air-sea interface. Separation into individual components is desirable and may be possible for some components, but would need to be clearly identified and defined in the Wavemill products.

2. Separating wind, wave and current contributions in the measured interferometric phase remains an important issue and a serious challenge. Wave breaking is known to play an important role, so any wind/wave mitigation strategy should ideally use one of the recent scattering models, which seek to account for wave breaking. With the relative importance of wind, waves and current effects changing also with radar frequency, polarisation and incidence angle, more extensive use should be made of present-day knowledge of microwave scattering from latest theoretical advances and recent experiences with Envisat ASAR, Radarsat-2 and TerraSAR-X when defining the Wavemill instrument and mission.
3. Validating Wavemill surface currents will present unprecedented difficulties, insofar as traditional sources of data used for validation of currents may not be appropriate to validate currents measured by Wavemill. Arguably, HF radars offer the closest match to Wavemill surface currents, although their much lower radar frequency will make them sensitive to currents as perceived by long ocean waves (25 meters or longer, depending on the HF radar frequency). Other means of validation, like current-meters and Acoustic Doppler Current Profilers (ADCP), will accurately measure currents at a given depth, but seldom report data closer than a few meters from the surface, thereby overlooking the strong vertical current shear in the top few meters. Finally, surface drifters could offer an acceptable solution, depending on drifter size and the depth of their drogue. All things considered, the simple flat plywood drifters developed and deployed by Goldstein et al. (1989) to validate airborne ATI currents may yet offer the best solution to measure truly near-surface water displacement, while minimizing the influence of wind drag on the body of the drifter.

3 VALIDITY OF WAVEMILL PRIMARY PRODUCTS

3.1 Introduction

The objective of this task was to determine the scientific validity of the primary Wavemill products through theoretical analysis, modelling, simulation and empirical analysis based on the SAR surface current report from the scientific review of the previous task, and using real data from the Wavemill Proof of Concept Campaign.

There were the following aspects to this work

- Simulation of Wavemill primary scientific products
- Scientific analyses and validation of Wavemill Proof of Concept Campaign data
- Definition and Ranges of instrument and satellite performance
- Impact of tropospheric disturbances on the quality of Wavemill primary scientific products.

3.2 Simulation of Wavemill Primary Scientific Products

Objectives

The objective of this sub-task, carried out by Starlab with some limited input from IFREMER, was to use the Starlab Wavemill End-to-End Simulator to assess the scientific validity of the Wavemill primary products (Surface currents) through the following steps:

- Theoretical analysis of the Wavemill measurement mechanism and determination of phenomena affecting the retrieved interferometric phase.
- Modelling of the identified phenomena with respect to their impact on the interferometric phase.
- Simulation of the identified phenomena from the proposed theoretical models.
- Critical comparison of simulation results with data reported in past studies and campaigns.

The Wavemill End-to-End Simulator is a tool, developed by Starlab, that simulates and evaluates the end-to-end performance of the Wavemill SAR interferometric system, from the generation of the SAR signal, including simulation of the ocean surface, to the production of final geophysical products, which consists of the reconstruction of sea-surface topography or surface current maps under different conditions.

An initial review and discussion identified some key dependencies that should be investigated through the simulator:

- *Doppler Bias* due to ocean surface movements, through dependency of the results on
  - Wind speed and direction
  - Incident angle
  - Swell wavelength
- The tail of the *Radar Cross-Section distribution* through dependency of the results on
  - Wind speed
  - Swell wavelength
- That a *Hydrodynamic modulation* model is introduced and is correctly implemented
- That the *azimuthal resolution loss* (or azimuth cut-off) was correctly represented, as tested at different wind speeds.

End to End Simulator Configuration and Investigations

For each of the simulator investigations the following steps were carried out:

- Specify the dimensions of the scene and the sampling (pixel size) required for the investigation.
- Extend the scene so the dimensions are an exact power of 2 to improve processing speed.

- Build a look up table based on the composite model for the Normalised Radar Cross Section (NRCS) according to Kudryatsev et al. [2005], for a range of incidence angles (0° - 90°). Assign a value to each pixel dependant on the local incident angle
- Define a “raw data” matrix with dimensions and spacing determined by the instrument configuration, and compute the following parameters in time (i.e. for each radar pulse generated):
  - Pixel position over the ocean surface.
  - Pixel velocity due to wave motion.
  - Wind drift (equal to Bragg waves phase speed).
  - Current velocity.
  - Local incidence angle
- Project the antenna pattern over the scene, and “integrate” (i.e. calculate the reflected signal characteristics of) pixels that fall within this pattern & store the output in the raw data matrix.

The simulator was set up in an “ERS-like” configuration (Table 1) so that results could be tested against previously recorded data.

	Configuration		
Parameter	**“ERS-like”**	**PoC Airborne**	**Wavemill Error Budget**
Pulse Repetition Frequency (PRF)	1,680.0 Hz	700.0 Hz	3,200.0 Hz
Transmitter bandwidth	15,549,900 Hz	1.3e+08 Hz	60.0e+06 Hz
Pulse Duration	3.712 e-05 ms	1.2 e-06 ms	7.407 e-05 ms
Carrier Frequency	5.2966865e+09 Hz	9.99999999e+09 Hz	1.1991698e+10 Hz
Sampling Frequency	18,963,103 Hz	1.495 e+08 Hz	66.0 e+06 Hz
Azimuth Angle	0.0°	45.0°	45.0°
Nominal Satellite Altitude	777.83 km	3000.0 m	508226.13 m
Nominal Satellite Velocity	7,480.91 m/s	250.0 m/s	7624.68 m/s
Image size	4.5 km x 4.5 km		

Table 1: Wavemill End to End Simulator set up values for various configurations

Doppler Bias

The dependency of “Doppler Bias” (or Doppler centroid anomaly) against wind speed, wind direction, and swell wavelength was tested and found to show expected behaviour. Figure 1 shows that the simulator calculated the Doppler bias would reduce with increasing wind speed in the radial direction, and that these results are consistent with data from the Envisat ASAR.

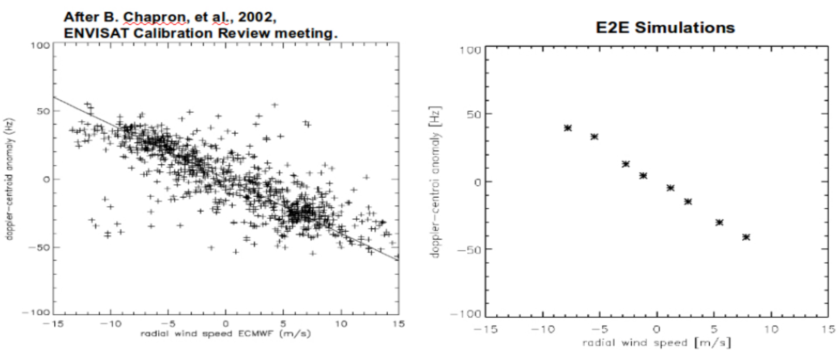

Figure 1: Doppler Bias versus wind speed (directly upwind or downwind: 90° or 270°). (Left) As measured by Envisat ASAR, (right) as calculated in the Wavemill end to end simulator.

Figure 2 shows the results for wind direction, incident angle and swell wavelength. The results match expectations according to theory:

- Wind direction: Doppler anomaly is at absolute maximum for upwind/downwind directions (90°-270°) and zero for cross wind (0°)
- Incidence Angle: Doppler anomaly is expected to increase with incidence angle [e.g. Mouche et al., 2012].
- Swell Wavelength: According to theory [Mouche et al., 2012] an increase in surface tilt leads to an increase in induced Doppler anomaly. Here the Doppler anomaly changes from ~70 Hz to -20Hz as the swell wavelength increase from 50m to 200m.

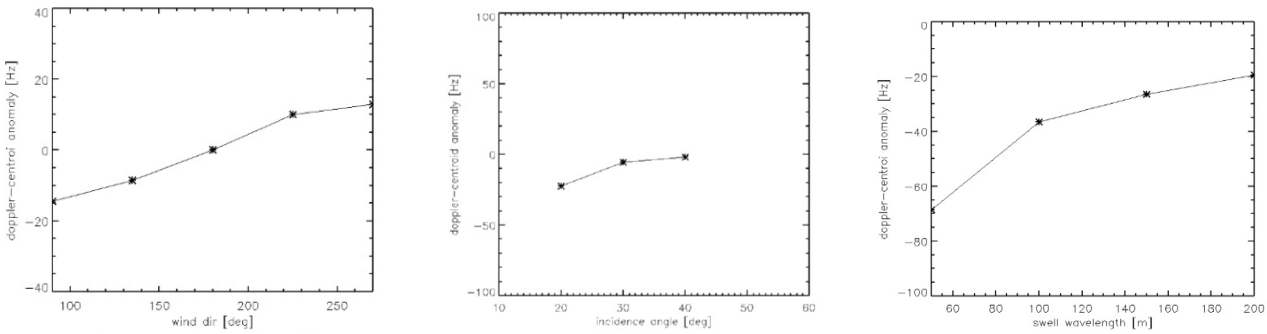

Figure 2: Simulator calculated Doppler Bias against (right) wind direction (wind speed is 7 m/s), (centre) incident angle (wind speed = 5 m/s, wind direction is crosswind = 180°), (right) swell wavelength (wind speed = 5 m/s, wind direction is crosswind = 180°; swell amplitude = 2m).

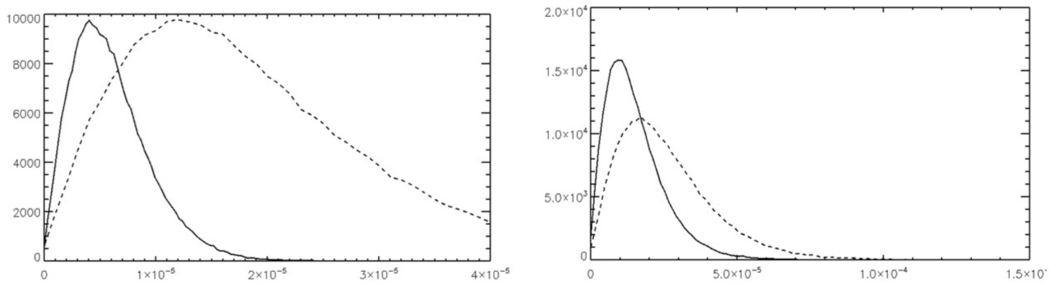

Figure 3: NRCS Distribution functions from the Wavemill End to End Simulator: Wind direction 90° (upwind), Swell amplitude 2m, Swell wavelength 50m (solid line) and 200m (dashed line). (Left) Wind Speed 5m/s (Right) Wind speed 20 m/s.

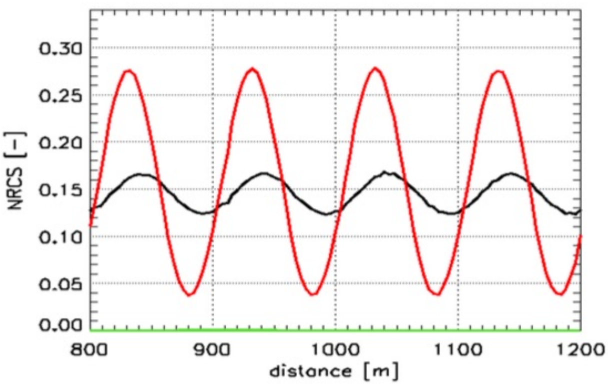

Figure 4: Hydrodynamic modulation function (black) versus wave profile (red)

Normalised Radar Cross Section (NRCS)

The dependency of the NRCS distribution against wind speed, and swell wavelength was tested and the results shown in Figure 3. Again the simulator can be seen to predict expected dependencies:

- Backscattering increases with increasing wind speed.
- NRCS distribution at low wind speed is more sensitive to local changes in tilt angle than at high wind speeds, tilt angle changes introduced in Figure 3 by changing the swell wavelength.

Hydrodynamic Modulation

Figure 4 shows the hydrodynamic modulation function (in red) as it varies with the wave profile (in red). The hydrodynamic modulation can be seen to be a maximum at the leading edge of the wave, as expected.

Azimuth Resolution Loss

The ability of the simulator to accurately represent azimuth resolution loss due to increased orbital velocity was tested by producing SAR images of point targets with wind speeds of 3 m/s and 14 m/s. At higher wind speeds the point target could be seen to be widened and shifted in the along track direction. In addition the Azimuthal Correlation Function (ACF) for a (simulated) Single Look Complex image was computed to calculate the azimuthal cut-off wavelength. In Figure 5 the ACF is seen to become relatively insensitive beyond 200m and to reach a minimum at ~300m. These lie within the range of the fetch dependent azimuth cut-off wavelengths from Kerbaol et al [1998].

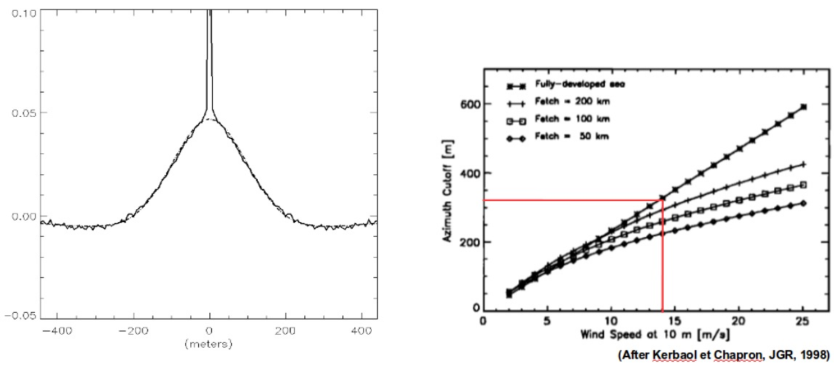

Figure 5: Azimuth Cut Off. (Left) The Azimuthal Correlation Function for a simulated SAR image for a wind speed of 14 m/s. (Right) Azimuth cut off wavelength for different wind speed and fetch conditions (after Kerbaol et al., 1998)

Simulating Proof of Concept Campaign Data

Once it was confirmed that the simulator was producing expected results and representing the key geophysical processes accurately, it was used to simulate the data from the Wavemill Proof of Concept Campaign. Table 1 lists the configuration for this experiment (X-band radar on board on airborne platform).

The input ocean spectrum was provided by NOC, and was based on the wave data from a buoy in the campaign area. This was combined with a Kudryatsev fit for the small wave spectrum and used as input to the simulation. The wind (5 m/s, 180°) vector from a nearby meteo-station was used to simulate the NRCS. The final simulated current vectors are seen in Figure 6.

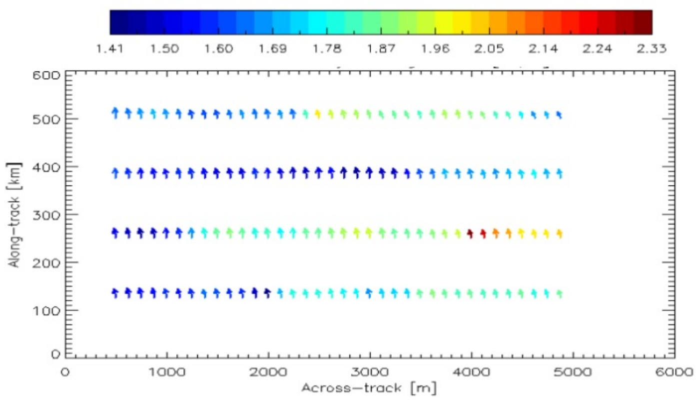

Figure 6: Surface Current Velocity vectors from the Wavemill End-to- End Simulator for the conditions present during the Proof of Concept Campaign.

The simulated results (mean current direction 318°, and mean current speed 1.7 m/s) agree well with the input conditions (326° and 1.12 m/s).

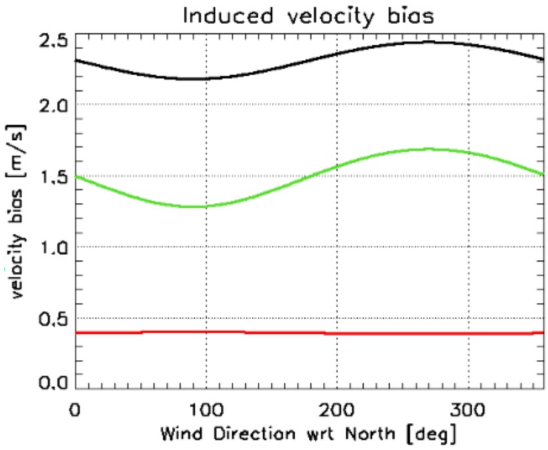

Figure 7: Velocity error induced by different wind speeds as a function of wind direction: red 3 m/s; green 7 m/s; black 14 m/s.

Towards an Error Budget

The final task with the Wavemill End-to-End simulator was to generate an estimate of the error in the retrieved surface current velocity due to wind induced waves. Figure 7 shows the induced velocity bias for wind speeds of 3 m/s, 7 m/s and 14 m/s, input values as given in Table 1. It can be seen that a wind speed of 3 m/s introduces a low bias of 0.4 m/s which does not vary significantly with wind direction, whereas wind speeds of 7 m/s and 14 m/s introduce larger biases (~1.5 m/s and ~2.2 m/s respectively) which show a minimum in the upwind direction (90°) and a maximum in the downwind direction (270°).

Summary of Wavemill Simulator Task

The Wavemill End-to End Simulator's ability to realistically represent key features linked to SAR ocean surface imaging has been validated using several simulations.

- Doppler Bias
- Sensitivity of distribution's tail to wind and waves
- Hydrodynamic modulation (only if swell and wind are aligned)
- Azimuth Cut-Off

The outcomes of these tests were compared to literature results where available, and showed agreement. It was concluded that the software is correctly simulating the Wavemill primary products

A scenario using conditions present during the Proof of Concept Campaign was simulated, and seen to give surface current velocities with same order of magnitude as those observed.

A preliminary geophysical error budget has been estimated for wind-induced waves. It was found that a wind speed of 3 m/s introduces a low bias of 0.4 m/s which does not vary significantly with wind direction, whereas wind speeds of 7 m/s and 14 m/s introduce larger biases (~1.5 m.s and ~2.2 m/s respectively) which show a minimum in the upwind direction (90°) and a maximum in the downwind direction (270°)

3.3 Analyses of Wavemill Proof of Concept Campaign Data

Introduction – The Wavemill Proof of Concept Campaign

This task was carried out by NOC. A Wavemill Proof of Concept study was carried out in 2011, by flying the Wavemill airborne demonstrator [Wavemill PoC, 2012] over the Irish Sea and taking measurements in a star pattern. This study was supported under a previous ESA project. The objective of re-analysing the data within the WaPA study was to apply new technical and scientific understanding developed during the study, to estimate the error induced by winds and waves on the retrieved surface currents and so to work towards an inversion strategy to retrieve surface current data from a space-borne Wavemill instrument.

Geophysical Conditions

The analysis carried out for WaPA concentrated on data collected between 00:18 and 01:27 on the 26th October 2011. Figure 8 shows the location of the PoC flights and summarises the wind, wave and current conditions. The surface currents and waves were provided by an ADCP and wave buoy deployed at the Mersey Bar Light, and the wind velocity by the Oceansat-2 scatterometer which overflew the location at 00:15. Local HF radar and meteo stations confirmed these observations.

Wavemill Airborne PoC data

The airborne Wavemill SAR system comprises four antennae functioning in X-band and VV polarisation. It was deployed on 26th October in a “Javelin” configuration with a (50 cm) physical interferometric baseline only in the along track direction. The SAR data used for this re-analysis were:

- Amplitude of single look images from the master or slave antenna (no $\sigma 0$, no calibration) at high resolution;
- Interferogram (or interferometric phase) at high resolution;
- Surface current computed by Starlab at a spatial resolution of about 100 m.

The spatial resolution of the high-resolution products varies across track from 1m at far range to 5m at near range. Along track resolution is 5m.

In the Javelin configuration, the squint angle at the surface changes with range. At near range, the squint angle is ±65° for the fore or aft antenna at near range, ±45° at mid range and ±32° at far range. Figure 8 shows the coverage and location of these data.

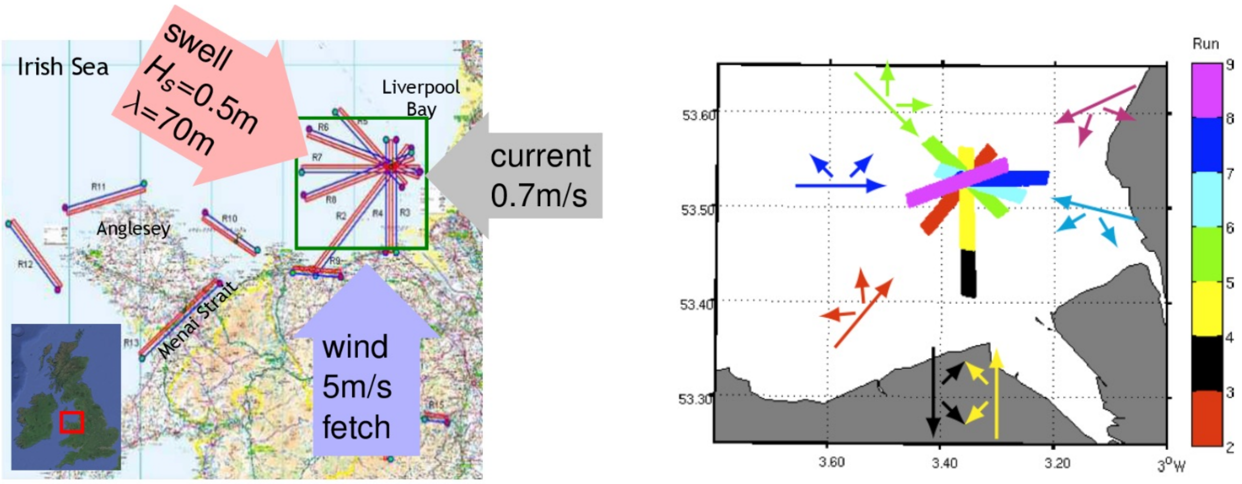

Figure 8: Wavemill PoC location, conditions and data. (Left) Flight pattern and geophysical conditions on the 26th of October, 2011. Blue lines and elongated red strips represent respectively the aircraft flight track and the SAR sampled area. (Right) Airborne data re-analysed for WaPA. Individual runs are represented by a different colour. The aircraft flight direction for each run and line of sight direction of the fore and aft antennae are represented by the large and small arrows respectively.

Model for Surface Current Retrieval

To retrieve surface current from the SAR ATI measurements, a model derived from Chapron et al. [2005] was used to estimate the velocity contribution from wave modulation of the radar cross section (Figure 9). This model includes two main terms:

- a gain factor for the radar cross section, which varies with wind speed, wind direction and incidence angle.

- an integral to take account of the wave orbital velocity as it relates to the measured (directional) wave spectrum.

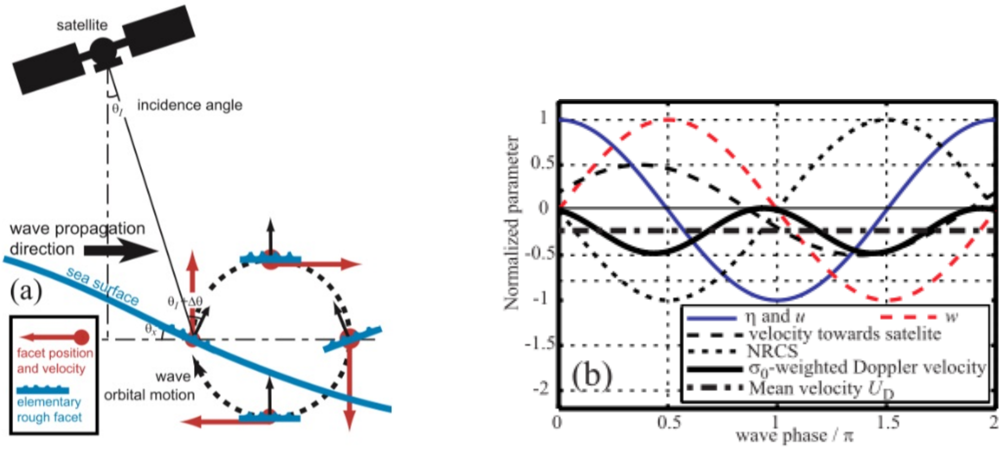

Figure 9: Schematic of the conceptual model of the measurement of surface velocity and the contribution of radar cross-section modulation by waves and (b) examples of parameters over a sinusoidal wave from [Chapron et al., 2005]

The characteristics of the overall modelled "wave artefact" surface velocity are shown in Figure 10 for various azimuth angles (relative to wind direction and wind speeds).

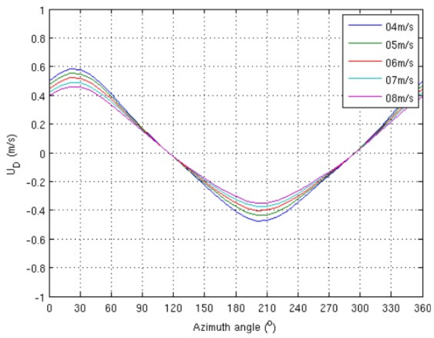

Figure 10: Wave artefact surface velocity computed with [Chapron et al., 2005] model for various wind speeds as a function of azimuth angle for an incidence angle of 27°. The computation uses the buoy wave spectrum extended with a KHCC spectrum for small waves (λ < 5 m).

Data Analysis

The main focus of the analysis was to verify the wind-wave artefact model. The SAR ATI interferograms were converted to apparent line of sight surface and then surface component velocities (Figure 11) for each of the runs shown in Figure 8.

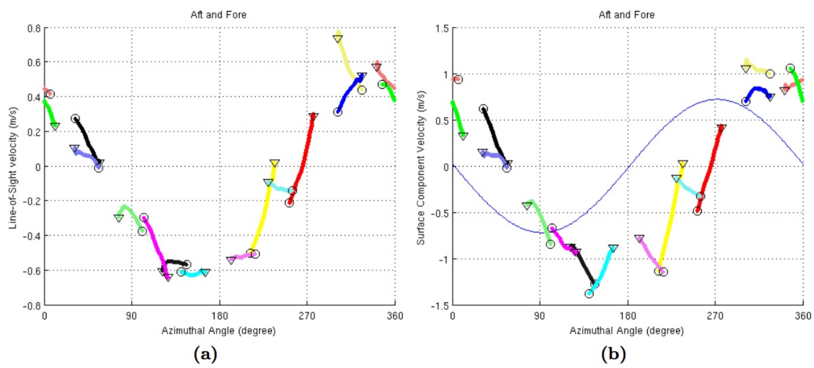

Figure 11: Median (a) line-of-sight (b) surface velocity as a function of azimuth angle for each run. Same colour code and legend as in Figure 8. In (b), the blue curve represents the projected component of the sea surface current (as measured by the ADCP) for every azimuth angle.

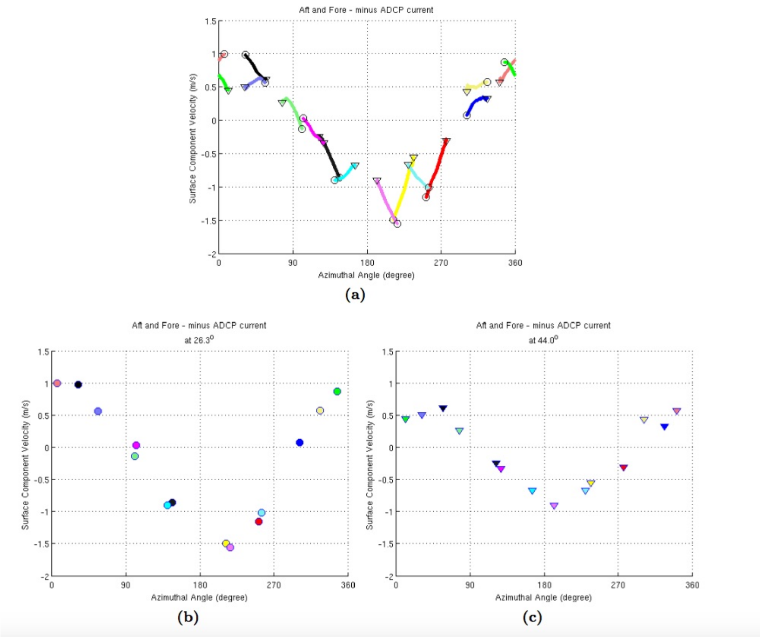

Figure 12: (a) Median residual current (computed as measured surface velocity minus ADCP current) for each run against azimuth angle. (b) same as (a) but for the near range only. (c) same as (a) but for far range only. Same colour code as Figure 8.

The surface current as measured by the ADCP was then removed, to give the residuals seen in Figure 12. These residuals can be seen to show good agreement with the modelled wave induced current predicted by the Chapron et al. [2005] model (Figure 10), although the amplitude from the model is about 0.5 m/s at 27° which is lower than the observed (~1 m/s) at 26.3°

The results also indicate, as expected, lower amplitude of the wave-induced artefact current amplitude at far range (high incidence angles) than at near range.

Along track analysis of individual run data (not shown here) also demonstrated that the aircraft roll and drift angles have significant impact on the derived velocity, even though the antennae should not feel these attitude motions because they are gimbal mounted.

Conclusions

The re-analysis of the Proof of Concept Campaign data focussed on applying a model for the wave induced surface current to see how well this matched the residual surface current measured by the airborne Wavemill SAR system, once the known surface current had been removed.

This analysis found that:

- The characteristics of wind-wave artefact velocity (at X-band) was in good agreement with a model derived from ENVISAT empirical data (C-band) even under different oceanographic conditions.
- The variation of this wave induced current with incidence angle and phase is in agreement with a simple theoretical model [Chapron et al., 2005]
- The amplitude of the wave artefact current estimated by the model (~0.5 m/s at 27°) is lower than that derived from the airborne measurements (~1.0 m/s at 27°)

It is recommended that:

- Further airborne flights are carried out under a range of geophysical conditions to further develop and verify the model and support the development of a reliable inversion strategy
- To enable both wind and current to be independently extracted from the airborne Wavemill SAR measurements, VV and HH polarisations would be needed, as well as a calibrated measurement of the radar backscatter at nadir incidence ($\sigma 0$).

3.4 Ranges of Instrument and Satellite Performance

Objectives

The objective of this task, carried out by ADS, was to establish the qualitative relationship between the required imaging / image quality parameters (that are determined by the product performance requirements) and the Wavemill instrument physical and operating parameters (Table 2), and to:

- explain the instrument performance / implementation trade offs.
- to ensure that all the design interdependencies are identified.

Imaging / image quality parameters	**Instrument physical / operating parameters**
Swath Width	Transmit frequency
Incidence Angle (coverage / access)	Transmitted / received pulse bandwidth
Range ambiguity ratio	Transmit pulse duty cycle
Azimuth ambiguity ratio	Pulse Repetition Frequency
Sensitivity	Antenna length and height
Radiometric resolution	Elevation and azimuth beam pattern
Polarimetry	Transmitted / received polarisation
Revisit	Power (mean, peak)
Around-orbit operating cycle	Number of independent looks (range, azimuth)
Spatial Resolution (range)	Data rate
Spatial Resolution (azimuth)	Data Compression
	Orbit
	Instrument / spacecraft thermal control
	Antenna configuration (mass, complexity)

Table 2: Wavemill imaging / image quality parameters and instrument physica and operating parameters

Interdependencies

Interdependencies between imaging and instrument parameters were mapped for groups of parameters: Instrument PRF, spatial (range and azimuth) resolution, radiometric resolution, swath width, range and azimuth ambiguity ratio, polarimetry, sensitivity, revisit, orbit operating duty cycle. Figure 13 gives examples for PRF and range resolution dependencies

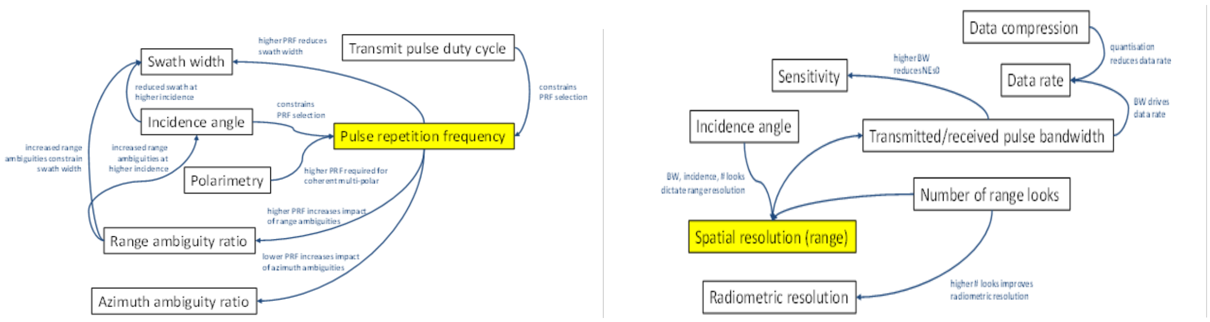

Figure 13: Theoretical and quantitative links between instrumental parameters for (left) PRF dependencies and (right) range resolution dependencies

Some key interdependencies then fall out of this analysis (also see Table 3):

- The swath width requirement will specify the maximum PRF. The maximum PRF that will allow a swath width of 100km is 2025 Hz.
- The length of the antenna in the along track direction determines the available Doppler bandwidth. The PRF should be sufficiently high to sample the Doppler bandwidth without aliasing. A PRF of 2025 Hz implies an antenna length of 8.5m which is too long to accommodate in a Vega spacecraft, so some compromise on swath width or accepting azimuth ambiguities may be required.

- High PRF gives poor range ambiguity but good azimuth ambiguity, whilst lower PRF gives good range ambiguity but poor azimuth ambiguity. It could be argued that modest ambiguity performance could be tolerated in the open ocean, but may be a design issue if good performance in the coastal zone is required.
- Increasing the PRF increases the input data rate
- The mean transmit power is proportional to the PRF
- Better radiometric performance and sensitivity is achieved with higher PRF
- A wider swath would require a shorter antenna in elevation, a narrow swath would require a wider antenna
- Dual Polar operation implies a more complex antenna. There are a number of optional configurations / compromises, including full VV-HH operation, bursts of VV and HH in ScanSAR like mode, dual polar imaging on one side only, alternate orthogonal pulses, compact polarimetry (transmission of circularly polarised pulses).

Requirement	System / Instrument Parameter	Additional Consequences
Swath Width	PRF Antenna Dimensions	Coverage / revisit Data Rate Mean Power Azimuth looks Azimuth ambiguity ratio
Coverage / revisit	Orbit Swath width	
Polarisation	PRF Swath width Mean power Data Rate	Coverage Thermal Antenna mass and complexity Orbit duty cycle
Max current velocity	Along track phase separation centre	Spacecraft length Accommodation
Min current velocity	Minimum phase shift	Phase accuracy
Spatial Resolution	Pulse bandwidth Azimuth bandwidth	Instrument noise Antenna length Number of available looks
Sensitivity	Transmit power PRF Pulse bandwidth Antenna dimensions	Visible sea state Received echo power

Table 3: Wavemill Performance requirements and consequences on instrument /platform / mission configuration

Impact on instrument Design of Wavemill Performance Requirements

Following on from the above analysis, specific characteristics of the Wavemill instrument and platform impacted by the performance requirements have been identified to include:

Instrument configuration:

- The split between XTI and ATI and their relative contributions.
- The inclusion of dual-polarisations and its knock-on affect on power, data and complexity.
- The requirement on current retrieval performance in low wind conditions (>2m/s) which provides a poor SNR and drives a more stringent control of the ambiguity performance than might be expected.
- The need to have a (likely not-yet-developed) metrology system to measure antenna geometry.

Instrument data processing and downlink:

- The very large data throughput of the instrument (~2Gbits per antenna) in combination with the need to have raw SLC data downlinked to the ground without pre-processing.
- The probable under-capacity of traditional X-band downlink rates, and the dependence of the mission on advanced very high-rate communications.

Instrument compatibility with the launcher:

- The requirement to be compatible with the VEGA class launcher, in combination with other requirements, puts extreme demands on the power, radiator area, and instrument/platform configurations possible.

Coverage:

- The need to have full global ocean coverage, which in turn puts large demands on the power requirement for such an interferometric SAR instrument, as well as the downlink strategy

This has lead to some initial observations on potential modifications to initial assumptions:

- The instrument design has moved to an *ATI only* solution, because of the inability to separate across & along track components of the data, with one acting as an effective error on the other.
- In order to adequately deal with ambiguities, either the use of *longer antenna lengths* than the original 4m will be required, or the *use of a Displaced Phase Centre Antenna (DPCA).*
- The use of a single polar instrument has given way to a likely *dual-polar implementation* in order to achieve the required wind/current discrimination.
- Some form of *data compression* is likely to be needed for the large quantities of raw instrument data, although raw data will be provided up to the maximum allowable data bandwidth.
- Both *single and dual sided operation* is now being considered and has been shown to be viable with respect to performance.

Conclusions

The current (updated) baseline assumption about the instrument configuration are for a Dual polarisation, squinted ATI instrument in an in-line 'Javelin' configuration, with a folding antenna to generate required antenna length and additional booms to generate required baseline, and a waveguide antenna for lightness and simplicity with passive beams. Parameters are given in Table 4.

Parameter	**Value**
Polarisation	VV and HH
Mid swath incidence angle	30°
Near swath incidence angle	> 25°
Swath width	100km (dual sided) or 200km (single sided)
Centre frequency	13.5 GHz (Ku-band)
Transmit bandwidth	25 MHz
Intermediate product size	~14m

Table 4: Current assumptions for Wavemill instrument parameters

In terms of operational set up, whilst DPCA operation has been considered, it was not thought to be required as long as antenna length is sufficient to control ambiguities. Operation would be in a burst inter-leaved mode (akin to ScanSAR), with bursts for each beam. The single versus dual sided operation trade-off remains open.

In terms of the key performance requirements:

- Product size of 1km to 4km
- Total Surface Current Accuracy of 5 cm/s, within a wind speed range of 3 m/s – 20 m/s
- Minimum surface wind 2 m/s

It is currently believed this configuration could achieve the required performance at the 4 km x 4 km product size, except at very low wind conditions (where very poor SNR would reduce performance). Indeed finer product resolution should be available at higher wind speeds and higher currents.

3.5 Impact of Tropospheric Disturbances

Introduction

With the Wavemill instrument expected to operate at Ku band, there is the potential for the SAR imaging to be affected by atmospheric disturbances. Starlab carried out a short investigation to investigate the scale of potential impacts. Three such sources were considered:

- Atmospheric Phase Screen.
- Faraday Rotation
- Atmospheric water content – specifically rain

Atmospheric Phase Screen (APS)

Atmospheric Phase Screen is the term commonly used to refer to the SAR phase offset dependent on the atmosphere refractivity index. Changes in the refractivity index imply different signal propagation velocities, hence different atmospheric phase component. The effect of APS on SAR phase becomes especially evident for higher frequency bands so it is to be expected that (Ku-band) Wavemill signals will be strongly affected by atmospheric delay.

Given that atmospheric conditions can vary significantly from one acquisition to another, APS is an important source of error in repeat-pass interferometry. However Wavemill is a single-pass interferometer and as such, even if SAR acquisitions are affected by an atmospheric phase offset, APS effect on interferometric phase is expected to be negligible. For further information on APS see Pusségur et al. [2007].

Faraday Rotation

The free electron content of the ionosphere produces a rotation in the polarisation of microwave signals passing through. This effect, known as Faraday rotation, translates into attenuation due to polarization rejection for single-pol sensors. It also complicates the retrieval of geophysical parameters from polarimetric data. The magnitude of this effect is inversely proportional to the frequency [Wright et al., 2003], and for high frequency bands FR can be discarded as negligible (the maximum polarisation rotation for a Wavemill configuration at Ku band would be 0.55°).

Rain

It is well established that satellite Ku-band measurements can be severely degraded by heavy rain, due to:

- Signal contamination by direct backscattering from rain (clutter).
- Signal attenuation, significant at high frequency bands.
- Changes in surface roughness induced by raindrops, which modify the NRCS of the surface.

We briefly investigate the potential impact of each of these effects below.

Volume Backscattering

Starlab applied a rain cell model proposed by Moore and Ahamad [1993] to the Wavemill configuration and derived Figure 14 for the Signal to Clutter ratio (essentially the ratio of the backscattering of the rain and the backscattering from the sea surface) as a function of rain rate and incident angle.

"Moderate" rain rates lie between 2.5 to 7.6 mm/hr, and in this range the SCR lies above 15 dB, which causes no difficulty. Only when the main beam is passing through heavy rain (rain rate > 7.6 mm/hr) will the volume backscattering have a significant impact on the SCR, bringing it below 15 dB, and this rate occurs in ~3% of all rain events.

Attenuation

Rain attenuation can be simply modelled as a function of rain rate. Figure 14 gives the two-way attenuation estimated for Ka band (which is more attenuated than Ku band) for different incident angles and rain rates. This assumed a 4 km thick rain cell with a homogeneous rain rate.

Assuming an attenuation of less than 5 dB are acceptable, then only for rain rates of 2 mm/hr and over will rain cause potentially problematic attenuation (this rate is found in ~2% of all rain events).

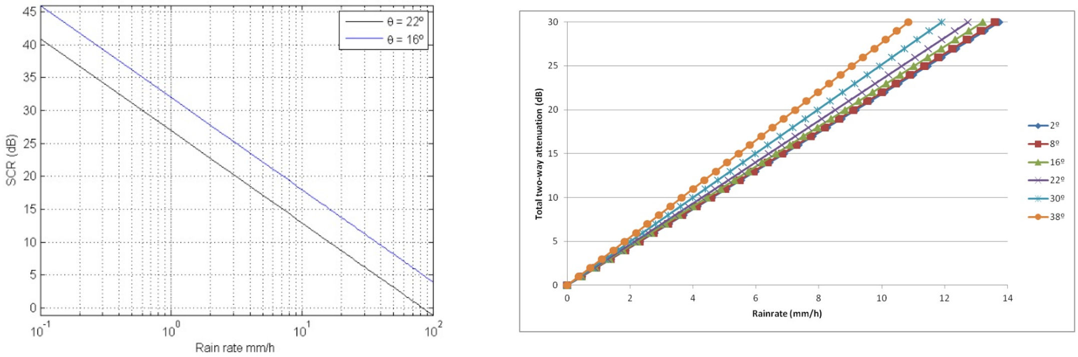

Figure 14: Rain effects. (Left) Signal to Clutter Ratio as a function of rain rate for different incidence angles. (Right) Total two-way attenuation (Ka Band) as a function of rain rate and incidence angle

Changes to Surface Roughness

The impact of rain droplets on the ocean surface can increase the roughness and can, for heavy rain have a larger effect than the wind on NRCS at low wind speeds. A direct consequence of this increase of NRCS by rain-induced roughness is the overestimation of wind speed. For higher wind speeds (> 6 m/s) the effect of rain is not so evident except for very heavy rain (rates > 10 mm/hr).

Summary

Faraday Rotation and Atmospheric Phase Screen will not impact the accuracy of the Wavemill ATI imaging process because the imaging is carried out on a single pass basis.

Moderate rain (2 – 10 mm/hr) and heavy rain (> 10 mm/hr) do have the potential to affect the ability of Wavemill to measure surface currents, through volume backscattering, attenuation and altering surface roughness. In the latter case, rain will have a greater impact under low wind speed conditions. From rainfall statistics it is anticipated that these rain rates are to be found in under 3% of all rain events.

4 IMPACTS OF OCEAN SURFACE WIND ON WAVEMILL MEASUREMENTS

A critical aspect of the ability of the Wavemill system to provide accurate measurements of the surface current will be the capability of an inversion scheme to accurately represent and extract the separate contributions of the wind field and the surface current to the scattered and retrieved SAR signal.

The main goal of this task, carried out by IFREMER, was to study the feasibility of retrieving estimates of the surface wind vector and associated Doppler shift contributions either directly from Wavemill measurements (normalized radar cross section (NRCS) measurements and total Doppler), or alternatively in combination with first guess ancillary information (e.g, atmospheric model, scatterometer estimates, tide model, altimeter anomalies, etc.). This would then lead to proposed strategies to best estimate the residual Doppler and the desired associated surface current.

4.1 Review of the scatterometer systems and foreseen limitations for Wavemill

The purpose of this aspect of the study was to look at the proposed Wavemill system in terms of its potential to act as a scatterometer and retrieve ocean wind fields. Results from previous scatterometer missions (ERS-1, ERS-2, Quickscat, NSCAT) and from the Tropical Rainfall Measurement Mission (TRMM) were reviewed and further analysed.

It was identified that the main limitations of the Wavemill configuration to measure wind velocity are:

- The lower incidence angles (compared to “normal” scatterometer systems), as the sensitivity of NRCS to wind is lower at lower incidence angles (e.g. Tran et al., [2007]).
- The low incidence angle may also introduce a non-negligible sea state dependency.
- two fixed antennae limits azimuthal sensitivity, and probable ambiguities in the retrieved wind direction, though the additional Doppler shift information available from Wavemill may help.

However, Wavemill will offer the new opportunity to combine Doppler measurements and NRCS measurement from different look angles, and this may offer a partial solution to the above limitations.

4.2 Inversion of the synthetic cross sections and Doppler anomalies to retrieve the wind vector and error analysis

The objective of the Wavemill inversion scheme is to extract separate estimates of wind velocity and surface current, ideally without the need for external a priori information. The approach developed by IFREMER to retrieve wind speed information is based on the combination of measurements of Doppler anomalies and NRCS. The general approach followed developments presented in Chapron et al. (2005), and Mouche et al. [2012] showing how the Doppler centroid anomaly could be used to retrieve geophysical information about both wind and sea surface current. Figure 9 illustrates how the residual Doppler comes from the line-of-sight motions of the surface scattering elements relative to the fixed Earth. Accordingly, in the absence of an underlying sea surface current, the Doppler shift induced by the near surface wind is interpreted as the mean line-of-sight velocity of the radar detected scatter elements. The Doppler signal and NRCS varies along the moving wave profiles, in a way that is correlated to the horizontal and vertical orbital velocities. Thus the Doppler shift is dependent on a number of factors [see Mouche et al, 2008]:

- Doppler shift increases with increasing wind speed (for a given incidence angle and direction)
- Doppler shift is a maximum in the upwind direction, minimum downwind and zero when the wind is in the azimuthal direction.

To support the investigation IFREMER applied and analysed models and data from a number of sources, including

- for Ku-band NRCS data, NSCAT and TRMM Precipitation Radar (PR) data and GMFs.
- For C-band, NRCS data Envisat SAR NRCS data and CMOD5_N GMF NRCS data.

- For the Doppler shift data, Ku-band data. No measurements were available, so instead the RCA [Mouche et al., 2008], DopRim [Hansen et al., 2012] theoretical models were used,
- For Doppler C-band, Envisat SAR data [Chapron et al., 2004] were used. In particular the empirical model derived from these data, the CDOP empirical GMF was used.

IFREMER adapted a methodology developed by Mouche et al [2012] for Envisat C-Band SAR data and applied it to the Wavemill Ku-Band configuration. This approach uses a Bayesian inversion scheme to minimise a cost function (Equation 1), which includes a term for NRCS (left function of KMOD) and for Doppler shift (right function of KDOP)

$$J(\vec{u}) = \sum_{i=1,2}\left(\frac{\sigma_0 - KMOD(\vec{u})}{\Delta\sigma_0}\right)^2 + \sum_{i=1,2}\left(\frac{df - KDOP(\vec{u})}{\Delta df}\right)^2$$

Equation 1

As identified above, Ku band data exist for NRCS, and it is relatively straight forward to adapt the well known CMOD function for C-band NRCS to Ku band to form the “KMOD” function. However, there are no equivalent Ku band for Doppler shift, so a key part of this adaption involved the definition of a new model for Ku Band Doppler shift - “KDOP”, using the C-band data and models listed above. A simple and practical approach was adopted based on the RCA model of Mouche et al [2008], noting that in the range of incidence angle expected for Wavemill, there is a very close relationship between the sea surface velocity predicted by this model at C-Band and Ku-Band. It then followed that the Ku Band Doppler shift f_D could be calculated from CDOP empirical data by scaling the C-Band Doppler shift by the Ku/C wave number ratio.

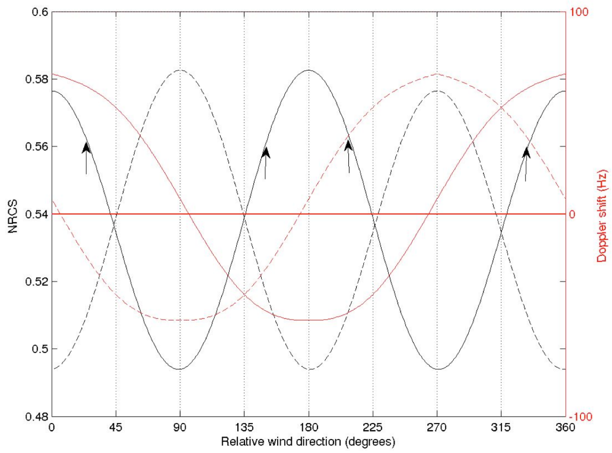

Figure 15: Normalized Radar Cross Section (left scale, black curves, NRCS in natural units) and Doppler shift (right scale, red curves, in Hz) as a function of the relative wind direction. 0° is upwind for antenna 1 (solid line) and crosswind for antenna 2 (dashed line). Arrows locate, for a given wind direction of 30°, the 4 different solutions where the NRCS of both antenna are equal.

These developments then allowed Normalised Cross section and Doppler Shift to be calculated at Ku Band for the two antenna Wavemill geometry. Figure 15 shows these two parameters, plotted against relative wind direction for a 7 m/s wind speed and an incidence angle of 20°, with the two Wavemill antenna viewing the sea surface at orthogonal azimuth angles. This figure illustrates how the availability of Doppler shift information can help to resolve ambiguity problems. The arrows identify, for the example of 30° in wind direction, the 4 different solutions where the NRCS of both antenna are equal. Processing of a two-antenna system solely measuring the NRCS can only give four equally probable wind vectors. If the Doppler shift data is available, then just knowing the sign of this quantity for the two antenna identifies the correct solution. This can be further illustrated by analyzing the behaviour of different cost functions minimizing in a least-square approach the differences between the measured and modelled quantities.

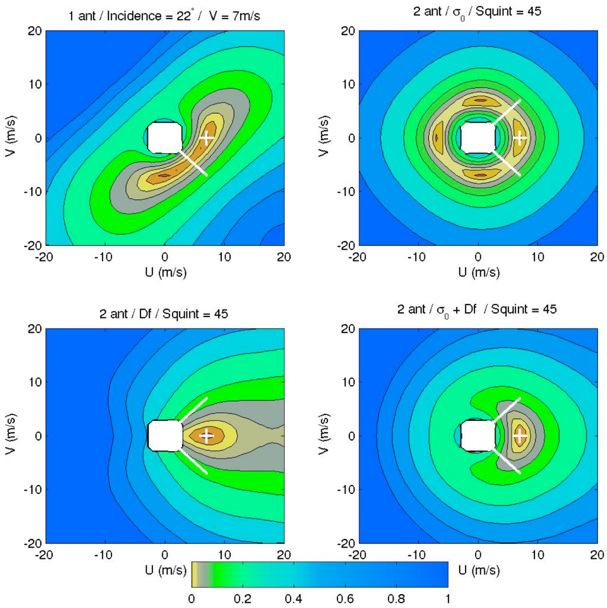

Figure 16: Cost function for a value of (7,0) m/s for the wind components (white cross) and (22,45) degrees for the incidence and squint angles. Top right: 2 antennas with NRCS only used; Top left: 1 antenna with NRCS and Doppler used; Bottom left: 2 antennas with Doppler only used; Bottom right: 2 antennas and NRCS and Doppler used. The looking azimuth is drawn as a white bar with the looking point at (0,0). The white patch is the area where the wind speed is lower than 3 m/s and the cost function not computed.

In a more generalised approach, the cost function of Equation 1 can be calculated for different numbers of antennas (the index i) for a given “true” wind vector in the (U,V) wind component space. Thus Figure 16 show the cost function for a 7 m/s wind in the U direction, for different antenna configurations (see the legend). For the two top panels (the left representing a single antenna – Envisat like configuration, and the top right two antenna but only NRCS information), a priori information is needed to remove the ambiguity which is mainly directional. The bottom left panel using only two Doppler shift measurements shows that a Bayesian scheme would give one unique and well determined solution, assuming that the noise figures are adequate. This illustrates the potential of Doppler measurements to isolate the true wind direction. The bottom right panel shows the full configuration if all NRCS and Doppler measurements are used for a two-antennas Wavemill geometry. Retrieval is still improved for the wind speed estimation since the cost function presents a better defined shape close to the minimum. This initial analysis is encouraging, as it shows that that the Wavemill geometry with 22° incidence angle, and anticipated low signal to noise ratio, can be fully exploited to provide high quality wind vectors at km-scale.

A Monte-Carlo analysis was then carried out to provide an estimate of errors in retrieved wind vectors. For any given wind vectors the true NRCS and Doppler shift were calculated using the corresponding GMFs, and then a set of 1000 random realisations of (NRCS, Df) produced by fitting a normal distribution with a standard deviation set by realistic noise values for measured NRCS (5%, 5 Hz), and Doppler Shift (3%, 3Hz). Each of these 1000 pairs was then input to the Bayesian wind inversion scheme for different scatterometer configurations (including Wavemill!)

Figure 17 shows errors for wind speed and direction for Wavemill 2 and 3 antenna configurations and for ASCAT, and it can be seen that for the ASCAT configuration the bias and root mean square error are azimuth dependent, whereas once the Doppler information is available, as in the Wavemill configurations this azimuth sensitivity is not present. The modelled rms error in wind direction for (3%, 3 Hz) noise are 6° in direction and 0.3 m/s in wind speed which is well within specification. The addition of a third antenna (red to green) is not seen to reduce errors significantly. This analysis was repeated for squint angles (40° and 64°), representing the expected inner and outer edges of the Wavemill swath. The results for 40° are very similar to those of Figure 17, whereas for 64° a small but not problematical azimuthal dependency of rmse in direction and speed can be seen.

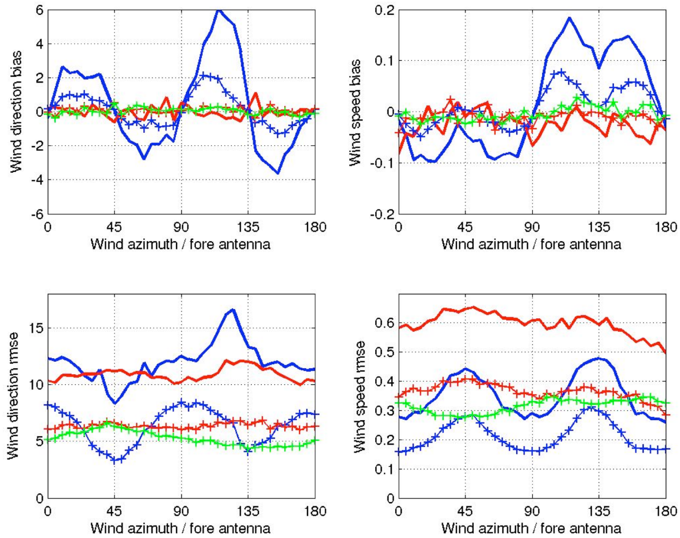

Figure 17: Wind speed (m/s, right panels) and direction (degrees, left panels) biases (top panels) and root mean square errors (rmse, bottom panels) as a function of the wind azimuth (0° (180°) corresponds to upwind (downwind) / the fore antenna) for a squint angle of 45°. The geometry configuration is for Wavemill 2-antenna (red lines) and 3-antenna (green lines), and ASCAT-like (blue lines) configurations and the noise figures are (5%, 5 Hz, solid lines) and (3%, 3 Hz, plus symbols) for the NRCS and Doppler shift, respectively. The wind speed is 8 m/s.

A wind speed of 8 m/s was used for these simulations as this is close to the mean wind speed over the global ocean, but it is well established that accurate sensing of low wind speeds is more difficult, because of a lower signal to noise ratio and a less well defined sea geometry. Monte-Carlo simulations for a wind speed of 4 m/s found that the bias and rmse in wind speed is comparable at 4 m/s and 8 m/s but that directional errors are larger at 4 m/s as a result of the lower azimuthal modulation predicted by the GMF.

A final aspect of the study was to investigate the impact on the accuracy of wind retrieval when a surface current is present. To a first approximation a surface current will affect the Doppler Shift measurement but not the NRCS. The surface current will itself induce a Doppler shift, and this can be introduced into the Cost Function in Equation 1. Figure 18 presents the cost function values of the for a 8 m/s wind vector upwind for the fore antenna with an input Doppler shift modified to account for a 1 m/s surface current in the cross-track direction (i.e at an angle of 45° to the wind vector). The upper left panel shows that the ASCAT-like configuration (as it does not use Doppler shift) is not impacted as expected. Results for other panels show that the retrieved wind direction is nearly aligned with the surface current and that the retrieved wind speed is, as expected, larger than the true one. The three-antennas configuration (bottom right panel) enables to reduce this wind speed bias. These results however depend on the weighting of the cost function terms, but show that, in presence of current, the Doppler information cannot be used in a blind way.

A Monte-Carlo error analysis showed that even a quite low surface current (0.5 m/s) induces unacceptably large wind direction errors whatever the angle between the true wind and the current (except if they are aligned). It was therefore concluded that the presence of a surface current impacts the Doppler shift data insuch a way that the retrieved wind vectors no longer fit with the KMOD model making the cost function residuals well above a threshold defined for a wind-only case. In such a case the wind vector can be estimated using only the NRCS data with help of an ancillary wind information.

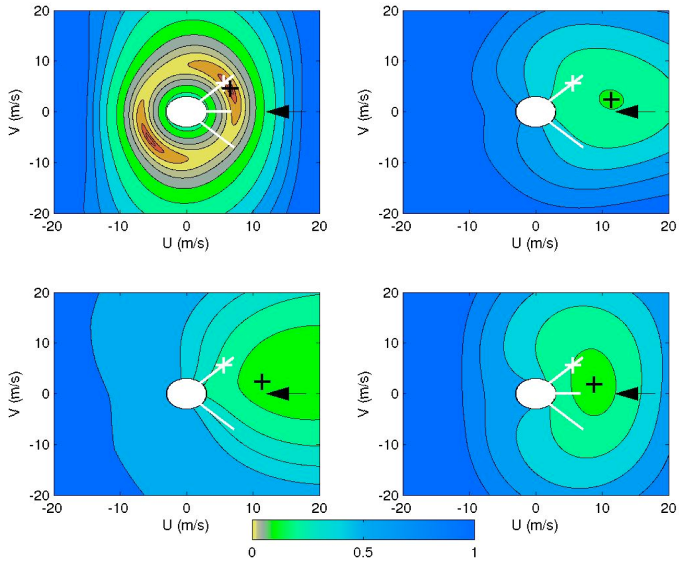

Figure 18: Cost function for a wind vector of 8 m/s upwind for the fore antenna (white cross) and (25,45) degrees for the incidence and squint angles. Top left: 3 antennas with NRCS only used; Top right: 2 antennas with NRCS and Doppler used; Bottom right: 3 antennas with NRCS and Doppler used; Bottom left: 2 antennas with Doppler only used. The looking azimuth is drawn as a white bar with the looking point at (0,0). The white patch is the area where the wind speed is lower than 3 m/s and the cost function not computed. The black cross locates the retrieved wind vector for each configuration and the black vector features a 1 m/s a cross-track surface current.

4.3 Discussion and Recommendations

The main goal of this WaPA task was to study the feasibility to retrieve estimates of the surface wind vector and their associated Doppler shift contributions from Wavemill measurements (normalized radar cross section (NRCS) measurements and total Doppler), or in combination with first guess ancillary information (e.g, atmospheric model, scatterometer estimates, tide model, altimeter anomalies, etc.).

The study on the capability of the Wavemill system as a scatterometer led to the conclusion that the usual requirements in term of wind vector accuracy are fulfilled, for the given Doppler shift and NRCS noise figures, when the Doppler shift is uniquely wind-driven.

One expected, but still important, result is that the Doppler shift information provided by the Wavemill SAR-like processing, resolves the 180° ambiguity in the wind direction estimated from a standard bayesian wind inversion, meaning that the use of an a priori wind information (ancillary information usually from a NWP numerical model) is not required. It has been also shown that the large Doppler shift sensitivity to the wind direction, at the quite low Wavemill incidence angles, helps to regularize the wind vector errors as a function of the viewng azimuth. Finally, it appears that the across-track variability of the squint angle does not induce across-track change in the statistical distribution of wind vector errors, which is a good point.

Wind inversion results have also been presented in the case where a third antenna, looking in the across track direction, is added to the current Wavemill concept. This was done for two reasons:

- It shows what would be gained from an ASCAT-like standard processing when the Doppler information is available;
- It anticipates the Wavemill capability to be used as an ASCAT-like scatterometer if the Doppler information is not usable for any reason. Indeed it was assumed in the Monte Carlo simulations that the NRCS and Doppler shift information are uniquely related to the wind vector. This is explicit in the GMFs we have used but not true for real data.

Knowing surface wind and current are both main contributors to Doppler data, a sensitivity study of the wind inversion investigated the impact of a surface current on the effectiveness of the wind retrieval and showed that ignoring the surface current contribution leads to unacceptable errors in the retrieved wind vectors. A rule has been proposed to identify, after the wind processing, which data are likely to be contaminated by surface currents.

For Wavemill as a surface current instrument, it was therefore concluded that the Doppler shift data cannot be used in a wind inversion scheme “à la Mouche [2012]” to estimate the wind vector and its contribution to surface velocity. Using solely radar cross sections and ancillary wind information to help directional ambiguity removal could be a way to estimate a wind vector independently of the Doppler measurements, but this way is very sensitive to errors in the ancillary information. Indeed, four wind vectors aliases are produced by a two-antennas scheme and any shift in the ancillary wind spatial patterns, likely to occur frequently, will almost systematically result in the choice of a wrong alias. As shown, the addition of a third antenna could offer a solution.

In conclusion:

- A third antenna looking cross-track would be a reliable solution to mimic a standard ASCAT-like system using only radar cross-sections for the wind inversion, to obtain a reliable first guess for an iterative wind/current inversion scheme
- It is recommended that Wavemill operates at higher incidence angles than those used for this study (18° to 25°). Getting closer to 30° would bring very significant benefit
- Dual-pol cross section and Doppler measurements needed to better identify the surface current and wind contributions

5 POTENTIAL SECONDARY WAVEMILL PRODUCTS

5.1 Introduction

Introduction

The main scientific objective of the Wavemill instrument is to provide surface current measurements according to the requirements specified in Donlon [2013]. However the instrument as configured has important potential to provide secondary products of significant scientific value. Thus a task of WaPA was to provide a review and assessment of potential secondary products under the themes of Inland Water (Rivers and Lakes), Ocean Atmosphere Interactions and Cryosphere. The following section summarises the findings from thee tasks.

The baseline assumption for all is that Wavemill will operate in Ku-Band (HH polarisation) with the “Javelin” configuration, measuring over a dual sided swath of 100km with a 45 squint angle and an incident angle of ~20°. However, given that the investigations into performance for primary products, and into the scatterometry aspects suggested that improved performance could be offered with multiple polarisation and larger incidence angles, the partners were asked to consider the potential benefits and problems to secondary products of these possible variations in the instrument design.

5.2 Inland Waters (Rivers and Lakes)

Starlab reviewed the potential of the Wavemill instrument to provide useful measurements of inland waters, specifically rivers and lakes and concluded that, as Wavemill can provide ATI but not XTI operation and so cannot offer direct measurements of water level. Thus to provide useful measurements of river discharge and lake / reservoir storage, Wavemill measurements of velocity and water body (horizontal) extent would have to be combined with data from other sources.

- Discharge might be measured from surface velocity coupled with external information on the channel, for rivers > 100 m wide. There is a possible synergy with the potential stage/slope capabilities of SWOT
- Storage estimates will only be feasible with external knowledge of depth/stage in a pure ATI configuration.
- In order to measure discharge or storage in a single satellite pass, XTI or altimetry payload is required
    - o In this case yaw steering over land would be necessary to monitor calm waters
- River current velocity estimates can complement stream gauges or provide coverage for non-gauged streams
- To simultaneously comply with discharge accuracy and resolution requirements, a strip-map operation mode over land should be considered.

5.3 Ocean Atmosphere Interactions

IFREMER reviewed the potential for deriving so-called secondary products from a Wavemill instrument in the theme of air-sea interactions and swell waves, leading to the development of more advanced algorithms to advance knowledge regarding the coupled wind-wave systems, in the challenge to provide quantitative mapping of the upper ocean dynamics.

It was concluded that Wavemill offers significant potential to quantitatively describe high-resolution ocean surface properties in response to atmospheric and ocean forcing. This would help to advance our knowledge of interface exchanges, especially momentum, heat and gases, as well as to better assess dissipation pathways between the atmosphere and the ocean.

Wavemill could potentially offer unique combined information, obtained at different line-of-sight direction (Azimuthal Diversity-AD), from both Normalized Radar Cross Section (incidence, polarization) and Doppler Radar signals (incidence, polarization).

Dual Polarisation is particularly important in helping to separate the contributions of small scale Bragg scattering and from the contribution of steep scatterers and breaking waves seen in the non-polarised backscatter.

Swell systems could be characterised through the surface roughness signature of wave-swell interactions.

The development of new algorithms would be required to support these applications

5.4 Cryosphere Products

Polar Imaging reviewed the potential for Wavemill to provide useful secondary products in cryosphere applications.

The cryosphere is an important application for any earth observing technology because it is considered likely to play a critical role in amplification of CO_2-induced global warming and can have a major impact on global sea level. In addition, operational interest in the Arctic is adding to scientific interest as summer sea ice has retreated opening up routes for navigation and resource exploitation.

Wavemill offers several potential benefits to the broader earth-observing network as follows:

- Novel estimation of high frequency sea ice motion, currently not sampled by any space-borne sensors;
- Sampling of the thin surface layer of the cryosphere facilitated by the high operating frequency (Ku band), in particular snow cover, which is inadequately sampled by existing space-borne sensors.
- Observations of poorly sampled dynamic processes, particularly in regard to the marginal sea-ice zone and terrestrial snow cover;
- Complementary observation capabilities to many existing and planned satellite missions, including altimeters and SARs,that would enhance the interpretation of observations from those sensors.
- The ability to observe currents and other oceanographic parameters in polar waters, in polynyas and larger leads, providing insight into ocean-ice interactions within pack ice.
- Speculatively, some interesting possibilities regarding the synergistic use of multiple parameters from Wavemill that could result in innovative products, for example in relation to retrieval of SWE using local slope.

Some key issues for cryosphere applications include the following:

- The temporal sampling is critical for terrestrial snow and sea ice applications and needs to be sufficient to capture dynamic processes, with ~daily revisit requirements for many parameters. In some cases it may be possible to achieve higher revisits by combining missions.
- Work with Core-H2O was important in establishing the potential of Ku band to many cryospheric applications, but focused more on terrestrial than marine applications. This work forms a good staging post for continuation of assessment of how Wavemill may be applied to cryospheric applications, once the design becomes fixed (and assuming that cryospheric applications are not driving the design of the mission).
- For many cryosphere applications at Ku band, there is insufficient data to suggest whether 20° or 30° incidence angle is strongly preferred. Exceptions include terrestrial snow cover, which appears to have greater sensitivity at 30° under freezing conditions, and sea ice - water discrimination, which is less ambiguous at 20°, but which can be compensated to some degree by the availability of dual polarisation at 30° incidence angle.
- Dual polarisation is useful for a number of cryosphere applications, including sea ice water discrimination at higher incidence angles. It is likely to be helpful for most cryosphere applications at 30°, although there is little clear evidence of the degree of utility at Ku band in general because of a lack of data (terrestrial snow has more data at Ku band, but also provides

little evidence for additional value from dual polarisation). In any event, dual polarisation is likely to have limited utility at 20° incidence angle.

- Wide swath imaging (>>200km) can enhance the temporal revisit, which may be very important for sea ice and terrestrial snow applications, but in a trade-off with spatial resolution, there is not an obvious advantage to many cryospheric applications. For applications that do not depend on rapid (~daily) revisit (e.g. over land ice), it is more important to retain relatively high spatial resolution. For marine and terrestrial snow applications, having the flexibility of a wide swath mode would be useful in order to adjust to temporal-spatial sampling to particular cryospheric applications and areas, but in general the high spatial resolution is important to retain. Analysis of the Wavemill orbit to provide information on revisits would be very useful in order to confirm the merits or otherwise of a wide swath imaging mode.

6 SYNERGISTIC INSTRUMENT DATA

6.1 Introduction

The purpose of this task (carried out by NOC and ADS) was to review the need for, and added scientific value of, additional remote sensing data to complement the Wavemill primary products and then to assess the technical implications of any additional instruments on the Wavemill platform.

Ancillary data fall under three categories:

- Ancillary data needed for inversion.
- Data needed for validation.
- Added scientific value of combining Wavemill data with data from other sensors.

For this part of the study the following assumptions were made for the Wavemill concept: Ku-band, SAR ATI, dual beam with 45° squint at the surface (achieved physically or electronically), one side swath ≈200km, VV and HH polarisation (at the ocean surface), mid-swath incidence angle 30°, altitude 500 to 600km, sun-synchronous ascending node at 6am or 6pm.

The Wavemill primary products are assumed to be:

- Ocean Surface Current at high resolution (1–5km);
- Ocean Wind Vector at high resolution (1–5km);
- Ocean wave swell spectrum.

It is worth keeping in mind that the quality of the derived current is highly related to the capacity to estimate accurately the wind and its associated wind-wave artefact velocity. A good knowledge of the Doppler frequency (or the interferogram phase) as well as $\sigma 0$ is essential.

6.2 Ancillary satellite data requirements for inversion

Anciillary data requirements for inversion

The only geophysical effect expected to have critical impact on the accuracy of the inversion is precipitation. Unfortunately, there are currently no precipitation products with the necessary accuracy at very high spatial resolution (1-5 km) or the sufficiently fast repeat visit to sample conditions during Wavemill satellite over flights. Similarly, the accuracy and resolution of Numerical Weather Prediction models is insufficient to assist the inversion.

As precipitation events have a strong diurnal cycle in some regions, Wavemill could optimise its sampling strategy (i.e orbit) to minimise the chance of data acquisition during rain events (not subject of this study). In addition, there will be a need to develop dedicated precipitation flags for Wavemill, to identify data where the retrieved current and wind speed will be biased.

Satellite data for validation

Only satellite SAR sensors provide measurements sufficiently analogous to Wavemill to permit direct validation of the Wavemill high-resolution wind and current products. Given the fast temporal decorrelation of physical phenomena at small spatial scales, particularly those related to wind, the time separation between Wavemill and the validation data would need to be of the order of a few hours at most. This could be achieved through formation flying with a contemporaneous SAR mission (e.g. Sentinel-1). To validate Wavemill against any other kind of data (e.g. altimetry, scatterometer), degradation of the spatial resolution of Wavemill products would be necessary. In this case, standard cross-over and validation methods could be used.

Added Scientific Value of Synergy with Other Sensors

The scientific literature indicates that significant added scientific value could be gained from exploiting Wavemill in synergy with high resolution SSH, SST and ocean colour data. Since the mass, power and downlink data budgets of Wavemill are all very challenging, there is no prospect of such sensors being accommodated onboard the same platform as the Wavemill instrument.

Sentinel-3 will carry all these sensors, so there would be great scientific benefit in combining Wavemill with Sentinel-3. Special effort would be required to ensure that Wavemill and Sentinel-3 data are acquired over the same area within a maximum of 1-2 days, which is the typical decorrelation of the ocean submesoscale features of interest to Wavemill. Matching orbits will be particularly difficult as the Sentinel-3 orbit (altitude 815km, desc. node 10am) is very different from the Wavemill orbit currently baselined (500-600km, desc. node 6am or 6pm). Nevertheless, the extensive coverage of Sentinel-3 afforded by the multiple satellites in the constellation and the wide swaths of the SST and ocean colour sensors will ensure global coverage in 1-2 days, thus ensuring reasonably frequent cross-overs with Wavemill.

6.3 Wavemill Platform Implications

The purpose of this task review was to focus on the direct and indirect implications on the mission requirements [Donlon, 2013] should any secondary payload be implemented, and to highlight similar impacts related to synergistic operations with another mission.

In terms of the implications of certain Wavemill Mission objectives on the instrument and platform configuration, the following key points are noted:

With a baseline of using the VEGA launcher, the Wavemill mission is mass, power, and volume limited. The VEGA launcher has a current performance of approximately ~1450kg to 525km, requires a significant power generation (~4kW), and has a significantly large antenna length of 10-20m in deployed length. Ultimately, these factors make the inclusion of a secondary payload, however useful, less likely as it puts extra pressure on the primary instrument to meet its performance requirements.

Data volume is another limitation, albeit external to the spacecraft itself. Data rates from the instrument are extremely high and any extra data bandwidth required for a secondary payload puts additional pressure on the system as a whole.

Synergistic observations could and should be exploited. However, these can be broken down into two quite different categories: i.e. those that require a significant change to the mission design/operation, and those that naturally occur with minimal impact. For example, designing different orbital periods within the mission lifetime to observe specific areas contemporaneously with other missions is possible, but comes with higher operational cost, and mission-design related complexity. However, optimising the nominal operational orbit of any future Wavemill mission to coincide with the observations of other missions (e.g. cross-over optimisation) can be done early in the mission design with relatively minimal impact to the mission complexity. The relative importance of the mission to meet what particular level of synergistic measurement should be established.

In terms of potential synergies with other missions, we note that the earliest potential launch data of Wavemill will be 2025, with a lifetime of 5 years, so there will be overlap with all Sentinel missions. In practice any ocean monitoring or altimetry mission can offer synergistic possibilities with Wavemill, in particular:

- Sentinel-2 will provide hi-res imaging of inland water and coastal areas, and could be compatible
- Sentinel-3 will provide ocean monitoring services
- Sentinel-6 will provide high precision altimetry
- Jason altimeters also compatible with complementary acquisitions
- SWOT will provide wide swath ocean high information
- Sentinel-1 is being used for current information from Doppler tracking
- CFOSAT will measure wind and waves at the ocean surface on a global scale

7 CONCLUSIONS

7.1 Summary of Results

The WaPA project carried out an investigation into the validity and utility of products from a Wavemill ocean surface current mission, including a consideration of the impact of different potential instrument configurations.

It was demonstrated that in the absence of a current it would be possible to retrieve the unambiguous wind vector without need for ancillary information, but that when there is a surface current, dual polarisation or a third antenna would be needed to separate wind and current contributions.

The Wavemill End-To-End Simulator was shown to accurately represent different test situations and allowed the calculation of a preliminary geophysical error budget. Analysis of the airborne Proof of Concept Campaign data confirmed that the data characteristics could be explained by relatively simple geophysical models, so indicating a strategy for inverting the measurements into the required geophysical products.

An investigation of instrument and satellite performance considered different potential configurations, including the possibility of dual polarisation and wide swath, and the requirements this placed on available power and data downlink capability. An approach which involved switching between different modes in different locations was suggested.

It was also shown that Wavemill measurements could be used to generate useful, potentially unique, secondary products in the marginal ice zone (ice motion and snow water equivalent) and in the realm of ocean atmosphere interactions.

7.2 Recommendations for further work

As identified above, the Wavemill concept has developed steadily since its first inception, and this evolution has continued in the period since the writing of the Statement of Work for the Wavemill Product Assessment and during the project itself. These evolutions have been strongly driven by the development of a better scientific understanding of the details and interplay between the various physical processes and motions underlying the Wavemill measurement of surface currents. In particular, it was established during WaPA that the orbital velocity of waves (forced by the wind) has a strong impact on the derived surface velocity, leading to errors of up to a few m/s. Re-analyses of the Wavemill airborne proof-of-concept data provided quantitative estimates of the magnitude of the effects and also showed that this wind-wave surface artefact velocity is reduced slightly at higher incidence angles. Moreover, WaPA activities on scatterometry highlighted that acquisitions at higher incidence angles (closer to 30°) lead to better estimates of the wind vector and important potential benefits of using additional information from HH polarisation. These analyses led to the conclusion that wind and current motions are intimately linked, and that further research is required to define the exact strategy for geophysical inversion of both wind and current, and to provide a quantified assessment of the optimal choice of incidence angles and the true benefits of polarisation diversity.

A consequence is that there are important aspects of the Wavemill Product Assessment study that require further work, around the development and validation of a strategy to invert the Wavemill radar measurements to mission products (surface current vector and wind vector), the need for multiple polarisation and on how the presence of a swell wave field impacts on the retrieval of surface currents.

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LIST OF WAPA PUBLICATIONS

Below we list in chronological order all the scientific papers and conference presentations made by members of the WaPA team, in which they have presented results from the WaPA project.

1. Gommenginger C., J. Marquez, G Burbidge, Y. Qulfen, D. Cotton and C. Buck, Wavemill Product Assessment – Defining potential products from a novel spaceborne interferometric SAR, 2013, International Meeting to Explore the Scientific Challenges for Determining Ocean Surface Currents from Space, ESA/ESTEC, Noordwijk, The Netherlands, 6-8 May 2013
2. Marquez, J., C. Gommenginger, G Burbidge, Y. Quilfen, D. Cotton, and C. Buck, Wavemill Product Assessment - Defining Potential Products from a Novel Spaceborne Interferometric SAR, Poster Presentation, 2013, EGU General Assembly, Vienna, Austria, 07-12 April 2013.
3. Cotton, D., J. Marquez, C. Gommenginger, G Burbidge, Y. Quilfen, C. Buck, Wavemill Product Assessment - Defining Potential Products from a Novel Spaceborne Interferometric SAR, 2013, ESA Living Planet Symposium, 9-13 September 2013.
4. Gommenginger C., J. Marquez, G Burbidge, Y. Qulfen, D. Cotton and C. Buck,, Wavemill: A new concept for high-resolution mapping of total ocean surface current vectors, 2013, ESA Living Planet Symposium, 9-13 September 2013.
5. Gommenginger C., J. Marquez, G Burbidge, Y. Qulfen, D. Cotton and C. Buck,, Wavemill: A new concept for high-resolution mapping of total ocean surface current vectors, 2014, EUSAR – 10th European Conference on Synthetic Aperture Radar, 2014, 3Berlin, Germany, 3-5 June 2014
6. Martin, A, C. Gommenginger, B. Chapron, J. Marquez, S. Doody, D. Cotton and C. Buck, Dual Beam Along-Track Interferometic Sar To Map Total Ocean Surface Current Vectors With The Airborne Wavemill Proof-Of-Concept Instrument: Impact Of Wind-Waves, 2015, IGARSS Milan, Italy 26-31 July 2015.

ANNEX 1 - ABSTRACT

Ocean Surface Current is one of the most important ocean properties for oceanographers and operators in the maritime domain. Improved monitoring of ocean currents is systematically the highest requirement that emerges from any science or end user requirement surveys.

Wavemill is a novel hybrid interferometric SAR system first proposed by ESA/ESTEC [Buck, 2005]. It offers the possibility of generating two-dimensional wide swath, high resolution, high precision maps of surface current vectors and ocean topography [Buck et al., 2009]. Based on a single spacecraft, it avoids the difficulties of synchronisation and baseline estimation associated with other interferometric SAR systems based on two or more satellites (e.g. the “cartwheel” or “helix” concept).

The Wavemill concept has developed steadily since its first inception in 2005. A number of Wavemill studies in recent years have gradually put together facts and figures to support the case for Wavemill as a possible space-borne mission.

The Wavemill Product Assessment study (WaPA) aimed to define the scientific capabilities and limitations of a space-borne Wavemill instrument in preparation for a possible submission of the Wavemill concept as a candidate Earth Explorer Core mission. The WaPA project team bought together expert scientists and engineers in the field of SAR imaging of ocean currents, and included the National Oceanography Centre (UK), Starlab (Spain), IFREMER (France and ADS (UK). Overall project management was provided by SatOC. The approach taken included:

- A review of SAR imaging of ocean currents in along-track interferometric mode to learn from previous experiments and modelling what key phenomena need to be accounted for to determine the true performance of a spaceborne Wavemill system
- Validation of proposed Wavemill primary products based on Wavemill airborne proof-of-concept data and numerical simulations to determine the capabilities and limitations of a spaceborne Wavemill instrument for ocean current vector and sea surface height mapping.
- An analysis of the potential for ocean wind vector retrieval from a space-borne Wavemill instrument.
- An investigation of possible secondary products from Wavemill relating to rivers, ocean/atmosphere interactions, ocean swell and cryospheric applications.
- An assessment of the synergy between Wavemill and ocean surface current products derived from other remote sensing techniques, accounting for the nature and variability of the measured properties, to identify any additional requirements on a future Wavemill mission

It was demonstrated that in the absence of a current it would be possible to retrieve the unambiguous wind vector without need for ancillary information, but that when there is a surface current, dual polarisation or a third antenna would be needed to separate wind and current contributions.

The Wavemill End-To-End Simulator was shown to accurately represent different test situations and allowed the calculation of a preliminary geophysical error budget. Analysis of the airborne Proof of Concept Campaign data confirmed that the data characteristics could be explained by relatively simple geophysical models, so indicating a strategy for inverting the measurements into the required geophysical products.

An investigation of instrument and satellite performance considered different potential configurations, including the possibility of dual polarisation and wide swath, and the requirements this placed on available power and data downlink capability. An approach which involved switching between different modes in different locations was suggested.

It was also shown that Wavemill measurements could be used to generate useful, potentially unique, secondary products in the marginal ice zone (ice motion and snow water equivalent) and in the realm of ocean atmosphere interactions.

The Wavemill concept has developed steadily since its first inception, and this evolution has continued throughout the project. These evolutions have been strongly driven by the development of a better

scientific understanding of the details and interplay between the various physical processes and motions underlying the Wavemill measurement of surface currents. In particular, it was established during WaPA that the orbital velocity of waves (forced by the wind) has a strong impact on the derived surface velocity, leading to errors of up to a few m/s.

A consequence is that there are important aspects of the Wavemill Product Assessment study that require further work, around the development and validation of a strategy to invert the Wavemill radar measurements to mission products (surface current vector and wind vector), the need for multiple polarisation and on how the presence of a swell wave field impacts on the retrieval of surface currents. Thus a proposal for further work to investigate these aspects has been submitted to ESA.