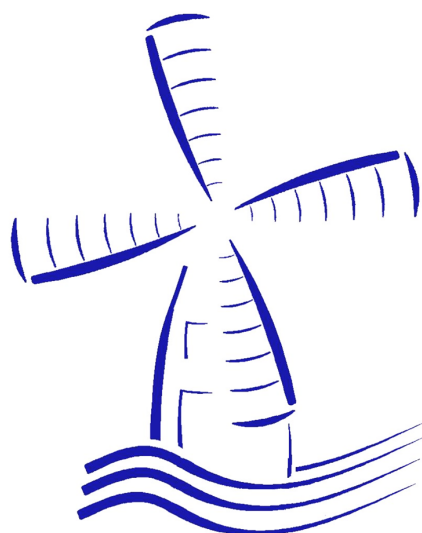




ESA General Studies Programme -

**Coastal and Open Ocean Surface Currents Mission Study:
Wavemill Product Assessment: WaPA
ESA contract No 4000107347/NL/AF**

Executive Summary

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EXECUTIVE SUMMARY

Introduction and 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.

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 brought 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

Review of SAR ATI Measurements of Surface Currents

NOC, carried out a review of SAR ATI measurements of surface current measurements, with the aim of identifying and summarising key issues relevant to the Wavemill concept.

The main implications for the development of the Wavemill instrument and mission were found to be:

- End-to-end performance assessments of Wavemill are required to establish requirements on attitude & navigation information to achieve the desired current retrieval accuracy.
- A phase validation strategy should be devised to assess residual phase errors after removal of platform-related errors..
- Full dual-polarisation capability is highly desirable and would help mitigate the SNR reduction associated with polarisation mixing in squinted systems. Partial dual-pol would offer a useful compromise, but only if high-enough SNR can be achieved.

The main implications for the definition of the Wavemill products are:

- Wavemill currents will differ considerably from currents measured by traditional means, making validation difficult. Some separation of the “total” current measured by Wavemill into individual

current components is desirable and may be achievable in some cases. Currents components provided should be unambiguously identified and clearly defined.

- Separating wind, wave and currents contributions remains challenging, and could seriously spoil the perceived accuracy and usefulness of Wavemill current data. Better use could be made of recent advances in microwave scattering models to define a Wavemill instrument and mission for which these inversion problems are more tractable.

It should also be noted that since this review was completed new insights on the SAR Doppler Centroid approach have been achieved.

Validity of Wavemill Primary Products

The validity of Wavemill primary products was assessed through four tasks:

- The use of the Wavemill end-to-end simulator, which has been developed by Starlab under separate funding,
- Re-analysis of data from the Wavemill Airborne Proof of Concept campaign, held in Liverpool Bay (UK) in October 2011.
- Considering ranges of instrument and satellite performance from an instrument and platform perspective
- Investigating potential causes of error due to atmospheric effects.

Wavemill End-to-End Simulator

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.

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, investigating:

- 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 (e.g. Figure 1). It was concluded therefore 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 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°).

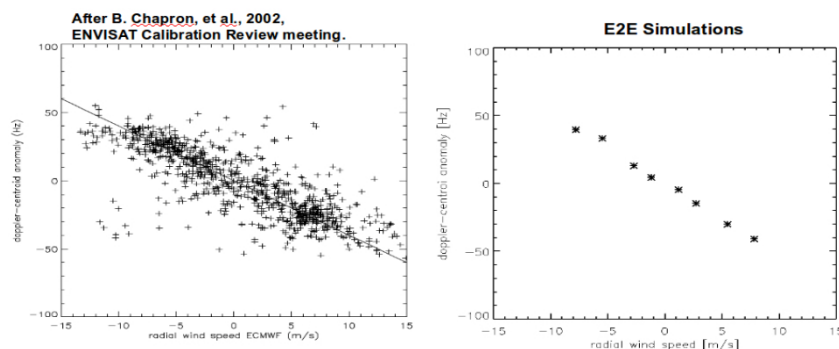


Figure 1: Doppler Bias versus wind speed (directly upwind or downwind: 90° or 270°). (Left) As measured by Envisat ASAR, (right) as calculated in the Wavemill end to end simulator.

Re-Analysis of Wavemill Proof of Concept Campaign Data

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 (Figure 2). This study was supported under a previous ESA project.

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 (Figure 3).

This analysis found that:

- The characteristics of wind-wave artefact velocity was in good agreement with a model derived from ENVISAT empirical data 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 was 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, VV and HH polarisations would be needed, as well as a calibrated measurement of σ_0 .

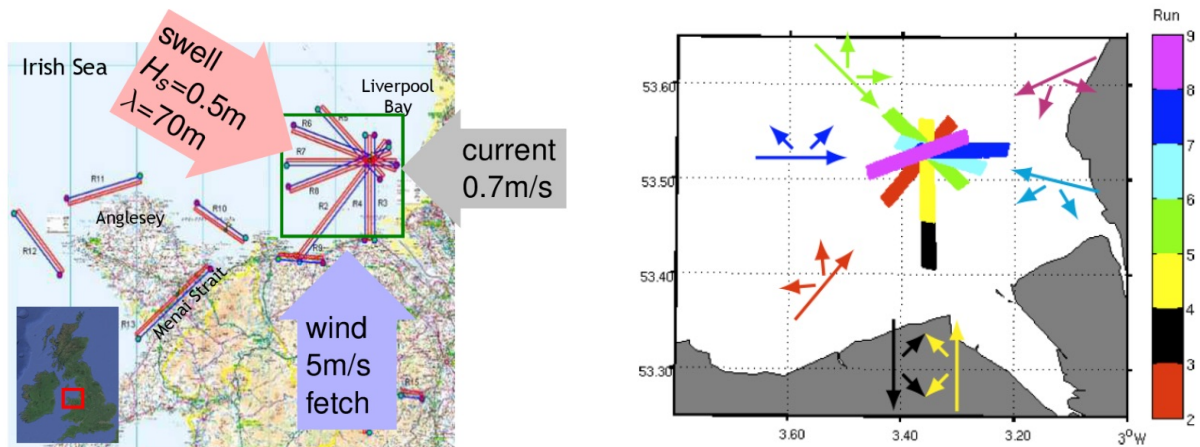


Figure 2: Wavemill PoC location, conditions & data. (Left) Flight pattern & conditions on the 26th of October, 2011. (Right) Airborne data re-analysed for WaPA. Individual runs are represented by a different colour. Flight direction and line of sight direction of the fore and aft antennae are shown the large & small arrows respectively.

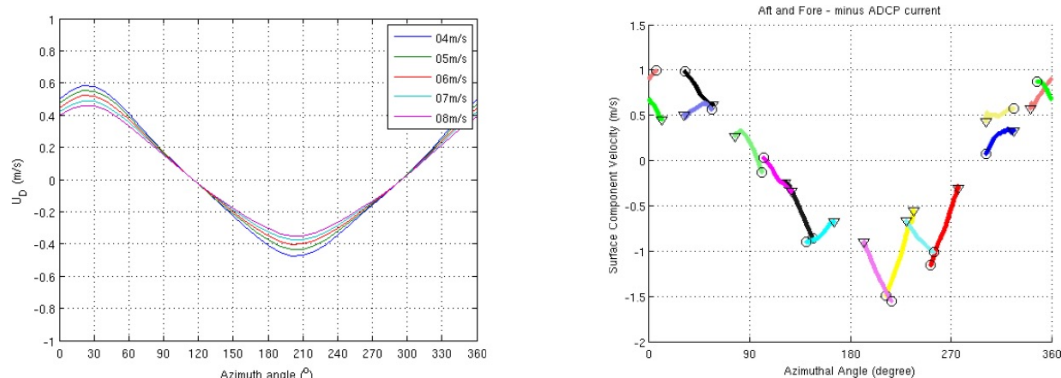


Figure 3: (Left) Modelled wave artefact surface velocity [Chapron et al., 2005] as a function of azimuth angle for an incidence angle of 27° . (Right) Measured median residual current (computed as measured surface velocity minus ADCP current) for each run against azimuth angle.

Ranges of Instrument and Satellite Performance

The objective of this task, carried out by ADS, was to establish the qualitative relationship between the required imaging / image quality parameters and the Wavemill instrument physical and operating parameters.

The analysis was based on the current (updated) baseline assumption about the instrument configuration of 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 with passive beams.

In terms of the key performance requirements it was concluded that this baseline 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). Finer product resolution should be available at higher wind speeds and higher currents.

Impact of Tropospheric Disturbances

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

It was concluded that 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 the 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.

Impact 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.

Therefore 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.

It was established 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.

For Wavemill as a surface current instrument, it was 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 (Figure 4). 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 are needed to better identify the surface current and wind contributions.

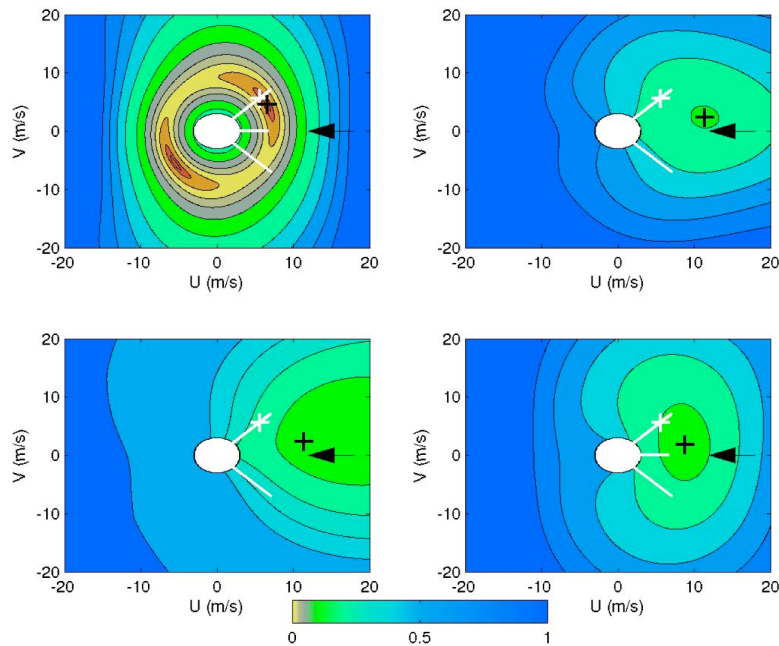


Figure 4: Scatterometer Studies - Cost function for a wind vector of 8 m/s upwind for the fore antenna (white cross) and (25,45) degrees for the incidence and squint angles. Top left: 3 antennas with NRCS only used; Top right: 2 antennas with NRCS and Doppler used; Bottom right: 3 antennas with NRCS 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.

Potential Secondary Wavemill Products

The main scientific objective of the Wavemill instrument is to provide surface current measurements according to the requirements specified in Donlon (2013). However there is also 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.

Given that the foregoing 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

Inland Waters (Rivers and Lakes)

Starlab reviewed the potential of the Wavemill instrument to provide useful measurements of inland waters, specifically rivers and lakes.

It was concluded that in the “Javelin” configuration, Wavemill can provide ATI but not XTI operation and so cannot provide 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. It was recommended that a strip-map operation mode over land should be considered to provide improved resolution.

Ocean Atmospheric Interactions Products

IFREMER carried out an assessment of potential application of Wavemill data in studies of ocean atmosphere interactions, and concluded that the Wavemill instrument 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. Particular points were:

- 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.

Cryosphere Products

Polar Imaging carried out an assessment of potential secondary products for cryosphere applications. Wavemill offers important new and /or supporting EO observing capabilities in a number of applications, as follows:

- Novel estimation of high frequency sea ice motion, not sampled by other space-borne sensors;
- Sampling of the thin surface layer of the cryosphere), 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;
- 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 Snow Water Equivalent using local slope.

It terms of preferred options instrument configuration and mission/orbit planning is was noted that dual polarisation would be useful for a number of applications, and that frequent (~daily) revisits would be needed to capture dynamic processes in the marginal ice zone

Synergistic Instrument Data

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 pm). 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.

Conclusions

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.

In addition to the primary mission to measure surface currents, 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.

Because understanding of scientific and technical issues around the Wavemill concept has continued to evolve during the progress of WaPA, there are important aspects of the study that require further investigation. Thus additional work is recommended to develop and validate a strategy to invert the Wavemill radar measurements to mission products (surface current vector and wind vector), to consolidate the requirement for multiple polarisation and to better understand how the presence of a swell wave field impacts on the retrieval of surface currents.