THE BENEFITS OF COMBINING COUPLED WAVE-CURRENT MODELS WITH SAR OBSERVATIONS FOR THE INTERPRETATION OF OCEAN-SURFACE CURRENTS

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ABSTRACT

This paper considers the use of coupled wave-current models in combination with synthetic-aperture radar (SAR) and along-track interferometric SAR (ATI) observations for the interpretation of the spatial structure of surface currents. The present status of the development of these models is summarised. Examples over shelf seas, shallow-water bathymetry and estuaries are discussed, for both conventional SAR imagery and along-track interferometry (ATI). The potential practical benefits of combined SAR and model products are outlined.

1. INTRODUCTION

Mesoscale features, such as eddies and fronts, play a key role in defining the ocean circulation and transport on regional and global scales. Models of the general ocean circulation at fine resolution, *e.g.* the Ocean Circulation and Climate Advanced Model OCCAM [1], are now beginning to reproduce more realistic mesoscale variability and to find more widespread use. There are also increasing demands to monitor and predict changes in the current field in coastal waters. Historically, many of the agencies responsible for water quality have used two-dimensional, depth-averaged models of the currents for prediction purposes. Such models are inadequate for many applications, because they neglect important hydrodynamic processes. More recent models represent the three-dimensional structure of currents and they include the coupling between the currents and the surface waves. However, these still require suitable input data and boundary conditions in order to produce reliable outputs.

Synthetic-aperture radar (SAR) observations are one source of relevant information which can be combined with these models. The SAR image modulations are related to changes in surface roughness associated, for example, with surfactant slicks or spatially varying surface currents via surface wave-current interactions. The novel technique of Along-Track Interferometry (ATI) measures the phase differences between two SAR images, slightly displaced along track, in order to obtain information on surface currents via estimates of the line-of sight velocities of the scatterers responsible for the radar signals.

Here we review results from both SAR images and ATI over a variety of sites, including estuaries, other coastal waters and shelf seas. The analyses are based on forward modelling of the radar signatures using surface wave spectra from a wave model, coupled to a model of the current field, together with a short-wave model. The modelled signatures are compared with the radar data in order to assess the ability to reproduce the observed oceanographic signatures.

2. SAR IMAGING MECHANISMS

The modelling of the SAR signatures assumes that the imaging process is described by the following steps:

- 1. Many oceanographic processes generate spatially varying currents with signatures at the surface. For example, the tidal flow over the sea bed introduces variations at the surface caused by the underlying bathymetry. Tidal intrusion fronts occur in estuaries when the denser sea water, intruding on an incoming tide, plunges beneath the ambient fresh water to form a characteristic V shape.
- 2. The surface currents interact with ambient short surface waves, altering their amplitudes and velocities.
- 3. These waves in turn cause spatial variations in the radar backscatter and the phase of the along-track interferogram.

The model for SAR image signatures was developed by [2] and it has now become widely accepted, although the details of the imaging mechanism continue to be the subject of research [3-5]. In particular, the directional properties of both short waves and their interaction with surface currents are poorly understood.

A model for ATI signatures was developed by [6]. Although the ATI modulations often appear to be more directly related than the SAR intensity modulations to the surface current, there are corresponding uncertainties in the imaging mechanisms. It should also be noted that ATI measures the line-of-sight velocity, and hence all oceanographic processes which make a significant contribution to this velocity need to be considered.

Here, we consider whether SAR and ATI observations can provide information on the spatial structure which can complement that obtained from models of the surface currents. In this context, the details of the imaging mechanism are not particularly important, except where distortions and loss of spatial resolution can occur. If these effects were significant, they would lead to a change in the position of features, or an inability to detect features of interest.

3. COUPLED WAVE-CURRENT MODELS

Apart from the example of the Tay Estuary case, we use a series of ocean current models and a coupled wave-current model in order to estimate the hydrodynamic conditions over the selected test sites. The current models are:

- The Proudman Oceanographic Laboratory's Coastal Ocean Modelling System POLCOMS [7] at 200 m resolution,
- OCCAM at a spatial resolution of 0.25° (latitude and longitude) [1], and
- The Princeton Ocean Model (POM) at 4-km resolution, used in the Hawaii Ocean-Mixing Experiment (HOME).¹

These models are forced by the wind speed and direction, the atmospheric pressure, and astronomical tides. The meteorological data come from analyses at the European Centre for Medium-range Weather Forecasting (ECMWF). The wind inputs are typically at a spatial resolution of 1° (latitude and longitude) and 6 hourly in time.

One key issue is the procedure to set the boundary conditions on the currents, the waves and the wind field for nonglobal models. This is usually achieved by nesting high-resolution local-area models within low-resolution large-scale models. For example, the South Wales test site is nested with a model of the Irish Sea at 1.85-km resolution. The accuracy of the available information on wind fields is a key factor for this procedure.

The wave models used here are WAM (**WA**ve **M**odel) [8] and SWAN (**S**imulating **WA**ves **N**earshore) [9]. These are third-generation models, which means that they are derived from the fundamental physics of wave interactions rather than from empirical formulations.

Our modelled currents include the effects of frictional forces in shallow water. From simulations [10], we find that these become dominant for water depths less than about 1 m, leading to a tendency for water to flow around an object rather than over it. The simulated pattern of flow over a Gaussian shoal shows little change as the water depth is reduced. Thus the assumption of local one-dimensional flow used by many authors appears to be a reasonable approximation in many cases, although more complicated flow is expected around the edges of bathymetric features.

We use two models for the currents in the Tay Estuary, namely a Tidal Flow Development (TFD) model [11] and a Tay Estuary Cross-Sectional Model [12]. Neither of these models includes any coupling to the wave field. An empirically established relation is used to derive the surface velocity from the depth-averaged velocity produced in the TFD model.

4. RESULTS FROM TEST SITES

4.1 Shallow-Water Bathymetry off South Wales

Our results for this data-set are discussed in [10]. Figure 1 shows some of the SAR images; these are spaceborne observations from ERS-2 at C band at a spatial resolution of 25 m. There is good correspondence with the bathymetric charts, and the dark and bright modulations reverse with the sense of the tide, consistent with the model of [2]. Figure 2 shows the current fields calculated from POLCOMS with coupling to the wave field included. The changes in the magnitude and direction of the currents are correlated with the bathymetric features shown in the charts in Figure 1. Figure 2 also shows the predicted SAR image modulations.

¹ See <u>http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/</u> and <u>http://chowder.ucsd.edu/home</u>



Figure 1. SAR images at opposite phases of the tidal cycle for Helwick and Nash Banks (left and right, respectively) with the associated bathymetric charts. The SAR images are © ESA 1995 and 1999.



12 Nov 1999 (ebb tide), scale (blue - red) 0 - 1.5 m/s



22 June 1995 (flood tide), scale (blue - red) 0 - 1.0 m/s



Helwick 12 Nov 1999 (-0.0005 to 0.0005)



Nash 22 June 1995 (-0.001 to 0.001)

Figure 2. Top: Magnitude and direction of the current from POLCOMS with one-way coupling (the effect of current on waves but not vice versa). Bottom: SAR image fractional modulations about the mean backscatter (dimensionless) calculated from Bragg scattering with the N-S component of the current. The numbers in brackets give the range of the grey scale. Left: Helwick Bank. Right: Nash Bank.

In [10] we showed that the imaging mechanism due to wave motions had an important influence on the visibility of these features. This mechanism is known as 'velocity bunching' because it displaces the ocean surface in opposite directions depending on whether a particular part of an ocean wave is moving towards or away from the radar. It is expected to be important at any site where the crests of the bathymetric features lie in the radar look direction.

We identify the following radar-imaging and oceanographic issues arising from the results for this site:

Radar issues The effects of wave motions can be important, depending on the viewing geometry. The model of [2] predicts that lower radar frequencies in general produce clearer image modulations. The spatial resolution also determines the accuracy with which SAR is able to detect changes in bathymetric features.

Oceanographic issues POLCOMS produces realistic two-dimensional surface currents in the presence of bathymetry. There are also uncertain aspects in the coupling to the wave field. One of the fundamental problems in comparing model results with actual SAR data is the accuracy of the input wind field and bathymetry used to drive the model.

4.2 ATI Observations off Hawaii and SW Japan

Our results for these data-sets are discussed in [13]. The data come from the NASA/JPL airborne SAR (AIRSAR) at L and C bands, with a spatial resolution of about 10 m. Figure 3 (left pair of images) shows the observed and simulated ATI phases for the Hawaii site. The ocean currents here are dominated by tides and by local wind-driven circulation due to channelling of the wind between two islands with large topographical features ('orographic steering'). Since OCCAM does not include the tidal and orographic effects, the tidal currents are treated by the University of Hawaii's HOME model (see Footnote 1 above). The HOME model has tidal forcing but no wind-driven flow. Thus our forward modelling reproduces a tidal-current feature observed in the ATI data near the NW tip of Big Island; it is predominantly red in Figure 3. However, we do not reproduce an area of current shear running diagonally from mid left to top right in the ATI data; it is predominantly green in Figure 3 but is partially corrupted by residual platform motion. This feature is thought to arise from changes in the wind-driven currents in the lee of the island, which are not represented in the input wind fields.

Figure 3 (right pair of images) show the observed and simulated ATI phases for the Kuroshio current off SW Japan. The predicted ATI signatures at L band are broadly similar to those observed, although there are some detailed discrepancies. These may be caused by the limited spatial resolution of the current and wind fields used in the modelling. Overall, the model current field appears to be missing some structure on scales less than about 50 km. Thus our modelling does not capture the observed rise in phase from 20 - 40 km followed by the fall in phase from 40 - 70 km (Figure 4). The accuracy of our results may also be limited by frequency dependences in the ATI imaging mechanisms, which may arise through the influence of the directional distribution of short waves on the hydrodynamic interactions with longer waves.



Figure 3. Left to right: Simulated and observed ATI phase for Hawaii site at L band. The observed phase is displayed on a colour table from -0.8 radians (red) to +1.2 radians (green). Simulated and observed ATI phase for Kuroshio site at L band. The observed phase is displayed on a colour table from -2 radians (red) to +2 radians (green).



Figure 4. Profiles of observed (red) and simulated (green) ATI phase for the Kuroshio site along the AIRSAR flight direction (azimuth). The profiles are at mid swath, for L band (left) and C band (right). The simulations assume that the dimensionless hydrodynamic transfer function has amplitude 4.5 and zero phase.

We identify the following radar-imaging and oceanographic issues arising from the results for this site:

Radar issues The radar modelling of the ATI phase relies on a good knowledge of the wind field and of the directional distribution of the short wave component of the wave height spectrum.

Oceanographic issues The results indicate the potential of ATI observations to provide information which is not represented by the current model, either because it relates to processes which occur on finer spatial scales than those of the model and the input data, or because of physical processes which are not represented in the model.

4.3 ATI Observations over the Tay Estuary, Scotland

Our results for this data-set are discussed by [14] and [15]. The ATI observations come from the DLR polarimetric airborne SAR (ESAR) at X band with a spatial resolution of about 2 m. The image of the ATI phase (Figure 5, left and middle) shows linear features which correspond to abrupt changes in velocity. The TFD model (Figure 5, right) shows a similar range of velocities to the radar data and it agrees that the higher velocities are on the north side of the estuary, although the model results tend to produce slightly higher velocities. The model also does not capture some of the frontal structure observed in the ATI data. This can account for the discrepancy in velocity, because the processes associated with the fronts result in higher frictional effects which act to reduce the flow velocity along the estuary.

We identify the following radar-imaging and oceanographic issues arising from the results for this site:

Radar issues The sensitivities to the wind field and the directional distribution of the short waves which were identified as critical issues for the other sites are not so well established here. Spatial resolution is a critical parameter, because of the need to resolve the frontal structure of interest.

Oceanographic issues 3D hydrodynamic models need to be developed for this site. The need for coupling to the wave field has not yet been assessed. However, the limited fetch in confined, estuarine environments suggests that the effect of the wave field is less important than it is for the other sites studied here, which are in more open waters.



Figure 5. Left: image of phase of along-track interferogram, on grey scale from black (-1.6 radians) to white (+1.6 radians). Middle: profiles of ground-range component of surface velocity along lines marked in the top right image. Right: modelled component of surface velocities in radar range direction, coincident with ATI data acquisition.

5. CONCLUSIONS AND RECOMMENDATIONS

Our results demonstrate that SAR and ATI data can usefully be combined with coupled wave and current models for practical applications where it is important to have correct information on surface currents. The SAR observations can detect dynamic features on finer spatial scales than those represented in present models of ocean circulation. They also provide information on features generated by physical processes which are presently not included in these models. As such, SAR and ATI offer a unique tool to validate and improve high-resolution models, particularly in dynamically complex areas such as the continental shelf break where physical processes are still poorly understood.

A more thorough analysis is required in order to assess the relative merits of detected SAR images and ATI observations. The visibility of features in both modes is affected by environmental conditions as well as the choice of

radar parameters. Note that it will be possible to revert to the detected image whenever it provides clearer features than those in the ATI mode, unless there are additional constraints on processing time and data rate.

Further research is needed to reduce the impact of uncertain factors in both the wave-current model and the SAR forward model. In particular, we identify the need for a better description of the directional distribution of the short-wave component of the wave height spectrum and for input wind fields at finer spatial and temporal resolution. A promising aspect for further study is the combination of ATI with wind information retrieved from the conventional SAR backscatter.

6. ACKNOWLEDGEMENTS

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