Remote Sensing of Environment 197 (2017) 58–71

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Towards wide-swath high-resolution mapping of total ocean surface current vectors from space: Airborne proof-of-concept and validation

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ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 14 April 2017
Accepted 19 May 2017
Available online xxxx

Keywords:
Ocean surface current
SAR
Doppler
Along-track interferometry
Airborne
Validation
Coastal
Bathymetry

ABSTRACT

Two-dimensional high-resolution maps of total surface current vectors obtained for the first time with an airborne demonstrator of the innovative Wavemill instrument concept are validated against HF radar data and compared with output from the POLCOMS high-resolution coastal ocean circulation model. Wavemill is a squinted along-track interferometric SAR system optimized for ocean surface current vector retrieval that operates at moderate incidence angles (~30°) and is compatible with spaceborne implementation. This paper represents the first comprehensive validation of the current retrieval capabilities of squinted along-track SAR interferometry in support of its development as a future European Space Agency Earth Explorer mission.

Wavemill airborne data were acquired in October 2011 in Liverpool Bay off the west coast of Great Britain in light southerly wind (5.5 m/s) and maximum tidal ebbing flow (0.7 m/s) conditions. Contributions to the measured SAR interferometric phase by surface gravity waves, known as the Wind-wave induced Artefact Surface Velocity (WASV), were removed using our best estimate of wind conditions and the (Mouche et al., 2012) empirical correction derived from Envisat ASAR. Validation of the 1.5 km resolution Wavemill current vectors against independent current measurements from HF radar gives very encouraging results, with Wavemill biases and precisions typically better than 0.05 m/s and 0.1 m/s for surface current speed, and better than 10° and 7° for current direction.

The sensitivity of the current retrieval to the wind vector used to compute the WASV is estimated. A ± 1 m/s error (bias) in wind speed has minimal impact on the quality of the retrieved currents. In contrast, the choice of wind direction is critical: a bias of ±15° in the direction of the wind vector degrades the accuracy of the airborne current speed against the HF radar by about ± 0.2 m/s. This highlights the need for future instruments to provide calibrated SAR Normalised Radar Cross Section data to support retrieval of wind and current vectors simultaneously.

Comparisons of POLCOMS surface currents with HF radar data indicate that the model reproduces well the overall temporal evolution of the tidal current (correlation of spatial fields against HF radar over two tidal cycles of 0.9) but that the model features a systematic 1-h delay in the timing of the maximum ebbing flow in eastern parts of the domain near the Mersey Bar Light buoy. At the maximum ebb flow, the model underestimates the current speed (bias of −0.2m/s) with respect to the HF radar and Wavemill data at the time of the flights. Both the HF radar and Wavemill data reflect much greater snapshot spatial variability of the ocean surface current field than is present in the model, resulting in poor correlation of instantaneous spatial fields (< 0.5) between POLCOMS and the HF radar data. The Wavemill data reveal high spatial variability of ocean surface currents at fine scales, which are not visible in the 4km resolution HF radar data. Wavemill detects several strong (1–1.5m/s) localized current jets associated with deeper bathymetry channels in shallow waters (< 10 m) that are too narrow or too close to land to be observed by the HF radar. The study confirms the value of synoptic wide-swath maps of high-resolution ocean surface current vectors for coastal applications and to validate and develop high-resolution ocean circulation models.

1. Introduction

High-resolution satellite images of sea surface temperature and ocean color reveal a multitude of small scale oceanic features that dominate the ocean variability at mesoscales O(10–100)km and

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http://dx.doi.org/10.1016/j.rse.2017.05.020

sub-mesoscales O(1–10)km. Submesoscales contain much of the ocean turbulent energy and play a major role in horizontal and vertical mixing, large-scale oceanic transports and ocean biology e.g. Martin and Richards (2001); Lapeyre and Klein (2006b); Lévy et al. (2010); Sasaki et al. (2014). Improved observations and characterization of the ocean variability at the submesoscale are needed to validate ocean circulation models and to develop improved model parameterizations that represent the impact of small oceanic features on the global ocean circulation, air-sea interactions, marine ecosystem responses and long-term climate change.

At present, there are no direct measurements from satellites of total ocean surface current vectors at high resolution. Techniques have been developed to estimate high-resolution current fields by tracking features in series of SST images, using either heat conservation principles or a quasi-geostrophy approach e.g. Emery et al. (1986); Kelly (1989); Lapeyre and Klein (2006a) but the methods have limited applications in cloud-covered regions. Satellite nadir altimeters give all-weather estimates of the across-track component of geostrophic currents but conventional altimeters do not resolve ocean variability in the sea surface height below 70–100 km scales (Dibarboure et al., 2014; Poje et al., 2014). Observing the ocean variability at smaller scales is the prime motivation of the Surface Water and Ocean Topography mission (SWOT), which aims to deliver two-dimensional maps of sea surface height at 1 km resolution using across-track interferometry (XTI) (Fu et al., 2010). From this, SWOT will seek to derive two-dimensional maps of geostrophic current vectors at a resolution of order 10 km over two 70 km swaths. However, there are many ocean surface currents beyond those caused by geostrophy. Other ocean currents that contribute to the total ocean surface current include tides, wind-driven currents, Stokes drift induced by ocean surface waves, currents linked to internal waves and small scale circulation close to unstable stratification. These occur on a multitude of different spatial and temporal scales and are particularly dominant near fronts, at continental shelf breaks and in shallow water and coastal regions.

Microwave imaging radars can remotely provide some direct estimates of the total ocean surface current by measuring the small Doppler shift induced by the ocean surface motion in reflected microwave signals. This has been demonstrated successfully with Synthetic Aperture Radar (SAR) systems using the Doppler Centroid Anomaly method (Shuchman and Meadows, 1980; Rufenach et al., 1983; Chapron et al., 2005) as well as with Along-Track Interferometry (ATI) systems (Goldstein and Zebker, 1987; Goldstein et al., 1989; Romeiser et al., 2014). These systems only measure Doppler signals in one line-of-sight direction, from which the component of the current perpendicular to the satellite track can be determined. Lyzenga et al. (1982) were first to suggest ways of measuring the Doppler signals with one system in several directions, either by using data from two quasi-simultaneous orthogonal flights or by using systems with antennas pointing in two different azimuth directions. A few studies have used orthogonal flights (Shemer et al., 1993; Graber et al., 1996) to derive current vectors but, so far, only the Dual Beam along-track Interferometer (DBI) developed and deployed by the University of Massachusetts (Frasier and Camps, 2001; Farquharson et al., 2004; Toporkov et al., 2005 and the Frequency-Modulated Continuous Wave (FMCW) ATI SAR deployed by the University of Washington (Farquharson et al., 2014a, 2016), have successfully measured current vectors in a single aircraft pass. Both systems use a squint angle of 20° (Toporkov et al., 2005) or 30° (Farquharson et al., 2014b) and very high incidence angles at the boresight (≈60°) to ensure high sensitivity to the surface current. Although these instruments give very good current vector maps, the range of high incidence angles of this concept makes it difficult to implement as a satellite mission (due to instrument power considerations).

Around the same time, a new satellite mission concept called Wavemill was proposed (Buck, 2005) to map both sea surface height and ocean surface fields over two wide swaths with a single system. The original Wavemill concept was conceived as a hybrid interferometer (i.e. including both along-track and across-track interferometric baselines) but the concept gradually evolved to focus on squinted along-track interferometry in order to optimize the retrieval of ocean current vectors. Wavemill differs from the DBI in two main respects: through the use of larger squint angles (∼45°) and of relatively low incidence angles (∼30°) that make it compatible with spaceborne implementation.

An airborne demonstrator of the Wavemill concept was developed and flown by Airbus Defence and Space UK in the frame of a European Space Agency project. Airborne data were acquired during the Wavemill proof-of-concept experiment, which took place in October 2011 in Liverpool Bay off the west coast of Great Britain. This paper presents the first comprehensive analysis of the surface current retrieval capabilities of the Wavemill concept during the campaign, including validation against independent in situ current measurements from HF radar and comparison with output from a high-resolution ocean circulation model. A small subset of these data acquired in a 7× 7 km^2 box around the Mersey Bar Light buoy (Fig. 1) were previously examined in Martin et al. (2016) to estimate the impact of ocean surface waves on Wavemill currents through the Wind-wave Artifact Surface Velocity (WASV). However, the analyses in this paper are not based on the WASV correction derived in Martin et al. (2016), and therefore constitute an entirely new and independent assessment of the capabilities of squinted SAR interferometry in support of its development as a spaceborne mission.

The paper is arranged as follows. Section 2 presents the Wavemill airborne campaign, the Wavemill airborne system and measurements, and the ancillary in situ and model data used in the analyses. The method to retrieve surface current vectors from the Wavemill airborne measurements and to correct for the WASV is presented in Section 3. Results are presented in Section 4 and discussed in Section 5. The paper closes with conclusions in Section 6.

2. Datasets

2.1. Overview of Wavemill airborne campaign

The Wavemill Proof-of-Concept Campaign was carried out in the last week of October 2011 over various sites in the Irish Sea off the

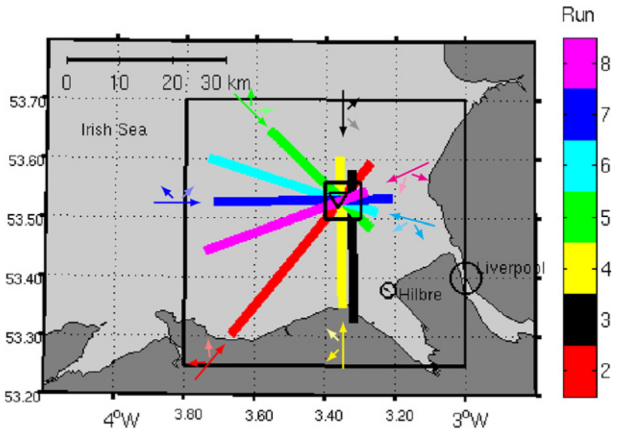

Fig. 1. Location of Wavemill airborne proof-of-concept data in the Liverpool Bay off the west coast of Great Britain, UK. Each run is represented by a different color. For each run, the long colored arrow represents the aircraft flight direction and the two small arrows represent the line-of-sight directions of the fore (pale color) and aft (bright color) pairs of antennas. The positions of Liverpool city and Hilbre Island are indicated by black circles. The triangle represents the position of the Mersey Bar Light (MBL) buoy. The small square around MBL represents the 7×7 km^2 area used in Martin et al. (2016) and for inter-run bias correction in this study. The larger square represents the study area presented in Figs. 4 and 5.