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Direct measurement of ocean waves velocity field from a single SPOT-5 dataset

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ABSTRACT

We present a method based on space-borne optical imagery from the SPOT5 satellite to directly measure the phase velocity fields of ocean waves. The panchromatic and multispectral scenes acquired by SPOT5 the same day on the same area are not strictly superimposable due to the different locations of the CCDs (Charged Coupled Device) in the focal plane of the instrument. In this manuscript, we propose a method that exploits the temporal lag that exists between the panchromatic and multispectral scenes to measure the ocean wave velocity fields. We firstly discuss the principle and the methodology. Then, we apply it offshore La Reunion Island. Finally, we compare and discuss the results against a swell propagation model. Our method is proven reliable and can be immediately extended to other push-broom sensors.

1. Introduction

Ocean waves represent an important oceanographic phenomenon for manifold reasons. For instance, they strongly influence the most superficial water layer where the exchanges and heat transfer between the ocean and the atmosphere take place. Moreover, the ocean swell highly affects coastal areas, being one of the principal agents responsible for coastal erosion. Furthermore, their propagation pattern being affected by shallow bathymetry, ocean wave velocity fields can provide invaluable information about the ocean floor topography at shallow depth.

Traditional swell measurement methods typically employ sensors mounted on buoys or sensors installed at depth to determine ocean state characteristics. These methods are of great precision and allow one to measure the swell parameters on a point-to-point basis and are therefore well adapted to regions where the ocean swell is spatially uniform. However, in coastal areas the ocean wave field is not spatially uniform as it is modified on its arrival at shallow depth by near-shore processes that depend on local bathymetry (shoaling, refraction, breaking, …). Therefore, it is of primary importance to measure the swell spatial variations. For instance, phenomena such as coastal erosion and marine flooding are highly dependent on the local wave characteristics. Since classical in situ instruments are often difficult to deploy in shallow water where waves break, wave models are often used to estimate the local sea state from the offshore wave buoys data. Space-borne imagery has been demonstrated complementary to in-situ measurements in overcoming some of the aforementioned limitations and it typically renders the ocean swell using two frequency bands of the electromagnetic spectrum, the microwave and the visible bands (e.g. Larouche & Lavoie, 1996). The microwave imaging technique consists in an active hyper-frequency system such as the Synthetic Aperture Radar (SAR). The SAR backscattered signal on the ocean surface is dominantly governed by Bragg scattering (e.g. Chapron et al., 2005; Plant & Keller, 1990; Thompson et al., 1991) so that it is the small scale ocean roughness, essentially driven by the wind, that allows for imaging of the ocean swell by radar. A large number of studies have demonstrated that SAR imaging systems are able to correctly evaluate the swell wavelengths and directions even though a certain number of conditions have to be respected for a SAR to image the ocean swell (e.g. Ardhuin et al., 2004; Beal et al., 1983; Breivik et al., 1998; Collard et al., 2005; Dobson & Vachon, 1994). Concretely, most of the aforementioned methods are based on the evaluation of swell spectra retrieved from the SAR imaging systems, not from direct measurements of the swell velocity field. To overcome this limitation, Chapron et al. (2005, 2004) evaluated the Doppler shift of radar echoes occurring during the synthetic aperture as a direct measurement of ocean surface wave velocity (e.g. Johannessen et al., 2008). Since the Doppler shift is analysed on a sub-aperture base, Doppler velocities are obtained at spatial resolutions of 2 km for a narrow swath SAR,

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and this pioneering method does not yet yield spatially detailed information close to the coast. Higher spatial resolution systems or space-borne Along-Track Interferometry (ATI) might overcome this SAR limitation.

Techniques based on space-borne sensors operating in the visible range of the electromagnetic spectrum capture the specular reflection of visible sunlight on the multiple facets of the ocean swell. These techniques are limited by clouds, and to periods for which the sun, the sensor, and the ocean wave field are in a favourable alignment to allow for the swell image formation. For these reasons, optical techniques have encountered a limited development compared to SAR methods. Still, a large number of studies have demonstrated the potential operational use of optical imaging systems for studying the ocean swell spectra from high resolution SPOT images (e.g. Populus et al., 1991) or for direct measurement of advective surface velocities from medium resolution satellite sensors such as AVHRR, MODIS (e.g. Crocker et al., 2007; Emery et al., 1986) and Nimbus 7 (Garcia & Robinson, 1989). Moreover, a number of studies have demonstrated the potential of airborne infra-red remote sensing to evaluate swell spectra (e.g. Dugan et al., 1996; Gelpi et al., 2001) and surface currents using airborne visible image time series (e.g. Dugan & Piotrowski, 2003). Nonetheless, the direct measurement of ocean wave velocity fields from high resolution visible space-borne imagery is still a challenge.

In this manuscript, we propose an innovative space-based method that jointly uses the panchromatic and multispectral instruments on-board the SPOT-5 satellite, respectively at 5 m and 10 m ground sampling distance (GSD), to directly measure the ocean surface velocity field at very high spatial resolution. Our method relies on two observations. First, owing to the SPOT-5 sensor's geometry, there exists a small temporal lag between "simultaneous" panchromatic and multispectral acquisitions. Because of this temporal lag, moving objects within the scene will therefore be imaged at different locations between panchromatic and multispectral images. Second, the relative displacement of objects between scenes can be measured with high accuracy and precision with well-established image cross-correlation techniques. We present the general concept of the method, test it, and discuss the results by comparing them with modelled ocean swell velocity offshore La Reunion Island (Indian Ocean). We conclude that our method is proven reliable and could be extended to most other space-borne optical sensors to increase temporal data sampling.

2. Geometry of the SPOT-5 panchromatic and multispectral sensors

Since 1986, SPOT satellites (SPOT 1–5) have been forming a constellation acquiring images of the Earth from a sun-synchronous near-polar, 832 km altitude orbit with 26 days repeat cycle. SPOT orbits and station positioning are precisely determined by the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) instrument hosted by the payload. The DORIS integrated system allows for the precise computation of SPOT position and velocity every 30 s. In particular, SPOT-5, launched in 2002, is continuously controlled in yaw steering mode by a programmed control loop and a star tracking unit that computes absolute angles along the three attitude axis and provides high accuracy attitude measures to the ground (Riazanoff, 2002). Among other imaging sensors, SPOT-5 is equipped with High Resolution Geometry (HRG1-2) instruments that acquire data in multispectral mode (XS1–2–3) at 10 m spatial resolution and in panchromatic mode (HMA-B) at 5 m GSD respectively. The panchromatic and multispectral scenes acquired the same day on the same area and by the same instrument are not strictly superimposable due to the different locations of the CCDs in the focal plane of the instrument. In particular, an image line acquired at a given time by one of the HRG instruments is approximately 9.24×10^{-3} rad in front of the subsatellite point in panchromatic mode (HMA) and 9.24×10^{-3} rad behind the sub-satellite point in multispectral mode (HS) (Fig. 1). This configuration has been exploited to extract Digital Elevation Models (DEM) as it gives rise to a slight parallax view (e.g. Mai & Latry, 2009; Massonnet et al., 1997; Vadon, 2003). Because the sensors are aimed at imaging exactly the same area on the ground, the panchromatic and multispectral scenes are therefore acquired with a temporal shift. For a given SPOT-5 dataset, the platform velocity vector is stored in the ancillary data file. In the case presented here, the imaging ground velocity is then ~7.53 km/s. If the platform is flying at a nominal 832 km altitude, it thus takes ~2.04 s to cross 18.48×10^{-3} rad (~15.37 km) considering that the Earth curvature is negligible over this distance. Therefore, considering a locally flat surface, if a cluster of pixels, i.e. the ocean waves, within the dataset has moved between the HMA and HS acquisitions, we can measure its velocity by measuring its pixel offset and dividing it by the time lapse between the acquisitions.

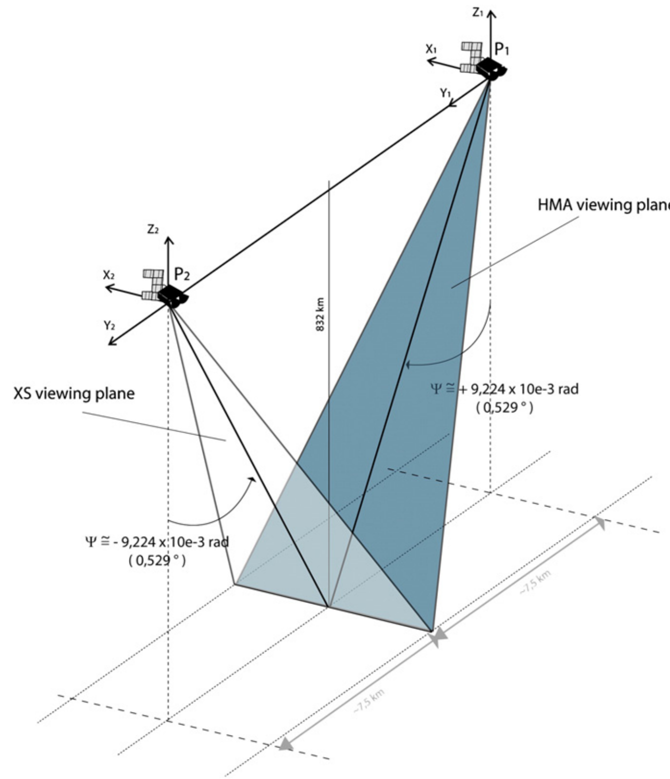

Fig. 1. Acquisition geometry of SPOT5 HRG instrument (modified by the authors after Riazanoff, 2002). X, Y and Z represent the attitude state vectors stored in the ancillary data files; P_1 and P_2 indicate the position of the platform at T_0 and $T_0+\Delta t$, when acquiring the HMA and XS data respectively. In this case study, $\Delta t = 2.04$ s.

3. Processing methodology

The conditions for light reflection on the water surface and the SPOT image formation over the ocean have been extensively described by Populus et al. (1991). In the presence of ocean waves higher than 1 m, the sun light reflected by the ocean wave slopes produces glints on the image according to the relative positions between the sensor, the wave front geometry, and the Sun azimuth and elevation. In principle, ocean wave propagation does not produce horizontal displacements of the medium. But given a fixed Sun-wave-sensor geometry, as the waves propagate, the sunlight will produce a glint on the slope of the waves that are in different positions (Fig. 2). Here we start from a set of two SPOT-5 scenes acquired 2.04 s apart (Fig. 3) and use the subpixel phase