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Inferring surface currents within submerged, vegetated deltaic islands and wetlands from multi-pass airborne SAR

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ABSTRACT

Water flow patterns across coastal and deltaic wetlands affect biogeochemical cycling, denitrification, organic carbon burial, and coastal landscape evolution. Our understanding of such patterns across these important landscapes is incomplete, however, because of the inherent difficulty of conducting spatially and temporally dense ground- or boat-based surveys in shallow, vegetated terrain. We conducted an airborne L-band synthetic aperture radar (SAR) acquisition campaign on Wax Lake Delta, Louisiana, USA, in May 2015, to investigate whether water velocities and flow patterns over kilometer scales can be determined from remote sensing. Thirteen SAR flight lines over the delta region were acquired in 3 h with six different flight directions, concurrently with a small boat campaign. We show that SAR azimuth displacement due to Doppler shift can be used to estimate the surface water flow relative to the static and submerged vegetation interspersed on delta islands, using a simple Bragg wave scattering model and accounting for the Bragg wave's free velocity and wind drift. At Wax Lake Delta, we find that ~0.40 m/s water velocities within the main deltaic channels slow to 0.1–0.2 m/s as flow spreads laterally across, and converges within, the vegetated islands, coinciding with shallow (< 0.5 m) depths and heightened flow resistance. This SAR-based technique opens up new avenues for understanding shallow submerged, vegetated coastal wetlands and deltas.

1. Introduction

Over 300 million people are living on or near river deltas (Syvitski and Saito, 2007). In many of these deltas, land loss due primarily to combined sea level rise and land subsidence threatens their ecological and economic productivity (e.g., Morton and Bernier, 2010; Tessler et al., 2015). Deltas are landforms built and maintained by a complex array of physical, biological, and chemical processes (Galloway, 1975; Orton and Reading, 1993). Flow routing is central to many of these processes because it is coupled to the morphodynamics of landform evolution, the rates of denitrification, and the construction of wetland ecosystems. However, flow routing on deltas is difficult to monitor due to considerable spatial extent and prevalence of very shallow water (< 0.5 m depth), which make both ground and boat surveys difficult. Only sparse in situ stream gage measurements of wetland flow velocities are usually carried out, leaving a major data gap for understanding deltaic wetland hydrology.

Remote sensing techniques can help fill this data gap. For instance, synoptic views and monitoring of vegetation colonization can be obtained from optical spectrometers deployed on satellite and aircraft platforms (Carle et al., 2015). Repeat bathymetry surveys derived from remote sensing can indicate whether a delta is retreating or advancing (Olliver and Edmonds, 2017). However, techniques to survey the bathymetry using optical (visible and laser) imagery can be impeded by water turbidity. Surface currents in a delta could be monitored from ground based High Frequency (HF) radar (Paduan and Rosenfeld, 1996), although large portions can be occluded by emergent vegetation. Air and spaceborne real aperture radar (RAR) and synthetic aperture radar (SAR) imagery have been investigated for the capability to provide coastal bathymetry (de Loor, 1981; Lodge, 1983; Alpers and Hennings, 1984; Romeiser and Alpers, 1997) and current velocities (Lyzenga and Shuchman, 1982; Goldstein et al., 1989), but are generally used in deeper waters and larger ocean channels.

Recent work on the Wax Lake Delta (WLD), a young and shallow river delta prograding in the Atchafalaya Bay, Louisiana, USA, has highlighted both the detailed topography of river deltas, and the complex flow paths across this topography (Shaw and Mohrig, 2014; Kolker et al., 2014; Hiatt and Passalacqua, 2015; Geleynse et al., 2015;

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Roberts et al., 2015; Shaw et al., 2016a). These remote sensing, modeling and field-based studies have shown that there are strong couplings between bed topography and flow in channels and through the wetlands on islands. Hiatt and Passalacqua (2015) showed that velocities on submerged islands are roughly one third as fast as flow through channels, and found that flow reversals from tides and winds can substantially affect the residence time of water in these islands. Shaw et al. (2016a) used streaklines from biogenic slicks in these regions to estimate flow direction, but could not resolve the flow speed. Synoptic measurements of flow velocity over islands could quantify the residence time of water in islands, an essential parameter in determining denitrification potential (Hiatt and Passalacqua, 2015). Furthermore, the effect of vegetation on flow speeds and patterns is poorly understood (Temmerman et al., 2005), and measurement of flow velocity in deltaic islands is critical to improve understanding of this factor.

In this study, we conducted an airborne field campaign to estimate flow velocities on islands of the WLD using a series of images that we acquired over a 3-h time period with the NASA airborne Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) in May 2015. Shaw et al. (2016b) used a similar series of UAVSAR images over the WLD to document morphologic changes of the submerged channels. They compared images acquired over a time span of several years and identified bathymetric change from the change in the SAR backscatter. In this study we specifically investigate the use of airborne SAR imagery to infer the 2-dimensional surface current velocity within a bathymetrically complex, shallow system, including on submerged parts of delta islands. The technique relies upon imaging the delta from multiple directions over tens of minutes, as opposed to Shaw et al. (2016b) which used yearly revisits. Such temporal and geometric constraints require an airborne system because a spaceborne SAR sensor has at most twice-daily overpasses and fixed imaging geometry. We qualitatively compare these derived surface currents with near coincident and adjacent currents derived by boat-based acoustic Doppler current profiler (ADCP) survey. In the following sections we first review background information on SAR-based methods for current estimation. Second, we describe the study area, radar and in situ measurements, and general features of the delta observed with the SAR. Third, we present a theory to derive the 2-D velocity field within shallow submerged vegetation, and apply it flow within a major channel and across the entire delta. Finally, we discuss the measurement uncertainty, errors and limitations.

2. SAR-based methods for current velocity estimation

As generally described by Holt (2004), radar backscatter from the ocean is related to ocean surface roughness components that are of similar scales to the radar wavelength. Because the ocean surface (composed of waves) is moving, it generates Doppler shifts in the radar signal, which can be used to map surface currents, as demonstrated by coastal high-frequency (HF) radars (Paduan and Rosenfeld, 1996) and airborne and spaceborne SAR (e.g., Lyzenga and Shuchman, 1982; Goldstein et al., 1989). In order to determine a current vector, radial velocities of the moving ocean surface must be observed from multiple viewing geometries and combined to form a vector velocity field, which is the technique employed by HF radar networks. A complicating factor is that the Doppler shift from a moving ocean surface can have contributions from multiple moving components including the surface current velocity, wave orbital velocities, and the wave-induced Stokes drift.

Two main techniques have been devised to retrieve the surface current information from SAR imagery. The first technique, called along-track interferometry (ATI), consists of two receiving antennas separated by a sufficiently small distance in the along-track direction to maintain coherent ocean returns (Chapman et al., 1994; Romeiser and Thompson, 2000). The phase difference of the same surface point retrieved from the two complex images is directly related to the displacement of that point during the small delay in acquisition between the two antennas. ATI studies from airborne (e.g. Goldstein and Zebker, 1987; Graber et al., 1996) and spaceborne (Romeiser et al., 2005) platforms have successfully demonstrated the feasibility of the technique, including over rivers (Romeiser et al., 2007). ATI provides the current component in the line-of-sight direction only. To get the full 2D description of the current, ATI must be conducted at different azimuth viewing directions (Goldstein et al., 1989). The second technique relies on the analysis of the Doppler centroid measured from a single receiving antenna and aims at recovering the Doppler shift residual due to the surface current after accounting for the technical details of the satellite or aircraft orbits, the instrument, as well as wave-related parameters and wind (Madsen, 1989; Chapron et al., 2005; Johannessen et al., 2008; Kudryavtsev et al., 2012). This approach requires precise stability and knowledge of the platform track and attitude, which is more readily attainable and accurately measured for spacecraft than aircraft. Similar to ATI, at least two images with different along-track flight directions must be acquired in a short timespan to get the full 2D description of the current, which is impractical for current spaceborne systems.

In this study we develop a technique which is related to the second technique described above, but instead of looking at the Doppler spectra, we use the azimuth displacement, which is a consequence of the Doppler shift effect, to infer the surface current velocity. Our technique involves measuring the azimuth displacement of the moving water with respect to stationary objects in the scene.

3. Study area and SAR survey

3.1. Wax Lake Delta

The WLD was initiated from a channel dredged in 1942 between the Atchafalaya River and the Atchafalaya Bay. The WLD has not undergone engineering modification since and has evolved naturally. The emergent and submerged part of the delta now covers about 150 km^2, with the permanently submerged area extending to 70 km^2 (Allen et al., 2012; Shaw and Mohrig, 2014). The emergent delta consists of a series of islands separated by relatively deep (< 3 m) channels that bifurcate downstream. Downstream of the emergent delta, channels become shallower as the flows they contain lose lateral confinement. Flows across the shallow (< 0.5 m) submerged tops of islands converge into drainage troughs that discharge effluent at positions located between the major distributary channels (Shaw et al., 2016a).

3.2. UAVSAR specifications

UAVSAR is a 1.257 GHz (L-band) SAR polarimetric instrument flown on-board a Gulfstream-3 aircraft operated for the U.S. National Aeronautics and Space Administration (NASA) under its Airborne Science Program (http://uavsar.jpl.nasa.gov/). The instrument is side-looking, imaging to the left of the aircraft heading, and emits and receives in both horizontal (H) and vertical (V) polarizations. The SAR images have a swath width of 22 km and a single-look resolution of 1.7 m in the slant range (line-of-sight) direction and 0.8 m in the along-track direction. The ground range resolution in the cross-track direction is $1.7/\sin(\theta_i)$ m, where θ_i is the incidence angle. UAVSAR has a very low noise floor, less than −50 dB (Fore et al., 2015), which makes it well suited for imaging oceanographic features with low radar backscatter. Other instrument specifications are reported in Table 1.

3.3. Aircraft acquisitions of Wax Lake Delta

On May 8, 2015, we conducted a UAVSAR field campaign to acquire a series of 13 images of WLD with a total of 6 different flight directions. The full time-series acquisition period took 2 h 50 min, with 15–20 min between each acquisition. A SAR image of the WLD is presented in