DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

RIVET Satellite Remote Sensing and Small Scale Wave Process Analysis

Hans C. Graber
RSMAS – Department of Ocean Sciences
Center for Southeastern Tropical Advanced Remote Sensing
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149, USA
phone: (305) 421-4952 fax: (305) 252-4407 email: hgraber@cstars.miami.edu

Roland Romeiser
RSMAS – Department of Ocean Sciences
University of Miami
4600 Rickenbacker Causeway
Miami, Florida 33149-1098, USA
phone: (305) 421-4645, fax: (305) 421-4701, email: rromeiser@rsmas.miami.edu

Brian K. Haus
RSMAS – Department of Ocean Sciences
University of Miami
4600 Rickenbacker Causeway
Miami, Florida 33149-1098, USA
phone: (305) 421-4932, fax: (305) 421-4701, email: bhaus@rsmas.miami.edu

Award Number: N00014-14-1-0643

LONG-TERM GOALS

The goals of this project are to utilize satellite remote sensing to understand the dynamics of inlets and river mouths, with focus on the New River Inlet and the Columbia River Mouth. High resolution synthetic aperture radar (SAR) images from TerraSAR-X, Cosmo-SkyMed and RadarSat-2 acquired at various frequencies, polarizations, incidence angles, and spatial resolutions will complement similar high resolution EO imagery (e.g. EROS-B) to obtain a comprehensive picture of inlet and river dynamics, and phenomena that causes outflow patterns and interactions of ocean waves with river currents.

OBJECTIVES

Using satellite imagery and local in-situ and remote sensing data from ships to describe inlet and river mouth dynamics and wave-current interactions.

a) Completion of processing and analysis for SAR and along-track InSAR images and EO images of New River Inlet and the Columbia River Mouth.

b) Derive and compute surface currents from interferometric along-track pairs of SAR images.

c) To estimate the bathymetry in the river mouth and the adjacent coastal ocean from surface wave refraction patterns.

d) Analysis of the measurements of cm-scale waves whose intensity variations are most visible in SAR imagery.

e) Characterization of interaction with strong currents, horizontal and vertical current gradients and topography.

f) Analysis of in-situ wind-stress that generates the short waves to determine the effect of peak wave refraction due to currents and topography on the local shear magnitude and direction.

g) An improved understanding of the physical mechanisms giving rise to observed SAR signatures of river plumes and fronts.

h) SAR derived wind speeds and wave height estimates for better understanding of the coastal wind and wave regime.

APPROACH

CSTARS collected extensive satellite images from high resolution SARs like TerraSAR-X, Cosmo-SkyMed and RadarSat-2 during two experimental phases, one at each river.

RIVET-I: New River Inlet

During the month long field experiment in the New River Inlet in May 2012 we collected more than 50 satellite images from different sensors and in different modes as listed in Table 1.

Table 1: List of satellite sensor, the imaging mode, the spatial resolution and the number of collects for the New River Inlet experimental phase.

Sensor	Mode	Resolution	# of Collects
Cosmo-SkyMed	**SpotLight**	**1 m**	**29**
TerraSAR-X	**Aperture Switching Mode**	**3 m**	**9**
RadarSat-2	**SpotLight**	**1 m**	**4**
EROS-B	**Panchromatic**	**70 cm**	**15**
GeoEye-1	**Multi-spectral**	**50 cm**	**1**
TOTAL COLLECTION			**58**

Figure 1 shows an example of both the types of EO and SAR imagery collected during the New River Inlet. A combination of such images with in-situ and ship-based measurements can yield an improved understanding of kinematic and dynamic processes. The SAR and EO images of the New River Inlet show several dynamical processes occurring within the inlet and outside the mouth as strong currents push a plume into the Atlantic waters and waves break along the shallow region of the river mouth. The plume front is well seen in the SAR image (see SAR image in Figure 1) due to enhanced

roughness and wave breaking caused by wave-current interactions [1]. Similarly the optical image shows the deep channel and shallower banks on either side of the main channel as well as wave pattern and waves breaking on the shoals (whitecapping) of the New River Inlet (see EO image in Figure 1). Sediment filtering out of the river is transported offshore and upwelling as it crosses the shoals, which is readily observed by EO satellites. Also underwater topography in coastal waters and river estuaries can be observed by SAR and EO sensors (bright areas on either side of the main channel image corresponds to shallow shoal, while main shipping channel is evident as a dark band) as well as morphological changes of inlets and rivers due to natural and/or man-made forces.

Figure 1: New River Inlet satellite images: Left: GeoEye-1 high resolution optical image collected on 2012-05-11 15:51 GMT. Right: Cosmo-SkyMed-2 high resolution spotlight image acquired on 2012-05-21 11:03 GMT.

<u>RIVET-II: Columbia River Mouth</u>

A second experiment was carried out in May/June 2013 at the Columbia River Mouth (CRM). The CRM is much more energetic and dynamic, and therefore, making small scale physics measurements challenging from relatively stable platforms. The collection included again a combination of SAR and EO images during the experimental phase. Using the aperture switching mode (ASM) small phase differences along-track interferometric pairs were acquired. Table 2 provides a summary of the satellite collections during the CRM.

Table 1: List of satellite sensors, the imaging modes, the spatial resolutions and the number of collects for the Columbia River Mouth experimental phase.

Sensor	Mode	Resolution	# of Collects
Cosmo-SkyMed	SpotLight	1 m	31
TerraSAR-X	Aperture Switching Mode	3 m	11
RadarSat-2	SpotLight	1 m	6
EROS-B	Panchromatic	70 cm	4
TerraSAR-X	SpotLight	1 m	4
TOTAL COLLECTION			56

Figure 2 shows one of the Columbia River Mouth SAR images from Cosmo-SkyMed on 27 September 2012 at 13:49 UTC. The image shows many obvious as well as subtle surface features. Off the river mouth internal waves and fronts related to the river plume are visible, whereas inside the river a front delineating quiescent waters strongly separates waters on the southern side of the river from fast moving, shear currents on the northern side.

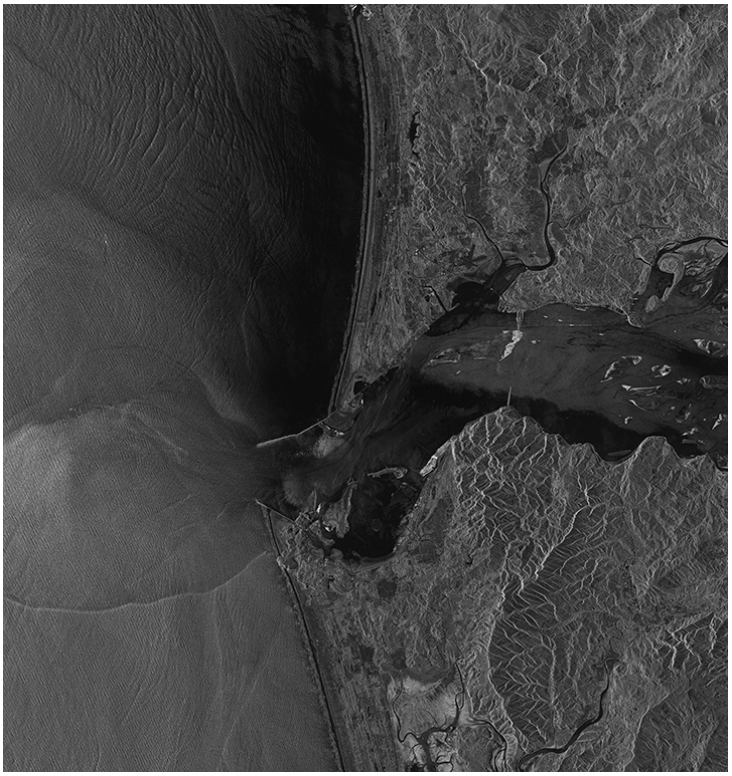

Figure 2: Columbia River mouth observed by Cosmo-SkyMed-1 stripmap image acquired on 27 September 2012 at 13:49 UTC. Interesting features are clearly visible both offshore the river mouth as well as inside.

WORK COMPLETED

We have demonstrated that surface current measurements from space is possible with SRTM (Romeiser et al., 2005, 2007) and recently with TerraSAR-X ATInSAR images (Romeiser et al., 2010), which work best where there is a strong east-west component of the flow, because the measured line-of-sight component is close to this direction for near-polar orbiting satellites. Figure 3 shows the line-of-sight (LOS) surface current fields in the New River Inlet obtained from TerraSAR-X ATI data collected on 19 May 2012 @ 11:23 UTC and from a model simulation using Delft-3D. Note the wave effect is quite significant and contributes to a large correction. In addition to absolute surface currents from ATInSAR, we can also derive information on current gradients from conventional SAR intensity images.

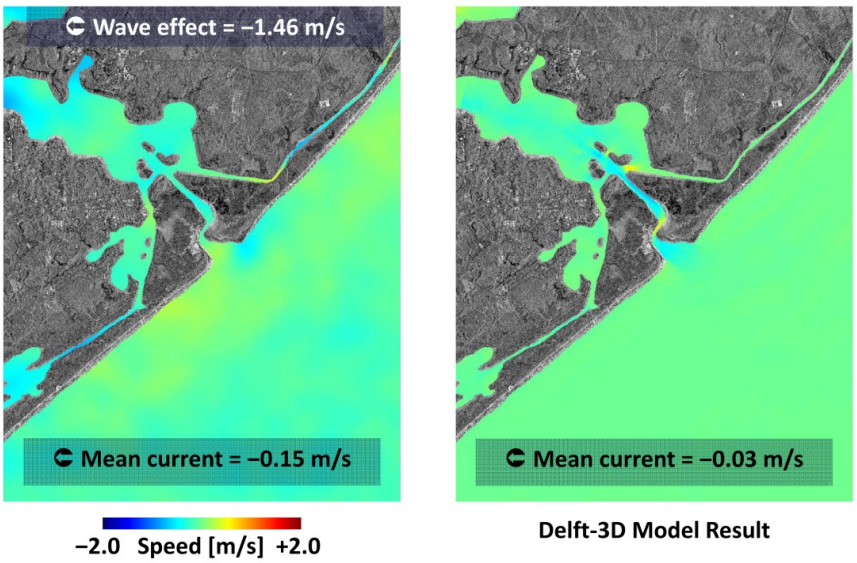

Figure 3: Comparison of the line-of-sight (LOS) surface currents on 19 May 2012 @ 11:23 UTC at the New River Inlet. Left: LOS currents from TerraSAR-X ATI data corrected for wave effect. Right: LOS projected surface currents from model simulations using Delft-3D.

In shallow, energetic river mouths and inlets complex interactions between wind-waves-currents and topography are prevalent (Haus et al., 2006). Consequently to validate SAR remote sensing in inlets and river mouths multiple spatially distributed observations across regions of significant current shear or topographic variability were made. Important physical quantities that were observed are the directional wave spectrum to wavenumbers greater than 125 rad m^{-1}, vertical current structure including near surface observations and local high resolution wind stress.

The wind stress observations are necessary due to significant spatial variability near river mouths often not represented in larger scale wind products, particularly if there are orographic effects and the stress veering caused by ocean currents (Zhang et al. 2009). Figure 4 shows a snapshot of surface roughness observations using polarimetric video and IR cameras as well as ultrasonic distance ranging.

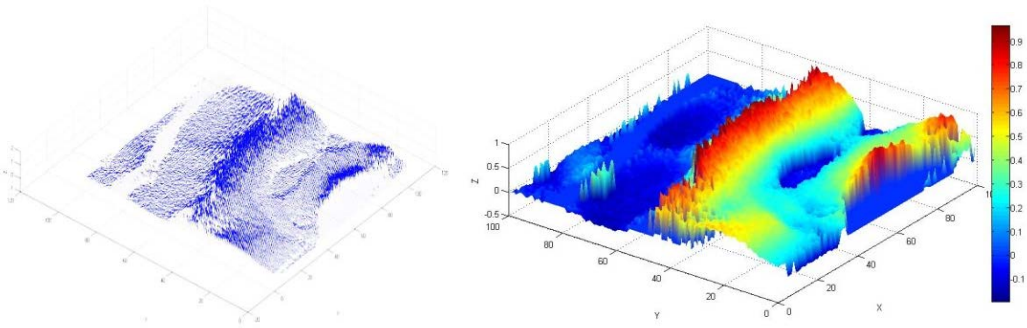

Figure 4: Left: Instantaneous surface slope vector field from polarimetric imagery during RIVET-I. Image size is ~10cm x 10cm, sampling rate is 54 Hz. Right: Surface topography derived from slope-vector field on left.

Through the RIVET experimental program polarimetric cameras on a variety of shipboard platforms were successfully deployed. The polarimetric cameras used for this research allowed the simultaneous acquisition of 3 polarization images at 0°, 45° and 90° linear polarizations states. These images were acquired at video framed rates of up to 54 Hz. From the analysis of those 3 images the polarization state at each pixel was calculated. Inversion of the polarization state of the surface was used to map the local surface slope vectors in 2-dimensional space (Zappa *et al.* 2008). This technique has been successfully implemented, calibrated in the ASIST laboratory and validated during the RIVET field experiments (Figure 5). Because the polarization cameras optimally observe reflected skylight at ~45º viewing angles they were positioned to view from various positions on ships platforms. After correctly accounting for viewing angles and platform motion, 2-D short wave slope spectra at unprecedented temporal and spatial resolution were observed (Figure 5).

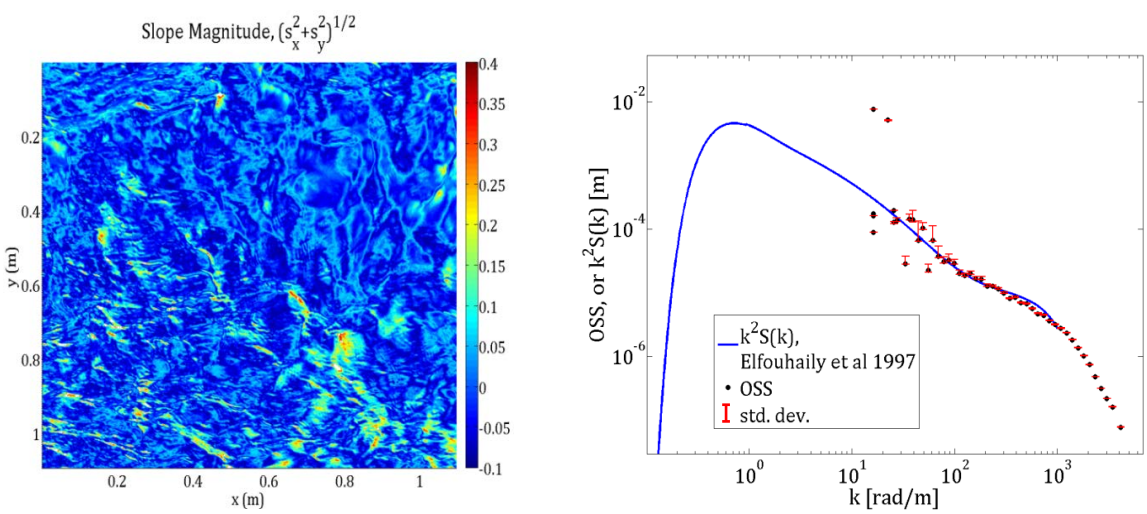

Figure 5: Left: Shipboard omni-directional slope image derived from single frame. Right: Wavenumber slope spectrum derived from that image (red dots) . Elfouhailey empirically based unified spectrum (blue line).

As a result, we can now resolve short wave spectra in the field fast enough to capture the wave growth and relaxation as the local wind gusts and wanes (Figure 6), the phase dependence short waves on longer waves and the effects of rain (Figure 7), wave breaking and surfactants on the ocean surface. Furthermore by measuring the dispersion relationship out to wavenumbers above 1000 we are working to extract remotely the surface currents and information on the surface tension and viscosity. This could prove to be very important for interpreting satellite imagery when slicks and convergence zones are identified.

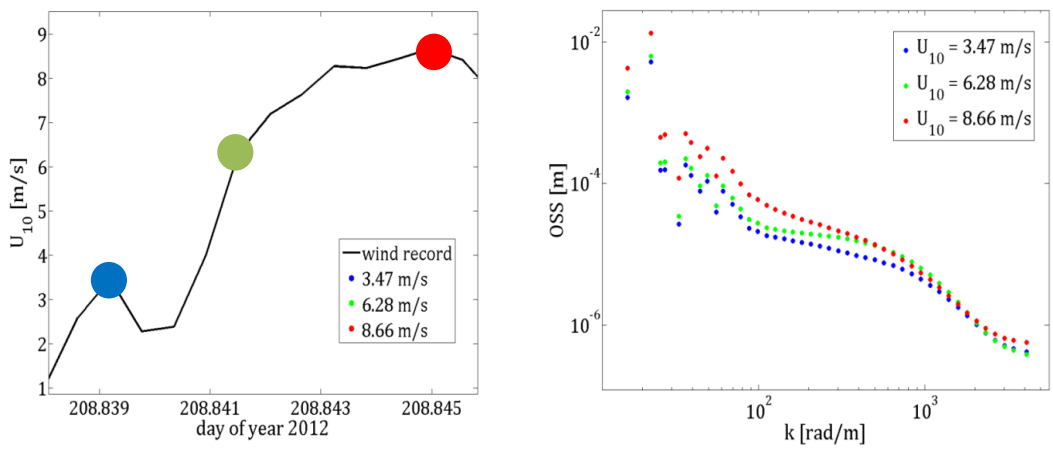

Figure 6: Left: Wind speed over 5-minutes showing increasing wind. Wavenumber slope spectra (single frame) shown at the positions. Right: Growth of the wave energy in specific wavenumber bands can be identified.

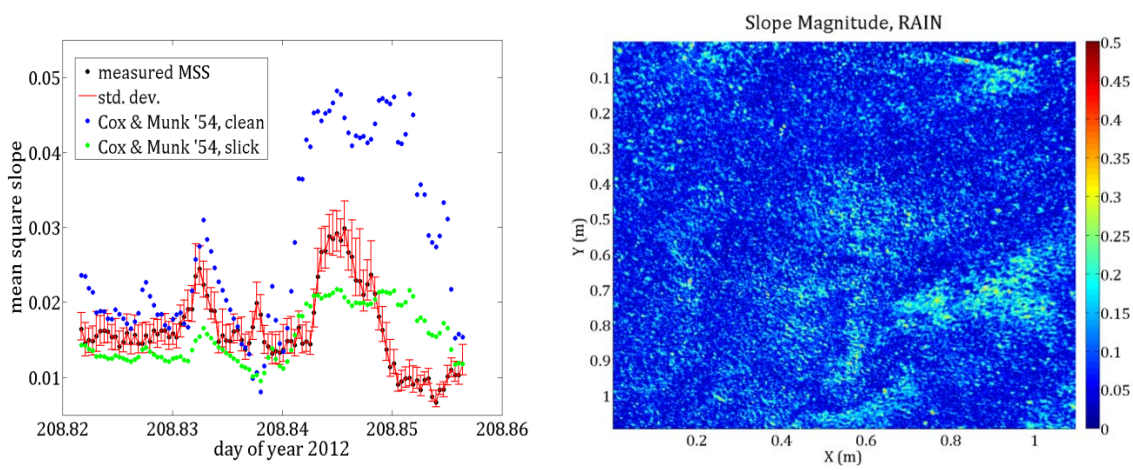

Figure 7: Left: Mean square slope over single images while underway, compared with Cox and Munk (1954) measurements. Note precipitous drop at end of record. Right: Image at end showing rain impacting surface which caused suppression of MSS.

RESULTS

Observations made at the New River Inlet in North Carolina, during the Riverine and Estuarine Transport experiment (RIVET), were used to evaluate the suitability of wind speed dependent, wind

stress parameterizations in coastal waters. As part of the field campaign, a small, agile research vessel was deployed to make high resolution wind velocity measurements in and around the tidal inlet.

Observations of wind stress angle, near-surface currents, and heat flux were used to analyze the cross-shore variability of wind stress steering off the mean wind azimuth. In general, for on-shore winds above 5 m/s, the drag coefficient was observed to be two and a half times the predicted open ocean value. Significant wind stress steering is observed within 2 km of the inlet mouth, which is observed to be correlated with the horizontal current shear.

These first results were described in Ortiz-Suslow, D.G., B.K. Haus, N.J. Williams, N.M. Laxague, A.J.H.M. Reniers, and H.C. Graber, 2015: The spatial-temporal variability of air-sea momentum fluxes observed at a tidal inlet. Submitted to *J. Geophys. Res*.

IMPACT/APPLICATIONS

None.

RELATED PROJECTS

RIVET II: Satellite Remote Sensing and Small Scale Wave Observations of the Columbia River Mouth
N00014-13-1-0144