In-Flight Data Processing for the Wide Swath Radar Altimeter (WSRA) for Real Time Reporting of Directional Ocean Wave Spectra from the NOAA WP-3D Hurricane Reconnaissance Aircraft

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Prepared for:

Joint Hurricane Test-bed (JHT) Opportunities for Transfer of Research and Technology into Tropical Cyclone Analysis and Forecast Operations

Submitted by

Ivan PopStefanija, Principal Investigator
ProSensing Inc.
107 Sunderland Road
Amherst, MA 01002-1098, USA

A. Abstract

This JHT project focuses on developing the processing algorithms and real-time software needed to perform in-flight data processing for the newly developed Wide Swath Radar Altimeter (WSRA). The WSRA is a novel digital beamforming radar altimeter developed with funding from the NOAA SBIR program, with additional support from the University of Massachusetts and DARPA. This instrument was first deployed aboard the NOAA P-3 hurricane reconnaissance aircraft during the 2008 hurricane season. Raw data gathered during several hurricane reconnaissance flights was processed into directional ocean wave spectra, demonstrating the functionality of the WSRA. Under this contract ProSensing will develop and deploy an in-flight processor to implement the required radar signal processing algorithms in real-time. This effort will include optimization of the WSRA digital beamforming and range centroid tracking algorithms, conversion of the processing algorithms into a multi-threaded C application, and deployment of a multi-core PC processor to execute in-flight processing.

Successful completion of this project will provide continuous real-time reporting of directional ocean wave spectra, significant wave height and the radius of 12’ seas from the NOAA P-3 aircraft to the National Hurricane Center through a satellite data link.

B. Work Performed

During the period of performance covered by this progress report we have performed the following tasks:

TASK 1. Development of a new robust surface elevations extracting algorithm

Throughout the summer of 2010, ProSensing engineers worked on the implementation of the real-time processing code for the unattended operation of WSRA system. This effort will includes optimization of the WSRA digital beamforming and range centroid tracking algorithms, conversion of the processing algorithms into a multi-threaded C application, and deployment of a multi-core PC processor to execute in-flight processing.

In the new code we also implemented several WSRA algorithm improvements:

(1) antenna beam pointing angle adjustment factor calculated based on the estimation of the antenna width distortion caused by the lateral movement of the aircraft during the data integration time.
(2) incremental (looped) estimation of the range to surface weighed by the range estimates in the neighboring beams,
(3) automatic adjustment of WSRA radar parameters as the auxiliary reported aircrafts

altitude changes,

(4) streamlining and automating the backend processing which estimates the ocean wave directional spectra from the surface elevations

(5) developing the script that would format the data products and transmit in-flight the WSRA output data file from the aircraft to the archiving and displaying computers at AOC in Tampa and HNC in Miami.

Once the WSRA front-end processing was translated from the original IDL code into C, the improvement in speed was significant and it was determined that the generation of 80 range and backscattered power values on each raster line could keep pace with a 10 Hz line generation rate in real-time, with just a 3-s gap between sets of 8700 lines. Since there would then be a single block of 8700 lines instead of 29 blocks of 300 lines transmitted to WSRAback.i, both backend programs were revised extensively with WSRAout.i being incorporated into WSRAback.i. Because the front-end processing is now determining the actual beam angles, WSRAback.i is running at about 8 times faster than real-time. The result is that a 14.5 minute (100 km) front-end data file can be processed into output information for display at NHC within 2 minutes of acquisition.

TASK 2. Preparation for the 2010 Hurricane season

We have encountered some difficulties in our efforts to repair the power amplifier. But after locating the manufacturer and learning the unit we had was obsolete, we had to purchase a new power amplifier which was delivered to ProSensing in the middle of June. Due to our internal scheduling conflicts, we startedworking on the software improvements for this year’s hurricane season. These improvements consisted of added robustness and data quality to the surface elevations extracting algorithm, and the development of the unattended operation of WSRA system. Mid-June the software engineer working on the project left ProSensing to attend to personal matters, an event that was unexpected and for which we were not prepared. This added a delay until ProSensing regrouped and hired a replacement. Nevertheless, our new software engineer proved be a strong and competent coder, and the WSRA was almost ready for shipment to AOC in the first week of August. By the second week in the code development and final testing were complete. The WSRA system arrived at NOAA/AOC hanger on August 18th.

TASK 3. Flights in Hurricane Karl

WSRA was installed on the WP-3D aircraft by mid-September and therefore missed the opportunity to fly on the several reconnaissance flights in the hurricane Earl. For the rest of the season,WSRA operated during one flight into a tropical disturbance south of Haiti and one reconnaissance flight into CAT-1 hurricane Karl. The second part of the hurricane season did not provide any additional opportunities to operate WSRA, as all the hurricanes keep far away from the US mainland.

TASK 4. Analysis of the unattended WSRA operation

All the parts of the WSRA software were successfully tested, including the transmitting of the data to AOC. Performance during flights of both software and hardware have shown the feasibility of fully-automated unattended operational WSRA, as both software and processing had sustained without gaps data processing in real-time.

During the flight and post-flight our software engineer made several adjustments to various processing parameters to improve the robustness of the unattended operation of the WSRA system. It also became apparent that backend software, which is calculating the directional wave spectra from the Level 3 data (range vs. angle), has a necessity to receive additional auxiliary information from the aircraft's data system. This additional information should include an update on the eye fix location and VORTEX messages which are issued by the aircraft at the time when it passes the center of the storm.

We have also concluded that frequency of reporting wave spectra to NHC should be variable depending on the aircraft distance from the eye of the hurricane. Wave spectra products updated should vary between 5 minutes at the edge of the hurricane to 30 minutes while flying through eye of the hurricane.

A reconnaissance flight into hurricane Karl was conducted at 12,000 feet, which is a higher altitude than the typically used for these types of flights. An important lesson we learned from the flight into hurricane Karl was that operating from 12,000 feet provides WSRA data with marginal quality.

Figure 1 shows two graphs with the WSRA radar return from ocean surface return where x-axis represents the incidence angle and y-axis represents range from the aircraft, while the value of the SNR is pseudo-color coded with white color representing 0 dB SNR. The left graph shows data obtained during the flight into Hurricane Karl at 12,400 feet altitude, and the graph on the right is from the data obtained in 2008 from Hurricane Ike from at 7,000 feet alitude. Figure 2 shows the two ocean surface topograhy, with differences between two topographies easily noticable.

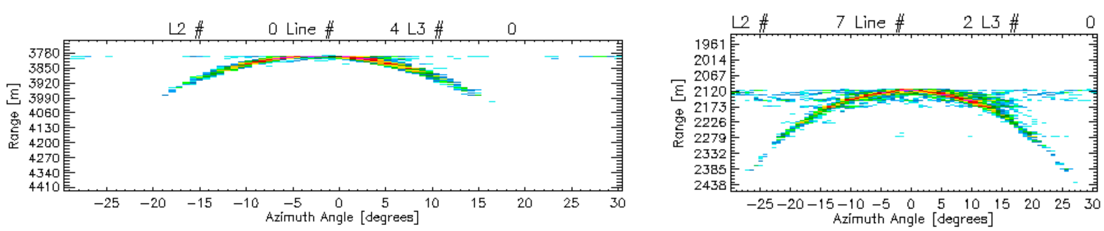

Figure 1. Ocean surface WSRA radar return. Left graph shows data obtained during flight

at 12,400 feet altitude and graph on the right shows data obtained during flight at 7,000 feet altitude

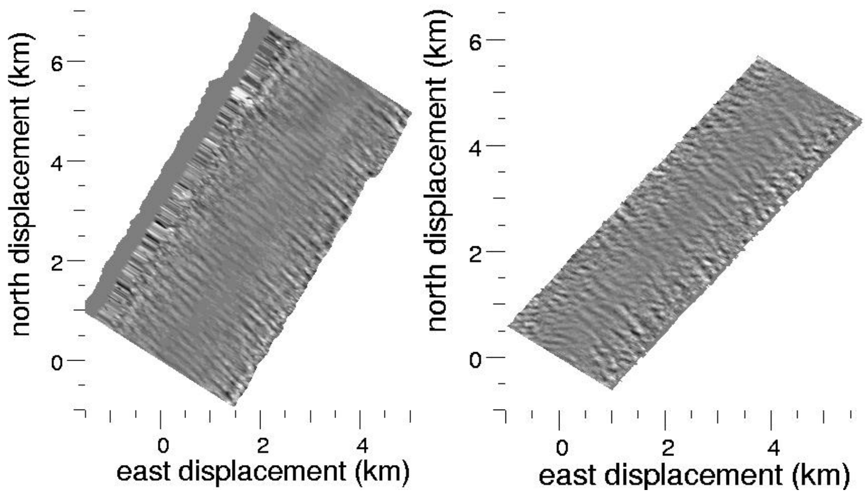

Figure 2. Ocean surface topografy obtained during flight into Hurricane Ike at 8,000 feet altitude

While it is possible to calculate wave spectra from the data set obtained at 12,000 feet with additional post-processing with some data editing; the cleaner topography such as obtained at 10,000’ altitude or lower is necessary for robust real-time unattended operation of the WSRA instrument. In conclusion, for good quality WSRA data needed for unattended self-configuring operation of WSRA, the aircraft’s altitude should not exceed 10,000 feet. *We recommend to the NOAA flight directors fly at 8,000 feet on reconnaissance flights when operating WSRA.*

TASK 5. Repair and Re-design of the WSRA hardware

Hardware issues that occurred during the flight into the Hurricane Karl led us to the re-design of the WSRA electronics (RF section). Specifically, we have eliminated a Ku band oscillator and modified the frequency up and down conversion scheme. The new re-designed RF section uses a single Ka-Band oscillator for both transmitter and receiver chain. The re-design WSRA was tested at our facility and then returned to NOAA/AOC where it is currently residing.

TASK 6. Wide Swath Radar Altimeter (WSRA) Wave Spectra from Hurricane Ike compared with WaveWatch III

At the IHC conference in March, 2011 we presented a poster showing the comparison between the wave spectra measured with WSRA instrument and spectra predicted by a wave model. For this comparison study we have processed raw data (Level-1) into directional ocean wave spectra (Level-3) gathered during the flight into Hurricane Ike on September 11, 2008. Data collected on this reconnaissance flight presented sufficient data to provide an overview of the wave field variation throughout all the regions of the storm. These WSRA obtained wave field spectra compared with the WaveWatch III (WW3) numerical wave model.

The WW3 results were provided by Isaac Ginis and Brandon Reichl of the University of Rhode Island. WW3 wave field were calculated for time of 1230 UTC on September 11, the midpoint of the 5-hour WSRA raw data acquisition period. There is generally a good agreement between the WSRA observations and the WW3 predictions of the spatial variation of wave height around the hurricane. The poster will show segments of WSRA wave topography throughout Hurricane Ike and detailed comparisons of the resulting directional wave spectra with the WW3 model predictions.

TASK 7. Storm Surge Measurement Potential of the Wide Swath Radar Altimeter

The Wide Swath Radar Altimeter (WSRA) has the potential to provide operational, targeted measurements of storm surge for land-falling hurricanes. The concept of airborne measurement of storm surge consists of subtracting the absolute altitude of the aircraft determined using the Global Positioning System (GPS) from the WSRA-measured distance to the sea surface. The result of that simple calculation is the absolute elevation of the water for the particular point in time and space. Wright, *et al*. (2009) demonstrated the technique in a research mode using the NASA Scanning Radar Altimeter (SRA), which has since been decommissioned.

Absolute range calibration of the WSRA can be determined and maintained during the flights using tide gauges within Tampa Bay when returning from each operation, as well as flying by tide gauges in the vicinity of the landfall.

The NOAA WP-3D aircraft carrying the WSRA flew through Tampa Bay as it returned from a flight into Hurricane Ike on September 11, 2008. The five circles in the left panel of xxx show the locations of tide gauges in the vicinity. At the time of the WSRA pass, the two yellow-highlighted tide gauges indicated that the water level was 24.58 m below the ellipsoid (0.83 m above msl) at St. Petersburg and 24.55 m below the ellipsoid (0.71 m above msl) at Port Manatee. The water level along the WSRA track would have been nearly constant at 24.56 m below the ellipsoid, making it ideal for calibrating the WSRA range measurement. The right side of xxx shows that the aircraft height varied by more than 20 m over the 5-km track.

An equation for absolute range calibration of the WSRA would be

$$R_{WSRA} + R_{bias} = h_{GPS} - \Delta h + 24.56 \text{ m} \qquad (1)$$

where R_{WSRA} is the range to the sea surface measured by the WSRA, R_{bias} is a constant range bias which compensates for any internal delays and converts the measured WSRA range to the distance from the antenna to the sea surface, h_{GPS} is the height of the aircraft GPS antenna above the ellipsoid, Δh is the vertical distance between the GPS antenna above the aircraft and the WSRA antenna beneath it.

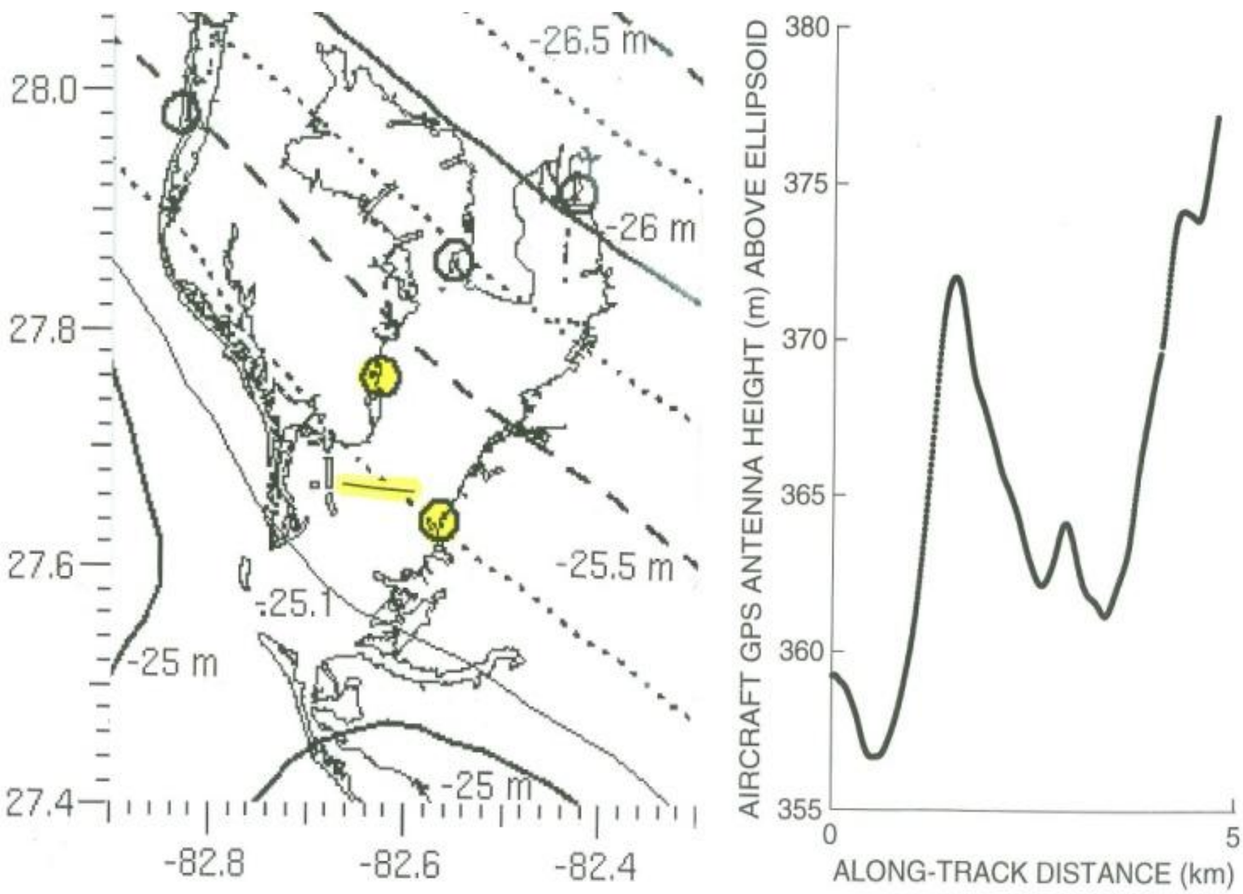

Figure 3. Left panel shows contours of geoid height relative to the ellipsoid in the Tampa Bay area. Right panel shows the GPS measured aircraft height above the ellipsoid along the straight 5-km flight segment yellow-highlighted in the left panel.

Substituting C = 29.89 m = 24.56 - R_{bias} - Δh, equation (1) can be rearranged to

$$R_{WSRA} - h_{GPS} - C = E_{RES} \qquad (2)$$

For error-free measurement, the value of E_{RES} would be zero. The curves in xxx show the aircraft pitch and roll variation along the flight segment of Figure 1 and the dots show the values of E_{RES}, the residual error computed from equation (2) at the WSRA 10 Hz rate. The values fluctuate about zero with a 13 cm standard deviation. The systematic deviations from zero appear to be correlated with aircraft roll. Those deviations could be reduced by more sophisticated processing, but simply averaging the data over 1 km reduces the standard deviation below 4 cm, excellent considering the 20 m aircraft height change.

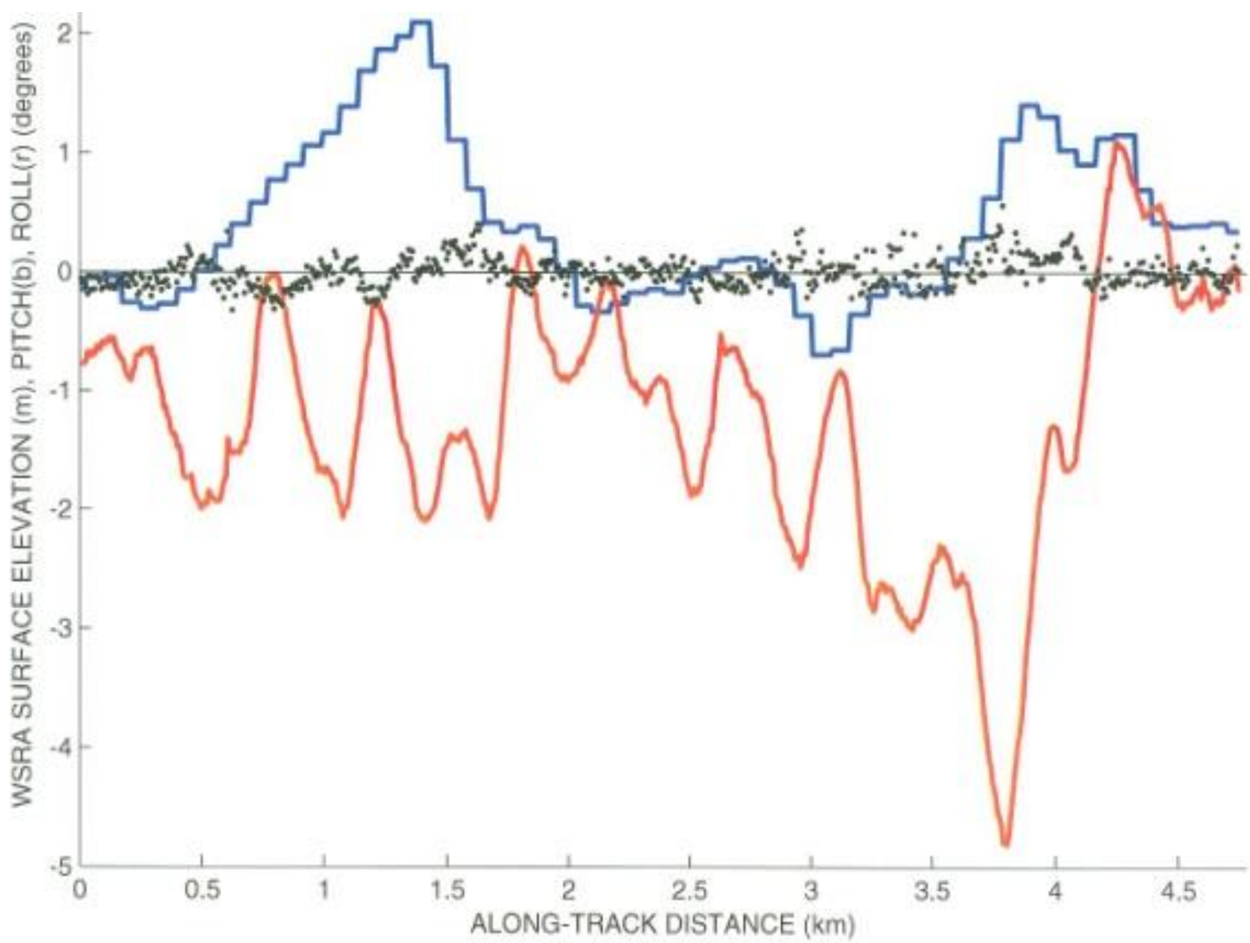

Figure 4. Curves show the aircraft pitch (blue) and roll (red) variation for the highlighted flight segment over Tampa Bay and dots represent the residual error E_{RES} as defined in equation (2).

Labor breakdown for the work performed during the Period 8/1/2010-2/28 2011

Employee Name	Title	Hours
Baldi, Chad A	**Electrical Engineer I**	10.00
Popstefanija, Ivan	**Principal Investigator**	83.00
Slavich, Nicholas M	**Software Engineer I**	303.00
TOTAL		**396.00**