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

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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. WSRA Installation on WP-3D #N42 aircraft for the test flight in early March

For the previous test flights, WSRA was installed on the N43 aircraft. Because of scheduling conflicts during the next season, NOAA AOC decided to install the WSRA on the #N42 aircraft. Therefore, this was a new installation for this instrument and NOAA AOC had to remake most of the harness and cooling lines running through the aircraft’s fuselage. ProSensing also had to modify the WSRA antenna installation on the N42 fearing which was significantly different from the fearing on the N43 aircraft. Modifications were done in such a manner that in the future the WSRA will be able to be installed on either aircraft. By the end of the February, the WSRA was successfully installed on NOAA’s WP-3D N42 aircraft.

TASK 2. WSRA test flight on March 3rd, 2010

In collaboration with NOAA/AOC, the WSRA test flight was conducted on March 3rd 2010. For the purposes of the testing the WSRA data quality against the varying aircraft parameters: flight altitude, pitch, roll, and most importantly, cross track movement of the aircraft (caused by flight level winds) we designed a specific flight pattern for this test flight.

Planned flight pattern that was reviewed and agreed with the NOAA AOC Aircraft Commander and Navigator was:

- **LEG 1 altitude 12000 feet** Segments 1-8: Two level attitude boxes with 2 minute duration segments and quick sharp 90 degree turns between the 4 segments. The 4 segments are oriented parallel to and perpendicular to the flight level wind. Begin box flying WNW into the wind. After LEG 1 complete: Descending 360 down to 10K to set up for LEG 2

- **LEG 2 altitude 10000 feet** Segments 1-8: Two level attitude boxes with 2 minute duration segments and quick sharp 90 degree turns between the 4 segments. The 4 segments are oriented parallel to and perpendicular to the flight level wind. Begin box flying WNW into the wind. After second box is complete turn back into the wind to begin next sequence:

- Segment 9: Roll LEFT from 0 degrees to -30 degrees (Rolling rate 2 seconds per degree Duration 1 minute Segment 10: Roll RIGHT from -30 degrees through zero to +30 degrees (Rolling rate 2 seconds per degree Duration 2 minute) Segment 11: Roll LEFT from +30 degrees back to 0 degrees (Rolling rate 2 seconds per degree Duration 1 minute)Segment 12: Pitch UP from nominal to +3 degrees greater than nominal (Pitching rate 5 seconds per degree Duration 15 seconds) Segment 13: Pitch DOWN from +3 degrees above nominal to -3 degrees below nominal (Pitching rate 5 seconds per degree Duration 30 seconds) Segment 14: Pitch UP from -3 degrees below nominal back to nominal pitch angle (Pitching rate 5 seconds per degree Duration 15 seconds) After LEG 2 complete: Reverse course and descend to 5K to return back to anchor point for beginning of LEG 3

- **LEG 3 altitude 5000 feet** Segments 1-8: Two level attitude box with 2 minute duration segments and quick sharp 90 degree turns between the 4 segments. The 4 segments are oriented parallel to and perpendicular to the flight level wind. Begin box flying NW into the wind. After second box is complete turn back into the wind to begin next sequence (this sequence is identical to the one at 10,000 feet):Segment 9: Roll LEFT from 0 degrees to -30 degrees (Rolling rate 2 seconds per degree Duration 1 minute Segment 10: Roll RIGHT from -30 degrees through zero to +30 degrees (Rolling rate 2 seconds per degree Duration 2 minute) Segment 11: Roll LEFT from +30 degrees back to 0 degrees (Rolling rate 2 seconds per degree Duration 1 minute) Segment 12: Pitch UP from nominal to +3 degrees greater than nominal (Pitching rate 5 seconds per degree Duration 15 seconds) Segment 13: Pitch DOWN from +3 degrees above nominal to -3 degrees below nominal (Pitching rate 5 seconds per degree Duration 30 seconds) Segment 14: Pitch UP from -3 degrees below nominal back to nominal pitch angle (Pitching rate 5 seconds per degree Duration 15 seconds) After LEG 3 complete: Reverse course and descend to 2K to return back to anchor point for beginning of LEG 4

- **LEG 4 altitude 2000 fee**t Segments 1-8: Two level attitude boxes with 2 minute duration segments and quick sharp 90 degree turns between the 4 segments. The 4 segments are oriented parallel to and perpendicular to the flight level wind. Begin box flying NW into the wind. After second box is complete, coordinate with ATC for LEG 5

- **LEG 5 altitude 1500 feet** Overfly Skyway and proceed down center of the mouth of Tampa Bay (we need at least 30 seconds of straight and level measurement at 1500 ft over the Bay in this segment to accomplish test objective). After 1500 ft segment is complete, lower altitude (1000 and/or 500 ft) if Pro Sensing requests.

The test flight was a partial success because the WSRA's Ka-Band power amplifier worked only intermittently during the flight. WSRA test data were collected only for one [LEG 3] which latter data analysis showed to be sufficient for meeting our goals of this flight test.

TASK 3. Development of a new robust surface elevations extracting algorithm

As work has progressed toward unattended operation for the WSRA, insights have been obtained that have lead to system design changes and refinements. For example, even though the WSRA antenna is a rigid, nearly square rectangle, it was recognized that its effective shape in the presence of a strong wind deforms to a parallelogram. Cross-track wind components modulate the effective width of the antenna, widening or narrowing the angular spacing of its 80 digitally generated beams.

Figure 1 below (the same as Figure 4 in the Second Year Proposal Renewal for this task) shows the false-color-coded power versus range for the 80 digitally-formed narrow beams spread over incidence angles of about ±30° for cross-track raster line 9 from a file recorded during the 3 March 2010 test flight. The aircraft height was 1520 m and the variation in range of the power backscattered from mean sea level would be $1520/\cos\Theta$ where Θ is the off-nadir incidence angle. That approximately parabolic increase in range is apparent in Figure 1, but there is also a significant amount of clutter, particularly at the shorter ranges.

The original algorithm, which generated the sets of lines in Figure 1, assumed that the nadir beam was the one with the minimum range. Because there is little range variation near nadir, elevation changes due to waves and fluctuations in the backscattered power can shift the minimum range of the peak power away from nadir, by about -2° in the case of line 9. The central red parabola indicates the projected ranges for the off-nadir beams and the black curves symmetrically displaced from it are the initial boundaries for the range window within which the centroid of the backscattered power will be determined.

The symmetrical red parabola matches the range variation of the backscattered power fairly well on the right side but is too short in range on the left side. This asymmetrical mismatch occurred because the error in the assigned position of the nadir beam combined with the beam angles being larger than their nominal values due to the modulation of the effective width of the WSRA antenna by a crosswind (Walsh, 2009).

On the right side the original algorithm functioned well. First, within the large initial window boundaries (black curves), it determined the range of the peak power, which was always associated with mean sea level. It then successively narrowed the window twice (green and blue curves) about that peak to eliminate extraneous signals before determining the range centroid of the power within the final window.

On the left side, because the initial range window (black curves) were not symmetrically positioned about the return from the sea surface, on 6 occasions they included extraneous signals which were larger than the returns from the sea surface. The successive windows then narrowed about the erroneous ranges and major errors in the range determination resulted.

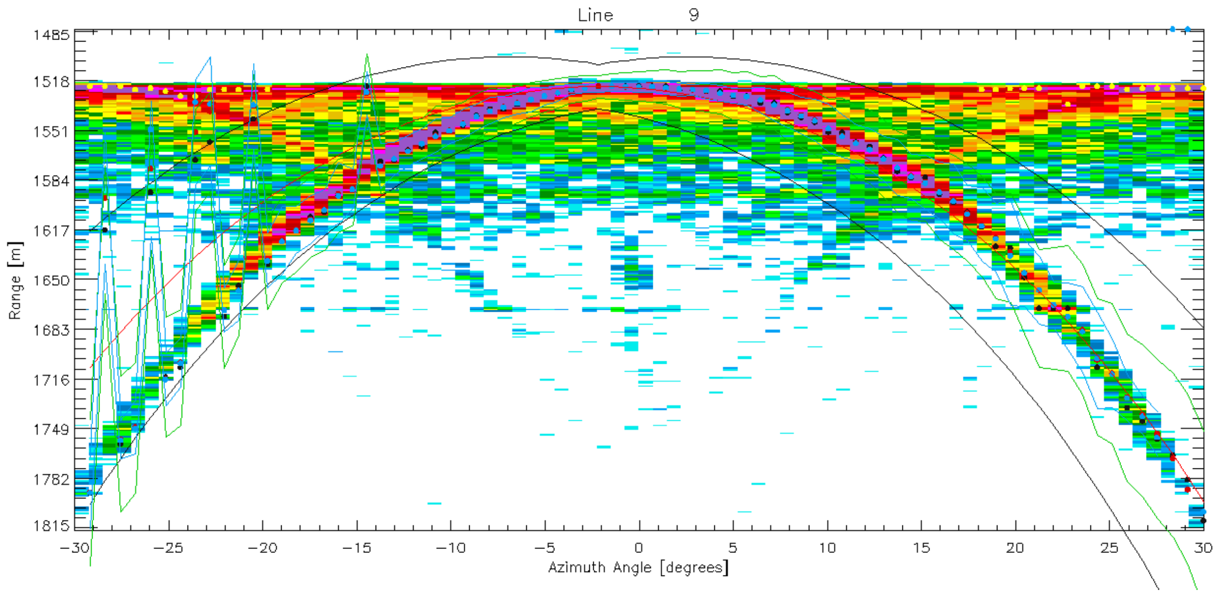

Figure 1 Swath image (range vs angle) of the WSRA radar return. Black green and blue lines showed the three step window limits of the old elevation extraction algorithm.

Figure 2 shows the result of processing the same line shown in Figure 1 using the improved algorithm. The original algorithm required a wide initial window because a small error in the initial assignment of the nadir beam would result in a large shift in the window location for the off-nadir beams, as seen on the left side of Figure 1. If the initial window had been half as wide in Figure 1, it would not even have included the sea return at -30°.

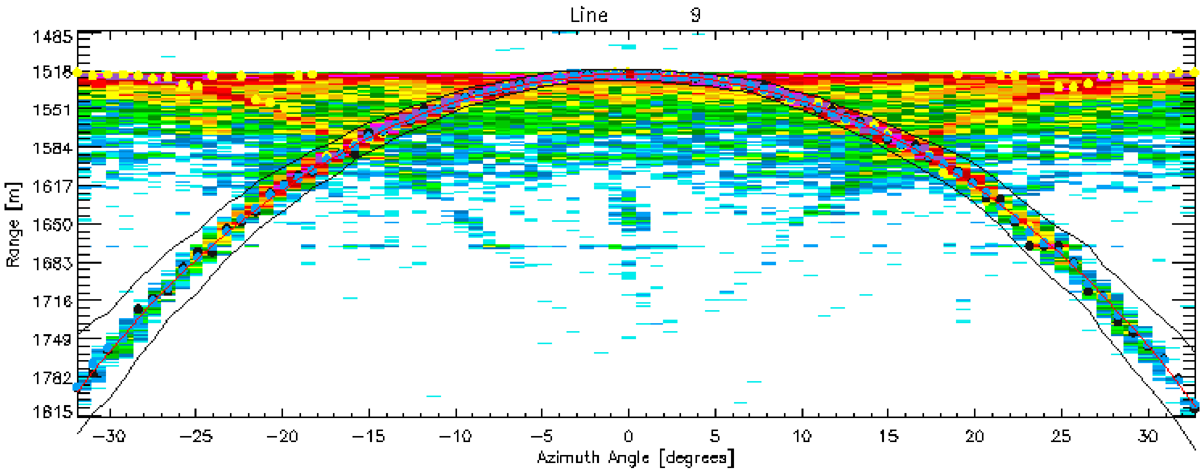

Figure 2. Swatdh image (range vs angle) of the WSRA radar return –same as in Figure 1. Black lines showed the one step window limits of the new robust elevation extraction algorithm.

The improved algorithm (Figure 2) uses only one narrow range window. That was made possible by working incrementally outward from nadir in both directions. Instead of assigning the initial window positions for all 80 beams based on the height and the position of the nominal nadir beam, only the range windows for the beams on either side of the nominal nadir beam are assigned. After the centroid ranges for those beams are determined, the windows are positioned for the beams next to them. Even if the variation of range to the sea surface differs significantly from the nominal variation because a crosswind has modified the effective width of the WSRA antenna and changed the beam angles, the incremental error from one beam to the adjacent beam will be small. And since the final centroid range determination is made for a given beam before the next window is positioned, the errors cannot accumulate. This allows the range window to be narrowed to the extent that would be reasonably expected to encompass only the sea return (Figure 2).

When the modulation of the effective width of the WSRA antenna was first recognized, the initial solution considered was to use the crosswind component from the aircraft data system and the WSRA PRF to determine the effective width of the antenna and the modified angles of the 80 composite beams to decrease the mismatch in the placement of the initial range windows (Figure 1).But the incremental technique has proven so robust there is no need to do that, as demonstrated by Figure 3.

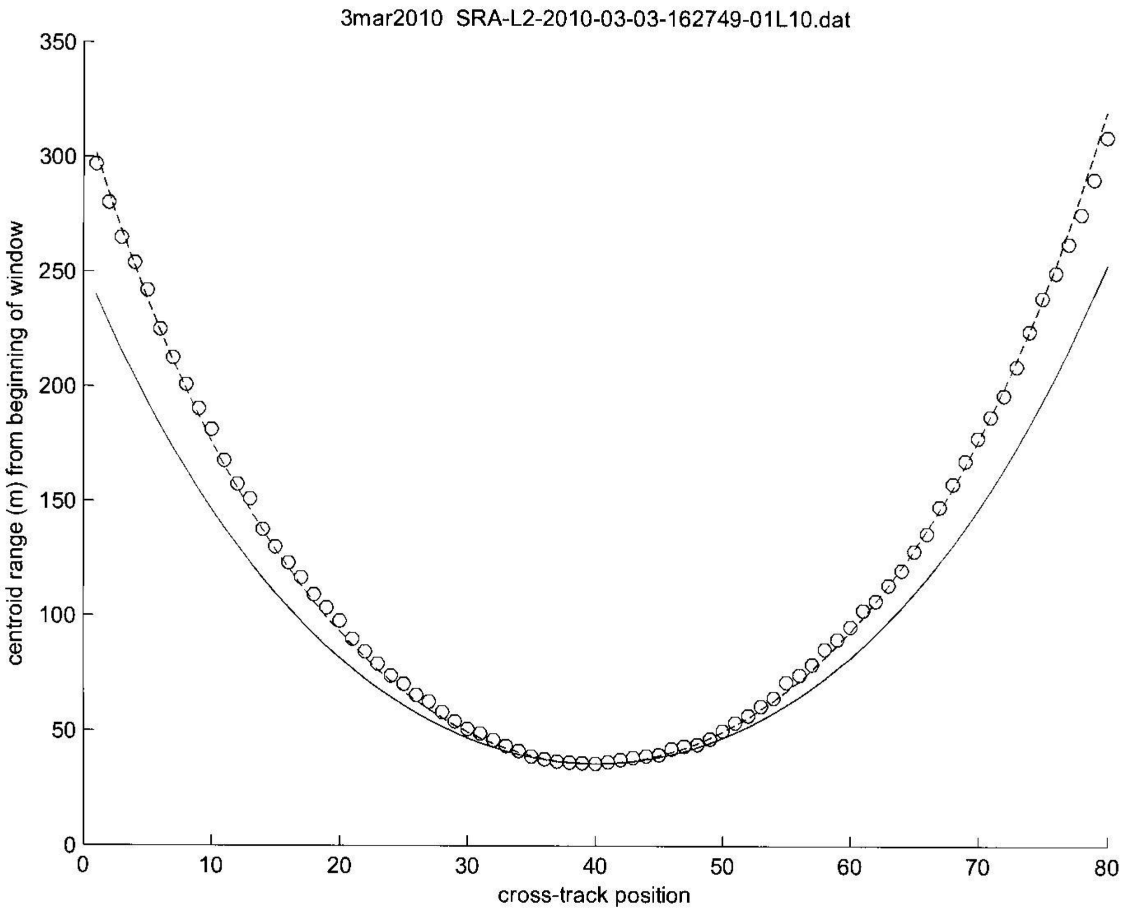

Figure 3.Extracted ranges based on the new robust surface elevation extraction algorithm.

The dashed curve in Figure 3 is h/cosθ for angles which are 11% larger than their nominal values. This spreading resulted from the cross-track wind component. The data points (o) were determined by running the algorithm using the nominal values of the angles which predicted the range variation shown by the solid curve. The nominal ranges differ by 60 m at the edge of the swath but there were still no outliers using the incremental technique and the centroid ranges were all accurately determined.

The incremental technique is not dependent on continually using wind speed data from the aircraft data system to function. Also, the nadir beam determination needs only be based on the minimum range for the very first line of a data file. Once the 80 ranges are determined for the first line, the location of the nadir beam as well as the actual beam angles are computed and used as a starting point for the following raster line.

The new front end range and angle determination technique lead to a significant refinement in the backend processing. Initially there were two independent Yorick programs developed for the backend processing. The original concept was that as groups of 300 raster lines of 80 range and backscattered power values across the swath were generated by the radar, they would be transferred to the backend computer to be processed into wave topography and directional wave spectra by Yorick program WSRAback.i. Once a total of 8700 lines had been transferred in 29 increments, Yorick program WSRAout.i would check for any new eye fix, integrate the time history of the hurricane wind field to eliminate the spectral artifact lobes, Doppler correct the real directional wave spectrum lobes, produce output spectra by averaging non-overlapping groups of five individual spectra, and correct the output spectra for reductions in spectral density due to spatial filtering by the antenna footprint and increases due to tilt modulation enhancement by off-nadir scattering effects. WSRAout.i would then transfer to average, corrected directional wave spectra to the aircraft data system along with a summary header containing wave field and flight parameters for transmission to a server at AOC from which they could be extracted and displayed at NHC by the JHT server.

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.

REFERENCE

Walsh, E. J., 2009: Final Report for the Joint Hurricane Testbed project “Operational Use of Near-Real-Time Sea Surface Directional Wave Spectra Generated from NOAA Scanning Radar Altimeter Range Measurements”, 30 November 2009.

TASK 4. 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 discovering the unit that 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 start the working 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 left ProSensing to attend to personal matters, an event that was unexpected and for which we were not prepared. This added a delay while 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. Unfortunately, a day or two before the final testing the new software engineer, Nick, had to have his appendix removed, which kept him out of work for five days. He was able to return the second week of August to finish up the code and final testing. The WSRA system arrived at NOAA/AOC hanger on August 18th.

Labor breakdown for the work performed during the Period 2/1-7/31, 2010

Employee Name	Title	Hours
Baldi, Chad A	Electrical Engineer I	15.50
Cunningham, Michael J	Electrical Technician	4.00
Lamoureux, Richard A	Electrical Technician	48.00
Lee, Geoffrey D	Mechanical Engineer	2.00
PopStefanija, Ivan	Principal Investigator	40.00
Seeger, Bethany A	Software Engineer II	4.00
Simakauskas, Brian H	Electrical Engineer I	10.50
Slavich, Nicholas M	Software Engineer I	80.10
TOTAL		**204.10**