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

Final report

February 28, 2012

Prepared for:

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

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A. Introduction

The NOAA airborne Wide Swath Radar Altimeter (WSRA) is a digital beamforming radar altimeter developed by ProSensing with funding from the NOAA SBIR and JHT programs, with additional support from the University of Massachusetts and DARPA. This JHT project focuses on developing the processing algorithms and software needed to perform in-flight and in real-time data processing for the newly developed Wide Swath Radar Altimeter (WSRA).

Under this contract, ProSensing developed and successfully deployed an in-flight processor to implement the required radar signal processing algorithms in real-time. Under this effort ProSensing performed the following work: optimized the WSRA digital beamforming and range centroid tracking algorithms, converted the processing algorithms into a multi-threaded C code based application, implementation of a multi-core PC processor to execute WSRA processing and data management software, and developed a script for managing unattended operation of WSRA system.

Successful completion of this contract provided continuous real-time reporting of directional ocean wave spectra and significant wave height from the NOAA P-3 aircraft to the National Hurricane Center (NHC) through a satellite data link.

B. Technical objectives

The main objective for this effort was to develop an in-flight, autonomous (i.e. unattended operation) data processor for the WSRA system that would provide in real-time reliable ocean wave measurements to the NHC. The WSRA wave data were transmitted to NHC in real-time on all reconnaissance missions with NOAA’s N42 aircraft during the 2011 hurricane season. This included three flights on three consecutive days into Hurricane Irene, which also included the landfall mission.

Important technical objectives performed to accomplish the main goal were:

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

We analyzed the WSRA raw data collected during the 2008 season (storms Fay, Gustav and Ike) to aid the development of a new robust surface elevations extracting algorithm. This effort included 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.

The WSRA processing algorithm is considerably more complex than most radar processing algorithms. The pre-processing algorithm requiring sequential sampling of the backscattered signal from 62 subarrays, a first level FFT for range processing, application of phase correction to each subarray's range profile, a second level FFT for digital beamforming to form a single strip image, non-coherent averaging of subsequent strips to reduce fading, and finally a centroid tracker to estimate surface height.

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 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/cosΘ 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.

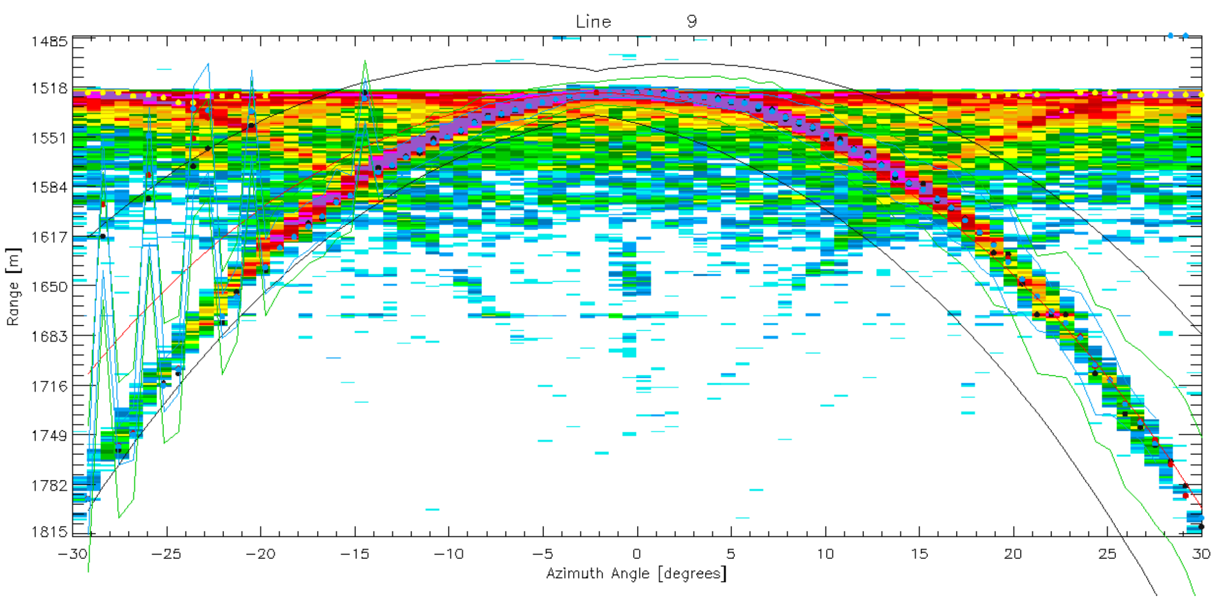

Figure 1. Swath image (range vs angle) of the WSRA radar return. Black green and blue lines showed the three step window limits of the old elevation extraction algorithm.

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. 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 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°.

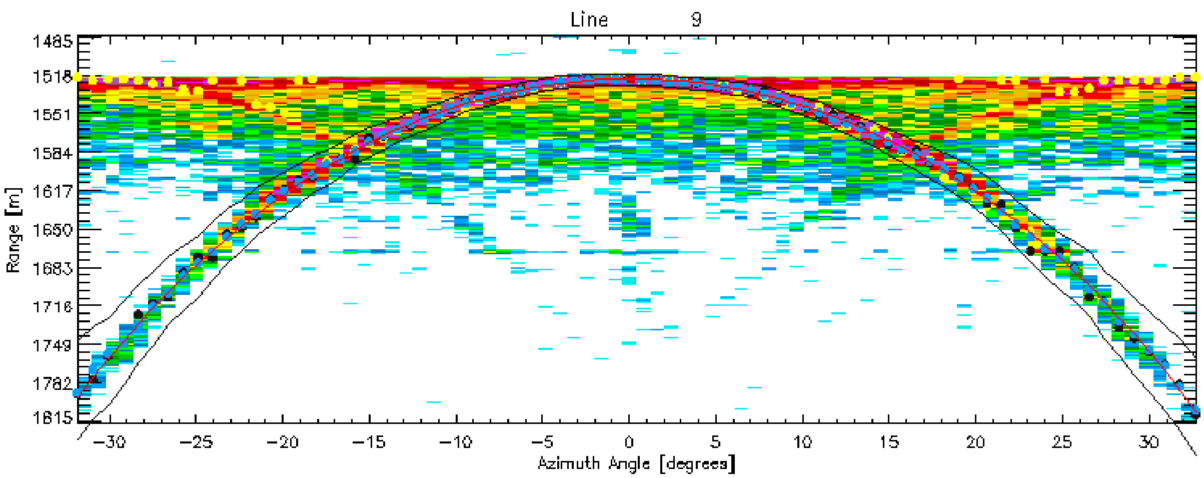

Figure 2. Swath image (range vs angle) of the WSRA radar return –same as in Figure 1. Black lines showed the one step window limits of the new robust elevation extraction algorithm.

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.

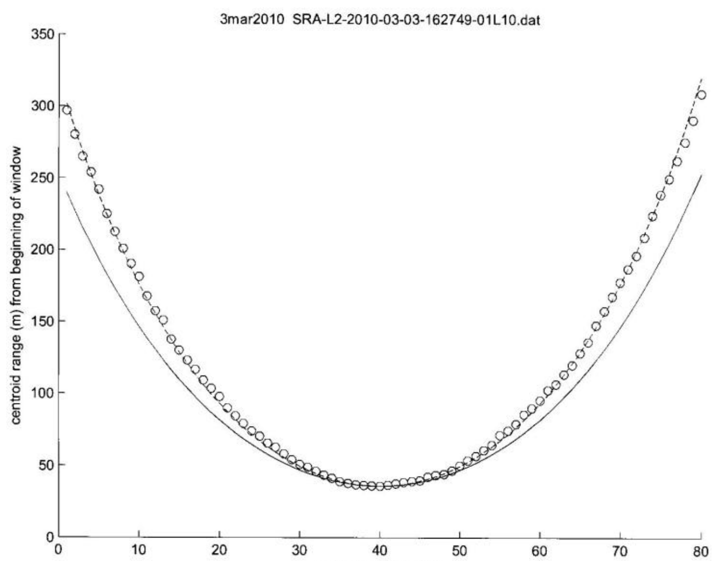

Figure 3. Extracted ranges based on the new robust surface elevation extraction algoritham.

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.

TASK 2. Development of fast and efficient WSRA processing code for calculation of ocean wave parameters

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 2700 lines had been transferred in 9 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.

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 included the implementation of new 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.

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 no gap between sets of 2700 lines. With the new configuration of the WSRA data packaging (2700 lines blocks), 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 processing WSRA radar data 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.

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 neighbouring 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.

TASK 3. Analysis of the unattended WSRA operation based on the flights during 2010 hurricane season and test flight in the spring of 2011

On the flights with WSRA system during 2010 all parts of the WSRA software where 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 hard sustained without gaps data processing in real-time.

During the flight and in 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) does have a necessity to receive additional auxiliary information from the aircraft's data system. This additional information should include 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

Reconnaissance flight into hurricane Karl was conducted at 12,000 feet which is a higher altitude then the typically used for this type of flights. A most important lesson we learned from the flight into hurricane Karl was that operating from 12,000 feet provides WSRA data with marginal quality.

Figure 4 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. Left graph shows data obtained during flight into Hurricane Karl at 12,000 feet altitude and the grpah on the right is from the data obtained in 2008 from Hurricane Ike from at 8,000 feet alitude.

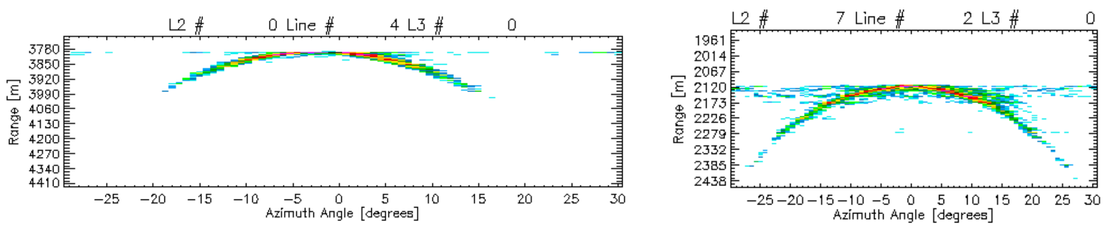

Figure 4. Ocean surface WSRA radar return Left graph shows data obtained during flight at 12,000 feet altitude and graph on the right shows data obtained during flight at 12,000 feet altitude

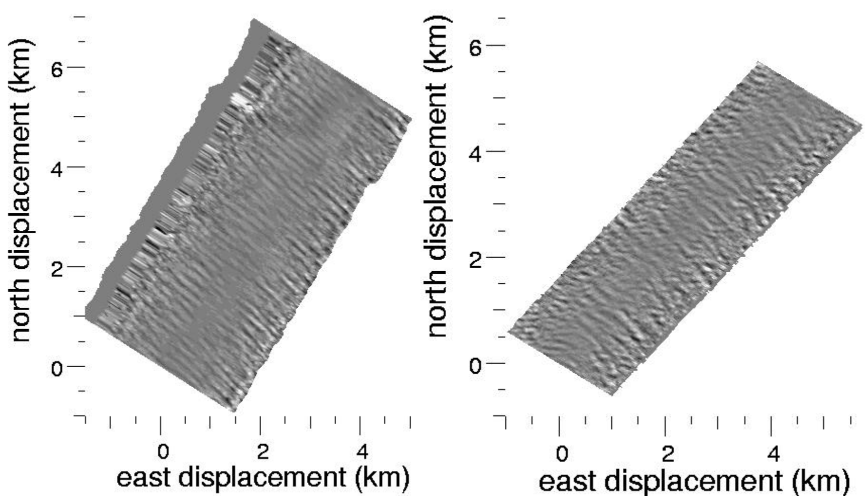

Figure 5. Ocean surface topography obtained during flight into Hurricane Ike at 8,000 feet altitude

While it is possible to calculate wave spectra from the data set obtained at 12,000 feet with additional post-processing; cleaner topography obtained at 8,000’ altitude is necessary for robust real-time unattended operation of 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 flying at 8,000 feet on reconnaissance flights when operating WSRA.

TASK 4. Development of software code for managing unattended operation of WSRA system

Throughout the spring and summer of 2011, ProSensing engineers worked on the implementation of the script that was managing WSRA processing software modules to achieve the unattended operation. WSRA software consist of following modules: (1) front-end radar signal processing code that converts the sampled radar echo (Level 1) into a multibeam (swath) ocean surface return (Level 2); (2) code that extracts cross track surface elevation strips (Level 3) from the radar return swath and (3) module that estimates directional ocean wave spectra from buffered surface elevation strips.

The script for managing unattended operation performs the following tasks: (1) synchronizing the operation of all the software modules, (2) monitoring the aircraft's altitude and reconfiguring the radar hardware accordingly, (3) receiving and processing VORTEX messages containing the hurricane eye fixes which helps resolving the 180 ambiguity of the ocean wave spectra, and (3) transferring the final WSRA data products significant ocean wave and directional wave spectra to a ftp site at NOAA AOC facilities. This transfer is accomplished using the onboard satellite connection

TASK 5. Operation of the WSRA during the 2011 Hurricane season

On June 28th of 2011, ProSensing, with support from NOAA, conducted an 8 hour test flight with WSRA installed on NOAA WP-3D N42. The main focus of this test flight was testing the unattended operation of WSRA. Several issues and problems with unattended operation have been discovered during the test flight. All the encountered problems (in-flight processing of the VORTEX message, hard drive speed, correct configuration of the data transfer command, etc.) have been subsequently resolved. Data collected on this flight also helped improve the robustness of all data processing modules. Several code and hardware modifications were implemented to improve the processing capability. These improvements allowed for a robust data collection up to 10,000 feet aircraft's altitude which is the typical hurricane reconnaissance altitude.

During the test flight on June 28th WSRA also collected the data during the low altitude (< 1000m) pass over the Tampa Bay. These data will be used for the calibration of the WSRA absolute altitude measurement by a comparison to several tidal gages placed in the Tampa Bay.

Flights during 2011 Hurricane season (only covering months of July and August)

On June 28th 2011 ProSensing supported the WSRA operation on WP-3D N42 aircraft in it's the first mission of the 2011 Hurricane season into TS Don. On June 28th TS Don was located in Gulf of Mexico, just south of New Orleans. All aspects of the automated WSRA operation of were successful. Data were transmitted to NOAA/AOC ftp site and from there to the computers located at the NOAA NHC facilities in Miami. **Figure 6** shows the WSRA data layer from the real-time display on the JHT server at NHC.

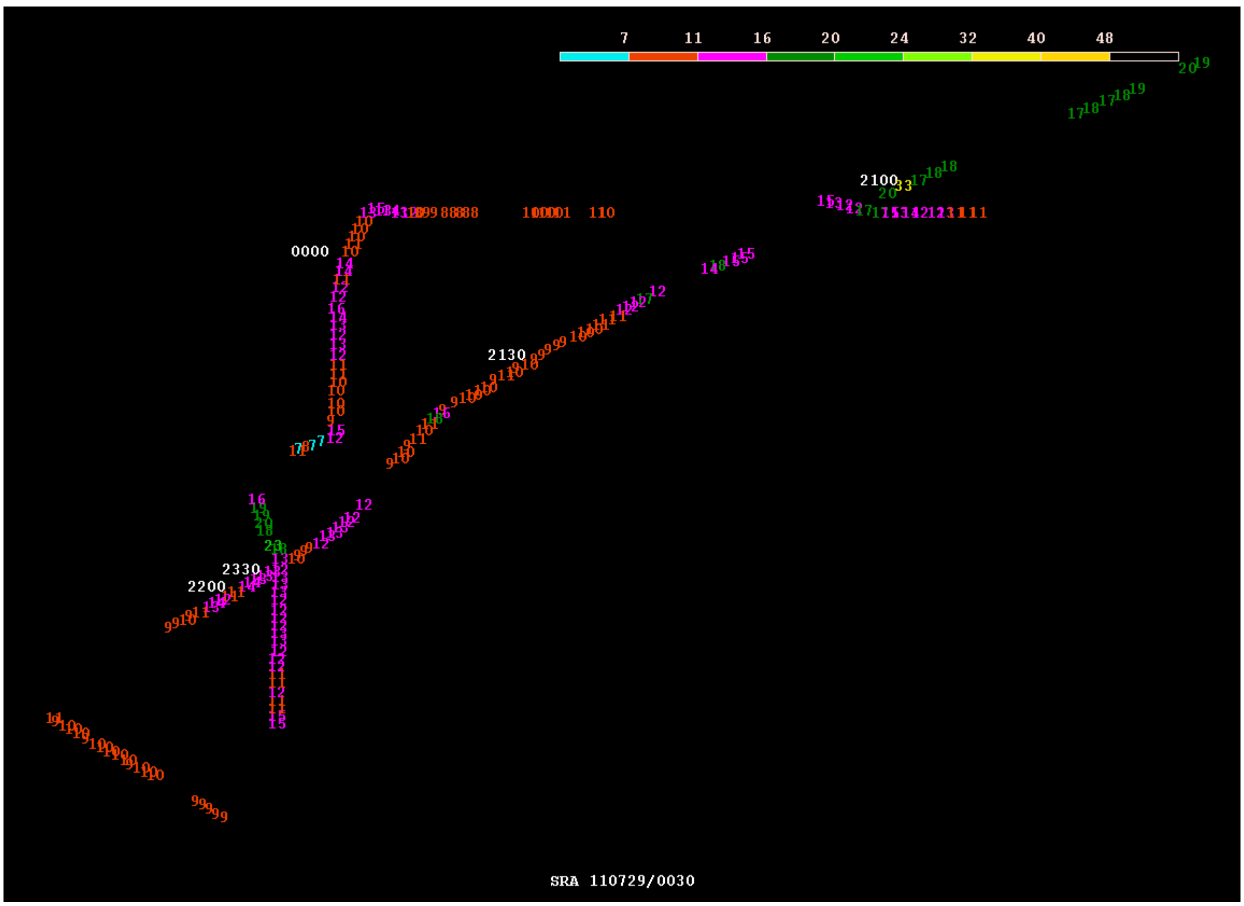

Figure 6. WSRA data layer from the real-time display at NHC during the flight into TS Don on July 28th 2011.

During the month of August WP-3D N42 with WSRA had four mission flights, three in hurricane Irene (each 12 hour missions on August 24th, 25th and 26th) and one in the tropical depression 13 in the Gulf (8 hour mission). On these flights WSRA was operated without the presence of ProSensing staff onboard the aircraft. After the start up by NOAA AOC staff, WSRA would operate unattended for the entire duration of the flight.

During the month of August ProSensing developed a small utility for display on Google Earth of WSRA data that have been transmitted from the aircraft. Figure 7 ,Figure 8Figure 9 show the images with WSRA data overlaid in Google Earth.

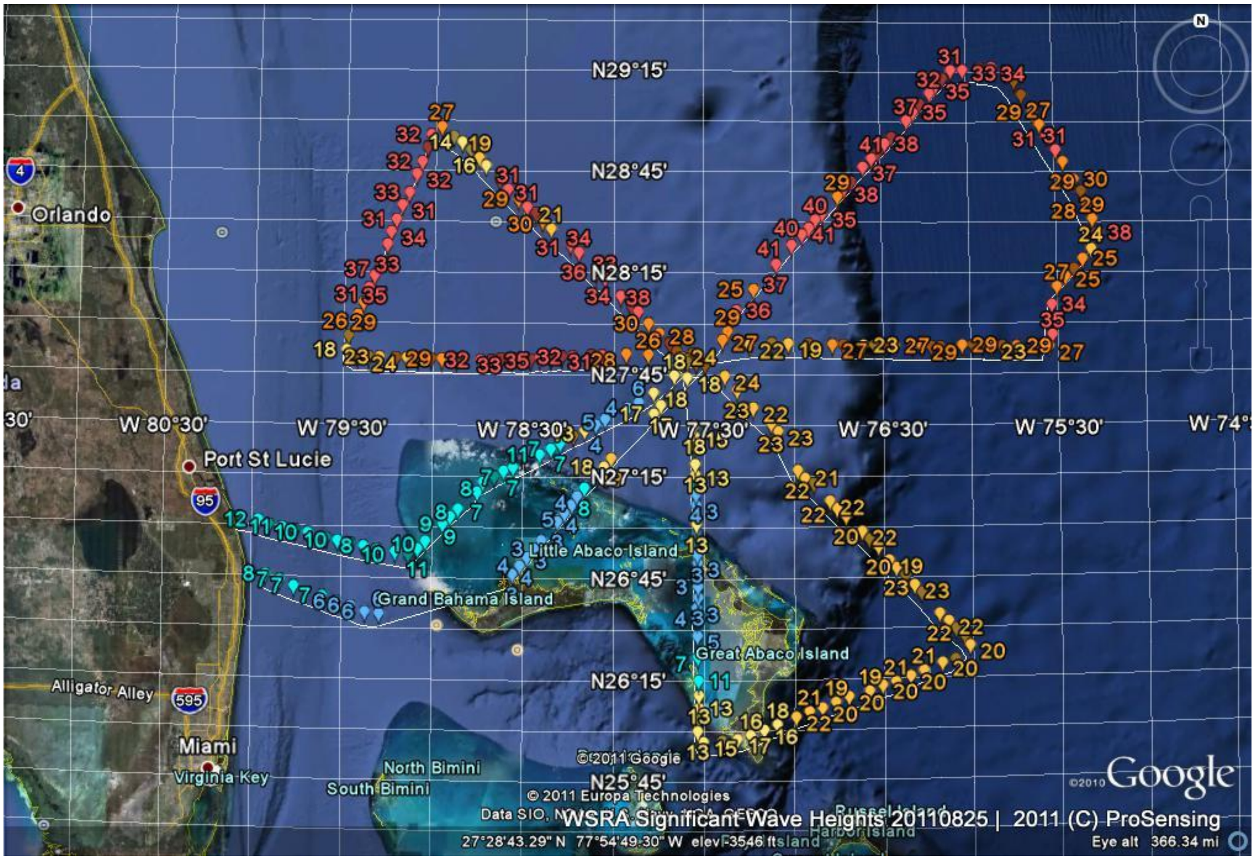

Figure 7. WSRA data from flight 20110825H into Hurricane Irene

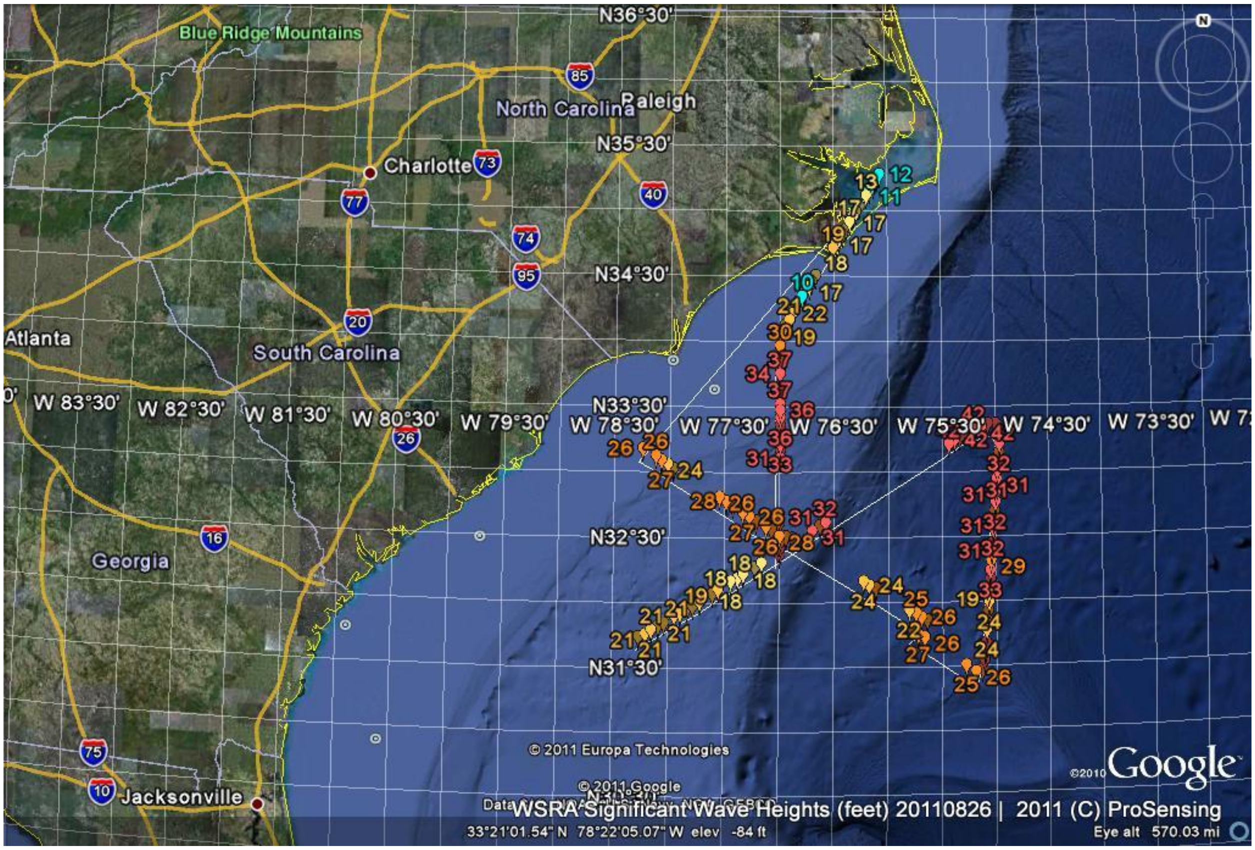

Figure 8. WSRA data from flight 20110826H into Hurricane Irene

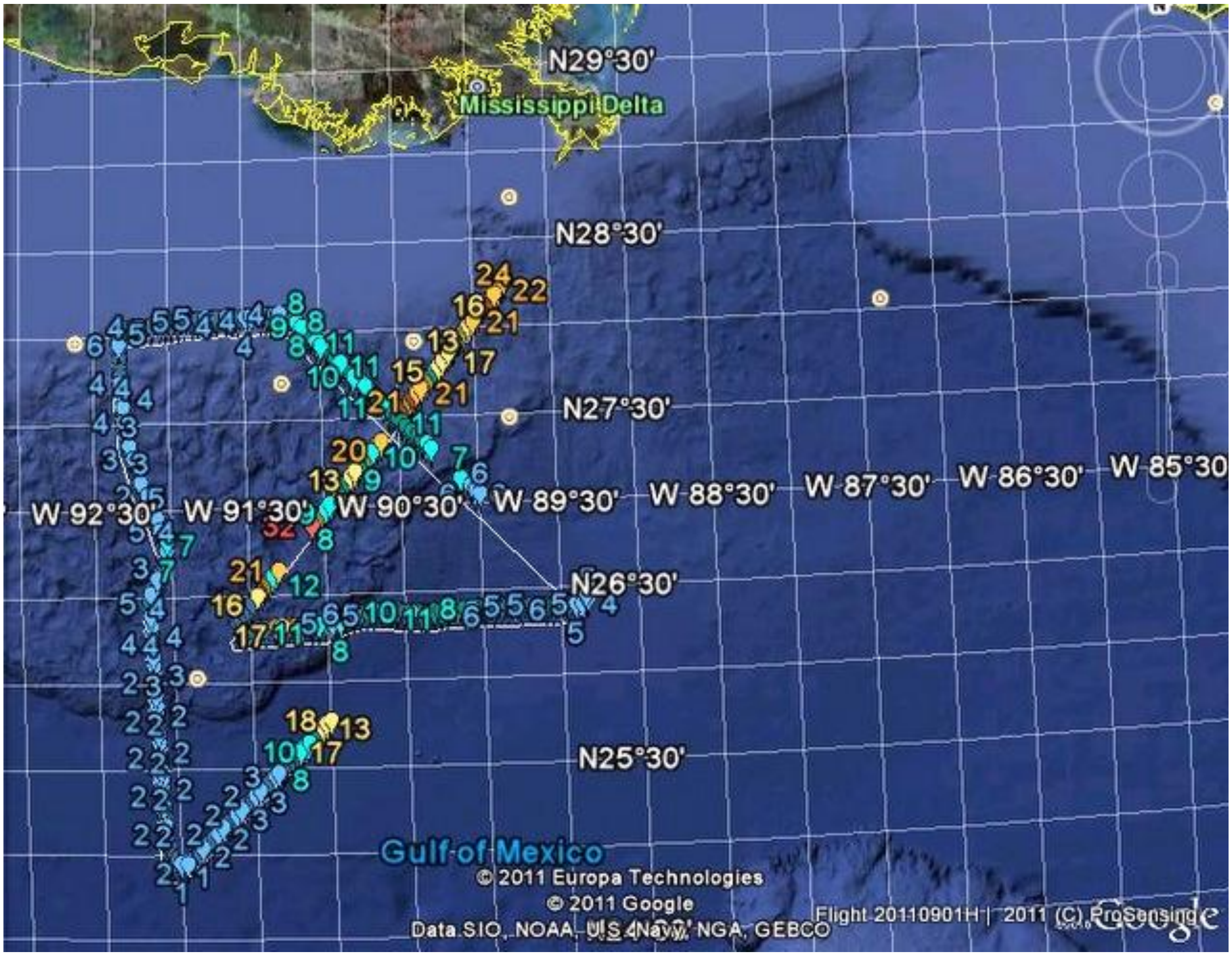

Figure 9. WSRA data from flight 20110901H into TD-13

Conclusion and future work

The main goal of this JHT effort, completing the development of the WSRA system for operational use by NOAA, has been accomplished. Last year, on June 28th, the WSRA was operated on WP-3D N42RF aircraft in its first mission of the 2011 hurricane season into TS Don, located in the Gulf of Mexico just south of New Orleans. All aspects of automated WSRA operation were successful. Data were transmitted to NOAA/Aircraft Operations Center (AOC) ftp site in Tampa, and from there to the computers located at the NOAA NHC facilities in Miami.

During the month of August, WP-3D N42RF with WSRA had four mission flights, three in hurricane Irene (12-hour missions on August 24th, 25th and 26th) and one in tropical depression 13 in the Gulf (8-hour mission). On these flights the WSRA was operated without the presence of ProSensing staff onboard the aircraft. After the startup by NOAA AOC staff, WSRA operated unattended for the entire duration of the flight.

For future work we recommend following the tasks, all intended to improve the quality of WSRA data products and the instrument's operational robustness in support of the NOAA hurricane research and operations missions.

Task 1: Incorporate WSRA radar returns from grating lobes

The WSRA radar collects data over a cross-track swath of 80 digitally formed beams. During the aircraft maneuvers with high roll angle the radar return from the ocean surface for the beams at large incidence angles is much lower than from the corresponding grating lobes with incidence angles significantly closer to nadir. Additional processing code needs to be developed that will make use of the grating lobe returns when possible. Implementation of this feature would improve the quality of the ocean surface topography data during high roll angle aircraft maneuvers or when flying through turbulent regions such as in the hurricane's eye wall.

Task 2: Web-based WSRA data display application

Develop a web-based application that will display the WSRA data products. This application, executed within the web browser, would connect in real time to the NOAA AOC server where the WSRA data are transferred from the aircraft. The WSRA display application should be compatible with popular web browsers such as IE and Firefox, and should be distributed to the researchers within NOAA interested in reviewing WSRA data products either in real-time or post-mission. This ease of access is important to ensure maximum dissemination and utility of the unique data the WSRA provides.

Task 3: Improvements in managing unattended operation of the WSRA

The script for managing unattended operation of the WSRA performs the following subtasks: (1) synchronizing the operation of all the software modules, (2) monitoring the aircraft's altitude and reconfiguring the radar hardware accordingly, (3) receiving in real-time and processing VORTEX messages containing the hurricane eye fixes, and (4) using the onboard satellite connection to transfer the final WSRA data products and ocean directional wave spectra to an ftp site at AOC from which they are automatically extracted by a server at NHC. To correctly calculate directional wave spectra, the WSRA processing code requires the hurricane track information for at least a 12-hour period prior to the current hurricane mission flight. The recent preflight hurricane track data must now be either manually entered by the operator, or manually transferred to the WSRA processing computer from a file prepared prior to the mission.

The WSRA code could be reconfigured so that the on-board WSRA code would process the radar data without requiring any hurricane track information, and therefore not requiring interaction with the operator. However, the hurricane track is necessary for resolving the 180° ambiguity of the WSRA-calculated ocean directional wave spectra. In the new processing configuration, two-dimensional ocean wave spectra transferred from the aircraft would have to contain the artifact lobes and would not be Doppler-corrected. Therefore, part of the WSRA processing would be executed on the ground-based computers, to which hurricane track information could be provided over much more stable Internet connections. This new processing step configured to be executed on the ground would eliminate the artifact lobes and Doppler-correct the directional wave spectra, and provide a WSRA data product file in the same format as expected by the existing WSRA ingest application executed on the NHC computers for display on the NOAA/NCAP N-AWIPS.

Completion of this task would improve the autonomous operability of the WSRA system and eliminate, or at least minimize, necessary monitoring and interaction with WSRA system by NOAA staff during the hurricane reconnaissance flights.