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Next Generation Airborne Hurricane Imaging Radiometer (HIRAD) - Improved Forecast Skill with Wide Field Imagery

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1.0 Introduction

Accurate monitoring of tropical cyclones and other extreme oceanic wind events can provide a better understanding of air - sea dynamics and the evolving relationship of weather and climate change as mentioned in the "Earth Science and Applications from Space: Decadal Survey" (National Research Council, 2007). Near real-time monitoring of ocean vector winds (OVW) by satellite can fill data gaps of surface-based ocean observing networks and aid weather forecasters who must issue forecasts and warnings for tropical and extra-tropical cyclones and other extreme marine wind events. These warnings provide tangible societal benefit for mariners who require safe, efficient passages and coastal populations who must prepare for the impact of hazardous weather (NOAA Workshop, 2006).

Current satellite Ku-band scatterometers, such as the QuikSCAT, are not capable of reliably measuring peak wind speeds in even Category 1 hurricanes because of insufficient spatial resolution, radar backscatter saturation with wind speed, and measurement degradation by rain. Future scatterometers (Extended Ocean Vector Winds Mission, XOVWM) with dual radar C/Ku-bands are predicted to extend wind measurements to ~80 m s^{-1}; nevertheless, they will still be significantly degraded by intense tropical cyclone (TC) rain rates. Further, a single polar-orbiting satellite would only provide a snapshot of TC wind conditions once or twice a day and could miss rapid hurricane intensification, which often occurs.

The Hurricane Imaging Radiometer (HIRAD) technology under development at the NASA, Marshall Space Flight Center MSFC) has the potential to augment the XOVWM and thereby meet the target spatial resolution requirement, improve the revisit time, and expand the limits of its observational capabilities to the full range of OVW and rain rates to meet the expressed national need for observations of hurricane-force winds. An aircraft version of HIRAD, which is currently under development at MSFC, is a synthetic thinned array radiometer (STAR) system with an innovative four-frequency C-band microstrip array antenna. This single polarization system will measure surface wind speed and is a precursor to a future dual polarization version with full OVW capability. Flying HIRAD on hurricane surveillance aircraft and a small-dedicated low earth orbiting (LEO) satellite in coordination with XOVWM will expand the OVW observational capabilities to extreme ocean surface winds (~100 m s^{-1}) and rain rates (>100 mm hr^{-1}) and will achieve the desired temporal sampling of ~ six hours.

2.0 Remote Sensing of Hurricane Winds from Aircraft

The Stepped Frequency Microwave Radiometer (SFMR) is the only remote sensing technique (active or passive) that has successfully measured surface wind speeds and rain rates in tropical cyclones. The SFMR uses a nadir-viewing horn antenna and receiver to measure TC wind speed and rain rate in a 1 km strip along the aircraft ground track. Since 1984, hurricanes have been routinely monitored using the SFMR on the NOAA HRD WP-3D aircraft (Uhlhorn and Black, 2003); and currently, the USAF Reserve 53rd Weather Squadron is installing SFMR's on ten of their C-130 hurricane reconnaissance aircraft for operational tasking by the National Hurricane Center.

The SFMR is the "gold standard" for hurricane surface wind measurements that has been validated (Uhlhorn et al., 2007) using independent in-situ Global Positioning System (GPS) dropwindsonde data collected during the active 2005 Atlantic hurricane season. The SFMR ocean wind speed retrieval quality, over the entire range of expected hurricane wind speeds up to 85 m s^{-1} (Saffir-Simpson Category 5) and even in the presence of heavy rain rates, was within 4 m s^{-1} root mean square difference of the dropwindsonde-estimated surface wind speed at 10 m height.

3.0 Passive Remote Sensing of Hurricane Winds from Satellite

Current satellite wind measurements are significantly degraded by typical TC rain rates in the eye-wall region of peak winds. Within the passive remote sensing community there are advocates that believe that polarimetric passive microwave sensors could be effective for monitoring hurricane force OVW, but others have expressed doubts. For OVW's below 20 m $s^{-1}$and under clear air and light rain conditions, WindSat's performance is good (Brown et al., 2006; Bettenhausen et al., 2006); however, to explore feasibility at higher wind speeds, the HIRAD team conducted an empirical study to examine the WindSat sensitivity in hurricanes. The study has direct relevance to the proposed HIRAD instrument since they share a C-band frequency, polarization and incidence angle. Inter-comparisons were made between WindSat brightness temperature (T_B) measurements during 2005 Hurricanes Dennis, Rita and Katrina, and TC surface wind fields from the NOAA HRD hurricane wind analysis system, H*Wind (Powell et al., 1998). Using the H*Wind system as "ground truth" brings together wind measurements from a variety of observing platforms into an objective analysis of the distribution of TC wind speeds. The raw WindSat observations are fully polarimetric top-of-atmosphere radiances at 10.7, 18.7, 23.8 and 37.0 GHz and dual linear polarized T_B at 6.8 and 23.8 GHz. The higher-frequency vertically-polarized channels are relatively insensitive to surface wind effects; so they are used to estimate the absorbing and emitting constituents of the atmosphere between the satellite and the surface. Once the atmosphere has been fully characterized, its contribution to the horizontally polarized (H-pol) radiance can be removed from those T_B observations and the underlying ocean surface emissivity can be derived. The emissivity is then matched-up with corresponding H*Wind surface wind speeds and are shown in Fig. 2 for 6.8 GHz, H-pol. Results clearly show that the satellite derived C-band ocean surface emissivity (at the outer edge of the proposed HIRAD swath) responds strongly to changes in wind speed up to 60 m s^{-1} (Category 4 hurricane). This strong emissivity response to surface winds, coupled with the demonstrated capability of SFMR multi-frequency passive observations to separate the complex rain and wind signals, unambiguously demonstrates the potential of a satellite-based HIRAD to retrieve wide-swath TC winds.

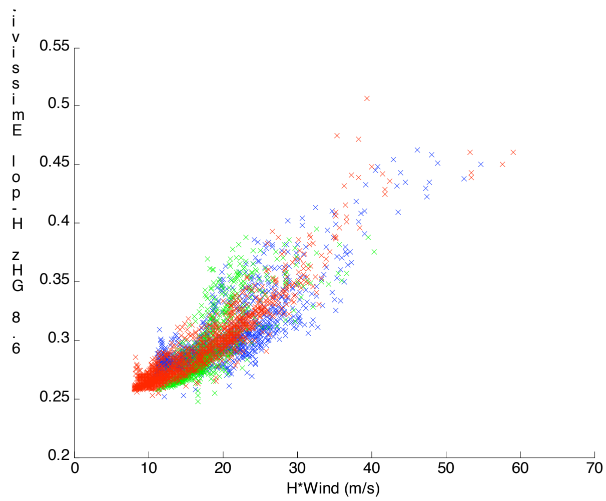

Figure 1. Ocean surface emissivity at 6.8 GHz, H-Pol vs. near surface wind speed from matchups of Windsat overpasses and NOAA H*Wind ground truth estimates for hurricanes Dennis (green), Katrina (red), and Rita (blue) 2006.

4.0 HIRAD Design Concept

HIRAD is a hybrid instrument design, based on the Stepped Frequency Microwave Radiometer (SFMR) and the Lightweight Rainfall Radiometer (LRR). SFMR is a real aperture instrument that operates at a number of distinct frequencies covering roughly the full C-Band octave. SFMR has a single nadir-pointing horn antenna and makes wind and rain estimates directly below the aircraft. The Lightweight Rainfall Radiometer (LRR) is an airborne synthetic thinned aperture radiometer that operates at a single X-Band frequency [2, 3]. It is a cross-track imager which uses Fourier synthesis software beam forming [4]. LRR is capable of estimating either rain rate or wind speed, but not both because of its single frequency of operation. SFMR, on the other hand, is able to retrieve rain rate and underlying ocean surface wind speed in severe, hurricane-strength, conditions because of its lower frequency, octave band operation. The HIRAD design combines the best features of SFMR and LRR. It will widen the restricted, nadir-only, coverage of SFMR to a cross-track field of view of greater than ± 60^{o} and it will expand LRR's capability to both wind and rain measurements.

The key to HIRAD's performance is its ability to operate as a Fourier synthesis imager at the discrete frequencies of 4, 5, 6 and 7 GHz. The HIRAD antenna is a planar array comprised of linear arrays of multi-resonant stacked microstrip patch elements.

The linear arrays produce a real-aperture fan beam antenna pattern that defines the instantaneous field of view. The fan beam antennas are themselves configured in a "thinned" linear array, and a synthetic-aperture pencil beam antenna pattern is formed in software from the cross-correlation products of all pairs of fan beam antennas. Thus, the HIRAD sensor provides push-broom imagery of brightness temperature with real aperture imaging along track and image synthesis cross-track. As an example, assuming an altitude of 11 km the along track spatial resolution at nadir is 1.0 km - 1.7 km over 7-4 GHz. The cross-track field of view, without significant grating lobe effects, is ± 61 deg. so that the swath width is approximately 3½ times the altitude or 40 km in this example, and the along track spatial resolution at the edge of the swath grows to approximately 2.0 km - 3.5 km over 7-4 GHz. The radiometric uncertainty in measurements of the brightness temperature (NEΔT) will be 0.2-0.3 K at the finest spatial resolution. This is more than adequate to produce rain rate and wind speed estimates at levels of uncertainty as good as SFMR.

5.0 HIRAD Measurement Simulations

HIRAD observations have been simulated from both aircraft altitudes and space to determine the potential benefits of wide swath measurements in characterizing hurricanes for use in operational analysis tools such as the NOAA H*Wind analysis system. Modeled surface wind vector and rain rate fields have been used and aircraft flight patterns for HIRAD measurement simulations have been designed to duplicate the timing and flight patterns used in routine NOAA and USAF hurricane surveillance flights. The spaceborne case simulates an orbital pass over the modeled hurricane from a TRMM orbit and altitude. The modeled storm is Hurricane Frances, 2004. The modeling methodology was that described by Chen et al. (2007), and the results include a realistic eye wall, rain bands, and other convective and mesoscale structure. Surface wind vector components, u and v, and rain rate are provided on horizontal grids of either 0.015 deg. (~1.6 km) or 0.05 deg. (~5.0 km) spacing in latitude and longitude. The 1.6 km data is useful for the aircraft simulations and the 5 km for the satellite simulation. A surface wind speed example is shown in Figure 2 for Frances on August 31, 2004 at 1800Z.

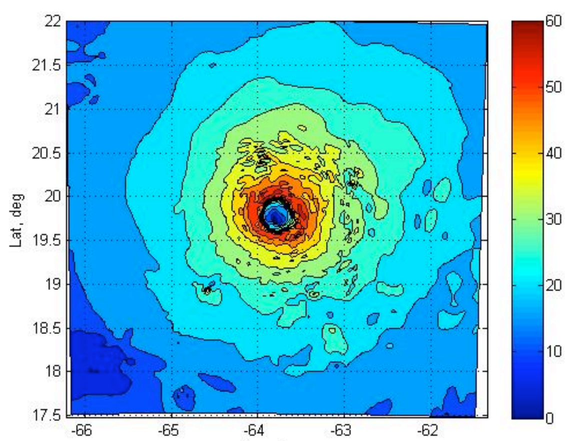

Figure 2. Modeled surface wind speed for Frances on Aug. 31, 2004 at 1800Z

A full 24 hours of modeled data was provided for August 31 so that actual aircraft flight duration, along with storm translation and intensity and structure variations, could be simulated. The modeled surface wind and rain fields are provided on 1 hour increments, and time interpolated wind fields are used in the surface sampling. The time interpolation is done using storm centric 1 hour data over the duration of the aircraft flight patterns, which are approximately 1½ - 2 hours, depending on the aircraft, or air speed, assumed.

The HIRAD sampling, as currently implemented, creates cross-track scans with each gridded wind speed value so that the spatial resolution over the HIRAD field-of-view is of the same size as the model grid both cross-track and along track. This resolution is similar to that of the planned instrument, but along track averaging and realistic image reconstruction cross-track will be added to the surface sampling as the simulations are developed. Contiguous scans are formed along the track in a pushbroom fashion as the platform flies along, as shown in Figure 3 for a standard Figure-4 flight pattern.

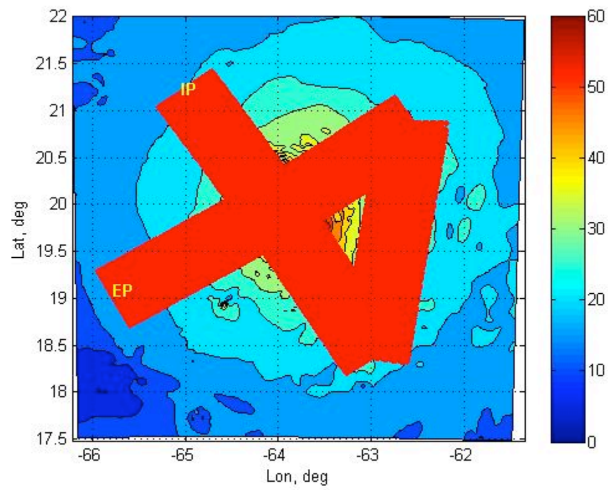

Figure 3. Example of HIRAD swath in standard Figure-4 flight pattern from aircraft at 20km altitude over Frances, 2004.

Both “Figure-4” and “Butterfly” patterns, which provide 2 and 3 passes through the eye, respectively, have been simulated for the aircraft cases and a single pass was simulated in the spaceborne case (at 5 km resolution). Three standard NOAA aircraft flight patterns; the Figure-4, the Butterfly, and the “Rotated Figure-4,” are diagrammed in Figure 4 below. The number of aircraft passes through the hurricane in a given time duration on site varies with each of these patterns and the objective for HIRAD will be to choose a flight pattern that provides maximum coverage per flight in imaging the storm. The HIRAD cross-track field-of-view is approximately ± 60 deg. which translates to a swath width of ~70 km at the highest aircraft altitude considered (20 km for a typical ER-2 flight). In the satellite case the swath was approximately 2000 km for an orbit altitude of 450 km.

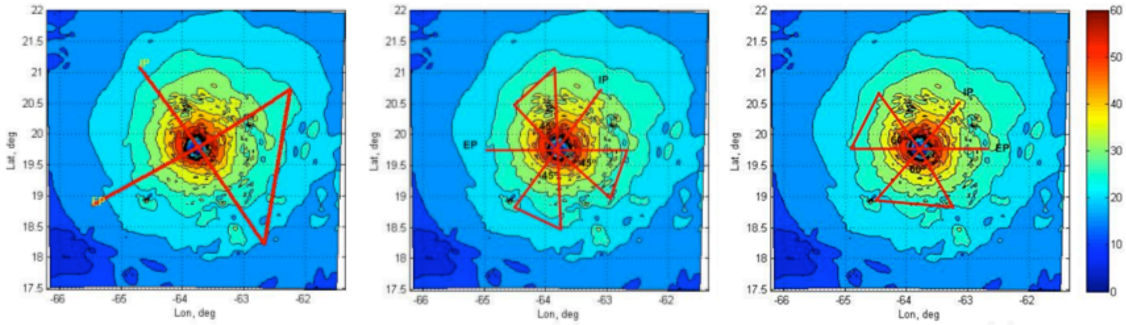

Figure 4. Standard NOAA flight patterns. Left to right; Figure-4, Rotated Figure-4, Butterfly.

Errors that are representative for HIRAD were added to all of the simulated wind speed observations. Wind speed errors were simulated using a simplified model that was calibrated with SFMR errors in estimating actual hurricane winds (Uhlhorn et al., 2007). The total SFMR error was separated into a surface component, rain free approximation, and an atmospheric component, where the standard deviation of the total error was the vector sum of these two as shown in Equation 1. Since SFMR is nadir viewing, the standard deviation of the HIRAD error was modeled over the full swath by applying a secθ dependence to the atmospheric component as shown in Equation 2.

$$\sigma^2{}_{T} = \sigma^2{}_{Sur.} + \sigma^2{}_{Atm.} \qquad (1)$$

$$\sigma^2{}_{Atm.} = 1.75(RR/15)\sec\theta \qquad (2)$$

For each simulation case, this model was used in a single trial way to produce pixel-by-pixel wind speed errors that were a function of modeled rain rate and viewing angle. The scatter plot in Figure 5 demonstrates the noise added over the swath by rain, primarily at the edges of the swath. In this simulation, HIRAD flies through the center of the eye and the altitude is high enough that the high wind speeds and most intense rain appear in the outer regions of the swath. This is where the effects of path length and rain rate on $\sigma_{Atm.}$ are the greatest. For these reasons, the largest wind speed error is at the higher wind speeds in Figure 5.

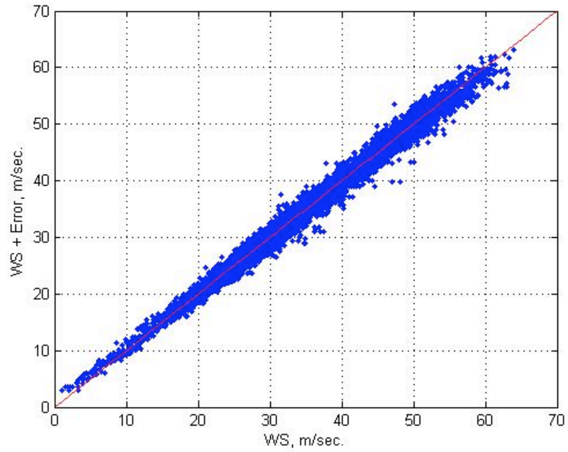

Figure 5. Comparison of modeled wind speed to wind speed with errors over the full swath.

Since this single trial method produces a few large errors in each simulation that can skew the results, in terms of maximum winds, a 2 sigma limit was applied to each random error and a 3x3 median filter was also applied to the resultant wind field. The NOAA H*Wind analysis tool has been used for evaluating HIRAD pay-off in simulations to date (http://www.aoml.noaa.gov/hrd/data_sub/wind.html). H*Wind assimilates wind measurements from a variety of observation sources and produces the distribution of wind speeds in a tropical cyclone. H*Wind products are used to improve the estimate of hurricane intensity. A more realistic wind turbulence model will be added to the simulations as they are developed.

6.0 Summary

There is a strong national interest in the observation and forecasting of extreme ocean wind events such as tropical cyclones. Current remote sensing observation capability, both satellite and aircraft based, is limited in wind speed/vector dynamic range, ability to retrieve wind information in the presence of rain, or coverage. HIRAD is being developed by the NASA, Marshall Space Flight Center as one potential solution to this limitation in capability. This paper has provided a brief tutorial on the science justification, the technology status, the instrument design concept, and current performance simulations related to HIRAD development. HIRAD is a passive, multi-frequency, C-band radiometer that builds on the success of the SFMR, which has measured surface wind speed up to 85 m/sec in the presence of intense rain. HIRAD, using synthetic thinned array technology, expands the SFMR capability to a large swath which increases coverage and offers potential for space application. HIRAD could possibly fill the gap alone or as a complement to the XOVWM.

7.0 References

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