IMPROVED MICROWAVE REMOTE SENSING OF HURRICANE WIND SPEED AND RAIN RATES USING THE HURRICANE IMAGING RADIOMETER (HIRAD)

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ABSTRACT

The Hurricane Imaging Radiometer (HIRAD) is a new imaging technology microwave remote sensor for hurricane observations that is currently under development by NASA Marshall Space Flight Center in partnership with the NOAA Hurricane Research Division, the University of Central Florida and the University of Michigan.

HIRAD is designed using passive microwave Synthetic Thinned Array Radiometry (STAR) technology to provide wide-swath images of ocean surface winds and rain rates in hurricanes. HIRAD is a next generation instrument that is derived from the operational airborne Stepped Frequency Microwave Radiometer (SFMR) that measures wind speed and rain rate along the ground track directly beneath the aircraft. This paper presents an overview of the HIRAD sensor, compares its measurement capabilities with SFMR, and provides examples of hurricane measurement capabilities from high-flying aircraft operating at 11 km and 20 km altitudes and a satellite HIRAD operating from a low inclination of 450 km orbit. Simulated measurement scenarios are presented, which illustrate wind speed and rain rate measurement spatial resolutions and swath coverage.

1. INTRODUCTION

In 2006, the National Oceanic and Atmospheric Administration (NOAA) Operational Ocean Surface Vector Winds Requirements Workshop was held at the National Hurricane Center in Miami, FL (NOAA Workshop, 2006); and presently their recommendations for ocean vector wind (OVW) measurements in hurricanes are not being met by the majority of the remote sensing instruments flown on either aircraft or satellites. In fact only the Stepped Frequency Microwave Radiometer (SFMR) has been demonstrated to measure hurricane force wind speeds in the presence of intense rain rates (Uhlhorn and Black, 2003). SFMR is a nadir-looking C-band radiometer that infers wind speed and rain rate along a ground track directly beneath the aircraft. SFMR operates on the NOAA WP-3D aircraft and currently, the United States Air Force Reserve 53rd Weather Squadron is flying SFMR on several of their C-130 hurricane reconnaissance aircraft for operational tasking by the National Hurricane Center.

The Hurricane Imaging Radiometer (HIRAD) is a new instrument being developed under a joint project between the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC), the NOAA Hurricane Research Division (HRD), the University of Michigan, and the University of Central Florida (UCF). HIRAD is designed using passive microwave Synthetic Thinned Array Radiometry (STAR) technology to provide wide-swath images of ocean surface winds and rain rates in hurricanes. HIRAD is a next generation instrument that is derived from the operational airborne SFMR; and it is proposed to fly in the 2010 hurricane season on NASA's ER-2 aircraft with a typical flight altitude of 20 Km.

2. HIRAD OVERVIEW

HIRAD has a hybrid design, based on SFMR's multi-frequency and the airborne Lightweight Rainfall Radiometer's STAR technology (Ruf and Principe, 2003). The HIRAD array antenna images the ocean brightness temperature by synthesizing a broad instantaneous field of view (IFOV) cross-track and sampling along-track in a push broom fashion.

HIRAD covers approximately the same C-band frequency range as SFMR (four frequencies: 4 - 7 GHz), but it operates over a wider swath of ± 61 degrees off-nadir (~ 3x the aircraft altitude) as shown in Fig. 1. Because of it's wide swath, the number of eye wall penetrations needed to measure the location of the maximum wind in a hurricane can be minimized with HIRAD, compared to SFMR.

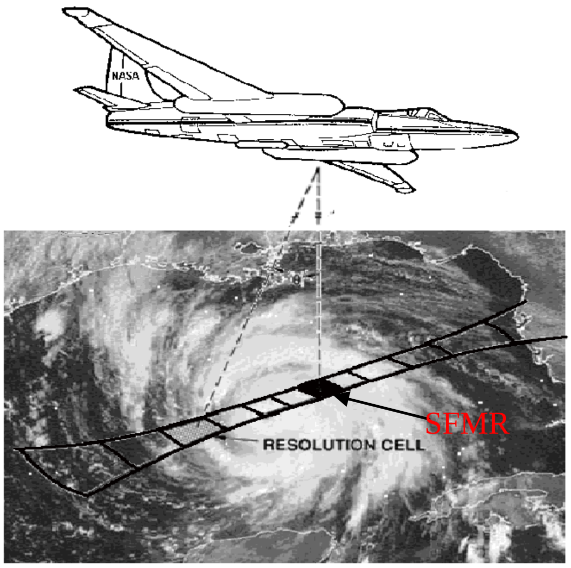

Figure 1. HIRAD instantaneous field of view swath in comparison to SFMR nadir viewing.

HIRAD provides high spatial resolution with an along-track footprint size that varies between 1 Km at nadir to 2 Km at the edge of the swath at 7 GHz (1.7 - 3.7 Km at 4 GHz) forming a bow tie shape IFOV from an aircraft altitude of 11 Km.

Further, a satellite version of HIRAD can sample the entire hurricane OVW region in one single pass with a high spatial resolution (5 – 12.5 Km). This is in contrast with other existing satellites with microwave remote sensors, which can image the hurricane, but are limited in their dynamic wind speed measurement range and are limited to regions with low rain rates.

3. HIRAD RETRIEVAL ALGORITHM

The SFMR ocean wind speed retrieval is based upon an empirical regression between nadir viewing brightness temperatures and surface wind speed. The use of multiple frequencies allows the separation of the strongly dispersive contribution of rain from the non-dispersive ocean emission.

Unfortunately the translation of this “simple” SFMR algorithm to the variable incidence angle HIRAD geometry is not trivial. The major reason for this difficulty is the unknown dependence of ocean surface emissivity with incidence angle at hurricane force wind speeds. For this reason, an ocean surface emissivity model is under development at the Central Florida Remote Sensing Lab (CFRSL) with a preliminary version described by El-Nimri et al. (2007). Using this model, CFRSL has also developed a HIRAD ocean surface wind speed and rain rate retrieval algorithm with details presented by Amarin et al. (2007).

An example of a HIRAD hurricane measurement simulation is presented in Fig. 2, where actual SFMR measured wind speed and rain rate values from a single aircraft track through Hurricane Katrina were used for the “nature run” to produce the brightness temperatures for a single HIRAD swath of ± 60 degrees off nadir. Next, the four frequency brightness temperatures were processed to retrieve wind speed and rain rates for 1° steps in earth incidence angle (EIA), and these results are presented in Fig. 3 along with the nature run surface values (from SFMR).

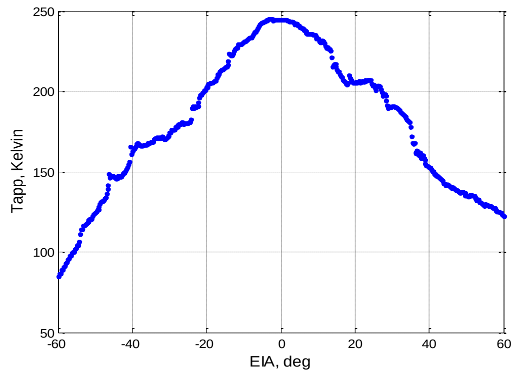

Figure 2 Apparent brightness temperature measurement scene over HIRAD swath (single instantaneous cross-track field of view) for the 7 GHz (highest frequency of operation)

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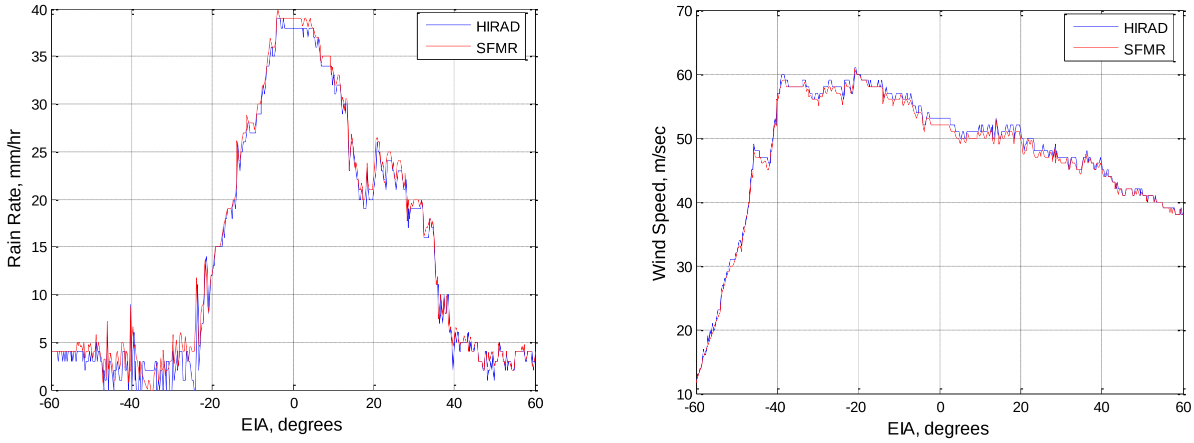

Figure 3 Simulated HIRAD hurricane wind speed and rain rate retrievals for a single cross-track IFOV.

For this example, the simulated aircraft was located in the eye-wall where max rain rates occurred at Nadir (0° EIA), the peak hurricane wind was located at -40° EIA, and the hurricane eye was located to the left beyond -60° EIA. These figures show that the simulated HIRAD retrievals (including realistic image reconstruction errors) were in excellent agreement with the surface truth wind speeds even in intense rain, which occupied much of the entire swath.

4. HIRAD QUICK OSSE SIMULATION

The conduct of "quick" Observing System Simulation Experiments (OSSE's), which used simulated HIRAD observations of Hurricane Frances along with H*Wind analyses as the discriminating tool, was described by Miller et al. (2008). The H*Wind analysis, a product of the NOAA Atlantic Oceanographic and Meteorological Laboratory's Hurricane Research Division, brings together wind measurements from a variety of observation platforms into an objective analysis of the distribution of wind speeds in a tropical cyclone. This product is designed to improve understanding of the extent and strength of the wind field, and to improve the assessment of hurricane intensity. See http://www.aoml.noaa.gov/hrd/data_sub/wind.html.

For this purpose, HIRAD wind speed observations were simulated from both aircraft and a low-earth-orbit (LEO) satellite. The simulated aircraft data were designed to duplicate the timing and flight patterns used in routine NOAA and USAF hurricane surveillance flights, and the spaceborne case simulates a HIRAD flying in a low earth orbit (LEO) similar to TRMM.

For the nature run, a Hurricane Frances August, 2004 simulation was performed using the state-of-the-art system described by Chen et al. (2007). This numerical model is non-hydrostatic in the atmosphere with detailed explicit microphysics and an interactive ocean wave model, which used a system of nested grids with the innermost one having a horizontal grid spacing of 0.015 degrees (~1.6 km) in longitude and latitude. The results include a realistic eye wall, rain bands and other convective and mesoscale structure. (See Fig. 4.)

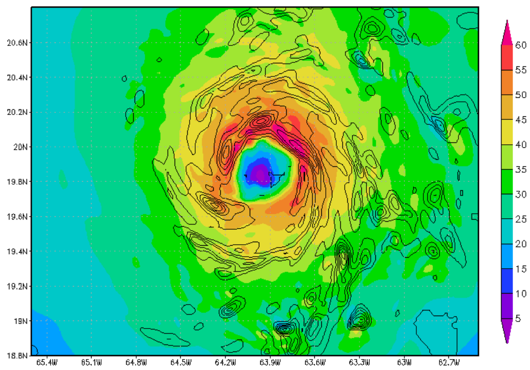

Figure. 4. Near-surface wind speed (m/s) as modeled for Hurricane Frances at 18z on 31 August, 2004 (from Miller et al., 2008). Wind speed is represented by the color scale, and rain rate with solid contours (interval = 20 mm/hr). Only a portion of the inner-most grid is shown.

An example of the coverage provided by the LEO HIRAD satellite with an approximate swath of 2000 km for an orbital altitude of 450 km and inclination of 35° is shown in Fig. 5.

Figure 5. Best case HIRAD coverage for one day.

For this “best case” one-day scenario, HIRAD is able to provide hurricane coverage during 5 passes, which occur in two groups of consecutive orbits separated by ~ 12 hours.

HIRAD simulated observations from airborne platforms are presented in Fig. 6 where typical “Figure-4” aircraft flight-line surveillance patterns from two different altitudes are shown. The upper left-panel illustrates the HIRAD wind speed measurements from an 11 Km aircraft altitude with swath coverage of ~ 40 Km, and the upper right-panel from a typical 20 Km ER-2 altitude with ~ 74 Km swath.

For HIRAD, wind speed measurement errors were simulated using a simplified model that was calibrated against the SFMR. The total SFMR error was partitioned into a surface (rain-free) component and a rain atmospheric component, where the standard deviation of the total error was the vector sum of these two. Since SFMR was nadir viewing, the standard deviation of the HIRAD error was modeled by applying a secθ dependence to the atmospheric component. For each simulation case, this model was used in a single trial to produce random wind speed errors that were a function of modeled rain rate and viewing angle (EIA) over the swath. Since this single-trial method produced a few large errors in each simulation that could skew the H*Wind results, a 2-sigma limit was applied to each random error and a 3x3 median filter was applied to the resultant wind field.

Also the corresponding H*Wind products are shown in lower panels of Fig. 6. As HIRAD is flown at a higher altitude, the swath is wider and hence the advantage is greater. Since H*Wind does not capture high-resolution features in any case (except for the wind maximum itself), the reduced spatial resolution due to higher altitudes does not degrade the H*Wind analysis. In fact, the vortex structure is much better defined for the high-altitude HIRAD than it is for the other case; however, even the lower-altitude HIRAD provides more information than SFMR and thus results in an arguably more realistic analysis. For example, the maximum wind speed is closer to that of the nature run.

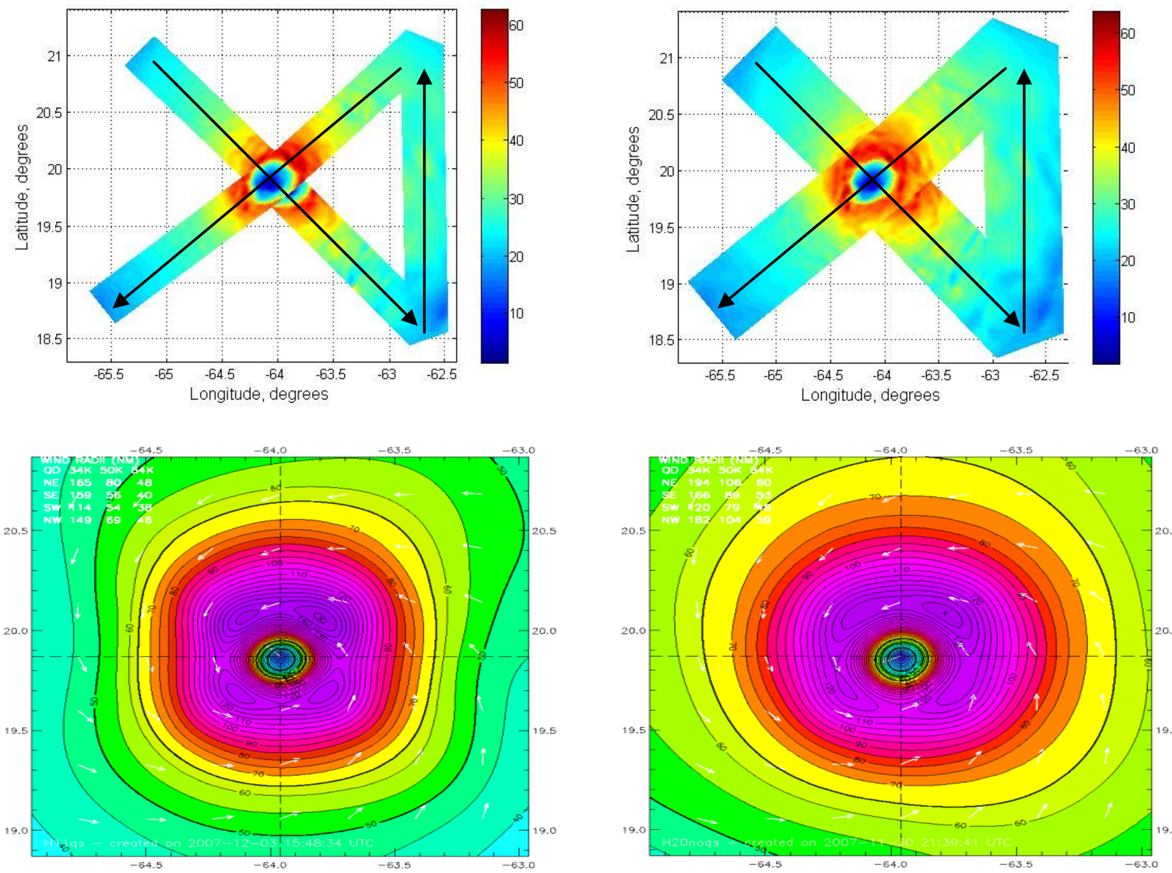

Figure 6. Simulated HIRAD wind speed measurements from different aircraft altitude "Figure-4" flight-lines (upper panels) and their associated H*Wind products (lower panels).

5. SUMMARY AND CONCLUSION

HIRAD can provide wide swath coverage for hurricane surveillance, which could provide tropical cyclone researchers and operational weather forecasters with valuable near-real time observations to aid in classifying hurricane peak winds and rainfall intensity as hurricanes approach landfall. Further, this innovative sensor offers the potential to significantly improve over existing airborne and spaceborne microwave remote sensors in its ability to image the hurricane surface wind fields with higher spatial resolution even in the presence of high rain rates.

6. References

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