A Feasibility Study for a Wide-Swath, Airborne, Hurricane Imaging Microwave Radiometer for Operational Hurricane Measurements

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ABSTRACT

This paper presents a conceptual design of an airborne Hurricane Imaging (microwave) Radiometer (HIRad) instrument for use in operational hurricane surveillance. The basis of the HIRad design is the Stepped Frequency Microwave Radiometer (SFMR) that has successfully measured surface wind speed and rain rate in hurricanes from the NOAA Hurricane Research Division's P-3 aircraft. Unlike the SFMR that views only at nadir, the HIRad provides wide-swath measurements between ± 45 degrees in incidence angle with a spot-beam spatial resolution of approximately 1-3 km. The system operates at four equally spaced frequency channels that cover a range between 4 GHz and 7 GHz.

1. INTRODUCTION

Contemporary hurricane numerical models such as MM-5 (Penn State/NCAR Mesoscale Model) have the ability to predict precipitation as well as to forecast storm evolution (intensity, size and track). To aid forecasting, the most important contribution that could be made from remote sensing platforms would be daily mapping of the surface wind field from the center of the storm to a distance just outside the ring of maximum winds located in or near the eyewall cloud. In the Atlantic basin such measurements are operationally available at limited times from sensors mounted on research aircraft, but none of the world's other hurricane basins have aircraft reconnaissance capabilities. Even in the Atlantic hurricanes are out of range of the aircraft for most of their lifetimes. Timely measurements of the surface wind fields in tropical cyclones, with wide swath (10's of km) and high resolution (1 km), would dramatically improve model initialization and resulting forecasts.

II HURRICANE IMAGING RADIOMETER

A. Instrument Heritage

Retrievals of hurricane ocean surface wind speed and rain rate have been performed operationally by the Stepped Frequency Microwave Radiometer (SFMR) from aircraft by NOAA Hurricane Research Division (HRD) for more than a decade. SFMR was originally developed by the NASA Langley Research Center in the 1970s [Jones *et al.,* 1981] and it has continued to be an integral part of NOAA operations since. Wind speed and rain rate are retrieved simultaneously from measurements of microwave brightness temperature (T_B) made by the nadir-viewing SFMR on board a NOAA P-3 flying at ~25,000 ft (7.6 km). Winds in excess of 180 mph (150 m/s) and rain rates of greater than 100 mm/h have been successfully estimated by the SFMR and validated against weather radars, dropsondes released from aircraft, and extrapolations of flight-level winds. Even at these extreme levels, the T_B responses to both wind speed and rain rate have not reached saturation.

The SFMR scans between 5 and 8 GHz with a variable number of channels. Retrievals have been demonstrated with as few as two and as many as eight channels. A minimum of two T_B channels is required to uniquely separate the contrasting spectral signatures of surface emission and rain. Additional channels serve to over-constrain the system of equations that relate the T_B measurements to the state parameters of wind speed and rain rate. This effectively reduces the sensitivity of the retrieval algorithm to instrument noise and common-mode calibration biases. The current operational NOAA sensor uses eight channels.

B. HIRad Instrument Description

The Hurricane Imaging (microwave) Radiometer (HIRad) is a candidate airborne sensor for future operational surface wind speed and rain rate measurements in hurricanes and typhoons. This sensor is an interferometric microwave radiometer that uses a one-dimensional thinned synthetic aperture array antenna to synthesize multiple simultaneous beams in a push-broom configuration. When used on an operational hurricane surveillance aircraft such the NOAA HRD's Gulfstream-IV (Fig. 1), the hurricane may be imaged with high resolution as shown in Fig. 2 & 3.

Unlike the SFMR, that views only at nadir, the HIRad provides wide-swath measurements with simultaneous multiple "pushbroom" fan-beams between ± 45° in incidence angle. When flying at an altitude of 35,000 ft

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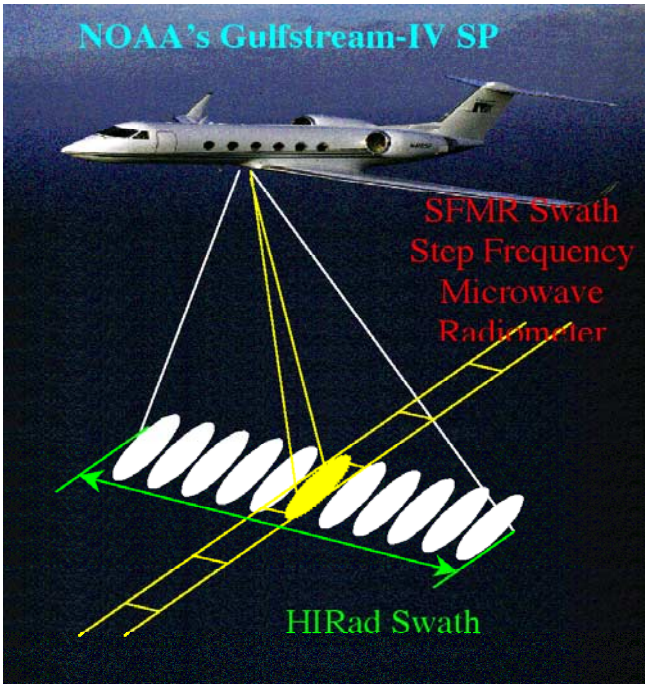


Fig. 1 HIRad measurements from NOAA's hurricane surveillance aircraft.

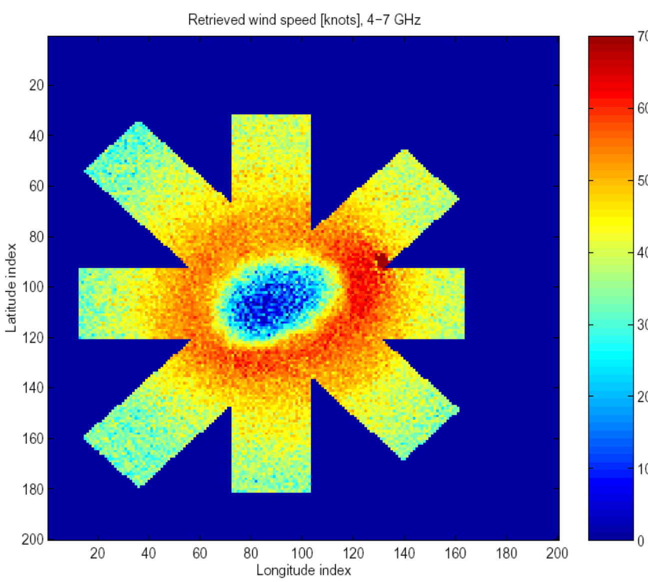


Fig. 2 Simulated HIRad measurements of surface winds from Hurricane Floyd (1999). Ordinate is latitude index (0.125° steps) and the abscissa is longitude index (0.125°). Color scale is 0-70 knts (36 m/s).

(11 km), HIRad provides a measurement swath of 22 km and a spatial resolution of 1-3 km depending upon the operating frequency and cross-track position in the swath. This geometry provides excellent opportunity to image the high wind gradients and spiral rain bands surrounding the hurricane eye while flying the typical "butterfly" transects. The image produced in Fig. 2 and 3 results from four transects of the eye. The advantage of HIRad over a profiling sensor such as SFMR is obvious. The equivalent SFMR coverage would be a single strip (one pixel wide) centered along each the aircraft track.

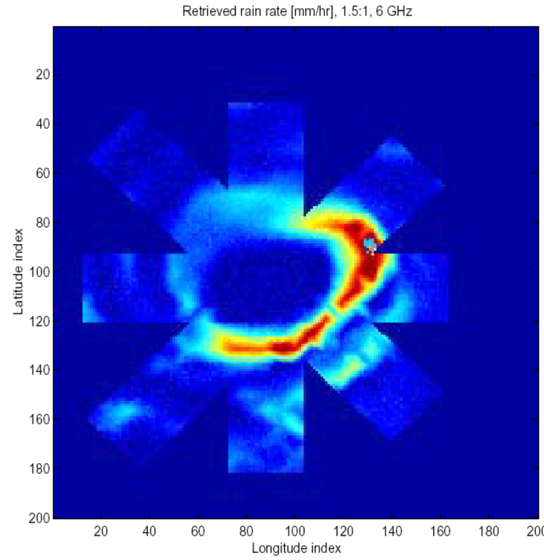


Fig. 3 Simulated HIRad measurements of rain rate from Hurricane Floyd (1999). Color scale is 0-130 mm/hr.

C. Synthetic Thinned Array Radiometer (STAR) System

The STAR instrument design presented here has a frequency plan similar to SFMR but provides a cross track swath at each frequency of 65 independent pixels covering $\pm 45^{\circ}$ about nadir. The pixels are generated using interferometric aperture synthesis [Ruf *et al.*, 1988]. The thinned aperture antenna array consists of 10 active fan beam antennas, each of which is a linear broadside phased array of 36 multi-resonant dipoles (see antenna design section). The linear arrays are oriented in the direction of flight of the aircraft so that their fan beam patterns define the cross track instantaneous field of view of the imager. Full two-dimensional images are then formed by push broom aircraft motion.

The flat panel antenna array (1.1x1.1 m aperture x 25 cm thick) consists of a rectangular grid of 38x38 multi-resonant dipoles with ten receiver front-ends. The small element size ($0.4\ \lambda_{free\ space}$ at 4 GHz and $0.7\ \lambda_{free\ space}$ at 7 GHz) allows the design of the array without introduction of grating lobes into the scanning field of view. A multi-slot antenna array element (Fig. 4) is being developed for the 4-7 GHz frequency range. Four resonant frequencies (4, 5, 6 & 7 GHz) were selected for the design. The multi-resonant element is realized by multiple narrow slots in the wall of a specially configured thin cavity. Excitation of the slots is via a stripline inside the cavity and passing directly underneath the slots. Because of the very close proximity of all the slots, there is significant slot-to-slot field interaction. Therefore, the fundamental design was developed and optimized through electromagnetic computational simulations, which model the entire configuration as a single device. Test results on the initial laboratory constructed element demonstrates the four resonant frequencies as predicted. More attention to details in fabrication will be addressed in the next test article in order to improve the impedance match at all frequencies.

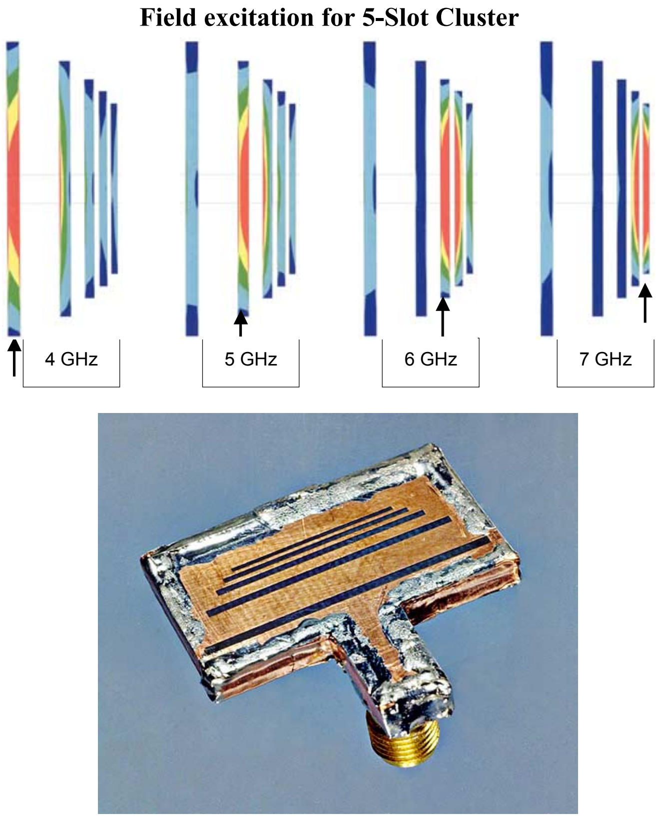


Fig. 4 Antenna element for HIRad array. Top panel illustrates the field excitation and the bottom panel shows a brass-board test article.

The outermost ring of dipoles are passively terminated to ensure consistent mutual coupling between active elements, leaving a 36x36 central grid. The 26 rows of dipoles that do not comprise the 10 active fan beams are also passively terminated. Which 10 of the 36 possible rows are active is determined using an interferometric sampling algorithm [Ruf, 1993].

Each active fan beam antenna is connected to a frequency agile correlating radiometer receiver. The input stage of each receiver features a reference load and injected noise diode for absolute system calibration followed by a wideband low noise amplifier covering the 4-7 GHz input frequency range. The frequency selection is achieved by single sideband downconversion to a fixed narrowband (20 MHz) intermediate frequency (IF) range using a variable local oscillator, in a manner adapted from the SFMR design. The IF signal is digitized (prior to detection) with a coarse 2-bit digitizer and then digitally quadrature demodulated to baseband and complex cross-correlated between receivers using technology and signal processing algorithms developed under a NASA Global Precipitation Measurement Mission technology development incubator [Ruf *et al*., 2000].

D. *HIRad Simulated Performance Results*

HIRad hurricane measurements are simulated using a statistical Monte Carlo technique. The wide-swath coverage provided from typical aircraft altitudes is capable of mapping the entire hurricane eye wall during a few flight tracks across the storm. These simulated retrievals show good accuracy for surface wind speed and rain rate under realistic hurricane conditions. An example of the spatial distribution of retrieval errors is presented in Fig. 5. The top panel is the modeled wind field with the error in the retrieved wind speed directly below. The maximum errors ~ 5 m/s occur at light winds inside of the eye, and at stronger winds where the system is optimized, the error is less. Also note that the wind speed errors are not correlated with the location of strong rain (panel 3rd from top). Directly below the model rain intensity is the rain rate retrieval error. Again the largest errors are for light rains inside of the eye, and for stronger rains, where the system is optimized, the errors are less. Also note that rain rate errors are independent of wind speed. Scatter diagrams of the wind speed and rain rate retrieval errors are presented in Fig. 6 for the entire hurricane. As discussed above, the errors reduce as the wind speed and rain rate increase. At light winds and rain there is a sensitivity issue because of selecting the low frequency microwave channels (4 GHz - 7 GHz). However, at the strong wind speeds and rain intensity associated with tropical cyclones there is an exponential increase in T_b with these increasing parameters, and the retrievals improve.

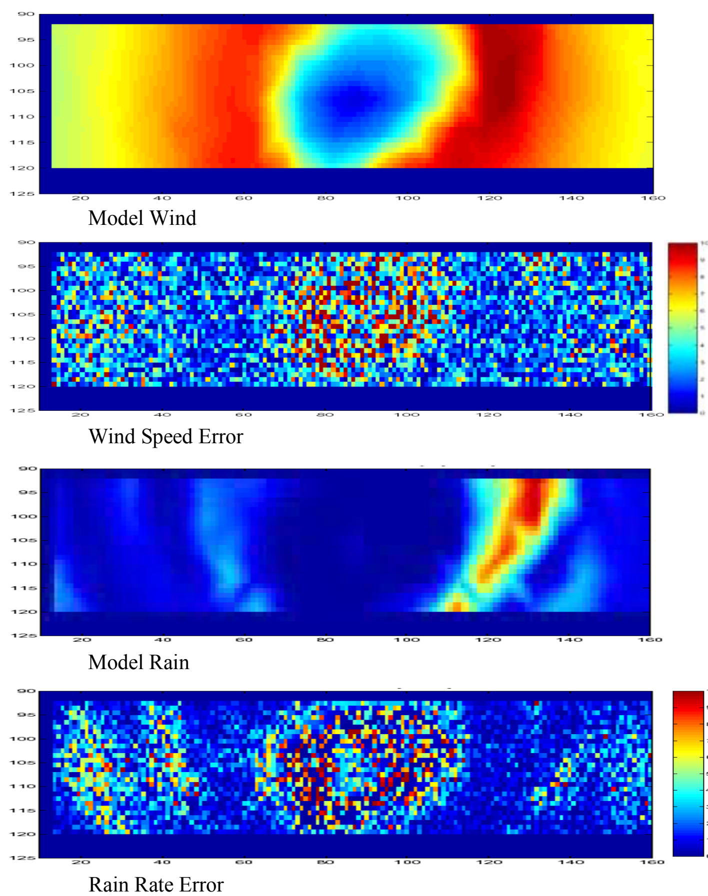
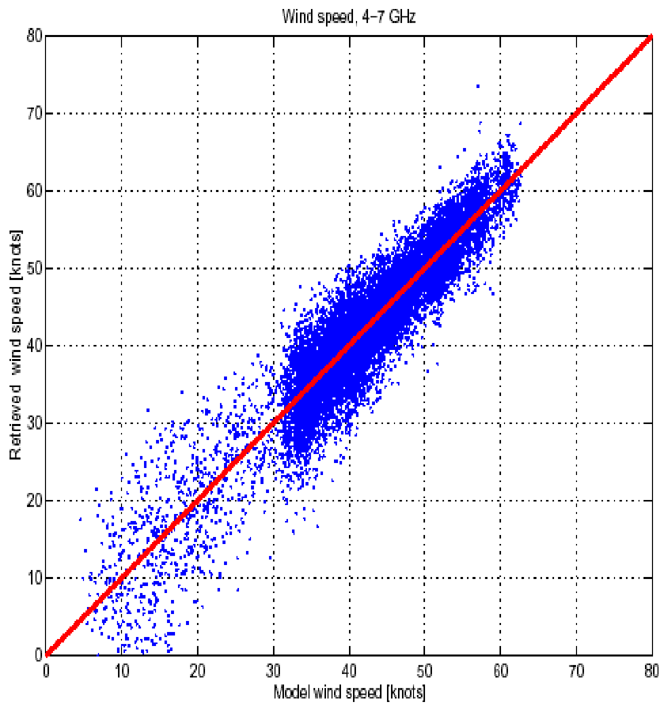


Fig. 5 HIRAD simulated east-West flight leg. Top panel is the modeled wind speed; next is the retrieved wind speed error - color bar is 0-10 knts (5.2 m/s), next is the modeled rain intensity and the bottom panel is the corresponding rain rate retrieval error - color bar is 0-10 mm/hr.



(a) - HIRad wind speed error - entire hurricane image

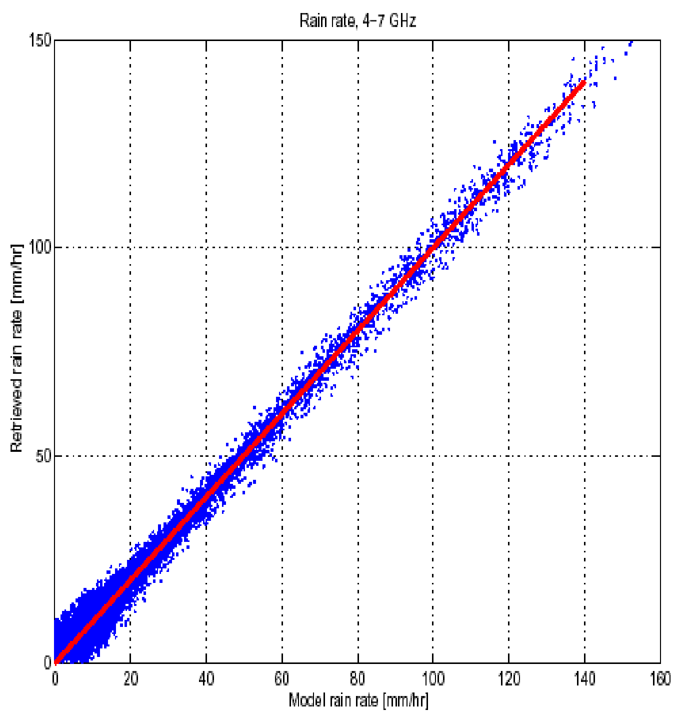


Fig. 6 HIRAD simulated hurricane retrieval error. Top panel is the wind speed error and the bottom panel is the corresponding rain rate error

III Conclusions

This design study has demonstrated the feasibility of developing a new Hurricane Imagine Radiometer using currently available technologies for Synthetic Thinned Array Radiometers. There is significant potential for this candidate airborne sensor for future operational surface wind speed and rain rate measurements in hurricanes and typhoons.

ACKNOWLEDGMENT

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