Instrument Design Simulations for Synthetic Aperture Microwave Radiometric Imaging of Wind Speed and Rain Rate in Hurricanes

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Abstract -- The measurement of peak winds in hurricanes is critical to forecasting intensity and direction prior to landfall. To date, the NOAA Stepped Frequency Microwave Radiometer, SFMR, is the best tool for providing this information. NASA is now developing the Hurricane Imaging Radiometer, HIRad, which is a candidate follow-on instrument to improve on the SFMR. HIRad will use synthetic thinned array technology to provide wide swath images, adding to the nadir profiles of the SFMR New developments in radiative transfer modeling for hurricane force winds and large incidence angles are required for HIRad. This paper describes modeling and simulations for HIRad, some of the applications in HIRad design to date, and end-to-end performance simulations.

I. Introduction

The Hurricane Imaging Radiometer, HIRad, is currently under development by NASA's Marshall Space Flight Center, in collaboration with NOAA's Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division. HIRad is a synthetic thinned array radiometer [1] that will provide wide swath measurements of surface wind speed and path integrated rain rate in hurricanes. The development of a radiative transfer model and retrieval algorithm for hurricane force winds over the full range of incidence angles is required for the design and implementation of HIRad.

In order to forecast hurricane intensity, knowledge of the maximum surface wind speed is a primary requirement, and currently the Stepped Frequency Microwave Radiometer, SFMR is the best tool for providing this information. The SFMR is mature technology with wind speed and rain rate retrievals that are largely considered reliable. The HIRad model development will incorporate and build on the SFMR algorithms and use SFMR measurements in hurricanes for validation and for deriving an incidence angle dependent surface model.

This paper will describe key elements in the HIRad retrieval algorithm, some of the applications of the forward model in HIRad design studies, and its application in end-to-end simulations that are under development for performance evaluation and demonstration of the value of HIRad operationally.

II. Background

A. HIRad Instrument

The Hurricane Imaging Radiometer (HIRad), currently under development, is a multi-frequency, C-band (4-7 GHz), synthetic aperture thinned array radiometer designed to make wide swath measurements of surface wind speed and rain rate in hurricanes from aircraft, and potentially from space. It builds on the technology of two existing sensors, the Stepped Frequency Microwave Radiometer (SFMR) [2] and the Lightweight Rainfall Radiometer (LRR) [3]. SFMR is a nadir viewing multi-frequency C-band instrument used operationally by NOAA for hurricane surveillance, and LRR is an X-band synthetic thinned array radiometer developed by NASA and the University of Michigan that makes cross-track images of rain rate. HIRad capitalizes on both to provide the large cross-track swath and the observation of both surface wind speed and path integrated rain rate.

B. HIRad Retrieval Algorithm

The calculation of blackbody microwave emissions from the earth and atmosphere is described by radiative transfer theory. The apparent brightness temperature as seen by a microwave radiometer viewing the ocean surface through an absorptive atmosphere includes the upwelling atmospheric brightness temperature, the downwelling brightness that is reflected from the sea surface, and the emitted sea surface brightness temperature. A particular challenge for HIRad is that it has to measure the wind speed dependent surface emission in the presence of heavy rain, as SFMR does, but over relatively long path lengths to cover the full swath. Therefore, modeling and retrieval algorithms that include a rain model for the hurricane environment and a wind speed model for hurricane force winds from nadir out to the swath edges were required.

In the HIRad retrieval algorithm, a forward model is used to compute a brightness temperature matrix for all possible combinations of wind speed and rain rate ranging from 0-100 m/sec and 0-100 mm/hr for the four HIRad frequencies. A layered atmospheric model that includes cloud liquid water and rain is used, and the ocean surface wind speed and rain rate are estimated using the statistical least-squares difference method where a minimum difference between the measured and modeled apparent brightness temperatures across all HIRad frequencies is found.

As part of the HIRad development then our radiative transfer model, RTM, had to be upgraded for use in design studies and for use in performance simulations. The selected approach was to use the SFMR rain algorithm and to develop a new wind speed model. SFMR brightness temperature measurements and wind speed and rain rate retrievals were used to validate the HIRad retrievals for the nadir viewing case, and were used in deriving the wind speed model over the full range of incidence angles [4].

C. The Rain Model

Heavy rain is particularly important in HIRad wide swath measurements due to the long path length to the edges of the swath. In heavy rain, the surface contribution to apparent brightness temperature is reduced while the atmospheric emission increases. Conceptually, for long path length the atmosphere might approach total opacity and mask the surface radiation. The consequence would be loss of sensitivity in the wind speed measurement.

Typically, power law relationships of the form,

$$K_r = aR^b$$

are used in modeling microwave absorption due to rain. The coefficient *'a'* is frequency dependent, which makes the model dispersive and enables the multi-frequency retrieval of rain rate.. The exponent *'b'* is a constant. There seems to be agreement in the literature [5-7] that for thunderstorm and hurricane drop size distributions a good value for the exponent *'b'* is approximately 1.15. However, suggested values for the coefficient *'a'* vary by more than a factor of 2.

Validation of the SFMR rain algorithm is still in under study. The SFMR is considered well calibrated in wind speed, using GPS dropsondes as truth [2], based on rain rate dependent wind speed estimates from simultaneous retrievals. Plus, a study to evaluate the rain model itself was done using the NOAA P-3 Tail Radar for comparison and concluded that the SFMR rain estimates were fairly good but biased low by approximately 5 mm/hr [7]. Nevertheless, recent results by Carswell [8] suggest that SFMR estimates may be low by as much as a factor of 2.5. This does bring SFMR observations of maximum rain in hurricanes into better agreement with numerical prediction models.

D. The Surface Model

The development and implementation of the HIRad wide swath measurement for extremely high wind speeds requires significant improvement in existing surface emission models. The SFMR retrieval algorithm has been validated up to 70 m/sec. but for nadir only, and other models are valid at incidence angles out to 60 deg., but only at wind speeds less than approximately 30 m/sec. Therefore, a high wind speed, wide swath model is being developed for HIRad [4].

This model is physics based and models the surface as wind roughened and foam covered at higher wind speeds, and with an emissivity consistent with the SFMR algorithm at nadir incidence. It models foam in terms of the fractional surface coverage and the emissivity of foam itself, which it treats as both frequency and incidence angle dependent. The incidence angle dependence in the model is derived from SFMR brightness temperature measurements in aircraft turns and banks corrected to surface brightness. It is currently in preliminary form since existing data is limited to incidence angles of approximately 35 deg. or less, but flight experiments are planned for 2007 with a nadir off-set SFMR configuration to increase the incidence angle coverage.

The preliminary model is extrapolated to high wind speeds and large incidence angles but compares well with existing models at nadir and high wind speeds and over all incidence angles at wind speeds less than approximately 30 m/sec.

III. RETRIEVAL VALIDATION

Even though the HIRad retrieval algorithm has key elements in common with the SFMR it is an independently developed forward model and inversion algorithm. One step in validating the HIRad method and code was through direct comparison to SFMR at nadir only. Partial off-nadir validation is implied through the preliminary wind speed model results, but complete validation awaits the nadir off-set SFMR experiment and future HIRad flights.

The comparison to SFMR retrievals serves as validation to the HIRad algorithm to the extent that the SFMR wind speed and rain rate estimates are currently accepted as valid and reliable. The NOAA WP-3D aircraft routinely deploys GPS dropwindsondes measuring horizontal wind vector. Paired samples of dropwindsonde and SFMR measurements in hurricanes during 1998, 1999 and 2001 were used for wind speed algorithm validation [2]. Final results showed the mean difference between the GPS measured wind and the SFMR retrieved wind was 1.67 m/s with a standard deviation of 3.29 m/s. Similarly, the SFMR wind algorithm has been validated at wind speeds greater than 70 m/sec in Katrina in 2005. SFMR rain rate retrieval has been evaluated by comparing to rain rate inferred from the NOAA tail radar on board of the WP-3D [7]. Comparisons came from Hurricane Bonnie in 1998 and Hurricane Humberto in 2001. Relative to radar rainfall estimates, the SFMR rain rates were found to overestimate in light rain and underestimate in heavy rain. A bias of 5 mm/hr of the SFMR rainfall estimate was found compared to the radar. Radar calibration for these comparisons traces back to the Precipitation Radar on TRMM and is quoted at ± 1-2 dB.

A total of five hurricanes; Katrina, Rita and Ophelia in 2005, Frances in 2004, and Fabian in 2003 were selected for comparing the two retrieval algorithms. The complete data set consists of multiple aircraft passes through each of these hurricanes. Figure 1 is an example of the comparison of retrieved wind speed and retrieved rain rate, in this case from a single pass through Katrina on August 28th. The peak observed wind speed was greater than 70 m/s, and the maximum rain rate was approximately 50 mm/hr. There was good general agreement between the two algorithms, with a mean difference in wind speed of -0.5 m/sec, and a mean difference in rain rate of -0.16 mm/hr. The HIRad algorithm is estimating higher rain than SFMR at high rain rates. The consistency of this is under study.

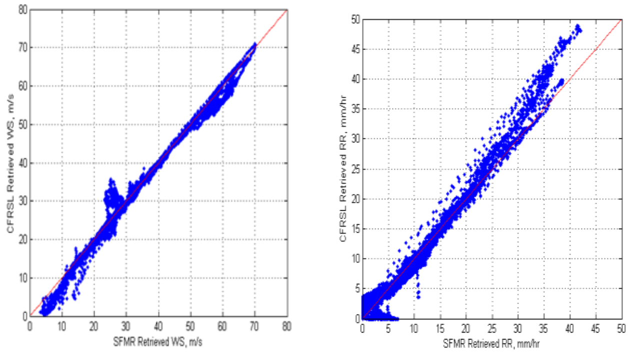

Figure 1. CFRSL retrieved wind speed and rain rate.

IV. FULL SWATH SIMULATIONS AND RETRIEVALS

Once the preliminary version of the upgraded wind speed model was available, wide swath simulation of hurricane observations were performed. With this capability, image reconstruction studies relevant to array design and performance were conducted. Actual brightness temperature scenes from SFMR passes in hurricane Katrina, and brightness temperatures derived from modeled wind and rain fields for hurricane Floyd, were used to simulate reconstructed images. These simulated images, were then used to evaluate retrievals over the full HIRad swath.

A. Synthesized Array Pattern

The HIRad thinned array antenna consists of 10 multi-frequency linear array fan beam antennas that sample the surface as a real aperture along track and synthesize pixels over the cross-track swath with image reconstruction software. For HIRad, with approximately an octave bandwidth of 4-7 GHz, the element spacing in the cross-track direction varies from less than $\lambda/2$ at 4 GHz to greater than $\lambda/2$ at 7 GHz. The total array dimension is approximately 0.8 m in the synthesis direction. These array design parameters determine the synthesized pattern characteristics and trade-offs between the instrument spatial resolution and cross-track field of view [9]. Design studies have been conducted using various image reconstruction algorithms as part of the HIRad development [10].

For simulation purposes, the visibility terms that represent the radiometer measurements are computed from [1],

$$V = G * T_b$$

and,

$$\hat{T}_b = G' * V$$

where,

$$G' = G^t \left(GG^t\right)^{-1}$$

The matrix 'G' characterizes the array, and brightness temperature, T_b, represents the actual brightness temperature scene [1]. Brightness temperature estimates, $\hat{T}_b$, in the reconstructed scene are the synthesized array patterns for the impulse response case.

B. Swath Width Definition

In designing the array, synthesized patterns and the presence of grating lobes, while using beam efficiency as the figure of merit, were used to trade off spatial resolution with swath width. The cross-track array element spacing was the driving factor in these trade-offs. Beam efficiency is the criterion used to assess the cross-track array element spacing in a spatial resolution vs. swath width analysis. The square of the synthesized pattern was used for beam efficiency calculations. For the preferred spacing of 2.3 cm, grating lobes were present at approximately 70 degrees in the 7 GHz pattern, limiting the useful part of the swath to approximately ± 60 degrees.

C. Image Reconstruction Simulations

For realism, actual SFMR measured brightness temperature profiles from hurricane Katrina were used to simulate cross-track scans for HIRad image reconstruction analyses. Starting with the retrieved wind speed and rain rate profiles from a selected SFMR pass, an apparent brightness temperature scene beneath the aircraft was computed as a function of nadir angle as if the aircraft were flying over selected parts of the storm at an altitude of 11 km. These simulations have been used to study various array taper functions for reconstructing images and other imaging optimization measures [10]. As an example, Fig. 2 is a case simulating the HIRad measurement, at 7 GHz horizontal polarization. Here the aircraft passes directly over the maximum wind and rain in the eye-wall, which produces a brightness temperature peak at the center of the swath that decreases to the swath edges. These results are for a uniform aperture taper, and the difference between the original profile and the reconstructed profile, at angles around 60 degrees, are primarily due to grating lobe effects. This demonstrates the usefulness of the swath out to ± 60 degrees.

Reconstructed images were computed at all four HIRad frequencies for this same case, and wind speed and rain rate profiles were produced using the HIRad retrieval algorithm.

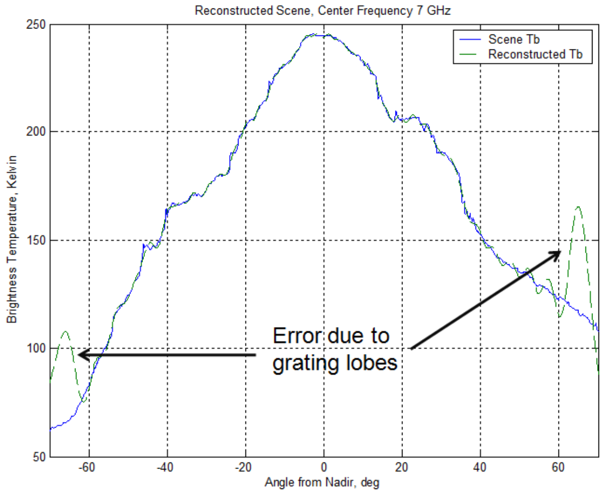

Figure 2: Actual and reconstructed brightness temperatures.

Fig. 3 shows simulation retrievals compared to the original wind speed and rain rate inputs. The mean difference in wind speed is -0.55 m/s and in rain rate is 0.6 mm/hr. These methods and algorithms will be built upon for more complete and realistic HIRad simulations in the future. Retrievals for multiple cross-track scans in hurricane Floyd wind and rain fields will be used to simulate 2 dimensional HIRad imaging.

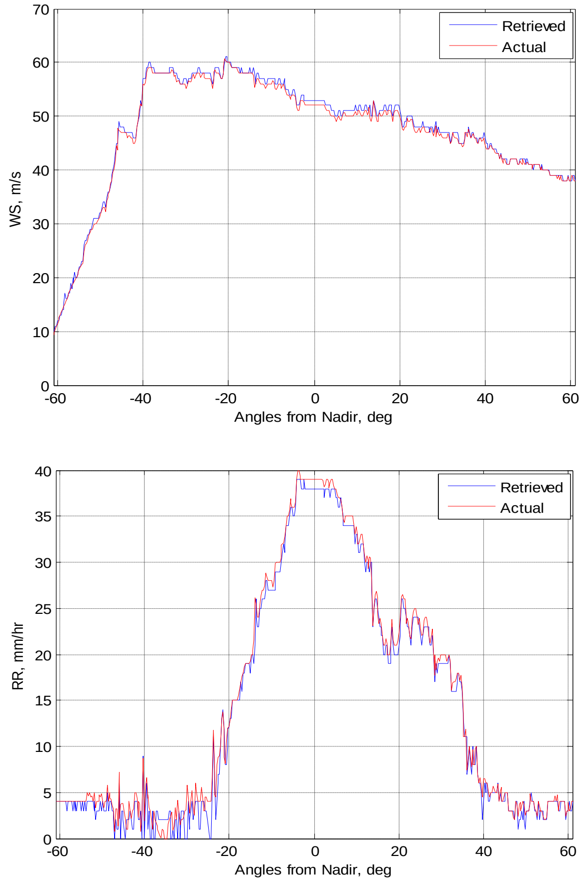

Figure 3: Simulated retrieved wind speed and rain rate.

V. CONCLUSION

A retrieval algorithm for simultaneously inferring surface wind speed and rain rate in a hurricane environment from wide swath microwave synthetic thinned array radiometric measurements has been developed. This retrieval algorithm is composed of a forward model with a rain model applicable to hurricanes and a surface wind speed model designed for wind speeds up to 70 m/sec, or more, and incidence angles greater than 60 degrees. The inversion algorithm uses a statistical least-squares difference inversion method for multi-frequency measurements. Retrievals compare well at nadir to SFMR retrievals and behave well out to large incidence angles in noise free simulations.

Pattern synthesis and image reconstruction studies have been included in the HIRad modeling and noise free simulations and have demonstrated good performance over a ± 60 degree swath. Retrieval algorithm performance is good in test cases simulating HIRad wide swath measurements in hurricanes from various locations in the storm.

These modeling and simulation tools are planned for use in Observation System Simulation Experiments, OSSEs, to evaluate the utility for HIRad in improving NOAA's hurricane surveillance and forecasting capability.

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