On the Correlation of Area-Extensive Measurement of Fractional Area Whitecap Coverage with Microwave Brightness Temperatures

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Abstract— **On August 21, 2007, while mounted in a U.S. Navy P3 aircraft, the Naval Research Laboratory's Airborne Polarimetric Microwave Imaging Radiometer (APMIR) and the University of Washington's FoamCam recorded microwave and video images of the sea surface in the Gulf of Mexico as a function of distance from the eye of Hurricane Dean. From a working altitude of 6.1 km, the FoamCam sea surface optical imagery determined sea state, including presence of whitecaps, while APMIR measured the ocean surface brightness temperature at bands from 6.6 GHz to 37 GHz. The specific brightness temperatures measured were 6.6VH, 6.8VH, 7.2VH, 10.7V and full polarimetric data at 19.35 and 37 GHz. Collocated nearly cotemporaneous data from both SSM/I and WindSat satellite radiometer overpasses were available, as were oceanographic and meteorological data from National Buoy Data Center buoys.**

As an initial result from the analysis of these datasets, this paper provides a comparison of the APMIR-measured brightness temperatures with those measured by SSM/I and WindSat. The APMIR data and the surface video imagery is also used to investigate the relationship between linearly polarized microwave brightness temperatures and whitecap coverage. Future analysis directions for this data are discussed at the end of the paper.

***Index Terms*—Foam fraction, whitecap coverage, microwave radiometry, sea foam, wind speed.**

I. Introduction

By producing bubbles, sea spray and sea-salt aerosols, large-scale breaking waves (or whitecaps) are involved in the planetary heat budget, air-sea gas exchange, atmospheric marine boundary layer visibility, tropical cyclone intensification, and aerosol radiative forcing of climate [see 1 and the references therein]. In addition, whitecaps affect both microwave radiometric retrievals of ocean-surface wind vector [2] and salinity [3], and visible wavelength retrieval of ocean color [4]. Better measurements of the fractional area foam coverage due to whitecaps, F_c, coupled with a physically sound accounting of foam effects on ocean surface electromagnetics would facilitate both inclusion of the effects of breaking waves on geophysical processes and also increase the accuracy of the above-mentioned parameters retrieved from satellite measurements.

Traditionally, F_c is estimated as a function of wind speed. However, water temperature, atmospheric stability, wave age, wave-current interaction, and wind history also influence F_c. Developing a predictive relation for wave breaking capable of estimating F_c over the range of conditions encountered globally requires that the dependence of F_c on these additional factors be understood. The existing database of F_c compiled from photographs, while valuable in gaining knowledge, represents only a limited range of conditions. Thus, an algorithm estimating F_c from satellite-measured brightness temperature, T_B, of the ocean surface has been developed within the framework of WindSat mission [5]. Using satellite-based estimates, we can assemble a database of F_c with global coverage, and a much greater range of variability. This, in turn, will allow the improvement of existing or the development of new models for F_c, which more fully account for effects of additional factors.

As part of this effort, the Radiometry and Sea Surface Imagery (RASSI) experiment took place off the east coast of the United Sates and over the Gulf of Mexico in August 2007. Foam coverage and microwave brightness temperature were measured using aircraft-mounted instruments. In addition, both satellite-based microwave radiometric data and *in situ* oceanographic and meteorological data were available. This data set provides: 1) a basis to investigate the relation(s) of foam coverage, obtained both photographically and radiometrically, to environmental conditions on regional scales; 2) ground truth for validation and performance assessment of satellite-based retrievals of foam coverage.

II. Experiment Description

The core component of RASSI was five flights aboard a U.S. Navy P-3 assigned to Scientific Development Squadron One (VXS-1). Mounted in the bomb bay of the P-3 were the Airborne Polarimetric Microwave Imaging Radiometer (APMIR) and FoamCam, a high-resolution, high-altitude digital video camera system. The flights, originating and terminating at Patuxent River Naval Air Station, were scheduled for spatial and temporal coincidence with either the WindSat or SSM/I overpasses and also overflew National

Manuscript received April 18, 2008. This work was supported by the Naval Research Laboratory (NRL) and the National Polar-Orbiting Environmental Satellite System Integrated Program Office (IPO/NPOESS).

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978-1-4244-1987-6/08/$25.00 ©2008 IEEE

Data Buoy Center (NDBC) buoys for the collection of ground truth data.

The APMIR system provided vertically- and horizontally-polarized microwave brightness temperatures at 6.6, 6.8, 7.2, 19.35, and 37GHz, and fully polarimetric data at 19.35 and 37 [6]. Additional data at 10.7 and 22.235 GHz were taken, but these radiometers had hardware failures during this experiment that limited their data taking capabilities. Data was taken at a nominal incidence angle of 53 degrees. This gave a footprint of roughly 1 km x 2 km for the 19 and 37 GHz radiometers at the typical altitude of 6000 m.

The principle components of FoamCam are a Hitachi KP-F120 1.3 megapixel progressive scan monochrome digital camera and a Fujinon C22x17A-M41 1 inch format 17 mm to 374 mm 3-motor zoom lens mounted in a nadir-viewing configuration. At maximum focal length, the spatial resolution was 17 cm per pixel at an aircraft altitude of 6.7 km.

This paper will focus on a flight to the Gulf of Mexico made on August 21, 2007 when Hurricane Dean was centered in the Bay of Campeche at the southern edge of the gulf. The breaking waves in the outer wind field of a hurricane presented a serendipitous opportunity to obtain a remarkable data set. The spectacular sea surface images of wave breaking not only provide data for the originally planned experimental objectives, but go well beyond our expectations as we can now study the evolution of the wave field as a function of radial distance towards the eye of the storm. This is not something we had anticipated being able to do prior to the flight and makes the RASSI data set an incredibly valuable resource.

Figure 1 shows the flight path across the Gulf of Mexico and the position of the storm (19.7N, 92.2W) at 23:45 UTC, 08/21/07.

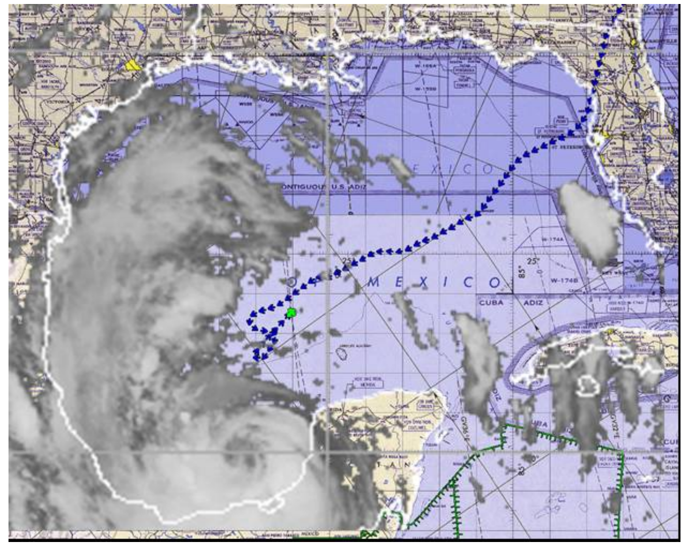

Figure 1. Flight track on August 21, 2007 from 2057 UTC to 2338 UTC overlaid on map of the flight region. Superimposed on map is an IR image of the region taken at 2345 UTC on August 21, 2007.

III. ANALYSIS

The focus for APMIR data processing to this point has been the 19V/H and 37V/H data. During the course of the flight over the Gulf of Mexico, the aircraft performed a set of three circles at seven positions (stations) following an approximately radial approach to the storm center. The stations were chosen to be approximately evenly-spaced along the flight line, with the added constraint that the circles be conducted in a relatively cloud-free region to allow visibility of the surface for FoamCam and to minimize cloud contamination of the microwave data. The data was corrected to a nominal earth incidence angle of 53 degrees, with the correction taken from radiative transfer modeling with inputs specific to the location of the data. The data was binned into 5-degree azimuth blocks. The data was filtered based on excessive standard deviation in a bin, large absolute value variation from adjacent bins, and large excursions from the mean over the whole three-circle data file. For the results shown here, the remaining data was averaged, removing the azimuthal dependence. Final thermal and pointing corrections rounded out the processing.

The video images were analyzed for fractional area foam coverage, F_c, using the procedures described by [7] and [8] with brightness thresholds selected using the procedure described by [9]. The foam coverages shown here are for actively breaking waves (i.e., whitecaps) only and do not reflect surface covered by both decaying bubble plumes and actively breaking waves. Subsequent analysis will look at the difference between these two estimates of foam coverage.

Figure 2 shows the retrieved wind vectors from WindSat. The temporal matching between the WindSat overpasses and RASSI observations varied from a minimum of 12 minutes for Station 7 to a maximum of 150 minutes for Station 1.

Microwave brightness temperature, T_B, was retrieved from WindSat and SSM/I [10]. The SSM/I T_B data are mapped on 1°x1° regular grid and were re-sampled to 0.5°x0.5° grid using standard bi-linear interpolation. WindSat T_B data were used without regridding.

IV. RESULTS

Figure 3 shows the comparisons of T_B at 19 GHz (V and H pol) and 37 GHz (V and H pol) measured by APMIR, WindSat, and SSM/I. Generally, the APMIR T_B values agree with the satellite-derived T_B data both in terms of absolute value and trend of brightness temperature with location. One systematic difference is that the APMIR 37 GHz data at both polarizations exhibit a negative bias when compared to the satellite data. The causes for this bias are not known at present and the subject of further study.

Figure 4 shows T_B at 18-19 GHz (H and V pol), and 37 GHz (H and V pol) for both WindSat and APMIR plotted as a function of F_c from the FoamCam images. The data in the figure show that T_B increases with F_c except at the highest foam coverage, confirming the expected strong correlation

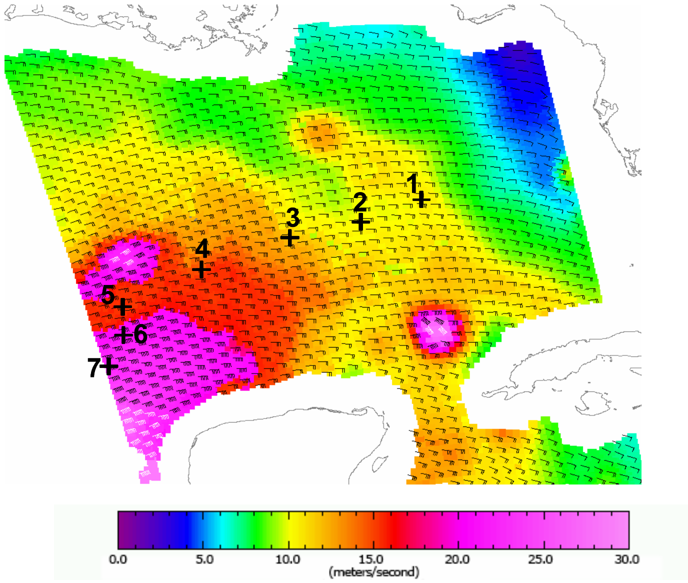

Figure 2. Wind field derived from WindSat data. Crosses represent locations where circle patterns were flown for microwave and video data collection.

between T_B and F_c. A second result from Figure 4 is that at both 18-19 GHz and 37 GHz, the magnitude of the change in brightness temperature, ΔT_B, for H pol is larger than the change in T_B for V pol (from 16 to 22 K for H pol versus 5 to 10 K for V pol). This provides field confirmation of laboratory measurements showing that H polarization is more sensitive to the presence of sea foam than the V polarization.

A final observation is that these foam ΔT_B values are smaller for WindSat implying a decrease of sensitivity to the foam signal from the surface due presumably to the atmosphere interference. Furthermore, this effect is larger for 18-19 GHz than for 37 GHz, with ΔT_B for H pol at 18-19 GHz for APMIR and WindSat being 22 K and 18 K, respectively. In contrast, at 37 GHz, H pol, ΔT_B for APMIR and WindSat are 16.2 K and 15.6 K, respectively. This suggests that the atmosphere has more effects on the satellite-based measurements at 18-19 GHz than at 37 GHz.

Unresolved issues at this point are the decrease in ΔT_B for the WindSat data versus APMIR and the roll-off of T_B with F_c at the highest foam coverage. While there are no definite reasons for the former, it is possible that the roll-off of T_B with F_c might be due to problems in the image processing for Station 7. Station 7 was conducted at twilight, when light conditions were marginal for high-altitude photography and noise in the image may be biasing F_c high. This point is under further investigation at the present time.

V. Conclusions and Way Forward

High altitude radiometric and video data of the ocean surface in the Gulf of Mexico were collected during the Radiometric and Sea Surface Imagery (RASSI) experiment. These are combined with ancillary meteorological and oceanographic data from buoys and satellite overpasses in a focused data set

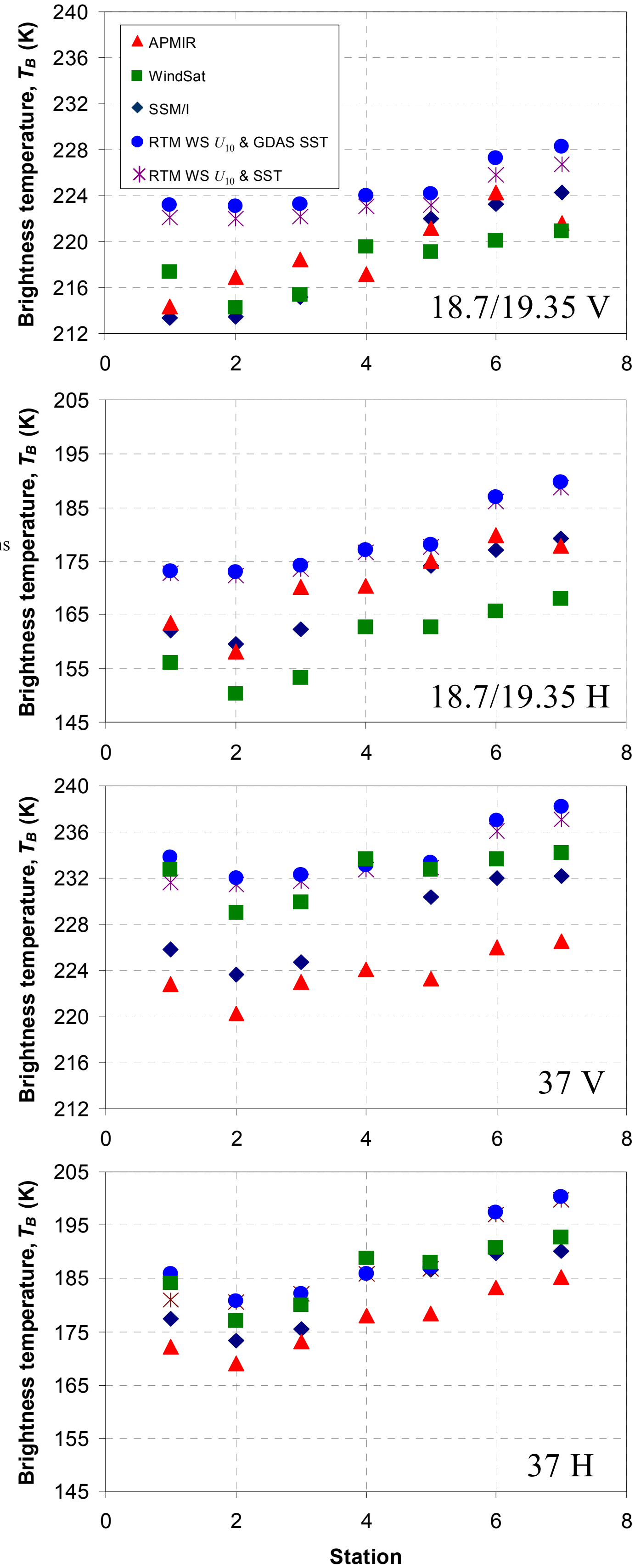

Figure 3. Comparison of brightness temperatures.

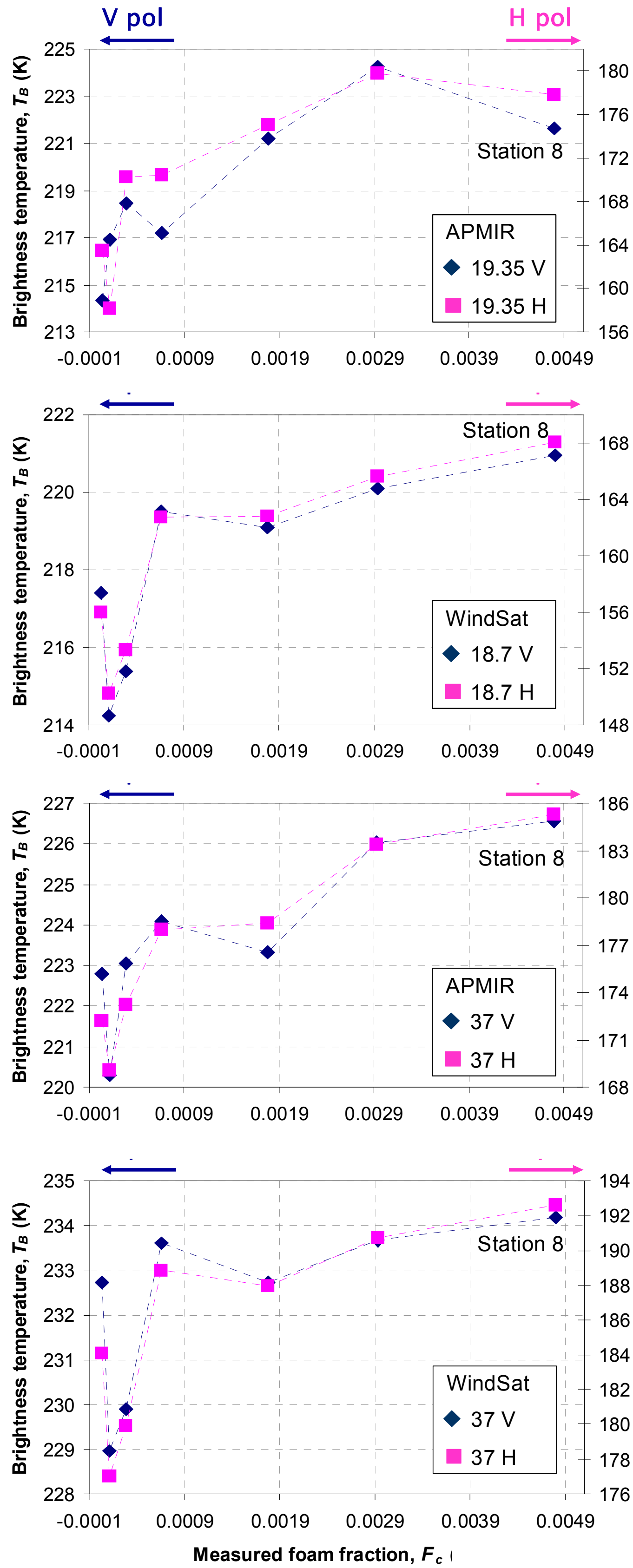

Figure 4. Brightness temperature as a function of foam fraction.

aiming at investigation of the relationship between foam coverage F_c and brightness temperature T_B on a regional scale under various conditions. Preliminary results for T_B and F_c in the vicinity of Hurricane Dean (21 August, 2007) in the Gulf of Mexico have been reported here.

To further the data processing, the polarimetric channels at 37 and 19 GHz will be examined. In parallel, the most appropriate threshold level for the determination of foam coverage from the video imagery will be identified. Further processing will include the radiometric and video data collected in the Atlantic Ocean on flights prior to the Gulf of Mexico flight. The effect of different footprints for the video camera, APMIR and WindSat will be considered. The high altitude data and the high resolution camera will allow analysis of whitecap coverage as a function of spatial scale, from areas on order of 0.04 km^2 up to several tens of square kilometers. Investigation of the effects of additional factors, such as atmospheric stability, SST, and wave field characteristics on T_B and F_c is planned. The information from additional radiometric channels and improved analyses will provide a more complete picture of the relationship between foam coverage and brightness temperature on a regional scale under a range of meteorological and environmental conditions.

ACKNOWLEDGMENT

The authors would like to thank Navy Scientific Development Squadron One (VXS-1) for their support.

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