MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Surface Wind Speed and Significant Wave Height Validation Module

Investigator(s): Heather Holbach and Ivan PopStefanija (ProSensing Inc.)

Requirements: Categories 2–5

Plain Language Description: This module will collect data in mature hurricanes to continue improving surface wind speed and rain rate estimates from the Stepped-Frequency Microwave Radiometer (SFMR) at high wind speeds and when the aircraft is not flying straight and level. It will also identify the extent of 8 ft significant wave height waves. Improved measurements from the SFMR and knowledge of the surface wave field have numerous implications for forecasting and research efforts, such as providing more accurate observations to estimate tropical cyclone (TC) intensity and size along with improved estimates of marine hazards. These improvements allow for better watches and warnings for a TC's potential impacts to be provided to emergency managers and the general public and leads to more accurate research results.

Mature Stage Science Objective(s) Addressed:

1) Collect Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in mature hurricanes. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*IFEX Goal 2*]

Motivation: Surface winds in a tropical cyclone are essential for determining its intensity and size. Over the past several hurricane seasons, surface wind speed estimates from the Stepped-Frequency Microwave Radiometer (SFMR), dropsondes, and surface-adjusted flight-level winds in major hurricanes have not been consistent. By obtaining better collocated SFMR, dropsonde, and flight-level measurements in major hurricanes we will be able to determine what the cause of the inconsistency is. Better collocations of the SFMR and dropsondes will lead to improved calibration of the SFMR algorithm for high wind speeds by removing spatial collocation errors related to dropsonde drift.

Currently, the SFMR is used for obtaining surface wind measurements at nadir. Due to poor knowledge about sea surface microwave emission at large incidence angles in high wind speed conditions, SFMR winds are only retrieved when the antenna is pointed directly downward from the aircraft during level flight. Understanding the relationship between the SFMR measured brightness temperatures, surface wind speed, wind direction, and the ocean surface wave field at off-nadir incidence angles would allow for the retrieval of wind speed measurements when the aircraft is not flying level. At off-nadir incidence angles the distribution of foam on the ocean surface from breaking waves impacts the SFMR measurements differently than at nadir and is dependent on polarization (Holbach et al. 2018). Therefore, by analyzing the excess brightness temperature at various wind speeds and locations within the TC environment at various off-nadir incidence angles, the relationship between the ocean surface characteristics and the SFMR measurements will be quantified as a function of wind direction relative to the SFMR look angle and polarization.

The Tropical Analysis and Forecast Branch (TAFB) at the National Hurricane Center (NHC) provides forecasts for significant wave heights of 8 ft and greater in their High Seas product (https://www.nhc.noaa.gov/abouttafbprod.shtml#HSF). These forecasts are important for informing mariners on the sea state conditions they may encounter while traversing the open oceans. The goal of this module is to collect sea state measurements from the Wide Swath Radar Altimeter (WSRA) to inform the analyses and forecasts produced by TAFB as well as to help calibrate the Wavewatch III ocean model.

Background: Historically, the SFMR has primarily served as a research instrument that measured surface wind speeds and rain rates in hurricanes. As early as 1980, data were collected to estimate surface wind speeds from the breaking waves on the sea surface, but they were used in a limited capacity due to various errors. Beginning in 1998-1999, SFMR data were regularly collected on the NOAA P-3 aircraft with reasonable estimates of surface wind speeds, but an algorithm upgrade in the mid-2000s significantly improved the data (Uhlhorn et al. 2007). The SFMR still struggled at the low wind regime and within rainy conditions, which prompted a second algorithm update that became operational in 2015 (Klotz and Uhlhorn 2014). Since the 2015 update, more SFMR data has been collected in major hurricanes, which has revealed some potential issues with the high wind speed portion of the algorithm that require further investigation.

Currently, if the aircraft pitch or roll angle exceeds a threshold of ± 10°, surface wind speeds and rain rate are not reported by the SFMR. These thresholds result in surface wind speeds not being provided when the aircraft turns or if the aircraft exceeds the pitch threshold, for example, while flying a constant pressure surface through the eyewall where the highest wind speeds are usually measured. By improving our understanding of the physics of the air-sea interaction between the wind and sea surface in the extreme environment of TCs, it will be possible to develop corrections for the SFMR algorithm to obtain surface wind speed measurements when the aircraft is not flying level.

NHC/TAFB has been producing High Seas forecasts since 2003. The lowest threshold used in the forecasts is a significant wave height of 8 ft. This 8 ft threshold is used by cruise ships to identify areas to avoid. Navy vessels generally tend to avoid 12 ft seas and very large cargo ships often will continue traversing seas up to 20 ft. Observations of the sea state are quite sparse in the open ocean, especially in TCs, and are generally limited to observations by buoys. Sea state observations from the WSRA will provide much needed measurements for informing and validating the High Seas forecasts and improving the Wavewatch III ocean model.

Goal(s): Improve the wind speed and rain rate estimates obtained by the P-3 SFMRs. Improve NHC/TAFB's High Seas analyses and forecasts and NOAA's Wavewatch III ocean model by collecting WSRA significant wave height data in the environment of TCs.

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Hypotheses:

1. Collecting directly collocated SFMR and dropsonde data will reduce errors in the high wind speed portion of the SFMR algorithm.
2. Collecting high-incidence angle SFMR data will allow for quantification of the changes in the SFMR brightness temperatures at off-nadir incidence angles that are related to the wind direction relative to the SFMR look angle and polarization.
3. Collecting WSRA significant wave height data will improve TAFB's High Seas analyses and forecasts as well as help improve the Wavewatch III ocean model.

Objectives:

1. Collect collocated SFMR and dropsonde data in high wind regions (surface wind speeds ≥ 100 kts)
2. Collect off-nadir SFMR observations at several different incidence angles in several different storm-relative locations.
3. Collect WSRA significant wave height data for all regions of the storm with significant wave heights ≥ 8 ft.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): The goal of the P-3 SFMR validation module is to collect collocated high wind speed (≥ 100 kts) SFMR and dropsonde data. For the single aircraft P-3 SFMR validation module (P-3 Pattern #1), either P-3 (NOAA42 or NOAA43) can be used, but NOAA43 is preferred. The P-3 will fly inbound through the eyewall releasing a dropsonde targeting the surface wind speed maximum or a sequence of 3 dropsondes released in rapid succession to increase the odds of observing the surface wind speed maximum. The P-3 will then enter the eye and turn outbound approximately 30–40° azimuthally downwind of the inbound leg to overfly the splash point of the dropsonde. It may be necessary to adjust the azimuthal separation of the inbound and outbound legs to account for eye size, storm strength, and flight altitude. Dropsondes released in hurricanes with smaller eyes tend to drift further downwind than those released in larger eyes. Dropsondes will also drift further downwind in stronger winds, especially if the layer of strong winds is deeper, and dropsondes released from higher altitudes will have more time to drift further downwind. Another option is to wait for the dropsonde(s) to splash, determine the splash location(s), and overfly the exact splash location(s). This will allow for the best spatial collocation; however, the temporal collocation will not be as close.

For the two aircraft P-3 SFMR validation module (P-3 Pattern #2), one P-3 (preferably NOAA43 with the USFMR and WSRA) will fly inbound and release a dropsonde targeting the surface wind speed maximum or a sequence of 3 dropsondes released in rapid succession to increase the odds of observing the surface wind speed maximum. The second P-3 (preferably NOAA42 with IWRAP) will fly inbound 30°–40° downwind of the first P-3 and approximately 5-6 min later (or the closest temporal spacing possible for safe operations) to overfly the splash location of the dropsonde(s). The two aircraft can be at different altitudes. As in the single P-3 module, it may be necessary to adjust the azimuthal separation of the two P-3s to account for eye size, storm strength, and flight altitude or to identify the actual splash location of the dropsonde(s).

For the SFMR high-incidence angle module (P-3 Pattern #3), preferably, two down-looking SFMRs should be mounted on the P-3 aircraft. The operational wing-pod mounted SFMR should be operating as usual. A second SFMR or the USFMR is to be mounted parallel to the latitudinal axis of the airframe (rotated 90° from the operational position). When the aircraft rolls, the operational SFMR will be collecting off-nadir data at H-pol and the second SFMR will be collecting off-nadir data at V-pol, simulating the data that the SFMR would collect when the aircraft pitches. The high-incidence angle modules can be flown during any mission with any flight pattern and are designed to obtain SFMR measurements in various locations of the TC environment at several different wind speeds during constant banked aircraft turns at several different roll angles, specified below. A full pattern for each module consists of three complete circles for each specified roll angle. *It is important to maintain as constant of a roll angle, pitch angle, and altitude and to stay within an area of similar surface conditions (i.e., constant surface wind speed, surface wind direction, and swell direction) as possible.* A dropsonde and AXBT pair should be released at the beginning of the pattern. The Wide-Swath Radar Altimeter (WSRA), if available, should also be obtaining measurements during the pattern for analysis of the ocean surface characteristics. The wave spectra obtained by the WSRA will allow for a more accurate investigation of the sensitivity of the SFMR to the surface wave characteristics. It is ideal to fly these modules in rain-free areas as to reduce the impact of the atmospheric emission on the SFMR measurements and to obtain measurements in regions of moderate to heavy precipitation, as deemed safe by the aircraft pilots, in order to understand the impact of varying the path length of the precipitation.

Module Options:

1. Zero wind, high incidence angle response
   - This module is designed to determine the antenna pattern corrections and possible impacts of sun glint
   - Fly circles at roll angles of 15, 30, 45, and 60 degrees

2. Moderate wind response (~15 m s^{-1}, 30 kts)
   - This module is designed to understand the mixed “phase” (i.e., foam vs roughness contributions to brightness temperature)
   - Fly circles at roll angles of 15, 30, and 45 degrees

3. Moderate winds (~15 m s^{-1}, 30 kts) and substantial swell or varying fetch length response
   - This module is designed to determine the sensitivity to stress
   - This can be performed on the way to the storm or in different sectors of the storm
   - Fly circles at roll angles of 15, 30, and 45 degrees

4. Strong wind response (>30 m s^{-1}, 60 kts)
   - This module should be flown in multiple storm quadrants (motion relative)

- Fly circles at roll angles of 15, 30, and 45 degrees

Thus far, measurements have been obtained in all storm-relative quadrants (Figure 1). However, there is a lack of observations in the rear storm-relative quadrants. To develop a more complete composite picture, *we are particularly interested in obtaining measurements in the rear quadrants* of storms (motion relative) this season. We would also like to focus on regions with wind speeds greater than 20 m s^{-1} and regions of stratiform precipitation.

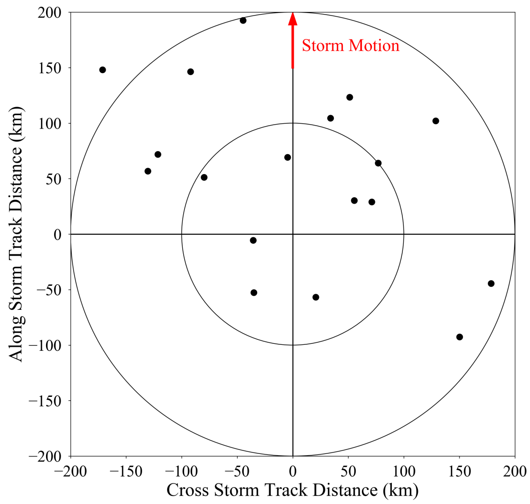

Figure 1: Storm-relative locations of high-incidence angle SFMR observations obtained in previous seasons.

The wave validation module (P-3 Pattern #4) can be conducted with any of the standard P-3 patterns. Data collection for the WSRA requires a flight radar altitude between 8 and 12 kft. It may be necessary to descend prior to reaching the planned IP in order to capture the extent of the 8 ft significant wave height waves. Guidance will be provided by the PIs prior to and during the flight on the estimated extent of the 8 ft significant wave height waves. Ideally, the 8 ft threshold would be captured by the WSRA in each quadrant of the storm. However, if it is not possible to observe the 8 ft threshold in each quadrant due to time constraints then it would be preferred to obtain those estimates in at least the front right (storm-relative) quadrant.

Links to Other Mature Stage Experiments/Modules: The Surface Wind Speed and Significant Wave Height Validation Module can be flown in conjunction with the following Mature Stage experiments: Gravity Wave, Ocean Winds, Rainband Complex Survey, RICO SUAVE, and TC Diurnal Cycle.

Analysis Strategy: The SFMR and dropsonde data collected during the P-3 SFMR validation module will be directly compared to identify any inconsistencies in the SFMR algorithm at high wind speeds. These collocated pairs will also be compared to the SFMR and dropsonde data used for the previous algorithm development, which were not directly spatially collocated, to identify the errors that may be present when using those data. Any USFMR or IWRAP data collected with the overflight of the dropsondes will also be used to investigate the dropsonde and IWRAP wind profiles. WSRA data collected in tandem will be used to analyze the surface wave field to identify any surface characteristics that may impact the SFMR observations. It is important that the aircraft maintain as straight and level of flight as possible when collecting the collocated data, so that no additional errors are introduced related to the conditions of flight.

The SFMR high-incidence angle data from these flights will be analyzed to quantify the double harmonic oscillation that is evident in high-incidence angle SFMR data collected during previous seasons (Holbach et al. 2018). The WSRA data will then be used to analyze the differences in the ocean surface characteristics to reveal any possible relationships between the double harmonic oscillation found in the SFMR measurements and the ocean surface characteristics. The surface wind direction from the dropsondes will be used to compute the relative look angle of the SFMR to the surface wind direction. Wind speed from the dropsondes will be used to quantify the differences in the SFMR brightness temperatures expected at nadir with the high-incidence angle measurements. SST from the AXBTs will be used as input to the brightness temperature algorithm.

The WSRA significant wave height measurements sampled at a 55-second rate are transmitted off the P-3 aircraft during flight to NHC/TAFB and incorporated into their High Seas analyses and forecasts. The data will also be analyzed to identify characteristics of the typical sea state for storms of various sizes, strengths, and translation speeds. The extent of various significant wave heights, starting at 8 ft, will be determined for each flight and compared to identify/validate relationships between significant wave height, storm size, strength, and translation speed. The results of the analysis will lead to a better understanding of the sea state in TCs, which will be used by forecasters and modelers to improve forecasts of the sea state in TCs.

References:

Holbach, H. M., E. W. Uhlhorn, and M. A. Bourassa, 2018: Off-Nadir SFMR Brightness Temperature Measurements in High-Wind Conditions. *J. Atmos. Oceanic Technol.*, **35**, 1865–1879, https://doi.org/10.1175/JTECH-D-18-0005.1

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