2019 NOAA/AOML/HRD Hurricane Field Program - IFEX

MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Stepped-Frequency Microwave Radiometer Module

Investigator(s): Heather Holbach (PI)

Requirements: Categories 2–5

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. Over the past several hurricane seasons, surface wind speed measurements 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 colocations of the SFMR and dropsondes will lead to improved calibration of the SFMR algorithm for high wind speeds by removing spatial colocation errors related to dropsonde drift.

Currently, the Stepped-Frequency Microwave Radiometer (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 tropical cyclone 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.

In addition, the proven track record of the P-3 SFMRs for providing surface wind data in tropical cyclones (Uhlhorn et al. 2007, Klotz and Uhlhorn 2014) has motivated the effort to obtain usable wind data from the G-IV SFMR. However, there is no documentation of the G-IV SFMR data and its usefulness under the current specifications of the G-IV flight patterns. To our knowledge no data from the G-IV SFMR has been released or used in any research or operational capacity. This data could potentially provide important information about the tropical cyclone wind radii as well as for mapping the environmental surface winds. The goal of this module is to validate the G-IV SFMR data with reliable, coincident P-3 SFMR data in the full spectrum of wind speeds and rain rates.

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 P-3 aircraft with reasonable estimates of wind speeds, but an algorithm upgrade in the mid-2000s significantly improved the data. The SFMR still struggled at the low wind regime and within rainy conditions, which prompted a second algorithm update that became operational in 2015. 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 ± 5°, wind speeds and rain rate are not reported for the SFMR. These thresholds result in 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 tropical cyclones, it will be possible to develop corrections for the SFMR algorithm to obtain wind speed measurements when the aircraft is not flying level.

An SFMR was also installed on the G-IV, but it has several additional factors with which to contend. Because of the aircraft altitude, the footprint size is ~4 times larger than the SFMR on the P-3. The SFMR on the P-3 was designed to only interpret rain below the melting level because the P-3 normally operates at those altitudes. The G-IV must not only interpret rain, but also ice particles in the column between the flight-level and melting level. The combined factors call into question the G-IV SFMR ability to produce reasonable wind speeds (and rain rates) along the flight track.

A third SFMR (upward looking) was installed on the P-3, NOAA42, to take measurements of the air column above the aircraft. This data has not been used in any research or operational capacity either, but could prove very useful for the G-IV SFMR validation. Figure 1 provides a schematic of the footprint size and coverage for the three SFMR instruments based on standard flight altitudes of 42,000 ft and 10,000 ft for the G-IV and P-3, respectively. Note that this schematic is not to scale.

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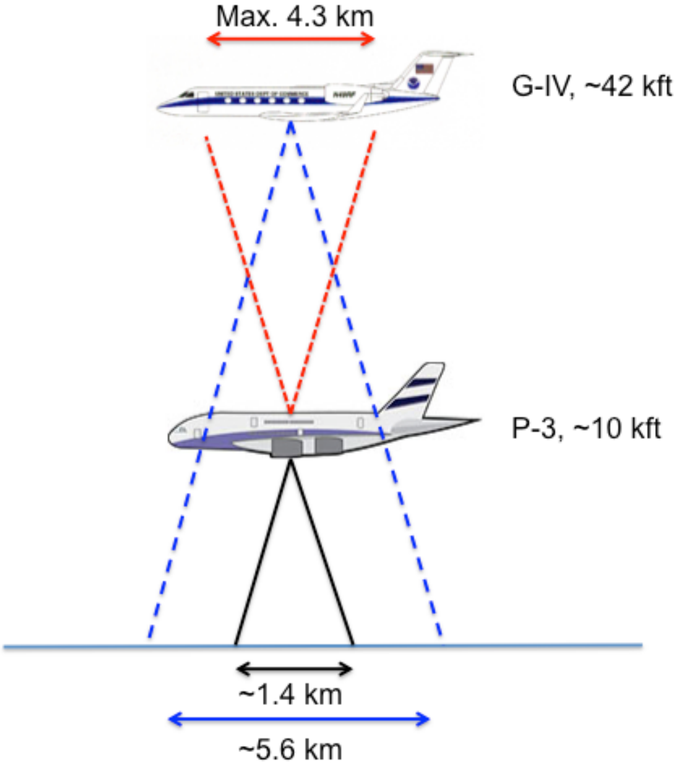

Figure 1. *A schematic figure of the footprint coverage for the various SFMR instruments is provided. Also indicated are the normal operating altitudes of each aircraft. This schematic is not to scale.*

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 temperature at off-nadir incidence angles that are related to the wind direction relative to the SFMR look angle and polarization.
3. Comparison of coincident G-IV and P-3 SFMR data will necessitate modifications to the G-IV SFMR processing and/or algorithm to account for the additional impacts on the received signal. It is expected that if the G-IV uses the P-3 processing algorithm, there will be noticeable deficiencies in the returned values.

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, either P-3 (NOAA42 or NOAA43) can be used. The P-3 will fly inbound through the eyewall releasing a dropsonde targeting 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 that 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.

For the two aircraft P-3 SFMR validation module, one P-3 (preferably NOAA 43) will fly inbound and release a dropsonde targeting 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 minutes later to overfly the splash location of the dropsonde. 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.

For the SFMR high-incidence angle module, 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 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 tropical cyclone 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 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 2). However, there is a lack of observation 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.

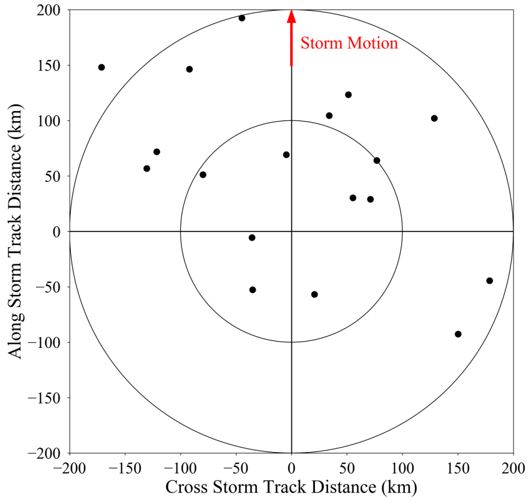

Figure 2: *Storm-relative locations of high-incidence angle SFMR observations obtained in previous seasons.*

The premise behind the G-IV SFMR validation module is fairly simple: coordinate small sections of overlapping flight tracks between the G-IV and P-3. It is expected that this module should fit into a larger experiment so as not to interrupt the overall goals of said mission. Because the G-IV and P-3 often fly very different patterns, the best way to have the aircraft overlap is using the circumnavigation pattern (see flight pattern document). This flight option would coordinate along the inner circumnavigation (G-IV), targeting an area that is experiencing intermittent but occasionally moderate to heavy rain. This flight strategy allows for comparison of similar strength wind speeds (consistent radius) with a large variety of rain rates. If the G-IV can fly a radial pass in conjunction with the P-3 (maybe possible for a tropical storm or weak hurricane), this would allow evaluation over a variety of wind speeds and rain rates. A third option would be to complete this module on a downwind leg of a P-3 standard in-storm pattern.

The two aircraft operate at different air speeds (~325 kt for the P-3 and ~440 kt for the G-IV), which limits the amount of time the aircraft will have reasonable coverage over the same portion of the ocean surface. Therefore, this module needs to be operated from the perspective of a preselected meeting point or midpoint of the pattern, which ensures both SFMR are observing the same portion of the ocean. The aircraft should be flying along the same heading during this coordinated overlap. For about 3-4 minutes prior to and after this midpoint, the two SFMR will have varying overlap in their footprints with the least overlap at the beginning and end of the module. A reasonable estimate of the duration of this module is ~8 minutes. Figure 3 is a schematic of the footprint coverage as a function of time within the module centered on the preselected midpoint. As confirmation of the wind speeds observed at the midpoint, a dropsonde should be launched from the P-3.

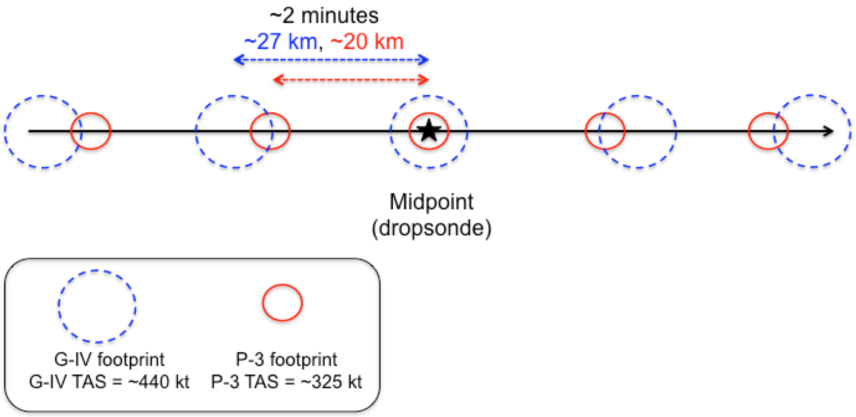

Figure 3. *A schematic diagram of the flight path of the G-IV and P-3 aircraft during the module is provided. The red and blue circles indicate the P-3 and G-IV SFMR footprint size, respectively. The timing between successive locations in the figure is ~2 minutes with the distance covered by each aircraft noted. This figure is not to scale as the footprint size is emphasized for visibility.*

Links to Other Mature Stage Experiments/Modules: The SFMR Module flown in conjunction the following *Mature Stage* experiments: TCDC Experiment, TC in Shear Experiment, TDR Experiment, Synoptic Flow Experiment, NESDIS JPSS Satellite Validation Experiment, and NESDIS Ocean Winds.

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 IWRAP data collected with the overflight of the dropsondes will also be used to investigate the dropsonde and IWRAP wind profiles.

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.

Data that are collected during the G-IV validation module will first be post-processed and quality-controlled. The two downward looking SFMR will be compared and statistically evaluated depending on the overlapping footprint coverage and distance from the midpoint. From this perspective, differences can be determined based on coverage, wind speed, and rain rate. A surface-adjusted wind speed from the dropsonde will serve as the truth to validate both SFMR. A determination of the additional impacts of the air column above the P-3 on the G-IV SFMR results could prompt further investigation into changes for the G-IV processing or algorithm. Comparison of the upward looking P-3 SFMR will serve as an independent measure of the above aircraft air column and will help confirm any impacts the G-IV SFMR encounters.

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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