STEPPED FREQUENCY MICROWAVE RADIOMETER RETRIEVAL ERROR CHARACTERIZATION

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ABSTRACT

The Stepped Frequency Microwave Radiometer (SFMR) is an instrument flown on research and reconnaissance aircraft through tropical and extratropical cyclones providing rain rate and surface wind speed estimates. Errors have been observed with the retrievals from SFMR, especially in extratropical cyclones over cold water, when compared with other sensors. In this paper, some of the SFMR wind speed errors that manifest over cold water are characterized using comparisons with *in situ* measurements by dropwindsondes.

Index Terms— Sea measurements, C-band, microwave radiometry, remote sensing, cyclones

1. INTRODUCTION

C-band radiometers have been used on aircraft for measuring high-speed ocean surface wind speeds since 1980. Jones *et al.* [1] describe the Langley Research Center (LRC) Stepped Frequency Microwave Radiometer (SFMR), a multi-frequency nadir-pointing C-band radiometer, which was flown twice through Hurricane Allen on a National Oceanic and Atmospheric Administration (NOAA) C-130 aircraft in 1980. This instrument was used to develop an early algorithm for remotely retrieving ocean surface wind speed and mean rainfall rate under the aircraft. The variation of the ocean surface and atmosphere under the aircraft with frequency, wind speed, and rain rate allows for retrieval of both parameters.

Currently, the NOAA Aircraft Operations Center (AOC) and the US Air Force Reserve (AFRC) operate several SFMRs instruments. These SFMRs are developed by ProSensing, Inc. of Amherst, MA and based on the design concepts of LRC SFMR. It is also a C-band nadir-pointing microwave radiometer and steps through six frequencies (4.74, 5.31, 5.57, 6.02, 6.69, and 7.09 GHz), dwelling at each for 0.5 s. This instrument, hereafter referred to as SFMR, is installed on each of the NOAA WP-3D and AFRC WC-130J aircraft.

The most recent SFMR retrieval algorithm was developed by Klotz and Uhlhorn [2], following earlier models in 2007 [3] and 2003 [4]. All of these models suffer from the limitation of having been developed solely with data taken in tropical environments below the freezing level, which compromises their efficacy under different atmospheric and ocean conditions.

Attempts to use SFMR data from flights through extratropical storms have had mixed results, but usually the wind speed retrievals are inconsistent with other ground-truth sources (c.f. [5]). As reliable retrievals in all conditions are important for validation and calibration of other remote-sensing instruments, this paper will demonstrate some of the errors associated with SFMR wind speed retrievals over cold water taken near or above the freezing level.

2. METHODOLOGY

2.1. SFMR Radiative Transfer Model Differences

There are a few differences between the SFMR radiative transfer model (RTM) described in literature and the one used here. Uhlhorn and Black [4] give the sky brightness temperature ($\mathrm{T_b}$) contribution in (A4) as:

$$T_{B,sky} = T_{B,down} + (1 - \tau_{r,\infty}\tau_{a,\infty})T_{B,cos}, \quad (1)$$

where $T_{B,down}$ is the downwelling atmospheric $\mathrm{T_b}$, $T_{B,cos}$ is the C-band brightness temperature due to the cosmic microwave background radiation, $\tau_{r,\infty}$ is the total transmissivity of the rain column, and $\tau_{a,\infty}$ is the total atmospheric transmissivity. In this paper, $T_{B,sky}$ is taken to be

$$T_{B,sky} = T_{B,down} + (\tau_{r,\infty}\tau_{a,\infty})T_{B,cos}. \quad (2)$$

Refer also to [6] for an independent justification of this change to the documented SFMR RTM.

In [2], the assumption is stated that the aircraft is below the freezing level in order to derive an equation for

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the rain column transmissivity. If one were to use the calculation for rain altitude presented in (8) in [2] for cold environments, negative rain altitudes sometimes result. Here, as in the previous SFMR RTMs, frozen precipitation does not significantly contribute to T_b. However, the aircraft is allowed to be above the freezing level, so we clarify the rain altitude calculation as

$$H_r = \begin{cases} h + \gamma^{-1} T_a, & T_a \geq -h\gamma \\ 0, & T_a < -h\gamma \end{cases}, \tag{3}$$

where h is the aircraft altitude, T_a is the air temperature at flight-level (°C), and γ is the mean lapse rate of a hurricane as determined from dropsonde temperature profiles [7]. At normal operational altitudes, T_a can be approximately $-15\,°C$ to $-10\,°C$ before rain contributions are neglected.

2.2. GPS Dropwindsonde Database

This paper uses a database of GPS dropwindsondes [8] (also referred to as simply dropsondes) from NOAA and AFRC aircraft as the ground truth. Since dropsondes sometimes do not report the wind vector at a height of 10 m (U_{10}), layer-averaging techniques are typically used to estimate this value [3], [5], [9]. Here the NHC method (J. Franklin, personal communication) was chosen to estimate U_{10}.

This method uses an altitude-weighted mean of the measurements from lowest 150 m between 10 m and 400 m. The lowest valid dropsonde measurement of air temperature, relative humidity, and air pressure along with sea-surface temperature (SST) from the NOAA/NCDC AVHRR Daily-OI-V2 model were used to convert U_{10} to U_{10N}. This U_{10N} estimate is considered to be the equivalent neutral wind speed at 10 m, which is then collocated and compared with the SFMR.

2.3. Excess Emissivity Due to Wind

Measured T_bs from SFMR and simulated T_bs from the RTM are used to calculate excess emissivity due to wind (EEW), or the emissivity of the ocean surface in excess of that due to the smooth-surface. This calculation assumes that the underlying models for atmospheric and rain transmissivity, rain absorption, and smooth-surface emissivity are accurate and that the SFMR T_bs are properly calibrated. It also assumes a rain-free environment or negligible effect of rain on the T_bs. The equation used to determine EEW is

$$\varepsilon_e = \frac{T_b - T_{b,up} - \tau_{r,a}\tau_{a,a}T_{b,sky}}{\tau_{r,a}\tau_{a,a}\left(T_s - T_{b,sky}\right)} - \varepsilon_s \tag{4}$$

where T_b is the measured T_b by SFMR, $T_{b,up}$ is the upwelling T_b from below the aircraft, $\tau_{r,a}$ and $\tau_{a,a}$ are the transmissivities of the rain column and atmosphere below the aircraft, respectively, T_s is the SST (K), and ε_s is the smooth-surface emissivity.

A new EEW model was developed from data collected in tropical cyclone conditions to correct a 1 to $3\,\mathrm{m\,s^{-1}}$ underestimation in SFMR retrievals between 15 and $40\,\mathrm{m\,s^{-1}}$ when compared with dropsondes. This model is not the focus of the present paper, but it was used to perform the retrievals shown in section 3 so an additional wind speed bias was not introduced.

3. RESULTS

Results presented in this paper are based on five years of collocated SFMR and dropsonde data collected in extratropical storms between 2011 and 2017, which included 146 dropsondes. The remaining seasons exhibited some errors that seem to be related to calibration. Samples are collocated in time and space, with respect to the dropsonde splash time and location. Only data within ±10 minutes and ±15 km are considered to be collocated.

SFMR T_bs, wind speeds, and ancillary data are averaged in 10 s groups and then filtered such that the remaining data is from within ±3° roll and ±2° pitch of the instrument. The data here are also limited by SST ($< 22\,°C$) to observe those relationships in the data related only to cold-water and cold-atmosphere operation.

Figure 1 shows the difference between SFMR-retrieved wind speed and dropsonde surface wind speed for four variables over cold water: SST, aircraft-ambient temperature (T_a), dropsonde wind speed, and the estimated difference between the air and sea temperature near the surface. Filled circles indicate the retrievals from the latest published geophysical model function (GMF) [2], empty circles show the results after applying our GMF corrections derived in tropical cyclone conditions, and asterisks depict the means after a correction has been applied to the T_bs.

The correction shown in Figure 1 is based on the air-sea temperature difference, and it largely eliminates the error dependence on SST and T_a. A small dependence may still exist on wind speed, but the observed trend could also be an artifact of the small number of points in the data set. The excluded years could be used to extend this analysis to better understand this behavior.

The air-sea temperature difference is derived from the altitude, T_a, and SST using a similar model as other components of the RTM (e.g., (3)). Assuming the temperature profile below the aircraft is linear, the air temperature at the surface $T(z = 0)$ can be estimated to be

$$T(z = 0) = T_a - \gamma h. \tag{5}$$

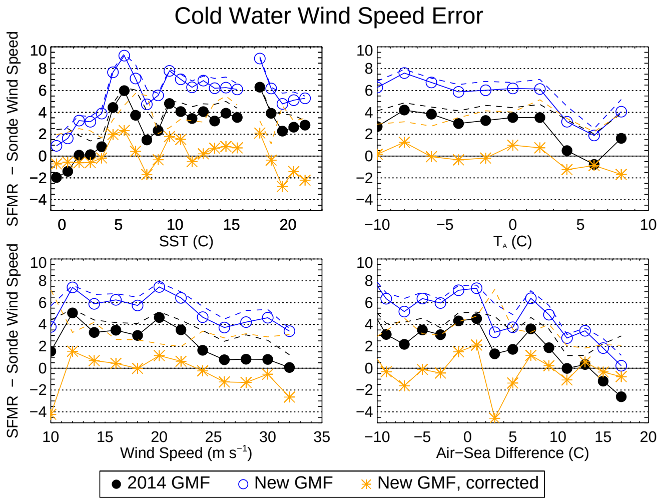

Fig. 1: SFMR wind speed retrieval error over cold water as a function of various independent variables; from left to right and top to bottom, the variables are SST, T_a, dropsonde wind speed, and the air-sea temperature difference near the surface. Filled circles indicate retrieval from the latest published EEW GMF, empty circles show the results after applying our new EEW GMF, and asterisks show the results after correcting T_bs and retrieving with our new GMF. Dashed lines indicate the RMS errors for the same colored data points.

4. CONCLUSIONS

As was stated in section 2.3, the data shown in this paper rely on the accuracy of various environmental models. We have shown errors with the SFMR GMFs, compared with collocated GPS dropwindsondes, as a function of four variables: sea-surface temperature (SST), aircraft-ambient temperature (T_a), dropsonde-estimated surface wind speed, and the air-sea temperature difference (which is dependent on the first two variables as well as altitude).

After correcting for the air-sea difference errors, a small trend in the mean difference between SFMR and dropsondes can still be observed as a function of wind speed. This may indicate that at higher SST or T_a the magnitude of the correction should be decreased. A means of transitioning SFMR retrievals between the behavior over cold water and that over warm water remains to be fully developed.

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