# AN IMPROVED MICROWAVE RADIATIVE TRANSFER MODEL FOR OCEAN EMISSIVITY AT HURRICANE FORCE SURFACE WIND SPEED

by

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# ABSTRACT

An electromagnetic model for predicting the microwave blackbody emission from the ocean surface under the forcing of strong surface winds in hurricanes is being developed. This ocean emissivity model will be incorporated into a larger radiative transfer model used to infer ocean surface wind speed and rain rate in hurricanes from remotely sensed radiometric brightness temperature. The model development is based on measurements obtained with the Stepped Frequency Microwave Radiometer (SFMR), which routinely flys on the National Oceanic and Atmospheric Administration's hurricane hunter aircraft. This thesis presents the methods used in the wind speed model development and validation results for wind speeds up to 70 m/sec.

The ocean emissivity model relates changes in measured C-band radiometric brightness temperatures to physical changes in the ocean surface. These surface modifications are the result of the drag of surface winds that roughen the sea surface, produce waves, and create white caps and foam from the breaking waves. SFMR brightness temperature measurements from hurricane flights and independent measurements of surface wind speed are used to define empirical relationships between microwave brightness temperature and surface wind speed. The wind speed model employs statistical regression techniques to develop a physics-based ocean emissivity model dependent on geophysical parameters, such as wind speed and sea surface temperature, and observational parameters, such as electromagnetic frequency, electromagnetic polarization, and incidence angle.

# In The Memory of My Father

Who made me believe that leaders are made...not born Eng. Fawwaz Methyeb EL-Nimri

> To the hands that rocked my cradle To the person who believed in me

> > То уои... МОМ

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# LIST OF ACRONYMS/ABBREVIATIONS

CFRSL	Central Florida Remote Sensing Lab
RTM	Radiative Transfer Model
EIA	Earth Incidence Angles
NOAA	National Oceanic and Atmospheric Administration
NESDIS	National Environmental Satellite Data and Information
	Service
SFMR	Stepped Frequency Microwave Radiometer
TPC	NOAA Tropical Prediction Center
NHC	NOAA National Hurricane Center
HRD	NOAA Hurricane Research Division
WCC	White Caps Coverage
HIRad	Hurricane Imaging Radiometer

# **CHAPTER 1 : INTRODUCTION**

Electrical engineering microwave communications technologies contribute significantly to environmental remote sensing. Microwaves are useful in remote sensing because of their ability to penetrate clouds and operate day or night and in severe weather to view the earth's surface. Therefore, microwave sensors play an important role in providing measurements of important atmospheric, oceanic, terrestrial, and ice environmental parameters; and they routinely operate from aircraft and satellites to provide these valuable environmental measurements for scientific research (e.g., global climate change) and operational utilization by federal governmental agencies (e.g., numerical weather forecasting).

#### 1.1 Thesis Objective

The Central Florida Remote Sensing Lab, CFRSL, is engaged in research to develop microwave remote sensing techniques for oceanic and atmospheric applications. The CFRSL has developed an analytical microwave radiative transfer model (RTM) that simulates passive microwave measurements from the ocean surface. This thesis provides an important upgrade to this RTM, by improved ocean surface wind speed modeling. The objective is to develop a physics-based microwave RTM that characterizes the sea surface microwave blackbody emissions for a variety of microwave instruments and measurement geometries. Developing such a RTM will yield an accurate prediction of polarized microwave brightness temperature over a wide range of ocean wind speeds, frequencies, and earth incidence angles (EIA). It will be useful in engineering design studies of passive microwave remote sensing instruments and for developing wind speed geophysical retrieval algorithms. This model will be accurate in up to frequencies of approximately 10GHz, wind speeds from zero to > 70 m/sec and incidence angles from the nadir to  $>45^\circ$ , for vertical and horizontal polarizations.

#### **1.2** Microwave Remote Sensing

In communications and most related disciplines, the system performance is usually determined by the signal-to-noise power ratio, S/N, at the receiver. For these applications, the signal level at the receiver input is calculated using link calculations, which involve the Friis transmission formula [1]. The system noise power is calculated by the incoherent summation of random electromagnetic noise power, which is generated in the receiver electronics, plus the blackbody noise power from the environment, which is received through the antenna. However, in passive microwave remote sensing applications, the antenna noise is treated as signal, which is used to infer various geophysical characteristics of the earth and the atmosphere. This signal is non-coherent microwave blackbody radiation from the earth's surface and the intervening atmosphere according to Plank's law [2].

Remote Sensing is defined as the science and technology by which the characteristics of objects or media can be identified, measured or analyzed without direct contact, using electromagnetic (EM) signals, which are reflected or emitted from the object/media. Microwave sensors have the ability to penetrate through clouds and may be operated day and/or night and under all weather conditions. They routinely operate from aircraft and satellites to provide measurements of important atmospheric, oceanic, terrestrial, and ice environmental parameters

for many applications including scientific research (e.g., global climate change) and operational utilization by federal governmental agencies (e.g., numerical weather forecasting).

#### 1.2.1 Rayleigh-Jeans Law

Blackbody radiation by definition refers to an object or medium which absorbs all radiation incidents upon it and then re-radiates energy according to Planck's radiation law. A blackbody radiates uniformly in all directions (isotropic) with a spectral brightness as shown in the following equation:

$$S(\lambda) = \frac{2\pi hc^2}{\lambda^5} \left( \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \right)$$
(1.1)

Where:

S (λ)	= blackbody energy spectral flux density, $W/m^3$ ,
h	= Planck's constant = $6.63 \times 10^{-34}$ joule sec
λ	= wavelength, m
k	=Boltzmann's constant = $1.38*10^{-23}$ joule/K
Т	= Blackbody absolute Temperature, Kelvin

c = speed of light =  $3*10^8$  m/sec

At microwave frequencies, the Rayleigh-Jeans law is an excellent approximation to Planck's law, and it is given as:

$$s(\lambda) = \frac{2\pi ckT}{\lambda^4}, W/m^2/m$$
(1.2)

$$=\frac{2\pi kT}{\lambda^2}, W/m^2/Hz$$
(1.3)

Where:  $ch/_{\lambda} << kT$ 

In this region, the spectral emissions are approximately straight lines when plotted against wavelength on a log-log scale, as shown in Figure 1.1 with a 100 Kelvin degree steps, Rayleigh-Jeans fractional deviation from Plank's Law (1.1) is < 1% provided that  $\frac{f}{T} < 3*10^8$  Hz/K [2].



Figure 1.1 : Rayleigh-Jeans approximation to Plank's law in microwave region.

In nature, it is unlikely to find objects/media that behave as blackbodies at all wavelengths (frequencies); so the concept of greybody emission is used. The emitted radiation from a greybody at a specific frequency is a fraction of the ideal blackbody emission; and the emissivity of a material is defined as the ratio of the greybody emission to the blackbody emission.

#### **1.2.2** Radiative Transfer Theory

The greybody radiation received by an airborne or satellite microwave radiometer (shown Figure 1.2 ) is the sum of three emission (brightness temperature) components:

- 1. Emission from the surface  $(T_{sur})$
- 2. Down-welling radiation reflected upward at the surface  $(T_{sky})$
- 3. Upwelling atmospheric radiation (T<sub>up</sub>)

The polarized power collected by a microwave antenna viewing a blackbody surface is:

 $P_r = (1/2)$  \* Surface Emission \* Isotropic Loss \* Antenna Effective Aperture where the factor (1/2) is for the power in one of two orthogonal polarizations. The surface blackbody emission is:

Surface emission

Emis <sub>surface</sub> = 
$$\left(\frac{1}{2}\right)\left(\frac{2\pi}{\lambda^2}\right)kT$$
,  $W/m^2/Hz$  (1.4)

For an ideal "spot-beam" antenna, the instantaneous field of view (IFOV) area is

$$A_{\rm IFOV} = \pi \frac{R^2 \beta^2}{4} , m^2$$
(1.5)

where  $\boldsymbol{\beta}$  is the antenna effective beamwidth in radians.

Propagation Loss (hemi-spherical radiation)

$$L_{prop} = \frac{2}{4\pi R^2} , m^{-2}$$
 (1.6)

where  $\boldsymbol{R}$  is the distance from the antenna to the surface in meters.

Antenna Effective "Capture" Aperture

$$\mathbf{A}_{e} = \left(\frac{8}{\pi}\right) * \left(\frac{\lambda}{\beta}\right)^{2}, m^{2}$$
(1.7)

 $P_r = kT$ , W/Hz

Given the receiver pre-detection bandwidth **B**, then

$$P_r = k * T_{app} * B \tag{1.8}$$

Where, Pr is the average blackbody power collected in a single polarization,  $T_{app}$  is the equivalent blackbody physical temperature or the apparent brightness temperature in Kelvin. Each component of brightness temperature is related to the physical temperature of its medium by the emissivity,  $\varepsilon$ , according to:

$$T_{sur} = \varepsilon^* T_{phy} \tag{1.9}$$

For the ocean surface, (1.9) gives the surface brightness temperature in terms of the ocean emissivity and the sea surface physical temperature. The emissivity characterizes the radiation transfer efficiency at the air/sea interface, and it satisfies energy conservation, such that emissivity is related to the surface power reflection coefficient by,

$$\varepsilon = 1 - \Gamma_{surface}$$

For smooth water,  $\Gamma_{surface}$  is equal to the square of the magnitude of the complex Fresnel voltage reflection coefficient, which is a function of the complex dielectric constant of sea water, incidence angle of observation, and the EM wave polarization.

As illustrated in Figure 1.2, brightness components  $T_{refl}$  and  $T_{sur}$  are also attenuated by the intervening atmosphere. Therefore, the total apparent brightness temperature,  $T_{app}$ , at the radiometer antenna aperture may be written as,

$$T_{app} = T_{UP} + e^{-\tau} \left( T_{sur} + T_{refl} \right)$$
(1.10)

where

$$T_{refl} = \left(T_{\cos} e^{-\tau} + T_{Down}\right) * \Gamma$$
(1.11)

where  $T_{up}$  is the atmospheric emission upwelling component along the antenna line of sight,  $T_{sur}$  is the surface emission,  $T_{ref}$  is the specular reflected atmospheric emission downwelling component,  $e^{-\tau}$  is the atmospheric transmissivity and  $T_{cos}$  is the cosmic brightness background, which is equal to 2.73 K. Therefore, the ocean surface is characterized by the brightness temperature  $T_b$  and the atmosphere is characterized by the optical opacity,  $\tau$ .



Figure 1.2 : Simplified microwave radiative transfer over the ocean.

#### 1.3 Ocean Surface Wind Speed Remote Sensing

Surface winds cause roughening of the ocean surface by the generation of small ocean waves of cm length. Roughening the surface decreases the power reflectivity and therefore increases the emissivity. Further, with time, the small waves transfer their energy to longer waves that eventually break and form white caps and foam patches. Foam has low reflectivity and can be considered as approximately a blackbody. The monotonic growth of the percentage of foam (foam fraction) coverage is the means to estimate the surface wind speed from measured brightness temperatures. For high wind speeds, such as in hurricanes, foam emission is dominant in the radiometer received signal. The objective of this thesis is to develop a physics-based wind speed model useful from low wind speeds approaching zero m/sec to category-5 hurricane wind speeds of > 70 m/sec.

#### **1.3.1 Satellite Radiometers**

Microwave radiometers that are widely used on weather satellites usually operate at number of frequencies (wavelengths) to separate the various Tb contributions from the surface and atmosphere. For example, weather satellites with multi-frequency radiometers are able to retrieve geophysical parameters like water vapor, cloud liquid water, rain rate for the atmosphere and ocean wind speed, and land/sea surface temperature for the earth surface. The use of microwave frequencies has the advantage of penetrating clouds, haze, smoke, light rain and snow; so microwave radiometers do not require clear skies to function properly.

Satellite radiometers cover a wide swath with nearly global coverage of the earth surface each day; therefore their importance lies in the daily measurements of key environmental parameters that are used for weather forecasting and long-term climate research. An example of the ocean surface wind speed global environmental measurement provided by the WindSat satellite radiometer is shown in Figure 1.3 [3].



Figure 1.3 : WindSat ocean surface wind speed 9-day average October, 1992.

#### **1.3.2 SFMR Measurements**

The measurement of hurricane maximum (one-minute sustained) surface winds is a requirement of the National Oceanic Atmospheric Administration's (NOAA) Tropical Prediction Center/National Hurricane Center (TPC/NHC). The NOAA/Hurricane Research Division's (HRD) Stepped-Frequency Microwave Radiometer (SFMR) is the prototype for a new generation of operational airborne remote sensing instruments designed for surface wind and rain measurements in hurricanes. The first experimental SFMR surface wind measurements were made in Hurricane Allen in 1980 [4], the first real-time retrieval of winds on board the aircraft in Hurricane Earl in 1985, and the first operational real-time transmission of winds to TPC/NHC in Hurricane Dennis in 1999 [5]. The use of the C-band frequency range from 4.5-7.22 GHz provides the ability to penetrate clouds and heavy rain and thereby to measure wind speeds on the surface and rain rate simultaneously.

The research performed in this thesis used Tb measurements collected by the SFMR at nadir and during aircraft banks for modeling nadir and off-nadir ocean surface emissivity, as will be described later in the coming chapters. Chapter 2 discusses the theoretical sea surface emission for smooth water and several semi-empirical rough ocean emissivity models. Next, Chapter 3 presents the development of the C-band wind speed emissivity model for nadir and off nadir viewing; and Chapter 4 discusses the validation of this C-band emissivity model with

measurements from SFMR. Finally Chapter 5 presents conclusion and recommendations for future work.

### CHAPTER 2: SEA SURFACE EMISSION

The principal component in the C-band microwave ocean RTM is the emission from the surface. It represents the largest portion from the received brightness temperature that is about 95% of the total emission with no rain. The emissivity of the surface is proportional to sea surface temperature, salinity, frequency and surface roughness and is modeled in to two parts:

- 1. Emission for a smooth specular surface
- 2. Emission for a rough surface

The contribution of each in the total surface emission will be described in the sections that follow.

#### 2.1 Physical Principles

In remote sensing, understanding the physics of EM wave propagation across a boundary between two dielectric media is essential to the interpretation of radiometric signals. For a microwave radiometer viewing a smooth ocean surface through a non-attenuating atmosphere, the EM propagation across the air/sea interface depends upon the difference in the characteristic impedances of the two media.

### 2.1.1 Fresnel Voltage Reflection Coefficient

Fresnel's equations describe the electric field (voltage) reflection and transmission for transverse EM waves at the interface of two semi-infinite dielectric media [2]. Figure 2.1 illustrates the behavior of an incident plane wave at the interface between air and sea water. A fraction of the signal crosses the interface and is refracted at an angle  $\theta_2$ ; and the other part is reflected at an angle  $\theta_1$ . In remote sensing, we are interested in the intensity (energy) of both the reflected and refracted signals that are collected by the radiometer.

The following voltage reflection coefficient equations are given for the electric field components both parallel (2.1) and perpendicular (2.2) to the plane of incidence (vertical and horizontal polarization respectively). Snell's Law is used to calculate the incident, reflected and transmitted rays according to (2.3) [6].



Figure 2.1: Plane wave reflection and transmission at the air/ocean interface.

$$\rho_{V-pol} = -\left[\frac{e_{r2}\cos\theta - \sqrt{e_{r2} - \sin^2\theta}}{e_{r2}\cos\theta + \sqrt{e_{r2} - \sin^2\theta}}\right]$$
(2.1)

$$\rho_{H-pol} = \left[\frac{\cos\theta - \sqrt{e_{r2} - \sin^2\theta}}{\cos\theta + \sqrt{e_{r2} - \sin^2\theta}}\right]$$
(2.2)

where  $e_{r2}$  is the sea water relative complex dielectric constant ( $e_{r1} = 1.0$  for air) and  $\theta = \theta_1 = \theta_1$ ' is the earth incidence (reflected) angle in degrees.

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{2.3}$$

where, n<sub>i</sub>=index of refraction, i =media 1 or media 2



Figure 2.2 : Typical ocean power reflection coefficient.

In Figure 2.2, the H-pol power reflection coefficient increases monotonically to unity reflection at an incidence angle of 90 deg, and the V-pol curve decreases and reaches zero reflection at an angle  $\sim 83$  deg, known as the Brewster angle. At this incidence angle, there is no reflection and the wave passes through the interface without refraction. At larger incidence angles, the reflection rapidly increases to 100% at 90 deg.

#### 2.1.2 Surface Emissivity

Emissivity is the ratio of radiation emitted by a surface to the theoretical blackbody radiation predicted by Planck's law. The emission from the ocean surface can be calculated using the Fresnel power reflection coefficient for V- and H-polarizations. Based upon the conservation of energy at the interface, the surface emissivity is given as

$$\varepsilon = 1 - \Gamma$$
 (2.4)

Where,

 $\Gamma$  = power reflection coefficient =  $|\rho|^2$ 

 $\rho$  = Fresnel voltage reflection coefficient

Smooth or specular emissivity is applicable to any flat surface with root-mean-square height variations very much smaller than the wavelength of the EM wave. The emissivity is equal to the power transmission coefficient for the refracted wave (blackbody microwave emission within the upper ocean layer) shown in Figure 2.1. The specular emissivity depends on incidence angle, polarization and the complex relative dielectric constants for both media. Because of the large changes in the dielectric properties of materials in the microwave region, surface emissivity is very important in microwave remote sensing to derive surface temperatures and to distinguish between different media (e.g., ice, land and ocean). Typically, knowledge of emissivity to an accuracy of 0.0003 or better is required to retrieve physical parameters from Tb measurements. The importance of this is that emissivity affects the magnitude of two Tb components of the radiative transfer model (RTM), namely; the calculation of the reflected downwelling emission from the atmosphere and the emission from the ocean surface.

### 2.1.3 Dielectric Constant of Sea Water

Precise knowledge of the complex dielectric constant (permittivity)  $\varepsilon_r$  of water is essential for studying the radiative transfer of microwave radiation that is emitted by the ocean surface. The dielectric constant is a function of frequency (f), surface water temperature T and salinity S, as shown in the Debye equation [6].

$$\varepsilon_r = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \left(\frac{j\lambda_R}{\lambda}\right)^{1-\eta}} - j\left(\frac{2\sigma\lambda}{c}\right)$$
(2.5)

Where,

 $j = \sqrt{-1}$ 

 $\lambda$  = radiation wavelength in cm

 $\varepsilon_{\infty}$  = dielectric constant at infinite frequency

 $\varepsilon_S$  = static dielectric constant at zero frequency

 $\lambda_R$  = relaxation wavelength in cm.

 $\eta$  = spread factor

 $\sigma$  = is the ionic conductivity determined by the dissolved salt content in S<sup>-1</sup>

c = is the speed of light in cm/sec

Over the past four decades several Debye models have been developed using experimental microwave measurements of pure and saline water [7, 8], but the latest and the one that is used in this thesis was developed by Meissner and Wentz [9] to match satellite radiometer measurements

over a wide range of frequencies. Figure 2.3 shows the real and imaginary parts of the dielectric constant versus frequency for fresh (salinity = 0 ppt) and salt water (salinity = 33 ppt) and a sea surface temperature of 20 °C.



Figure 2.3 : Real (upper panel) and imaginary part (lower panel) of dielectric constant for saline and pure water.

### 2.2 Sea Surface Emissivity

Traditionally, the sea surface emissivity has been modeled as the sum of a specular emissivity (based upon Fresnel reflection coefficient) plus a wind speed dependant rough emissivity that has been empirically determined such as in Stogryn [10], as shown in (2.6).

 $\varepsilon_{total} = \varepsilon_{smooth} + \varepsilon_{rough} \tag{2.6}$ 

#### 2.2.1 Smooth Water Emissivity

Applying the principal of the conservation of energy at the air/sea interface yields the following definition for the smooth (specular) emissivity in (2.4). Because the smooth water emissivity depends on Fresnel power reflection coefficient, it is a function of the complex dielectric constant of sea water. Further, it should be noted that the dielectric constant is also a function of the radiometer frequency, the water temperature and the salinity. A typical example is given in Figure 2.4, where the emissivity response is reversed compared to the power reflection coefficient i.e., V-pol increases and H-pol decreases versus incidence angle.



Figure 2.4 : Typical sea water emissivity for 4.55 GHz.

# 2.2.2 Rough Sea Surface Emissivity Model

The polarized microwave sea surface emission also depends upon the surface roughness, which comes from ocean waves that are produced by the friction of the surface wind. We can relate the variation of the surface emissivity to three mechanisms:

- 1. geometry changes due to short ocean waves
- 2. geometry changes due to long ocean waves
- 3. Sea foam.

The first has to do with diffraction of microwaves by short ocean waves that are small comparable to the radiation wavelength. The second mechanism has to do with long ocean waves compared to the radiation wavelength, which tilt the surface and thereby mix the H- and V-polarizations and change the incidence angle of the incident wave. Both mechanisms can be treated using a two-scale EM model of ocean facets that have their own reflection coefficient [10]. The third mechanism deals with the generation of sea foam caused by breaking gravity ocean waves. This has a large effect at high wind speeds due to the high emission of foam for both polarizations. All the three mechanisms can be parameterized in terms of the surface wind speed and relative wind direction (defined as azimuth viewing direction of the radiometer relative to the wind direction).

Optical experiments conducted by Cox and Munk [11] measured the slope spectrum of the ocean surface caused by surface winds. They based their findings on sun light that was reflected from the rough ocean surface. Microwave radiometer researchers such as Stogryn [10], have used the ocean slope spectrum results of Cox and Munk to model the microwave ocean emission as a function of surface wind speed microwave frequency and polarization, and these models have been verified over a range of wind speeds and EIA's, in numerous field measurements using ocean plateforms, aircraft, and satellite measurements [12, 13]. An example of the Stogryn model calculated smooth and rough emissivity for 4 and 8 GHz radiometer frequencies is given in Figure 2.5. Three curves of Tb are plotted for zero, 5 and, 10 m/sec and wind speeds, none of which have significant foam cover.



Figure 2.5 : Smooth and rough emissivity for 4 and 7 GHz and wind speeds of zero, 5 and 10 m/sec.

#### 2.3 Sea Foam

Most microwave RTM's treat sea foam as an approximate blackbody with low reflectivity and near-unity emissivity. The transformation of ocean wave energy from short to long wavelengths causes the long gravity ocean wave heights and slopes to grow until gravity causes them to break and produce "white caps" and foam. Since the emissivity of foam is approximately twice that of sea water, understanding the EM characteristics of foam and how it is produced and distributed over the ocean surface is crucial to calculating the rough surface emissivity.

#### 2.3.1 Effect of Foam on Oceanic Emission

Modeling the ocean surface emissivity depends on both smooth and rough surface emission modeling including the emission from foam, which becomes the dominant factor at higher wind speeds. Foam is produced by breaking waves on ocean surface and is responsible for increasing the emission from the foam-covered surface. The generally accepted hypothesis is that, Sea foam is a medium comprising many small air bubbles that float on the ocean surface and produce an impedance matching layer for the propagating EM waves (blackbody radiation in the sea water medium). This reduces the internal blackbody radiation reflection at the air/sea interface, which increases the ocean surface emissivity.
Many studies and experiments have been conducted to measure foam emission; as a function of microwave frequency, polarization and incidence angle [14, 15]. Based upon these experimental results, there are three major assumptions in modeling foam for an airborne (spaceborne) radiometer. The first assumption is that there is a statistical randomness in area-coverage distribution over the antenna foot print (instantaneous filed of view, IFOV) but that each radiometer measurement contains the same mean area coverage of foam. The second is that the foam layer is electromagnetically thick, which implies a thickness greater than a free space wavelength. Third, and most important, is that there exists a statistically stationary relationship between foam area coverage and surface wind speed. Also, in modeling foam emissivity we assume that the foam emissivity is not a function of wind speed.

#### 2.3.2 Emissivity of Foam

In 1970, an interesting attempt at a theoretical description of the emissivity of foam was made by Droppleman [14], his conclusion was that the complexity of the EM boundary value problem precluded the construction of a physically and mathematically convincing theoretical model. Thus, at least for the present, complete reliance must be placed on experimental data in studies relating to the radiometric effects of foam and its relationship with frequency and incidence angle. In 1972, Stogryn [15] developed an empirical expression for sea foam emissivity as a function of sea surface temperature, frequency, and incidence angle based on a review of previously published measurements of foam-covered sea surface. Recently, Rose et. al [16] performed experiments at frequencies 10 and 37 GHz for the range of incidence angle from 30° to 60°. Further, Padmanabhan et al. [17] performed foam emissivity experiments at three frequencies (10, 19 and 37 GHz) for 53° incidence. The emissivity of foam is approximately two times higher than that of calm water, which emphasizes the necessity to account for foam in the calculations of the total emissivity.

#### **2.3.3 Foam Fraction - Wind Speed Dependence**

Based upon empirical results, the formation of foam is highly correlated with surface wind speed and the breaking of gravity ocean waves. Foam fraction or area percentage of foam coverage increases with wind speed and is randomly distributed over the ocean surface on a spatial scale of 10's of meters. Because airborne radiometer antennas have footprints on the ocean surface of 100's meters diameters, the location of foam will appear uniformly distributed in an average sense. A recent study, to characterize the increase of foam fraction, used aerial photography taken at low-altitudes in hurricanes to study the white caps coverage (WCC) and foam coverage with wind speed [18].

Foam fraction is, obviously, independent of the radiometer parameters; frequency, polarization and incidence angle; therefore, it is modeled as a function of wind speed only. Foam begins to appear on the ocean surface at wind speeds of approximately 6 m/sec, where breaking waves start to form, and it increases approximately exponentially with wind speed. For example, from this thesis analysis at a wind speed of 70 m/sec, the foam coverage is estimated to be  $\sim 80$  %. At higher wind speeds, we assume that the percentage foam cover asymptotically approaches 100 %.

# **CHAPTER 3 : WIND SPEED EMISSIVITY MODEL DEVELOPMENT**

Experimentally, it has been observed that the surface wind over the ocean exhibits a strong modulation of the brightness temperature (surface emissivity). The importance of modeling the surface emissivity is that it affects the direct emission from the sea surface as well as the reflected downwelling brightness temperature from the atmosphere. Unfortunately, theoretical radiometric modeling of this rough surface emissivity has been challenging and of only limited success. One reason for this is that the small-scale ocean wave characteristics and their dependence on frictional wind drag on the ocean's surface are not well understood - mostly due to the difficulty of making the required wave measurements in the ocean environment. As a result, radiometric modelers have developed empirical relationships between the surface wind speed and the observed excess brightness temperature. In this chapter, selected models will be described as they relate to this thesis development of a high wind speed emissivity model for use in hurricane research.

### 3.1 Existing Wind Speed Emissivity Models

For smooth ocean surfaces, Fresnel power reflection coefficients are used to model the emissivity with respect to frequency, polarization and incidence angle as given in equation (2.1), (2.2) and (2.3). For slightly rough surfaces (wind speeds < 7 m/sec), there are both quasi-theoretical and strictly empirical approaches that are reasonably successful. Beyond 7 m/sec the breaking of ocean waves creates foam, which exhibits high emissivity. The foam percentage area

coverage varies with the surface wind speed, and this must be known to model the ocean emissivity. Empirical foam and ocean roughness radiometric models exist to characterize the emissivity up to approximately 20 m/sec. Beyond 20 m/sec, the ocean emissivity is not well known because of the rarity of radiometric observations of such events.

#### 3.1.1 Near-Nadir Models

For low wind speeds, the wind friction produced at the air/sea interface generates short ocean (capillary) waves, which increases the emissivity over that calculated using Fresnel power reflection coefficient.

One example of an emissivity model is Wilheit surface emissivity model, which is a function of EIA as well [12]. Wilheit combines the effect due to rough surfaces and foam formation in one term and then calculate his surface emissivity as shown in (3.1), and he divided his wind speed dependence function to three different wind speed regions:  $ws \le$  than 7m/sec, 7 < ws < 17 m/sec and  $ws \ge 17$  m/sec. In these three regions, he models the wind speed as linear, quadratic and then linear dependence for each region, respectively.

$$Emissivity_{Total} = F_n + (1 - F_n)E_{rough}$$
(3.1)

Where,

 $F_n$  = is a function of wind speed, n =1, 2, 3 wind speed regions

 $E_{rough}$  = the rough water emissivity.

Another thing to note about this model is that it uses the Lane and Saxton complex dielectric constant for saline and pure water [19]. This model has been validated using satellite measurements and ocean buoy wind speed measurements [12].

Another well popular surface emissivity model was developed by Stogryn [10] which is a function of EIA as well, This model treated total emissivity as the sum of two parts as shown in (3.2).

Emissivity  $_{total} = \alpha *$  foam emissivity + (1-  $\alpha$ )\*foam free emissivity (3.2) Where,

 $\alpha$  = percentage of foam coverage.

Stogryn based his model on measurements collected from research papers and laboratory experiments of foam coverage due to high winds which saturate foam at 35 m/sec to be 100% covering the ocean surface. In (3.2), it can be noticed that the foam has a big contribution on the total emissivity as wind speed increases.

The NOAA/SFMR wind speed algorithm is an empirical algorithm which regresses SFMR brightness temperature at the ocean surface against independent measurements of surface wind speed. It is applicable for nadir retrievals only and has been validated over a wide range of wind speed from 10 m/sec to > 70m/sec [5]. This yields the excess emissivity, which is the delta emissivity above a specular surface, as a function of frequency and wind speed given as:

Excess 
$$_{Emis.} = (a_2WS^2 + a_1WS + a_0)(1 + b_1Freq)$$
 WS <33.2 m/sec. (3.3)

Excess 
$$_{Emis.} = (c_1WS + c_0)(1 + b_1Freq)$$
 WS > 33.2 m/sec. (3.4)

Where,

WS = wind speed in m/sec.

*Freq.* = frequency in GHz.

 $a_n$  = wind speed coefficients, where n = 0,1,2

 $b_1$  = frequency coefficient.

 $c_n$  = wind speed coefficients, where n = 0,1

NOAA SFMR algorithm was modified after the 2005 hurricane season after observing hurricanes with higher wind speeds than previously (> 70 m/sec), like Kartina 2005.

Figure 3.1, shows the SFMR excess emissivity curves for six frequencies versus wind speed. The excess emissivity increases monotonically with wind speed and also, the emissivity increases weakly with frequency as seen by the spread of curves at high wind speed.



Figure 3.1 : SFMR excess emissivity wind model.

# 3.1.2 Off-Nadir Models

The last two emissivity models mentioned previously (Wilheit, Stogryn), have an incidence angle dependent term that can be used at higher incidence angels. Also, another well known and accredited surface emissivity model is available from Frank Wentz [20]. This model is restricted to a limited range of incidence angle (49 - 57) degrees which are common for

satellite radiometer observations. This model also combines the effect of foam percentage and other roughness effects in one term as:

$$Emissivity_{total} = (1 - F_{pn})R_{geo}$$
(3.5)

Where,

 $F_{pn}$  = is a function of wind speed, p = polarization, n =1, 2, 3 wind speed regions  $R_{geo}$  = sea surface reflectivity.

 $F_{pn}$  is a function of wind speed that is divided in to three different regions depending on wind speed and polarization. For V-Pol, there are two linear wind speed dependence regions; one for ws < 7, ws > 12, and a second quadratic wind speed dependence for  $3 \le ws \le 12$ . For H-Pol there are two linear wind speed dependence regions; one for ws < 7, ws > 12, and a quadratic wind speed dependence for  $7 \le ws \le 12$ . Wentz claims that the model is not applicable above 20 m/sec. also, there is a correction term to the vertical polarization Fresnel reflection coefficient in (2.1) that is a function of sea surface temperature.

Figure 3.2 show a comparison of the three different models for specular surface emissivity (zero wind speed) for 6.93 GHz. It can be noticed that they exhibit small but significant differences. Even though the differences are small, of the order of 0.01, this corresponds to a difference in brightness temperature of 3 K at 300° K sea surface temperature, which is considered to be large for model differences.

Wentz developed his own complex dielectric constant model [9] based on measurements from SSMI satellites and laboratory experiments. Wilheit used the model of Lane and Saxton [19] which has been improved by Stogryn [8] and Klien and Swift [7]. Stogryn based his complex dielectric constant model in part using studies taken by Lane and Saxton [20].



Figure 3.2 : Stogryn, Wilheit and Wentz wind speed model comparison for a wind speed of zero m/sec and Freq. = 6.93GHz.

Figure 3.3 shows a comparison for the rough emissivity models of the three modelers (Wilheit, Stogryn and Wentz) for 6.93 GHz. Again there are significant differences between models



Figure 3.3 : Stogryn, Wilheit and Wentz wind speed model comparison for a wind speed of 10 m/sec and Freq. = 6.93GHz.

Of the three, we consider Wentz to have the best surface emissivity model for higher incidence angles because it has been validated against satellite measurements and it performs well with geophysical retrievals.

# 3.2 CFRSL High Wind Speed Emissivity Model

The SFMR instrument flying on the NOAA aircraft has demonstrated the capability of making wind speed measurements in hurricanes even in the presence of heavy rain. Unfortunately the NOAA SFMR empirical wind speed retrieval algorithm only works at near-

nadir and cannot be easily extended to off-nadir (high EIA) measurements that are required for future airborne radiometer instruments. Thus, the CFRSL high wind speed emissivity model (this thesis) was developed to remove these shortcomings and provide the basis for an improved microwave radiative transfer model for hurricanes. The derivation of this CFRSL model is discussed in this section. The main objective is to provide an emissivity model with the wind speed response that matches that of the SFMR at nadir but also with off-nadir incidence angle capability.

#### 3.2.1 Near Nadir High Wind Speed Modeling

Modeling the surface in the presence of high wind speeds is difficult. The formation of high emissivity foam and its direct relationship to wind speed complicates the model. Some researchers combine the effect of foam and other roughness effects, like the Wilheit and Wentz models discussed above; but others preferred to separate it, like Stogryn.

The CFRSL emissivity model presented below follows Stogryn and accounts for the effects of foam on a physical basis. We choose to model the individual terms as follows:

$$\varepsilon = T_{sur} / SST \tag{3.6}$$

where, SST is sea surface temperature (Kelvin). It follows that,

$$\varepsilon = FF * \varepsilon_{foam\_freq} * f(EIA) + (1 - FF) * \varepsilon_{rough}$$
(3.7)

where,  $\varepsilon$  is total ocean surface emissivity

 $\mathcal{E}_{foam freq}$  is the frequency dependent emissivity of foam

## f(EIA) is the earth incidence angle (EIA) dependence of foam

## $\mathcal{E}_{rough}$ is the rough sea surface emissivity

In (3.7) the only known quantity is the  $\varepsilon_{rough}$  and the assumption of f(EIA) to be equal to one at nadir. The other parameters are derived from the NOAA SFMR algorithm and actual SFMR T<sub>b</sub> measurements in hurricanes. We justify using the NOAA SFMR excess emissivity [5] as "truth" because this algorithm has demonstrated excellent wind speed retrieval accuracy as compared with independent wind measurements over the range of 10 m/sec to > 70 m/sec. It must follow that the correct characterization of emissivity versus wind speed is a necessary condition to achieve accurate wind speed retrievals.

Based on experimental evidence [14] it is recognized that the emissivity of foam varies with frequency but not with wind speed; and it ranges between 0.85 - 0.90 in emissivity which is considered to be high. To solve equation (3.7) for  $\varepsilon_{foam_freq}$ , we use the foam fraction data of Melville [18], in Figure 3.4, to estimate that FF is approximately 98% at a wind speed of ~ 85 m/sec.



Figure 3.4 : Melville white caps coverage (WCC) measurements.

Further, at nadir incidence, f(EIA) = 1 in equation (3.7), which allows the frequency dependence to be determined using SFMR Tb observations. So, the frequency dependence was calculated using the total ocean emissivity derived from the SFMR algorithm at the six C-band frequencies. By examining the data, the following linear dependence with respect to frequency gave the best matching with minimum residuals:

$$\varepsilon_{foam\_freq} = a_0 + a_1 * f \tag{3.8}$$

Where,

*f* is the microwave frequency in GHz.

 $a_n$  = coefficients shown in Table 3.1.

Table 3.1 : Frequency coefficients for sea foam

Coefficients	Values
a <sub>0</sub>	0.036659
a <sub>1</sub>	0.57767

Assuming that the NOAA SFMR excess emissivity for nadir emissivity is correct and that FF is a function of wind speed alone, we use the statistical least square error method to solve for FF in (3.9). By examining the data, we modeled foam fraction as a  $4^{\text{th}}$  order polynomial of wind speeds < 75 m/sec, which yields minimum residuals.

$$FF = a_0 + a_1 * ws + a_2 * ws^2 + a_3 * ws^3 + a_4 * ws^4$$
(3.9)

where, ws is the ocean surface wind speed measured at 10 m above the surface

*FF* is foam fraction

 $a_i$  are coefficients that are shown in Table 3.2 below for wind speeds > 12 m/sec:

Coefficients	Values
$a_0$	0.080264
a <sub>1</sub>	- 0.014736
a <sub>2</sub>	0.00080548
a <sub>3</sub>	- 9.7783e-006
a4	4.5686e-008

Table 3.2 : Foam fraction wind speed coefficients values for WS > 12 m/sec

The wind speed coefficients are shown below in Table 3.3 are for wind speeds  $\leq 12$  m/sec.

Coefficients	Value
a <sub>0</sub>	0.0
a <sub>1</sub>	-1.2155*10 <sup>-22</sup>
$a_2$	8.4357*10 <sup>-23</sup>
a <sub>3</sub>	10-8
a4	6.5273*10 <sup>-25</sup>

Table 3.3 Foam fraction wind speed coefficients values for WS  $\leq$  12 m/sec

The validation of the FF model and the CFRSL surface emissivity model will be shown in Chapter 4 of this thesis.

#### 3.2.2 Off-Nadir High Wind Speed Modeling:

For Off-Nadir modeling to support the estimation of f(EIA), a SFMR Tb data subset during the NOAA aircraft high-banked turns was assembled and sorted according to wind speed and radial distance from the eye of the hurricane. These data were quality controlled to remove rainy pixels and other bogus Tb's e. g., radio frequency interference (RFI), land contamination, etc. Then, atmosphere corrections were applied to estimate the surface emission alone.

The SFMR instrument has an antenna beamwidth of  $\sim 16^{\circ}$  for all the six frequencies, which effects the Tb's for both nadir and off-nadir measurements. To remove this measurement distortion, an antenna pattern correction is applied. The SFMR antenna pattern is modeled as Gaussian as shown in Figure 3.5. This wide beam leads to averaging Tb's from near by incidence

angels as shown in Figure 3.6, in which the reflected and surface emissions will be weighted by the antenna pattern gain.



Figure 3.5 : SFMR antenna pattern gain.



Figure 3.6 : SFMR antenna viewing ocean surface.

The SFMR antenna is mounted on the bottom of the aircraft fuselage for nadir viewing along the ground track. It is mounted with perpendicular (horizontal) polarization in the plane of incidence, which is defined as the plane that contains the antenna line of sight and the normal to the sea surface, as shown in Figure 3.7. As the aircraft enters in to a bank and the SFMR antenna line of sight points off-nadir, the polarization becomes parallel (Vertical) to the plane of incidence. The result is that the brightness temperature will increase with incidence (roll) angle (*EIA*), as shown in Figure 3.8.



Figure 3.7 : Plane of incidence for off-nadir Tb measurements.



Figure 3.8 : Example of SFMR brightness temperature during an aircraft turn.

For Nadir looking, the effect of antenna pattern averaging combines both the horizontal and vertical surface emission equally. Above 20° incidence angle only Tb contribution from the V-Pol will be averaged; and in between, there will be a variable ratio (with EIA) between the H- and V-polarizations. To develop the Tb antenna pattern correction, we calculate a sliding weighted average (convolution) of the antenna gain pattern with the surface smooth emissivity versus EIA, which is illustrated in Figure 3.9 and 3.10.



Figure 3.9 : Antenna pattern weighting of surface emissivity at nadir.



Figure 3.10 : Antenna pattern weighting of V-Pol surface emissivity off-nadir.

The simulated SFMR measured emissivity is a 4<sup>th</sup> order polynominal (red curve) shown in Figure 3.11, which depends on EIA and frequency. The antenna pattern averaging is an additive term to the smooth emissivity (blue curve) from the CFRSL surface emissivity model; and the antenna pattern correction is the difference between the simulated measured (red) and modeled (blue) curves versus EIA.

Simulated measurement = 
$$a_4 EIA^4 + a_3 EIA^3 + a_2 EIA^2 + a_1 EIA + a_0$$
 (3.10)

where,

 $a_n$  =coefficients listed in Table 3.4

*EIA*= earth incidence angle, degrees

Coefficients Frequency	a <sub>0</sub>	a <sub>1</sub>	a <sub>2</sub>	a <sub>3</sub>	<b>a</b> 4
4.55	$8.718*10^9$	$-1.703*10^{7}$	$4.286*10^{5}$	$1.758*10^4$	0.364
5.06	8.686*10 <sup>9</sup>	-1.669*10 <sup>7</sup>	$4.292*10^5$	$1.773*10^4$	0.366
5.64	8.652*10 <sup>9</sup>	$-1.636*10^7$	$4.296*10^5$	$1.788*10^4$	0.368
6.34	8.615*10 <sup>9</sup>	$-1.600*10^7$	$4.300*10^5$	$1.804*10^4$	0.370
6.96	$8.582 * 10^9$	-1.569*10 <sup>7</sup>	$4.302*10^5$	$1.816*10^4$	0.371
7.22	8.568 *10 <sup>9</sup>	$-1.557*10^{7}$	$4.303*10^5$	$1.821*10^4$	0.372

Table 3.4 : Antenna pattern correction coefficients

 $\varepsilon_{measured} = \varepsilon_{smooth} + Pattern \ Correction$ 

Where,

 $\varepsilon_{smooth}$  = smooth surface emissivity computed using (2.4)

(3.11)

Figure 3.11, shows the antenna patter correction applied for the specular emissivity with respect to EIA for the 4.55 GHz. The antenna pattern correction at 45 degree *EIA* is ~2 K, and this value varies along the *EIA* region  $(0^{\circ} - 45^{\circ})$  by about (0.6 - 2) K difference.



Figure 3.11 : Surface emissivity before and after antenna pattern correction.

To solve for the incidence angle dependence f(EIA) in (3.7), we extract the measurements taken during the aircraft banks and then bin them into different wind speed regions and finally apply the antenna pattern correction to the SFMR measurements.

After correcting the measured SFMR brightness temperature for atmospheric effects, resulting in brightness temperature values referenced to the surface, a special algorithm was developed to solve (3.7) for f(EIA). The results were best fit using a 2<sup>nd</sup> order polynomial which showed minimum residuals. The algorithm used the least squares estimation method to solve for the coefficients in (3.12) for f(EIA) by minimizing the difference between the measured SFMR brightness temperature and modeled CFRSL brightness temperature, these coefficients were found for the 20< ws < 35 m/sec bin. The validation and the comparison between the measured and modeled brightness temperatures are shown later in Chapter 4 of this thesis.

$$f(EIA) = a_2 EIA^2 + a_1 EIA + a_0$$
(3.12)

Where,

 $a_n = \text{coefficients}, n=0, 1, 2$ , listed in Table 3.5

*EIA*= earth incidence angle, degrees

Table 3.5	: f(EIA)	coefficients
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Coefficients	Values
a <sub>0</sub>	- 3.1991*10 <sup>-6</sup>
a <sub>1</sub>	9.8423*10 <sup>-7</sup>
$a_2$	$1.1443*10^{-8}$

## **CHAPTER 4 : EMISSIVITY MODEL VALIDATIONS**

The CFRSL ocean wind speed surface emissivity model, given in (3.7), has been validated over a range of wind speed and incidence angles using SFMR data from NOAA aircraft flights in hurricane Fabian in 2003. Comparisons to the NOAA, SFMR wind speed retrieval algorithm provided validation at nadir incidence, and SFMR brightness temperature measurements taken during aircraft turns provided for off-nadir validation.

#### 4.1 SFMR Comparisons

The CFRSL wind speed surface emissivity model was validated for nadir observations by comparisons with the NOAA/SFMR excess emissivity model. The NOAA/SFMR algorithm was previously validated for wind speeds from 10m/sec to > 70m/sec. using dropwindsondes measurements.

In addition to the SFMR wind speed algorithm, the Wilheit and Stogryn surface emissivity models are often used. Figure 4.1 shows a comparison between these three with respect to wind speed at nadir. The SFMR model is considered to be the most trusted and is the standard for comparison because of its thorough validation. The Wilheit and Stogryn models both have deficiencies as shown in Figure 4.1. Wilheit has two different relationships for V and H polarizations and the two are not equal at nadir for wind speeds greater than approximately 10 m/sec, as is physically required. Plus, the V-Pol over estimates emissivity for wind speeds less than 30m/sec. and under estimates for wind speeds greater than 30 m/sec. Stogryn's model also fails to compare well with the SFMR. In his model the percentage of foam coverage reaches a maximum of 100% at approximately 35m/sec, which drives his total surface emissivity model to reach 100% at wind speeds slightly greater than 40 m/sec. This totally contradicts the SFMR performance where wind speeds greater than 70 m/sec. have been observed with no saturation effects.



Figure 4.1 : Surface emissivity comparison at nadir for SFMR, Welheit and Stogryn wind speed models.

Melville's data, from hurricane Isabel, for the percentage of foam coverage over the ocean was used to derive a physically realistic model in the form shown in (3.7). The procedure for deriving (3.7), as was fully discussed in Chapter 3, was to develop the nadir surface emissivity model by making f(EIA) equal to unity and using the data in Figure 4.2 to both derive the foam emissivity term and to validate, by comparison, the foam fraction term. The foam fraction was derived by a minimum least squares comparison to the SFMR excess emissivity algorithm and is shown in Figure 4.2 as the solid line. In this figure, Melville differentiates between total white cap coverage, WCC including streaks, and white caps due to actively breaking waves. The CFRSL foam fraction should be compared to the solid squares.



Figure 4.2 : Estimates of hurricane foam fraction from Melville (shown as symbols) and CFRSL foam fraction model (shown as solid line).

The nadir form for the CFRSL emissivity model was compared to the NOAA/SFMR model in terms of brightness temperature and the results are shown in Figure 4.3. The difference between the two models is less than half a Kelvin (0.5 K) over the whole range of wind speed from (12-70) m/sec and for all the six SFMR frequencies. But, for the range less than 10 m/sec. the difference is 1.1 K at the highest frequency. This is attributed to the CFRSL curve fit at lower wind speeds for the foam fraction formula. Also, the NOAA/SFMR excess emissivity

model hasn't been validated for wind speeds less than 10 m/sec. so further investigation in the low wind speed range is needed.



Figure 4.3 : Difference between SFMR and CFRSL surface wind speed model comparison.

For off nadir, SFMR measurements during aircraft banks were used to solve for f (*EIA*) in (3.7). Data from 58 banks inside and outside the eye of hurricane Fabian provided vertical polarization Tb's at different roll angels up to 35 degrees and wind speeds up to 40 m/sec. The closer the bank to the eye wall the higher the wind speed.

Since the SFMR antenna has a fairly large beamwidth of  $\sim 16$  degrees, Tb measurements at any given incidence angle are actually weighted averages of Tb over the entire beam.

Estimates for the correction due to the antenna beamwidth have been made using a weighted average sliding window technique, or a convolution of the antenna pattern gain and the specular emissivity model.

Corrections due to the atmospheric effect have been applied to the SFMR measurements to be able to compare the modeled and measured surface brightness temperature by applying some sensitivity studies to the atmosphere with different *CLW*, *WV* and Rain contents. Brightness temperatures with rain present were not used at low wind speeds; however, most high wind data corresponds to rainy locations and rain corrections must be used. For quality control, measurements were inspected for radio frequency interference (RFI).

# 4.2 Error Estimates

Since SFMR measurements are affected by the atmosphere, which represents approximately 10% of the total emission collected by the radiometer in the presence of light rain, and it varies from 2 - 6 K more depending on the assumed cloud liquid water (*CLW*) and water vapor (*WV*) levels. Care must be taken in the translation of SFMR measured brightness temperature, at aircraft altitudes, to the ocean surface by removing the atmospheric contributions.

In this section, atmospheric error contributions to SFMR measurements were determined and validation of the CFRSL emissivity model, by comparison to SFMR measurements referenced to the surface, was completed for low and moderate wind speeds. Four different hurricane atmospheres were investigated to determine the sensitivity to assumptions made. The measured SFMR brightness temperature during aircraft banks have been binned according to *WS* into three regions:

- 1. Low WS bin (0-10) m/sec
- 2. Medium WS bin (11-20) m/sec
- 3. High WS bin (> 20) m/sec.

and sensitivity studies have been conducted using the following assumed hurricane atmospheres:

- 1. No Atmosphere Correction Applied
- 2. Hurricane Atmos. (eye-wall) W. Frank (1977)
- 3. Hurricane Atmos. + High CLW (eye-wall)
- 4. Hurricane Atmos. (>400Km from eye) with no clouds W. Frank (1977).

Each of the above atmospheres has different values of atmospheric parameters that were entered into the CFRSL RTM to remove the atmosphere effect on the measured SFMR brightness temperature. Comparisons between the modeled (CFRSL) and measured (SFMR) surface brightness temperature were done using the low wind speed data, with no foam present, to evaluate the atmospheric correction using the Stogryn rough surface model, or the foam free term in (3.7).

Figure 4.4 shows surface brightness temperature in Kelvin versus earth incidence angle in degree for both measured SFMR brightness temperature and modeled CFRSL brightness

temperature for the low wind speed region. It is expected that the antenna pattern correction works particularly well for low wind speeds. The measured SFMR brightness temperature is higher than the modeled CFRSL brightness due to the intervening atmosphere. The mean difference between the measured and modeled is 5.1 Kelvin, which is weighted towards the near nadir region where there is more data.



Figure 4.4 : SFMR measured Tb compared to CFRSL modeled Tb for low wind speed (< 12m/sec).

Atmospheric corrections are based on the composite hurricane model of W. Frank [21], which describes a hurricane atmosphere with temperature and humidity profiles in the eye, eyewall, and every 2 deg. of latitude radially from the center of the eye. This is a composite model derived from data from a number of hurricanes. The second assumed atmosphere is the 0.7 deg profile from [21], or approximately 70 km from the eye, which is representative of the eye-wall region.

Atmospheric corrections were computed and applied to the measured brightness temperatures at all incidence angles for the water vapor profile in the eye-wall case. Both corrected SFMR brightness temperature and modeled CFRSL brightness temperature were compared. It was found that the modeled CFRSL brightness temperature was higher than the corrected measured SFMR brightness temperature by approximately 1 K.

The third atmospheric assumption includes the same water vapor profile as the previous case but also includes heavy clouds. Clouds are treated as extending up to the freezing level and having an integrated liquid water content of  $0.17 \text{ g/cm}^2$ , which is typical of the hurricane eyewall region. This is confirmed from satellite microwave radiometer images of cloud liquid water in hurricanes. In this case, the modeled CFRSL brightness temperature was higher than the corrected measured values by approximately 3.1 K due to the higher attenuation in the atmosphere from clouds. The modeled values are higher than measured, in the previous 2 cases, because the data is in the low wind speed region far from the eye-wall and the correction that has been applied is an over-correction.

Taking the fourth assumed atmospheric temperature and humidity profile, which is again from [21] and typical of a radial distance of approximately 400 km from the eye, the measured values arecompared to the model. This is considered to be the optimum atmosphere in the low wind speed case because most of the data in this range was collected at a radial distance approximately 400 km from the eye. At this distance from the center of the storm, clouds were not expected to be a significant factor either.

Figure 4.5 shows surface brightness temperature in Kelvin versus earth incidence angle in degree for both the corrected SFMR measured brightness temperature and modeled CFRSL brightness temperature. The modeled brightness temperature is higher than the corrected measurements but with only a small difference between the modeled and measurement of 0.87 Kelvin. This is in reasonable agreement for two reasons. First, the atmospheric assumptions used in correcting the measured brightness temperatures to correspond to surface brightness values are reasonable for low wind speed data, and second the difference of < 1 K is consistent with the accuracy of the CFRSL model for wind speeds < 10 m/sec, as shown in Figure 4.3, and represents the error contribution to total emissivity due to the foam free term. This error contribution is then considered in the derivation of *f* (*EIA*) for higher wind speed modeling.



Figure 4.5 : SFMR measured Tb, referenced to surface (Tsur), compared to CFRSL modeled Tb for low wind speed.

To be able to solve for f (*EIA*) higher wind speeds are needed since the f(*EIA*) function is in the foam part of (3.7). It's needed to have relatively high wind speed so that the foam will make more of a contribution and the foam free part less of a contribution.

Taking the second atmospheric assumption, which represents the eye-wall region, and using data in the 22 - 25 m/sec wind speed bin, SFMR measurements were corrected and compared to the surface emissivity model. This case included rainy pixels to increase the number of data points available at the higher wind speed. The presence of rain was accounted

for in the correction by estimating rain rate from the SFMR retrieved values and computing rain attenuation from the SFMR rain absorption coefficient model. Figure 4.6 shows surface brightness temperature in Kelvin versus earth incidence angle in degree for both the corrected SFMR brightness temperature measurement and the modeled CFRSL brightness temperature. Modeled CFRSL brightness temperature is higher than the measured SFMR brightness temperature but with a relatively small difference of 1.55 K between the modeled and measured.



Figure 4.6 : SFMR measured Tb, referenced to surface (Tsur), compared to CFRSL modeled Tb for 22-25 m/sec. wind speed.
The foam fraction corresponding to the 22-25 m/sec. bin, from Figure 4.2, is (23 - 27) %. Therefore, the error contribution from the foam free term is 0.7 K, leaving agreement between modeled and measured for 22-25 m/sec. of 0.85 K. This is a measure of the error introduced by the *f* (*EIA*) model term. Again, there is some uncertainty in the validity of the pattern correction in the higher wind speed region.

The method for development of a high wind speed, wide swath surface emissivity model has been described and results based on comparisons with SFMR data have shown good matching. Agreement between measurements and modeled surface brightness temperatures to approximately 1.5 K, or better, has been demonstrated with wind speeds up to 25 m/sec. and incidence angles from nadir to 35 deg. Broad beamwidth antenna pattern effects were corrected for and atmospheric contributions were accounted for in order to compare brightness temperatures at the surface. Rain free measurements were used at low wind speeds, but at higher wind speeds, where rain is usually present, corrections for rain effects were required.

A limited amount of data at perpendicular polarization (H-pol) exists from hurricane flights in 2005 to begin expanding the model to both polarizations. Also, more data at higher wind speeds is required for further analysis, and new measurements at higher incidence angles are required to complete development out to 45 deg.

## **CHAPTER 5 : CONCLUSION**

A wind speed algorithm has been developed for the design and calibration of microwave radiometers for remotely sensing geophysical characteristics of the ocean and atmosphere in hurricanes. It is a physically realistic model that defines the relationship between the emissivity, or brightness temperature, of the ocean surface and the wind speed over the surface. It relies on the increase of foam and streaks on the surface with increasing wind speed. The algorithm was tuned to the SFMR wind speed retrieval algorithm for nadir viewing, and provides an incidence angle dependent term derived from SFMR brightness temperature measurements in high aircraft banks. Good agreement with the SFMR algorithm, at nadir, and with SFMR off nadir brightness temperatures has been demonstrated.

All existing wind speed models have shortcomings in operating over a large wind speed range and/or a large incidence angle range. The Stogryn model includes an unrealistic wind speed/foam fraction relationship, the Wentz model does not extend to high wind speeds and is useful over only a relatively small incidence angle range, the SFMR is for nadir viewing only, and the Wilheit model underestimates excess emissivity by 0.1 at 70 m/sec. The CFRSL model was designed to perform well up to greater than 70 m/sec. and out to 45 deg. Since it is physics-based, it is adaptable to a range of instrument characteristics and measurement geometries. The model is formulated with a foam dependent term and a foam free term. The foam term was designed to saturate at wind speeds well beyond 70 m/sec. and to allow for frequency dispersion

in the model. The foam free term is intended to account for relatively low wind speed surface roughness effects. Both terms are incidence angle dependent, but the foam term provides the incidence angle dependence at high wind speeds.

Nadir comparisons between the CFRSL model and the SFMR model have shown good matching. For wind speeds of approximately 15 m/sec., the modeled brightness temperature difference between the two is less than  $\pm$  0.5 K. Also, agreement between measurements and modeled surface brightness temperatures to approximately 1.5 K has been achieved for wind speeds up to 25 m/sec. and incidence angles from nadir to 35 deg. These results are particularly good considering the fact that atmospheric corrections were required and rain attenuation corrections were required for the higher wind speed data.

Future studies will include more data in aircraft turns to enable better statistical analysis of high wind speed and high incidence angle measurements. In order to achieve incidence angles high enough to allow for antenna pattern correction to 45 deg. emissivity estimates, the SFMR antenna must be mounted at approximately 25 deg. in the future. Analysis of data from the AOC SFMR instrument is planned in order to define f(EIA) for horizontal polarization. The AOC instrument was operational on all NOAA flights in hurricanes in 2005. These accomplishments are all required in order to complete the wind speed model to where it can be incorporated into the HIRA for use in HIRad studies.

HIRad is an instrument concept envisioned as an improved SFMR. It is a synthetic aperture interferometric radiometer that provides a wide swath measurement of surface wind

speed and rain rate as opposed to the SFMR profile. HIRad measures out to  $\pm 45$  deg. with a swath equal to twice the aircraft altitude. This allows for the two dimensional imaging of wind speed and rain rate for an entire hurricane in less than 4 aircraft passes from an altitude of approximately 10 km. The improved wind speed model will be incorporated into the HIRA for design and trade studies for HIRad. These will be conducted using wind speed and rain rate maps for hurricane Floyd, 1999. Brightness temperature images will be computed from the hurricane Floyd data and retrievals will be simulated for various instrument parameters over incidence angles from 0-45 deg.

## **APPENDIX: SFMR INSTUMENT DISCRIPTION**

The NOAA/Hurricane Research Division's (HRD) Stepped-Frequency Microwave Radiometer (SFMR) is the prototype for a new generation of airborne remote sensing instruments designed for operational surface wind estimation in hurricanes. It was first flown in hurricane Allen in 1980 as reported in Jones et al. (1981) [4], Black and Swift (1984) [22] and Delnore et al. (1985) [23]. In the mid-1980's the instrument was redesigned and flown on the NOAA Hurricane Research WP-3 aircraft, and the first real-time retrieval of winds on board the aircraft in Hurricane Earl in 1985 as reported by Swift and Goodberlet (1992) [24]. The first operational transmission of SFMR winds to TPC/NHC occurred in Hurricane Dennis in 1999. Since 1980, the SFMR has flown on 95 flights in 30 tropical cyclones.

The concept for the first experimental SFMR was proposed by C. T. Swift and built by NASA's Langley Research Center in 1978. The original SFMR design involved a single nadirviewing antenna and receiver capable of making measurements of radio emission from the sea surface at four selectable frequencies 4.5, 5.0, 5.6, and 6.6 GHz. After 1981, the program was transferred to the University of Massachusetts Microwave Remote Sensing Laboratory (UMASS/MIRSL); and SFMR was updated in 1982 to six different frequencies with a better delta-T resolution and longer integration time.

The SFMR receiver was upgraded in 1995 which allowed for increased calibration stability, and used six different channels (4.55, 5.06, 5.64, 6.34, 6.96 and 7.22 GHz) with an along-track nadir-viewing antenna. Since the antenna half-power beamwidth ranges from  $22^{\circ}$  to

32°, at a typical flight altitude of 1500 m, the six C-band channels view the surface with antenna footprints from 600 to around 800 m depending upon the channel.

The SFMR instruments are mounted in to two places on the aircraft body, the first place is the bottom of the aircraft and that is the SFMR research instrument, as for the AOC SFMR it is mounted in a pod under the aircraft wing as shown in Figure 5.1.



Figure 5.1 : AOC SFMR instrument electronics.

Table 5.1 and Table 5.2 contain the SFMR research instrument beamwidth and the AOC SFMR instrument beamwidth. The main difference between the two is the way they are mounted under the aircraft which is very important since one is parallel with the plane of incidence at nadir and the other is perpendicular to the plan of incidence at nadir, one more difference is the beam width of the antenna and that the AOC instrument has less integration time and more calibrated channels.

Frequency, GHz	H-Plane	E-Plane	45 – Plane
4.3	16.2	16.7	16.1
4.8	16	16.2	15.3
5.3	15.7	15.5	14.8
5.8	15.5	16	14.6
6.3	16.8	20	16.9
6.8	19	16.5	17.6

Table 5.1 : Antenna gain pattern for the SFMR research instrument

 Table 5.2 : Antenna gain pattern for the AOC SFMR instrument

Frequency, GHz	3 dB Beamwidth	
5	28	
6	23	
7	19	

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