Polarization Signature in Micro-Wave Humidity Sounder Window Channels

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POLARIZATION SIGNATURE IN MICRO-WAVE HUMIDITY SOUNDER WINDOW CHANNELS

By

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ABSTRACT

Microwave Humidity Sounders (MHS) onboard NOAA-15, -16, -17, -18, -19 and EUMETSAT MetOp-A, -B provide radiance measurements at a single polarization state at any of the five observed frequencies. Microwave Humidity Sounder (MWHS) onboard the FengYun-3 (FY-3) satellite has a unique instrument design and provides dual polarization measurements at 150 GHz. In this study, the MWHS polarization signal is investigated using observed and modeled data. It is shown that the quasi-polarization brightness temperatures at 150 GHz display a scan angle dependent bias. Under calm ocean conditions, the polarization difference at 150 GHz becomes non-negligible when the scan angle varies from 10 to 45 degrees and reaches a maximum when the scan angle is about 30 degrees. Also, the polarization state is sensitive to surface parameters such as surface wind speed. Under clear-sky conditions, the differences between horizontal and vertical polarization states at 150 GHz increase with decreasing surface wind speed. Therefore, the polarization signals from the cross-track scanning microwave measurements in the window channels contain useful information of surface parameters. What is more, cloud liquid water is also proved to be a non-ignorable factor reducing the difference between horizontal and vertical polarization states at 150 GHz. Also, the availability of dual polarization measurements allows a one-to-one conversion from the antenna brightness temperature to sensor brightness temperature if there exist a cross-polarization spill-over.
CHAPTER ONE

INTRODUCTION

1.1. Overview of FY-3 Satellite Series

The FY-3 satellite series is a new generation of Chinese polar-orbiting satellite series, with the FY-3A/B/C successfully launched on May 27, 2008, December 5, 2010 and September 23, 2013 respectively. FY-3A and FY-3C are morning satellites, with the equatorial crossing time (ECT) around 10:00am, FY-3B is an afternoon satellite with ECT around 2:00pm. FY-3A/B satellites carry onboard 11 instruments, and FY-3C carries onboard 14 instruments, providing atmospheric sounding and other environmental observational data (Zhang et al., 2009). There are three microwave instruments including Microwave Temperature Sounder (MWTS), Microwave Humidity Sounder (MWHS), and Microwave Radiation Imager (MWRI). The two microwave instruments onboard FY-3A/B, MWTS and MWHS, are similar, but not identical, in channel specification to AMSU-A and MHS onboard the NOAA’s Polar-Orbiting Environmental Satellites (POES) series which started in 1998 (Goodrum et al., 2009; Zou et al., 2011). MWTS onboard FY-3A/B has only four channels located at atmospheric oxygen absorption band near 50-60 GHz and is mainly designed to provide information on atmospheric temperature profiles. MWTS channels 1-4 correspond to AMSU-A channels 3, 5, 7 and 9. MWHS onboard has five channels with three channels located at 183 GHz water vapor absorption line, the same as the Microwave Humidity Sounder (MHS). The two MWHS window channels are located at 150 GHz with horizontal polarization and vertical polarization, which are different from the two MHS window channels located at 89 and 157 GHz with single polarization. MWRI has most of the frequencies of the Advanced Microwave Scanning Radiometer–EOS (AMSR-E) onboard the NASA Aqua satellite, except for missing the C-band (6.9 GHz).
The FY-3 series will significantly contribute to the Global Environmental Observing System of Systems (GEOSS). The Earth’s atmosphere can be more frequently observed with the Chinese satellites. A preliminary evaluation of the instrument performance through a comparison with data from NOAA, MetOp and NASA Aqua satellite data revealed a good quality of MWTS, MWHS and MWRI data (Guan et al., 2011; Wang et al., 2012; Wang and Zou 2012; Zou et al., 2011; Zou et al., 2012a; Zou et al., 2012b; Zou et al., 2012c). In this study, we will investigate the polarization differences of measurements between two MWHS window channels and point out the potential values for satellite data assimilation and calibration.

1.2. Dual-Polarization Microwave Radiometers

It is well known that microwave radiation emitted from oceans in the low frequency range from 6 GHz to 37 GHz exhibits an obvious difference between the vertical and horizontal polarization states (Sasaki et al., 1987; Wilheit, 1979; Ruf, 1998; Rosenkranz, 1992). At a local zenith angle near 53 degree, the polarization difference is typically the largest and it decreases as surface wind speed increases. In 1978, the scanning multichannel microwave radiometer (SMMR) was flown on the Seasat and Nimbus-7 satellites and lasted from 25 October 1978 until 20 August 1987. The SMMR provided measurements of dual-polarized microwave radiances at 6.63, 10.69, 18.0, 21.0, and 37.0 GHz with the antenna beam intersects the Earth's surface at an incidence angle of 50.1 degrees (Gloersen et al., 1984). Since then, the Special Sensor Microwave Imager (SSM/I) was flown onboard the US Air Force Defense Meteorological Satellite Program (DMSP) satellites with frequencies and local incident angle similar to those of SMMR (Derksen et al., 2003; Dai and Che, 2009). Many of microwave imagers were launched after SMMR and SSM/I. Other microwave imager sensors onboard polar-orbiting meteorological satellites include the WindSat
radiometer onboard the Department of Defense (DoD) Coriolis satellite, MWRI onboard FY-3A/B, and the successor of AMSR-E, AMSR-2, onboard the Global Change Observation Mission 1st -Water (GCOM-W1) satellite. All SSM/I, SSMIS, WindSat, AMSR-E, MWRI, and AMSR-2 are conical scanning radiometers, which are characterized by a constant scan angle for all field-of-views (FOVs). Measurements from dual polarization had thus been used for remote sensing of wind speeds near the ocean surface (Hollinger, 1990; Wentz, 1991; Wentz, 1997; Mitnik and Mitnik, 2010; Akira, 2006).

Different from conically scanning total power passive microwave radiometers SMMR, SSM/I, AMSR-E, MWRI and AMSR-2, MWHS is a cross-track scanning sounder. The antenna scans from \(-53.38^\circ\) to \(53.38^\circ\) to provide a total of 98 FOVs within this scan range. MWHS has a nominal instantaneous field of view (FOV) of 15 km at nadir. The swath width of MWHS is about 2700 km. For a cross-track scanning instrument, the polarization state varies with scan angle (Thompson et al., 1998). It is exactly vertical or horizontal only at the nadir. The polarization signals contained in the new radiance observations at 150 GHz with two polarization states at different scan angles are not understood well and are the subject of this study. Chapter 2 presents the characterization description of MWHS, which also includes comparison with channel characterization of MHS. The theoretical introduction of polarized signals in satellite observation and their sensitivity with surface wind speed over ocean are provided in Chapter 3. Chapter 4 will provide the theoretical description of conversion between antenna temperature to sensor brightness temperature, along with the relationship between quasi and pure polarized sensor brightness temperature. The real-data analysis of MWHS data follow in Chapter 5, which contains analysis of the scan angle and latitudinal dependence of polarized signals and their sensitivity to surface wind speed and liquid water path.
CHAPTER TWO
CHARACTERIZATION OF MWHS

MWHS is a cross-track total power microwave radiometer. It has five channels in the frequency range from 150 GHz to 191 GHz. Three humidity sounding channels are located near the water vapor absorption line at 183.3 GHz with each channel having two pass-bands of a frequency offset from the center of ±1, ±3, and ±7 GHz, respectively. These channels have a pure vertical polarization at nadir. Two window channels are located at 150 GHz with quasi-vertical (V) and quasi-horizontal (H) polarization.

In a normal working mode for MWHS on orbit, two offset-fed parabolic antennas scan the Earth in a direction perpendicular to flight track. The microwave radiation incident on the antenna is fed to a corrugated feed horn via reflection, then polarization is segregated and frequency is divided by a quasi-optical system to obtain the observational data expressed in the form of counts (Gu S, 2012). The earth scanning aperture angle of MWHS is ± 53.35° and the sampling distance is 1.1°, resulting a total of 98 fields of view (FOVs). The scan period is 8/3 seconds. Corresponding to the two internal blackbody calibration targets, there are two antennas located at the zenith point. A total of seven platinum resistance thermometers (PRTs) are placed in the internal blackbody for monitoring the blackbody temperature, of which five are active and two are for backup. The space calibration scan angle is 107.1°. The antennas scan space and the internal blackbody with a uniform speed to obtain three sets of space view data and three sets of internal blackbody view data, respectively. These space view and internal blackbody data are used to complete the on-orbit two-point calibration for obtaining MWHS antenna temperatures.
FY-3A/B MWHS frequency receivers are designed in the double sideband mode. The stability of frequency is 5.0 MHz. The main beam efficiency of antenna is greater than 96.0% and cross-polarization beam efficiency is about 2%. Differences of channel frequency and polarization state between MWHS and MHS are provided in Table 2.1. In a scanning period, MWHS antenna scans the earth, space and internal blackbody target with a uniform speed, but moves with acceleration and deceleration in two fast switch sections.

Table 2.1: Frequency and polarization differences between MWHS and MHS channels

<table>
<thead>
<tr>
<th>channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWHS</td>
<td>150h</td>
<td>150v</td>
<td>183.31±1v</td>
<td>183.31±3v</td>
<td>183.31±7v</td>
</tr>
<tr>
<td>MHS</td>
<td>89.0v</td>
<td>157.0v</td>
<td>183.31±1h</td>
<td>183.31±3h</td>
<td>190.31v</td>
</tr>
</tbody>
</table>
CHAPTER THREE

POLARIZATION

3.1 Polarization of Electromagnetic Wave

MWHS channel 1 and channel 2 are of horizontal and vertical linear polarization. At the nadir view, they merely receive horizontal or vertical polarized radiation respectively. For an electromagnetic wave, the vibration directions of electric and magnetic intensity are perpendicular to each other. The electric intensity vibration direction is defined as the polarized direction of the electromagnetic wave. Four types of polarizations are indicated in Figure 3.1 with arrows representing the vibration directions of electric fields. Figure 3.1a, 3.1b, 3.1c and 3.1d are, respectively, electric field vibrations of vertical linear, horizontal linear, circular clockwise and elliptical clockwise polarized electromagnetic waves. These four parameters I, Q, U and V were introduced by Sir George Stokes to describe the radiated energy and polarization state of thermal radiation in Eq. 3.1, in which $E_v$ and $E_h$ are horizontally and vertically polarized components of electric field vibration, $c$ is a constant, and the superscript of the asterisk represents the conjugate operator.

$$I_s = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = c \begin{pmatrix} \langle |E_v|^2 \rangle + \langle |E_h|^2 \rangle \\ \langle |E_v|^2 \rangle - \langle |E_h|^2 \rangle \\ \langle E_v E_h^* \rangle + \langle E_h E_v^* \rangle \\ i \langle E_v E_h^* - E_h E_v^* \rangle \end{pmatrix}$$

(3.1)

For unpolarized electromagnetic waves with electric fields that vibrate randomly, the $Q$, $U$ and $V$ in Eq. 3.1 are zero. $I$ represents the total radiated energy, $Q$ characterizes the balance of vertical and horizontal electric field components, and $U$ and $V$ represent the correlation between them. The degree of polarization, linear polarization and circular polarization were defined as
\[ \sqrt{Q^2 + U^2 + V^2} / I, \sqrt{Q^2 + U^2} / I, \text{ and } V / I \] (Petty G W, 2006). Only linear polarized radiation is measured by MWHS and MHS due to their channel setting in Table 2.1.

![Diagram of electric field vibration directions](image)

Figure 3.1: Electric field vibration directions of (a) vertical linear, (b) horizontal linear, (c) circular clockwise and (d) elliptical clockwise polarized electromagnetic waves.

### 3.2 Reflection Coefficient

Random electric intensity vibration of an unpolarized electromagnetic wave could be limited to a certain direction or to a specific vibration form when it is linearly polarized, and then might be detected by corresponding polarization channels. Such a polarizing process could take place when the radiance is reflected by surfaces, transmitting crystals or being scattered by particles in the path of the beam (Kenworthy R W, 1961). In addition, the polarimetric microwave radiance reflected and emitted by sea surface is different for horizontal and vertical polarized radiance. The root causes for this difference are the reflection and emissivity coefficients of surface, which differ in various polarization directions, incident angles and surface properties. For instance, the polarized signals measured by MWHS window channels change with wind speed which effects the scattering coefficients and thermal emission of sea surface (Stogryn A, 1967). The Fresnel amplitude reflection coefficients of a linear polarized radiance reflected by a single interface are show in Eq. 3.2 and Eq. 3.3 (Hecht, 1987),
where $r_v$ and $r_h$ are reflectivity for vertically and horizontally polarized radiances, $n_0$ and $n_1$ are reflectivity of the two media between the interface, $\theta_0$ and $\theta_1$ stand for the incidence and refraction angles.

### 3.3 Scattering Coefficient

Radiance from all incident directions could be reflected into the fixed scanning direction of the MWHS window channels. Thus, the scattering coefficient defined by Peake (1959) is introduced to express the relationship between the incident and scattered radiances. The scattering coefficient of a polarized electromagnetic wave is a function of the incidence angle, scattering angle, and the physical properties of the surface, such as roughness caused by wind. An incident radiation comes from direction $k$ with polarization of $m$ and flux of $I$ falls at a surface with an area of $A$. If the $n$ polarized scattered radiance flux is $I_s$ at the $k$ direction and $R$ distance from the incident point, then the reflectivity coefficient $r_{mn}$ is defined as Eq. 3.4 (Peake, 1959).

$$ r_{mn}(k_0, k) = \lim_{A \to 0} \lim_{R \to 0} \frac{4\pi R^2}{A \cos \theta_0} \frac{(I_s)_n}{(I_0)_m} $$

The surface emissivity $\varepsilon_n(k_0)$ for specific polarization could also be expressed as Eq. 3.5 (Peake, 1959), where $n$ and $m$ stand for horizontal or vertical polarization and $\Omega_k$ represents differential solid angle $k$. 

$$ r_v = \frac{n_0 \cos \theta_0 - n_1 \cos \theta_1}{n_0 \cos \theta_0 + n_1 \cos \theta_1} \quad (3.2) $$

$$ r_h = \frac{n_1 \cos \theta_0 - n_0 \cos \theta_1}{n_1 \cos \theta_0 + n_0 \cos \theta_1} \quad (3.3) $$
\[
\varepsilon_n(k_0) = 1 - \frac{1}{4\pi} \int \left[ r_{nm}(k_0, k) + r_{nm}(k_0, k) \right] d\Omega_k
\] (3.5)

### 3.4 Observed Brightness Temperature

The energy received by MWHS window channels consists of three main parts expressed in Eq. 3.6 (Stogryn A, 1967). They are radiance emitted from the surface and transmitted through the atmosphere \( I_{\text{surf}} \cdot L_{\text{atm}} \), the downward atmospheric radiance transmitted through the atmosphere which is reflected by the surface \( I_{\text{ref}} \cdot L_{\text{atm}} \), and the upward atmospheric emission \( I_{\text{atm}} \).

\[
I_{\text{obs}} = (I_{\text{surf}} + I_{\text{ref}}) L_{\text{atm}} + I_{\text{atm}}
\] (3.6)

\( I_{\text{obs}} \), \( I_{\text{surf}} \), \( I_{\text{ref}} \) and \( I_{\text{atm}} \) in Eq. 3.6 are, respectively, radiance received by satellite radiometer, emission from surface, surface reflected downward atmospheric radiance, and upward atmospheric emission. \( L_{\text{atm}} \) is the transmittance of atmosphere. As the Rayleigh-Jeans approximation is valid for the microwave band, Eq. 3.5 would be derived to Eq. 3.7 for brightness temperature of specific polarization (Stogryn A, 1967).

\[
T_{\text{obs},n} = (\varepsilon_n T_{\text{surf}} + T_{\text{ref},n}) L_{\text{atm}} + T_{\text{atm}}
\] (3.7)

The subscript \( n \) represents the vertical or horizontal polarization, and \( \varepsilon_n \) stands for the surface emissivity of \( n \) polarization as in Eq. 3.5. The detailed expressions for \( I_{\text{ref}}, I_{\text{atm}} \) and \( L_{\text{atm}} \) in Eq. 3.7 are expressed in Eq. 3.8, 3.9, 3.10, and 3.11, according to Stogryn’s work, in which \( T_{\text{air}}(z) \) stands for air temperature in height of \( z \), \( \theta_0 \) is satellite zenith, and \( \kappa(z) \) is the extinction coefficient of air in height of \( z \).

\[
T_{\text{ref},n}(k_0) = \frac{1}{4\pi} \int [T_{\text{sky},n}(k_0) r_{mn}(k_0, k) + T_{\text{sky},m}(k_0) r_{nm}(k_0, k)] d\Omega_k
\] (3.8)

\[
T_{\text{sky},m} = T_{\text{sky},n} = \sec \theta_0 \int_0^\infty T_{\text{air}}(z') \kappa(z') \cdot \exp \left[ -\sec \theta_0 \int_0^{z'} \kappa(u) du \right] dz'
\] (3.9)
\[ L_{\text{air}} = \exp \left[ -\sec \theta \int_0^z \kappa(u) du \right] \]  
\[ T_{\text{air}}(k_0, z) = \sec \theta \int_0^z T_{\text{air}}(z') \kappa(z') \cdot \exp \left[ -\sec \theta \int_0^{z'} \kappa(u) du \right] dz' \]  

The MWHS window channel observed brightness temperature consists of the three main parts expressed by the right side of Eq. 3.7. We could infer that surface scattering change could affect the value of \( \varepsilon_n \) and \( T_{\text{ref},n} \) according to Eq. 3.5 and 3.8 respectively, and change the \( T_{\text{obs},n} \) consequently.

### 3.5 Sea Surface Scattering Coefficient

The MWHS channels 1 and 2 with central frequency of 150 GHz only detect radiance with a wavelength of 2 mm, which is much less than the mean sea wave height even in calm ocean areas. In this case, the expression of sea surface scattering coefficient could be presented in Eq. 3.12 (Stogryn A, 1967)

\[ r_{m,n}(k_0, k) = f_{mn} \exp \left[ -\frac{1}{2B^2} (\alpha^2 + \beta^2) \right] \cdot 2 \cdot \cos \theta_0 \cdot B^2 g_x g_y \]  

where \( f_{mn}, \alpha, \beta, \) and \( B \) are parameters merely dependent on zenith angle \( \theta_0 \) and \( \theta \), and azimuth angle \( \phi_0 \) and \( \phi \) of incident and reflected beams respectively. Their expressions are listed in Eq. 3.13-3.24 (Stogryn A, 1967).

\[ \alpha = \sin \theta_0 \cos \phi_0 - \sin \theta \cos \phi \]  
\[ \beta = \sin \theta_0 \sin \phi_0 - \sin \theta \sin \phi \]  
\[ B = \cos \theta_0 + \cos \theta \]  
\[ f_{hh} = \delta \left| R_h(v_0 \cdot k)(v \cdot k_0) + R_v(h_0 \cdot k)(h \cdot k_0) \right|^2 \]
The mean-square slopes \( g_x \) and \( g_y \) are defined as the variance of surface slope, and empirically depend linearly on wind speed as indicated in Eq. 3.25 and Eq. 3.26 (Cox and Munk, 1954).

\[
g_x^2 = 0.003 + 1.92 \times 10^{-3} \omega \pm 0.002 \tag{3.25}
\]

\[
g_y^2 = 3.16 \times 10^{-3} \omega \pm 0.004 \tag{3.26}
\]

The mean-square slope increases with sea surface wind speed \( \omega \), which leads to brightness temperature increasing for horizontal polarization (Petty G W, 2006). MWHS channels 1 and 2 are window channels, the surface emissivity term \( \varepsilon_{surf} T_{surf} L_{am} \) in Eq. 3.7 plays the principal role in determining the observed brightness temperature. For the band range of 1-40 GHz, both the observed brightness temperature of horizontal and vertical polarization would increase with respect to higher wind speed, which was demonstrated by many previous works (Isozaki et al 1984; Stogryn 1972; Hollinger 1970; Wentz 1983).
Figure 3.2: Brightness temperature of MWHS channel 1 (a), channel 2 (b) and difference between them (c, channel 1 minus channel 2) for ascending nodes on March 1, 2011 over ocean areas.
In addition, the brightness temperatures of vertical polarization are greater than those of horizontal polarization, and the horizontal polarization brightness temperature is more sensitive with the increment of wind speed.

The global distribution of MWHS channel 1, channel 2, and the difference between them are shown in Figure 3.2. The difference between horizontal and vertical polarization channels in Figure 3.2c shows large positive and negative values over middle and high latitudes. The positive difference values concentrate near the limb position while the negative one appears in the inside area of the swath.
CHAPTER FOUR

THEORETICAL DESCRIPTION

4.1. Conversion between Antenna Temperatures to Sensor Brightness Temperatures

As the MWHS antenna scans across from a limb position to nadir and then to a limb position on the other side, it receives signals from both the horizontal and vertical polarizations and obtains the so-called quasi-vertical ($T^Q_a$) and quasi-horizontal ($T^Q_b$) antenna temperature (Choudhury et al., 1992; Lei et al., 2008; Bauer and Schluessel, 1993). The MWHS measured quasi-vertical and quasi-horizontal antenna temperatures ($T^Q_a$, $T^Q_b$) are related to the quasi-vertical and quasi-horizontal sensor brightness temperatures ($T^B_a$, $T^B_b$) according to the following equations (Weng et al., 2013)

\[ T^Q_a = \eta^{vv}_{me} T^B_b + \eta^{hv}_{me} T^Q_b + S^Q_a \]  
(4.1)

\[ T^Q_b = \eta^{hh}_{me} T^Q_b + \eta^{vh}_{me} T^B_a + S^Q_a \]  
(4.2)

where $\eta^{vv}_{me}$ and $\eta^{hh}_{me}$ are the co-polarized antenna beam efficiencies; $\eta^{hv}_{me}$ and $\eta^{vh}_{me}$ are the cross-polarized antenna beam efficiencies; $S^Q_a$ and $S^Q_b$ are the antenna temperatures of the satellite platform seen by the side-lobes. For a normal scan of MWHS, the first two terms in Eq. 4.1 and 4.2 are the earth radiation entering into the receiver system through the main beam which is determined by 2.5 times half-power beam width, and the last term is the radiation scattered and emitted from satellite platform and/or antenna reflector to the receiver.

Based on Eq. 4.1 and Eq. 4.2, it is seen that the sensor brightness temperature ($T^B_a$, $T^B_b$) can be uniquely determined from simultaneous measure of antenna brightness temperatures at both polarizations at the same frequency ($T^Q_a$, $T^Q_b$) if ($S^Q_a$, $S^Q_b$) are negligible or known. With single
polarization measurements such as MHS channels, the conversion from antenna temperatures to sensor brightness temperatures becomes non-unique if the antenna subsystem has a significant spill-over from cross-polarization (i.e., $I_{me}^{hv} \neq 0$, $I_{me}^{vh} \neq 0$).

### 4.2. Quasi-Polarized Sensor Brightness Temperature

The quasi-horizontal and quasi-vertical sensor brightness temperatures from a cross-tracking radiometer, $T_{b}^{Qh}$ and $T_{b}^{Qv}$, are related to the pure polarized brightness temperatures $T_{b}^{v}$ and $T_{b}^{h}$ as follows (Weng et al., 2013):

$$T_{b}^{Qv} = T_{b}^{v} \cos^2 \theta + T_{b}^{h} \sin^2 \theta$$  \hspace{1cm} (4.3)

$$T_{b}^{Qh} = T_{b}^{v} \sin^2 \theta + T_{b}^{h} \cos^2 \theta$$  \hspace{1cm} (4.4)

where $\theta$ is the scan angle. In CRTM, pure polarized brightness temperatures $T_{b}^{v}$ and $T_{b}^{h}$ are firstly calculated, which are then converted to quasi-vertical and quasi-horizontal sensor temperatures $T_{b}^{Qv}$ and $T_{b}^{Qh}$ using Eq. 4.3 and Eq. 4.4.

Figure 4.1 shows the variations of simulated sensor brightness temperatures $T_{b}^{Qv}$ and $T_{b}^{Qh}$ at 23.80, 31.40, 89.00 and 157.00 GHz with scan angle using Community Radiative Transfer Model (CRTM). It is seen that the sensor brightness temperature at horizontal polarization ($T_{b}^{Qh}$) varies differently from that at vertical polarization ($T_{b}^{Qv}$) at all four frequencies shown in Figure 4.1. The sensor brightness temperature at horizontal polarization slightly decreases with scan angle from 0 to about 26° and then increases rapidly with scan angle, while brightness temperature at vertical polarization increases quite rapidly with scan angle till about 38° scan angle and then decreases only slightly with scan angle. Variations of the differences of sensor brightness temperature difference between horizontal and vertical polarization channels are provided in Figure 4.2. The
largest positive difference between horizontal and vertical polarizations appears near the 53° scan angle. There also exists a minimum difference between horizontal and vertical polarization channels at the 32° scan angle where brightness temperature at horizontal is about 5-15K smaller than brightness temperature at vertical polarization.

Figure. 4.1: Sensor brightness temperatures of quasi-horizontal polarization ($T_{b}^{Oh}$, dashed line) and quasi-vertical polarization ($T_{b}^{Qv}$, solid line) channel with frequency of 23.80 GHz (a), 31.40 GHz (b), 89.00 GHz (c) and 157.00 GHz (d) at different scan angle using a middle latitude winter profile.
Figure 4.2: Sensor brightness temperature difference between quasi-horizontal and vertical polarization channels ($\Delta T_b = T_b^{Qh} - T_b^{Qv}$) with frequency of 23.80 GHz (black), 31.40 GHz (blue), 89.00 GHz (magenta) and 157.00 GHz (red) at different scan angle shown in Figure 4.1.
CHAPTER FIVE

REAL-DATA ANALYSIS

5.1. Scan Angle Dependence

FY-3B MWHS observations and the National Centers for Environmental Prediction (NCEP) global forecast system (GFS) 6-h forecast surface wind fields during a one and half month period from 0000 UTC March 1 to 1800 UTC April 14, 2011 are used in this study.

Figure 5.1: Scatter plots of MWHS channels 1 and 2 antenna brightness temperatures at the 1st (a), 23rd (b), 49th (c) and 98th (d) FOVs during 0000 UTC March 1 to 1800 UTC April 14, 2011 only for data with surface wind speed less than 3 m s$^{-1}$.

\[ T_a^Qh \] (K)
\[ T_a \] (K)
\[ T_a^Qh \] (K)
\[ T_a \] (K)

(a) (b)
(c) (d)
Figure 5.2: Antenna brightness temperature differences between MWHS channels 1 and 2 \( (\Delta T_a = T_a^{Qh} - T_a^{Qv}, \text{ red circle}) , \text{ mean difference (blue curve) and data counts (gray bar) from} \) (a) model simulations and (b) observations within 45N-50N with collocated surface wind speed less than 3 m s\(^{-1}\). All data from 0000 UTC March 1 to 1800 UTC April 14, 2011 are used.

Figure 5.1 provides scatter plots of MWHS channels 1 and 2 brightness temperature observations at the 1st, 23rd, 49th and 98th FOV only for data points with surface wind speed less
than 3 m s\(^{-1}\). Note that these two temperatures are antenna brightness temperatures and have not been converted to sensor brightness temperature due to a lack of information on MWHS antenna efficiency. It is seen that there exists a branch with brightness temperatures at the horizontal polarization (channel 1) being larger than channel 2 at the 1st and 98th FOVs. At the 23rd FOV, there is a branch with brightness temperatures at the horizontal polarization (channel 1) being smaller than channel 2. For the 49th FOV, channel 1 correlates very well with channel 2. Scan dependence of brightness temperature differences between channels 1 and 2 within 45N-50N and mean differences are shown for both observations and model simulations in Figure 5.2. As expected, the modeled polarization differences (Figure 5.2a) are negligible at nadir over calm oceans when wind speed is less than 3 m s\(^{-1}\). The difference between channels 1 and 2 switches sign from the 8th to the 9th FOVs or from the 90th to 91th FOVs, resulting a “W-shaped” mean differences between channels 1 and 2 from both observations and model simulations. The mean differences between channels 1 and 2 from MWHS observations (Figure 5.2b) are similar to those of model simulations (Figure 5.2a) except for a large spread, a non-zero mean at nadir and smaller mean values at the largest scan angles. Such differences between model simulations and observations are probably caused by the radiation scattered and emitted from satellite platform to the receiver, which is seen by the side-lobes of the antenna.

5.2. Latitudinal Dependence

The mean and standard deviation of the brightness temperature differences between MWHS channels 1 and 2 for MWHS observations and CRTM simulations during a one and half month period from 0000 UTC March 1 to 1800 UTC April 14, 2011 are shown in Figure 5.3. The polarization between MWHS channel 1 (e.g., horizontal polarization) and MWHS channel 2 (e.g., vertical polarization) are largest and positive (e.g., 10 K) at the largest scan angle. The second
largest differences are located near ±30° scan angles. Polarization differences are smallest near nadir. These are consistent with theoretical simulations of the differences between horizontal and vertical polarizations at 150 GHz (Figures 4.1-4.2). The polarization differences from MWHS observations are asymmetric (Figure 5.3a, 5.3c) and those from model simulations are symmetric (Figure 5.3b, 5.3d), reflecting probably the contribution of the radiation scattered and emitted from satellite platform to the receiver (i.e., $S_a^{Q_v}$ and $S_a^{Q_h}$ in Eq. (1)). The standard deviations are larger over regions where the mean differences are large.

Figure 5.3: Latitudinal dependence of (a)-(b) mean and (c)-(d) standard deviation of the antenna brightness temperature differences between MWHS channels 1 and 2 for MWHS observations (left panels) and simulated sensor brightness temperature difference (right panels) from 0000 UTC March 1 to 1800 UTC April 14, 2011.
Figure 5.4: Scatter plots of antenna temperature differences between MWHS/FY-3B channels 1 and 2 at FOV 20 for observations on ascending orbits in March 2011 in clear-sky conditions within three arbitrarily chosen domains: (a) 30N - 40N, 130W - 170W, (b) 30S - 40S, 100W - 140W, and (c) 50S - 60S, 140W - 180W. The mean (thick solid) and standard deviation (vertical thin line) calculated at a wind speed interval of 3 m s$^{-1}$ are also shown.
Figure 5.5: Variation of the (a) mean and (b) standard deviation of the antenna brightness temperature difference between horizontal and vertical polarization states at 150 GHz frequency with surface wind speed using data within 30N-40N and 130W-170W under clear-sky conditions in March 2011. The first to tenth FOVs are indicated by dot symbol in (a) and solid line in (b) and FOVs 11-20 by circle symbol in (a) and dotted line in (b).
5.3. Polarization Sensitivities to Surface Wind Speed

Finally, polarization sensitivities to surface wind speed under clear-sky conditions are examined. Clear-sky MWHS FOVs are found by requiring that (1) they collocate with AMSU-A and MHS measurements from NOAA-18 with a temporal difference being less than 1 hour and a spatial distance being less than 30 km; and (2) the collocated AMSU-A derived cloud liquid water path (LWP) or the collocated ice water path (IWP) is less than 0.01 kg m\(^{-2}\). More than 700 collocated samples are found in March 2011. Figure 5.4 presents scatter plots of brightness temperature differences between horizontal (MWHS channel 1) and vertical polarization (MWHS channel 2) at FOV 20 for data on FY-3B ascending orbits in March 2011 in three arbitrarily chosen domains. The corresponding mean and standard deviation calculated at a wind speed interval of 3 m s\(^{-1}\) are also shown in Figure 5.4. It is seen that the polarization differences decrease with increasing surface wind speed. The brightness temperatures at horizontal polarization state can be more than eight degrees lower than the brightness temperatures at vertical polarization state.

The scan dependence of the variations of the mean differences of brightness temperature between horizontal (channel 1) and vertical (channel 2) with surface wind speed are provided in Figure 5.5. The polarization differences are smallest at FOVs 10 and 11, which are two FOVs with their scan angle closest to 45°. As the scan angle further increases or decreases from 45°, the sensitivity of the polarization signature increases. When surface wind speed is smallest, the polarization differences are largest. It is therefore concluded that the polarization differences of microwave humidity measurements at 150 GHz from FY-3B MWHS channels 1 and 2 contain useful information of surface wind speed.
5.4 Polarization Sensitivities to Cloud Liquid Water

Figure 5.6 shows the antenna temperature of MWHS channels 1 and 2 and the difference between them, as well as the visible image of GOES-11 channel 1 over the ocean area near the west coast of the United States and Mexico. Comparing Figure 5.6c and Figure 5.6d shows the significance of the cloud’s effect on polarization difference over the ocean area in the latitude range of 26 N - 36N. The polarization difference of the MWHS observation decreases remarkably over regions covered by clouds.

![Antenna temperature of MWHS channel 1 (a), channel 2 (b), and difference between them (c, channel 1 minus channel 2) over ocean near California coast area from 1933UTC to 1942UTC (right swath), 2115UTC to 2123UTC (middle swath), and 2245UTC to 2302UTC (left swath) on March 5, 2011. The visible image of GOES-11 channel 1 (0.5-0.7μm) at 2100UTC, March 5, 2011 is shown in (d).](image-url)
To further study the clouds’ effect on brightness temperature difference between horizontal and vertical polarization, we collocate data from MWHS onboard FY-3B with that from AMSU-A onboard NOAA-18, as cloud liquid water could be retrieved by measurements of AMSU-A channel 1 and channel 2 (Weng 2003). Figure 5.7 illustrates the collocation, of which the spatial and temporal collocation criterions are 50 kilometers and 3 hours, respectively, on a portion of an ascending node on March 01, 2011. When more than one MWHS data meet the collocation criterian, the one closest to AMSU-A data is selected.

Figure 5.7: Footprint locations of AMSU-A onboard NOAA-18 (large red circle) and MWHS onboard FY-3B (small filled circle). The small red filled circle represents the collocated MWHS FOV position to AMSU-A FOV position with the spatial and temporal collocation criterions of 3 hours and 50 kilometer respectively on a portion of an ascending node on March 01, 2011.
Figure 5.8: Scatter plot of MWHS antenna temperature difference between channels 1 and 2 (H - V) for All FOVs (a), FOVs 1 b) and 23 (c) with respect to LWP of collocated AMSU-A during March, 2011.
Figure 5.9: Mean MWHS H – V (a) and its data counts (b) with respect to MWHS beam positions for collocated pairs of AMSU-A FOV and MWHS FOV with color representing the LWP range (blue: 0 mm $\leq$ LWP < 0.05 mm; red: 0.05 mm $\leq$ LWP < 0.2 mm; magenta: 0.2 mm $\leq$ LWP) in the collocated AMSU-A FOV during March, 2011.

The variance of antenna temperature difference between horizontal and vertical polarization with respect to cloud liquid water for all MWHS FOVs are shown in Figure 5.8a, those for MWHS FOV 1 in Figure 5.8b, and for FOV 23 in Figure 5.8c. Figure 5.8 makes it obvious that the antenna temperature difference of horizontal and vertical polarization decreases in accordance with increases in cloud liquid water. In Figure 5.9, mean value antenna temperature difference between
horizontal and vertical polarization and its data counts with respect to MWHS beam positions are presented for different collocated cloud liquid water measurements. Figure 5.9 (a) shows that the antenna temperature differences of H and V reach its maximum for all MWHS FOVs under clear-sky conditions defined by cloud liquid water less than 0.05 mm. The data counts of MWHS FOV collocated with AMSU-A data increase for the FOVs further from the nadir, since the distances between neighboring FOVs are smallest in the nadir and increase with scan angle. Therefore, the differences of microwave humidity measurements at 150 GHz from FY-3B MWHS channels 1 and 2 also contain useful information about the cloud.
CHAPTER SIX

SUMMARY AND CONCLUSIONS

Traditionally only a single polarization is measured for AMSU-A and MHS. The MWHS onboard FY-3A/B provides for the first time measurements of dual polarization at 150 GHz. It allows an investigation of the benefit for cross-track radiometers such as MHS and AMSU-A to measure both horizontal and vertical polarizations at the same frequency. Using the model simulations, it is shown that scan-angle dependences of brightness temperatures at 150 GHz horizontal and vertical polarizations are similar to those at lower frequency AMSU-A channels, but of a slightly smaller magnitude. The largest polarization differences are found at scan angles $53.35^\circ$ and $33^\circ$, respectively, but with opposite signs. The polarization differences at 150 GHz based on MWHS observations are shown to be sensitive to surface wind speed and cloud liquid water. It is also pointed out that the availability of dual polarization observations at microwave temperature- and humidity-sounding frequencies would also make the conversion from antenna temperature to sensor brightness temperature a well-determined inverse problem. Further investigation will be carried out to assess the calibration accuracy with a dual polarization than a single polarization.
REFERENCES


BIOGRAPHICAL SKETCH

Xu Chen was born in Yueyang city, Hunan province of China in 1989. He attended Nanjing University of Information Science and Technology and received his Bachelor of Science in Atmospheric Science (Atmospheric Physics and Environment) in 2011. Mr. Chen went to Florida State University and started his graduate study in Department of Earth Oceanic and Atmospheric Science since 2011 fall semester. His research interests include data assimilation and microwave remote sensing.