Interpretation of TRMM TMI Images of Tropical Cyclones

Thomas F. Lee,* Francis J. Turk, Jeffrey Hawkins, and Kim Richardson

Marine Meteorology Division, Naval Research Laboratory, Monterey, California

Received 14 January 2002; accepted 21 June 2002

ABSTRACT: Images of the 85-GHz frequency from the Special Sensor Microwave Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) spacecraft are routinely viewed by forecasters for tropical cyclone analyses. These images are valued because of their ability to observe tropical cyclone structure and to locate center positions. Images of lower-frequency SSM/I channels, such as 37 GHz, have poor quality due to the coarse spatial resolution, and therefore 85 GHz has become the de facto analysis standard. However, the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), launched in 1997, has much better spatial resolution for all channels than the SSM/I. Although originally designed to investigate precipitation for climate research, real-time images are now sent into tropical cyclone forecast offices, and posted to Web pages of the Naval Research Laboratory and the Fleet Numerical Meteorology and Oceanography Center, both in Monterey, California. TMI images of 37 GHz have a number of properties that make them useful complements to images of 85 GHz. They have the capacity to detect low-level circulation centers, which are sometimes unseen at 85 GHz. Also, because the 37-GHz channel generally senses atmospheric layers much nearer to the surface than 85 GHz, parallax error is less, allowing more accurate fixes. This paper presents several case studies comparing the

* Corresponding author address: Thomas F. Lee, Marine Meteorology Division, Naval Research Laboratory, Monterey, CA 93943-5502.
E-mail address: lee@nrlmry.navy.mil
two TMI frequencies and offers some forecasting guidelines for when to use each.

**KEYWORDS:** Remote sensing; tropical meteorology; synoptic-scale meteorology; convective processes; tropical cyclones

1. Introduction

Satellite reconnaissance of tropical cyclones is vital to the mission of the National Hurricane Center (NHC) in Miami, Florida, and especially to the Joint Typhoon Warning Center (JTWC) at Pearl Harbor, Hawaii. The tropical systems tracked by JTWC occur in the Pacific and Indian Oceans and, unlike Atlantic storms, are not penetrated by heavily instrumented aircraft to determine storm position and intensity, prompting the increased reliance on satellite images. Even within basins monitored by aircraft, certain subregions are often primarily assessed using satellite data. Unfortunately, most visible and infrared images have shortcomings that make them less than ideal for tropical cyclone reconnaissance. First, cirrus shields often obscure important low-level structure, including rainbands and precipitation-free circulation centers. Second, high-resolution visible images are only available during the daytime, forcing nighttime reliance on infrared images, which usually do not show low cloud detail well even when cirrus higher clouds are absent.

Fortunately, passive microwave frequencies are insensitive to cirrus clouds. Useful images from passive microwave instruments came into existence during the late 1980s based on the Special Sensor Microwave Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) satellites (Lee et al., 1999; Hawkins et al., 2001). The 85-GHz frequency from the SSM/I became the standard for interpretation of storm structure by forecasters, since out of the four frequencies imaged, it alone had sufficient resolution to support high quality images. In particular, these images allow forecasters to locate the cloud-covered eyes or centers of low-level circulations that cannot be detected otherwise. In 85-GHz images the primary signature is the depression of brightness temperature (Tb) caused by ice scattering within deep convection and precipitating anvil clouds (Spencer et al., 1989). Images of lower frequencies are dominated by elevated Tb, mainly arising from emission from liquid hydrometeors near or below the freezing level (Negri et al., 1989; Spencer et al., 1989). More recently, 89- and 150-GHz images from the Advanced Microwave Sounding Unit (AMSU-B) aboard the National Oceanic and Atmospheric Administration’s (NOAA) polar-orbiting satellites have become available to forecasters (Kidder et al., 2000). Interpretation of these images is similar to that of SSM/I 85-GHz imagery. Real-time reconnaissance of tropical cyclones has become one of the most important applications of passive microwave radiometry from space.

In late 1997, operationally useful imagery became available from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). See the cover image of the *Bulletin of the American Meteorological Society’s* August 1998 issue (Vol. 79, No. 8) for an example. The primary purpose of the TRMM
satellite is to provide detailed precipitation estimates over the Tropics to support climate research. However, since real-time data have become available in 1998 to JTWC and NHC, TMI images have become a mainstay of satellite analysis. They are also used operationally by the NHC as provided by the Naval Research Laboratory (NRL), Marine Meteorology Division. The images are based on the superior spatial resolution footprints of the TMI, which enables forecasters to use lower-frequency imagery (i.e., 37 GHz) than can be used from the lower-resolution SSM/I sensor. This paper presents several case studies of storms for which TMI images were available. First, it compares the appearance of TMI images of the various frequencies. Second, it demonstrates that the optimal frequency for interpretation depends to some degree on the tropical cyclone intensity, size, and structure. Third, it discusses how polarization correction techniques can remove ambiguities for a particular frequency. The paper closes with a summary that compares the utility of images from the 85-GHz channel with corresponding images from 37 GHz.

2. Passive microwave imaging

The SSM/I instrument is a passive microwave radiometer that collects radiation naturally emitted by the surface of the Earth and the intervening atmosphere (Table 1). In the Tropics, large gaps appear between successive 1400-km swaths of the SSM/I. However, in recent years there have been at least two, and sometimes three, DMSP polar-orbiting spacecraft with SSM/I instruments in orbit at any given time, increasing the frequency of coverage and reducing the gaps (Hawkins et al., 2001). Thus, most tropical cyclones have been covered two to four times a day in near–real time.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>TRMM TMI</th>
<th>DMSP SMM/I</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarization</td>
<td>Footprint size</td>
</tr>
<tr>
<td>10.65</td>
<td>V, H</td>
<td>63 x 37</td>
</tr>
<tr>
<td>19.35</td>
<td>V</td>
<td>30 x 18</td>
</tr>
<tr>
<td>21.235</td>
<td>V</td>
<td>23 x 18</td>
</tr>
<tr>
<td>37.0</td>
<td>V, H</td>
<td>16 x 19</td>
</tr>
<tr>
<td>85.5</td>
<td>V, H</td>
<td>7 x 5</td>
</tr>
</tbody>
</table>

The TRMM TMI sensor (Table 1) is similar to the SSM/I, but there are several fundamental differences (Kummerow et al., 1998). Flying at approximately one-half the altitude, the TMI has significantly superior spatial resolution and yields one additional frequency (10.65 GHz). While the large footprint of this additional channel does not support images that are operationally useful for observing tropical cyclone structure directly, this channel does improve retrieval of surface winds in regions of heavy cloudiness and light precipitation (Connor and Chang, 2000). Unlike the sun-synchronous SSM/I, which was launched into
morning and evening orbits (no coverage in the middle of the day and night), the TMI can collect data at all times of day and night. Its unique equatorial orbit covers mainly the Tropics (from about 38°S to 38°N), suiting it well to the mission of observing tropical cyclones.

The TMI antenna beam views the surface of the Earth with a nadir angle of 49°, which results in an incident angle of 52.8° at the Earth’s surface. The TMI antenna rotates about a nadir axis at a constant speed of 31.6 rpm. The rotation draws a circle on the Earth’s surface. Only 130° of the forward sector of the complete scan are used for the observations. The TMI, like the SSM/I, scans only in one direction from the spacecraft. However, the whole TRMM spacecraft is rotated through 180° every few weeks or so to keep the Visible and Infrared Scanner (VIRS) radiative cooler in the shade. Switching the orientation of the spacecraft has important implications for parallax distortions in images (see section 4).

There are a number of products that can be derived from SSM/I and TRMM brightness temperatures that give important quantitative information about the marine atmosphere. These include sea surface wind speed (not direction), integrated water vapor, precipitation rate, and cloud liquid water. However, these are not the most useful forecaster products for monitoring tropical cyclone structure and position. This is because the derived products are computed by combining a variety of frequencies and therefore appear at an averaged spatial resolution that smoothes or eliminates important detail. Instead, forecasters prefer Tb images from a single frequency that can produce higher-resolution images. The latter products are used as interpretation tools in a similar way as infrared or visible images have been used traditionally. However, there are significant ambiguities in the interpretation of single-frequency TMI images at 85 and 37 GHz. The dual-polarized nature of the TMI measurements often allows useful corrections for these ambiguities. These corrections will be discussed in the context of the following case studies. Some of the examples come from the NRL’s tropical cyclone Web page. On this page (http://www.nrlmry.navy.mil/sat_products.html/, click on “tropical cyclones”) virtually all passive microwave images from TMI (since fall 1998) and from SSM/I (since summer 1997) are available for tropical cyclones worldwide. In other cases, the raw data are reprocessed for close-up views.

3. Case studies

3.1 Tropical Storm Fernanda, eastern Pacific Ocean, 20 August 1999

Tropical Storm Fernanda was moving into cooler waters and had weakened to an intensity of about 21 m s⁻¹ (40 kt) at the time of a Geostationary Operational Environmental Satellite (GOES) infrared image (Figure 1). The top of the cirrus canopy was displaced significantly to the west of the clouds composing the low-level center. In such situations, forecasters periodically have difficulty estimating a circulation position from infrared images out of confusion about which cloud level to observe. Furthermore, the warm tops of the low-level cloud circulation are difficult to distinguish from the sea surface, causing further confusion (Lee,
The TMI 85-GHz image shows a small area of depressed Tb (dark gray shades) on the left (western) side of the storm, indicating ice-phase precipitation aloft (Movie 1, alternating with the 37-GHz image). Away from the convection, exposed bands of cloud/rainwater create a cyclonic circulation pattern, but there is little evidence of a cloud-free center in the 85-GHz image. At 37 GHz, on the other hand (Movie 1), a ring of cloud/rainwater marks the center of circulation. The discrepancy between the two images is a function of the difference in sensitivity to cloud/rainwater at 37 versus 85 GHz. At 37 GHz there is enhanced

See the online version of this paper to view animation.

sensitivity for liquid water paths in the range from about 0 to 0.5 mm. This range is represented often in the water-laden core regions of tropical cyclones (Weng and Grody, 1994). However, the 85-GHz channel saturates in amounts greater than about 0.3 mm, eliminating spatial detail in the images. The 85-GHz channel has some sensitivity to smaller amounts (Spencer et al., 1989), explaining the suggestion of Weng and Grody (Weng and Grody, 1994) to use the 85-GHz channel to retrieve liquid water in stratus clouds. However, for tropical cyclones this channel has only limited ability to depict variations in cloud water.

Thus, 37 GHz is the preferred channel to resolve low-level eye structure in
the absence of deep convection. Lower-frequency channels might even be better suited to this purpose, but their relatively poor spatial resolution limits their effectiveness. For comparison, the SSM/I 37-GHz image is shown for a nearly coincident time (Figure 2). The ability to detect the circulation center is severely compromised compared to Movie 1, the TMI image of the same frequency. Thus, most forecasters have preferred 85-GHz images. Up until the time that TMI images became available, satellite images of the lower frequencies simply did not have the spatial resolution sufficient for tropical cyclone analysis.

3.2 Hurricane Irene, Atlantic Ocean, 17 October 1999

At 1200 UTC on 17 October, Hurricane Irene, located off Georgia, had estimated maximum sustained surface winds of about 34 m s\(^{-1}\) (65 kt). Movie 2 shows a TMI 37-GHz image alternating with a TMI 85-GHz image. There were two other TMI passes (not shown) over the storm in this time window, making a total of three passes in about 5 h. This wealth of data occurs because the TRMM orbit has very favorable refresh rate characteristics at around 35\(^\circ\)N or 35\(^\circ\)S, near the northern (and southern) extent of its orbit, such that consecutive views of a storm are often available to forecasters within a few hours of each other. This allows for detailed analysis of storm structure and evolution over a short time period. The 37-GHz image in Movie 2 shows the low-level circulation center in a region of depressed Tb. This signature arises because 37 GHz is sensitive to cloud/rainwater in the exposed core of the tropical cyclone. Although the 85-GHz image suggests a cyclonic circulation, it does not show a closed eye as in the 37-GHz image. Similar to the case of Fernanda, the low-level rain/cloud field of Irene saturates the 85-GHz channel, such that little detail can be discerned.

3.3 Hurricane Floyd, Atlantic Ocean, 15–16 September 1999

Movie 3 shows alternating 85- and 37-GHz images of Floyd moving northward into North Carolina (best track intensity about 57 m s\(^{-1}\) or 110 kt). Figure 3 is a GOES infrared comparison image. The 85-GHz image shows little detail south of the storm center. The lack of low Tb indicates that convection is absent in this region, but the dark blue color (relatively high Tb) suggests a high liquid water content. However, as was the case in Movie 1, the 85-GHz signal saturates in this environment, making the image detail vanish. A forecaster who relied solely on such an 85-GHz image could make the mistake of believing that there was not important structure in this region. With interactive enhancement some improvement is possible using this channel, but the basic problem of saturation over low-level rain/clouds cannot be easily overcome. The 37-GHz image in Movie 3 offers an improved view of this portion of the storm, showing detail over a large low-level feeder rainband. Unlike 85 GHz, the 37-GHz channel, with its enhanced sensitivity to large amounts of cloud/rainwater, resolves the structure in this region. Thus, forecasters have important additional information.

3.4 Tropical Cyclone Paul, south Indian Ocean, 16 April 2001

At the time of the TRMM TMI overpass, Paul was an intense tropical cyclone with estimated maximum surface winds near 57 m s\(^{-1}\) (110 kt). The eye was
sufficiently large that it could be observed in all the frequencies of the TRMM TMI (four out of five frequencies alternate in Movie 4). Warm emissions from water clouds and rain dominate at the three lowest frequencies (19, 21, and 37 GHz). Thus, clouds and rain appear bright against a dark (cold) sea surface background in images of these channels. However, the 85-GHz image has a different appearance in Movie 4. The predominant storm signature here is from scattering from ice precipitation aloft, appearing black (cold) against a bright (warm) background. The eye at 85 GHz is slightly larger and displaced somewhat toward the southwest with height compared to the other channels, an effect explained more
fully below. However, before images of 37 and 85 GHz can be optimally compared, an interpretation ambiguity between deep convection and the surface of the ocean must be resolved in the two channels, especially for 37 GHz. This ambiguity and the correction to it can be seen in Movie 5. The 37-GHz image shows the eye as darker (lower Tb) than the surrounding rainbands (bright). This is because the radiometrically cold “ocean” can be sensed through the thin clouds in the eye region. However, a section of the nearby eyewall has erupted into particularly intense convection, leading to a pronounced ice scattering signature. This feature appears in similar low Tb (blue) as the adjacent eye and storm
surroundings. The resulting ambiguity can mislead forecasters into believing that
the cold convection is a portion of the eye. To correct this difficulty we compute
a polarization correction temperature (PCT) image that corrects the Tb of regions
of little or no clouds/rain to approximate the surface air temperature. We get the
PCT formula for 37 GHz by rearranging Equation (6.48) from Grody (Grody,
1993):

\[
PCT_{37} = 2.18 \times 37V - 1.18 \times 37H.
\]
In order to construct a consistent user product that depicts convection, the sea surface, and low-level clouds/rain, the following red/green/blue composite was implemented. The PCT37 image is placed in the red gun scaled from 260 to 280 K (reverse tonality), the 37-GHz V image is placed into the green gun scaled from 160 to 300 K, and the 37-GHz H image is placed into the blue gun scaled from 180 to 310 K. The resulting color composite product is shown in Movie 5 and alternates with the raw 37-GHz image for comparison. The sea surface in the color product appears green. Deep convection, including the portion of the eyewall mentioned above, appears pink. Low-level water clouds and rain appear cyan.

As a comparison with the 37-GHz color product, Movie 6 shows a similarly
Movie 4. Loop showing four TMI frequencies of Tropical Cyclone Paul: 10 H, 21 H, 37 H, and 85 H GHz. Parallax shift of central eye is annotated on 85 GHz. Image dimensions are approximately 600 km on a side. North is up.

See the online version of this paper to view animation.

constructed product for 85 GHz (Lee et al., 1999; Hawkins et al., 2001) In this case the formula for PCT is (Spencer et al., 1989)

\[
PCT_{85} = 1.1818 \times 85V - 0.818 \times 85H. \tag{2}
\]

For the 85-GHz color product, the PCT image is placed in the red gun scaled from 220 to 310 K (reverse tonality), the 85-GHz V image is placed into the green gun scaled from 270 to 290 K, and the 85-GHz H image is placed into the
blue gun scaled from 240 to 300 K. The resulting product, alternating with the 37-GHz color product in Movie 6, shows convection in red, clouds/rain in cyan, and the sea surface in a dark gray. Since the 85-GHz signal is dominated by ice scattering from convection at upper levels, the red color tends to dominate the 85-GHz composite in Movie 6. At 37 GHz, on the other hand, only the most intense convection affects the signal in a prominent way. Therefore, the most significant signal comes from low-level clouds and rain (cyan). Only the most intense ice scattering appears pink.
The differing sensitivities to ice scattering in the two frequencies help explain the parallax shift (Haferman et al., 1996; Hong et al., 2000) of the storm eye toward the southwest in the 85-GHz product. Scattering hydrometeors produce opacity much higher in the eyewall at 85 GHz (a red ring around the eye in Movie 6) than occurs at 37 GHz (area of pink in Movie 6). The higher the altitude of the opacity, the greater is the parallax error. Thus, the high altitude of the eyewall leads to a marked horizontal displacement on the 85-GHz product.

When capturing the data that produced Movie 6, the satellite was moving
from the southwest toward the northeast, but the TMI instrument was pointed in the opposite direction, from the northeast to the southwest. Thus, the parallax distortion caused high-altitude features (e.g., the eyewall) to be dislocated toward the southwest in the 85-GHz product. If the same scene had been imaged during a period in which the sensor was pointing in the same direction as the motion of the satellite, from the southwest toward the northeast, then the eye would have been displaced in the opposite direction in the 85-GHz product. The eyewall in the 37-GHz color product (cyan ring around the eye) represents rain near the surface of the ocean. Therefore, the parallax is negligible, and the 37-GHz position of the eye in this image is a much more reliable indicator of true storm position. The horizontal displacement between the eye on the 85- versus the 37-GHz color product is about 20 km.

4. Discussion

Over the core of tropical cyclones, the TMI 37-GHz channel generally has much greater sensitivity to variations in cloud/rainwater than does the 85-GHz channel. This advantage at 37 GHz appears when convection is absent and stratiform water/rain clouds are exposed (e.g., Floyd and Fernanda). In particular, 37-GHz images can detect eyes and low-level rainbands unseen at 85 GHz. Where significant ice scattering is absent and there is therefore little need for removal of ambiguity between precipitation and the sea surface, PCT corrections are generally not necessary.

Images at 37 GHz (e.g., Paul) can also lead to accurate position estimates of eyes and eyewalls. However, there are sometimes ambiguities between deep precipitating convection and the surface of the ocean in uncorrected images at 37 GHz. In the context of Tropical Cyclone Paul, we demonstrated how a PCT correction could eliminate this difficulty. Using the 37-GHz PCT color combination technique, the ice scattering signal from the precipitating eyewall aloft appeared pink. The cloud/rainwater signal from the low-level eyewall appeared cyan. The 85-GHz color product showed precipitation-sized ice particles (red) and a large eye aloft. The 37-GHz color product, on the other hand, showed hydrometeors near or below the freezing level, and a smaller eye near the surface. This is consistent with the observation that in mature tropical cyclones the diameter of the eye increases significantly with height (Jorgensen, 1984; Marks and Houze, 1987). A second influence on eye size and shape is the parallax effect, which produces dislocation and stretching over convective precipitation features.

The 37-GHz channel has two main disadvantages that limit its usefulness in discerning storm eyes. Infrequently, circulation centers are simply too small to be seen in TMI 37-GHz images, owing to the instrument’s relatively coarse footprint size. Second, scattering from intense convection over the central eyewall region of a storm can be mistaken as a large eye in uncorrected 37-GHz images. At other times, the center position can be misdiagnosed because nearby convection distorts the appearance of the cloud/rain spirals. Fortunately, PCT processing can help to remove the interpretation difficulties based on this problem.

After the success of the TRMM mission, the prospect for continued use of lower-frequency passive satellite microwave radiometry for tropical cyclone re-
connaissance is bright in the near future. The Advanced Microwave Scanning Radiometer (AMSR) improves on the SSM/I heritage with dual-polarized channels ranging from 6.9 to 89 GHz. The polar-orbiting AMSR-E is currently flying on the Earth Observing System (EOS) Aqua satellite with a 1.6-m dish. Its swath width is similar to that of the SSM/I (1445 km), but the large dish will allow instantaneous fields of view similar to the TMI (14 km × 8 km at 37 GHz and 6 km × 4 km at 85 GHz). Thus, it will support images of 37 GHz similar in quality to the figures shown in this paper. The AMSR flown on the Advanced Earth Observing Satellite-II (ADEOS-II) is nearly identical to the AMSR-E but it has a 2.0-m dish and two additional channels to better sense the lower troposphere.

By late in this decade a Global Precipitation Measurement (GPM) constellation of orbiting passive microwave sensors will be in place with fresh updates of microwave data as often as every 3 h over any specific location. This constellation will combine a series of small, dedicated satellites with existing systems such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS) series and the DMSP Special Sensor Microwave Imager Sounder (SSMIS). GPM is poised to be a centerpiece for global water cycle science, but also offers an unprecedented opportunity to observe tropical cyclones from multiple satellites in near–real time. If the temporal refresh rate is sufficient, sequences of images can be looped, offering spectacular and informative graphic displays for forecasting professionals and the general public. However, the differing viewing parallaxes of the various satellites could cause convective signatures to appear to shift from one image to the next.

The NRL tropical cyclone Web site (http://www.nrlmry.navy.mil/tc-bin/tc_home) offers a variety of passive microwave satellite views of tropical cyclones. Images based on 85 GHz are featured, but TMI 37-GHz images are also included. Both uncorrected images and PCT-corrected color composites are available for viewing.

Acknowledgments. The support of the research sponsor, the Oceanographer of the U.S. Navy, through the program office Space and Naval Warfare Systems Command, under Program Element 0603207N, is gratefully acknowledged. We also wish to acknowledge the Office of Naval Research, Program Element PE-060243N. The authors thank the NASA TRMM Science Data and Information System team, including Erich Stocker, for providing TRMM TMI data. Dr. Steve Miller of NRL Monterey offered invaluable suggestions.

References


