# SATELLITE-BASED ESTIMATION OF PRECIPITATION USING PASSIVE OPAQUE MICROWAVE RADIOMETRY\*

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### ABSTRACT

This paper will provide an overview of the progress in satellite-based precipitation estimation using passive opaque microwave radiometry. Precipitation estimation has traditionally involved transparent microwave frequency bands near frequencies such as 6, 10, 18, 23, 37, and 89 GHz on instruments such as the Special Sensor Microwave Imager (SSM/I) on the DMSP (Defense Meteorological Satellite Program) satellites, the TRMM (Tropical Rainfall Measurement Mission) Microwave Imager (TMI), and the Advanced Microwave Sounding Radiometer for the Earth Observing System (AMSR-E) on the NASA Agua satellite. Since 1990, there have been several instruments with opaque microwave channels in the 54-GHz oxygen or the 183-GHz water vapor resonance bands such as the Advanced Microwave Sounding Unit (AMSU-A/B) on NOAA-15, NOAA-16, and NOAA-17. Chen and Staelin have developed a precipitation estimation algorithm for AMSU-A/B and AMSU/HSB (Humidity Sounder for Brazil) on Aqua that relies primarily on these frequency bands. Improvements are anticipated with the launch of more instruments similar to AMSU and the launch of the Advanced Technology Microwave Sounder (ATMS) with improved resolution and sampling aboard the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) and the NPOESS satellites. Studies with the NAST-M (NPOESS Aircraft Sounder Testbed-Microwave) aircraft-based instrument which is equipped with 54-, 118-, 183-, and 425-GHz radiometers also suggest that future satellitebased precipitation estimation efforts could benefit from additional opaque bands. This paper will describe results from studies with NAST-M, the method of Chen and Staelin (2003), and the simulation system for developing a precipitation retrieval algorithm for ATMS.

## 1. INTRODUCTION

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Precipitation estimation has traditionally involved only transparent microwave frequency bands near frequencies such as 6, 10, 18, 23, 37, and 89 GHz on instruments such as the Special Sensor Microwave Imager (SSM/I) on the DMSP (Defense Meteorological Satellite Program) satellites, the TRMM (Tropical Rainfall Measurement Mission) Microwave Imager (TMI), and the Advanced Microwave Sounding Radiometer for the Earth Observing System (AMSR-E) on the NASA Aqua satellite. Such transparent channels (also called window channels) show warm signatures in the presence of water vapor over a radiometrically cold reflective ocean background and scattering signatures in the presence of ice particles over land.

Since 1990, there have been several instruments with opaque microwave channels in the 54-GHz oxygen or the 183-GHz water vapor resonance bands such as the Advanced Microwave Sounding Unit instruments AMSU-A and AMSU-B on the NOAA-15, NOAA-16, and NOAA-17 satellites; AMSU/HSB (Humidity Sounder for Brazil) on the NASA Agua satellite; AMSU-A/MHS (Microwave Humidity Sounder) on the NOAA-18 satellite; the Special Sensor Microwave Imager/Sounder (SSMIS) on the DMSP F-16 satellite; and the Special Sensor Microwave Atmospheric Temperature Sounder (SSM/T-1) and Water Vapor Profiler (SSM/T-2) aboard some of the DMSP satellites. With the launch of such instruments, there have been attempts to use opaque channels to estimate precipitation. Staelin and Chen (2000) and Chen and Staelin (2003) developed algorithms for estimating precipitation using AMSU-A/B and AMSU/HSB. More instruments with channels in the 54-GHz and 183-GHz bands will be launched in the future. Some of these include AMSU-A/MHS on NOAA-N'. METOP-1, METOP-2, and METOP-3; and the Advanced Technology Microwave Sounder (ATMS) on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) and the NPOESS satellites. The additional instruments and improvements in the instruments are likely to contribute to improvements in future precipitation retrieval algorithms.

This paper will present efforts for sensing precipitation using opaque microwave radiometry at the MIT Research Laboratory of Electronics and MIT Lincoln Laboratory. Section 2 will describe the physical basis for precipitation sensing using the opaque microwave channels. Section 3 will describe the results of studies with the aircraft-based NPOESS Aircraft Sounder Testbed-Microwave (NAST-M). Section 4 will give an overview of the work of Chen and Staelin (2003) on AMSU. Section 5 will describe current efforts to develop a precipitation algorithm for ATMS before the launch of NPP. Section 6 will discuss possibilities for improving precipitation estimation algorithms by improving signal processing and estimation methods.

#### 2. PHYSICAL BASIS

Unlike window channels which generally are sensitive to the surface due to atmospheric transparency, opaque channels can be insensitive to the surface depending on the deviation of the frequency from an oxygen or water vapor resonance line. An important property of opaque microwave channels is their atmospheric sounding capabilities. Channels in opaque bands can be characterized by weighting functions which describe the sensitivity of each channel to each part of the atmosphere. The weighting functions of AMSU are shown in Fig. 1. For example, the weighting function of AMSU-A channel 7 has a peak around 10 km, so it is sensitive primarily to the layer of the atmosphere in a neighborhood around 10 km in altitude. The temperature profile weighting functions for the AMSU-A 54-GHz band can be expressed as a function of altitude because oxygen is well-mixed throughout the atmosphere. On the other hand, water profile weighting functions for the 183-GHz band are expressed as a function of water vapor burden instead of altitude since water vapor profile can vary significantly over time. The bell-shaped weighting functions of opaque microwave channels and the placement of weighting function peaks throughout the lower and middle atmosphere facilitate the sensing of atmospheric temperature and water vapor profile. Temperature profile can be important to precipitation estimation since warmer air can hold more water vapor.



Figure 1. AMSU-A (left) and AMSU-B (right) weighting functions.

Opaque channels can be used to estimate precipitation rate because of their sensitivity to atmospheric temperature and water vapor profile and because ice particles in convective clouds scatter radiation from cold space resulting in cold signatures (Fig. 2). The precipitation rate due to a convective cell is approximately proportional to the product of the vertical updraft velocity and the water vapor concentration, i.e. the maximum rate at which water vapor can condense and precipitate from the atmosphere. Stronger vertical updraft velocities result in higher cloud-top altitudes, more abundant hydrometeors, and larger hydrometeors. Information about cloud-top altitude can be revealed by the magnitudes of cloud-induced perturbations since clouds with higher tops will show perturbations in channels with weighting functions peaks that are higher in the atmosphere. Opaque channels can reveal information about hydrometeor abundance because greater guantities of hydrometeors tend to result in increased scattering of thermal radiation from cold space which leads to lower Information about particle size distributions can be brightness temperatures. revealed by a comparison of scattering signatures in different opaque bands since channels with higher frequencies are sensitive to smaller hydrometeors.



Figure 2. A Satellite Observing Convective Precipitation

## 3. NAST-M

The NPOESS Aircraft Sounder Testbed (NAST) is a risk reduction effort by the Integrated Program Office for NPOESS that offers the testing of future hardware and the development of retrieval algorithms. It has been flown on high-altitude research aircraft such as the NASA ER-2 or the Scaled Composites' Proteus. NAST-Microwave (NAST-M) is a suite of passive microwave radiometers, which target the 54-, 118-, 183-, and 425-GHz bands and provides data at ~2.5 km diameter footprints on the surface near nadir. NAST-M has been used to study

precipitation in the studies of Blackwell et al. (2001) and Leslie and Staelin (2004).

The recent addition of the 183-GHz and 425-GHz radiometers to NAST-M (Leslie and Staelin, 2004) enables NAST-M to be sensitive to smaller hydrometeors than previously possible with only the 54-GHz and 118-GHz radiometers. Fig. 3 shows observed radiance data from convective storms over the Pacific Ocean. Fig. 3 clearly shows the increase in the area of the precipitation signature with frequency which is expected since hydrometeors traveling in the convective updraft are blown horizontally by wind shear. Smaller (and therefore lighter) hydrometeors can carried by horizontal wind shear over longer distances while larger (and therefore heavier) hydrometeors fall more quickly and therefore cover shorter horizontal distances. A comparison of the brightness temperature images with corresponding video images shows that these four frequency bands together can be used to view the inner dynamics of convective precipitation clouds.



**Figure 3.** Convective cell comparison with the NAST-M spectrometers between channels sharing similar clear-air temperature weighting functions. NAST-M video images of the clouds are also presented with cloud-top altitude marked to the right of the images (stereoscopy). PTOST March 14, 2003 (Leslie and Staelin, 2004).

NAST-M data are also being used to improve simulation capabilities which are important in algorithm development. Statistical retrieval algorithms require large comprehensive data ensembles for training. Physical retrievals involve an iterative process that uses a radiative transfer algorithm. The quality of algorithms developed using either approach is limited by the accuracy of the radiative transfer algorithm used. Using data from a cloud-resolving circulation model as inputs, radiative transfer algorithms can be tuned so that the resulting simulated radiances match NAST-M observations. The model and algorithm have a multitude of parameters such as drop size distribution and intrinsic density. This will allow greater accuracy in the radiative transfer aspect of retrieval algorithm development.

Studies with NAST-M's higher-frequency spectrometers suggest the possibility of including microwave instruments on geostationary satellites. Geostationary satellites currently do not have microwave radiometers mainly because adequately fine spatial resolutions require large antennas. Higher-frequency spectrometers require smaller antennas which could make it feasible to build a microwave radiometer for geostationary satellites.

## 4. AMSU

AMSU is a cross-track passive microwave radiometer. AMSU-A has channels near 23.8, 31.4, and 89.0 GHz and 12 channels in the opaque 54-GHz oxygen resonance band and provides data at 50-km resolution near nadir. AMSU-B has channels near 89 and 150 GHz and 3 channels in the opaque 183-GHz water vapor resonance band, and it provides data at 15-km resolution near nadir.

Chen and Staelin (2003) (also Chen (2006b)) developed an algorithm that uses primarily (but not exclusively) the channels in the 54-GHz and 183-GHz bands. Another notable feature is the extensive use of signal processing methods. At the heart of the algorithm is a feedforward neural net. Before the data is fed into the neural net, it is processed using signal processing techniques such as principal component analysis, image sharpening, and regional Laplacian interpolation. The inputs to the neural net are as follows:

- Inferred 15-km-resolution cloud-induced perturbations near 52.8, 53.6, 54.4, 54.9, and 55.5 GHz
- 183±1-, 183±3-, and 183±7-GHz 15-km AMSU-B data
- The leading three principal components characterizing 50-km AMSU-A cloud-cleared brightness temperatures near 52.8, 53.6, 54.4, 54.9, and 55.5 GHz
- Two surface-insensitive principal components that characterize the AMSU-A window channels near 23.8, 31.4, 50, and 89 GHz and the AMSU-B channels (except the AMSU-B 89-GHz channel)

• The secant of the satellite zenith angle

The opaque channels are used in several ways. One use involves detecting precipitation. Usually, the 183±7-GHz brightness temperature is used to detect precipitation because it is capable of sounding lower in the atmosphere than the other 183-GHz channels and is not usually sensitive to surface variations making it suitable for detecting precipitation over both land and sea. Occasionally, the atmosphere can become so cold and dry that the 183±7-GHz channel becomes sensitive to the surface. In this case, the more opaque 183±3-GHz channel is used instead. Opaque channels can also be used to extract information about the atmospheric temperature profile surrounding precipitation. Brightness temperature images from AMSU-A channels 4 to 8 (near 52.8, 53.6, 54.4, 54.94, and 55.5 GHz, respectively) are cleared of cold perturbations due to clouds using regional Laplacian interpolation. The result is an estimate of what would be seen by AMSU-A in the absence of precipitation. This result is useful for characterizing the temperature profile surrounding precipitation. A principal components transform was applied to the cloud-cleared brightness temperatures before being used by the neural net. The cloud-cleared brightness temperatures are useful also for characterizing cloud-top altitude. The differences between cloud-cleared and observed brightness temperatures indicate the contribution of precipitation to the observed brightness temperatures.

In addition to regional Laplacian interpolation and principal component analysis, image sharpening also plays an important role in the algorithm. 54-GHz data is provided at 50-km resolution. However, it is important to do retrievals at the finer resolution if possible because many details about the fine structure of precipitation can be unacceptably obscured at 50-km resolution. Cloud-induced perturbations are computed for the 183-GHz band at 15-km resolution using the 183±7-GHz or 183±3-GHz channels depending on which one is used to detect precipitation. This perturbation image is then filtered to 50-km resolution. The perturbation of a 54-GHz channel at 15-km resolution is computed by multiplying the perturbation of the same 54-GHz channel at 50-km resolution by the ratio of the 183-GHz perturbation at 15-km resolution to that at 50-km. At this point, the result is suitable for 15-km precipitation retrievals. This result will naturally inherit morphological features of the 183-GHz data. However, improvement was observed in the algorithm as a result of image sharpening over using 54-GHz perturbations at 50-km resolution.

This algorithm was trained using data from the NEXRAD radar network which provided good coverage over the eastern U.S. Fig. 4 shows images of AMSU rain rates and nearly simultaneous NEXRAD retrieved rain rate. Fig. 5 shows a comparison of AMSU vs. NEXRAD rain rates over the testing set of Chen and Staelin (2003), and Table 1 shows the RMS discrepancies between AMSU and NEXRAD rain rates over 38 orbits between Oct. 1999 and Oct. 2000. The agreement between AMSU and NEXRAD, although not perfect, is encouraging. In Fig. 4, AMSU and NEXRAD seem to agree on where it is raining and where

there is heavy rain. In Table 1, for each NEXRAD rain rate range between 1 and 32 mm/h, the RMS discrepancies of 50-km AMSU and NEXRAD rain rate estimates is about equal to the range of rain rates.



**Figure 4.** Precipitation rates (mm/h) observed above 0.5 mm/h on September 13, 2000, 0130 UTC. (a) 15-km NEXRAD retrieval and (b) 15-km AMSU retrieval (Chen and Staelin, 2003).



Figure 5. Comparison of AMSU and NEXRAD estimates of rain rate at 15-km resolution

NEXRAD range	15-km resolution	50-km resolution
<0.5 mm/h	1.0	0.5
0.5-1 mm/h	2.0	0.9
1-2 mm/h	2.3	1.1
2-4 mm/h	2.7	1.8
4-8 mm/h	3.5	3.2
8-16 mm/h	6.9	6.6
16-32 mm/h	19.0	12.9
> 32 mm/h	42.9	22.1

 Table 1. AMSU/NEXRAD Discrepancies (mm/h) (Chen and Staelin, 2003)

AMSU has also been used to study snow and polar precipitation (Chen, Leckman, and Staelin [2003a, 2003b]). It is expected that the opaque channels on AMSU can be used to study snow and polar precipitation since whether precipitation ends up as rain or snow depends primarily on the surface temperature. The presence of AMSU on the NOAA-15, NOAA-16, and NOAA-17 satellites also enabled a study of the diurnal variations of precipitation using 3 satellites (Chen and Staelin, 2005).

There are many improvements that can be made to the Chen-Staelin algorithm. The window channels such as those near 23.8 and 31.4 GHz which have traditionally been used in algorithms for instruments like TRMM TMI and AMSR-E were not optimally used but were only inputs to linear principal component transforms. Improvements to this algorithm could involve incorporating methods from algorithms for TMI and AMSR-E.

## 5. ATMS

Research on precipitation algorithms using opaque microwave channels will continue with the launch of new instruments. Some of these instruments include AMSU-A/MHS on NOAA-18, NOAA-N', METOP-1, METOP-2, and METOP-3. The ATMS, a similar instrument, is scheduled to be launched in 2009 aboard NPP and will be put aboard the NPOESS satellite series.

Recently, work has been done to develop a precipitation algorithm for ATMS. ATMS offers several advantages over AMSU. The set of channels on ATMS is similar to that on AMSU. ATMS also has additional 183.31±4.5-GHz, 183.31±1.8-GHz, and 51.76-GHz channels. However, it does not have a 15-km 89.0-GHz channel as AMSU-B does. ATMS also offers improvements in resolution and sampling (Fig. 6). The 23.8-GHz, 31.4-GHz, 54-GHz, and 89-GHz channels on ATMS are sampled every 17.6 km near nadir as opposed to 50 km by AMSU-A. Unlike AMSU-A/B and similar instruments, the sampling of these channels is the same as that of the 183.31-GHz channels which eliminates the need for the resampling done in the Chen-Staelin algorithm. Additionally, the 54-GHz channels and the 89-GHz channel have a resolution of ~33 km (as opposed to 50 km on AMSU-A) and are Nyquist sampled which increases the information content available in these channels. One disadvantage is that the 23.8-GHz and 31.4-GHz channels have 5.2° resolution as opposed to 3.33° on AMSU-A.











In the absence of any real data, it is necessary to do studies based on simulations. A system for simulating ATMS brightness temperatures has been developed (Fig. 7). This system uses atmospheric data (e.g. temperature profile, water vapor profile, hydrometeor mass mixing ratios, etc.) from the 5<sup>th</sup> Generation Pennsylvania State University / National Center for Atmospheric Research Mesoscale Model (MM5) with the Goddard Cumulus Ensemble statistical hydrometeor model (Tao and Simpson, 1993), and the TBSCAT radiative transfer model due to Rosenkranz (2002) with electromagnetic hydrometeor modeling due to Surussavadee and Staelin (2006). The simulation system also requires accurate knowledge of angular relationships and appropriate filtering of simulated brightness temperatures on the MM5 grid to the locations and resolutions of ATMS fields of view so that the simulated brightness temperatures matches what would be seen by ATMS as closely as possible. A toolbox for MATLAB has been developed by Chen for this purpose.



**Figure 8.** Observed AMSU-B (left) and simulated ATMS (right) 183±7-GHz brightness temperatures around 1630 UTC on Dec. 8, 2002.

Fig. 8 compares simulated ATMS 183±7-GHz brightness temperatures with those observed by AMSU-B around the same time. There is agreement in the range of brightness temperatures seen. However, the AMSU-B data shows the arms extending from the hurricane eye in a spiraling manner while the simulated ATMS data shows only a single ring. The morphological difference is due to the inaccuracy of the NCEP analyses used to initialize the MM5 model.

Since the ATMS channel set is very similar to that of AMSU, future work on ATMS could involve adapting part or all of the Chen and Staelin (2003) algorithm for ATMS. The Chen and Staelin (2003) algorithm did not make optimal use of the window channels, so better use of the window channels could be a new feature for the ATMS algorithm. However, one factor that could hinder the optimal use of window channels is the 5.2° resolution of the 23.8- and 31.4-GHz channels.

## 6. SIGNAL PROCESSING AND ESTIMATION

The development of precipitation estimation algorithms could benefit from improvements in signal processing and estimation techniques in addition to improvements in instrumentation and physical models. Problems to be studied could include understanding how to exploit the Nyquist sampling of the 54-GHz band on ATMS and understanding how to train neural nets to learn circular dependencies.

Recently Chen (2006a) has studied the ability of neural nets to learn circular dependencies. Neural nets have been used in various estimation problems in earth science remote sensing. Training neural nets to learn circular dependencies could be relevant to precipitation estimation since precipitation can depend on time of day, season, and geolocation. The study of Chen (2006a) showed that using topologically appropriate representations of circular data can reduce the RMS error achievable with neural nets with a given number of weights and biases over conventional linear representations and can reduce the complexity needed for a neural net to achieve a specified RMS error.

## 7. SUMMARY

A review of work on using passive opaque microwave radiometry to sense precipitation with NAST-M, AMSU, and ATMS has been presented. The studies of Leslie and Staelin (2004) with NAST-M demonstrated the utility of the 54-, 118-, 183-, and 425-GHz bands for estimating rain rate. The study of Chen and Staelin (2003) with AMSU showed the utility of 54-GHz and 183-GHz data for

estimating precipitation. The improvements of ATMS over AMSU suggest that better algorithms are possible for ATMS than for AMSU. Future work will also include efforts to make the best use of window channels which already have been shown to be useful for precipitation sensing. Possibilities for improvements in signal processing and estimation were also discussed.

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