

6 Global precipitation measurement

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6.1 Introduction

Observations of the space-time variability of precipitation around the globe are imperative for understanding how climate change affects the global energy and water cycle (GWEC) in terms of changes in regional precipitation characteristics (type, frequency, intensity), as well as extreme hydrologic events, such as floods and droughts. The GWEC is driven by a host of complex processes and interactions, many of which

are not yet well understood. Precipitation, which converts atmospheric water vapor into rain and snow, is a central element of the GWEC. Precipitation regulates the global energy and radiation balance through coupling to clouds and water vapor (the primary greenhouse gas) and shapes global winds and atmospheric transport through latent heat release. Surface precipitation directly affects soil moisture and land hydrology and is also the primary source of freshwater in a world that is facing an emerging freshwater crisis. Accurate and timely knowledge of global precipitation is essential for understanding the multi-scale interaction of the weather, climate and ecological systems and for improving our ability to manage freshwater resources and predicting high-impact weather events including hurricanes, floods, droughts and landslides.

In terms of measurements of precipitation, it is critical that data be collected at local scales over a global domain to capture the spatial and temporal diversity of falling rain and snow in meso-scale, synoptic-scale and planetary-scale events. However, given the limited weather station networks on land and the impracticality of making extensive rainfall measurements over oceans, a comprehensive description of the space and time variability of global precipitation can only be achieved from the vantage point of space.

The spatial and temporal scales required to resolve the impact of precipitation for different hydrometeorological processes are illustrated in Fig. 1. This figure shows that surface water can vary on the order of minutes and meters; measurements at these scales are relevant for landslide and flooding conditions. Short-term ($< \sim 1$ day) weather related events include for example, flood warnings, urban drainage and hydropower optimization. Seasonal to inter-annual (~ 1 day to several decade) hydrological scale events include management of irrigation and water supply reservoirs, land use decisions and culvert operations. Oceanic processes near coastlines have fine resolution requirements, while open ocean processes can span decades or hundreds of years and thousands of kilometers. On the climate scale for long-term planning over 50 years to centuries, hydrologists must anticipate minor and major dam needs and assess environmental impacts of water resources. As can be expected, satellite observations cannot measure to all the spatial and temporal scales required for hydrometeorological applications.

Nevertheless, satellites can provide certain types of data at high spatial and temporal scales. The first images of clouds in relationship to meteorological processes were provided by the Television and Infrared Observation Satellite (TIROS-1), which was launched in April 1960. These early investigations noted the importance of satellite observation

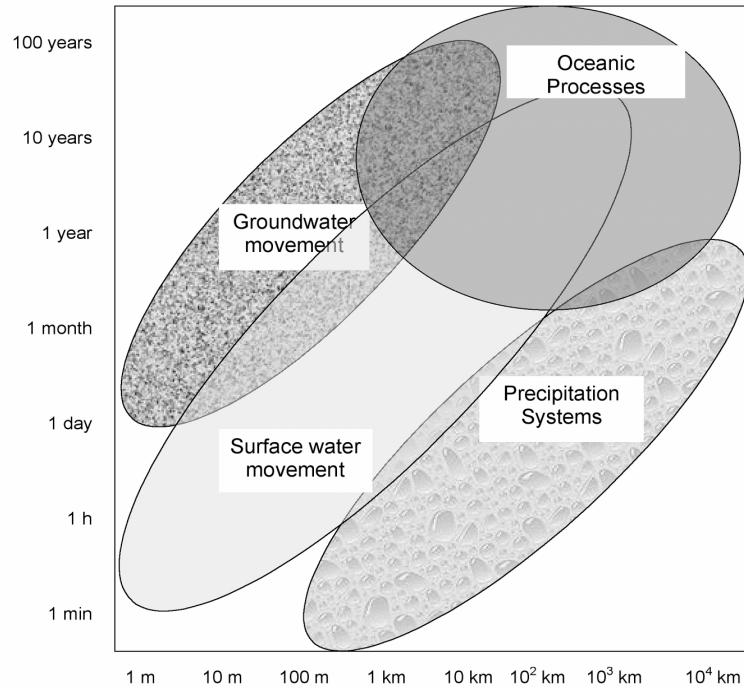


Fig. 1. Schematic of selected atmospheric, surface and subsurface hydrologic processes and their temporal and spatial scales of occurrence (from Bloschl and Sivapalan 1995)

of clouds since precipitation is inherently linked with clouds (Kidder 1981) although properly resolving the spatio-temporal precipitation from space would prove to be a challenging task.

Currently, observations of cloud tops using visible and infrared sensors from geostationary orbits such as the Geostationary Operational Environmental Satellites (GOES) spacecraft are done with near continuous (fine temporal) scans at footprint resolutions of 1–8 km. Kidd (2001) summarizes other geostationary satellites and reviews various approaches inferring precipitation from visible and infrared sensors. Measurements of rainfall rate inferred from cloud top data do not probe into the cloud nor provide information on the vertical structure and microphysics of clouds. Active radars at Ku, Ka and W band (~14, 35 and 95 GHz, respectively), for example, can measure profiles of precipitating hydrometeor characteristics (e.g., size) within clouds.

Passive precipitation radiometers (~10–89 GHz) can measure the integrated cloud water and ice paths and are used to estimate rain rate (Barrett and Beaumont 1994; Petty and Krajewski 1996; Smith et al. 1998). Passive radiometers in the 1990's and 2000's typically had horizontal surface footprints of 5–50 km, while radar footprints were on the order of 1–10 km. While there are a few active and several passive precipitation sensors in orbit, none are currently in geostationary orbit and thus the temporal resolution is limited to the number of overpasses per day.

Wideband multifrequency passive radiometers can provide microphysical information about both liquid and frozen hydrometeors in clouds. Passive microwave sounders with multiple channels centered around oxygen and water vapor absorption lines provide vertically-resolved information on the temperature and water vapor profiles of clear air atmospheres and the sounder channels are also sensitive to hydrometeors for retrievals of cloud properties (Chen and Staelin 2003; Kidder et al. 2000; Spencer 1993). Current active microwave satellite radars (at Ku and W-band) provide fine-scale vertical profile structure information about atmospheric clouds (Meneghini et al. 2000; Stephens et al. 2002). Combined radar-radiometer systems, such as the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000; Simpson et al. 1988) are particularly important for studying and understanding the microphysical processes of precipitating clouds and for accurate estimates of rainfall rate. Since TRMM is a single satellite in a non-Sun-synchronous 35° orbit, it cannot provide fine temporal resolution alone. A generation of blended, 3-hourly rainfall products has emerged to exploit the temporal resolution of geosynchronous techniques, the improved accuracy of passive microwave techniques and the direct rainfall measurement from active microwave sensors (See Ebert et al. 2007, for a review of these multi-sensor techniques and past intercomparison activities). The next stage in the evolution of precipitation observations from space is the Global Precipitation Measurement (GPM) Mission, which is designed to unify a constellation of research and operational satellites to provide integrated, uniformly-calibrated precipitation measurements at every location around the globe every 2–4 h.

This Chapter begins with a brief history and background of microwave precipitation sensors, with a discussion of the sensitivity of both passive and active instruments, to trace the evolution of satellite-based rainfall techniques from an era of inference to an era of physical measurement. Next, the highly successful Tropical Rainfall Measuring Mission will be described, followed by the goals and plans for the GPM

Mission and the status of precipitation retrieval algorithm development. The Chapter concludes with a summary of the need for space-based precipitation measurement, current technological capabilities, near-term algorithm advancements and anticipated new sciences and societal benefits in the GPM era.

6.2 Microwave precipitation sensors

Satellite-based remotely-sensed visible and infrared imagery provides high spatial resolution from instruments of moderate aperture size ($<1\text{m}$), even at geosynchronous distances. However, due to the large hydrometeor extinction at infrared and visible wavelengths, such sensors are unable to probe through most cloud cover. In contrast, microwave, millimeter-wave and sub-millimeter-wave remote sensing provides the capability of probing through clouds and precipitation while retaining useful sensitivity to hydrometeors (Staelin 1981; Njoku 1982; Ishimaru 1991). Three common types of microwave sensors exist: active radars and passive radiometric imagers and sounders. Cloud and precipitation radars are those that observe the direct backscatter from hydrometeors. Imagers operate primarily in the window regions of the microwave spectrum away from oxygen and water vapor absorption lines. The atmosphere tends to be relatively transparent in these window regions so that a robust signal can often be obtained as a function of total water in the atmospheric column. Sounders operate in microwave absorption lines in order to profile the atmospheric temperature and water vapor contents but have recently been found to have some uses in the detection and quantification of cold season precipitation and are expected to provide indirect information about light rain over land. Recent reviews by Kidd (2001) and Levizzani et al. (2007) are excellent resources complementary to this discussion.

Passive precipitation radiometers measure brightness temperature (T_B) which is a function of the upwelling electromagnetic radiation intensity $I(z, \theta, f)$ where f is the radiometer frequency, θ is the angle of observation and z is the height of observation. This radiation intensity is a measure of the vertically integrated emission, reflection and scattering of passively-generated thermal radiation from the Earth's surface, atmospheric gases and cloud and precipitation hydrometeors. The radiation intensity is typically converted to a brightness temperature using the Rayleigh-Jeans approximation to Planck's Law. Microwave window radiometers are designed to operate in the electromagnetic

spectrum away from strong absorption lines of oxygen and water vapor. With relatively little attenuation from oxygen or water vapor in these ‘window’ regions, microwave radiometers can probe through cloud layers to provide information about precipitation to near the Earth’s surface. In the absence of large hydrometeors and away from absorption lines, the radiative transfer equation may be written as (Olson et al. 2001):

$$T_B \approx \varepsilon T_s \exp(-\tau) + T_{atm} [1 - \varepsilon \exp(-\tau) - (1 - \varepsilon) \exp(-2\tau)] \quad (1)$$

From this, it is immediately evident that window channel radiometers can be designed to retrieve T_s (the surface temperature), ε (the surface emissivity which is closely related to the wind speed over oceans and the vegetation cover over land) and τ , the atmospheric absorption. Absorbing constituents in the media are the residual water vapor effects, cloud water and rain water. Water vapor is usually observed using a weak absorption line near 22.235 GHz. Cloud water and rain water can then be estimated from the residual absorption but distinguishing one from the other is difficult unless scattering is sufficiently large so as to distinguish the two signals.

For large raindrops and frozen hydrometeors, scattering by microwave radiation cannot be ignored. The degree of sensitivity depends on the frequency of observation, the hydrometeor phase (e.g., cloud water, rain droplets, ice, snow, graupel, and/or hail), the hydrometeor density and particle size distribution (Gasiewski 1993). For example, frequencies below ~20 GHz respond to only the strongest liquid precipitation, while frequencies above ~220 GHz respond to even light non-precipitating ice clouds such as cirrus. Equation (1) can be expanded to include the contribution from scattering as would be observed at height z and observation angle θ . For a horizontally planar-stratified atmosphere, the radiative transfer equation with frequency dependence assumed is (Gasiewski 1993):

$$\cos \theta \frac{dT_B(z, \theta)}{dz} = -K_e(z)T_B(z, \theta) + K_a(z)T(z) + K_s(z) \int_0^\pi \bar{P}(z, \theta, \theta')T_B(z, \pi - \theta') \sin \theta' d\theta' \quad (2)$$

In this equation, $T(z)$ is the atmospheric temperature profile at height z , while K_a , K_e , K_s are the bulk layer absorption, extinction and scattering coefficients for the layer dz and the assumed frequency f . The reduced

phase matrix, \bar{P} describes the fraction, magnitude and polarization of energy scattered from angle θ' to angle θ at z and f . The bulk asymmetry parameter G is used to define the phase matrix and the asymmetry provides a measure of the direction of scattering (e.g., mostly forward, backward, or isotropic). In performing the integration to solve Eq. (2) for T_B , the contributions from the boundary conditions (surface and cosmic background) are incorporated.

Fundamental to interpreting Eq. (2) is the concept that scattering increases very rapidly with frequency across the microwave domain. Adding higher frequency channels (freq >40 GHz) to radiometers is thus useful to exploit this scattering signature. While absorption continues to be important for liquid particles at these frequencies, ice particles become almost pure scatterers at these frequencies due to their dielectric properties. Figure 2 shows computed brightness temperatures from 1 to 1000 GHz for representative cloud types as would be observed over a calm ocean surface. The representative cloud types shown here include convective rain with ice aloft, falling snow, non-precipitating anvil ice and clear air with low and high water vapor. The saturation at the water vapor absorption sounding channels (e.g., 23, 183, 380, 448, 556, 752,

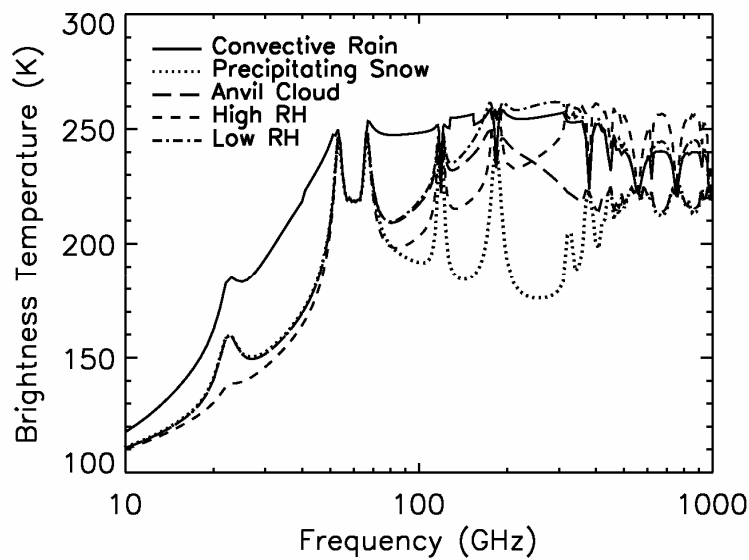


Fig. 2. Representative brightness temperatures from 10 to 1000 GHz for five different atmospheric and cloud conditions (from Skofronick-Jackson 2004)

987 GHz) is apparent in the figure, while the evidence of the oxygen channels (e.g., 50–60, 118, 368, 424, 487, 715, 834 GHz) is limited to the lower frequency channels. For precipitation sensing over oceans, the window channels with center frequencies near 10, 18, 36 and 89 GHz have proved to be the most useful. To capture the heaviest precipitation rates (and more information about the surface features during the absence of precipitation), 6 GHz can be added. Over land, where the highly variable surface temperature and emissivity contaminate the brightness temperature signal for lower frequencies $< \sim 90$ GHz, precipitation estimates can be obtained by relating the scattering from ice aloft to the rain at the surface using channels with center frequencies near 89, 150 (or 166) GHz and at multiple offsets from the 183 GHz water vapor absorption line (e.g., 183 ± 1 , 183 ± 3 , 183 ± 7 GHz). These higher frequency channels are sensitive to the ice particles in clouds (causing an increase in scattering and hence a reduction in the brightness temperature). Thus the 150 and 183GHz channels have also been shown to be useful in estimating falling snow characteristics (e.g., Ferraro et al. 2005; Skofronick-Jackson et al. 2004). Frequencies above ~ 200 GHz have been proven to be useful for estimating information about ice in clouds through aircraft instrumentation (Evans et al. 2005), but no dedicated cloud ice satellite missions at these frequencies exist at this time.

Another important aspect of instrument sensitivity is that if designed to do so, radiometers can receive electromagnetic energy in a fully polarimetric mode (i.e., measuring the four Stokes parameters, Gasiewski 1993; Skou and Le Vine 2006). Typically, satellite precipitation sensors measure only the vertical (V) and/or horizontal (H) polarizations that are related to the Stokes parameters, though ground-based radars are moving toward fully-polarimetric measurements. Differences in measured V and H can emanate, for example, from oceanic wave patterns and their foam crests or from oriented ice particles in clouds. The information content of V versus H polarization is exploited to improve retrieval accuracy of various parameters.

Multi-frequency window radiometers such as the Scanning Multichannel Microwave Radiometer (SMMR) launched in 1978 (Njoku et al. 1980) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) first launched in 1987 (Hollinger et al. 1990) make use of window channels to retrieve surface wind speed, column water vapor, cloud water and rainfall over the oceans. Lower frequencies (e.g., 10 and 6 GHz) are needed to retrieve parameters such as sea surface temperature. These lower frequency channels were first flown on TRMM's Microwave Imager (TMI)

launched in 1997 (Kummerow et al. 1998) and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) launched in 2002 (Kawanishi et al. 2003), respectively. The WindSat instrument on the Coriolis satellite launched in 2003 (Gaiser et al. 2004) further adds wind direction capabilities by measuring all four Stokes parameters at the low frequencies that are most sensitive to the surface state. These window channel passive precipitation sensors typically operate in a conically-scanning mode at $\sim 53^\circ$ inclination angle that is fixed throughout the scanning operation such that the V and H polarized signals are not mixed as can occur in cross-track scanning systems (Ulaby et al. 1981).

Passive microwave sounders such as the Microwave Sounding Unit (MSU), first launched in 1978 (Kidder and VonderHaar 1995), followed by the Advanced MSU (AMSU-B) first launched in 1998 aboard National Oceanic and Atmospheric Administration (NOAA)-15 satellite, the Humidity Sounder of Brazil launched on the Earth Observing System (EOS) Aqua spacecraft in 2002 and the Microwave Humidity Sounder (MHS) instruments aboard the European Meteorological Operational (MetOp) satellite launched in 2006 and also on the NOAA-18 launched in 2005, all operate near the oxygen (60 and 118 GHz) bands and/or the water vapor (183 GHz) bands. These radiometers are designed to derive profiles of temperature and water vapor by sounding the atmosphere at multiple frequencies around the absorption lines. The relatively high frequencies employed by these radiometers, however, make them sensitive to scattering by liquid and frozen hydrometeors. The atmosphere becomes more opaque as the water vapor increases, particularly closest to the center of the absorption lines and this reduces the channel sensitivity to surface emissivity. This can be advantageous when the surface emissivity is not well known as is the case over land surfaces, especially over most frozen surfaces.

For active remote sensing, radars transmit and receive signals. The signal returned to the receiver provides a measure of the interacting media through the backscattering from that media. Depending on its design, radars can measure the distance from the media and the amount and relative size of the particles in the media. The media probed by radars includes, for example, clouds, vegetation and soil. The advantage of precipitation radars is their ability to sense information on the location and size distribution of cloud particles. Essentially, they provide a detailed vertical distribution of the precipitation particles in the cloud. The radar equation (see Atlas 1990 for derivation) shows that the intensity of the signal received by the radar is dependent on the size of the particle, r , to the sixth power. There is also sensitivity to the liquid

versus frozen particles in the cloud. In fact, in the melting layer of clouds, radars often exhibit what is called the bright band. The bright band is caused by the exterior melting of large frozen particles that makes them appear as large raindrops to the radar. Unfortunately, depending on their operating frequency, radars suffer from attenuation (higher frequencies saturate at shorter distances from the transmitter as the cloud optical depth increases). Techniques (Meneghini et al. 2000; Iguchi and Meneghini 1994) have been developed to address and remove the attenuation so that the full vertical picture from radars can be analyzed. Even though these attenuation correction techniques can be further improved to reduce the mismatch between what the radar retrieves and the actual conditions in the cloud, the utility of precipitation radars has been proven with the first precipitation radar in space on TRMM, launched in 1997. In addition, TRMM has shown that combining active and passive sensor measurements can provide a powerful tool for investigating precipitation and cloud particle microphysics.

6.3 Rainfall measurement with combined use of active and passive techniques

While passive microwave radiometers can provide information about precipitating liquid and/or ice particles, the inference of rain rates from microwave brightness temperatures requires additional information and assumptions. One way to vouch for the validity of passive microwave retrieval techniques for rainfall estimation is to compare results with coincident estimates from an active sensor such as precipitation radar. The combined use of active and passive microwave sensors also provides complementary information about the macro and microphysical processes of precipitating clouds, which can be used to reduce uncertainties in combined radar/radiometer retrieval algorithms. TRMM is a joint satellite precipitation mission between the United States National Aeronautics and Space Administration (NASA) and the Japan Aerospace and Exploration Agency (JAXA) that uses both radar and radiometer instrumentation to provide more accurate rain rate estimates than what can be accomplished by either sensor alone (Simpson et al. 1988). Launched in 1997, TRMM quickly became the world's prototype satellite for the study of precipitation and climate processes in the tropics (Kummerow et al. 2000). The orbit for TRMM was designated as an inclined non-Sun-synchronous processing orbit extending between 35°N

and 35°S in order to focus efforts on tropical rainfall and hurricanes. TRMM, which continues to provide data for nearly ten years after launch, has been a tremendous success both in terms of advancing scientific understanding of the global water cycle and practical societal applications (NRC 2007).

The success of TRMM can be traced back to a complement of carefully designed precipitation sensor instrumentation (Table 1). The satellite includes the first rain radar instrument in space along with a radiometer and other instrumentation. The five instruments on TRMM were designed to provide information and products independently, as well as be linked for joint product deliverables. The conically-scanning (53° inclination) TRMM Microwave Imager (TMI) serves as the radiometer with frequencies at 10.7, 19.3, 21.3, 37.0 and 85.5 GHz, with V and H polarization on all channels except 21.3 GHz, which has vertical polarization only. The TMI had a swath width of 760 km at a 350 orbital altitude and footprint resolutions ranging from 36 km × 60 km for 10.7

Table 1. TRMM sensor summary – Rain package (derived from Kummerow et al. 2000)

Instrument	Radiometer (TMI)	Radar (PR)	Visible and Infrared radiometer (VIRS)
Channels	10.7, 19.3, 21.3, 37.0 and 85.5 GHz (dual-polarized except for 21.3: vertical only)	13.8 GHz	0.63, 1.61, 3.75, 10.8 and 12 μm
Resolution	10 km × 7 km field of view at 37 GHz	4.3-km footprint and 250-m vertical resolution	2.2-km resolution
Scanning Mode	Conically scanning (53° inc.)	Cross-track scanning	Cross-track scanning
Swath Width	760 km	215 km	720 km

GHz to $4 \text{ km} \times 7 \text{ km}$ for 85.5 GHz. The Precipitation Radar (PR) operates at 13.8 GHz with a 4.3 km footprint and 250 m vertical resolution at the 350 km orbital altitude. The PR operates in cross-track scanning mode, having a 215 km swath at the 350 km orbit. The other instruments include the Visible and Infrared Radiometer (VIRS), the Lightning Imaging Sensor (LIS) and the Clouds and the Earth's Radiant Energy System (CERES). Mission changes since launch include the failure of the CERES in mid-1998 and in August of 2001 TRMM's orbit was boosted to $\sim 400 \text{ km}$ to conserve fuel that had been required at the lower orbit for station keeping.

The unique function of the PR is to provide the three-dimensional structure of rainfall, obtaining high quality rainfall estimates over ocean and land and improve TRMM rainfall estimates through combined radar-radiometer retrieval algorithms (Tao et al. 2000). The PR instrument was designed and built by JAXA. The TMI design was based on the SSM/I onboard the DMSP satellites since 1987. The TMI, built in the United States, has added V and H polarized 10.7 GHz channels and a slightly different water vapor channel at 21.3 GHz. The TMI provides increased swath coverage, sensitivity to higher rain rates and a link to passive precipitation radiometers on other satellites. The VIRS uses visible and infrared channels to provide additional information related to precipitation. VIRS also provided a connection between TRMM data and visible/infrared data sets from geostationary satellites.

TRMM has a series of measured and estimated products that are used to fulfill the scientific objectives of the mission. There are three major levels of these TRMM products: the Level 1 Earth-located and calibrated radiance/reflectivity swath data; the Level 2 physical retrieval swath-format products; and the Level 3 gridded products. The primary Level 2 operational products associated with TRMM include: (1) radar surface scattering cross-section and total path attenuation; (2) classification of rain (convective/stratiform) and height of bright band; (3) surface rainfall and three-dimensional (3D) structure of hydrometeors and heating over the TMI swath; (4) surface rainfall and 3D structure of hydrometeors over PR swath; and (5) surface rainfall and 3D structure of hydrometeors derived from TMI and PR simultaneously. Major operation products at Level 3 include: (1) 5° gridded TMI-only monthly rain-ocean; (2) 5° gridded PR monthly average; (3) PR-TMI monthly average; (4) TRMM multi-satellite (3-hourly, 0.25° resolution); and (5) TRMM multi-satellite precipitation merged with ground-based gauge measurements.

Ground validation has been an important component of TRMM. Techniques to produce quality controlled ground radar data sets and

estimated surface rainfall rates based on ground radar have been developed. These efforts have led to validation at monthly and instantaneous time scales. The ground validation efforts have been instrumental in verifying the accuracy of the TRMM rain estimates and have led to improvements in calibrating the ground radars.

The validation of satellite products is classically defined as a ground-based observing strategy intended to assess whether or not the satellite products meet their stated accuracy requirements and objectives. In the case of TRMM, this philosophy was translated to quasi-continuous operation of four ground radar sites for which TRMM and ground-based rainfall products were compared. Findings from these four sites (Houston, Texas; Melbourne, Florida, Darwin, Australia; and Kwajelin Atoll) revealed that products were indeed generally within the stated objectives. However, direct comparison between rainfall estimates from the TRMM PR and TMI revealed that differences between the satellite estimates had regional and seasonal components leading to questions about the representativeness of the fixed validation sites. In addition, it is now clear that the nature of the errors themselves is very important. Small, but systematic rainfall errors over a large domain may be difficult to detect at individual ground validation sites. Yet, these errors are critical for climate studies and precipitation process studies. On the other hand, larger random errors are that assumed to cancel in climatologies may have significant consequences on hydrologic applications. Future precipitation missions need to work toward improving instrument accuracies, retrieval capabilities and validation of retrieved products.

6.4 The Global Precipitation Measurement (GPM) mission

The GPM Mission is an international satellite mission to unify and advance global precipitation measurements from a constellation of research and operational microwave sensors. The goal of this upcoming mission is to provide uniformly calibrated precipitation observations at every location around the world every 2–4 h to advance the understanding of the Earth's water and energy cycle and to improve the monitoring and prediction of weather, climate, freshwater availability, as well as high-impact natural hazard events such as hurricanes, floods and landslides. The GPM Mission is a primarily science mission to better understand the microphysics and the space-time variability of global precipitation. At the same time, by making precipitation observations

available in the near real-time to wide segments of the user community, GPM has tremendous potential for practical benefits to society. The GPM Science Objectives thus embrace both fundamental research and application-oriented research (see Table 2). Each of the five high-level objectives listed in the table represents a key science driver for the measurement and sampling strategies for the mission.

Table 2. Scientific Objectives of GPM

1. Advancing Precipitation Measurement Capability from Space
<ul style="list-style-type: none">• Measurements of microphysical properties and vertical structure information of precipitating systems using active remote-sensing techniques.• Combination of active and passive remote-sensing techniques to provide a calibration standard for unifying and improving global precipitation measurements by a constellation of dedicated and operational passive microwave sensors.
2. Improving Knowledge of Precipitation Systems, Water Cycle Variability and Freshwater Availability
<ul style="list-style-type: none">• Four-dimensional measurements of space-time variability of global precipitation to better understand storm structures, water/energy budget, freshwater resources and interactions between precipitation and other climate parameters.
3. Enhancing Climate Modeling and Prediction
<ul style="list-style-type: none">• Estimation of surface water fluxes, cloud/precipitation microphysics and latent heat release in the atmosphere to improve Earth system modeling and analysis.
4. Advancing Weather Prediction and 4-D Reanalysis
<ul style="list-style-type: none">• Accurate and frequent measurements of precipitation-affected microwave radiances and instantaneous precipitation rates with quantitative error characterizations for assimilation into numerical weather prediction systems.
5. Improving Hydrometeorological Modeling and Prediction
<ul style="list-style-type: none">• High resolution precipitation data through downscaling and innovative hydrological modeling to advance predictions of high-impact natural hazard events (e.g., flood/drought, landslide and hurricanes).

The GPM scientific program requires measurements of the four-dimensional distribution of precipitation and its variability from diurnal to inter-annual time scales, quantitative estimates of the associated latent heat release and detailed information on bulk precipitation microphysics including the particle size distribution (PSD) information. The integrated application goals of GPM ensure that the knowledge gained by advanced precipitation measurement capabilities from space is transferred to meeting the extended goals in monitoring freshwater availability, climate modeling, weather prediction and hydrometeorological modeling.

Global precipitation measurements provide the necessary framework for understanding changes in the global water cycle and the context in which to interpret causes and consequences of local trends in water-related variables. Within the United States, GPM is envisioned to be the first in a series of Earth science missions in the coming decade to improve the understanding of the Earth's water and energy cycle (NRC, 2007). Such improvements will in turn improve decision support systems in broad societal applications identified by international communities (e.g., water resource management, agriculture, transportation, energy, health, etc.). In terms of international programs, GPM serves as a cornerstone for the development of a unified satellite constellation for monitoring global precipitation under the Committee on Earth Observation Satellites (CEOS) within the Global Earth Observing System of Systems (GEOSS) Program to provide comprehensive, long-term and coordinated observations of the Earth. During its mission life, GPM will be a mature realization of a multi-national CEOS Precipitation Constellation.

6.4.1 GPM mission concept and status

The GPM concept centers on deploying a Core spacecraft carrying both active and passive microwave sensors to serve as a 'precipitation physics observatory' and a 'calibration reference' for a constellation of dedicated and operational passive microwave sensors (most of which are in Sun-synchronous polar orbits) to produce accurate, uniform global precipitation products within a consistent framework. The GPM core spacecraft will carry the first Ku/Ka-band Dual-frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI) with high-frequency capabilities in a non-Sun-synchronous orbit at 65° inclination. The GMI is specifically designed to serve as a reference standard for constellation radiometers by employing a state-of-the-art calibration system. The DPR will provide detailed microphysical

measurements including particle size distribution information and vertical structure of precipitating cloud systems, which will be used in conjunction with cloud-resolving models to provide a common cloud/hydrometer database for precipitation retrievals from both the Core and Constellation radiometers. The combination of the DPR with Ku and Ka bands and the GMI with 10–183 GHz channels will enable GPM to take on the new science of estimating falling snow and light rain characteristics over both ocean and land surfaces. It is expected that the GPM core instrumentation will provide estimated rain rates from ~0.2–110 mm/h.

The role of the constellation satellite system is to provide the best possible global and temporal coverage with a partnership of international space agencies over the GPM mission life. The constellation build-up will follow a ‘rolling wave’ strategy with a flexible architecture to capitalize on ‘satellites of opportunity’. Each constellation member may have its own unique scientific mission, while participating in the partnership via sensors with precipitation measurement capabilities, such as a conically scanning radiometer and/or cross-track humidity sounder.

GPM is a currently a partnership between NASA and JAXA, with opportunities of additional partnerships with U.S. and international space agencies. NASA will provide the Core Spacecraft with a GMI instrument. JAXA will provide the DPR and launch service for the Core Satellite. In addition, NASA plans to provide a constellation satellite to be flown in an orbit that optimizes the GPM constellation coverage based on available partner assets over the mission life. This NASA Constellation Spacecraft will also augment the sampling provided by the Core Observatory for improved cross-satellite calibration of constellation radiometers, as well as enhanced capabilities for near real-time weather (e.g., hurricane) monitoring and prediction. The Core is planned for a ~400 km orbital altitude, while the NASA constellation is expected to be at ~650 km altitude with a non-Sun-synchronous orbit at ~40° inclination. Both spacecrafts are designed for a prime mission of 3 years, with consumables for a minimum of 5 years of operation. The GPM Core Spacecraft and instruments are under development by NASA and JAXA for an anticipated launch date of June 2013 with the NASA Constellation Spacecraft to be launched in 2014.

The current constellation partnership plans (see Fig. 3) include conical-scanning microwave imagers; e.g., Japan’s Global Change Observation Mission – Water (GCOM-W) (Shimoda 2005), French and Indian Megha-Tropique (Aguttes et al. 2000), United States DMSP satellites (Hollinger et al. 1990)) augmented by microwave temperature/humidity sounders over land including Advanced Technology

Microwave Sounder (ATMS) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) and NPOESS-C1 (Bunin et al. 2004) and Microwave Humidity Sounder (MHS) on NOAA-N' and the European MetOp satellite (Edwards and Pawlak 2000). The inclusion of microwave humidity sounders in the baseline GPM sampling reflects recent advances of precipitation retrievals from sounder instruments such as AMSU-B (with channels at ~ 89 , 150 , 183 ± 1 , 183 ± 3 , 183 ± 7 GHz), which have been shown to be comparable in quality to those from conical-scanning radiometers over land (Lin and Hou 2007). These sounder instruments make it possible for GPM to provide a precipitation estimate every 1–2 h at every location on land over the prime mission life. Over oceans, the sounder retrievals are not as accurate due their inability to detect warm rain systems and thus not included in the baseline GPM sampling. Without the sounders, the average revisit time over oceans for the GPM constellation ranges from 2 to 4 h over the first three years of the mission. Overall, the GPM constellation can provide better than 3-hour sampling over as much as 90% of the globe if all anticipated partner assets are available. The GPM sampling is designed for graceful degradation of performance if partner assets are not available or launched on schedule.

The GPM mission is supported on the ground by (1) a NASA-provided mission operations system for the operation of the Core and NASA Constellation Spacecrafts, (2) a Ground Validation (GV) System consisting of an array of ground calibration and validation sites, provided by NASA, JAXA and international and U.S. domestic partners and (3) a NASA-provided Precipitation Processing System (PPS) in coordination with GPM partner data processing sites to produce near-real-time and standard global precipitation products. The PPS will have the data processing and communications capacity to process the full quantity of input data from the space segment and ancillary GPM sources as it is generated and to create science products in three categories: immediate real-time, outreach and research data. The PPS will process Level 1, 2 and 3 products (similar to TRMM). The PPS shall be sized to handle all data from the NASA Core Observatory, NASA Constellation Spacecraft and partner assets. In addition, the NASA Precipitation Measurement Missions (PMM) Science Team together with its JAXA counterpart work to ensure the scientific success of the GPM mission in the sensor design, retrieval algorithm development and validation, as well as innovative methodologies for data utilization in applications that range from numerical weather prediction to hydrological modeling and prediction.

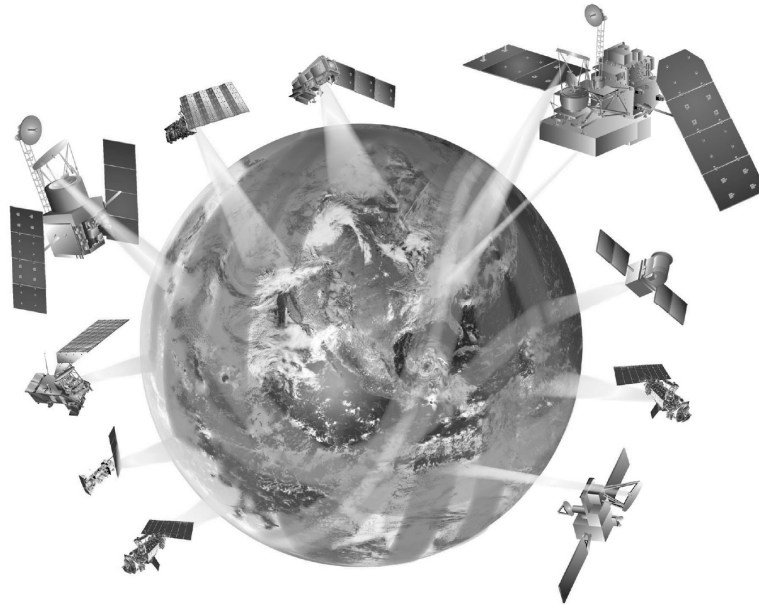


Fig. 3. The GPM Mission configuration with Core Spacecraft (*upper right*), the NASA Constellation Spacecraft (*middle left*) and partner constellation satellites providing global coverage

6.4.2 GPM core sensor instrumentation

For the GPM Mission, NASA and JAXA will design, develop and operate two spaceborne instruments – the GMI and DPR. The GMI provides measurements of precipitation intensity and distribution, while the DPR provides three-dimensional estimates of cloud and microphysical properties. The GMI and DPR are designed to work together to provide better precipitation estimates than either sensor alone. The sampling strategy of the DPR and GMI is shown in Fig. 4. As illustrated in the figure, the DPR Ka-band has a 125 km swath with a vertical resolution of 250 or 500 m, the Ku-band has a 245 km swath with 500 m vertical resolution, while the GMI extends measurements beyond the DPR domain to the larger swath width of 885 km.

NASA will provide two GMIs, one for the Core Spacecraft and one for the NASA Constellation Spacecraft. GMI is being designed to make simultaneous measurements of a range of precipitation rates, including

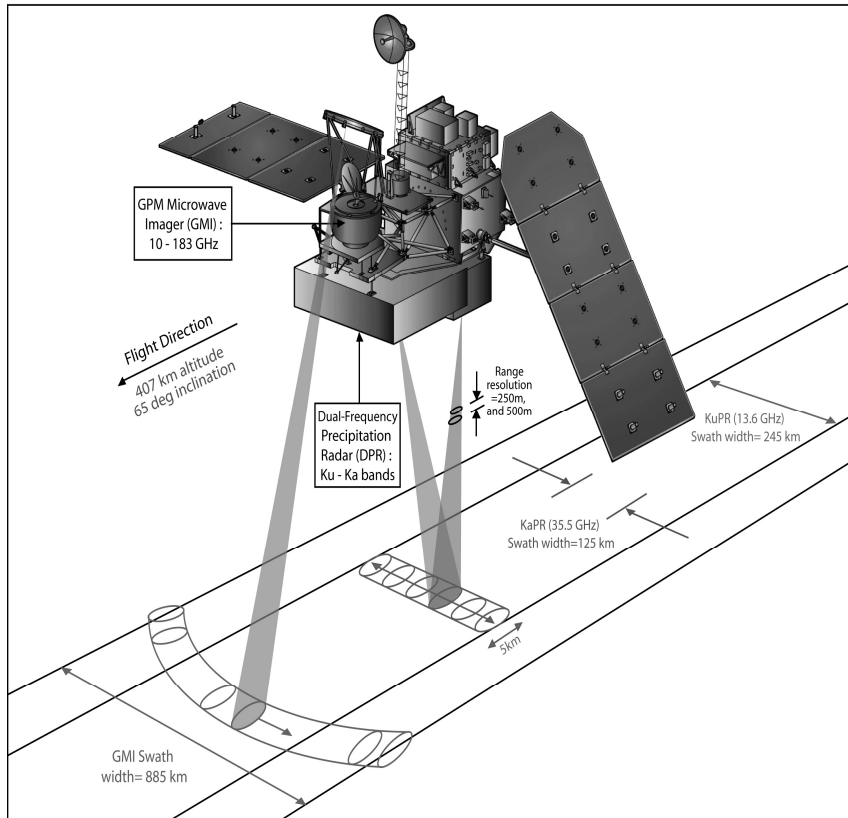


Fig. 4. The GPM Core Spacecraft with the DPR and GMI instruments

light rain and snowfall often found at the Earth's higher latitudes. These measurements are key to understanding the precipitation processes and storm structures of mid-latitude and high-latitude systems, both over land and water. The frequency and footprint characteristics of the GMI for the Core Observatory and Constellation Observatory are provided in Table 3 and the GMI instruments operate in a conically-scanning mode as shown in Fig. 4.

The GMI is being designed to have independent calibration measurements to ensure accuracy. GMI's calibration is achieved through the use of the standard methodology of hot and cold load gain measurements that provide an instrument count (measure of intensity) to brightness temperature value (Ulaby et al. 1981). In addition, both the hot and cold load measurement ports will have injected noise diode

inputs. This will provide hot+noise and a cold+noise calibration points. If there is a detected hot load failure due to sun impinging on the hot load, the measurements from the cold and cold+noise can be used to calibrate the GMI radiometer. Further, the noise diodes provide a method to track the non-linearity drift in the radiometer signals over time. It is especially important to quantify this drift when using GMI radiometer measurements to estimate parameters to be used for climate warming studies, such as sea surface temperature.

The DPR under development by JAXA will provide three-dimensional measurements of cloud structure, precipitation particle size distribution (PSD) and precipitation intensity and distribution while serving as an orbiting reference system for the passive microwave-based precipitation estimations. The dual frequency design of the DPR will utilize the differential attenuation of the returned signals to infer information about the bulk characteristics of the particle size distribution (e.g., the diameter that divides the rain water content into two equal parts) and hydrometeor category (e.g., rain, snow, mixed, wet graupel/hail). Particularly at 35 GHz,

Table 3. The frequencies and footprints for the GMI instrument

Frequency (GHz)	V/H Polarization	Core footprint (km) (at 405 km altitude)	Constellation footprint (km) (at 650 km altitude)
10.65	V & H	19.4 × 32.2	30.8 × 51.7
18.7	V & H	11.2 × 18.3	18.0 × 29.4
23.8	V	9.2 × 15.0	14.8 × 24.1
36.5	V & H	8.6 × 14.4	13.8 × 23.1
89.0	V & H	4.4 × 7.3	7.1 × 11.7
165.5	V & H	4.4 × 7.3	7.1 × 11.7
183.31±3	V	4.4 × 7.3	7.1 × 11.7
183.31±8	V	4.4 × 7.3	7.1 × 11.7

cloud drops may contribute to the integrated attenuation of precipitating clouds as a function of cloud depth and possibly the characteristics cloud drop spectra (e.g., marine versus continental clouds). The DPR operates in a cross-track scanning mode as shown in Fig. 4. The frequencies are Ku (13.6 GHz) and Ka (35 GHz) and have a footprint of 5km at nadir for the Core Observatory.

6.4.3 Ground validation plans

The GPM validation program is being developed with a somewhat modified paradigm with respect to the methodology used for TRMM. Aside from verifying GPM products through statistical comparisons with ground-based measurements, GPM requires that certain validation sites be equipped to additionally diagnose the underlying causes of any retrieval algorithm discrepancies. This diagnosis component, when framed in the context of meteorological conditions is intended to: (a) provide invaluable information regarding the algorithm's expected performance in other regions; and (b) provide information that algorithm developers typically need in order to improve algorithms. The metrics to be used include the ability to predict the success or failure of the algorithms, based upon meteorological circumstances, as this is a quantitative measure of our understanding.

While it is important to learn from prior and current satellite-precipitation measurement missions such as TRMM, GPM must also be forward-looking. It is becoming apparent that the future of precipitation research is probably not one in which satellite data is used in isolation. Instead, integration of satellite precipitation measurements with ground observations and cloud resolving models is likely to replace satellite-only precipitation products, particularly for applications such as hydrology that require precipitation as input.

For GPM, the GV strategy follows a three-prong approach to focus on the different needs of validation. There will be Statistical Validation sites, Precipitation Process sites and Integrated Application sites. The surface precipitation statistical validation sites will be used for direct assessment of GPM satellite data products. These will be co-located with existing or upgraded national network (e.g., Weather Surveillance Radar 88 Doppler (WSR-88D), etc.) and dense gauge networks. Their primary purpose will be to validate the satellite estimates using statistical and other procedures. There will need to be sites over ocean and land surfaces. Complications due to different sampling volumes of the satellite versus

the ground sensors will need to be addressed. Contributions to the error in the comparisons and validation will be investigated and analyzed.

The precipitation process sites are used for improving understanding of precipitation physics, modeling and satellite retrieval algorithms and provide valuable observations both pre and post launch. These sites will focus on tropical, mid- and high-latitude precipitation studies. The sites will include orographic/coastal sites and targeted sites for resolving discrepancies between satellite algorithms. Sites will be selected for validating the newer products of GPM, namely light rain and falling snow. These sites may include aircraft for in situ measurements and mobile instrument assets that can be moved to different locations, for example, to observe snow in cold seasons and tropical rain in warm seasons. These process sites will be used to improve and validate the physics of cloud resolving models, land and hydrology models and coupled land-atmosphere models.

The integrated hydrological sites will focus on improving hydrological applications. These sites will be co-located with existing watersheds maintained by other US agencies and international research programs. The idea is to integrate or assimilate the precipitation estimates into hydrological and/or climate models. The expectation is that precipitation will improve the model predictions, yet part of the process is to assess the impacts of errors in the precipitation estimates on errors in the predicted hydrology or climate application.

In advance of GPM, ground validation is occurring to provide data for the falling snow algorithm developers. Data sets are needed to (1) develop and validate models that convert the physical properties (shape, size distribution, density, ice-air-water ratio) of single snowflakes to their radiative properties (asymmetry factor and absorption, scattering and backscattering coefficients); and (2) relate the bulk layer radiative properties (summation of the single particle radiative properties over a discrete vertical layer) to calculated and observed passive microwave radiances and radar reflectivities. These models are central to physically-based snowfall retrieval methods, as well as the characterization of likely retrieval uncertainties. In the past, the microwave community has used a number of approximate models all giving different results based on choices of parameters and assumptions. The snowfall retrieval algorithm community cannot make significant advances without a better understanding of the relationships between non-spherical snowflakes and their radiative properties.

In the winter of 2006–2007, GPM participated in the Canadian CloudSat/CALIPSO Validation Program field campaign (C3VP, <http://c3vp.org/>) held near Toronto, Canada, to measure data for retrieval

algorithm development. This provided an opportunity to collect data in cold-latitudes needed for falling snow retrieval algorithm development and provide a basis for improving retrieval accuracy. The C3VP field campaign ground-based assets collected high resolution dual frequency (DPR matched) polarimetric radar measurements of snow/rainfall rate, particle type and mass-content coincident to aircraft sampling, precipitation particle size distributions and shapes measured near the ground under cover of radar and aircraft and a comprehensive set of measurements of environmental conditions. The C3VP field campaign used aircraft to collect in situ microphysics in snow and mixed-phase precipitation events of lake effect snow bands and in synoptic snow conditions. Overpasses by the CloudSat radar (94 GHz), the NOAA AMSU-A and AMSU-B and the AMSR-E radiometers provided microwave satellite data. These measurements will lead to improved information for defining relationships between the physical properties of frozen precipitation and its active and passive radiative signatures. Since international partnership is key to ensuring the success of the GPM GV program, similar collaborations on ground validation are underway between NASA and other international research organizations including the Finnish Meteorological Institute.

6.5 Precipitation retrieval algorithm methodologies

It is not enough to collect observed satellite data and ground measurement data sets. Reliable and accurate retrieval algorithms must be developed, tested, validated and improved as our understanding of the underlying physical processes or the retrieval mechanics is enhanced or updated. For passive radiometers, four retrieval methodologies have been used in the past: empirical algorithms, neural network approaches, maximum likelihood methods and Bayesian techniques. Because the Bayesian techniques permit real-time estimation as well as a link to the understanding of the physical state and underlying processes, they have been the cornerstone of the TRMM passive algorithms and are being considered for the GPM algorithms. Due to the greater sampling of the precipitation column by spaceborne radars and the less ill-posed nature of the radar retrieval problem in general, analytical inversion methods have been at the heart of most TRMM-era algorithms. However, in recognition of the inherent uncertainties in radar reflectivity measurements, variational techniques incorporating additional constraints on the inversion of radar data have also been employed with success.

Retrieval algorithms for satellite-based precipitation estimates from both active and passive sensors are complicated by the fundamentally underconstrained nature of the inversion problem. Precipitating clouds simply have more free parameters, including their size, shape and internal distribution of hydrometeors along with their associated sizes, shapes and compositions, than can realistically be retrieved from a finite set of satellite observables. Assumptions regarding the composition of clouds are, therefore, necessary. These assumptions and how they are represented in algorithms, are the chief source of discrepancies among existing rainfall products (Stephens and Kummerow 2007). The key to building a consistent framework within GPM is thus to merge these physics assumptions across active and passive and combined active-passive algorithms. This can be accomplished using the GPM core satellite that is designed explicitly to observe precipitating cloud microphysical structure with greater accuracy than ever before. The ability to create an inventory of naturally occurring cloud states with the details afforded by the GPM core satellite greatly simplifies the construction of Bayesian algorithms, which in turn can be used to derive products from the constellation of radiometers. Consistent retrievals from the constellation satellites would then simplify the construction of merged microwave/IR products for very high space/time resolution products and allow for precipitation data assimilation into General Circulation Models (GCMs) and Numerical Weather Prediction (NWP) models.

The algorithm development efforts for GPM reflect a hierarchy of products, as described above. Most critical in this hierarchy are the dual frequency radar algorithms, which serve as the basis for the merged radar-radiometer algorithm implemented on the core satellite. The merged algorithm is applied to the core satellite data streams to create a priori databases representing our best estimate of observed cloud structures. These representative databases are then incorporated in the construction of the constellation algorithm(s), which should then be applicable to any spaceborne radiometer irrespective of the sensor details. The consistent rainfall estimates derived from the radiometer constellation serve as a calibration reference in combined microwave/infrared techniques designed to provide high resolution hourly rainfall.

6.5.1 Active retrieval methods

The GPM core satellite will carry a dual frequency radar operating at 13.6 and 35.5 GHz. From this dual frequency radar one can, in principle, determine two parameters of the drop size distribution at each range bin in the vertically sampled profile. While this is a significant step forward from TRMM and most surface radars that rely on measurements at a single frequency, it is not enough to unambiguously determine rainfall rate. For a general gamma size distribution of raindrop sizes one needs three independent measurements to specify the three free parameters of the gamma distribution. Practical considerations such as radar calibration uncertainty, sub-pixel variability and gaseous and particle attenuation complicate the inversion. Because the three free parameters of the gamma distribution cannot be unambiguously determined from two radar frequency measurements, robust solutions require that one assumes plausible relationships between drop size distribution parameters, their radiative properties and the observations.

The reflectivity and total beam attenuation of a precipitation radar target can be related directly to the sum of the radiative backscattering and extinction cross-sections of individual particles in the target volume. It follows that the effective radar reflectivity $Z_{e\lambda}$ and extinction k_λ at wavelength λ characterizes the backscattering and extinction, respectively, from a unit volume of the precipitating atmosphere. While the relations between drop size and backscattering and extinction are well specified by Mie formulas for individual spherical particles, the rainfall rate as well as the reflectivity and extinction depend not upon individual drops, but upon the size distribution of these drops in a unit volume. This size distribution, $N(D)$, has multiple degrees of freedom and cannot be uniquely characterized by $Z_{e\lambda}$ or even by $Z_{e\lambda}$ combined with k_λ . The general strategy adopted for the dual frequency radar algorithm is thus one that describes the size distribution as having two free parameters that are then determined by the two radar frequencies. Even within this framework, a number of potential solutions exist, especially in frozen precipitation cases where multiple particle habits with distinct size distributions may occur.

There are four approaches currently being considered for retrievals from the DPR on GPM. In the first approach, particle sizes follow a gamma distribution of the form $N(D) = N_0 D^\mu \exp(-\Lambda D)$ in which μ is assumed fixed and then the classical solution developed by Hitschfeld and Bordan (1954) for attenuating radars is employed. This technique assumes power law relations hold between the extinction k_λ and $Z_{e\lambda}$ at each of the frequencies in order to correct for the intervening attenuation.

While the single frequency Hitschfield-Bordan solution is known to be unstable, the dual frequency method has the additional constraint that the rainfall rate at each range gate should be the same for each of the frequencies employed. This method does not require knowledge of the total beam attenuation from a surface reference technique, but it has the disadvantage that the accuracy of rain estimates is limited by the accuracy of the assumed PSD model.

A second technique relies on differential or integral equations for the parameters of the PSD. For a fixed μ , one can directly obtain a set of coupled differential equations for N_0 and Λ (or more commonly the mass weighted median diameter, D_0 , which is related by $\Lambda = (\mu + 3.67) / D_0$) as a function of range, r , that can be solved numerically. Once N_0 and D_0 are estimated, the rain rate and equivalent water content profiles can be derived. These N_0 , D_0 equations can be solved either in a forward-going (from the storm top downward) or backward-going (from the surface upward) direction. Although the forward-going solutions do not require an independent estimate of path attenuation, the estimates tend to become unstable as the rain rate increases. The backward solutions are more stable and, in the rain, are independent of cloud water and mixed-phase particles above the rain layer. However, the procedure requires accurate estimates of the total path attenuation at both frequencies.

When the total attenuation is unknown or has a high degree of uncertainty, however, a different approach is needed. The third approach requires one to assume that N_0 and D_0 are somehow related. While there are many possible methods of implementing this constraint, a well known method is that of Marzoug and Amayenc (1994), who assume that the normalized intercept parameter, N_0^* , is constant along the radar path. This approach can be used both for single and dual-frequency radars and with or without an attenuation constraint. In the dual-frequency case, a relationship between the specific attenuation profiles at the two frequencies is assumed and various parameters are adjusted to minimize the root mean squared difference along the radar path.

The fourth proposed method is one in which the difference between the measured reflectivities for the two frequencies at two ranges is utilized. This 'difference of differences' provides an estimate of the differential path attenuation over a range interval. The attenuation can then be related directly to rainfall rate, taking advantage of the fact that the two quantities are nearly linearly related. While this method has historically been applied to systems in which one wavelength suffers little or no attenuation, it can in principle be applied to any wavelength combination. The major source of error arises from non-Rayleigh

scattering at the higher frequency in the presence of large drop sizes, an effect that biases the estimate of attenuation.

For intermediate rain rates from several mm/h to about 15 mm/h and where accurate estimates of path attenuation can be obtained, the DPR can provide size distribution information along the full column including the snow, rain and mixed-phase regions. In the more general situation, the most robust approach will depend upon the signal provided by each of the wavelengths, uncertainty in total attenuation estimates from the surface reference technique in providing the total attenuation as absolute calibration and system noise considerations. The performance of the various methods and how best to apply them are areas of active research in the GPM community. Merely having two frequencies instead of the single frequency available on TRMM will, however, significantly reduce the uncertainties irrespective of the final method (or combination of methods) chosen for GPM. A study designed to provide a better understanding of the improvement in spaceborne radar estimates from TRMM to GPM was recently performed (Haddad et al. 2006). This analysis used cloud model results as well as storm ‘snapshots’ synthesized from high resolution airborne radar measurements and from TRMM overpasses. The study showed that uncertainty in estimates of the surface rain rate should be substantially smaller with the GPM core suite of instruments than it was with the TRMM radar and radiometer. Figure 5 summarizes the main conclusion: GPM-core’s inner-swath algorithm should yield rain rates estimates with an uncertainty less than 20% for rain rates between 1.5 and 12 mm/h (as opposed to the TRMM radar’s 40%), though we will be hard-pressed to achieve such a small uncertainty at lighter rain rates (because the corresponding 14-GHz and 35-GHz signatures are not sufficiently different) or at higher rain rates (because significant attenuation at 35-GHz will affect the results).

6.5.2 Combined retrieval methods for GPM

The dual frequency radar rain estimates may be further improved by using the GMI on board the core spacecraft. Unlike the two radar frequencies that sample a common volume, merging satellite radar and radiometer information is considerably more challenging. Additional difficulties arise due to the varying resolutions of the radiometer channels, the different view direction of the radiometer and radar and ultimately the different aspects of the cloud and underlying surface that result from the different viewing geometries. A number of methods have been developed for the TRMM satellite starting with the operational

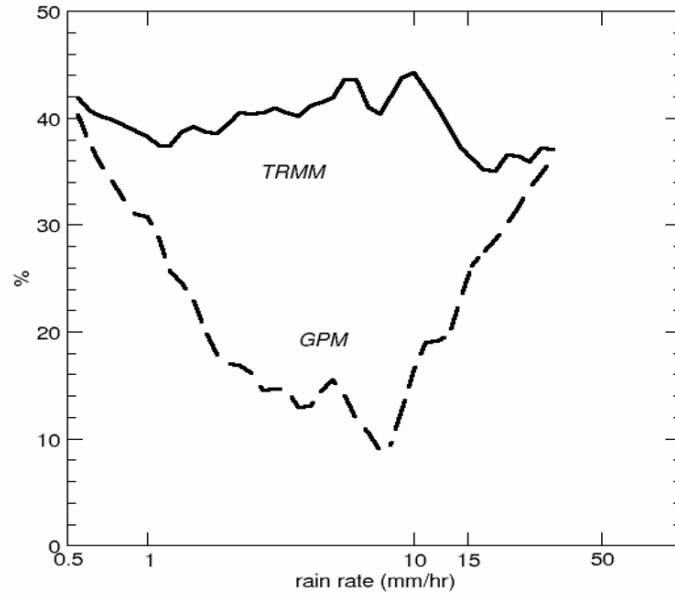


Fig. 5. Uncertainties of GPM-Core and TRMM rain rate estimates based on simulations (derived from Haddad et al., 2006)

algorithm developed by Haddad et al. (1997), followed by Grecu et al. (2004) and Masunaga and Kummerow (2005). While each approach is somewhat different, they all share the common goal of using the radiometer signal as an integral constraint on the column attenuation seen by the radar. This is particularly important in lighter rainfall cases where the surface reference estimates of attenuation are too noisy, leaving the radar with only an assumed drop size distribution for interpreting the surface rainfall. While each approach is somewhat different, the solutions each produce a hydrometeor profile, particle size distribution and surface parameters for which simulated brightness temperatures and reflectivities are consistent with the actual measurements.

Since a number of formulations for the combined radar/radiometer retrieval for TRMM have already been established, the GPM algorithm is being developed along the same lines – by varying the cloud and background constituents until a solution consistent with both the DPR and the GMI observations is obtained. While limited to the narrow swath of the dual frequency radar, this solution is nonetheless critical for the GPM concept in that it forms the basis for the constellation radiometer algorithm discussed in the next section.

6.5.3 Passive retrieval methods

A number of different approaches have been taken for deriving rainfall rates from passive microwave sensors, including empirical and neural network methodologies. However, a class of physically based algorithms to retrieve the precipitation profile (e.g., Evans et al. 1995; Kummerow and Giglio 1994; Kummerow et al. 1996, 2001; Marzano et al. 1999; Smith et al. 1994a, b) is especially well suited for the general framework needed by GPM. These physically-based algorithms retrieve precipitation rate, but also provide information that will lead to a better understanding of the relationships between the cloud state and the observations. This framework accommodates not only the core and constellation sensors currently envisioned for GPM, but any future sensors that have yet to be specified. The combined radar/radiometer algorithm discussed in the previous section thus serves not only to establish the most complete product from the GPM core satellite itself, but it also can be used to produce an a priori Bayesian database of candidate solutions for the constellation radiometer algorithms. The a priori database consists of vertical profiles of precipitating clouds with associated computed brightness temperatures for each profile. Since one can compute T_{BS} at any sensor frequency, the same microphysical cloud profiles remain consistent across all constellation members.

The radiometer algorithms in the TRMM era were dominated by schemes using cloud resolving models (CRMs) to produce a priori databases of cloud profiles. The ability of explicit cloud resolving models to faithfully reproduce and fully represent the actual microphysics structure of observed storms is one of the essential conditions for most of these algorithms to give reliable results. While CRMs were approaching this condition in the TRMM era, the use of these CRMs also created problems that complicated the inversion scheme. Most important was the lack of representativeness that was introduced when a finite and typically small number of these models were used to represent all raining environments. The a priori database generated by the GPM core satellite, whether it uses ancillary information from CRMs or not, will overcome this representativeness problem by creating a priori databases of hydrometeor profiles as they were observed in nature. Any radar profile can serve as the observational basis of the a priori database; for example, the database can be initialized with TRMM and CloudSat results and updated as microphysical profiles from the DPR become available.

With regard to ice-phase precipitation, creating representative a priori databases will require some effort. Ice-phase hydrometeors occur above the freezing level in most precipitation systems and therefore radiative transfer calculation through the entire precipitation column must account for raindrops as well as ice-phase and mixed-phase particles in the column at the higher microwave frequencies (37–200 GHz). There will also be northern-latitude cold-season events where there is no melting layer and the precipitation falls in the form of frozen hydrometeors. Therefore, not only do the cloud profile microphysics need to be appropriate for these precipitation systems, but also the models to compute high frequency (37–200 GHz) radiative properties from physical models of ice-phase and mixed-phase particles need to be developed with care. Liquid precipitation hydrometeors are most commonly modeled as homogeneous dielectric spheres, so that standard Mie codes may be utilized to compute their radiative properties. For most ice-phase hydrometeors (snow crystals and aggregates, rimed graupel particles, etc.), the spherical assumption is typically motivated more by convenience and by the lack of practical alternatives, than by realism. At frequencies at or above ~60 GHz, the spherical approach is no longer accurate for highly nonspherical hydrometeors, such as dendrites and aggregates (Liu 2004; Kim 2006). The computation of the radiative properties of nonspherical snow and mixed-phase particles at higher frequencies requires computationally intense numerical solutions, such as the Finite-Difference Time Domain (Yang and Liou 1995; Sun et al. 1999), Conjugate Gradient (Meneghini and Liao 2000), the Discrete-Dipole Approximation (DDA) methods (Purcell and Pennypacker 1973), and/or the Generalized Multiparticle Mie model (Xu 1997). Inclusion of meltwater in these calculations only adds to their complexity. In order to compute the radiative properties of ice- and mixed-phase particles, one must have representative habits, densities and PSDs of the particles for use in the rigorous calculation of their radiative properties. Field campaigns and investigations are underway to provide such data for GPM era algorithms and to determine the best methodology for computing the radiative properties of these particles.

6.5.4 Merged microwave/infrared methods

Having a consistent set of rainfall products from each of the passive microwave radiometers in the GPM constellation is an essential step

forward in producing the desired 3-hour rain rate estimates at high space/time resolution. In order to achieve consistent precipitation estimates from all constellation members for the desired temporal coverage, GPM scientists are developing techniques to inter-calibrate the radiometer brightness temperatures and precipitation rates from constellation member instruments using GPM Core sensor measurements as a reference. This inter-calibration will provide common standards for GPM data streams without interfering with the calibration requirements of the individual constellation members. An initial goal would be to ensure common file formats among the brightness temperature data sets. Later goals might include common microphysical databases that can be used to physically link the observations, via forward radiative transfer models, among the different sensors.

While consistent 3-hour precipitation estimate coverage is important, there are and always will be, applications such as hydrology that require even greater temporal and spatial resolution. In addition to downscaling, a number of techniques have been developed that use the passive microwave estimates as anchors for geostationary based infrared (IR) rainfall estimates (see Ebert et al. 2007). These estimates can, in principle, be made at 15-minute intervals with resolution equaling that of the IR data itself. The techniques themselves vary, but perhaps the simplest to envision is a simple morphing algorithm such as the one developed by Joyce et al. (2004) in which the rainfall derived by two passive microwave overpasses of a given scene is morphed (in an image sense) between one overpass and another. The morphing is guided by cloud motions derived from the more frequent IR images, bracketed by the microwave overpasses. The technique itself is, therefore, not dependent upon the nature of the microwave algorithm itself – merely the instantaneous rainfall product at the time of the overpass. The objective is the creation of a rain product with the temporal and spatial resolution of the IR data, but bias-corrected by the microwave rain estimates. The merged microwave/infrared methods will thus benefit immediately from the constellation algorithms being developed for GPM in that GPM will take advantage of coincident measurements by the Core Observatory in a non-Sun-synchronous orbit intersecting the constellation satellites to ensure that the microwave products being used for bias correction are consistent with one another – an essential ingredient to make these algorithms perform optimally. The complementary information provided by the DPR and the GMI on the GPM Core satellite is the key to integrating multiple satellite precipitation estimates within a consistent framework to improve the accuracy of global 3-hour precipitation products.

6.6 Summary

Water cycling and the future availability of fresh water resources are immense societal concerns that impact all nations on Earth as it affects virtually every environmental issue. Precipitation is also a fundamental component of the weather/climate system for it regulates the global energy and radiation balance through coupling to clouds, water vapor, global winds and atmospheric transport. Accurate and comprehensive information on precipitation is essential for understanding the global water/energy cycle and for a wide range of research and applications with practical benefits to society. However, rainfall is difficult to measure because precipitation systems tend to be random in character and also evolve and dissipate very rapidly. It is not uncommon to see a wide range of rain amounts over a small area; and in any given area, the amount of rain can vary significantly over a short time span. These factors together make precipitation difficult to quantify, yet measurements at such local scales are needed for many hydrometeorological applications such as flood and landslide forecasting.

Historical, multi-decadal measurements of precipitation from surface-based rain gauges are available over continents, but oceans remained largely unobserved prior to the beginning of the satellite era. Early visible and infrared satellites provided information on cloud tops and their horizontal extent; however, wide-band microwave frequencies proved extremely useful for probing into the precipitating liquid and ice layers of clouds. It was only after the launch of the first SSM/I on the DMSP satellite series in 1987 that precipitation measurements over oceans from passive microwave radiometers have become available on a regular basis. Recognizing the potential of satellites as a vital tool for measuring global precipitation from the vantage point of space, NASA and the predecessor of JAXA launched in 1997 the Tropical Rainfall Measuring Mission (TRMM) satellite carrying the first precipitation radar and a multi-frequency microwave imager to confirm the validity of space-based precipitation measurements from passive microwave radiometers. The success of TRMM has led the widespread use of merged multi-satellite precipitation products in a broad range of scientific research and practical applications (NRC 2005).

Encouraged by the success of TRMM, NASA and JAXA are jointly planning a new international satellite mission named the Global Precipitation Measurement (GPM) mission to develop the next-generation of global precipitation measurements. The GPM mission consists of the Core Spacecraft, a NASA-provided Constellation

Spacecraft and multiple U.S. and international partner precipitation satellites in order to provide global rain rate estimates with footprint resolutions from 5 to 50 km and temporal resolutions of 2–4 h. GPM's Core Spacecraft will have measurement capabilities beyond that of TRMM by carrying a dual-frequency (Ku and Ka) radar and a wide-band (10–183 GHz) radiometer with extra calibration hardware to serve as a reference standard for cross-calibrating rainfall estimates from a constellation of passive microwave imagers and sounders. This GPM Core Spacecraft sensor package is designed to observe precipitating cloud microphysical structure with greater accuracy than ever possible, leading to improved retrieval algorithms and a better understanding of precipitation processes through estimations of not only moderate and high rain rates, but also light rain and falling snow over both land and oceans.

Operations, data processing and ground validation are built into the GPM mission framework. Ground validation ensures that the satellite estimates are statistically accurate, that precipitation process knowledge is gained at the macroscopic and microphysical scales and that integrated application goals, especially in terms of hydrology, are addressed and validated as part of GPM. The data processing system is designed to process the Core and constellation data streams to produce real-time estimates, research products and outreach information. Much effort is spent and will continue to be spent, on algorithm development. The algorithm heritage from TRMM will lead the initial directions for the radar-only, radiometer-only and combined radar-radiometer retrieval methodologies. With the additional channels on the DPR and GMI, algorithm performance is expected to improve such that rain rate estimates from ~0.2 to 110 mm/h will be available from the Core Spacecraft. Further, information gained from the Core Spacecraft algorithm development will greatly enhance retrievals from the constellation members.

GPM precipitation estimates will be available globally and this availability is perhaps most important to the developing nations where freshwater resources are critical. In 2002, GPM was identified by the United Nations as an outstanding example of peaceful uses of space. The GPM concept is currently serving as the scientific basis for the formulation of an international Precipitation Constellation by the Committee on Earth Observation Satellites (CEOS) under the auspices of the Global Earth Observing System of Systems (GEOSS). GEOSS is an inter-governmental effort to provide coordinated, comprehensive and long-term observations of the Earth. During its mission phase, the GPM

Mission will be a mature realization of the CEOS Precipitation Constellation for the benefits of many nations.

The anticipated societal benefits of GPM are manifest in the integrated science plans of the mission. Given the central importance of precipitation in the global water and energy cycle, GPM measurements will make significant contributions to the understanding of the detailed microphysics and the space-time variability of precipitation. The precipitation estimates and knowledge gained from GPM will also be useful for weather forecasting through four-dimensional data assimilation and climate forecasting through better estimates of soil moisture and freshwater fluxes into the oceans. GPM's integrated application goals will support improvements in climate prediction at seasonal to inter-annual scales. This is possible, in part, because variations in precipitation patterns are traceable to cycles in global atmospheric dynamics such as the El Niño/Southern Oscillation and the Madden Julian Oscillation. A majority of these patterns are driven by oceanic processes affecting atmospheric and precipitation processes that will be measured at temporal resolutions of 2–4 h over the oceans by GPM constellation satellites. Further, GPM's observations continue the multi-decadal history of satellite precipitation estimates. While these are a few of GPM's integrated application goals, stakeholders such as those in public health, agriculture and urban planning will find GPM's global high resolution, accurate precipitation data useful for their decision support systems and operational requirements. GPM represents a truly significant milestone in international partnership in providing state-of-the-art global precipitation estimates for both scientific research and societal applications.

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