NASA Contributions to Precipitation Remote Sensing

National Aeronautics and Space Administration (NASA)

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1.0 Introduction

Precipitation has been identified as one of the key geophysical parameters required by most of the GEO societal benefit areas. NASA has a long and continuous history of supporting precipitation research through satellite missions, ground validation efforts and improvement of both instrument calibration and precipitation retrieval algorithms. All of these activities facilitate and enhance the use of precipitation data by precipitation researchers, climate researchers and near-realtime application users.

Precipitation focused activities at NASA are numerous and have a wide breadth. It would be impossible to cover them all in a study of this type. However, this study will present three satellite missions in which precipitation is a main focus. It summarizes the current highly-successful Tropical Rainfall Measuring Mission (TRMM). It then goes on to describe two future missions: NPOESS Preparatory mission and the Global Precipitation Measurement (GPM) mission.

The paper includes an author list but it must be pointed out the information was collected from documents and websites in which a much broader group of authors was involved. It is important to point out that while text blocks are not directly quoted in this document much of the text is a direct copy of website information and paper presentation. This document seeks only to synthesize the information and tie it into a consistent presentation.

2.0 Tropical Rainfall Measuring Mission (TRMM)

TRMM was launched in November 1997 on a 3 year mission with an additional 2 years of expendables on-board. Currently TRMM is in the 14th year of this 3 year mission. NASA has once again approved the continuation of TRMM for another two years. Current solar activity analysis indicates that fuel on TRMM will reach into 2014 and perhaps beyond.

In early 2001 (three years into the mission), TRMM scientists faced an early end of the mission in 2002 or 2003 due to lack of fuel. After careful analysis of the benefits and drawbacks, the TRMM science teams (U.S. and Japan) proposed increasing the orbit altitude by about 50 km in order to decrease atmospheric drag and extend mission life. After extensive review, NASA and JAXA agreed to the mission extension plan and ordered the boost to the higher altitude. *The boost to 402.5 km (+/- 1.0 km) was carried out in August 2001* and TRMM has operated at that altitude since that date. The exact altitude chosen (402.5 km) is related to the pulse repetition frequency (PRF) of the PR. TRMM has now operated at the higher 400-km altitude for a longer period (~ 9.5 years) than at the earlier, lower 350-km altitude (~ 3.7 years).

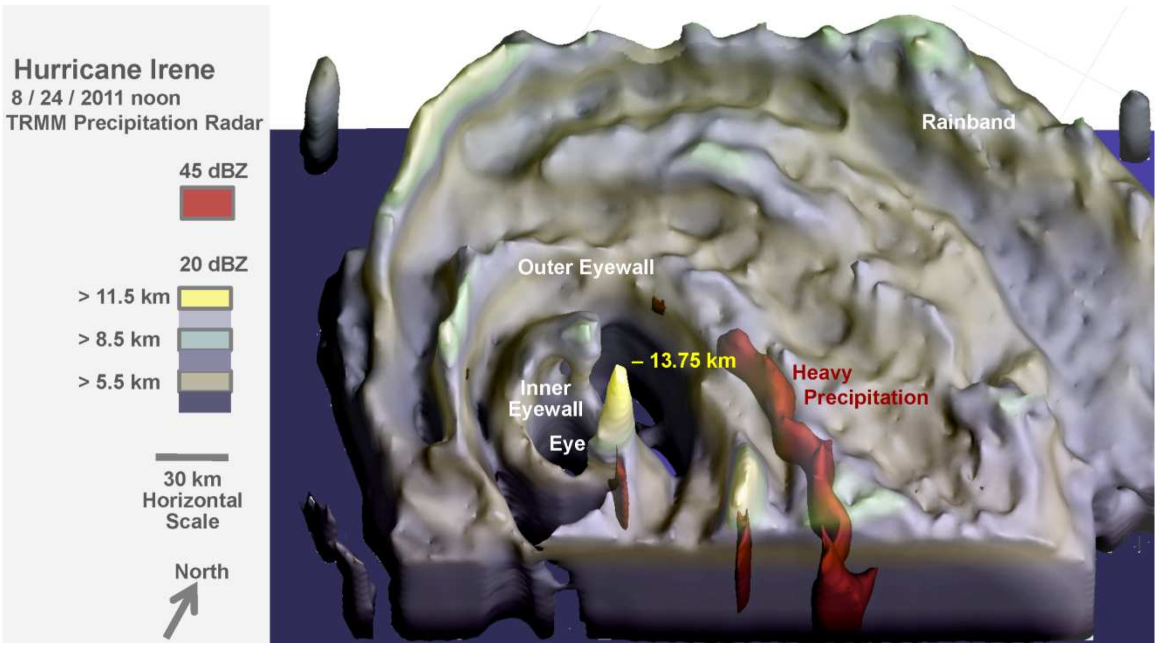
The Tropical Rainfall Measuring Mission (TRMM), launched in late 1997, is a joint mission between NASA and JAXA, the Japanese space agency. The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35°) have made TRMM the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics. TRMM has met and exceeded its original goal of advancing our understanding of the distribution of tropical rainfall and its relation to the global water and energy cycles. TRMM has evolved from an experimental mission focusing on tropical rainfall climatology into the primary satellite in a system of research and operational satellites used for analyzing precipitation characteristics on time scales from 3-hr to inter-annually and beyond. Continuation of TRMM data will allow the community to better link the TRMM data set to that of the Global Precipitation Measurement (GPM) mission to be launched in 2013.

The overall science objective of the extended TRMM mission is to determine the time and space varying characteristics of tropical rainfall, convective systems, and storms and how these characteristics are related to variations in the global water and energy cycles. This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions for both the Water and Energy Cycle and Weather focus areas, i.e., "How are global precipitation, evaporation and the water cycle changing?" and "How can weather forecast duration and reliability be improved? Having a long, accurate record of quasi-global precipitation characteristics is critical to achieving NASA Earth Science goals.

Significant scientific accomplishments have already come from TRMM data, including reducing the uncertainty of mean tropical oceanic rainfall; a documentation of regional, diurnal, and inter-annual variations in precipitation characteristics; the first estimated profiles of latent heating from satellite data; improved climate simulations; increased knowledge of characteristics of convective systems and tropical cyclones; and new insight into the impact of humans on rainfall distributions. The availability of real-time TRMM data has led to significant applications and fulfillment of national operational objectives through use of TRMM data, primarily in the monitoring of tropical cyclones, in hydrological applications and in assimilation of precipitation information into forecast models.

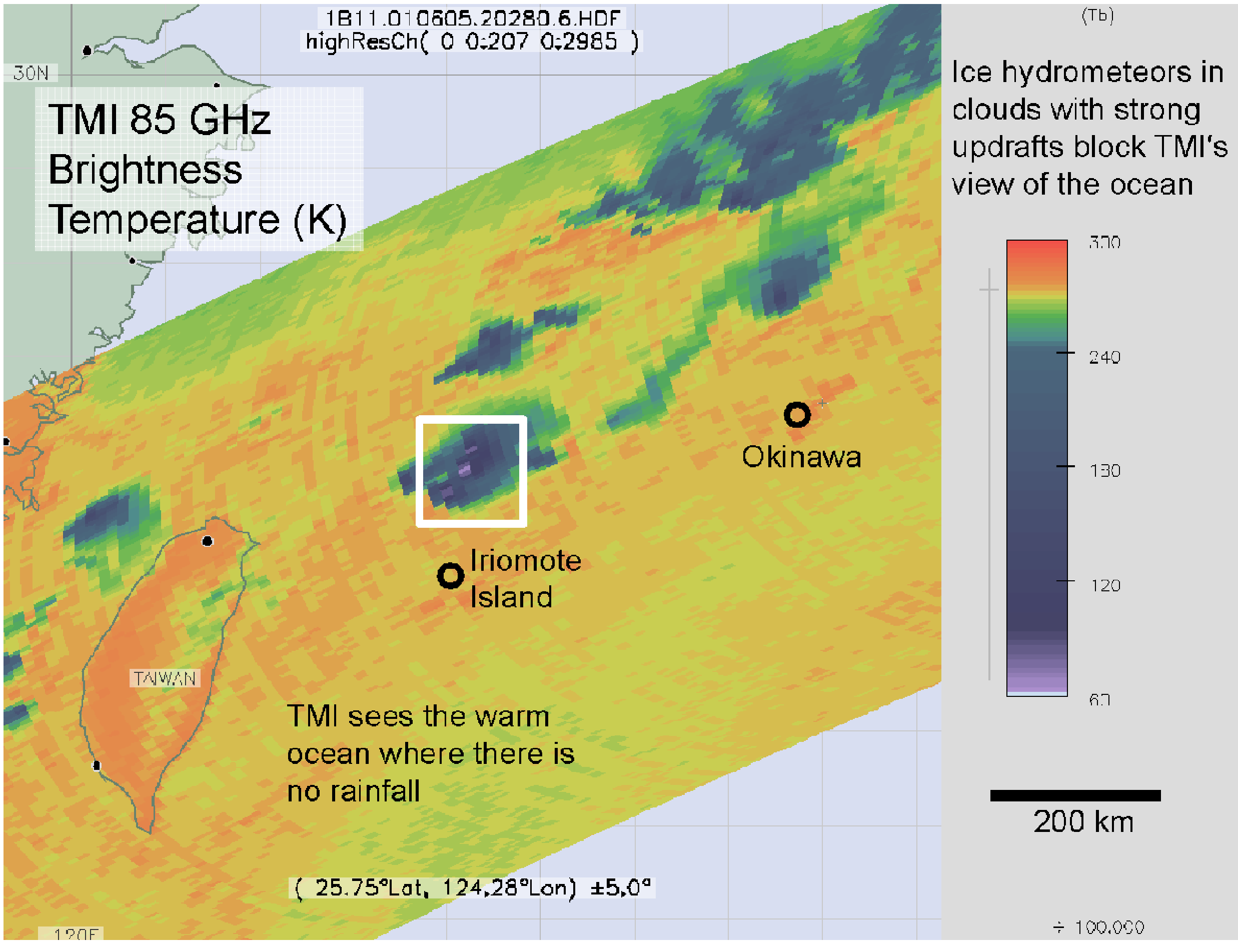
The primary TRMM instruments are the *Precipitation Radar (PR)*, the first and only rain radar in space, and the *TRMM Microwave Imager (TMI)*, a multi-channel passive microwave radiometer, which complements the PR by providing total hydrometeor (liquid and ice) content within precipitating systems. The *Visible Infrared Scanner (VIRS)* is used to provide the cloud context of the precipitation structures and is used as part of a transfer strategy to connect microwave precipitation information to infrared-based precipitation estimates from geosynchronous satellites. These three instruments form the original TRMM rain package and are used singly and jointly to understand precipitation processes, structure and climatology. In addition, the *Lightning Imaging Sensor (LIS)*, an Earth Observing System (EOS)-funded instrument, has complemented the rain sensors, improved understanding of convective dynamics, and provided a climatology of global lightning flash rates.

The PR has provided a unique opportunity to look into the vertical structure of tropical storm systems. The following graphic of the internal structure of hurricane Irene demonstrates the usefulness of this instrument.

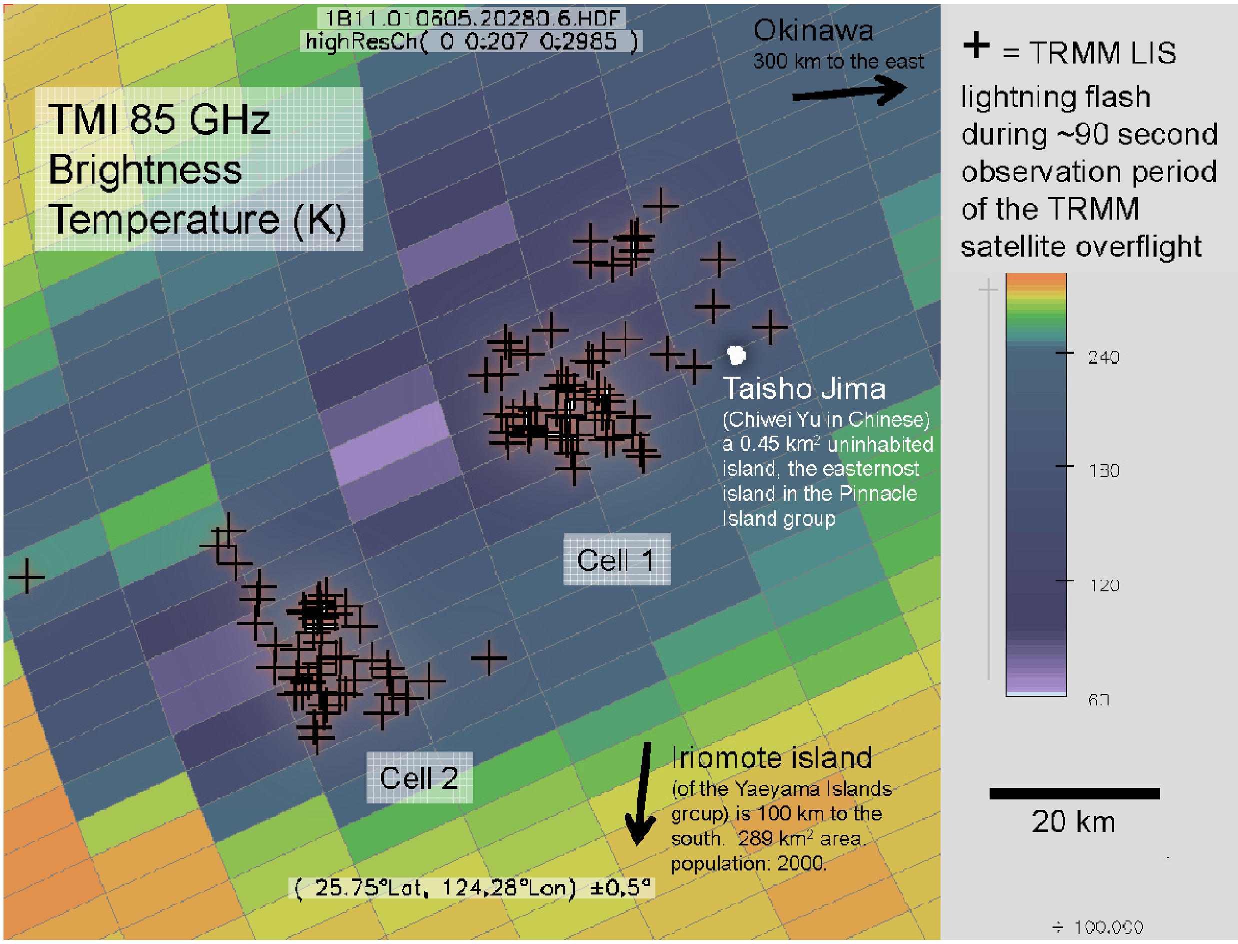


The PR shows the very tight structure of the inner eyewall and also the development of the outer eyewall. The shading shows the height of the storm system with the highest tower at 13.75 km. The large volume is an isosurface containing all locations where radar reflectivity exceeds 20 dBz, indicating lighter rainfall. The heavy area is contained in the red volume for which radar reflectivity exceeds 45 dBz. Before TRMM such data was unavailable via satellite remote sensing over large areas of the ocean.

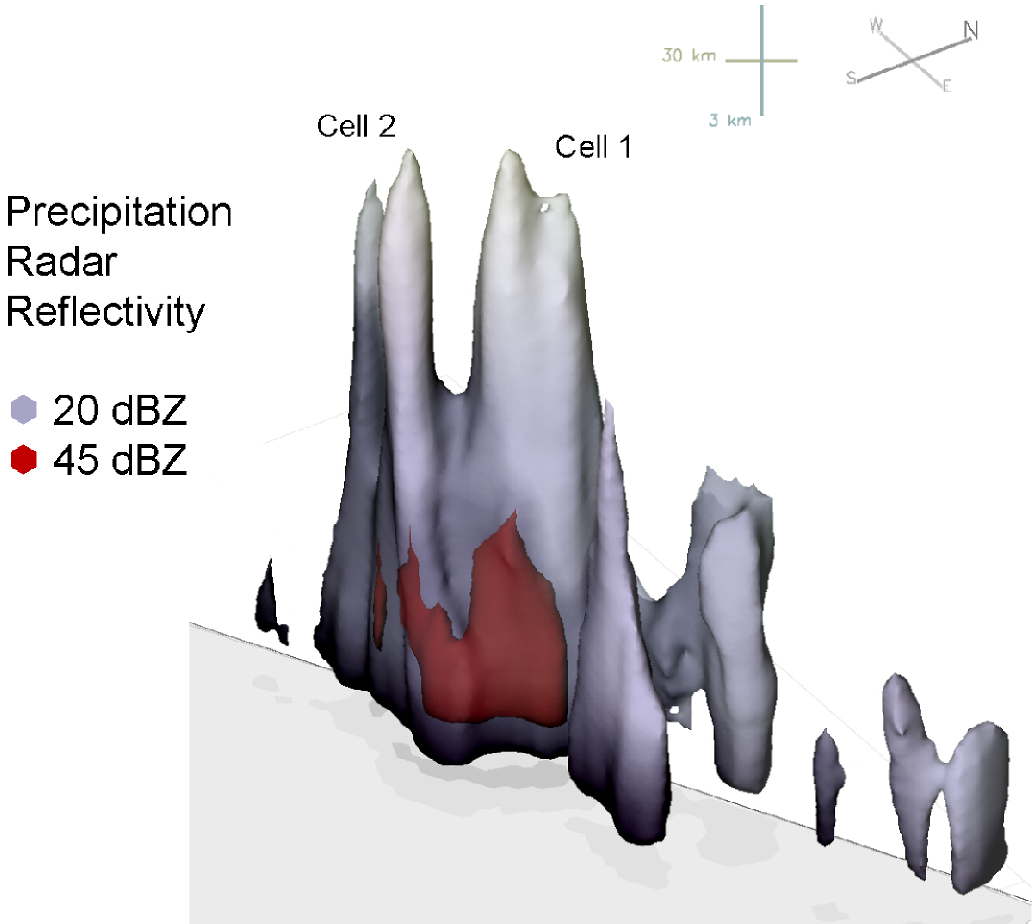
The following three sequences of images show the advantage of TRMM instrumentation as a package with each instrument adding additional information. The graphic shows insolated intense convective cells near Iriomoteisland off Okinawa Japan. The first image is the 85GHz scattering channel Tb from TMI that shows two very cold cells.



The next graphic zooms to the cell area and uses the data from TRMM Lightning Imaging System (LIS) superimposed on the TMI Tb. Noteworthy is the large number of lightning flashes ~90 per minute. It is unusual over the ocean to have more than 5 lightning flashes per minute. This demonstrates that the cells contain very strong updrafts and possibly hail. Such a system is clearly hazardous to ship and air traffic. It also demonstrates the potential usefulness of the TRMM instrument suite for disaster warning and monitoring.



The last image is from the PR and shows the vertical structure of the two cells clearly seen in the image above. The PR images show an 20 dBzisosurface showing light precipitation and a core of 45 dBz collocated with the LIS lightening flashes. The TRMM instrument suite demonstrates the synergism of the different sensor looks at the same scene. A major contribution of NASA's TRMM.



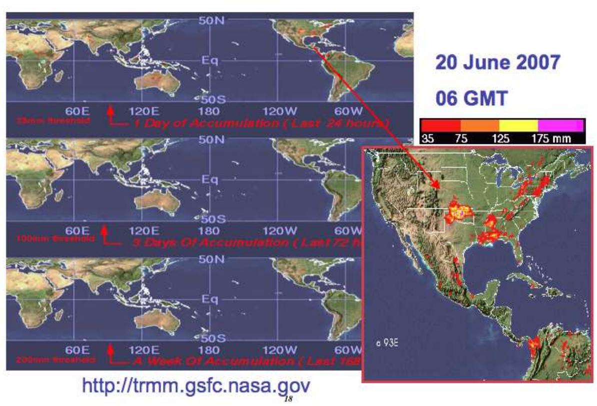
Because of the TRMM orbit, it has enabled the heretofore-difficult quantification of the diurnal cycle of precipitation and convective intensity over global tropics (land and ocean) on fine scales (0.25°). In addition to studies characterizing the diurnal cycle on global scales, the continued accumulation of data has allowed for more studies of the diurnal cycle at regional scales including southeastern China, Indochina peninsula, India and western equatorial Africa. Studies have also focused on local scales in central India, the southern Himalayan foothills, and the central Tibetan Plateau during summer monsoon periods, and east of the eastern Tibetan Plateau during the Mei-Yu season, where the interaction of large-scale circulation and local topography plays a key role. As pointed out in the next section, NASA also initiated a major effort in tropics in conjunction with LBA focused on TRMM data (TRMM-LBA)

TRMM data have also providedthe first comprehensive estimates of how rainfall is directly related to latent heat release in the atmosphere**,** a key characteristic in understanding the impact of tropical rainfall on the general circulation of the atmosphere. Based on hydrometeor vertical structure information from PR, TMI, and model-based cloud information, TRMM scientists have derived climatologies of latent heating profiles for analysis and comparison with global models. Recently, with the help of improved partitioning and definition of convective/stratiform rainfall in PR data, improved

Convective–Stratiform Heating (CSH) algorithm-derived heating profiles were developed for the global tropics. In addition, the analysis of 13 years of TRMM data provides a baseline climatology of the vertical structure of atmospheric radiative heating in today's climate and an estimate of the magnitude of its response to environmental forcings on weekly to interannual time scales.

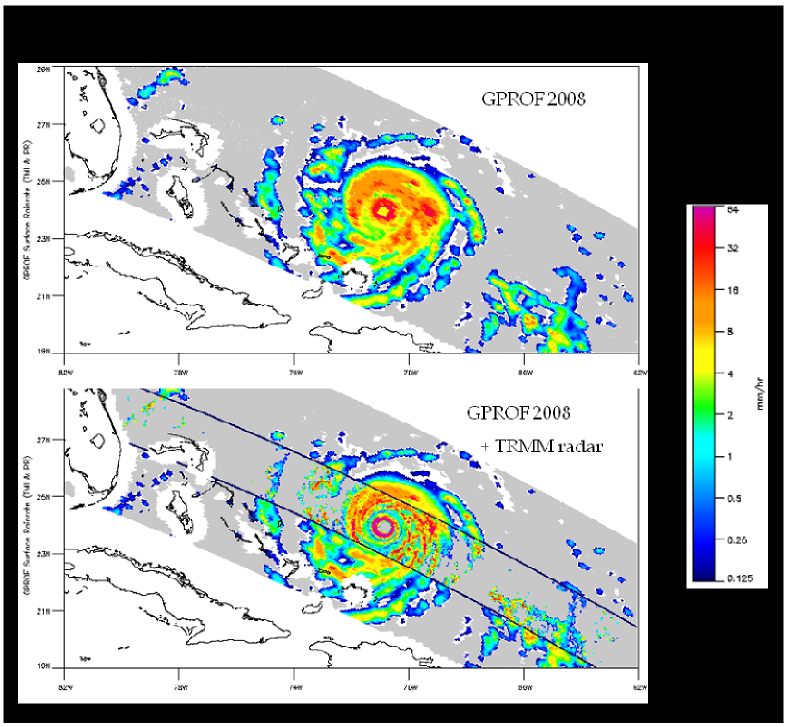
With the TRMM satellite producing the best instantaneous rain estimates, those estimates have been used to calibrate or adjust rain estimatesfrom other satellites to provide analyses at higher time resolution than available from one satellite . The TRMM multi-satellite precipitation analysis (TMPA) provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25° × 0.25° and 3 hourly)**.** The TRMM multi-satellite rainfall products are now being used for a variety of important studies, including validation of meteorological reanalyses, hydrologic modeling, analysis of oceanic precipitation systems, characterization of monsoon convection (Xu et al. 2009), closure of water budgets, as well as for other hydrometeorological applications.

TMPA is also produced in near-realtime approximately 6 hours after data collection. This product merges radiometer imager and sounder retrievals. It fills in gaps with 4km 1 hour IR products statistically calibrated by the microwave imager data. This product is used in applications listed above but is also integral to prototype flood monitoring and is available in a TIFF/WF format that can readily be included in GIS systems as is done by the Pacific Disaster Monitoring Center on the island of Maui, Hawaii. Because of time availability and almost global coverage this has become the one of the most used product in the TRMM product list.



Example of the real-time heavy rain/flood potential product available from the TRMM web page, http://trmm.gsfc.nasa.gov.The 1-, 3-, and 7-day accumulations are obtained from the real-time TMPA product. Flood potential is assessed based upon the duration and amount of rainfall.

In 2011, TRMM completed a reprocessing of all its data products (version 7) using new and improved algorithms. One of the exciting changes is in the GPROF (Goddard Profiling) retrievals which replaced a cloud resolving model based a-priori profile database with an a-priori database built from two years of PR data (pre-boost). The figure below shows, with the exception of resolution, thatin v7 TMI and PR present a very consistent in their surface precipitation measurements, at least over oceans.



- Use TRMM PR as "truth"
- Database is built from PR rain and observed TMI Tb
- Bayesian scheme used to retrieve rainfall (TMI only). Database sorted by SST and TPW

Ground Validation

As part of the original 3 years of the mission NASA funded field experiments as part of TRMM. These experiments focused on the microphysics of weather systems. Their aim was to provided information that would improve the TRMM retrieval algorithms as well as provide comparative data points. This combination of ground validation and space mission is part of the synergistic approach to NASA mission planning. Four important field experiments were funded: TEFLUN-A/B, TRMM-LBA, KWAJEX. All contributed to continuous improvement of TRMM retrieval algorithms as well as increasing our understanding of weather in the tropics.

In a synergistic and holistic research approach, field experiments not directly connected with the TRMM mission have gained the advantages of using TRMM data as part of their activities. While TRMM has been used in many such field experiments, this paper will summarize only a recent use for the purposes of illustration.

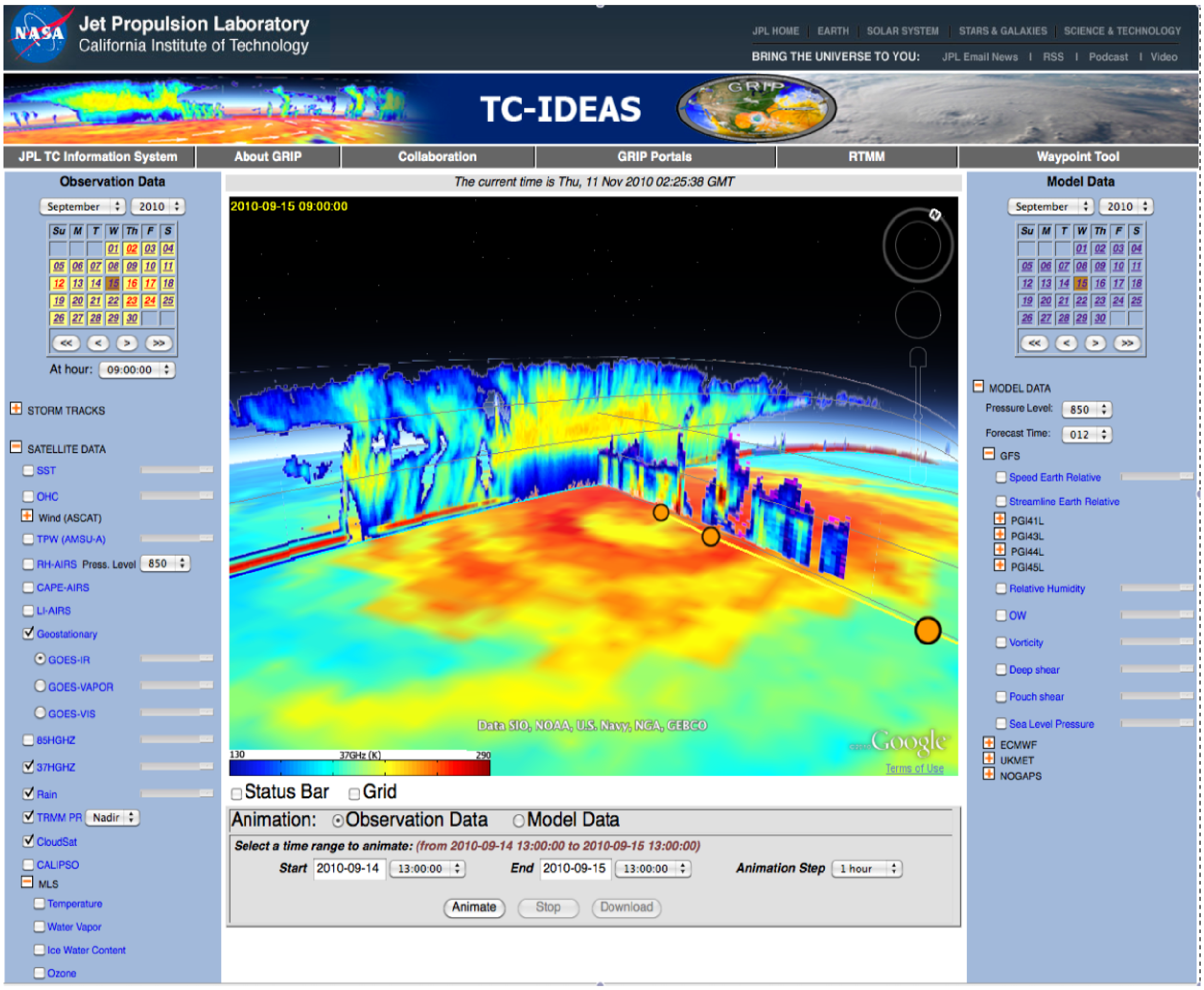
The Genesis and Rapid Intensification Processes (GRIP) experiment was a NASA Earth science field experiment in 2010 that was conducted to better understand how tropical storms form and develop into major hurricanes. NASA used the DC-8 aircraft, the WB-57 aircraft, and the Global Hawk Unmanned Airborne System (UAS) configured with a suite of in situ and remote sensing instruments used to observe and characterize the lifecycle of hurricanes.

The GRIP deployment was 15 August – 30 September 2010 with bases in Ft. Lauderdale, FL for the DC-8, at Houston, TX for the WB-57, and at NASA Dryden Flight Research Facility, CA for the Global Hawk. This campaign capitalized on a number of ground networks, airborne science platforms (both manned and unmanned), and space-based assets. The field campaign was executed according to a prioritized set of scientific objectives. In two separate science solicitations, NASA selected a team of investigators to collect NASA satellite and aircraft field campaign data with the goal of conducting basic research on problems related to the formation and intensification of hurricanes.

The spaceborne and airborne observational capabilities of NASA put it in a unique position to assist the hurricane research community in addressing shortcomings in the current state of the science. The relatively recent launch of several new satellites, the prospect of using a high-altitude UAS for hurricane surveillance, and the emergence of new remote sensing technologies offered new research tools that needed to be explored and validated. Of great importance were new remote sensing instruments for wind and temperature that can lead to improved characterization of storm structure and environment.

Satellite observations can play a very important in airborne field campaigns, since they provide a comprehensive description of the environment that is essential for the experiment design, flight planning and post-experiment scientific data analysis. To facilitate the 2010 NASA Genesis and Rapid Intensification Processes (GRIP) aircraft campaign, NASA's Precipitation Processing System (PPS) provided near-realtime (NRT) access to the full-resolution (250-m vertical) TRMM PR data to support the Jet Propulsion Laboratory (JPL) NRT web portal that provides satellite and model data over the Atlantic basin (http://grip.jpl.nasa.gov). The portal was developed with contributions from other GRIP science team members and the coordinated PREDICT (NSF) and IFEX (NOAA) field experiments.

The NASA JPL GRIP portal integrates model forecasts with satellite observations from a variety of instruments and platforms. The availability of the TRMM-PR data in NRTallowed users to interrogate a large number of atmospheric and ocean parameters to better understand the large-scale and the storm-scale processes associated with hurricane genesis, track and intensity changes. For example, the figure below depicts vertical reflectivity profiles from nearby overpasses of TRMM-PR and NASA's CloudSat radar, depicting Hurricane Igor on 15 September 2010, overlaid on top of 37H GHz imagery from the TRMM Microwave Imager (TMI).In addition to supporting the airborne mission planning, these data serve as a very rich source of information during the post-field campaign analysis stage. A diverse set of satellite observations together with model forecasts provides a good spatial and temporal context for the high-resolution (but limited in space and time) airborne observations.



This use of NASA satellite missions (TRMM and CloudSat) within field experiments demonstrates the integrated, synergistic approach adopted by NASA among its precipitation activities. Such synergism enhances both the potential for improving understanding of precipitation and improving retrieval algorithms for both current and future precipitation focused missions. It should be remembered that GRIP is only a single example and NASA mission data have been used in many national and international field experiments. As part of NASA efforts at continuity and extending good ideas into other missions, the GRIP web interface to field experiment information has been adopted for the GPM field experiments.

Besides field experiments, a key component of the TRMM project is the Ground Validation (GV) effort (http://trmm-fc.gsfc.nasa.gov/trmm_gv). The GV effort is primarily a data collection and product generation program. Ground-based radar, rain gauge and disdrometer data are collected and quality-controlled, and validation products are produced for comparison with TRMM satellite products. Detailed information and product analysis is available on the TRMM GV web site. The four primary GV sites are Darwin, Australia; Houston, Texas; Kwajalein, Republic of the Marshall Islands; and, Melbourne, Florida (Wolff et al 2005). There is also a significant effort being supported at NASA Wallops Flight Facility (WFF) to provide high quality, long-term measurements of rain rates (via a network of rain gauges collocated with National Weather Service gauges), as well as drop size distributions (DSD) using a variety of instruments, including impact-type Joss Waldvogel, laser-optical Parsivel, as well as two-dimensional video disdrometers. DSD measurements are also being collected at Melbourne and Kwajalein using Joss-Waldvogel disdrometers.

The largest part of the validation effort involves the routine, careful collection, processing and product generation of ground-based radar, rain gauge and disdrometer data in order to produce standard validation products. Products are produced using techniques developed to carefully quality control ground radar data sets and estimate surface rainfall rates, adjusted by quality-controlled rain gauge data.

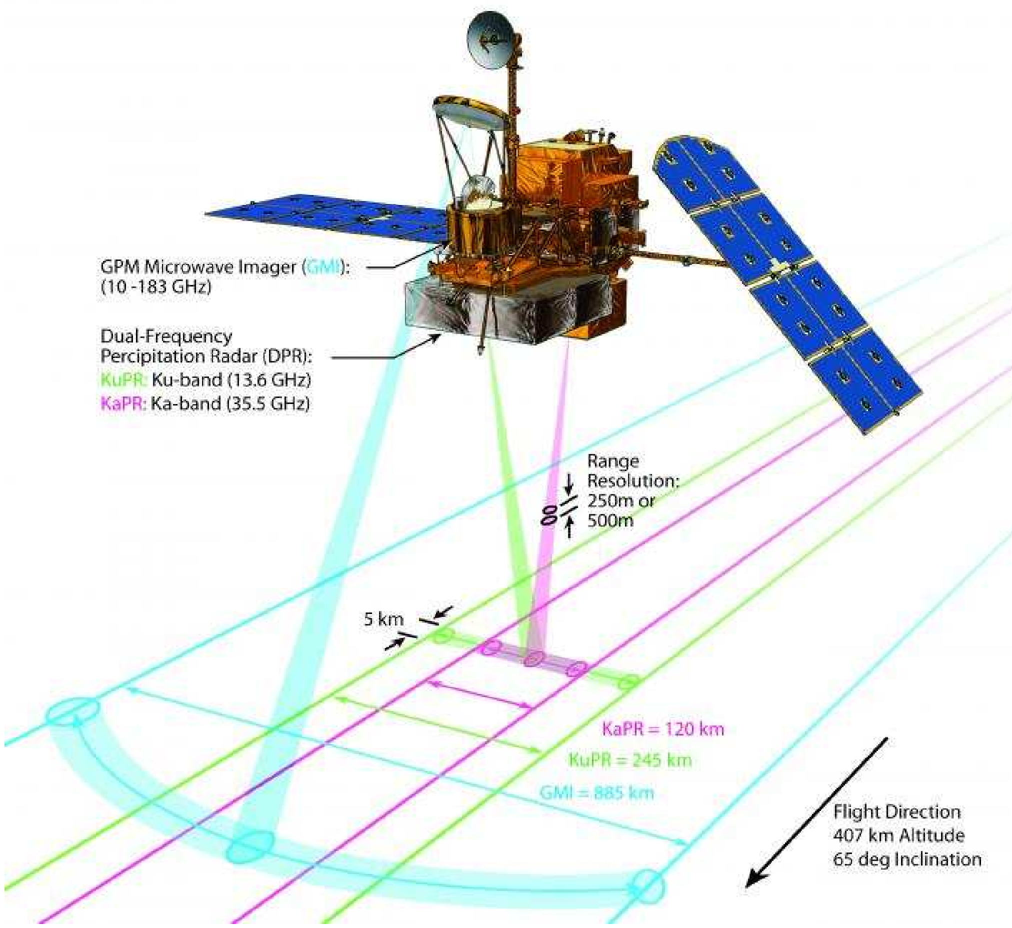
In addition, NASA efforts have also led to improvements in algorithms for ground based retrievals and improvements in ground radar algorithms. The TRMM GV program has made significant accomplishments over the last several years. A methodology to monitor and correct radar reflectivity calibration using ground clutter area reflectivity distributions, referred to as the Relative Calibration Adjustment (RCA) methodology, is now fully operational and has provided near-real-time feedback to Kwajalein radar staff of any possible issues with the Kwajalein radar. This RCA has the ability to detect and correct past changes in radar calibration (±0.5 dB) and antenna elevation pointing errors (±0.1°), but is also prescient in detecting impending failures of the radar system. Application of the RCA to correct the historical data record for Kwajalein has salvaged a vital and irreplaceable climate precipitation record (12+ years) at this key oceanic GV site. Through the use of dual-polarimetric (DP) data from the Kwajalein radar (KPOL), an algorithm has been adapted to determine absolute reflectivity calibration by a self-consistency approach thereby verifying the RCA methodology.

3.0 Global Precipitation Measurement (GPM) mission

As part of its continuous investment in precipitation measurement, NASA has developed a mission that while offering continuity with the TRMM measurement extends and enhances those measurement. In July 2013, NASA/JAXA will launch the Global Precipitation Measurement (GPM) core satellite.

The GPM mission is an international network of satellites that provide the next-generation global observations of rain and snow. Building upon the success of the Tropical TRMM, the GPM concept centers on the deployment of a “Core” satellite carrying an advanced radar / radiometer system to measure precipitation from space and serve as a reference standard to unify precipitation measurements from a constellation of research and operational satellites. Through improved measurements of precipitation globally, the GPM mission will help to advance our understanding of Earth's water and energy cycle, improve forecasting of extreme events that cause natural hazards and disasters, and extend current capabilities in using accurate and timely information of precipitation to directly benefit society. GPM, initiated by NASA and the Japanese Aerospace Exploration Agency (JAXA) as a global successor to TRMM, comprises a consortium of international space agencies, including the Centre National d'ÉtudesSpatiales (CNES), the Indian Space Research Organization (ISRO), the National Oceanic and Atmospheric Administration (NOAA), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and others.

The GPM Core Observatory will carry the first space-borne Ku/Ka-bandDual-frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI). The DPR instrument, which will provide three dimensional measurements of precipitation structure over 78 and 152 mile (125 and 245 km) swaths, consists of a Ka-band precipitation radar (KaPR) operating at 35.5 GHz and a Ku-band precipitation radar (KuPR) operating at 13.6 GHz. Relative to the TRMM precipitation radar, the DPR is more sensitive to light rain rates and snowfall. In addition, simultaneous measurements by the overlapping of Ka/Ku-bands of the DPR can provide new information on particle drop size distributions over moderate precipitation intensities. In addition, by providing new microphysical measurements from the DPR to complement cloud and aerosol observations, GPM is expected to provide further insights into how precipitation processes may be affected by human activities.



The GMI instrument is a conical-scanning multi-channel microwave radiometer covering a swath of 550 miles (885 km) with thirteen channels ranging in frequency from 10 GHz to 183 GHz. The GMI uses a set of frequencies that have been optimized over the past two decades to retrieve heavy, moderate and light precipitation using the polarization difference at each channel as an indicator of the optical thickness and water content.

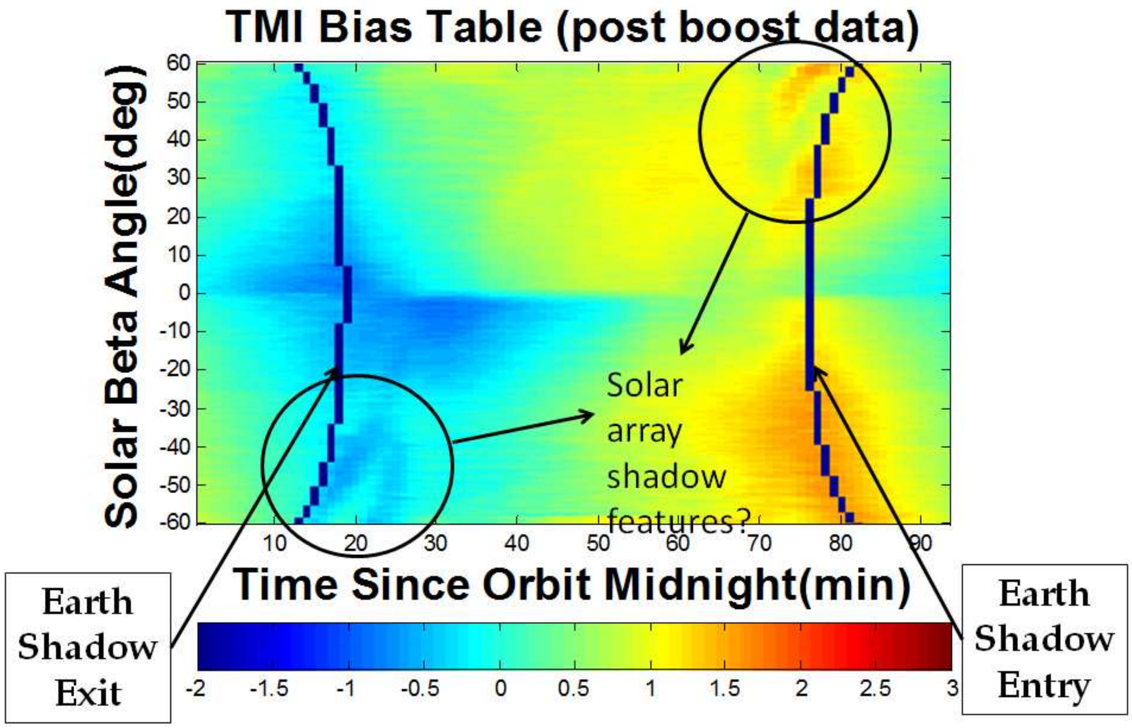
NASA is spending considerable effort and resources in ensuring that the GMI is the best calibrated microwave imager to date. This is very important if it is to fulfill its role in being part of the transfer standard for intercalibration with other microwave radiometers. Special care is being taken in isolating the cold and warm loads as well as providing monitoring of temperatures to ascertain possible environmental heating of components key for instrument calibration. In addition to the warm and cold load, GMI also has noise diodes that can be used to characterize non-linearityand can also be used to quality control the standard calibration approach. Should issues arise in either warm load, the noise diodes can be used along with the cold sky to calibrate the GMI even with issues in the warm load. The noise diodes also provide the possibility to carry out a 4-point calibration scheme for quality control purpose. All the effort and expense is to ensure that the instrument is the best possible and to provide as much information about the environment in which it operates as possible. This goes a long way toward insuring that GMI operation will be well understood and therefore usable at a transfer standard to other microwave imagers and sounders. Additionally, the Precipitation Processing System has been given the requirement to continuously monitor the calibration of GMI to detect as quickly as possible any perturbations that could lead to retrieval or data assimilation issues.

Continuity of science knowledge from TRMM is guaranteed by the funding of a Precipitation Measurement Missions science team that includes investigators using TRMM data and those working on GPM. Often they are the same people. Another characteristic of the PMM is inclusion of non-NASA and international science investigators on the team. This ensures continues interactions among the international precipitation community.

Just as in TRMM, GPM will service not only the research community but provide near-realtime data including merged radiometer products to a diverse range of applications across agencies, research institutions and the global community.

An important aspect of the GPM mission science is the intercalibrationof radiometers at the brightness temperature stage. To carry out this responsibility, the PMM science team has established an intercalibration working group (X-cal) that is developing the process whereby intercalibration of microwave radiometers both imager and sounders can be properly intercalibrated. Part of this effort is the development of tools to support continuously monitoring and analysis of the radiometer collocated matchups to ensure that the nothing has disrupted or impacted the intercalibration adjustments.

The X-cal team has been using TRMM as a surrogate reference standard and comparing T_b among sensors and develop an intercalibration process. As part of this study it was found that TMI has an orbital thermal bias caused by entry and exit of solar eclipse. This seems almost certainly related to TMI having a slightly emissive reflector. The following image graphically shows this issue.



The x-cal team then developed a bias correction table that was used in TRMM v7 to largely reduce the bias in TMI T_b. So, in this case the development of a new mission approach was used to improve T_b in an existing mission. This activity also demonstrated that the X-cal team process was sufficient to detect and correct T_b issues.

The X-cal team is also an observer and contributor to the international Global Space-based Intercalibration System (GSICS)effort. It contributes to the aims of this organization and when effective uses the research undertaken by this group.

Combined DPR+GMI retrievals. While the DPR algorithms represent a major advancement over the TRMM PR by providing not only estimates of the 3D precipitation structure but also estimates of the PSD characteristics, ambiguities still exist as a result of a number of assumptions. These assumptions include the vertical profiles of water vapor and cloud liquid water as well as the 'shape' parameter, μ, of the size distribution and the mass densities of snow aggregates and graupel. The purpose of the combined DPR+GMI retrieval is to use the multi-channel GMI radiances as additional constraints on the DPR profiling algorithm over the radar swath. Specifically, some of the above-mentioned assumptions can be constrained by usingvariational procedures that minimize departures between simulated and observed brightness temperatures, or by using filtering approaches which determine an ensemble of radar solutions that are consistent with the brightness temperatures and their uncertainties. Thus, the resulting combined precipitation retrievals are consistent with both DPR reflectivity profiles and multi-channel GMI radiances within the framework of maximum-likelihood estimation. The combined retrieval methodology will be based on approaches developed and tested within the TRMM mission. Several improvements, such as the incorporation of a more complex radar-only retrieval algorithm, the optimization over an extended set of assumptions, and the inclusion of uncertainty estimates in the final products are planned. The combined DPR+GMI retrievals, which are expected to provide the highest quality precipitation estimates, will be used to construct an *a priori* database that relates hydrometeor profiles to microwave radiances over the range of observed brightness temperatures. The advantage of databases constructed directly from combined observations over cloud-model derived databases has been already demonstrated and an early version over oceans only is part of TRMM V7. This database will be applicable not only to the Core GMI retrieval but also to constellation radiometer retrievals.

Ground Validation

The GPM Ground Validation (GV) Program is designed to support pre-launch algorithm development and post-launch product evaluation. The traditional approach to ground validation is to use ground-based observations to directly assess the quality of satellite products. Among the lessons learned from TRMM GV is that while such comparisons are useful and necessary, ground measurements have their own set of uncertainties that must be carefully monitored and quality-controlled. More importantly, in order to improve physically-based satellite retrieval algorithms, ground observations must go beyond the collection of surface precipitation data to provide ancillary information within a precipitating column to identify sources of errors in retrieval algorithms and their associated assumptions under a variety of environmental conditions. Ground validation should also use hydrological measurements (e.g. streamflow data, snowpack depths, etc.) and water budget analyses as time/area-integrated constraints to quantitatively assess multi-satellite precipitation products and “downscaled” high resolution precipitation analyses using models. Hence, GPM is collaborating with domestic and international partners to leverage fixed-site measurements existing within operational national networks and to conduct a series of pre- and post-launch field campaigns. Collectively these activities comprise the core set of GPM GV approaches:

• *Direct statistical validation* via use of national networks: Contributions of calibrated ground observations from operational and research instruments, regional and continental scale precipitation and hydrological products with associated error models, the development of downscaling models, and other related activities on largeregional or continental scales;

• *Physical validation* via process studies and field campaigns: Contributions of targeted ground and aircraft measurements of cloud microphysical properties, precipitation, multi-frequency radar reflectivity, and radiances; modeling activities related to atmospheric simulation and retrieval algorithm testing; other relevant observations on local to regional scales

• *Integrated validation* via assessment of hydrometeorological application: Contributions related to assessment of satellite precipitation products at integrated hydrological sites using stream gauges and other hydrological measurements, formulation and application of downscaling methodologies, and analysis of the utility of satellite precipitation products for basin-scale water budget studies.

Within the framework of the above three approaches, five interdependent satellite, algorithm, modeling, and validation activities are targeted in order to quantify and understand measurement and algorithm uncertainties, propagation of those uncertainties through the product development chain, and ultimately the impact on applications (i.e., end-to-end validation). These five activities are: (1) core satellite error characterization focused on validation of DPR reflectivity, attenuation correction, drop size distribution, and rain rate retrievals; (2) constellation satellite validation focused on detailed statistical comparisons of retrieved rainfall rates; (3) assessment of radar/radiometer retrieval algorithm uncertainties;(4) CRM validation- both activities supported through detailed measurements of cloud and precipitation properties as applied to the retrieval algorithm(s) physical framework; and (5) coupled atmosphere/land surface model validation set in the end-to-end framework of hydrometeorological analysis, water budget, and forecast system application.

The reference architecture for GV physical process studies is based on a seriesof Intensive Observation Periods (IOPs) bracketed by Extended Observation Periods (EOPS). EOPs are best interpreted as scaled-down field campaignsoperating for an extended period- e.g., 6-12 months. EOPs leverage *existing*operational network and/or research instrumentation and datasets (e.g., radar, gauge). Select GV instrumentation is added to expand sampling duration.

IOPs are relatively short duration (4-6 week), *targeted field campaigns* conducted with a dense complement of ground and airborne instrumentation that may or may not occur in conjunction with an EOP. Notwithstanding the shorter operations timeframe and dense ground instrumentation, the most distinguishing characteristic of an IOP is the inclusion of coordinated aircraft sampling (high-altitude radar/radiometer + in-situ microphysics aircraft).

Contributing to achieving these objectives has been a number of field experiments designed to address retrieval challenges, assumptions, and issues.

A total of five NASA-led and several international GV field campaigns are planned (Table 1; periodicity of ~12-24 months, C3VP already completed).

Table 1. GPM field campaign schedule

Objective	**Date/Location**
Snowfall retrievals [Completed]	C3VP, winter 2006-7, Ontario Canada. Joint with Canada, CloudSat
Detection and retrieval of Warm-rain over land Deep convection over land	Pre-CHUVA, Mar. 2010, Alcantara, and other regions of Brazil; Joint with Brazil.
Retrievals of high	LPVeX, Sept.-Oct.

latitude light precipitation	2010, Finland/Baltic; Joint with FMI, CloudSat
Physical basis for GMI DPR rain retrievals over land surfaces	MC3E; Apr-June 2011, DOE ARM Central Facility, OK
Snowfall retrievals	GCPEX, Jan-Feb. 2012. Ontario Canada (Joint with EC)
Hydrologic/Physical validation in complex terrain.	2013,CoPRHEX, HMT Southeast, North Carolina; joint with NOAA
Cold season validation	2015, TBD
Hydrologic validation	2016, TBD

4.0 NPOESS Preparatory Project (NPP)

Over the last decade NASA launched a series of satellites that offer an unparalleled view of Earth from space. That series, known collectively as NASA's Earth Observing System (EOS), has provided striking new insights into many aspects of Earth, including its clouds, oceans, vegetation, ice, and atmosphere. However, as the EOS satellites age, a new generation of Earth-observing satellites are poised to take over.

The NPOESS Preparatory Project (NPP) represents a critical first step in building this next-generation satellite system. Goddard Space Flight Center is leading NASA's effort to launch a satellite that will carry the first of the new sensors developed for this next-generation system, previously called the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and now the Joint Polar Satellite System (JPSS).

NPP will orbit the Earth about 14 times each day and observe nearly the entire surface. The NPP satellite continues key data records that are critical for climate change science. This mission is another example of NASA’s commitment to provide continuity of measurement between missions to service both the research and the applications community.

NPP will carry a diverse payload of scientific instruments to monitor the planet. The 4,600-pound (2,100 kilogram) spacecraft, which is about the size of a small school bus, will cross the equator each afternoon at about 1:30 p.m. local time. It will carry five key instruments: the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder (CrIS), the Ozone Mapping and Profiler Suite (OMPS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and Clouds and the Earth's Radiant Energy System (CERES).

Scientists will use ATMS, a 22-channel passive microwave radiometer, to create global models of temperature and moisture profiles that meteorologists will enter into weather forecasting models. CrIS, a Michelson interferometer, will monitor characteristics of the atmosphere, such as moisture and pressure that will be used to produce improvements in both short-and-long term weather forecasting. OMPS, a suite of hyperspectral-imaging spectrometers, will measure Earth's ozone levels, particularly near the poles where ozone levels fluctuate the most. VIIRS, a 22-band radiometer similar to the MODIS instrument, will collect visible and infrared views of Earth's dynamic surface processes, such as wildfires, land changes, and ice movement. VIIRS will also measure atmospheric and oceanic properties, including clouds and sea surface temperature. Finally, CERES, a 3-channel radiometer measuring reflected solar radiation, emitted terrestrial radiation, and total radiation, will monitor the natural and anthropogenic effects on the Earth's total thermal radiation budget.

ATMS is the instrument on this mission most closely focused on precipitation measurement and precipitation is one of the key products of the instrument. However VIIRS, just as MODIS, will add its own contributions to precipitation study. This packaging of the two instruments is very synergistic and portends not only great continuity of existing measurement but enhancement and extension of the measurements.

As part of the NASA continuity emphasis, ATMS is a partner sensor of the GPM mission and will be one of the sensors that will be intercalibrated by GPM to ensure consistent mission datasets. So, while ATMS is part of its own mission and an early version of JPSS, it also is essential to the precipitation measurement in GPM.

5.0 Conclusion

This paper has presented some examples of NASA's commitment to precipitation as a key measurement. It has described 3 major space missions centered on precipitation and shown how they are interrelated. They provide a synergistic use of resources. Most importantly NASA has approached these missions at the request of the user community, both research and applications. It has coordinated hardware aspects, science advances, and established ground validation approaches that validate and augment the space assets. NASA has extended the improvement in calibration techniques from one precipitation mission into the next.

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