

CLOUD AND PRECIPITATION OBSERVATION BY SPACEBORNE RADAR IN JAPAN: CURRENT AND FUTURE MISSIONS

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ABSTRACT:

The Tropical Rainfall Measuring Mission (TRMM) is a Japan-US joint satellite mission which equips the world first spaceborne precipitation radar (PR) as well as microwave imager (TMI) and has been producing very valuable precipitation data more than twelve years. This long term precipitation record including vertical profile information from the TRMM PR made it possible to provide not only the precise global precipitation amount but also improve the understanding tropical cyclones such as typhoons and hurricanes and diurnal cycles of rainfall. It is worth to note that the precipitation climatology developed from the PR data has been used to evaluate Global Climate Models for the prediction of the climate change and the global cloud resolving model such as NICAM. The follow-on mission of the TRMM which is called the Global Precipitation Measurement (GPM) mission is planned to be launched in 2013. The GPM mission consists of the Core satellite which equips dual frequency (14 GHz and 35 GHz, the former is same frequency as the TRMM/PR) radar to improve the estimation accuracy of rainfall and to observe the light rain and snowfall and constellation satellites which equip microwave radiometer to gain the sampling of precipitation.

Satellite cloud remote sensing started with optical sensors to estimate cloud characteristics such as the effective radius. In 2006, NASA's CloudSat satellite was launched to observe the cloud using 95-GHz cloud radar. CloudSat has been providing the vertical structure of clouds and even light rain and enables us to see the cloud and precipitation properties at the same time. In Japan, spaceborne cloud radar similar to the CloudSat but upgraded in terms of sensitivity, long life time and the additional Doppler capability is being developed for EarthCARE mission which is a JAPAN-ESA joint program aiming to reveal the aerosol-cloud processes, to realize more precise Earth radiation budget estimation using cloud radar and lidar (laser radar), and to improve future predictions of the global warming.

1. INTRODUCTION

Water is an essential element of the Earth's environment and is indispensable for our life and economic activities. Many places in the world now face water problems, such as water shortages and floods, and global warming and climate change can affect the global water cycle. At the same time, cloud is a key parameter for predictions of the global warming, and exerts a principal influence on the planetary energy balance. Satellite observation helps to measure global cloud and precipitation homogeneously and quantitatively. There active radars which can obtain detailed vertical profile of rain and/or cloud information are powerful tools for satellite Earth Observation. This paper introduces current and future Japanese satellite missions to observe cloud and precipitation by spaceborne radars.

2. TRMM/PR

The TRMM satellite is an Earth-observation satellite that measures the tropical rainfall distribution (Simpson et al., 1988, 1996). The TRMM was proposed as a joint project between the US, National Aeronautics and Space Administration (NASA), and Japan, National Space Development Agency of Japan (currently, Japan Aerospace and Exploration Agency, JAXA)

and Communications Research Laboratory (currently, National Institute of Information and Communications Technology, NICT). Japan developed the world's first spaceborne precipitation radar. The TRMM satellite was launched in November 1997, and still continues its observation more than 12 years beyond the designed lifetime of three years. The TRMM satellite flies in a non-sun-synchronous orbit to measure rainfall with large daily variation quantitatively. The inclination angle of the orbit is 35 degrees, and the satellite orbits the Earth every 90 minutes, 16 times per day, and observes rainfalls between 35 degrees latitude north and 35 degrees south. The satellite altitude was boosted in August 2001 from 350 km to 402.5 km, in order to extend the lifetime by reducing atmospheric drag.

The TRMM satellite has five sensors on board, the Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible Infrared Scanner (VIRS), Clouds and Earth's Radiant Energy System (CERES), and Lighting Imaging Sensor (LIS) (Kummerow et al. 1998). The three-dimensional structure of precipitation over the land and ocean can be derived by PR (Kozu et al. 2001). The PR is a 128-element active phased array that allows a cross-track scanning over a swath width of 215 km with a cross-range spatial resolution of about 4.3 km. After the altitude change in August 2001, the swath width is 245 km. and the spatial resolution is about 5.0 km. The operating frequency of the PR is

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13.8 GHz. The PR has a minimum detectable rain rate of 0.5 mm/h with range resolution of 250 m. The instrument anomaly of the PR happened on 29th May 2009, and the PR was restarted using redundant components in mid-June 2009. A history of the PR system design was summarized in Okamoto et al. (2003).

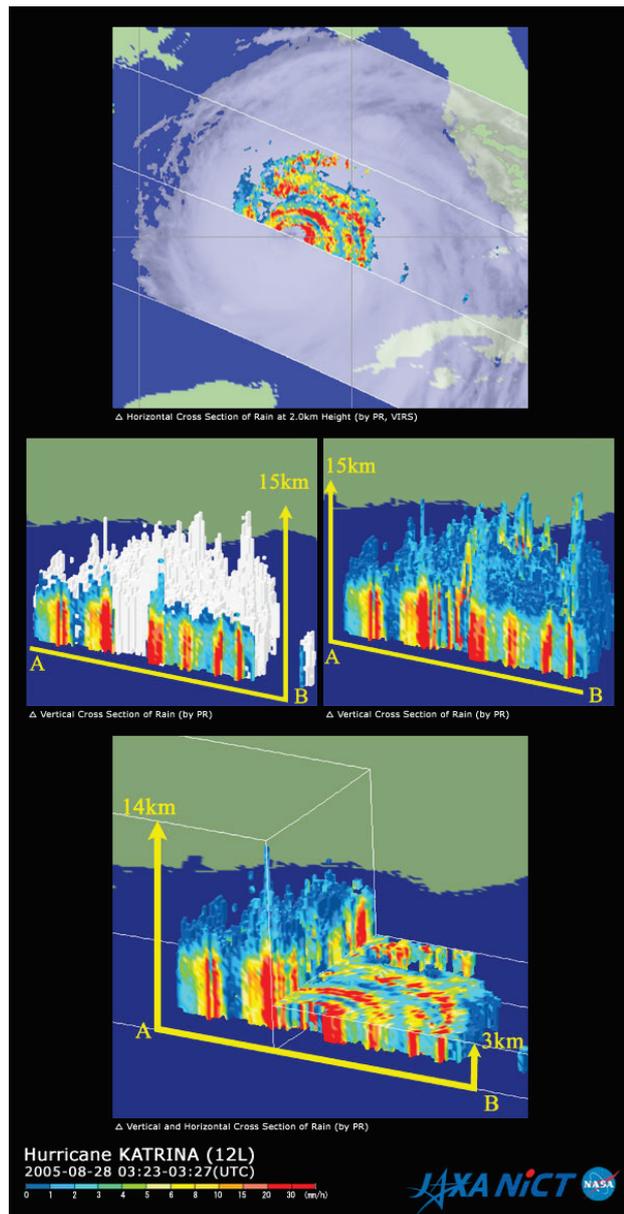


Figure 1. Hurricane Katrina over the Gulf of Mexico on August 28, 2005 observed by the TRMM/PR. a) Horizontal cross section of rain at 2.0 km height. b and c) vertical cross section of rain. d) Vertical and horizontal cross section of rain.

By observation results during more than twelve years, the TRMM instruments can reveal tropical precipitation system climatology. At the same time, the combined use of PR and the TMI has greatly improved the technique of rainfall estimation. The TRMM has observed a lot of severe tropical cyclones such as Hurricane Katrina which hit the southern coastal area of the United States on August 29, 2005 and Hurricane Nargis which hit the Myanmar on May 2-3, 2008. The PR has revealed the three-dimensional structure of tropical cyclones over the ocean,

which was rarely observed before the launch of it. Figures 1 show Hurricane Katrina over the Gulf of Mexico on August 28, 2005 observed by the PR. JAXA operates “JAXA/EORC Tropical Cyclone Database” (JAXA/EORC, 2005) using the TRMM datasets and the passive microwave imager datasets of the AMSR and the AMSR-E. Accumulated tropical cyclone data should be valuable if it will be investigated statistically in the climatological point of view. Moreover, the algorithm of the microwave radiometer has been developed using various attributes of precipitation derived from the TRMM satellite data by the Global Satellite Mapping of Precipitation (GSMaP) Project (Kubota et al. 2007; Aonashi et al. 2009). Hourly global rainfall maps have been provided in near real time (about four hours after observation) with the GSMaP algorithm using TRMM TMI, Aqua AMSR-E, DMSP SSM/I and GEO IR data (JAXA/EORC, 2007).

Thus, more than 12 years after the satellite’s launch, it continues to perform excellent observations and provide valuable meteorological and climatological data relating to precipitation.

3. GPM/DPR

3.1 Concept of the GPM mission

As accuracy of satellite precipitation estimates improves and observation frequency increases, application of those data to societal benefit areas, such as weather forecasts and flood predictions, is expected, in addition to research of precipitation climatology to analyze precipitation systems. There is, however, limitation on single satellite observation in coverage and frequency. Currently, the GPM mission is scheduled under international collaboration to fulfill various user requirements that cannot be achieved by the single TRMM satellite.

GPM is composed of a TRMM-like non-sun-synchronous orbit satellite (GPM core satellite) and multi-satellites carrying microwave radiometer instruments (constellation satellites). The GPM core satellite carries the Dual-frequency Precipitation Radar (DPR), which is being developed by JAXA and NICT, and the GPM Microwave Imager (GMI) provided by NASA, and will achieve more accurate but narrower observation as a calibrator to other constellation satellites. The GPM core satellite is scheduled to be launched in 2013. Constellation satellites, which carry a microwave imager and/or sounder and are planned to be launched around 2013 by each partner agency for its own purpose, and will contribute to extending coverage and increasing frequency.

To take over the results that have been achieved by TRMM and to facilitate development of those results, the GPM mission is planned to meet user requirements that cannot be achieved by TRMM or are expected to be improved in GPM: 1) expansion of observation coverage; 2) increase of observation frequency; and 3) improvement of observation accuracy.

3.2 Instruments of the GPM core satellite (DPR and GMI)

The DPR on board the GPM core satellite is composed of two radars: a Ku-band (13.6-GHz) Precipitation Radar (KuPR) and a Ka-band (35.5-GHz) Precipitation Radar (KaPR). KaPR aims at sensitive observation, and can detect weaker rainfall and snowfall that cannot be measured by KuPR. Since KuPR can detect heavier rainfall, simultaneous observation of KaPR and KuPR will enable accurate measurement of precipitation from heavy rainfall in the tropics to weak snowfall in high latitudes.

Rain echo is affected by precipitation attenuation, and its amount depends on radar frequency and raindrop size. By matching position of radar beams and timing of transmitted pulses for KuPR and KaPR, and measuring precipitation particles at the same place simultaneously by dual-frequency, size of precipitation particles (raindrop size distribution) can be estimated by differences in precipitation attenuation. This information will improve accuracy of precipitation estimation. It is also expected to identify rainfall and snowfall by using differences in precipitation attenuation for dual-frequency.

The GMI instrument on board the GPM core satellite is a multi-channel conical-scanning microwave radiometer developed by NASA, and it is based on the TMI on board the TRMM satellite. The major role of the GMI is to improve accuracy of rainfall/snowfall estimates by simultaneous observation with the DPR, and to work as a bridge between highly accurate observation by the core satellite and frequent observations by the constellation satellites. GMI is also expected to serve as a 'radiometric standard' for the other microwave radiometers on board the GPM constellation satellites, and to reduce differences in rain rate estimation arising from biases of instruments. The GMI is characterized by thirteen microwave channels ranging in frequency from 10 GHz to 183 GHz. In addition to carrying channels similar to those on the TMI, the GMI carries four high frequency, millimeter-wave, channels of about 166-GHz ('window' channel) and 183-GHz (water vapor channel). Addition of those high frequency channels is expected to contribute to improvements in accuracy of weak rainfall and snowfall estimates, especially over the ocean and land in high-latitudes. With a 1.2 m diameter antenna, the GMI will provide significantly improved spatial resolution over TMI.

4. RADAR ALGORITHM DEVELOPMENT OF THE GPM

4.1 DPR algorithm

DPR Level 1 algorithm will be developed by JAXA (Shimizu et al., 2009), and DPR Level 2 and 3 algorithms will be developed by the DPR Algorithm Team led by Japan, which is under the NASA-JAXA Joint Algorithm Team.

DPR algorithms will be based on the TRMM/PR standard algorithms to a maximum extent, and developed utilizing dual-frequency information. Algorithms are to produce KuPR only products, KaPR only products, and/or Dual-frequency Precipitation products using both KuPR and KaPR data, as DPR Level 2 algorithms. It is important to develop algorithm applicable to both PR and KuPR in order to produce long-term continuous data set.

In producing KaPR and Dual-frequency Precipitation products, there are several components that have to be developed and evaluated. Relating to utilization of KAPR data, Correction of attenuation in Ka-band by non-precipitation particles, such as clouds; Development of technology to estimate parameters relating to non-uniform beam filling using high-density observation in Ka-band; and retrievals of solid precipitation using high-sensitive observation in Ka-band should be developed. For effective utilization of dual-frequency observation, Estimation of drop size distribution by simultaneous observation in dual-frequency; and Evaluation of accuracy of Surface Reference Technique in dual-frequency should be developed.

4.2 DPR/GMI combined algorithm

DPR/GMI combined Level 2 and 3 algorithms will be jointly developed by the DPR/GMI Combined Algorithm Team, which is under the NASA-JAXA Joint Algorithm Team.

Physical consistency between DPR and DPR/GMI combined algorithms will be emphasized, and utilization of DPR Level 2 algorithms, completely or in part, as a DPR component will be considered. Database of rain rate profiles obtained from DPR/GMI combined algorithms will be provided to algorithm development of Global Precipitation Map and GMI for contributing to improving their accuracy.

In producing the DPR/GMI combined products, the following components have to be developed and evaluated:

- Methods for improving rainfall estimation accuracy by using GMI Brightness Temperatures; and
- Development and improvement of algorithms for estimating microwave surface emissivity over the land.

5. EARTH/CARE/CPR

Clouds and aerosols are known to play crucial roles in the climate system; however, they are also main sources of uncertainty in our knowledge, and especially large efforts are needed to evaluate their interactions (IPCC 2007). JAXA is carrying out the EarthCARE (Earth Clouds, Aerosols, and Radiation Explorer) mission in cooperation with the European Space Agency (ESA) under the ESA's Earth Explorer Program. The primary objective of the EarthCARE mission is to improve our understanding of the roles of clouds and aerosols and their interaction in the context of the Earth's radiation budget and climate in order that they may be represented well in regional and global climate models and in numerical weather prediction models. Currently, JAXA expects the EarthCARE data to be used to improve cloud formation processes in cloud system resolving models and radiative characteristic models of aerosols and clouds. Then, the improved models can be used to analyze the EarthCARE data and reduce the inconsistency between satellite-observed data and calculated results through the assimilation process.

To achieve the purposes written above, JAXA and the National Institute of Information and Communications Technology (NICT) are in charge of the Cloud Profiling Radar (CPR) and ESA is in charge of the Atmospheric Lidar (ATLID), Multi-spectral Imager (MSI), and Broadband Radiometer (BBR). The three agencies will work collectively. This is one more advantageous point over the A-train mission. Furthermore, the CPR was designed with the capability of measuring vertical profiles of Doppler velocity. This measurement will be the first attempt to obtain Doppler Velocity from space. This paper describes the scientific strategy and plans for each activity in Japan.

This mission is a joint ESA-JAXA-NICT mission to carry a CPR and a Mie lidar (ATLID) on the same satellite platform accompanied by an imager (MSI) and a Broadband Radiometer (BBR). This package is the most advanced one to measure the vertical stratification of the atmosphere with clouds and aerosols. The CPR and lidar will provide information of the vertical stratification of the atmosphere. This capability is especially important to understand the phenomenon of aerosol and cloud interaction. The MSI and BBR will add information

on horizontal distribution of aerosols and clouds and of broadband radiative fluxes, respectively. An important task of EarthCARE is providing useful data to reduce the uncertainty in evaluation of radiative forcing of clouds and aerosols. This will bring about the enormous benefit of increasing the modeling ability of cloud- and aerosol-laden atmospheres. Doppler velocity sensing, a new capability realized in EarthCARE/CPR observation, is another innovation of the EarthCARE platform that will produce a new dataset of global cloud particle motion data.

5.1 Introduction of the science in the EarthCARE mission

Clouds and aerosols are the key players in deciding the Earth's climate, affecting the atmosphere in two opposite ways, such as reflecting sunlight, i.e., the albedo effect, and absorbing terrestrial radiation, i.e., the greenhouse effect. However, these two opposite effects are main sources of uncertainty in our knowledge, and large efforts are needed to evaluate their interactions (IPCC, 2007).

The primary objective of the EarthCARE mission is to improve our understanding of the roles of clouds and aerosols and their interaction in the context of the Earth's radiation budget and climate in order that they may be represented well in regional and global climate models and in numerical weather prediction models (EarthCARE Science Plan, 2007).

We follow the primary objectives of the EarthCARE mission, which can be broken down into several items listed below as derived from the MRD (Mission Required Document):

- To observe the vertical profiles of natural and anthropogenic aerosols on a global scale, and to infer their radiative properties and interaction with clouds,
- To observe the vertical distributions of atmospheric liquid, water, and ice on a global scale, as well as inferring their transport by clouds and their radiative impact,
- To observe cloud distribution (e.g., cloud phase, vertical overlap patterns, and horizontal fluctuations), cloud-precipitation interactions, and the characteristics of vertical motions within clouds, and
- To utilize retrieved aerosol and cloud properties to estimate profiles of atmospheric radiative heating and cooling.

To accomplish these objectives, we, JAXA and the NICT, are developing a CPR with the ability to obtain Doppler velocity of atmospheric particles and the algorithms to yield L1 datasets of it. The other instruments, ATLID, MSI, and BBR, and their algorithms for L1 datasets are being developed by ESA and their collaborators.

Therefore, EarthCARE will attain these objectives by inferring simultaneously the vertical structure and horizontal distribution of cloud and aerosol fields and radiative fluxes at the top of the atmosphere (TOA) over all climate zones as defined in the EarthCARE Science Plan (2007). EarthCARE will infer:

Properties of aerosol layers:

- The occurrence of aerosol layers, their profile of extinction coefficient, boundary layer height.
- The presence of various types of aerosols including those from anthropogenic and natural sources.

Properties of cloud fields:

- Cloud boundaries (top and base heights) including multi-layer clouds.
- Height-resolved fractional cloud amounts and overlap rates.

- The occurrence of ice, liquid, and super-cooled cloud layers.
- Vertical profiles of ice water content and effective ice particle size and shape.
- Vertical profiles of liquid water content and effective droplet size.
- Small-scale (1 km or less) fluctuations in these cloud properties.

Other Properties

- Vertical velocities to characterize cloud-scale convective motions and ice sedimentation.
- Drizzle rates and estimates of heavier rainfall rates.
- Narrowband and broadband reflected solar and emitted thermal fluxes at the top of the atmosphere from measured radiances.

The final scientific goal of the EarthCARE mission is to understand how much climate sensitivity the Earth-Atmosphere system has, and how the climate is driven by clouds, aerosols, and their interaction.

EarthCARE data will be used to improve cloud formation processes in cloud system resolving models as well as radiative characteristic models of aerosols and clouds. Then, the improved models can be used to analyze the EarthCARE data and reduce inconsistency between satellite-observed data and calculated results through the assimilation process. We have several numerical models to simulate aerosol and cloud fields on various scales from meso to global. The MIROC coupled atmosphere-ocean General Circulation Model (GCM) will be useful in evaluating the climate sensitivity and interaction of aerosols and clouds with the climate systems. The Nonhydrostatic Icosahedral Atmospheric Model (NICAM) (Satoh et al., 2008) can simulate the global cloud system with a spatial scale of several kilometers without cumulus parameterization, which produces a large uncertainty in the GCM models.

Another important plan is to utilize EarthCARE data in numerical weather prediction (NWP) simulations and assimilations. The JMA/MRI (Japan Meteorological Agency/Meteorological Research Institute) is an important potential user of data for developing an assimilation method and for improving weather prediction.

5.2 CPR Products

JAXA and NICT are in charge of producing CPR L1b data, such as Received Echo Power, Radar Reflectivity, Surface Radar Cross Section, and, particularly, Doppler Velocity and Covariance of Pulse Pair, which are categorized as L1b standard products of JAXA.

Other CPR L2 products are divided between standard products and research products because some research products from CPR will use Doppler velocity, whose accuracy is very sensitive to the movements of the EarthCARE satellite. The research community asked to generate high-resolution data better than 10 km numerical model use. Although it was decided that CPR data would be integrated as 10 km in the original specification, we then decided to produce CPR products with 1-km resolution.

There are currently two CPR L2a algorithms which have been developed. Those are retrieval from the CPR L1b data without Doppler velocity and with Doppler velocity, respectively. ECMWF data, such as the profile of water vapor, pressure, and temperature, are used in both algorithm flows, and the gas correction will be applied to obtain the radar reflective factor. In this procedure, the algorithms for hydrometeor masks will make

cloud mask products, which are shown in the second layer of the flow chart.

Hydrometeor-type Algorithms are developed by Yoshida (Yoshida, to be submitted) and applied to the corrected radar reflective factor. Then, cloud particle types, such as water, two-dimensional ice, three-dimensional ice, water-precipitation, and ice-precipitation, are discriminated.

Finally, Hydrometeor Microphysics Algorithms calculate microphysical parameters, such as the optical thickness, effective radius, liquid water path (LWP), ice water path (IWP), rain water content, snow water content, rain rate, and snow rate.

In this flow, hydrometeor mask algorithms with synergistic use of CPR and ATLID are developed by Hagihara (Hagihara et al., 2010) and will be applied. Hydrometeor-type algorithms will be applied. They will then yield the L2b cloud hydrometeor products (Sato et al., 2009). Finally, hydrometeor microphysics algorithms (Okamoto et al., 2010; Sato et al., 2009; Yoshida et al., 2010) will be applied to retrieve the products, such as the effective radius of water and ice, LWP, IWP, optical thickness, liquid water content (LWC), ice water content (IWC), rain water content, snow water content, rain rate, and snow rate. These algorithms were applied to shipborne observation, and comparisons to the model calculations were also done (Sato et al., 2010).

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