

## RAINFALL OBSERVATION FROM SPACE – APPLICATIONS OF TROPICAL RAINFALL MEASURING MISSION (TRMM) AND GLOBAL PRECIPITATION MEASUREMENT (GPM) MISSION –

T. Kubota<sup>a\*</sup>, M. Kachi<sup>a</sup>, R. Oki<sup>a</sup>, S. Shimizu<sup>a</sup>, N. Yoshida<sup>a</sup>, M. Kojima<sup>b</sup>, K. Nakamura<sup>c</sup>

<sup>a</sup> Earth Observation Research Center, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505 Japan - (kubota.takuji, kachi.misako, oki.riko, shimizu.shuji, yoshida.naofumi) @jaxa.jp

<sup>b</sup> GPM/DPR Project Team, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, Ibaraki 305-8505 Japan - kojima.masahiro @jaxa.jp

<sup>c</sup> Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601 Japan - nakamura @hyarc.nagoya-u.ac.jp

**KEY WORDS:** global precipitation observation, TRMM, GPM, satellite, precipitation radar, global rainfall map

### ABSTRACT:

Satellite observation is a unique and effective tool to cover a large area homogeneously in a short time. In this paper, we introduce two missions for rainfall observation, i.e., the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission. The TRMM satellite is the first satellite mission focused on rainfall observation. TRMM is a joint mission between Japan and the U.S. and was launched in November 1997. The TRMM carries the world's first satellite-borne Precipitation Radar (PR) developed by Japan, in addition to instruments, such as an infrared imager and a passive microwave imager (TRMM Microwave Imager; TMI). The combined use of PR and the TMI has greatly improved the estimation of rainfall amount. It has also revealed the three-dimensional structure of tropical cyclones over the ocean, which was rarely observed before the TRMM satellite. 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. Currently, the GPM mission, led by Japan and the U.S., is scheduled under international collaboration. One major characteristic of the GPM mission as follow-on and expansion of the TRMM satellite is operation of the GPM core satellite, which will carry dual-frequency precipitation radar (DPR) and a passive microwave radiometer, with a non-sun-synchronous orbit as a "calibrator" to other satellites. The other is its collaboration with a constellation of several other satellites developed by each international partner (space agency), each of which will carry passive microwave radiometers and/or microwave sounders, to increase observation frequency. The TRMM satellite focused on observation of the tropics, and the GPM mission will cover broader areas including high latitudes.

### 1. INTRODUCTION

Satellite observation is a unique and effective tool to cover a large area homogeneously in a short time. Its advantage is obvious when it observes geophysical parameters varying both in temporally and horizontally, like rainfall. Before satellite observation, it is difficult to gain distribution of rainfall over whole globe regardless of land or ocean. Rainfall observation by rain gauges and ground radars only covers small areas of the global Earth's surface, since the most of regions is covered with water or inlands difficult to access.

In this paper, we introduce two missions, i.e., the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission. The TRMM is the first satellite mission focused on "rainfall" observation. The TRMM was launched in November 1997. The GPM is follow-on and expansion mission of the TRMM satellite.

In this paper, we will summarize achievements by the TRMM satellite, current status and algorithm development of GPM mission in Japan

### 2. TRMM

The TRMM satellite is an Earth-observation satellite that measures the tropical rainfall distribution (Simpson et al., 1988, 1996). Major characteristics of the TRMM satellite are described in Table 1. 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, and provided an H-II rocket to launch the TRMM satellite. The US provided the observatory, four other sensors, and the satellite operation systems. TRMM observation data are processed in both countries and distributed among users. The TRMM satellite was launched from Tanegashima Island, Japan, in 28 November 1997 (JST), 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

\* Corresponding author. Takuji Kubota, Earth Observation Research Center, Japan Aerospace Exploration Agency.

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 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).

Launch weight	Approx. 3.62 ton
Launcher	H-II rocket
Launch date	November 28, 1997 6:54 AM (JST)
Altitude	Approx. 350 km (402.5 km since August 24, 2001)
Orbit	Circular orbit (Non-sun-synchronous)
Inclination	Approx. 35 degrees
Shape	At lift-off: 5.1 m (length), 3.7 m (diameter) In orbit: 5.1 m (length), 14.6 m (in paddle direction)
Weight	Total: 3,524 kg Fuel: 890 kg Dry weight: 2,634 kg
Power	Ave. 850 W Attitude control Zero momentum three-axis stabilized
Attitude control	Zero momentum three-axis stabilized
Data transmission	Via TDRS 32 Kbps (real time), 2 Mbps (play back)
Design life	3 years and 2 months
Mission instrument	Precipitation Radar (PR) TRMM Microwave Imager (TMI) Visible Infrared Scanner (VIRS) Clouds and Earth's Radiant Energy System(CERES)

Table 1 Major Characteristics of the TRMM Satellite

By observation results during more than twelve years, the TRMM instruments can reveal tropical climatology. Figure 1 indicated surface rain rate by the PR and sea surface temperature by the VIRS during Jan. 1998–Dec. 2007. Figures 2 show surface rain rate by the PR on January and July during 1998–2007. The combined use of PR and the TMI has greatly improved the technique of rainfall estimation. Figures 3 show differences between zonally averaged surface rain rates estimated by the PR or the TMI during 1998. They are compared in terms of land surfaces (i.e., ocean or land) and their version numbers. They demonstrate that both estimates become closer with progress of algorithm developments. 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 4 show surface rain rate of the cyclone Nargis observed by TRMM/PR over the Bay of Bengal and vertical cross section of rain by the PR (Kubota et al. 2008). 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. Figure 5 shows an example of the database. We have picked up the data and images of the typhoons and the hurricanes, and constructed the database by them.

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). Figure 6 shows an example and it will be described also in Section 4.4.

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.

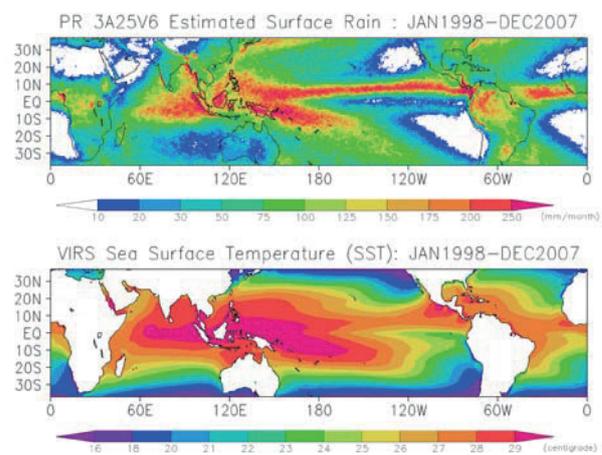


Figure 1. Surface rain rate by the PR (upper) and sea surface temperature (SST) by the VIRS (lower) during Jan. 1998–Dec. 2007. The unit of the rain rate is mm/month and that of the SST is centigrade.

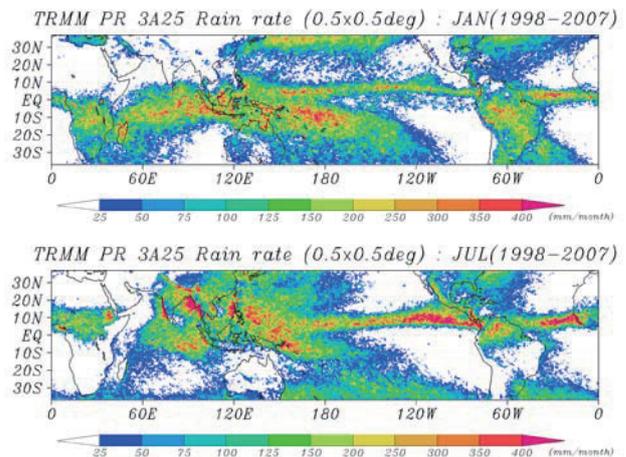


Figure 2. Surface rain rate by the PR on January (upper) and July (lower) during 1998–2007. The unit of the rain rate is mm/month.

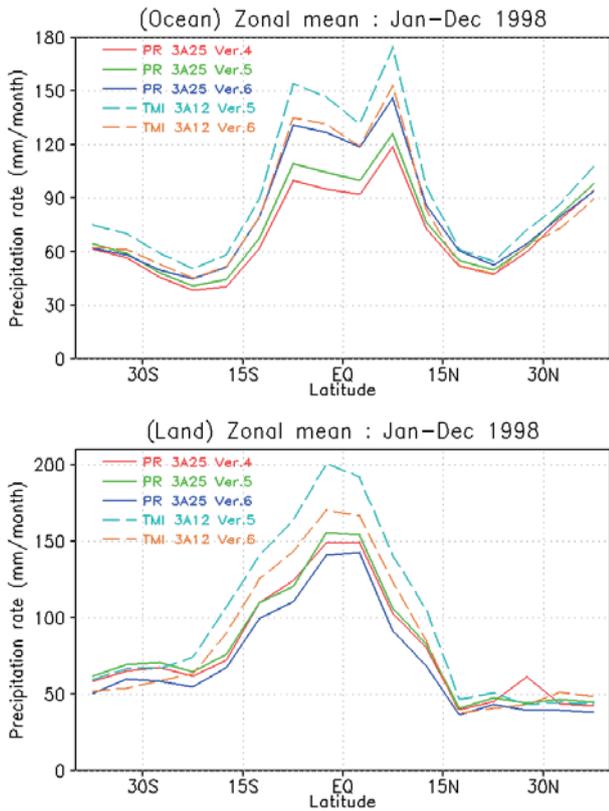


Figure 3. Zonally averaged surface rain rates estimated by the PR (solid lines) or the TMI (dashed lines). The upper panel shows the over-ocean result and the lower shows the over-land result.

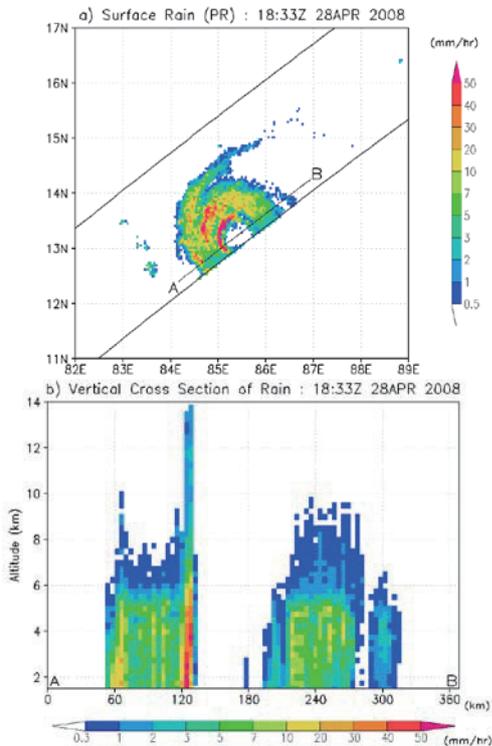


Figure 4. a) Surface rain rate of the cyclone “Nargis” observed by TRMM/PR at 18:33Z 28th April 2008 over the Bay of Bengal (Orbit number: 59552). b) Vertical cross section of rain by TRMM/PR over the A-B segment of the upper panel. (Kubota et al., 2008)

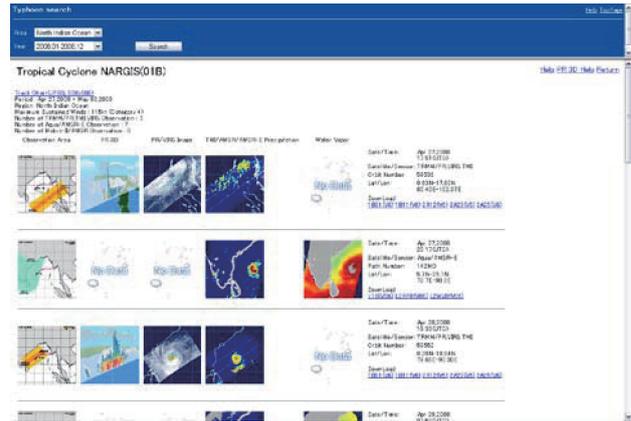


Figure 5. An example of “JAXA/EORC Tropical Cyclone Database” (JAXA/EORC, 2005).

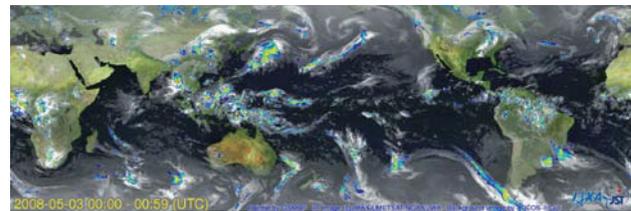


Figure 6. An example of “Global rainfall map in near real time” on 0Z 3<sup>rd</sup> May 2008 (JAXA/EORC, 2007).

### 3. GPM

#### 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. Major characteristics of the GPM Core Satellite are described in Table 2. 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.

Orbit	Non-sun-synchronous
Inclination	Approx. 65degrees
Altitude	Approx. 400 km
Mission instrument	Dual-frequency Precipitation Radar (DPR) GPM Microwave Imager (GMI)
Mission life	3 years (target: 5 years)
Launch date	2013

Table 2 Major Characteristics of the GPM Core Satellite

### 3.2 Instruments of the GPM core satellite

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.

### 3.3 Collaboration with Constellation Satellites

In the case of low orbital satellites, such as TRMM and Aqua, single-satellite cannot observe frequently at each local point. To overcome this weakness and achieve frequent observation, the GPM mission will work with other satellite missions in the world. As the number of constellation satellites increases, the coverage for a given time increases, and hence the sampling interval at a given point decreases. In the GPM era, one primary satellite and eight constellation satellites will produce 3-hour

global precipitation maps that will be delivered to users in near real time.

Constellation of several satellites developed by each international partner (space agency) will carry passive microwave radiometers and/or microwave sounders and be in operation around 2013. The DPR and GMI instruments on board the core satellite will serve as a 'calibrator' for data obtained by constellation satellites.

## 4. ALGORITHM DEVELOPMENT OF THE GPM

### 4.1 Overview

To meet the GPM objectives, retrieval algorithms will require global applicability, robustness, and long-term stability (Kachi et al. 2009). Algorithms that can be extended and applied for similar instruments (e.g., PR, and microwave radiometers on board the other satellites) and historical data records are preferable for integrated retrieval. Computationally efficient, fast-processing algorithms are important for the operational applications of the products.

### 4.2 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, the following components have to be developed and evaluated:

- 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.)
- 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.)

### 4.3 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.

#### 4.4 Global Precipitation Map algorithm

Global Precipitation Map algorithms will be developed in Japan, and will be composed from three algorithm, they are Microwave imager rain retrieval algorithm (MWI algorithm), Microwave sounder rain retrieval algorithm (MWS algorithm), and Microwave-Infrared (IR) combined algorithm (MVK algorithm).

Global Precipitation Map algorithms will be developed based on outcomes from the Global Satellite Mapping for Precipitation (GSMaP) project, which was sponsored by the Japan Science and Technology Agency (JST) under the Core Research for Evolutional Science and Technology (CREST) framework between 2002 and 2007 (Okamoto et al., 2005; Kubota et al., 2007; Aonashi et al., 2009; Ushio et al., 2009). The MWI algorithm, which is being developed as the standard algorithm for precipitation products of the Advanced Microwave Scanning Radiometer 2 (AMS2) on board the first generation of Global Climate Change Mission-Water (GCOM-W1) satellite, will be improved and applied to GMI and other microwave imagers on board constellation satellites. The MWS algorithm will be developed ensuring consistency with the MWI algorithm.

In production of the Global Precipitation Map products, the following components have to be developed and evaluated:

- Smooth transition from the current PR-based database to the future DPR-based database; and
- Improvement of accuracy of rainfall over high-latitudes using high-frequency channels available in GMI and microwave sounders.

Prototype system for Global Precipitation Map products has been in operation since October 2008 in near-real-time basis, and browse images and binary data available (JAXA/EORC, 2007).

## 5. REFERENCES

Aonashi, K., J. Awaka, M. Hirose, T. Kozu, T. Kubota, G. Liu, S. Shige, T. Kida, S. Seto, N. Takahashi, Y. N. Takayabu, 2009. GSMaP passive, microwave precipitation retrieval algorithm: Algorithm description and validation. *J. Meteor. Soc. Japan*, 87A, pp.119-136.

JAXA/EORC, 2005. JAXA/EORC Tropical Cyclone Database. [http://sharaku.eorc.jaxa.jp/TYP\\_DB/index\\_e.shtml](http://sharaku.eorc.jaxa.jp/TYP_DB/index_e.shtml) (accessed 31 May 2010)

JAXA/EORC, 2005. Global rainfall map in near real time. <http://sharaku.eorc.jaxa.jp/GSMaP/index.htm> (accessed 31 May 2010)

Kachi, M., R. Oki, S. Shimizu, T. Kubota, and N. Yoshida, T. Iguchi, K. Nakamura, 2009. Status of algorithm development and CAL/VAL plans in the JAXA GPM project. *Proc. SPIE*, Vol. 7474, 74740P; doi:10.1117/12.830261.

Kozu, T., T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa, H. Kumagai, K. Okamoto, M. Okumura, H. Nakatsuka and K. Nishikawa, 2001. Development of precipitation radar onboard the tropical rainfall measuring mission satellite. *IEEE Trans. Geosci. Remote Sens.*, 39, pp.102-116.

Kubota, T., S. Shige, H. Hashizume, K. Aonashi, N. Takahashi, S. Seto, M. Hirose, Y. N. Takayabu, K. Nakagawa, K. Iwanami, T. Ushio, M. Kachi, and K. Okamoto, 2007. Global Precipitation Map using Satelliteborne Microwave Radiometers by the GSMaP Project : Production and Validation, *IEEE Trans. Geosci. Remote Sens.*, 45, 2259-2275.

Kubota, T., M. Kachi, S. Shimizu, N. Yoshida and R. Oki, 2008. Precipitation Monitoring of Cyclone Nargis from Satellites , *Journal of The Remote Sensing Society of Japan*, 28, 4, pp.361-365.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue and J. Simpson, 1998. The Tropical Rainfall Measuring Mission (TRMM) Sensor Package. *J. Atmos. Ocean. Technol.*, 15(3), pp. 809–817.

Okamoto, K., 2003. A short history of the TRMM precipitation radar” in Cloud Systems, Hurricanes and The Tropical Rainfall Measurement Mission (TRMM) : A Tribute to Dr. Joanne Simpson. *Meteor. Monogr., Amer. Meteor. Soc.*, pp. 187-195.

Okamoto, K., T. Iguchi, N. Takahashi, K. Iwanami, and T. Ushio, 2005. The global satellite mapping of precipitation (GSMaP) project. *Proc. 25th IGARSS*, pp.3414-3416.

Shimizu, S., N. Yoshida, H. Hanado, and T. Higashiuwatoko, 2009. Level 1 algorithm development of spaceborne dual-frequency precipitation radar (DPR) for GPM. *Proc. 29th IGARSS*.

Simpson, J., ed., 1988: Report of the science steering group for a tropical rainfall measuring mission (TRMM),. NASA/Goddard Space Flight Center, USA. 94pp.

Simpson, J., C. Kummerow, W.-K. Tao and R. F. Adler, 1996: On the Tropical Rainfall Measuring Mission (TRMM). *Meteor. Atmos. Phys.*, 60, pp. 19-36.

Ushio, T., T. Kubota, S. Shige, K. Okamoto, K. Aonashi, T. Inoue, N. Takahashi, T. Iguchi, M. Kachi, R. Oki, T. Morimoto, and Z. Kawasaki, 2009. A Kalman filter approach to the Global Satellite Mapping of Precipitation (GSMaP) from combined passive microwave and infrared radiometric data. *J. Meteor. Soc. Japan*, 87A, pp.137-151.

## 6. ACKNOWLEDGMENTS

The authors would like to express their gratitude to US and Japan project/science team members of TRMM and GPM.