APPENDIX 2

OVERVIEW OF THE GLOBAL PRECIPITATION MEASUREMENT (GPM) AND THE PRECIPITATION MEASURING MISSION (PMM)

1. Introduction

“Precipitation” is one of most important environmental parameters. Changes in its amount and distribution may affect our everyday life, and they may cause serious damages to human lives and properties. Too much precipitation causes floods, and too less of it causes droughts. Agricultural production depends on precipitation. It is one of the three foremost weather prediction variables along with temperature and wind. Precipitation is a true global variable that determines the general circulation through latent heating, which is an "engine" for circumglobal winds, and reflects climate changes. It is a key component of air-sea interaction and eco-hydrometeorological modeling.

Although there is no doubt that precipitation is such an important component of our environment, it is one of the least known physics components of cloud, weather and climate prediction models. Because of its large variability in space and time, its distribution over the globe is not accurately known. Knowledge of the spatial and temporal distribution of global precipitation is a key to improving our understanding of weather and climate systems.

The Tropical Rainfall Measuring Mission (TRMM) satellite, which archived tropical/subtropical rainfall data more than 17 years, was a joint Japan-US mission. TRMM, launched in the end of November 1997 by the Japanese H-II rocket, focuses on measuring tropical/subtropical rainfall and their diurnal variations, and covers latitude from 35S to 35N (Kummerow et al. 1998). TRMM had three precipitation sensors: the Precipitation Radar (PR), the world first space-borne precipitation radar developed by Japan (Kozu et al. 2001), and the TRMM Microwave Imager (TMI) and the Visible Infrared Scanner (VIRS) developed by the U.S., which enabled observation of rainfall structures by multiple sensors, simultaneously.

Because of the success of the TRMM satellite, several requirements for the successor mission emerged from the science and operational user community. The Global Precipitation Measurement (GPM) mission was proposed to fulfill those requirements (Hou et al. 2014, Skofronick-Jackson et al. 2017). GPM is a satellite program to measure the global distribution of precipitation accurately in a sufficient frequency so that the information provided by this program can drastically improve weather predictions, climate modeling, and understanding of water cycles. Its feasibility has been studied at Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). Accurate measurement of precipitation has been achieved using the Dual-frequency Precipitation Radar (DPR) installed on the GPM Core Observatory (Kojima et al. 2012, Iguchi 2020). The DPR on the GPM Core Observatory is being developed by JAXA and the National Institute of Information and Communications Technology (NICT).

2. The Tropical Rainfall Measuring Mission (TRMM)

The Tropical Rainfall Measuring Mission (TRMM) satellite (Figure 1) was launched by H-II rocket No. 6 in November 1997, and completed its mission in April 2015.

Major characteristics of the TRMM satellite are described in Table 1. TRMM is joint mission between Japan (JAXA (former NASDA) and NICT (former CRL)) and the U.S. (NASA). The major objective of TRMM is to determine accurate rainfall amount associated with tropical convective activities, which is a drive source of global atmospheric circulation. To this purpose, the TRMM satellite focuses on rainfall observation, and carries the world's first satellite-borne Precipitation Radar (PR) developed by Japan, in addition to conventional instruments such as infrared imager and microwave imager (TRMM Microwave Imager: TMI). The combination use of PR and TMI has greatly improved the estimation of rainfall amount and has succeeded in observing climate changes, as with El Niño and La Niña. Since the three-dimensional structure of rainfall over the land and ocean can be derived from PR, TRMM has also revealed the three-dimensional structure of typhoons over the ocean, which was rarely observed before TRMM. The success of TRMM shows the potential of satellite remote sensing contributions for understanding the water cycle on Earth and improving weather forecasts.

The TRMM satellite also targets rainfall observation in the tropics and sub-tropics. In order to measure tropical rainfall that has large diurnal variation, it flies in non-sun-synchronous orbit with an inclination angle of 35°. Although the designed lifetime of the satellite was about 3 years, the satellite altitude was boosted from 350 km to 402.5 km in August 2001 to extend the lifetime by reducing atmospheric drag. In March 2009, more than 11 years after the satellite's launch, it continues its excellent observation and provides valuable meteorological and climatological data relating to precipitation, through long-term observation of the current status of rainfall in the tropics and sub-tropics, for understanding water cycle mechanisms.

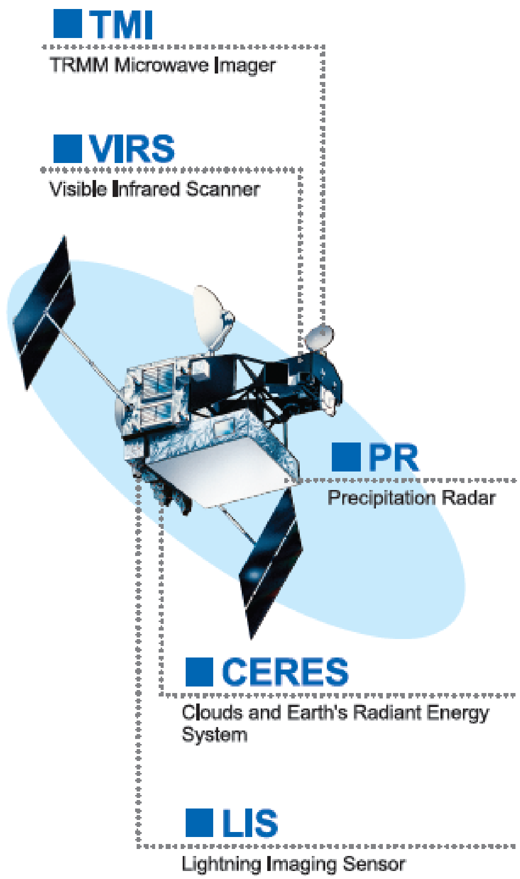

Figure 1 Overview of the TRMM Satellite and the Five on board Sensors

Table 1 Major Characteristics of the TRMM Satellite

Orbit	Non-sun-synchronous circular orbit
Inclination	Approx. 35 degrees
Altitude	Approx. 350 km (402.5 km since August 24, 2001)
Launch date	November 28, 1997 6:54 AM (JST)
Design life	3 years and 2 months
Mission instrument	Precipitation Radar (PR) TRMM Microwave Imager (TMI) Visible Infrared Scanner (VIRS) Lightning Imaging Sensor (LIS) Clouds and Earth's Radiant Energy System (CERES)

3. The Global Rainfall Measurement (GPM)

1. 3.1 From TRMM to GPM

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. Therefore, the Global Precipitation Measurement (GPM) mission was prpposed under international collaboration to fulfill various user requirements that cannot be achieved by the single TRMM satellite.

One major characteristic of GPM as follow-on and expansion of TRMM is to operate the GPM Core Observatory, which carries an active precipitation radar and a passive microwave radiometer, with a non-sun-synchronous orbit as a calibrator to other satellites. The other is a collaboration with a constellation of several satellites developed by each international partner (space agency) that carries passive microwave radiometers and/or microwave sounders, to increase observation frequency. Although the TRMM satellite focused on observation of the tropics, the GPM mission covers broader areas, including high latitudes.

3.2 Concept of the GPM Mission

TRMM is single satellite mission for scientific research. On the other hand, the GPM mission (Fig. 2) is an international mission to achieve high-accurate and high-frequent rainfall observation over a global area. GPM is composed of a TRMM-like non-sun-synchronous orbit satellite (GPM Core Observatory) and multi-satellites carrying microwave radiometer instruments (constellation satellites). The GPM Core Observatory 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 has been achieve more accurate but narrower observation as a calibrator to other constellation satellites. Constellation satellites, which carry a microwave imager and/or sounder by each partner agency for its own purpose, and can 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.

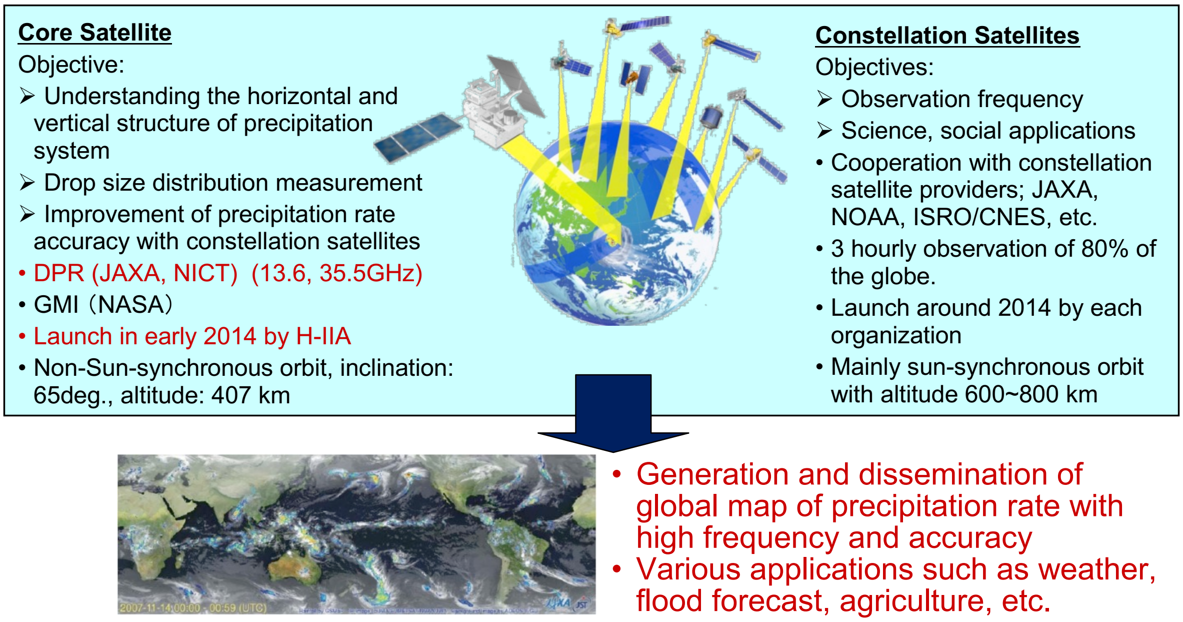

Figure 2 Overview of the GPM Mission

3.3 Overview of the GPM Core Observatory

The GPM Core Observatory (Table 2 and Figure 3), which is being jointly developed by Japan and the U.S., was launched in February 2014. The core satellite carries a Dual-frequency Precipitation Radar (DPR) developed by Japan, and a GPM Microwave Imager (GMI) developed by U.S. The orbit of the core satellite is non-sun-synchronous with an inclination angle of 65°. This orbit was selected to meet certain requirements, such as to measure diurnal variation of rainfall in mid- and high-latitudes as well as the tropics for around 2 months.

Table 2 Major Characteristics of the GPM Core Observatory

Orbit	Non-sun-synchronous
Inclination	65 degrees
Altitude	407 km
Launch date	February 28, 2014 03:36 AM (JST)
Mission life	3 years (target: 5 years)
Mission instrument	Dual-frequency Precipitation Radar (DPR) GPM Microwave Imager (GMI)

The Dual-frequency Precipitation Radar (DPR) on board the GPM Core Observatory 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 enables 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 cannot be obtained by single-frequency radar, such as TRMM's PR, and can improve accuracy of precipitation estimation. It is also expected to identify rainfall and snowfall by using differences in precipitation attenuation for dual-frequency.

The GPM Microwave Imager (GMI) instrument on board the GPM Core Observatory 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 TRMM Microwave Imager (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 can provide significantly improved spatial resolution over TMI.

The roles of the GPM primary satellite are to collect as much microphysical information as possible for accurate rain estimation by performing synchronous observation with the GMI and the DPR and to provide calibration standards for the other microwave radiometers on the constellation satellites.

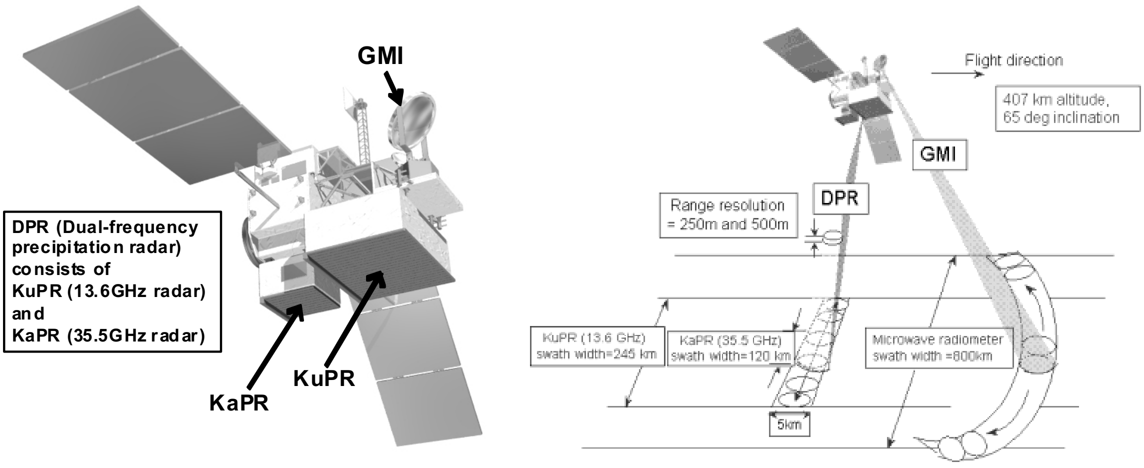

Figure 3 Overview of the GPM Core Satellite and Concept of Precipitation Observation

3.4 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 works with other satellite missions with microwave radiometers in polar-orbiting satellites. As the number increases, the coverage for a given time increases, and hence the sampling interval at a given point decreases. In the GPM era, eight sun-synchronous polar-orbiting satellites enable global observation of precipitation every 3 hours. In the GPM era, one primary satellite and eight constellation satellites produces 3-hour global precipitation maps that are delivered to users in near real time.

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

4. Precipitation Measuring Mission (PMM)

Measurements of Convection (vertical atmospheric motion) by Doppler velocities from spaceborne radar is desirable for understanding of cloud-precipitation process. On the other hand, estimating Doppler velocities from space is very challenging because of satellite motion, velocity folding, and nonuniform beam filling.

World's first satellite-based Ku-band (13GHz) doppler precipitation radar (KuDPR) is planned in the JAXA's PMM. The KuDPR will be two-antenna system that adopts Displaced Phase Center Antenna (DPCA) approach (Durden et al. 2007, 2023, Tanelli et al. 2016, Nakamura and Furukawa 2023). The DPCA approach can lead to more accurate Doppler measurement.

In June 2023, JAXA's Precipitation Measuring Mission (PMM) Project Team was established on for the PMM observatory carrying the Ku-band Doppler Precipitation Radar, with participation in NASA AOS mission.

In December 2022, Implementation Plan of the "Basic Plan on Space Policy" noting the Precipitation Radar Satellite Phase B activity targeting the launch of JFY2028 (April 2028 to March 2029) was released from Cabinet Office of the Japanese government.

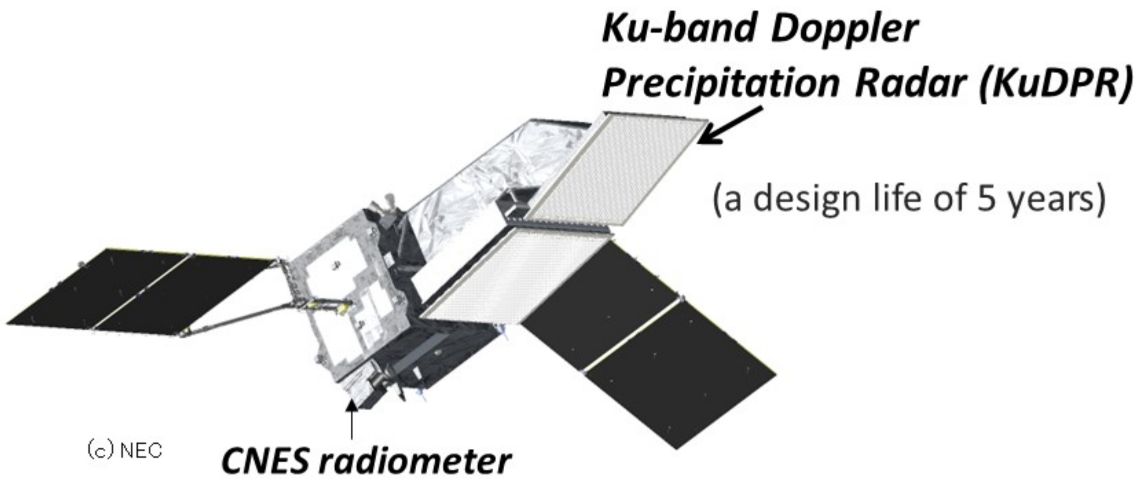

Figure 4 A concept of the PMM observatory

REFERENCES

Hou, A. Y., and Coauthors, 2014: The Global Precipitation Measurement Mission. Bull. Amer. Meteor. Soc., 95, 701–722.

Iguchi, T., 2020: Dual-frequency Precipitation Radar (DPR) on the Global Precipitation Measurement (GPM) mission's core observatory, Satellite precipitation measurement, Springer, https://doi.org/10.1007/978-3-030-24568-9_11.

Kojima, M., T. Miura, K. Furukawa, Y. Hyakusoku, T. Ishikiri, H. Kai, T. Iguchi, H. Hanado, and K.

Nakagawa, 2012: Dual-frequency precipitation radar (DPR) development on the global precipitation measurement (GPM) core observatory, Proc. SPIE 8528, Earth Observing Missions and Sensors: Development, Implementation, and Characterization II, 85281A, doi:10.1117/12.976823.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package, J. Atmos. Oceanic Technol., 15, 808-816.

Kozu, T, T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa, H. Kumagai, K. Okamoto, M. Okumura, H. Nakatshka, and K. Nishikawa, 2001: development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. IEEE Trans. Geosci. Remote Sens., 39, 102-116.

Skofronick-Jackson, G., W.A. Petersen, W. Berg, C. Kidd, E.F. Stocker, D.B. Kirschbaum, R. Kakar, S.A. Braun, G.J. Huffman, T. Iguchi, P.E. Kirstetter, C. Kummerow, R. Meneghini, R. Oki, W.S. Olson, Y.N. Takayabu, K. Furukawa, and T. Wilheit, 2017: The Global Precipitation Measurement (GPM) Mission for Science and Society. Bull. Amer. Meteor. Soc., 98, 1679–1695, https://doi.org/10.1175/BAMS-D-15-00306.1