Global Satellite Mapping of Precipitation (GSMaP) for GPM

Algorithm Theoretical Basis Document (ATBD)

Algorithm Ver.6

Prepared by

GPM Global Rainfall Map Algorithm Development Team

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1. OVERVIEW

1.1. Background

Development of precipitation map algorithm including microwave radiometer/sounder algorithms has been continued cooperation with the member of Global Satellite Mapping of Precipitation (GSMaP) project (Okamoto et al., 2005; Kubota et al., 2007) in Japan. GSMaP project was sponsored by the Japan Science and Technology Agency (JST) under the Core Research for Evolutional Science and Technology (CREST) framework, and completed its major activity in March 2008. Since April 2008, GSMaP activities have implemented under Japanese Precipitation Measuring Mission (PMM) Science Team, which is joint science team between Tropical Rainfall Measuring Mission (TRMM) and its successor mission, Global Precipitation Measurement (GPM).

Since GSMaP algorithms targeted production of “best” precipitation estimates, they didn’t consider real-time operation and/or data availability. To meet user requirements of such a data in near-real-time, JAXA has developed and operates global rainfall map production system, a prototype for GPM era, in near-real-time since October 2008, and hourly and 0.1-degree resolution binary data and images available via internet (http://sharaku.eorc.jaxa.jp/GSMaP/) four hours after observation.

Core algorithms of the system are based on those provided by GSMaP project; microwave radiometer rainfall retrieval algorithm (Aonashi *et al.*, 2009), microwave sounder rainfall retrieval algorithm (Shige *et al.*, 2009), microwave imager/sounder rainfall retrieval algorithm (Kubota *et al.*, 2011), and microwave-infrared (IR) merged algorithm (Ushio *et al.*, 2009).

1.2. Principles

GPM-GSMaP algorithm consists of following three main algorithms.

- Microwave imager rainfall retrieval algorithm (MWI algorithm)
- Microwave sounder rainfall retrieval algorithm (MWS algorithm)
- Microwave imager/sounder rainfall retrieval algorithm (MWIS algorithm)
- Microwave-IR combined algorithm (MVK algorithm)
- Gauge calibrated rainfall algorithm (MVK_Gauge algorithm)

In developing GPM-GSMaP algorithms, developers should pay attention to following points:

- Develop algorithms based on outcomes from the GSMaP project, which was sponsored by JST under the CREST framework between 2002 and 2007;
- Improve the MWI algorithm, which is being developed as the standard algorithm for precipitation products of the Advanced Microwave Scanning Radiometer 2 (AMSR2) on board the Global Climate Change Mission - Water (GCOM-W) satellite, and apply it to GPM Microwave Imager (GMI) and other microwave imagers on board constellation satellites;
- Develop the MWS algorithm ensuring consistency with the MWI algorithm;

- Improve database of rain rate retrievals using TRMM Precipitation Radar (PR) data, and apply its methodology to Dual-frequency Precipitation Radar (DPR) data;
- Cooperate with the AMSR2 precipitation group in algorithm development and calibration and validation activities; and
- Develop a near-real-time algorithm based on the standard algorithm.

2. INPUT DATA

GPM-GSMaP algorithms uses multi satellite data and ancillary data as inputs. Followings are summary of input data.

2.1. Microwave Imager

Table 1 shows current and/or future conical scanning passive microwave imagers, which will be used as inputs of GPM-GSMaP.

Table 1 Summary of current and planned conical scanning passive microwave imagers (as of August 2014)

Satellite	Height (km)	Instrument	frequency (GHz)	Data Period	Data Provider
TRMM	402	TMI	10.7, 19.4, 21.3, 37, 85.5	Dec.1997 - present	NASA
Aqua	705	AMSR-E	6.9, 10.7, 18.7, 23.8, 36.5, 50.3, 52.8, 89	Jun. 2002 - present (Oct. 2012)	JAXA
ADEOS-II	802	AMSR	6.9, 10.7, 18.7, 23.8, 36.5, 89	Apr. 2003 - Oct. 2003	JAXA
DMSP-F11	833	SSM/I	19.4, 22.2, 37, 85.5	Dec. 1991 - May 2000	DoD/NOAA
DMSP-F13	833			Dec. 1995 - Nov. 2009	DoD/NOAA
DMSP-F14	833			Dec. 1997 - Aug. 2008	DoD/NOAA
DMSP-F15	833			Dec. 1999 - present (retrieved over ocean only since Aug. 2006)	DoD/NOAA
Megha-Tropiques	833	MADRAS	18.7, 23.8, 36.5, 89, 157	Oct. 2012 - Jan. 2013	CNES/ISRO
GCOM-W1	700	AMSR2	6.9, 7.3, 10.7, 18.7, 23.8, 36.5, 50.3, 52.8, 89	Jul. 2012 - present	JAXA
GPM Core Observatory	407	GMI	10.7, 19.4, 21.3, 37, 85.5, 166, 183.31±3, 183.31±7	Mar. 2014 - present	NASA
DWSS-1	TBD	TBD	TBD	TBD	DoD/NOAA

2.2. Microwave Sounder

Table 2 shows current and/or future cross-tracking passive microwave imagers, which will be used as inputs of GPM-GSMaP.

Table 2 Summary of current and planned cross-tracking passive microwave imagers (as of August 2014)

Satellite	Height (km)	Instrument	frequency (GHz)	Data Period	Data Provider
NOAA-N15	807	AMSU-A/ AMSU-B	23.8-89.1 (AMSU-A), 89.0±0.9, 150.0±0.9, 183.31±1, 183.31±3, 183.31±7 (AMSU-B)	Oct. 1998 - Mar. 2011 (AMSU-B not operational)	NOAA
NOAA-N16	849			Jan. 2001 – Jun. 2014	NOAA
NOAA-N17	810			Aug. 2002 – Apr. 2013	NOAA
NOAA-N18	854	AMSU-A/ MHS	23.8-89.1 (AMSU-A), 89, 157, 183.311±3, 183.311±5, 190.311 (MHS)	May 2005 - present	NOAA
NOAA-N19	870			Apr. 2009 - present	NOAA
MetOp-A	817			May 2007 - present	EUMETSAT
MetOp-B	817			Sep. 2012 - present	EUMETSAT
NPP	824	ATMS	23.8-88.2, 165.5, 183.31±1, 183.31±1.8, 183.31±3, 188.31±4.5, 188.31±7	launched in Oct. 2011	NOAA
JPSS-1	824	ATMS		to be launched in 2017	NOAA

2.3. Microwave Imager/Sounder

Table 3 shows current and/or future conical scanning passive microwave imager/sounders, which will be used as inputs of GPM-GSMaP.

Table 3 Summary of current and planned conical scanning passive microwave imager/sounders (as of August 2014)

Satellite	Height (km)	Instrument	frequency (GHz)	Data Period	Data Provider
DMSP-F16	833	SSMIS	19.4, 22.2, 37, 91.7, 60-63, 50-59, 150, 183.31±1, 183.31±3, 183.31±7	Nov. 2005 - present	NOAA
DMSP-F17	850			Mar. 2008 - present	NOAA
DMSP-F18	850			Oct. 2009 - present	NOAA
DMSP-F19	850			to be launched in 2014	DoD/NOAA
DMSP-F20	850			to be launched in 2020	DoD/NOAA

2.4. Geostationary Satellite IR Imager

Globally-merged full-resolution IR Data, which is merged from the ~11 micron IR channels aboard geostationary satellites (Table 4) in about 4 km grid size, provided by NOAA Climate Prediction Center (CPC), will be used as inputs for MVK algorithm.

Table 4 Summary of geostationary satellites (as of August 2013)

Satellite	Sub-satellite Longitude	Parameter	Data Provider
MTSAT-1R (old GMS)	140E	~11 micron IR channels	JMA
GOES-E (8, now 12)	75W		NOAA
GOES-W (10, now 11)	135W		NOAA
Meteosat-8 (old 7)	0E		EUMETSAT
Meteosat-5	63E		EUMETSAT

2.5. Space-borne Precipitation Radar

Data and information from space-borne precipitation radars (Table 5) will be used to develop database and/or precipitation physical models, and not directly.

Table 5 Summary of space-borne precipitation radars (as of August 2013)

Satellite	Height (km)	Instrument	frequency (GHz)	Data Period	Data Provider
TRMM	402	PR	13.8	Dec.1997 - present	JAXA
GPM Core Observatory	407	DPR	13.6, 35.5	Mar. 2014 - present	JAXA

2.6. Atmospheric Condition

Japan Meteorological Agency (JMA) Global Analysis (GANAL) and Forecast data set, which are 6-hourly and 0.5 degree grid box, are used as ancillary data of atmospheric condition for calculating look-up tables, which are referred by MWI and MWS algorithms. ANAL data will be used to process standard products, and FCST data will be used to process near-real-time products. For the past period, the Japanese 55-year Reanalysis (JRA-55) data (6-hourly, model grid (TL319L60)) will be used instead of operational data.

2.7. Sea Surface Temperature

J JMA Merged satellite and in situ data Global Daily Sea Surface Temperatures (MGDSST) data, which is daily and 0.25 degree grid box, will be used as ancillary data of Sea Surface Temperature (SST) for calculating look-up tables, which are referred by MWI and MWS algorithms.

2.8. Rain Gauge

NOAA CPC Unified Gauge-Based Analysis of Global Daily Precipitation data set, which is daily and 0.5 degree grid box, will be used as input to MVK algorithm to calculate gauge-calibrated rainfall.

2.9. Topographic Data

The Shuttle Radar Topography Mission 30-arc second (SRTM30) dataset, which is provided by U.S. Geological Survey (USGS), will be used as information to estimate upward motion in the orographic/nonorographic rainfall classification scheme. Original 30-arc second mesh (about 900 m) and regionally divided data is resampled in 0.05 degree grid box and integrated as global data. See http://dds.cr.usgs.gov/srtm/version2_1/SRTM30/srtm30_documentation.pdf for more detail.

2.10. High Resolution Ocean/Land Flag

Ocean/Land/Coast flag database will be used in the coast detection scheme. The dataset is produced in 30-arc second mesh, and mainly uses the SRTM Water Body Data provided by the Geospatial-Intelligence Agency (NGA) and NASA for the region south of 60N, and the Global Self-consistent, Hierarchical, High-resolution Shorelines (GSHHS) provided by NOAA's National Geophysical Data Center for the region north of 60N.

3. OUTPUT DATA

3.1. Hourly product

3.1.1. Temporal resolution

Hourly.

3.1.2. Horizontal resolution

0.1 degree latitude/longitude grid.

3.1.3. Coverage

Coverage of output data is from 180W to 180E in longitude and 90S to 90N in latitude. However, current algorithm only estimates rainfall over the region from 60S to 60N, and missing values are stored in outside regions.

3.1.4. Output format

HDF5 and TEXT (CSV) formats.

3.1.5. Hourly precipitation rate (HourlyPrecipRate)

Hourly rain rate at each pixel. Unit is mm/hour. Missing value is -9999.9.

3.1.6. Satellite information flag (SatelliteInfromationFlag)

Information of satellites that observe each pixel within 1-hour. Described in bit.

3.1.7. Observation time flag (ObservationTimeFlag)

Relative time of nearest microwave radiometer (imager/sounder) observation at each pixel, on the basis of start time (XX:00) of observation at XX (UTC).

3.1.8. Gauge-calibrated hourly precipitation rate (HourlyPrecipRateGC)

Hourly rain rate at each pixel, calibrated by using ground-based gauge observation over land. Pixels over the ocean, same values as Hourly precipitation rate are stored. Unit is mm/hour. Missing value is -9999.9.

3.1.9. Gauge quality information (GaugeQualityInformation)

Number of rain gauge used in gauge adjustment at each pixel within one day. Original values in 0.5 degree grid box are stored in corresponding pixels in 0.1 degree grid box in same values. For the near-real-time product, values of 1 or 0 are stored for with or without adjustment.

3.2. Monthly product

3.2.1. Temporal resolution

Monthly.

3.2.2. Horizontal resolution

0.1 degree latitude/longitude grid.

3.2.3. Coverage

Coverage of output data is from 180W to 180E in longitude and 90S to 90N in latitude. However, current algorithm only estimates rainfall over the region from 60S to 60N, and missing values are stored in outside regions.

3.2.4. Output format

HDF5 and TEXT (CSV) formats.

3.2.5. Monthly mean hourly precipitation rate (MonthlyPrecipRate)

Monthly mean rain rate at each pixel. Unit is mm/hour. Missing value is -9999.9.

3.2.6. Number of observations (ObservationNumber)

Number of observation within one month. Missing value is -9999.

3.2.7. Standard deviation (StandardDeviation)

Standard deviation within one month. Mission value is -9999.9.

3.2.8. Monthly mean gauge calibrated precipitation rate (MonthlyPrecipRateGC)

Monthly rain rate at each pixel, calibrated by using ground-based gauge observation over land. Pixels over the ocean, same values as Hourly precipitation rate are stored. Unit is mm/hour. Missing value is -9999.9.

3.2.9. Gauge quality information（GaugeQualityInformation）

Number of rain gauge used in gauge adjustment at each pixel within one month. Missing value is -9999.

4. ALGORITHM DESCIPTION

4.1. Microwave Imager Algorithm (GSMaP_MWI)

GSMaP microwave imager (MWI) algorithm retrieves global precipitation rates from satellite microwave imager (TMI, GMI, AMSR, AMSRE, AMSR2, SSM/I) bright temperatures (TBs). To develop this algorithm, we improved that of Aonashi *et al.* (2009) by introducing the orographic rain adjustment method etc.

The basic idea of the MWI algorithm is to find precipitation rates that give radiative transfer model (RTM)-calculated TBs that best fit with TMI TBs. The MWI algorithm employs polarization corrected temperatures (PCTs) at higher frequencies (37 and 85 GHz for TMI) over land and coast, TBs with vertical polarization at lower frequencies (10, 19, and 37 GHz for TMI) in addition to the higher frequency PCTs over ocean. (For SSM/I, this algorithm employs TB polarization differences at 19 GHz instead of TBs at 10GHz.)

The MWI algorithm consists of the forward calculation part to calculate the LUTs, and the retrieval part to estimate precipitation rates from the observed TBs using the LUTs.

In the forward calculation part, we calculate LUTs for homogeneous precipitation by incorporating atmospheric and surface variables of the Japan Meteorological Agency (JMA) global analyses or forecasts and precipitating cloud models based on TRMM observation etc. (Takayabu, 2008; Takahashi and Awaka, 2005) into the RTM program of Liu (1998). We also calculate LUTs for orographic precipitation, following Shige et al. (2013) and Taniguchi et al. (2013). We then derive LUTs for inhomogeneous precipitation from the above LUTs using the approximation of Aonashi and Liu (2000).

The retrieval part performs a detection of precipitation, a retrieval using scattering signals, and an over-ocean retrieval using emission signals. For the detection of precipitation, we adopt the methods of Seto *et al.* (2005), Kubota *et al.* (2007), and Kida *et al.* (2009) over land, coastal areas, and ocean, respectively. In the retrieval using scattering signals, we employ dual frequency PCTs (at 37 and 85 GHz for TMI). We introduce an adjustment method using indices of frozen precipitation depth and surface temperature. In addition, we detect orographic precipitation areas where we use LUTs for orographic precipitation (Yamamoto and Shige, 2014). In the over-ocean retrieval using emission signals, we derive precipitation rate by minimizing a cost function for lower frequency, vertically-polarized TBs (10, 19, and 37 GHz for TMI) with the scattering retrievals as the first guess.

The orographic/nonorogrpahic rainfall classification scheme (Yamamoto and Shige 2014) is a revised scheme developed by Shige *et al.* (2013), Taniguchi *et al.* (2013), and Shige *et al.* (2014). This scheme consists of orographically forced upward motion w (m s^{-1}) and moisture flux convergence Q (s^{-1}) as following equations;

$$w = \frac{Dh}{Dt} = u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} \quad (1)$$

$$Q = -\left(\frac{\partial(uq)}{\partial x} + \frac{\partial(vq)}{\partial y}\right) \quad (2)$$

where h is elevation (m) derived from the Shuttle Radar Topography Mission 30-arc second (see (SRTM30, see section 2.9) with horizontal grid spacing approximately 1 km, u and v are the horizontal surface wind (m s^{-1}) from the GANAL data, and q is water vapor mixing ratio (kg kg^{-1}) calculated from GANAL surface dew point temperature or relative humidity. h is averaged over horizontal length scale 50 km in the calculation of w. An orographic rainfall pixel is defined as

$$w > 0.01 \text{ m s}^{-1}, Q > 0.3\times\ 10^{-6} \text{ s}^{-1} \quad (3)$$

When both conditions are satisfied, the LUT switches from the original rain type to an orographic one.

The vertical profile model for orographic precipitation generates profiles using the same process as in the original model, except when orographic rainfall conditions are met. Under these conditions, regional orographic precipitation profiles in 5° × 5° boxes are generated for the entire PR coverage (40°N−40°S, 0°−360°). Since some areas do not have enough sample numbers the orographic precipitation profiles are used over the Indian subcontinent (15°−20°N, 70°−75°E). These orographic rainfall conditions are applied over all land regions.

Precipitation-size ice particle density for orographic rainfall is set at 100 kg m^{-3} and that for non-orographic rainfall is 400 kg m^{-3}.

The scheme is switched off for regions (e.g. the Sierra Madre Mountains in the United States and Mexico) where strong lightning activity occurs in the rainfall type database because deep convective systems for the regions are involved in the orographic rain condition.

4.2. Microwave Sounder Algorithm (GSMaP_MWS)

The GSMaP over-ocean rainfall retrieval algorithm for microwave sounders (MWS) was developed by Shige et al. (2009) based on the GSMaP algorithm for microwave imagers (MWI). This algorithm combines an emission-based estimate from brightness temperature (Tb) at 23 GHz and a scattering-based estimate from Tb at 89 GHz. Precipitation inhomogeneities are also taken into account. Improvements of rain/no-rain classification method over coast and mitigation of underestimation in mountainous areas (Shige et al., 2013, Taniguchi et al., 2013) have been done.

The GSMaP over-land rainfall retrieval algorithm for MWS is a scattering algorithm that mainly relies on Tb data at 89 GHz and its rain/no-rain classification method has been developed utilizing Tb data at 150 GHz and 180 GHz (Kida et al. 2012).

In the MWS algorithm, LUT is fitted by a five degree polynomial function of incident angle number. The MWS algorithm saves coefficients of the regression function. The LUT is reconstructed from the regression coefficients in the retrieval algorithm for MWS.

4.3. Microwave Imager/Sounder Algorithm (GSMaP_MWIS)

The GSMaP rainfall retrieval algorithm for microwave imager/sounders (MWIS) was developed by Kubota et al. (2011) based on the GSMaP algorithm for microwave imagers (MWI). SSMIS does not have 10 GHz channels same as SSM/I, the algorithm combines emission-based estimates using TB polarization differences at 19 GHz, in addition to emission-based estimates using TB at 19 GHz vertical polarization and scattering-based estimates using TB at 89 GHz, over the ocean. Precipitation inhomogeneities are also taken into account. See Kubota et al. (2011) for more details.

The GSMaP over-land rainfall retrieval algorithm for MWIS was developed based on the GSMaP algorithm for microwave imagers (MWI).

4.4. Microwave-IR Merged Algorithm (GSMaP_MVK)

GSMaP_MVK is a product that integrates passive microwave radiometer data with infrared radiometer data in order to have high temporal (1 hour) and spatial (0.1 degree) resolution global precipitation estimates. The product (GSMaP_MVK) is produced based on a Kalman filter model that refines the precipitation rate propagated based on the atmospheric moving vector derived from two successive IR images. The detail of the algorithm can be found in Ushio et al. (2009).

4.5. Gauge-calibrated rainfall algorithm (GSMaP_Gauge)

GSMaP_Gauge is a product that adjust the GSMaP_MVK estimate with global gauge analysis (CPC Unified Gauge-Based Analysis of Global Daily Precipitation) supplied by NOAA. The product also has the same spatial and temporal resolution with GSMaP_MVK and GSMaP_NRT, which is 0.1 degree and 1 hour. The adjustment is applied to the estimation only over land, and the rain rate over ocean, GSMaP_Gauge and GSMaP_Gauge_NRT, are same as that from GSMaP_MVK and GSMaP_NRT for near real time version, respectively. The rain rate of GSMaP_Gauge is calculated based on the optimal theory which adjusts the GSMaP_Gauge hourly rain rate so that the sum of the 24 hour GSMaP_Gauge rain rate is roughly same as the gauge measurement (Ushio *et al.*, 2013).

4.6. Near-real-time Algorithm (GSMaP_NRT)

Near-real-time algorithm is based on standard algorithm, but some simplification in the processing are implemented to keep operability and data latency in near-real-time. Major differences between near-real-time and standard processing are as follows.

- JMA forecast data is used as atmospheric information
- Latest available MGDSST data is used as SST information
- Only temporarily forward cloud movement is used in microwave-IR merged module
- Only the error parameters are used to adjust the GSMaP_NRT estimation in gauge adjustment module

5. MODULES

5.1. Overview

Figure 1 is algorithm flow of GPM-GSMaP.

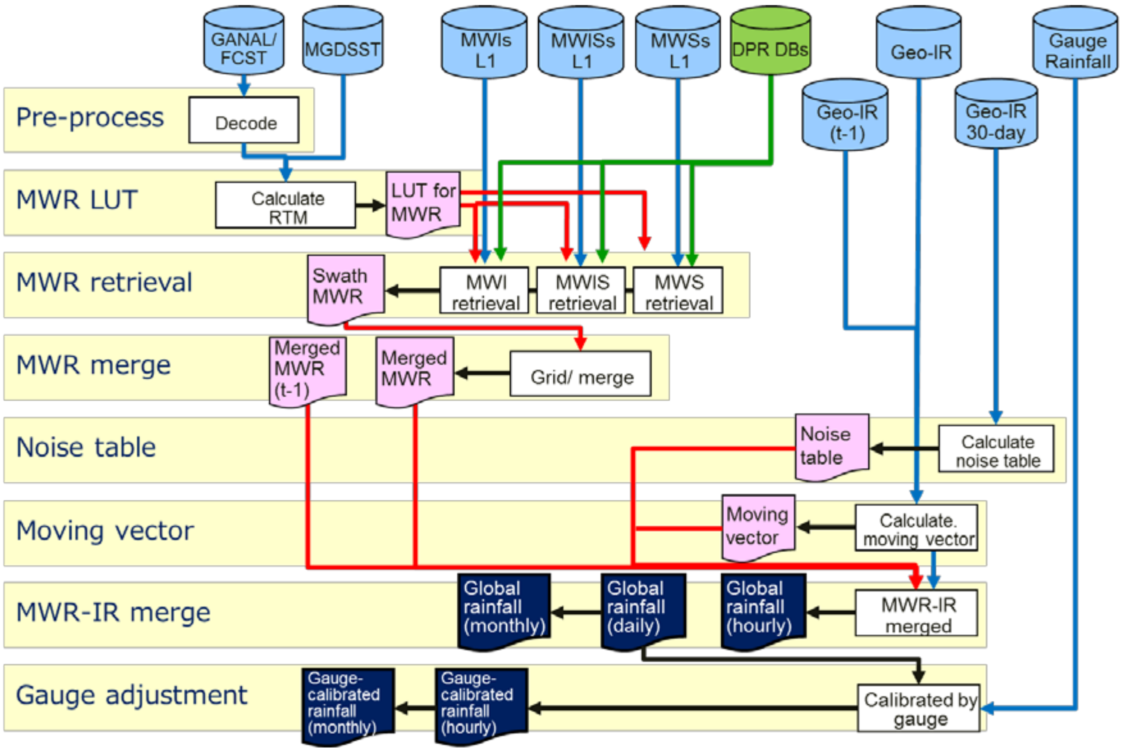

Figure 1 Algorithm flow of GPM-GSMaP

5.2. Major modules

Followings are major modules constructed the GPM-GSMaP algorithm.

- Pre-processing module
- Microwave radiometer (MWI, MWS, MWIS) look-up table module
- Microwave radiometer retrieval module
- Microwave radiometer merging module
- Noise table processing module
- Cloud moving vector calculation module
- Microwave-IR merging module
- Gauge adjustment module

6. VALIDATION

6.1. Validation Plan

Precipitation has wide fluctuation in temporal and horizontal variation, and one of the most difficult geophysical parameters to compare directly to ground observations. Basically, validation of precipitation uses current operational ground-based radar and rain gauge networks, but comparison with space-borne precipitation radar is critical in terms of accuracy and homogeneity of ground truth data. Also, simultaneous observation of cloud physics of solid precipitation and microwave radiometer is needed to evaluate scatter algorithm, we plan to coordinate with the validation plan and campaign experiments for the GPM Dual-frequency Precipitation Radar.

6.2. Comparison with Space-borne Precipitation Radar

The Global Rainfall Map and/or each microwave radiometer retrieval will be routinely compared with space-borne radars, such as TRMM/PR and GPM/DPR.

6.3. Comparison with Ground-based Data

The Global Rainfall Map and/or each microwave radiometer retrieval will be compared with JMA AMeDAS (rain gauge), Radar-AMeDAS (gauge-calibrated ground-based radar analysis (merged and gridded data) over Japan), and ground-based radar.

Also, in collaboration with the GPM Ground Validation team, the Global Rainfall Map will be validated and evaluated its accuracy in global scale, by using ground-based observation data in various climate zones outside Japan, such as East Asia, over the ocean, etc.

6.4. Collaboration with GCOM-W1/AMSR2

Validation of GSMaP_MWI algorithm will collaborate with validation activities of the GCOM-W/AMSR2 project. GCOM-W project routinely produces match-up dataset of AMSR2 observations with space-borne precipitation radar or ground-based rain gauge and radar data, and compares them. Those results will be uploaded to the GCOM-W/AMSR2 Validation web site (in operation since 2012),

6.5. Collaboration with International Precipitation Working Group

The team will join international precipitation inter-comparison activities led by the International Precipitation Working Group (IPWG) co-hosted by the Coordination Group of Meteorological Satellites (CGMS) and World Meteorological Organisation (WMO), to contribute coherent validation of precipitation products. Kyoto University, in collaboration with the JAXA/GPM research project, is currently operating Japanese IPWG validation web site for inter-comparison of multi-satellite precipitation products (http://www-ipwg.kugi.kyoto-u.ac.jp/IPWG/sat_val_Japan.html). The team will coordinate with this activity to implement comparison and monitoring time-series of the Global Rainfall Map and/or each microwave radiometer retrieval with JMA Radar-AMeDAS rainfall analysis in hourly and daily basis.

7. ALGORITHM DEVELOPMENT SCHEDULE

Figure 2 shows algorithm development schedule of GPM-GSMaP, as of August 2014.

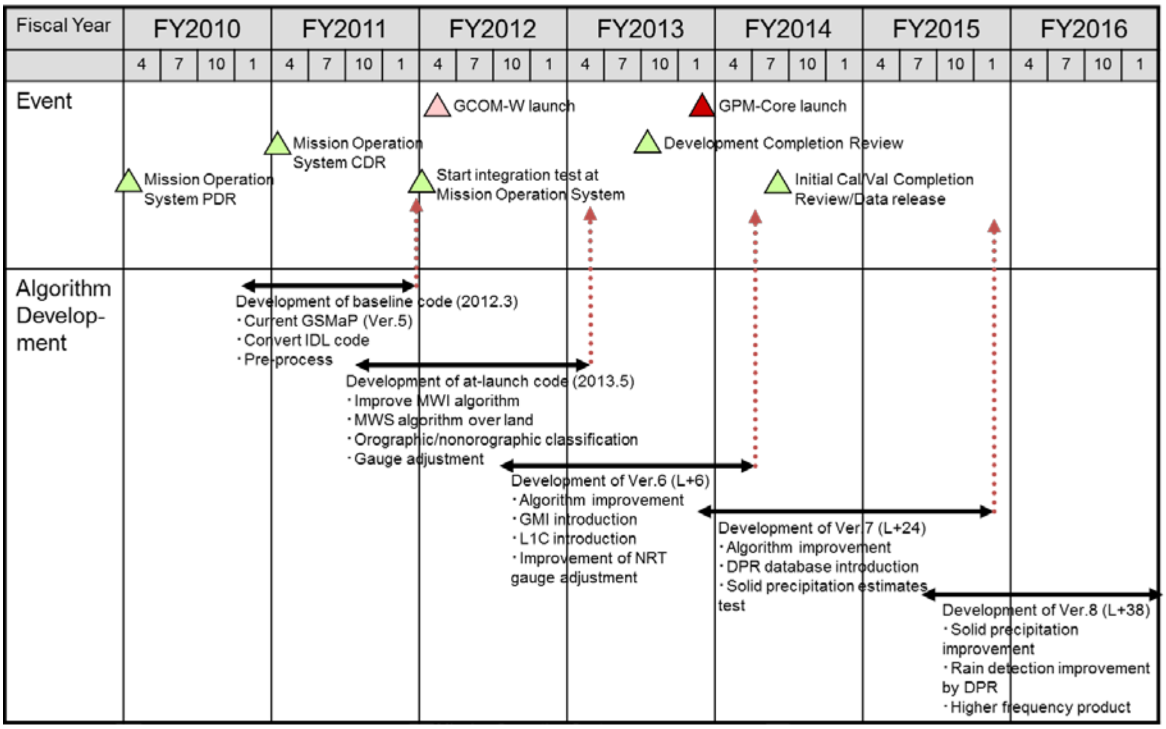

Figure 2 Schedule of algorithm development (as of August 2014)

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