

**GPM Combined Radar-Radiometer Precipitation
Algorithm Theoretical Basis Document (Version 3)**

William S. Olson, Hirohiko Masunaga

and the

GPM Combined Radar-Radiometer Algorithm Team

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1. Introduction

The GPM Combined Radar-Radiometer Algorithm performs two basic functions: first, it provides, in principle, the most accurate, high resolution estimates of surface rainfall rate and precipitation vertical distributions that can be achieved from a spaceborne platform, and it is therefore valuable for applications where information regarding instantaneous storm structure are vital. Second, a global, representative collection of combined algorithm estimates will yield a single common reference dataset that can be used to “cross-calibrate” rain rate estimates from all of the passive microwave radiometers in the GPM constellation. The cross-calibration of radiometer estimates is crucial for developing a consistent, high time-resolution precipitation record for climate science and prediction model validation applications. Because of the Combined Algorithm’s essential roles as accurate reference and calibrator, the GPM Project is supporting a Combined Algorithm Team to implement and test the algorithm prior to launch. In the pre-launch phase, GPM-funded science investigations may lead to significant improvements in algorithm function, but the basic algorithm architecture has been formulated. This algorithm architecture is largely consistent with the successful TRMM Combined Algorithm design, but it has been updated and modularized to take advantage of improvements in the representation of physics, new climatological background information, and model-based analyses that may become available at any stage of the mission. This document presents a description of the GPM Combined Algorithm architecture, scientific basis, supporting ancillary datasets, inputs/outputs, and testing plan.

2. Background

GPM Instruments

The GPM core mission satellite observatory is shown in Fig. 1. From this platform, the Dual-frequency Precipitation Radar (DPR) scans cross-track in relatively narrow swaths at Ku band (13.6 GHz) and Ka band (35.5 GHz). The dual-frequency radar reflectivity observations are nearly beam-matched over the 125 km Ka-band swath, with a horizontal resolution of approximately 5 km, and a vertical resolution of 250 m in standard observing mode. The Ku band radar scans over a wider, 245 km swath. The GPM Microwave Imager (GMI) scans conically over an 885 km wide swath at frequencies of 10.65, 18.7, 23.8, 36.5, 89.0, 165.5, 183.31 ± 7 , and 183.31 ± 3 GHz. Measured brightness temperatures are in two polarizations (vertical and horizontal) at all but the 23.8 GHz and 183.3 GHz channels, which provide only vertical polarization measurements. The GMI observations are diffraction limited, with the lowest-resolution footprints (approx. 26 km) at 10.7 GHz and the highest-resolution footprints (approx. 6 km) at the 89.0 GHz and higher frequency channels.

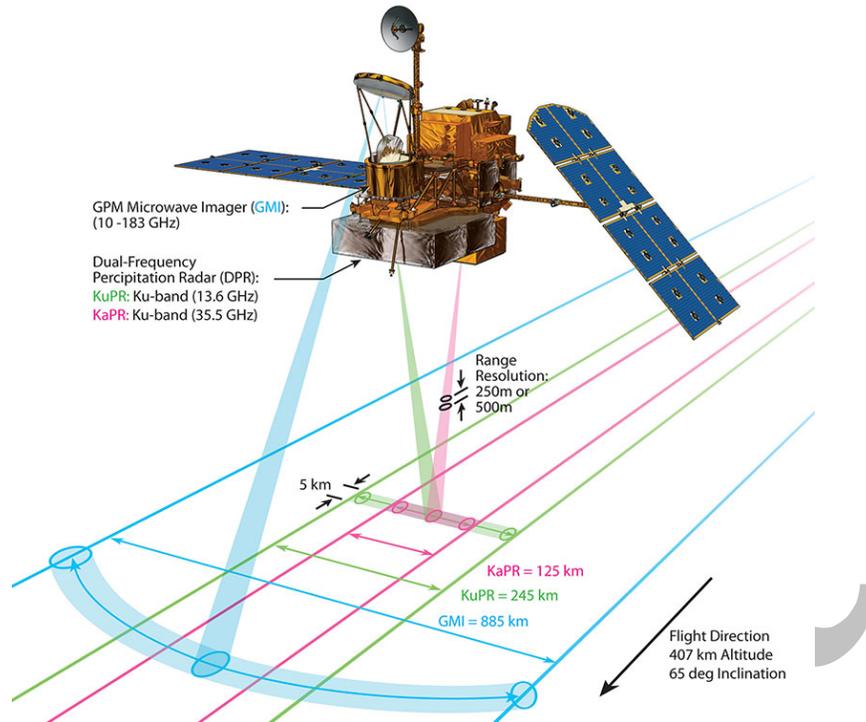


Fig. 1. Configuration of the GPM core observatory, illustrating the scanning geometry of the DPR and GMI instruments.

Implications for Algorithm Design

The current GPM Combined Radar-Radiometer Algorithm architecture is descended from a rich heritage of algorithms that were developed for the TRMM mission, as well as other algorithms developed and applied to airborne radar-radiometer data. In TRMM, only Ku-band radar observations were available from the radar instrument (the Precipitation Radar, or PR), and only lower-frequency (10 - 85 GHz) brightness temperature measurements were available from the microwave radiometer (the TRMM Microwave Imager, or TMI). The TRMM Facility Combined Algorithm used radiometer information to essentially reduce uncertainties in estimates of radar-derived total path-integrated attenuation to the earth's surface to perform an improved attenuation correction of the radar reflectivity vertical profile. The improved attenuation correction was effected by adjusting a single parameter of the precipitation particle-size distribution over the entire precipitation vertical profile. This single parameter represented a rain-normalized, mass-weighted mean particle diameter, which was assumed to be locally constant over the scale of TMI footprints. Adding horizontal variations of this parameter would have introduced too many free parameters to the inversion problem.

The GPM Combined Algorithm takes advantage of the additional Ka band radar channel to glean more specific information about the precipitation size distribution and associated attenuation in each gate. The estimation of

precipitation size distribution parameters is further aided by precipitation attenuation information from the GMI channels, which have an extended spectral range relative to the TMI. However, if the Ka band reflectivities do not provide additional information due to very light rain (Rayleigh limit), or they are severely attenuated in heavy precipitation, then the combined algorithm must make a natural transition to a single-frequency, Ku band solution in which a more approximate estimation of precipitation size distribution parameters is performed.

Regardless of whether or not the Ka band data are applicable, however, information from the GMI brightness temperatures can be used to make further adjustments of path attenuation due to non-precipitating cloud liquid water and water vapor, which are not directly sensed by the DPR. In addition, there are precipitation microphysical parameters, such as the intercept of the particle size distribution and the density of ice-phase precipitation that may be adjusted using radiometer information.

Ultimately, the degree to which any precipitation or environmental parameters can be adjusted is limited by the information content of the DPR and GMI observations and any additional information provided by *a priori* data, such as the natural ranges of particle size distribution parameters, cloud water contents, etc., and how these parameters covary spatially. Therefore, as outlined in section 3, the combined algorithm is designed to be able to accept both different physical modeling assumptions and *a priori* constraints on estimated parameters.

3. Algorithm Architecture

Overview

The current algorithm design is based upon an Ensemble Kalman Filtering (EnKF) approach for inverting the DPR reflectivities and GMI brightness temperatures to estimate precipitation profiles; see Anderson (2003) for a general description of EnKF approaches. The general architecture of the GPM Combined Algorithm is illustrated in Fig. 2a,b. There are four primary modules in the Combined Algorithm: an Environment Module, which establishes the environmental background of the precipitation distributions to be estimated, a Ku Radar Module, which produces ensembles of Ku radar-consistent precipitation profile solutions at each DPR footprint location, a Forward Model Module, that simulates the remaining DPR and GMI measurements, and a Filter Module, that modifies the Ku radar-derived precipitation ensembles to be more consistent with remaining observations. The outputs of the algorithm are the mean (best estimate) and standard deviation (uncertainty of estimate) of the DPR-GMI filtered ensemble of estimated precipitation profiles at each DPR footprint location. Following is a description of the algorithm flow from the ingest of satellite sensor data to the output of precipitation estimates.

The Environment Module (Fig. 2a) first ingests DPR Level 2 calibrated reflectivities at Ku and Ka band (if available) as well as Level 1C intercalibrated brightness temperatures from the GMI. To stay within computer memory limitations, a maximum of 300 scan lines of DPR data and corresponding GMI data are processed by the algorithm at a time. Therefore, the flow diagram of Fig. 2a represents the processing of one swath segment, which is repeated until the entire orbit is processed. The DPR footprint locations define an approximate 5 km x 5 km grid on the earth's surface, and these footprints are used to represent the solution grid for algorithm-estimated precipitation profiles.

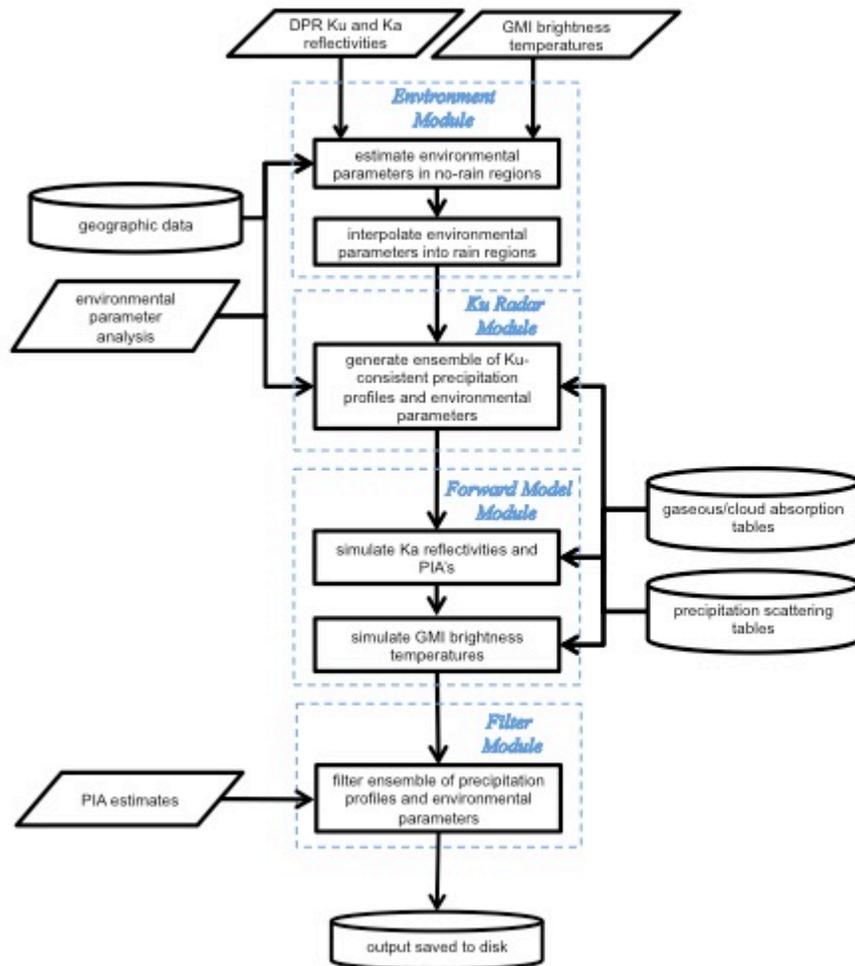


Fig. 2a. Processing schematic for the Combined Radar-Radiometer Algorithm.

The next step is to assign surface water fraction and elevation values to the DPR footprint locations. Surface water fraction and elevation values are drawn from a static geographic database and interpolated to the DPR footprint locations.

To create a uniform grid of input data, the GMI brightness temperatures (**TB**) are interpolated from the GMI scans to the DPR footprint locations. A screening method is then applied to the GMI data to determine if precipitation is "possible" at each footprint location. The screening method is derived from the GPROF Algorithm V6 methodology; see McCollum and Ferraro (2005). If precipitation is not possible according to the screening method, a Bayesian estimator is applied to the interpolated TB data to derive environmental parameters. The environmental parameters include column-integrated water vapor (*TPW*), cloud liquid water path (*CLWP*), surface skin temperature (*Tsfc*), and 10-m altitude wind speed (*U10m*). After the environmental parameters are estimated in regions where rain is not possible, they are linearly interpolated into the regions where rain is possible, creating a complete field of environmental parameters on the DPR grid.

The Ku Radar Module (Fig. 2a) ingests all output from the Environment Module, including the fields of GMI-derived environmental parameters on the DPR grid. In regions where precipitation is detected, the interpolated estimates of water vapor, cloud water, surface skin temperature, and 10-m wind speed are derived from relatively coarse-scale GMI observations (~15 km) in non-precipitating conditions, and therefore it is not expected that the interpolated estimates will accurately represent conditions in precipitating clouds at the spatial resolution of the DPR grid (5 km). For example, water vapor and cloud amounts may be enhanced in precipitation regions relative to their surroundings. Moreover, even if the environment of a given radar profile is correctly specified, it is not certain that all parameters describing the precipitation size distribution (PSD) in each radar range bin can be retrieved from the Ku- and Ka-band reflectivity profiles at that location.

Therefore, to represent the *a priori* distributions of environmental and PSD parameters at each DPR footprint location where precipitation is detected, ensembles of 3D parameter fields are generated. Typically, 50-member ensembles of these parameter fields are generated; only a coarse representation of any *a priori* pdf's of the parameters are needed, since subsequent EnKF filtering of the ensembles will effectively modify the original pdf's to create new, "interpolated" pdf's of the parameter fields consistent with the observations. A detailed description of the filtering will follow in this subsection.

The 3D ensembles of environmental parameters in precipitation regions can be generated based upon the interpolated GMI estimates or derived independently. Different methods for generating the 3D ensembles are under investigation. Currently, the *Tsfc* and *U10m* values spatially interpolated from the GMI estimates are specified for all ensemble members, and pressure and temperature vertical profiles are parameterized as functions of *Tsfc*. On the other hand, water vapor and cloud water vertical profiles are currently drawn from static CRM-generated databases that represent the region of algorithm

application, and these profiles are assigned to DPR footprint locations to create the 3D ensembles. The water vapor density profile, \mathbf{q}_v , and cloud water content profile, \mathbf{q}_{cl} , are randomly assigned to each ensemble member from distributions of profiles stored in the static database. The atmospheric profiles are re-sampled in the vertical at the nominal bin resolution of the DPR (250 m).

To the 3D ensembles of T_{sfc} , U_{10m} , pressure, temperature, \mathbf{q}_v , and \mathbf{q}_{cl} are added PSD parameters at the nominal radar bin resolution. It is assumed that the precipitation particle size distribution in each bin is described by a normalized gamma distribution (Testud et al. 2001),

$$n(D) = N_w f(\mu) \left(\frac{D}{D_m} \right)^\mu \exp\left(-\frac{(4+\mu)}{D_m} D \right), \quad (1)$$

where

$$f(\mu) = \frac{6(4+\mu)^{\mu+4}}{4^4 \Gamma(4+\mu)}. \quad (2)$$

Here, N_w is the intercept of the normalized distribution, D_m is the volume-weighted mean diameter, μ is the distribution shape factor, D is the liquid-water equivalent diameter of the particle, and $n(D)$ is the spectral number density of particles with diameter D . Since there are at most two independent radar-derived reflectivity observations associated with each DPR range bin, the solution strategy is to fix one of the three free parameters of the size distribution, allow a second that varies slowly in space to be modified by the EnKF filtering, and determine a third using the radar data, since the first two parameters are defined for a given ensemble member. In the current algorithm, μ is assumed constant across all of the ensembles. An autoregressive function is used to generate N_w values in each profile, starting with a random value drawn from an assumed pdf at the top of the profile. These profiles of N_w are randomly assigned at a sample spacing coarser than the DPR grid and then interpolated to the DPR footprint locations. The purpose of the autoregressive generation and spatial interpolation of N_w profiles is to create correlated values of N_w across the precipitation field in any given ensemble member, since such correlations are observed in field studies; e.g., Tokay and Bashor (2010); Thurai et al. (2011). Fixing and imposing spatial correlations on N_w values helps to limit the effective number of free parameters in the estimation problem. The third parameter, D_m , in each range bin is inverted from the profile of Ku band reflectivities and the given ensemble member profiles of μ and N_w at each DPR footprint location, as described forthwith.

To estimate the PSD parameters at each DPR footprint location, the reflectivity profile at Ku band is first corrected for gaseous and cloud water attenuation in each of the 50 ensemble member environmental profiles. The

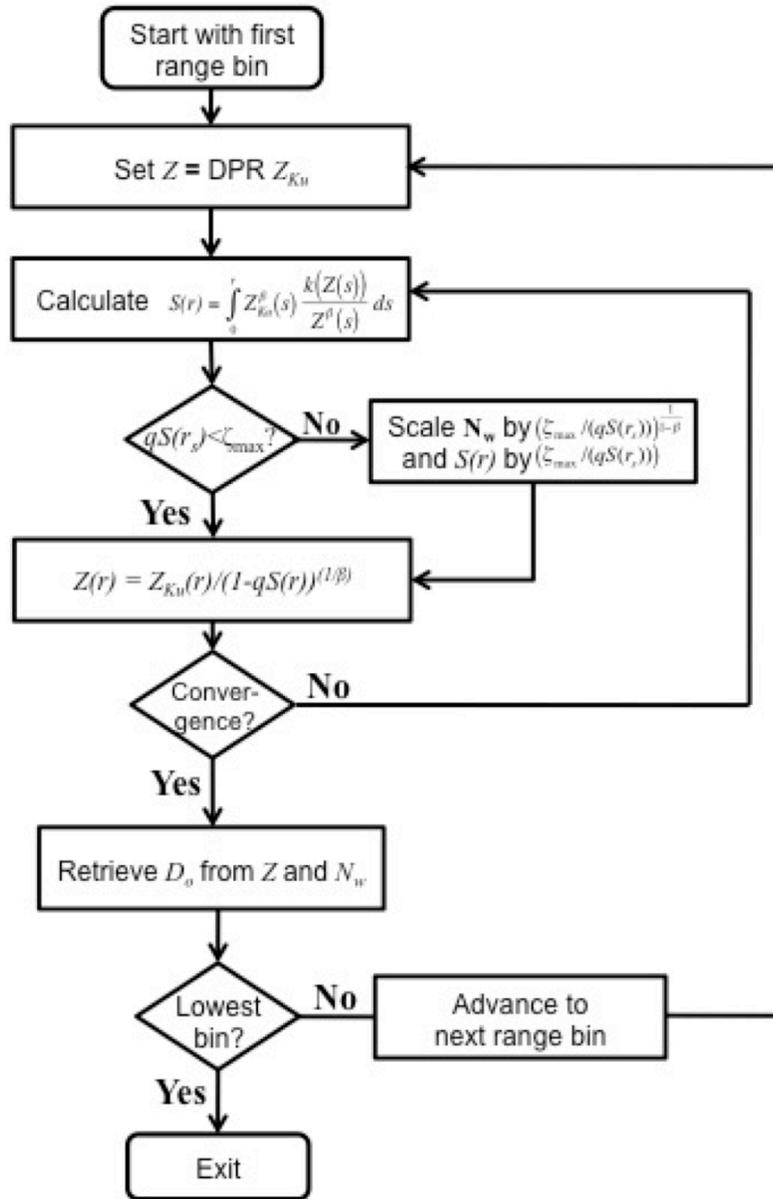


Fig. 2b. Schematic for the generalized Hitschfeld-Bordan, contained in the Ku Radar Module; see Fig. 2a.

specific absorption by atmospheric gases and cloud water as a function of pressure, temperature, humidity and cloud water content is drawn from tabulated values at the Ku band frequency. The remaining attenuation in each ensemble member reflectivity profile is due to precipitation.

Using the gas/cloud absorption-corrected Ku reflectivity profile, Z_{Ku} , associated with a given ensemble member, a generalized Hitschfeld-Bordan method is applied to solve for the profile of D_m for that member; see Grecu et al. (2011). The generalized Hitschfeld-Bordan method is a single-wavelength,

forward recursive method that iteratively computes the effective reflectivity and extinction by precipitation in a given range bin; then attenuation-corrects the reflectivity in the next range bin of the profile; see Fig. 2b. In the generalized approach, the iteration of reflectivity and extinction calculations is made computationally efficient through an analytical manipulation of the radar equation; see Grecu et al. (2011). The iteration equation is

$$Z(r) = \frac{Z_{Ku}(r)}{\left[1 - q \int_0^r Z_{Ku}^\beta(s) \frac{k(Z(s))}{Z^\beta(s)} ds\right]^{1/\beta}}, \quad (3)$$

where $Z(r)$ is the attenuation-corrected reflectivity at range r , $Z_{Ku}(r)$ is the measured reflectivity at that range, $k(Z)$ is the specific extinction corresponding to reflectivity Z , $q = 0.2 \ln(10)$, and $k = \alpha Z^\beta$ is an approximate k-Z relation that is introduced to reduce the number of iteration steps. The actual relationships between precipitation extinction and reflectivity are represented by static "scattering" tables of these quantities for a range of N_w and D_m values, given μ . In high-attenuation regimes, numerical instabilities are avoided by rescaling the N_w profile; see Fig. 2b. The generalized Hitschfeld-Bordan method is applied to all of the member profiles in the ensemble at each Ku-band footprint location.

If valid Ka-band data and/or GMI brightness temperature data are available, the algorithm passes to the Forward Model Module; see Fig. 2a. Recall that each ensemble member profile is actually part of a 3D field that spans the swath segment, and so there is a 50-member ensemble of 3D environmental/precipitation parameter fields that are input to the Forward Model Module. Now, first considering only one ensemble member 3D field of environmental/precipitation parameters, the single scattering properties at each radar bin location of the 3D field are calculated using the gaseous/cloud absorption and precipitation scattering tables previously described. The single-scattering properties are used to simulate the Ka reflectivities, \mathbf{Z}_{Ka} , and PIA's at Ku and Ka band, PIA_{Ku} and PIA_{Ka} , respectively. Also, the surface emissivities at the GMI frequencies can be calculated from the $Tsfc$ and $U10m$ values that are also defined for that ensemble member. This is sufficient information to perform forward radiative transfer calculations of the upwelling microwave radiances at the GMI channel frequencies and polarizations at the DPR footprint locations. The ensemble member is now associated with a 5 km (DPR) resolution field of simulated \mathbf{Z}_{Ka} , PIA_{Ku} and PIA_{Ka} , and upwelling radiances across the swath. A convolution of the upwelling radiance fields by the GMI antenna patterns yields a simulation of the GMI brightness temperatures, \mathbf{TB} , at the DPR footprint locations. The simulations of \mathbf{Z}_{Ka} , PIA_{Ku} and PIA_{Ka} , and \mathbf{TB} are repeated for all of the ensemble member fields.

In the Filter Module (Fig. 2a), the covariances between the unknown \mathbf{q}_v , \mathbf{q}_{cld} , $\log_{10}(\mathbf{N}_w)$ and the simulated observations are then computed from the ensembles of the parameters. With respect to DPR, the ensemble covariances describe how variations of the unknown parameters in the ensemble should relate to variations in observed \mathbf{Z}_{Ka} , PIA_{Ku} and PIA_{Ka} . Similarly, covariances between the unknowns and the simulated \mathbf{TB} are also computed. In this case, however, only the covariances of unknown parameters located at the DPR footprint coinciding with the maximum of the GMI antenna pattern are computed. This limitation is for practical implementation of the algorithm, since the \mathbf{TB} at any location are, in principle, a function of the unknowns across substantial areas of the swath, but including all of these dependencies leads to a computationally unmanageable procedure.

The covariances between the unknowns and simulated observations, combined with the actual observations, are used to update the ensemble of Ku-band solutions with the EnKF. Let $\mathbf{X}_i = [\mathbf{q}_{v-i} \ \mathbf{q}_{\text{cld}-i} \ \log_{10}(\mathbf{N}_{w-i})]^T$ be a vector of the unknown parameters in the i th ensemble member at a given DPR footprint location. Also, let $\mathbf{Y} = [\mathbf{Z}_{\text{Ka}} \ \mathbf{PIA}, \mathbf{TB}]^T$ be a vector of observed Ka-band reflectivities, path-integrated attenuations, $\mathbf{PIA} = [\text{PIA}_{\text{Ku}} \ \text{PIA}_{\text{Ka}}]^T$, derived from the surface reference technique, and GMI observations, all at a given DPR footprint location. In addition, let $\mathbf{H}(\mathbf{X}_i)$ the simulation of the observations \mathbf{Y} from the unknown parameters of the i th ensemble member. Then, at each DPR footprint location and for each ensemble member, the EnKF update, \mathbf{X}_i' , is given by

$$\mathbf{X}_i' = \mathbf{X}_i + \mathbf{PH}^T (\mathbf{HPH}^T + \mathbf{R})^{-1} [\mathbf{Y} - \mathbf{H}(\mathbf{X}_i)], \quad (4)$$

where

$$\mathbf{PH}^T = \frac{1}{N-1} \sum_{i=1}^N (\mathbf{X}_i - \bar{\mathbf{X}}) [\mathbf{H}(\mathbf{X}_i) - \overline{\mathbf{H}(\mathbf{X})}]^T, \quad (5)$$

$$\mathbf{HPH}^T = \frac{1}{N-1} \sum_{i=1}^N [\mathbf{H}(\mathbf{X}_i) - \overline{\mathbf{H}(\mathbf{X})}] [\mathbf{H}(\mathbf{X}_i) - \overline{\mathbf{H}(\mathbf{X})}]^T, \quad (6)$$

and

$$\mathbf{R} = \begin{bmatrix} \mathbf{W}_{\text{Z}_{\text{Ka}}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{W}_{\text{PIA}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{W}_{\text{TB}} \end{bmatrix}. \quad (7)$$

Here, \mathbf{PH}^T is the ensemble covariance of the unknown parameters and the simulated observations, \mathbf{HPH}^T is the ensemble covariance of the simulated observations, \mathbf{R} is a matrix of the uncertainties in the observations, and N is the number of ensemble members. Estimated \mathbf{PIA} from the surface reference

technique are provided by the Level 2 Radar Algorithm output.

The form of (4)-(7) is similar to Eqs. (8)-(11) in Grecu and Olson (2008), but applied to the combined radar-radiometer estimation problem. The objective is to modify the environmental and precipitation profile parameters from the Ku-band solution to the extent that the observed \mathbf{Z}_{Ka} , \mathbf{PIA} , and \mathbf{TB} contain additional information. If the observed \mathbf{Z}_{Ka} are not available or are totally attenuated by heavy rain, or if the rainfall is light (Rayleigh regime, where $Z_{Ku} = Z_{Ka}$), then the Ku-band solution will not be modified by the \mathbf{Z}_{Ka} , although the \mathbf{PIA} and \mathbf{TB} data can still alter the solution.

Equation (4) is applied to all 50 ensemble member profiles at each DPR footprint location, creating an output ensemble of μ , N_w , and D_m profiles and environmental parameters that are consistent with the observed reflectivities and path-integrated attenuations at both Ku and Ka band, as well as the observed brightness temperatures.

The outputs of the Filter Module are ensembles of environmental/precipitation parameters consistent with both the DPR and GMI observations and their errors. The best estimate of the environmental/precipitation parameters at any DPR location is given by the mean of the ensemble,

$$\bar{\mathbf{X}} = \frac{1}{N} \sum_{i=1}^N \mathbf{X}_i, \quad (8)$$

and the uncertainty of the best estimate is given by the ensemble standard deviation,

$$\mathbf{s}_x = \left[\frac{1}{N-1} \sum_{i=1}^N (\mathbf{X}_i - \bar{\mathbf{X}})(\mathbf{X}_i - \bar{\mathbf{X}})^T \right]^{1/2}. \quad (9)$$

The uncertainty, \mathbf{s}_x , represents the error in the best estimate resulting from errors in the observations as well as ambiguities due to the limited information content of the observations. Note that other precipitation-related parameters, such as the surface rainfall rate or precipitation liquid water content can be estimated using (4), (8), and (9), by adding these to the vector \mathbf{X}_i .

Once the output of the Radiometer Module is saved to disk, the next 300 scan lines of DPR and coincident GMI data are processed, and so on, until the whole orbit is processed.

In the following subsections, the basic functions of the three primary modules of the Combined Radar-Radiometer Algorithm, including input and output parameters, are described. Supporting modules, datasets, and tables are

described in section 4.

Environment Module

The basic function of the Environment Module is to ingest one orbit of DPR reflectivities, as well as an orbit of GMI brightness temperatures, and produce fields of environmental (non-precipitation) parameters at DPR sampling resolution. The sensor inputs required are the calibrated DPR Z_{Ku} and Z_{Ka} profiles from the Level 2 Radar Algorithm, and the intercalibrated GMI TB from the Level 1C Radiometer Algorithm. One orbit of input data from each of these algorithms is required, but in addition, two 50-scan overlap fields of GMI data at the orbit boundaries is needed.

In addition to these sensor inputs, the Environment Module requires Level 2 Radar Algorithm ancillary environmental data that include pressure, temperature, vapor density, cloud liquid water content, surface skin temperature, and wind speed at 10-m altitude, interpolated to the DPR footprint locations and range bin altitudes, as appropriate. These data are provided by the Vertical Profile Submodule (VER) of the Radar Algorithm, which interpolates the Japanese Meteorological Agency's (JMA) analyses and forecasts to the DPR locations/range bins; see section 4 for details. The analysis fields of total precipitable water, TPW_{anal} , non-precipitating cloud liquid water path, $CLWP_{anal}$, surface skin temperature, $Tsfc_{anal}$, and 10-m altitude wind speed, $U10m_{anal}$ are used to constrain Bayesian estimates of these environmental parameters. The Environment Module also requires input from a static geographic database that includes surface water coverage and elevation information; see section 4.

The Bayesian estimator of environmental parameters in the Environment Module requires supporting data that describe the relationships between the environmental parameters and upwelling microwave brightness temperatures at the GMI channel frequencies/polarizations. These relationships are represented by databases of environmental parameters and physically consistent microwave brightness temperatures. A database relating environmental TPW , $CLWP$, $Tsfc$, and $U10m$ to microwave brightness temperatures over ocean backgrounds has been developed, and so currently, estimates of these environmental parameters are performed only over open ocean regions. The Bayesian estimator will be extended to over-land applications by including over-land distributions of environmental parameters and physically-consistent microwave brightness temperatures in the supporting database; see section 4 for details.

The output of the Environment Module are estimates of TPW , $CLWP$, $Tsfc$, and $U10m$, that are interpolated into precipitation regions to create a complete field of environmental parameters across the Ku band swath.

Ku Radar Module

The Ku Radar Module accepts input fields of environmental parameters from

the Environment Module as well as DPR Ku reflectivity information. Its primary function is to estimate ensembles of environmental and precipitation parameters consistent with these input data at each DPR footprint location, using the generalized Hitschfeld-Bordan approach. Specifically, input to the Radar Module are fields of environmental TPW , $CLWP$, $Tsfc$, and $U10m$ from the Environment Module, as well as calibrated \mathbf{Z}_{Ku} from the Level 2 Radar Algorithm, passed through the Environment Module. Other inputs from the Level 2 Radar Algorithm are precipitation detection and classification information that establish the basic *a priori* vertical structure of the precipitation where it is detected. Precipitation detection data are derived from the Preparation Submodule (PRE) of the Radar Algorithm, while classification information is derived from the Classification Submodule (CSF) of that algorithm.

The Ku Radar Module also draws upon tabulated gaseous/cloud absorption coefficients and single-scattering parameters that have been pre-computed for the purpose of algorithm efficiency. Tables of gaseous absorption coefficients at Ku and Ka band, as well as the GMI channel frequencies, are currently calculated as functions of pressure, temperature, and vapor density. Tables of cloud water/ice absorption coefficients at the same frequencies are currently calculated as functions of temperature and equivalent liquid water content; see section 4 for details.

Because precipitation of all phases produces scattering as well as absorption/emission of microwaves, and since the particle size distribution, phase, and temperature of precipitation determine its bulk scattering and absorption/emission characteristics, separate databases are used to tabulate the single-scattering properties of precipitation. In these tables, values of reflectivity, extinction coefficient, scattering coefficient, and asymmetry parameter are tabulated as functions of μ , D_m , and $\log_{10}(N_w)$, which define a normalized gamma distribution of precipitation particle sizes. Ice, liquid water, and mixed-phase particles are represented in the tables. Using the tables, the scattering parameters are derived at Ku band in the Ku Radar Module.

Ensembles of Ku-band consistent ensembles of μ , D_m , and $\log_{10}(N_w)$ are calculated in the Ku Radar Module using the generalized Hitschfeld-Bordan method.

The output of the Radar Module are ensembles of 3D fields of pressure, temperature, vapor density, cloud water content, μ , N_w , and D_m , and 2D fields of $Tsfc$ and $U10m$, consistent with the DPR fields of Z_{Ku} and their uncertainties.

Forward Model Module

The Forward Model Module accepts input ensemble fields of environmental/precipitation parameters, as well as observed \mathbf{Z}_{Ku} , \mathbf{Z}_{Ka} , and \mathbf{TB} , from the Ku Radar Module. Its primary function is to perform forward radiative calculations

of **Z_{Ka}**, **PIA**, and **TB**, for each ensemble input field.

In addition to the inputs from the Ku Radar Module, the Forward Model Module utilizes the static gaseous/cloud absorption and scattering tables described in the previous subsection. Based upon the input ensembles of pressure, temperature, vapor density, cloud water, μ , N_w , and D_m fields, the Forward Model Module derives the corresponding fields of single-scattering parameters for each ensemble member at the DPR and GMI channel frequencies using these tables. In addition, the fields of T_{sfc} and $U10m$ associated with the ensembles are used to calculate the ocean surface emissivity, based upon the model of Wilheit (1979). Currently over other surfaces, emissivities are estimated using the TELSEM tool in conjunction with analysis data (to provide *a priori* information); see section 4.

The atmospheric temperature and single-scattering properties, as well as the surface skin temperature and emissivities, at each DPR footprint location are used to simulate the **Z_{Ka}** and **PIA**, and they are also input to a radiative transfer model to calculate the upwelling microwave radiances at that location. Eddington's Second Approximation, which accounts for multiple-scattering effects but which is also computationally-efficient, is utilized for these calculations; see Kummerow 1993; Olson et al. 2001. However, the delta scaling of radiative parameters that accounts for strong forward scattering by ice-phase precipitation is also applied; see Joseph et al. (1976). see Kummerow 1993; Olson et al. 2001. The upwelling radiances are convolved by the GMI antenna patterns to simulate the **TB** at the GMI channel frequencies and polarizations.

The Forward Model Module passes through the 3D ensemble fields of pressure, temperature, humidity, cloud water content, μ , N_w , and D_m , and 2D ensembles of T_{sfc} and $U10m$, generated by the Ku Radar Module. To this it adds simulated ensembles of **Z_{Ka}**, **PIA**, and **TB**, as well as the surface emissivities at the GMI channel frequencies and polarizations.

Filter Module

The Filter Module accepts the 3D ensemble fields of environmental and precipitation parameters as well as the simulated **Z_{Ka}**, **PIA**, **TB**, and surface emissivity fields as input. It also requires observed **Z_{Ka}**, **PIA**, and **TB** as input. Its primary function is to filter the 3D ensemble fields to create new ensembles that are consistent with all valid DPR and GMI observations, and their uncertainties. Based on the updated ensembles, it also computes “best estimates” of the precipitation parameters and their uncertainties.

Specifically, the Filter Module uses the covariances between the input 3D ensemble fields and the simulated observations from the Forward Model Module, and combines these with actual observations of **Z_{Ka}**, **PIA**, and **TB** to perform an ensemble Kalman filtering update of the input ensemble

precipitation parameter fields. Ka-band reflectivities are drawn from the L2 Radar Algorithm Preparation (PRE) Submodule, and Ku/Ka path-integrated attenuation observations are taken from the L2 Radar Algorithm Surface Reference Technique (SRT) Submodule. GMI brightness temperatures are drawn from the GMI L1C algorithm output of cross-calibrated data. Details of the ensemble filtering method may be found in Grecu and Olson (2008) and Grecu et al. (2011).

Output of the Filter Module includes best estimates of the environmental parameter fields, such as 3D distributions of air pressure, temperature, vapor density, and cloud liquid water. With respect to precipitation, 3D distributions of precipitation size distribution parameters, precipitation water content, and precipitation rate are output, as well as 2D distributions of surface precipitation rate. In addition, the fractions of liquid in the 3D distributions of precipitation water content and precipitation rate and 2D distributions of precipitation rate are output. Estimates of the uncertainties of 3D precipitation water contents and rates, as well as uncertainties of surface precipitation rates, are produced. Also output are by-products of the estimation method, including 3D distributions of corrected radar reflectivity factor at Ku and Ka bands, and 2D distributions of estimated path-integrated attenuation at Ku and Ka bands and surface emissivities/brightness temperatures at the GMI channel frequencies/polarizations.

4. Ancillary Datasets

In the current algorithm formulation, only the Analysis Data, described below, must be ingested from an external source during Combined Algorithm processing. The other databases and tables are static and will be read into memory upon the execution of the algorithm software.

Geographic Data

A geographic database containing water coverage and elevation information at 5 km resolution is required by the Environment Module; see section 3. Water fractions in the database are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m resolution land-water mask, and elevations are derived from the Shuttle Radar Topography Mission 30" (SRTM30) data, both re-projected to the NASA Land Information System (LIS) 1 km grid. Finally, the 1 km resolution data are averaged to 5 km to match the resolution of the DPR.

Analysis Data

Analysis data are required to produce initial estimates of environmental parameters such as TPW_{anal} , $CLWP_{anal}$, $Tsfc_{anal}$, and $U10m_{anal}$. The current algorithm design requires space-time interpolation of these data from the Japanese Meteorological Agency's (JMA) global analyses (GANAL) during standard algorithm processing. The data are interpolated to the DPR

footprint/range bin locations and overpass times in the Vertical Profile Submodule (VER) of the Level 2 Radar Algorithm and then output. For near real-time processing, the JMA analysis is supplemented with JMA forecast fields, but if these fields are not received in time for any reason, Japanese 25-year Re-analysis (JRA-25) data are substituted for the JMA analysis/forecast data in the VER processing.

Databases Supporting Bayesian Estimation of Environmental Parameters

The Bayesian estimator of environmental parameters requires supporting data that represent the relationships between the environmental parameters and upwelling microwave brightness temperatures at the GMI channel frequencies/polarizations; see section 3. Currently, estimates of the environmental parameters *TPW*, *CLWP*, *Tsfc*, and *U10m* are performed only over open ocean regions. Therefore, the database that supports the Bayesian estimation of these parameters contains large, *a priori* distributions of *TPW*, *CLWP*, *Tsfc*, and *U10m* and associated upwelling brightness temperatures at the GMI channel frequencies/polarizations. The environmental parameter distributions of the supporting database are derived from SSM/I retrievals; then the parameters are used to construct simple vertical profiles of temperature, water vapor, and cloud water. The microwave absorption properties of atmospheric gases and cloud liquid water are derived from the microwave single-scattering tables described below. Surface microwave emissivities as functions of *Tsfc* and *U10m* are given by the Wilheit (1979) model. Finally, radiative transfer calculations of upwelling brightness temperatures corresponding to the environmental conditions are performed using Eddington's Second Approximation for an assumed plane-parallel atmosphere; see Kummerow 1993; Olson et al. 2001.

Land surface emissivities are derived from the Tool to Estimate Land Surface Emissivities in the Microwave (TELSEM) software; see Aires et al. (2010). TELSEM is a program that allows the user to interpolate an atlas of land surface emissivities and their interchannel covariances to the GMI channel frequencies/polarizations and viewing angle. The atlas is drawn from a 16-year, quarter-degree resolution dataset of emissivities based upon cloud-cleared SSM/I observations; see Prigent et al. (2006). Shown in Fig. 3 are global distributions of TELSEM-derived mean emissivities and emissivity standard deviations drawn from the corresponding TELSEM covariance matrices.

Filipe Aires (personal communication) has identified ten land surface regimes for which the emissivities/covariances are self-similar, and so the regime-dependent mean emissivities and their covariances can be computed. It follows that a multichannel eigenvector representation of the emissivities in each regime can also be derived. Our work has shown that for most land

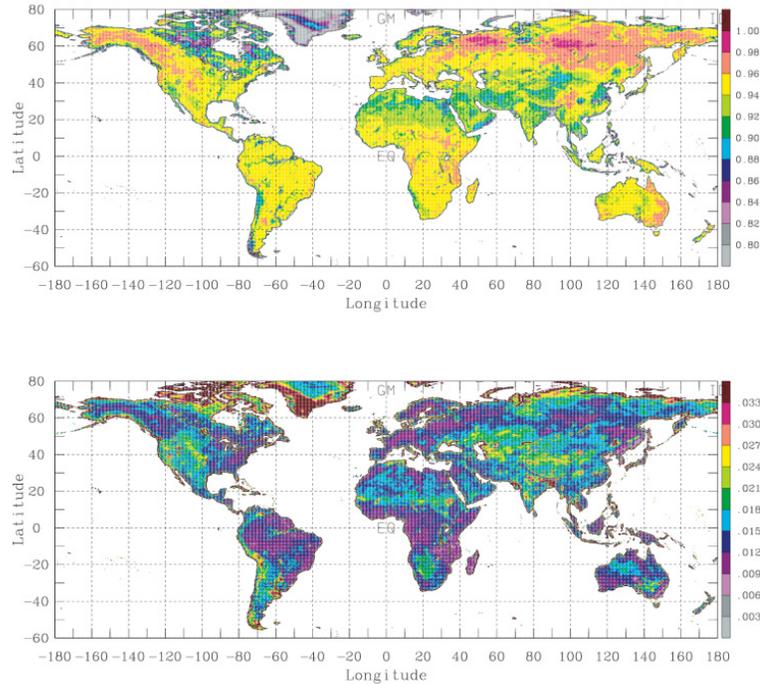


Fig. 3. TELSEM mean emissivity estimates at 31.4 GHz (top), together with the corresponding emissivity standard deviations (bottom) from the TELSEM covariance matrices.

surfaces, the weighting of one or two emissivity eigenvectors can well represent most of the multichannel variability of surface emissivities.

Microwave Absorption and Single-Scattering Tables

Two types of tables are produced by the GPM Radar Algorithm and Combined Algorithm Teams. The first table type contains microwave absorption coefficients for atmospheric gaseous constituents indexed by pressure, temperature, and humidity, and also cloud water/ice absorption coefficients indexed by temperature and liquid-equivalent cloud water content. Tables of gaseous absorption coefficients at Ku and Ka band, as well as the GMI channel frequencies, are currently calculated as functions of pressure, temperature, and vapor density using the Millimeter-wave Propagation Model 1993 (see Liebe, 1989; Liebe et al. 1992). Tables of cloud water/ice absorption coefficients at the same frequencies are currently calculated as functions of temperature and equivalent liquid water content using Rayleigh theory.

Because precipitation of all phases induces scattering as well as absorption/emission of microwaves, and since the particle size distribution, phase, and temperature of precipitation determine its bulk (size distribution integrated) scattering and absorption/emission characteristics, separate tables are used to store the single-scattering properties of precipitation. This second table type contains bulk reflectivities, extinction coefficients, scattering coefficients, and asymmetry parameters of precipitation at Ku and Ka band, as well as the GMI channel frequencies. These bulk scattering parameters are integrated over an assumed gamma distribution and indexed by μ , N_w , and D_m , which define the normalized gamma distribution. Separate tables are generated for liquid and ice-phase precipitation at different temperatures; for mixed-phase precipitation, tables are created for different displacements relative to the freezing level. All particles are currently assumed to be spherical, homogeneous mixtures of ice, air, and liquid water, with different fractions of each depending on the precipitation phase.

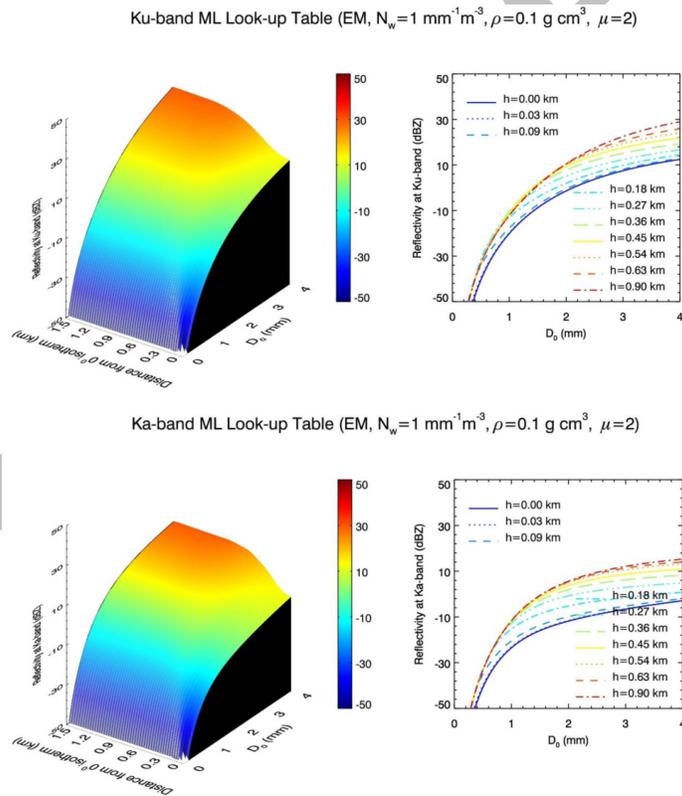


Fig. 4. Graphical illustrations of Ku-band (top) and Ka-band (bottom) scattering table entries for radar reflectivities within the melting layer. Color plots show the variation of reflectivity (given N_w) with both D_0 and distance below the 0°C level. Line plots show the same information for specific depths below the 0°C level.

A graphical illustration of entries in the second table type is shown in Fig. 4 for Ku and Ka band reflectivities of melting snow particle distributions at various

depths below the freezing level. The initial snow particles and partially melted particles are assumed to be spherical, homogeneous ice-air or ice-air-liquid mixtures. Anticipated particle modeling improvements will include non-spherical melting snow, but the form of the tables will remain essentially unchanged, facilitating comparisons of different particle models on Combined Algorithm performance

5. Summary of Algorithm Input/Output

Input to the Combined Algorithm is derived from Level 2 Radar Algorithm (2AKu, 2AKuENV, 2ADPR) products and from the Level 1C Radiometer Algorithm GMI (1CGMI) product, as well as the ancillary datasets described in section 4.

The output of the Combined Algorithm is the 2BCMB product, which contains two swaths of data. Precipitation estimates in the NS output swath are derived from coincident DPR Ku band reflectivities/PIA's and GMI brightness temperatures, and these estimates will extend across the entire Ku band swath. Precipitation estimates in the MS output swath are derived from coincident DPR Ku and Ka band reflectivities/PIA's and GMI brightness temperatures. The MS precipitation estimates are therefore limited to the DPR Ku-Ka overlap swath. Since the MS swath estimates draw upon the maximum amount of information from the GPM Core sensors, these estimates will be the main tool for cross-calibrating the GPM constellation radiometer precipitation estimates through the creation of *a priori* databases. The same Combined Algorithm software architecture is used to create either the NS or MS output swaths.

A complete listing of Combined Algorithm input/output parameters is included in Appendix A. Output volumes and algorithm processing requirements are included in Appendix B and C, respectively.

6. Algorithm Testing Plan

Prior to the GPM Core Observatory launch, testing of the Combined Algorithm or Algorithm components will fall into three categories: Sensitivity Testing, Physics Testing, and Pre-launch Validation. After GPM Core launch, Sensitivity Testing and Physics Testing will continue, and Pre-launch Validation activities will evolve into Post-launch Validation.

Sensitivity Testing

Sensitivity tests basically quantify the impact of different algorithm modifications on output products. So, it is possible that even if the Combined Algorithm investigators suspect that a particular algorithm modification should have a significant impact based upon previous work or intuitive reasoning, that modification may actually have little impact or an impact that was not foreseen.

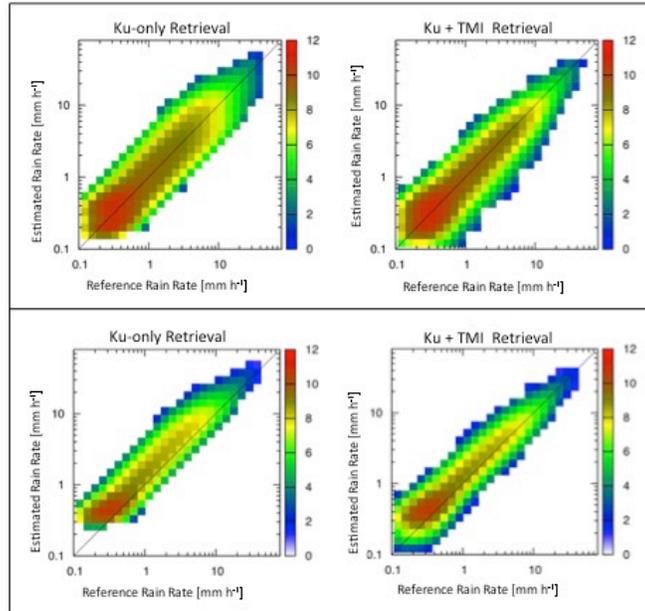


Fig. 5. Shown in the top panels are 2D histograms of synthetic retrievals of surface rain rate vs. reference rain rates, using only Ku band input data (left panel) and using both Ku band and TMI input data (right panel). The bottom panels are the same, except that the mean of the initial guess N_w values is assumed to be 4x the mean of the actual reference values.

Sensitivity testing can therefore be used to prioritize or re-focus areas of algorithm development based upon the specific impact algorithm modifications have on output.

Input data for sensitivity testing can vary depending on the algorithm modification. Typically, we will use Ku band radar data from either airborne sensors or TRMM observations to synthesize Ka band radar reflectivity and GMI brightness temperature observations. In this way we can ensure physical consistency between the radar and radiometer channels using the same forward modeling assumptions. The following are some ongoing and planned areas of sensitivity testing:

- impact of changes in algorithm methodology
- impact of different input data (e.g., radar vs. radar-radiometer)
- impact of PSD description
- impact of assumed environmental/precipitation parameter correlations
- impact of particle scattering assumptions
- impact of precipitation phase transition assumptions
- impact of land surface characterization and physical parameterizations
- impact of source of ancillary (analysis) data
- impact of radar non-uniform beamfilling assumptions

- impact of radar multiple-scattering effects

This list is by no means exhaustive.

An example of sensitivity testing is the study of the impact of DPR and GMI input data on Combined Algorithm estimates relative to estimates based upon the DPR input data alone. Shown in Fig. 5 are 2D histograms (similar to scatterplots) of estimated surface rainfall rates from algorithm applications to synthetic data versus the known reference rainfall rates. Only the Ku band reflectivity data are utilized in the algorithm applications illustrated on the left-hand side of the figure, while both Ku band and TMI brightness temperature data are utilized in the algorithm applications illustrated on the right-hand side. If the initial guess ensemble of N_w values has the same mean as the reference values, then the addition of the TMI observations reduces the scatter of estimated rainfall rates relative to the reference values. If the initial guess ensemble of N_w values is biased by a factor of 4 relative to the reference values, there is a greater bias correction if both the Ku band and TMI observations are utilized.

Sensitivity testing is expected to be a long-term activity, extending past the GPM Core launch, which will help us to improve our understanding of the Combined Algorithm's response to a variety of potential modifications.

Physics Testing

The objective of Physics Testing is to verify assumptions in the forward models that relate environmental/precipitation parameters to sensor observations. Since the current TRMM and GPM radars and radiometers have relatively low resolution, field campaign observations from airborne and ground-based instrumentation generally provide superior data for physics testing. These data may include remote sensing radar and radiometer observations as well as in situ measurements.

Ongoing or planned areas of physics testing include

- assessment of appropriate physical models for ice-phase precipitation
- assessment of proper parameterizations for the ice-to-liquid phase transition
- assessment of appropriate physical models for mixed-phase precipitation
- assessment of physical models for land surface emissivities

Fig. 6 illustrates a precursor of physics testing to determine appropriate physical parameterizations of ice-phase precipitation in the Combined Algorithm. In this test, different physical models are assumed for describing the single-scattering properties of ice-phase precipitation in a precipitation estimation algorithm. The estimation algorithm is applied to Dual-frequency Airborne Precipitation Radar (APR-2) Ku and Ka band observations from the

Genesis and Rapid Intensification Processes (GRIP) field campaign. The reflectivity observations (not shown) indicate a stratiform precipitation region with embedded convective elements. It is evident from the figure that the choice of ice-phase precipitation scattering model has an impact on the estimation of the precipitation mass-weighted particle diameter, water content, and rainfall rate.

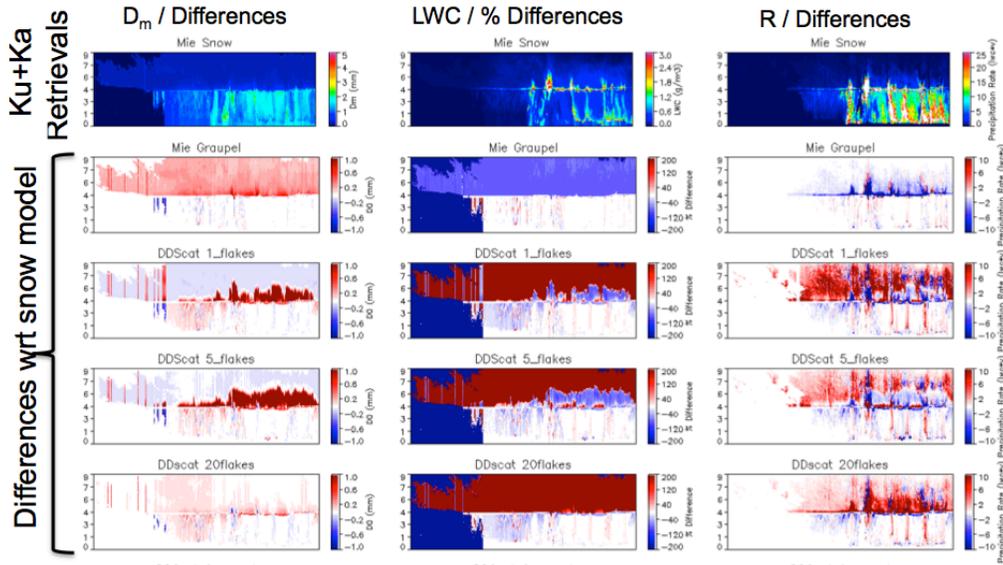


Fig. 6. Top row are estimated mass-weighted mean diameter, D_M , liquid water content, LWC, and rain rate, R , based upon airborne APR-2 Ku and Ka band radar data. Ice-phase precipitation is assumed to be spherical snow particles with mixed ice-air dielectric properties. Shown in the second row are the differences between Ku/Ka band estimates assuming spherical, mixed-dielectric graupel particles and mixed-dielectric snow particles. Shown in the third, fourth, and fifth rows are the differences between estimates assuming structured snow particles composed of multiple dendritic flakes and spherical mixed-dielectric snow particles.

During the Midlatitude Continental Convective Clouds Experiment (MC3E) field campaign, the GPM Cold-season Precipitation Experiment (GCPEX), and the Integrated Precipitation and Hydrology Experiment (IPHEX), airborne dual-frequency radar observations are coupled with coincident microwave brightness temperature measurements and in situ microphysics probe observations of precipitation. The precipitation algorithm will be applied to these combined radar-radiometer data to see if reasonable fits to the data can be achieved, and to see if agreement with in situ observations is possible, given different assumed ice scattering parameterizations.

Physics testing is expected to be a long-term activity, extending past the GPM

Core launch, that will help us improve our understanding of the Combined Algorithm's forward model and its uncertainties.

Pre-launch Validation

Prior to the GPM Core Observatory launch, the Combined Algorithm will be examined to determine (a) in TRMM applications, how Combined Algorithm precipitation estimates compare to TRMM V7 Algorithm estimates and well-calibrated ground-based radar estimates, and (b) whether or not Combined Algorithm estimates are expected to meet the GPM Level-1 Science Requirements. It is stated in the Science Requirements that the algorithm should be capable of estimating instantaneous surface rainfall rates at 50 km resolution with a bias and random error within 50% at 1 mm h⁻¹ rain rate and within 25% at 10 mm h⁻¹ rain rate.

With respect to TRMM applications, the Combined Algorithm performance should be similar to what might be expected outside the GPM Ka band swath, where only Ku band and GMI brightness temperature observations will be available. Shown in Fig. 7 are preliminary comparisons of surface rain rate estimates from the TRMM V7 Radar Algorithm (2A25), the TRMM V7 Combined Algorithm (2B31), and the GPM prototype Combined Algorithm (EnKF). Note the general similarity between the rain rate estimates, which is attributed to the similar physical basis of all three algorithms.

Although coincident ground-based radar observations are not available for the precipitation systems shown in Fig. 7, well calibrated radar with raingages sited within the radar observing domain are available from the Melbourne, Florida and Kwajalein Atoll, Republic of Marshall Islands ground validation sites; see Wolff et al. (2005). Both sites feature S-band, nearly non-attenuating radars; the KPOL radar at Kwajalein is polarimetric and the Melbourne WSR-88D radar will be upgraded to polarimetric in January, 2012. Polarimetric capability will help improve quality control of the data and provide more definitive rain rate estimates. These high quality ground validation estimates will be compared to Combined Algorithm estimates to providing evidence for whether or not the Science Requirements will be met by the algorithm.

In addition, the GPM Validation Network (VN) and Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation product called Q2, will provide large-scale coverage of three dimension reflectivity distributions and surface rainfall rates, respectively, for identifying locally large discrepancies between satellite and ground-based measurements. Both products are based upon the US WSR-88D radar network. The VN network covers the southeast US within the TRMM range of observations, providing geometrically "matched" reflectivity data from the network and the TRMM PR; see Schwaller and Morris (2011). Processing of TRMM estimates from the prototype Combined Algorithm in the same way will facilitate similar intercomparisons. Of particular interest is how well the attenuation corrected reflectivities from the Combined Algorithm agree

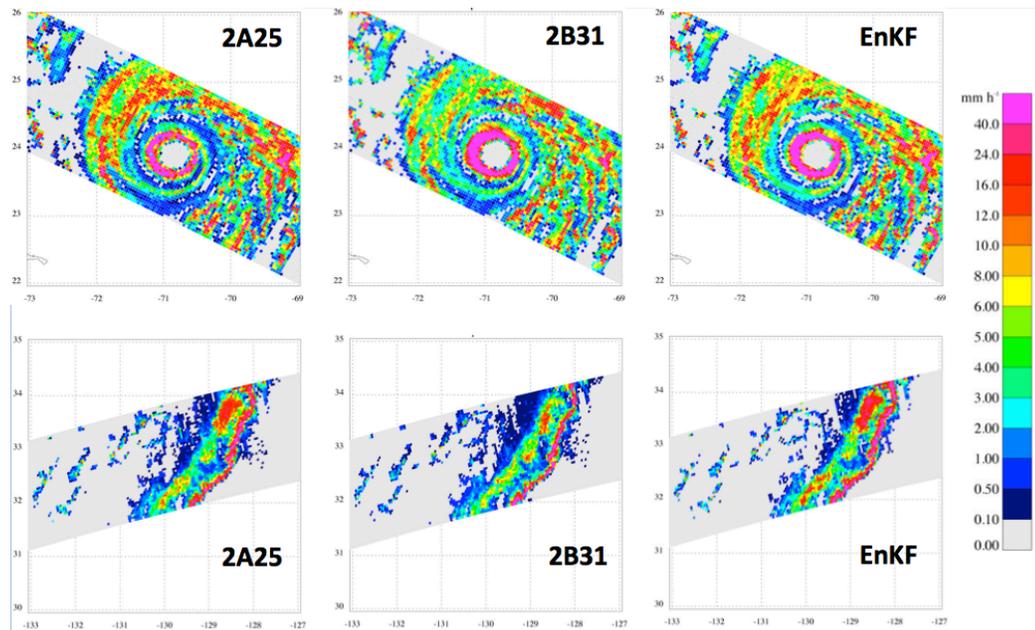


Fig. 7. Top row, estimated surface rainfall rates in Tropical Cyclone Floyd at 09 UTC 13 September 1999 from the TRMM V7 2A25 (radar-only), TRMM V7 2B31 (radar-radiometer) and TRMM EnKF (prototype GPM radar-radiometer) algorithms. Bottom row, same as top row but TRMM estimates are for a wintertime cold frontal band over the Eastern Pacific Ocean at 00 UTC 19 February 2001.

with the VN S-band reflectivities, that are essentially unaffected by attenuation. To do these intercomparisons properly, a small Mie correction should be applied to the Combined estimates of attenuation-corrected Ku band reflectivities; see Liao and Meneghini (2009). The NOAA MRMS Q2 product is a 1 km, 5 minute resolution instantaneous rain rate product derived from the National Weather Service NEXRAD radar network and Environment Canada radars in lower Canada, as well as coincident raingages; see Vasiloff et al. (2007); Amitai et al. (2009). Like the VN, the Q2 data have the advantage of broad spatial coverage, with observations extending over the continental US starting in 2006.

In addition to the evaluation of Combined Algorithm estimates using TRMM data, the full algorithm implemented at the PPS will be tested with synthetic input data derived from Cloud-System Resolving Models (CSRMs). Table 1 indicates CSRMs simulations that have been performed to serve as a testbed for prototype GPM algorithms. These simulations correspond to recent field campaign observing periods and cover a broad range of climatic regimes and precipitation systems types. Field observations from aircraft and ground-based radars, disdrometers, etc., that were deployed during these campaigns will be used to help validate the structure and microphysics of the simulated precipitation.

Radar reflectivities and PIA's at Ku and Ka band and brightness temperatures at the GMI channel frequencies and polarizations are simulated from the CSRМ microphysics fields. The single-scattering properties of precipitation and radiative transfer are computed as they are in the forward radiative model of the Combined Algorithm. The simulated DPR and GMI data are then put in the same file formats as the Level 1 data at PPS. The objective is to mimic the inputs to the algorithm for the purpose of testing both the basic function of the algorithm within the PPS environment as well as the credibility of algorithm-estimated

Table 1. Listing of CSRМ simulations that will provide a testbed for synthetic retrieval tests in the Pre-launch era.

Campaign	Case & Date	Details
C3VP (Canada)	Lake effect 1/19/2007	Lake effect snow extended from Great Lakes. Narrow and shallow, but robust snow band.
	Synoptic 1/21/2007	Large-scale, relatively spatially homogeneous snow fall event.
LPVEx (Finland)	High 0°C Level 9/21/2010	Large-scale, mixed-phase stratiform rain with relatively high (~2400m) altitude of melting band.
LPVEx (Finland)	Low 0°C Level 10/20/2010	Large-scale, mixed-phase stratiform rain with low (~1000m) altitude of melting band.
MC3E (Oklahoma)	Squall line 4/25/2011	Multi-cell MCS and stratiform rain.
	Squall Line 5/20/2011	Severe convection, severe t-storm with trailing stratiform rain.
TWP-ICE (Darwin)	Cumulus Congestus 1/19/2007	Shallow cumulus congestus
	MCS 1/21/2007	Propagating MCS

precipitation fields. Regarding the latter, the precipitation fields of the CSRМ testbed provide a reference, or "truth", against which algorithm estimates may be directly compared. The bias and random error of algorithm estimates will then be evaluated with respect to the Science Requirements to judge the potential of the algorithm to meet those Requirements.

Post-launch Validation

After the GPM Core Observatory launch and initial checkout period, ground validation of Combined Algorithm estimates of precipitation will continue using data from the radar sites at Melbourne and Kwajalein. These data-intensive sites will be augmented with observations from NASA's NPOL radar and supporting raingage network at NASA Wallops Flight Facility, as well as higher-latitude sites in Finland, Canada, and S. Korea. By the time of GPM launch, the US National Radar Network will be completely upgraded to dual-polarization, leading to improved accuracy of quantitative precipitation estimates from the MRMS

Validation strategies will be much the same as those used to evaluate TRMM-based algorithm estimates in the Pre-launch era; see the preceding subsection.

Metrics

As shown in Olson et al. (2006), the use of instantaneous, 50 km resolution rain rate estimates represents a reasonable compromise in resolution for evaluating algorithm errors. Although validation at resolutions down to 5 km (the nominal DPR resolution) may be attempted, the influence of satellite vs. ground radar collocation errors degrades any derived statistics. Accumulation of these estimates over seasons could reveal spatial patterns of bias (relative to reference estimates) that would be helpful for diagnosing systematic algorithm errors.

Standard bivariate statistics of the "errors" between Combined Algorithm rain estimates and ground-based estimates, such as the mean error (bias), error standard deviation, and correlation coefficient will be computed, generally stratified by the rain intensity. These statistics can be used to assess the algorithm's performance relative to the Level 1 Science Requirements, for example. However, information more relevant to algorithm improvement can be gained if the statistics are stratified by other variables that indicate specific state dependencies of the error. For example, are the errors functions of surface skin temperature, total precipitable water, or other variables that indicate the climate regime, or, are the errors functions of the precipitation system or type, such as the convective/stratiform class? Stratification of statistics to reveal state dependencies of algorithm error will be important for diagnosing algorithm deficiencies, especially in the early phases of the GPM Core mission.

In addition to meeting the L1 Science Requirements, a measure of the success of our effort will be the quantification of any improvements in combined radar-radiometer estimates relative to radar-only estimates within the GPM Combined Algorithm framework.

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Appendix A. Listing of Input/Output Parameters

Input Parameters

This listing includes only those parameters that will be ingested from GPM Algorithms that are external to the Combined Radar-Radiometer Algorithm code. The given array size arguments correspond to:

nscan = number of DPR scans per granule, approximately 7900
nray = 49 rays of Normal Swath (NS) Ku band data
nrayMS = 25 rays of Matched Swath (MS) Ka band data
nrayHS = 24 rays of High sensitivity Swath (HS) Ka band data
nbin = 176 range bins of NS or MS radar data per ray
nbinHS = 88 range bins of HS Ka band data per ray
method = 6 methods for estimating path-integrated attenuation from the SRT
nNode = 5 bin nodes identified in the radar-defined DSD structure
nwind = 2 wind components: u, v
nwater = 2 water vapor and cloud liquid water profile parameters

nscan1 = number of lower-frequency (S1) GMI scans in the granule, approx. 2954
nscan2 = number of higher-frequency (S2) GMI scans in the granule, approx. 2954
npixel1 = 221 pixels per lower-frequency (S1) GMI scan
npixel2 = 221 pixels per higher-frequency (S2) GMI scan
nchannel1 = 9 channels of lower-frequency (S1) GMI data per pixel
nchannel2 = 4 channels of higher-frequency (S2) GMI data per pixel
nchUIA1 = 1 number of lower-frequency (S1) unique incidence angles
nchUIA2 = 1 number of higher-frequency (S2) unique incidence angles

from the 2AKu Radar Algorithm

Year

year of the Ku scan (2 byte integer, nscan); from the 2AKu Radar Algorithm.

Month

month of the Ku scan (1 byte integer, nscan); from the 2AKu Radar Algorithm.

DayOfMonth

day of month of the Ku scan (1 byte integer, nscan); from the 2AKu Radar Algorithm.

Hour

hour of the Ku scan (1 byte integer, nscan); from the 2AKu Radar Algorithm.

Minute

minute of the Ku scan (1 byte integer, nscan); from the 2AKu Radar Algorithm.

Second

second of the Ku scan (1 byte integer, nscan); from the 2AKu Radar Algorithm.

MilliSecond

millisecond of the Ku scan (2 byte integer, nscan); from the 2AKu Radar Algorithm.

DayOfYear

day of the year of the Ku scan (2 byte integer, nscan); from the 2AKuRadar Algorithm.

SecondOfDay

second of the day of the Ku scan (8 byte float, nscan); from the 2AKu Radar Algorithm.

Latitude

latitude of Ku footprint (4 byte float, nray x nscan); from the 2AKu Radar Algorithm.

Longitude

longitude of Ku footprint (4 byte float, nray x nscan); from the 2AKu Radar Algorithm.

elevation

altitude above the Earth ellipsoid of the surface gate in Ku ray (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

landSurfaceType

water/land/coast and surface type at Ku footprint location (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule). Note that this information is used to interpret surface reference technique output.

localZenithAngle

local incidence angles of DPR ray relative to local zenith on the Earth ellipsoid (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

flagPrecip

flag indicating detection of precipitation or no precipitation in Ku ray (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (PRE

Submodule).

binRealSurface

surface range bin in Ku ray (2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

binStormTop

range bin of storm top in Ku ray (2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

heightStormTop

altitude of storm top in Ku ray (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

binClutterFreeBottom

range bin of the lowest clutter-free bin of Ku ray (2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

sigmaZeroMeasured

measured surface normalized radar backscattering cross-section at Ku (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

zFactorMeasured

measured reflectivity at Ku (2 byte integer, nbin x nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

ellipsoidBinOffset

offset along Ku ray between earth ellipsoid and midpoint of surface range bin (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (PRE Submodule).

binZeroDeg

range bin of the zero degree isotherm in Ku ray (2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (VER Submodule).

heightZeroDeg

altitude of the zero degree isotherm in Ku ray (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (VER Submodule).

flagBB

flag indicating the detection of a bright-band in Ku ray (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

binBBPeak

range bin of the bright-band maximum reflectivity, if detected, in Ku ray

(2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

heightBB

altitude of the bright-band maximum reflectivity, if detected, in Ku ray (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

qualityBB

quality flag for bright band detection in Ku ray (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

type_Precip

classification of precipitation type in Ku ray (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

qualityTypePrecip

quality of classification of precipitation type in Ku ray (4 byte integer, nray x nscan); from the 2AKu Radar Algorithm (CSF Submodule).

PIAalt

total 2-way path-integrated attenuation to the surface based upon surface reference technique methods for Ku (4 byte float, method x nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

RFactorAlt

reliability factors of total 2-way path-integrated attenuation estimates based upon surface reference technique methods for Ku (4 byte float, method x nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

PIAweight

weights of individual 2-way total path-integrated attenuation estimates to form effective estimate for Ku (4 byte float, method x nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

pathAtten

effective total 2-way path-integrated attenuation to the surface based upon weighted averages of surface reference technique methods for Ku (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

reliabFactor

reliability factor of effective total 2-way path-integrated attenuation estimate based upon surface reference technique methods for Ku (4 byte float, nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

reliabFlag

reliability flag for composite total 2-way path-integrated attenuation estimate based upon surface reference methods for Ku (2 byte integer, nray x nscan); from the 2AKu Radar Algorithm (SRT Submodule).

phase

particle phase based on Ku (1 byte integer, nbin x nray x nscan); from the 2AKu Radar Algorithm (DSD Submodule).

binNode

bin node for partitioning radar profile based on Ku (4 byte integer, nNode x nray x nscan); from the 2AKu Radar Algorithm (DSD Submodule).

flagParticle

particle flag based on Ku (1 byte integer, nbin x nray x nscan); from the 2AKu Radar Algorithm (DSD Submodule).

from the 2AKuENV Radar Algorithm**airTemperature**

air temperature interpolated to Ku range bins (4 byte float, nbin x nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

airPressure

air pressure interpolated to Ku range bins (4 byte float, nbin x nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

waterVapor

water vapor density interpolated to Ku range bins (4 byte float, nwater x nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

cloudLiquidWater

cloud liquid water content interpolated to Ku range bins (4 byte float, nwater x nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

surfacePressure

surface air pressure interpolated to Ku footprint location (4 byte float, nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

groundTemperature

surface skin temperature interpolated to Ku footprint location (4 byte float, nray x nscan); from JMA data using the 2AKuENV Radar Algorithm (VER Submodule).

surfaceWind

10-meter wind speed interpolated to Ku footprint location (4 byte float, nwind x nray x nscan); from JMA analysis using the 2AKuENV Radar Algorithm (VER Submodule).

from the 2ADPR Radar Algorithm (NS)

Year

year of the Ku scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

Month

month of the Ku scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

DayOfMonth

day of month of the Ku scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

Hour

hour of the Ku scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

Minute

minute of the Ku scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

Second

second of the Ku scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

MilliSecond

millisecond of the Ku scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

DayOfYear

day of the year of the Ku scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in NS).

SecondOfDay

second of the day of the Ku scan (8 byte float, nscan); from the 2ADPR Radar Algorithm (in NS).

Latitude

latitude of Ku footprint (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (in NS).

Longitude

longitude of Ku footprint (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (in NS).

elevation

altitude above the Earth ellipsoid of the surface gate in Ku ray (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

landSurfaceType

water/land/coast and surface type at Ku footprint location (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS). Note that this information is used to interpret surface reference technique output.

localZenithAngle

local incidence angles of DPR ray relative to local zenith on the Earth ellipsoid (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

flagPrecip

flag indicating detection of precipitation or no precipitation in Ku ray (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

binRealSurface

surface range bin in Ku ray (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

binStormTop

range bin of storm top in Ku ray (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

heightStormTop

altitude of storm top in Ku ray (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

binClutterFreeBottom

range bin of the lowest clutter-free bin of Ku ray (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

sigmaZeroMeasured

measured surface normalized radar backscattering cross-section at Ku (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

zFactorMeasured

measured reflectivity at Ku (2 byte integer, nbin x nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

ellipsoidBinOffset

offset along Ku ray between earth ellipsoid and midpoint of surface range bin (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in NS).

binZeroDeg

range bin of the zero degree isotherm in Ku ray (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (VER Submodule in NS).

heightZeroDeg

altitude of the zero degree isotherm in Ku ray (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (VER Submodule in NS).

flagBB

flag indicating the detection of a bright-band in Ku ray (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

binBBPeak

range bin of the bright-band maximum reflectivity, if detected, in Ku ray (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

heightBB

altitude of the bright-band maximum reflectivity, if detected, in Ku ray (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

qualityBB

quality flag for bright band detection in Ku ray (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

type_Precip

classification of precipitation type in Ku ray (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

qualityTypePrecip

quality of classification of precipitation type in Ku ray (4 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in NS).

PIAalt

total 2-way path-integrated attenuation to the surface based upon surface reference technique methods for Ku (4 byte float, method x nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

RFactorAlt

reliability factors of total 2-way path-integrated attenuation estimates based upon surface reference technique methods for Ku (4 byte float, method x nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

PIAweight

weights of individual 2-way total path-integrated attenuation estimates to form effective estimate for Ku (4 byte float, method x nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

pathAtten

effective total 2-way path-integrated attenuation to the surface based upon weighted averages of surface reference technique estimates for Ku (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

reliabFactor

reliability factor of effective total 2-way path-integrated attenuation estimate based upon surface reference technique methods for Ku (4 byte float, nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

reliabFlag

reliability flag for effective total 2-way path-integrated attenuation estimate based upon surface reference methods for Ku (2 byte integer, nray x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in NS).

phase

particle phase based on Ku (1 byte integer, nbin x nray x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in NS).

binNode

bin node for partitioning radar profile based on Ku (4 byte integer, nNode x nray x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in NS).

flagParticle

particle flag based on Ku (1 byte integer, nbin x nray x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in NS).

from the 2ADPR Radar Algorithm (MS)

Year

year of the Ka scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

Month

month of the Ka scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

DayOfMonth

day of month of the Ka scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

Hour

hour of the Ka scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

Minute

minute of the Ka scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

Second

second of the Ka scan (1 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

MilliSecond

millisecond of the Ka scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

DayOfYear

day of the year of the Ka scan (2 byte integer, nscan); from the 2ADPR Radar Algorithm (in MS).

SecondOfDay

second of the day of the Ka scan (8 byte float, nscan); from the 2ADPR Radar Algorithm (in MS).

Latitude

latitude of Ka footprint (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (in MS).

Longitude

longitude of Ka footprint (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (in MS).

elevation

altitude above the Earth ellipsoid of the surface gate in Ka ray (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

landSurfaceType

water/land/coast and surface type at Ka footprint location (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS). Note that this information is used to interpret surface reference technique output.

localZenithAngle

local incidence angles of DPR ray relative to local zenith on the Earth ellipsoid (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

flagPrecip

flag indicating detection of precipitation or no precipitation in Ka ray (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

binRealSurface

surface range bin in Ka ray (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

binStormTop

range bin of storm top in Ka ray (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

heightStormTop

altitude of storm top in Ka ray (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

binClutterFreeBottom

range bin of the lowest clutter-free bin of Ka ray (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

sigmaZeroMeasured

measured surface normalized radar backscattering cross-section at Ka (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

zFactorMeasured

measured reflectivity at Ka (2 byte integer, nbin x nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

ellipsoidBinOffset

offset along Ka ray between earth ellipsoid and midpoint of surface range bin (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (PRE Submodule in MS).

binZeroDeg

range bin of the zero degree isotherm in Ka ray (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (VER Submodule in MS).

heightZeroDeg

altitude of the zero degree isotherm in Ka ray (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (VER Submodule in MS).

flagBB

flag indicating the detection of a bright-band in Ka ray (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

binBBPeak

range bin of the bright-band maximum reflectivity, if detected, in Ka ray (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

heightBB

altitude of the bright-band maximum reflectivity, if detected, in Ka ray (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

qualityBB

quality flag for bright band detection in Ka ray (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

type_Precip

classification of precipitation type in Ka ray (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

qualityTypePrecip

quality of classification of precipitation type in Ka ray (4 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (CSF Submodule in MS).

PIAalt

total 2-way path-integrated attenuation to the surface based upon surface reference technique methods for Ka (4 byte float, method x nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

RFactorAlt

reliability factors of total 2-way path-integrated attenuation estimates based upon surface reference technique methods for Ka (4 byte float, method x nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

PIAweight

weights of individual 2-way total path-integrated attenuation estimates to form effective estimates for Ka (4 byte float, method x nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

pathAtten

effective total 2-way path-integrated attenuation to the surface based upon weighted averages of surface reference technique estimates for Ka (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

reliabFactor

reliability factor of effective total 2-way path-integrated attenuation estimate based upon surface reference technique methods for Ka (4 byte float, nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

reliabFlag

reliability flag for composite total 2-way path-integrated attenuation estimate based upon surface reference methods for Ka (2 byte integer, nrayMS x nscan); from the 2ADPR Radar Algorithm (SRT Submodule in MS).

phase

particle phase based on Ka (1 byte integer, nbin x nrayMS x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in MS).

binNode

bin node for partitioning radar profile based on Ka (4 byte integer, nNode x nrayMS x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in MS).

flagParticle

particle flag based on Ka (1 byte integer, nbin x nrayMS x nscan); from the 2ADPR Radar Algorithm (DSD Submodule in MS).

from the 1CGMI Algorithm (S1)

Year

year of the GMI scan (2 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

Month

month of the GMI scan (1 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

DayOfMonth

day of month of the GMI scan (1 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

Hour

hour of the GMI scan (1 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

Minute

minute of the GMI scan (1 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

Second

second of the GMI scan (1 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

MilliSecond

millisecond of the GMI scan (2 byte integer, nscan1) from the 1CGMI Algorithm (in S1).

DayOfYear

day of year of the GMI scan (2 byte integer, nscan1); from the 1CGMI Algorithm (in S1).

SecondOfDay

second of day of the GMI scan (8 byte float, nscan1); from the 1CGMI Algorithm (in S1).

Latitude

latitude of the GMI footprint (4 byte float, npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

Longitude

longitude of the GMI footprint (4 byte float, npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

Quality

quality of the lower-frequency calibrated brightness temperatures (1 byte integer, npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

incidenceAngle

earth incidence angle of the GMI lower-frequency data (4 byte float, nchUIA1 x npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

sunGlintAngle

sun glint angles of the GMI lower-frequency data (1 byte integer, nchUIA1 x npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

incidenceAngleIndex

index of the incidence angle array for each lower-frequency channel (1 byte integer, nchannel1 x nscan1); from the 1CGMI Algorithm (in S1).

Tc

common calibrated GMI brightness temperatures in the lower-frequency data swath (4 byte float, nchannel1 x npixel1 x nscan1); from the 1CGMI Algorithm (in S1).

from the 1CGMI Algorithm (S2)

Year

year of the GMI scan (2 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

Month

month of the GMI scan (1 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

DayOfMonth

day of month of the GMI scan (1 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

Hour

hour of the GMI scan (1 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

Minute

minute of the GMI scan (1 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

Second

second of the GMI scan (1 byte integer, nscan2) from the 1CGMI Algorithm (in S2).

MilliSecond

millisecond of the GMI scan (2 byte integer, nscan2) from the 1CGMI

Algorithm (in S2).

DayOfYear

day of year of the GMI scan (2 byte integer, nscan2); from the 1CGMI Algorithm (in S2).

SecondOfDay

second of day of the GMI scan (8 byte float, nscan2); from the 1CGMI Algorithm (in S2).

Latitude

latitude of the GMI footprint (4 byte float, npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

Longitude

longitude of the GMI footprint (4 byte float, npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

Quality

quality of the higher-frequency calibrated brightness temperatures (1 byte integer, npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

incidenceAngle

earth incidence angles of the GMI higher-frequency data (4 byte float, nchUIA2 x npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

sunGlintAngle

sun glint angles of the GMI higher-frequency data (1 byte integer, nchUIA2 x npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

incidenceAngleIndex

index of the incidence angle array for each higher-frequency channel (1 byte integer, nchannel2 x nscan2); from the 1CGMI Algorithm (in S2).

Tc

common calibrated GMI brightness temperatures in the higher-frequency data swath (4 byte float, nchannel2 x npixel2 x nscan2); from the 1CGMI Algorithm (in S2).

Output Parameters

Note standard output products are sampled at 250 m vertical resolution. The given array size arguments correspond to:

nscan = number of DPR scans per granule, approximately 7900
nrayNS = 49 rays in each Ku band (NS) scan
nrayMS = 25 rays in each matched Ku-Ka (MS) scan
nbinC = 88 vertical range bins at 250 m intervals
nbinEnv = 10 range bins for environmental parameter sampling
nbinLow = 9 range bins for low-resolution PSD parameter sampling
nbinPhase = 5 range bins indicating phase transitions
nbinTrans = 10 range bins describing the precipitation liquid phase fraction through the mixed phase layer
nPSDhigh = 1 parameters for describing the precipitation particle size distribution at 250 m resolution
nPSDlow = 2 parameters for describing the precipitation particle size distribution at low vertical resolution.
nAB = 2 power law parameters to describe particle densities
nKuKa = 2 indices for the Ku and Ka channels
nchan = 15 GMI channels, including separate accounting for the double side-band channels.

from the 2BCMB Combined Radar-Radiometer Algorithm (NS)

Year

year of the Ku band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

Month

month of the Ku band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

DayOfMonth

day of month of the Ku band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

Hour

hour of the Ku band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

Minute

minute of the Ku band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

Second

second of the Ku band scan (1 byte integer, nscan); from the 2BCMB

Combined Algorithm (in NS/ScanTime).

MilliSecond

millisecond of the Ku band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/Scantime).

DayOfYear

day of year of the Ku band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

SecondOfDay

second of day of the Ku band scan (8 byte float, nscan); from the 2BCMB Combined Algorithm (in NS/ScanTime).

Latitude

latitude of Ku band footprint (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

Longitude

longitude of Ku band footprint (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

ioQuality

6-digit flag describing the quality of input data and precipitation estimate (4 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/FLG).

1's digit:	0 if estimate is valid 9 if no estimate
10's digit:	0 if Ku data valid and rain detected at Ku 1 if Ku data valid but no rain detected 9 if bad Ku input data
100's digit:	0 if Ku SRT gives viable PIA estimate 1 if σ_{Ku} is within noise of background 2 if σ_{Ku} is completely attenuated 9 if bad Ku input data
1000s digit:	0 if freezing level derived from Ku bright band 1 if freezing level derived from meteorological analysis 9 if bad Ku input data
10000's digit:	0 if Ku classified as stratiform or convective 1 if Ku classified as indeterminate 2 if precip not detected at Ku (no feature) 9 if bad Ku input data
100000's digit:	0 if at least some measured brightness temperatures are valid

9 if no measured brightness temperatures are valid

surfaceElevation

altitude above the Earth ellipsoid of the surface gate in Ku band ray (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

surfaceType

water/land/coast and surface type at Ku band footprint location (4 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

localZenithAngle

local incidence angle of Ku band ray relative to local zenith on the Earth ellipsoid (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

precipitationFlag

flag indicating detection of precipitation or no precipitation in Ku band ray (4 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

surfaceRangeBin

surface range bin in Ku band ray (2 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

lowestClutterFreeBin

lowest clutter free bin in Ku band ray (2 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

ellipsoidBinOffset

offset along Ku ray between earth ellipsoid and midpoint of surface range bin (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

stormTopBin

storm top range bin in Ku band ray (2 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

stormTopAltitude

storm top altitude in Ku band ray (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

zeroDegBin

freezing level bin in Ku band ray (2 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

zeroDegAltitude

freezing level altitude in Ku band ray (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

precipitationType

classification of precipitation type in Ku band ray (4 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

precipTypeQualityFlag

quality of classification of precipitation type in Ku band ray (4 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

piaEffective

effective total 2-way path-integrated attenuation to the surface at Ku band, based upon weighted averages of surface reference technique estimates (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

piaEffectiveSigma

uncertainty of effective total 2-way path-integrated attenuation at Ku band based upon surface reference technique methods (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

piaEffectiveReliabFlag

reliability flag of the effective total 2-way path-integrated attenuation at Ku band, based upon weighted averages of surface reference technique estimates (2 byte integer, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS/Input).

surfaceAirPressure

surface air pressure at the Ku band footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfaceAirTemperature

surface air temperature at the Ku band footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfaceVaporDensity

surface vapor density at the Ku band footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

skinTemperature

surface skin temperature at the Ku band footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

envParamNode

bin numbers where environmental pressure, temperature, and vapor density are sampled (2 byte integer, nbinEnv x nrayNS x nscan) from 2BCMB Combined Algorithm (in NS).

airPressure

air pressure along the Ku band ray at the envParamNode locations (4 byte float, nbinEnv x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

airTemperature

air temperature along the Ku band ray at the envParamNode locations (4 byte float, nbinEnv x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

vaporDensity

vapor density along the Ku band ray at the envParamNode locations (4 byte integer, nbinEnv x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

cloudLiqWaterCont

cloud liquid water content along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

cloudIceWaterCont

cloud ice liquid-equivalent water content along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS). Currently this parameter is not assigned.

phaseBinNodes

bin numbers indicating (0) storm top, (1) top of mixed-phase layer, (2) maximum reflectivity in mixed-phase layer if bright band detected; otherwise, the freezing level from analysis, (3) bottom of mixed-phase layer, and (4) bottom of rain layer (2 byte integer, nbinPhase x nrayNS x nscan); from 2BCMB Combined Algorithm (in NS).

liqMassFracTrans

fraction of the precipitation mass that is liquid in the transition between ice and liquid-phase precipitation, starting from the top of the mixed-phase layer (phaseBinNode 1) and proceeding downward along the Ku band ray at 250 m sampling resolution (4 byte float, nbinTrans x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

liqRateFracTrans

fraction of the precipitation rate that is liquid in the transition between ice and liquid-phase precipitation, starting from the top of the mixed-phase layer (phaseBinNode 1) and proceeding downward along the Ku band ray at 250 m sampling resolution (4 byte float, nbinTrans x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

precipTotRate

precipitation rate along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

precipTotRateSigma

uncertainty of precipitation rate along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

precipTotWaterCont

precipitation water content along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

precipTotWaterContSigma

uncertainty of precipitation water content along the Ku band ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

precipTotPSDparamHigh

precipitation drop-size distribution mean volume diameter (D_m) along the Ku band ray at 250 m sampling resolution (4 byte float, nPSDhigh x nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

PSDparamLowNode

bin numbers where low-resolution precipitation PSD parameters are sampled (2 byte integer, nbinLow x nrayNS x nscan) from 2BCMB Combined Algorithm (in NS).

precipTotPSDparamLow

precipitation drop-size distribution parameters ($\log(N_w)$, μ) along the Ku band ray at reduced sampling resolution (2 byte integer, nPSDlow x nbinLow x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfPrecipTotRate

surface precipitation rate at Ku footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfPrecipTotRateSigma

surface precipitation rate uncertainty at Ku footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfLiqRateFrac

fraction of the surface precipitation rate that is liquid at the Ku footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

tenMeterWindSpeed

10-meter wind speed at Ku footprint location (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

surfEmissivity

microwave surface emissivities at the GMI channel frequencies/polarizations and viewing angle, including separate emissivities for the double side-band channels at 183.3 ± 7 and 183.3 ± 3 GHz, at Ku footprint location (4 byte float, nchan x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

simulatedBrightTemp

upwelling microwave surface brightness temperatures at the GMI channel frequencies/polarizations and viewing angle, but at Ku band footprint resolution, including separate brightness temperatures for the double side-band channels at 183.3 ± 7 and 183.3 ± 3 GHz (4 byte float, nchan x nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

pia

total path-integrated attenuation at Ku (4 byte float, nrayNS x nscan); from the 2BCMB Combined Algorithm (in NS).

correctedReflectFactor

attenuation-corrected radar reflectivity factor along Ku ray at 250 m sampling resolution (4 byte float, nbinC x nrayNS x nscan); from the 2BCMB Combined Algorithm.

from the 2BCMB Combined Radar-Radiometer Algorithm (MS)

Year

year of the Ka band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

Month

month of the Ka band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

DayOfMonth

day of month of the Ka band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

Hour

hour of the Ka band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

Minute

minute of the Ka band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

Second

second of the Ka band scan (1 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

MilliSecond

millisecond of the Ka band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/Scantime).

DayOfYear

day of year of the Ka band scan (2 byte integer, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

SecondOfDay

second of day of the Ka band scan (8 byte float, nscan); from the 2BCMB Combined Algorithm (in MS/ScanTime).

Latitude

latitude of Ka band footprint (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

Longitude

longitude of Ka band footprint (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

ioQuality

6-digit flag describing the quality of input data and precipitation estimate (4 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/FLG). Currently, this is just a replica of the NS mode ioQuality flag.

1's digit: 0 if estimate is valid
 9 if no estimate

10's digit: 0 if Ku data valid and rain detected at Ku
 1 if Ku data valid but no rain detected
 9 if bad Ku input data

100's digit:	0 if Ku SRT gives viable PIA estimate 1 if σ°_{Ku} is within noise of background 2 if σ°_{Ku} is completely attenuated 9 if bad Ku input data
1000s digit:	0 if freezing level derived from Ku bright band 1 if freezing level derived from meteorological analysis 9 if bad Ku input data
10000's digit:	0 if Ku classified as stratiform or convective 1 if Ku classified as indeterminate 2 if precip not detected at Ku (no feature) 9 if bad Ku input data
100000's digit:	0 if at least some measured brightness temperatures are valid 9 if no measured brightness temperatures are valid

surfaceElevation

altitude above the Earth ellipsoid of the surface gate in Ka band ray (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

surfaceType

water/land/coast and surface type at Ka band footprint location (4 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

localZenithAngle

local incidence angle of Ka band ray relative to local zenith on the Earth ellipsoid (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

precipitationFlag

flag indicating detection of precipitation or no precipitation in Ka band ray (4 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

surfaceRangeBin

surface range bin in Ka band ray (2 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

lowestClutterFreeBin

lowest clutter free bin in Ka band ray (2 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

ellipsoidBinOffset

offset along Ka ray between earth ellipsoid and midpoint of surface range bin (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

stormTopBin

storm top range bin in Ka band ray (2 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

stormTopAltitude

storm top altitude in Ka band ray (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

zeroDegBin

freezing level bin in Ka band ray (2 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

zeroDegAltitude

freezing level altitude in Ka band ray (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

precipitationType

classification of precipitation type in Ka band ray (4 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

precipTypeQualityFlag

quality of classification of precipitation type in Ka band ray (4 byte integer, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

piaEffective

effective total 2-way path-integrated attenuation to the surface at Ku and Ka bands, based upon weighted averages of surface reference technique estimates (4 byte float, nKuKa x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

piaEffectiveSigma

uncertainty of effective total 2-way path-integrated attenuation at Ku and Ka bands based upon surface reference technique methods (4 byte float, nKuKa x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

piaEffectiveReliabFlag

reliability flag of the effective total 2-way path-integrated attenuation at Ku and Ka bands, based upon weighted averages of surface reference technique estimates (2 byte integer, nKuKa x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS/Input).

surfaceAirPressure

surface air pressure at the Ka band footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfaceAirTemperature

surface air temperature at the Ka band footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfaceVaporDensity

surface vapor density at the Ka band footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

skinTemperature

surface skin temperature at the Ka band footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

envParamNode

bin numbers where environmental pressure, temperature, and vapor density are sampled (2 byte integer, nbinEnv x nrayMS x nscan) from 2BCMB Combined Algorithm (in MS).

airPressure

air pressure along the Ka band ray at the envParamNode locations (4 byte float, nbinEnv x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

airTemperature

air temperature along the Ka band ray at the envParamNode locations (4 byte float, nbinEnv x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

vaporDensity

vapor density along the Ka band ray at the envParamNode locations (4 byte integer, nbinEnv x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

cloudLiqWaterCont

cloud liquid water content along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

cloudIceWaterCont

cloud ice liquid-equivalent water content along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS). Currently this parameter is not

assigned.

phaseBinNodes

bin numbers indicating (0) storm top, (1) top of mixed-phase layer, (2) maximum reflectivity in mixed-phase layer if bright band detected; otherwise, the freezing level from analysis, (3) bottom of mixed-phase layer, and (4) bottom of rain layer (2 byte integer, nbinPhase x nrayMS x nscan); from 2BCMB Combined Algorithm (in MS).

liqMassFracTrans

fraction of the precipitation mass that is liquid in the transition between ice and liquid-phase precipitation, starting from the top of the mixed-phase layer (phaseBinNode 1) and proceeding downward along the Ka band ray at 250 m sampling resolution (4 byte float, nbinTrans x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

liqRateFracTrans

fraction of the precipitation rate that is liquid in the transition between ice and liquid-phase precipitation, starting from the top of the mixed-phase layer (phaseBinNode 1) and proceeding downward along the Ku band ray at 250 m sampling resolution (4 byte float, nbinTrans x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

precipTotRate

precipitation rate along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

precipTotRateSigma

uncertainty of precipitation rate along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

precipTotWaterCont

precipitation water content along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

precipTotWaterContSigma

uncertainty of precipitation water content along the Ka band ray at 250 m sampling resolution (4 byte float, nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

precipTotPSDparamHigh

precipitation drop-size distribution mean volume diameter (D_m) along the Ka band ray at 250 m sampling resolution (4 byte float, nPSDhigh x

nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

PSDparamLowNode

bin numbers where low-resolution precipitation PSD parameters are sampled (2 byte integer, nbinLow x nrayMS x nscan) from 2BCMB Combined Algorithm (in MS).

precipTotPSDparamLow

precipitation drop-size distribution parameters ($\log(N_w)$, μ) along the Ka band ray at reduced sampling resolution (2 byte integer, nPSDlow x nbinLow x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfPrecipTotRate

surface precipitation rate at Ka footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfPrecipTotRateSigma

surface precipitation rate uncertainty at Ka footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfLiqRateFrac

fraction of the surface precipitation rate that is liquid at the Ka footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

tenMeterWindSpeed

10-meter wind speed at Ka footprint location (4 byte float, nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

surfEmissivity

microwave surface emissivities at the GMI channel frequencies/polarizations and viewing angle, including separate emissivities for the double side-band channels at 183.3 ± 7 and 183.3 ± 3 GHz, at Ka footprint location (4 byte float, nchan x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

simulatedBrightTemp

upwelling microwave surface brightness temperatures at the GMI channel frequencies/polarizations and viewing angle, but at Ka band footprint resolution, including separate brightness temperatures for the double side-band channels at 183.3 ± 7 and 183.3 ± 3 GHz (4 byte float, nchan x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

pia

total path-integrated attenuation at Ku and Ka bands (4 byte float, nKuKa

x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

correctedReflectFactor

attenuation-corrected radar reflectivity factor at Ku and Ka bands at 250 m sampling resolution (4 byte float, nKuKa x nbinC x nrayMS x nscan); from the 2BCMB Combined Algorithm (in MS).

Appendix B. Output Product Volumes

The volume of the Combined Algorithm output product, based upon the output parameters listed above, is approximately 130 MB per orbit file in internally compressed HDF5 format.

Appendix C. Processing Requirements

The current configuration of the Combined Algorithm requires input from five modules of the GPM Radar Algorithm: the Preparation Module, Vertical Profile Module, Classification Module, DSD Module, and Surface Reference Technique Module. Output of these modules is expected from the Level 2 Radar Algorithm software; however, the computational requirements of this routine could add significant latency to Combined Algorithm processing.

A primary input to the Vertical Profile Module is JMA global analyses (GANAL) for standard processing and JMA global analyses/forecasts for near-real-time processing. Therefore, this input should be accommodated in PPS operations.

The current version of the algorithm requires approximately 15 minutes on a single PPS processing node to process a typical orbit of data, using multi-processor capability. Parallel processing will be achieved using POSIX thread libraries. Although some economies in the coding can reduce this processing time, they may result in degraded performance of the algorithm. Granules of DPR and GMI data will be subdivided into roughly 30 (300 DPR scan line) segments to keep required memory within limits on a given processing node.