March 20, 2017

Caveats for the CMB Level 2 Product in the GPM V05 Public Release

The Combined Radar-Radiometer Algorithm (CMB) L2 V05 product includes precipitation estimates over the broader, NS (Ku+GMI) swath as well as estimates over the narrower, MS (Ku+Ka+GMI) swath. The input of the CMB L2 algorithm is derived from DPR L2 and GMI L1 products. In particular, the CMB L2 algorithm depends upon inputs from the DPR L2 Preparation Module, Classification Module, Surface Reference Technique Module, and the Vertical Structure Module. From GMI L1, the CMB L2 algorithm utilizes the intercalibrated brightness temperature observations.

During the early GPM mission (prior to June 2014) many tests and modifications of the DPR performance were carried out, and these had an impact on not only DPR products but also the CMB L2 estimates that depend on them. Therefore, CMB L2 precipitation estimates from the early mission should be used with caution. A listing of the orbits impacted by these tests and modifications can be obtained from the GPM Radar Team.

Mainlobe and sidelobe clutter contamination of DPR reflectivities is reduced using radar beam reshaping and statistical corrections. The combination of these applications reduces clutter successfully over most surfaces, but there are still "exceptional" regions where clutter signatures are still evident. Also, ice-covered land surfaces produce Ku-band radar surface cross-sections at nadir view that sometime exceed the upper limit of the radar receiver range. Estimates of Ku-band path-integrated attenuation from the Surface Reference Technique Module are possibly biased in these regions. Since radar reflectivities and path-integrated attenuations are utilized by the CMB L2 algorithm, precipitation estimates in these "exceptional" regions should be used with caution.

The current CMB L2 algorithm uses the Ku-band radar reflectivities from the Preparation Module to detect either liquid- or ice-phase precipitation. The lowest detectable reflectivity for DPR at Ku band is ~13 dBZ, and so light snow or very light rainfall may not be detected and quantified by the algorithm.

In addition to the impact of input data from DPR L2, there are uncertainties due to the current limitations of the CMB L2 algorithm's physical models and other assumptions that also have an impact on precipitation estimates. In particular, the physical models for scattering by ice-phase precipitation particles now feature realistic nonspherical particle geometries but are still undergoing development. The scattering models for ice- and mixed-phase precipitation will likely be improved in future product releases. Also, the effects of radar footprint non-uniform beamfilling and multiple scattering of transmitted power are addressed in CMB L2, but the mitigating strategies are not yet generalized and have not been analyzed in detail. Multiple scattering primarily affects Ka-band reflectivities, and sometimes eliminates earth surface reflection in regions of strong radar attenuation, while footprint non-uniform beamfilling impacts the interpretation of both Ku- and Ka-band radar data. As a consequence, both NS and MS mode precipitation estimates associated with intense convection, in particular, should be treated with caution. Finally, the assumed *a priori* statistics of precipitation particle size distributions can have an influence on estimated precipitation. As particle size distribution data are collected during the mission, more appropriate assumptions regarding the *a priori* statistics of particle sizes will be specified in the algorithm. At this stage of the mission, however, relatively simple assumptions regarding particle size distributions have been introduced into the algorithm, and so biases in estimated precipitation and underlying particle size distributions can occur.

It should also be noted that both precipitation estimates and retrievals of environmental parameters from CMB L2 have not yet been comprehensively validated using ground observations. Such a validation effort is under way and will continue after the V05 release of the CMB L2 product. Therefore, it is very important that users of the public release product keep in contact with the CMB Team for updates on the validation of precipitation estimates and any reprocessing's of the CMB L2 algorithm product.

Preliminary validation of the CMB L2 V05 product has revealed good consistency between estimated surface precipitation rate and raingage-calibrated radar, with correlations ~ 0.85 between 0.5 degree-resolution instantaneous estimates of surface precipitation rate and gage-calibrated radar (Multi-Radar Multi-Sensor [MRMS] product) over the continental US and coastal waters. Overall, there is a low bias of NS and MS mode rain rates on the order of a few percent. Zonal mean precipitation rates agree well with zonal mean precipitation rates from the Global Precipitation Climatology Project (GPCP) product within the 40 ^{o}S to 40 ^{o}N latitude band. Estimated zonal means at higher latitudes are underestimated relative to GPCP, due in part to the limited sensitivity of the DPR radar to light snow and drizzle. In the global mean, NS and MS mode estimates differ by less than a percent. Although there is good agreement and consistency of large-scale mean precipitation estimates between 40 ^{o}S and 40 ^{o}N, regional and seasonal means exhibit biases that are the subject of current investigations.

There could potentially be significant changes in the CMB L2 rain rate products in the transition from V05 to V06 due to possible tuning of the DPR radar calibration as well as adjustments and improvements of the CMB algorithm. Again, the users of the V05 public release product should keep in contact with the CMB Team for information regarding these changes.

CMB L2 V04 to V05 Changes

Numerous modifications have been made to the CMB L2 algorithm in the transition from V04 to V05, and the significant updates are summarized here. It may be noted at the outset, however, that the basic algorithm mechanics (i.e., estimation methodology) has not changed. The estimation method filters ensembles of DPR Ku reflectivity-consistent precipitation profiles using the DPR Ka reflectivities, path integrated attenuations and attenuated surface radar cross-sections at Ku and Ka bands, and GMI radiances. The filtered profile ensembles are consistent with all of the observations and their uncertainties, and the mean of the filtered ensemble gives the best estimate of the precipitation profile. The output file structure is essentially the same as in CMB V04, but a few additional variables are included for diagnostic purposes.

In the CMB V03 and V04 algorithms, estimated precipitation profiles were constrained by estimates of total path-integrated attenuation from the satellite to the earth's surface, derived from the DPR algorithm's surface reference technique (SRT) module; Grecu et al. (2016). However, an alternative approach is to develop a model for the normalized radar cross-section (σ^0) of the surface at the Ku and Ka channel frequencies of the DPR and relate that to a model of the surface emissivities (ε) at the GMI frequencies. Such a σ^0/ε model was developed by Munchak et al. (2016). The model is used to effectively constrain the simulated surface σ^0/ε in the algorithm's simulations of attenuated surface cross-section and upwelling brightness temperatures, which are compared to the observed attenuated cross-sections and brightness temperatures. In the CMB V05 algorithm, both the path-integrated attenuations and attenuated surface cross-sections are utilized to constrain solutions, even though there is some redundancy between these two observables. It should be noted, however, that some redundancy in the information content of observations leads to greater suppression of uncorrelated noise in algorithm estimates.

Another new feature of the V05 algorithm involves the algorithm's simulation of path-integrated attenuation at Ka band. Using off-line, high-resolution simulations of attenuation based upon ground-based radar fields, it was determined that the Ka-band path-integrated attenuation in vertical columns over DPR-sized footprints, derived using a Hitschfeld-Bordan method as it is done in the CMB algorithm, is significantly overestimated in convective regions where the footprints are partially filled with precipitation. The degree of partial filling, however, can be estimated using a 3x3 array of DPR footprints centered on the footprint of interest. In the CMB V05 algorithm, a scaling parameter based on the 3x3 array is used to modify the Hitschfeld-Bordan derived path-integrated attenuation at Ka band to properly account for partial filling of the radar footprint by precipitation. At Ku band, the effects of partial footprint filling on path-integrated attenuation are much smaller and are neglected in CMB V05.

The CMB V04 algorithm estimates exhibited a lack of sensitivity to path-integrated attenuation, such that the scaling of estimated attenuation relative to reflectivity was sometimes inappropriately high (i.e., the scaling was adjusted little from the initial guess), leading to overestimation of rain rates. Two changes are introduced into the CMB V05 algorithm to obtain more appropriate sensitivity. First, the prescribed uncertainties of SRT-derived path-integrated attenuations are reduced, forcing greater fidelity of solutions to observed path-integrated attenuations. Second, weak empirical constraints between particle size distribution mass-weighted mean diameters (D_m) and normalized intercepts (N_w) are imposed, such that larger D_m values tend to correlate with lower N_w values. The impact is a tendency for heavier rains not to amplify attenuation relative to reflectivity as much as before. The two changes described here lead to lower rain rates, particularly in moderate to heavy precipitation regions over land, using CMB V05.

Another aspect of the algorithm that is improved in V05 is the description of scattering by ice-phase precipitation particles. In all versions through V04, ice-phase precipitation particles were represented as spherically shaped, homogeneous mixtures of ice and air. In CMB V05, ice-phase precipitation in stratiform regions is represented using nonspherical particles with realistic geometries, as described in Kuo et al. (2016) and Olson et al. (2016). The rigorously computed microwave single-scattering properties of these particles are included in the algorithm's scattering tables. The nonspherical ice particles are less strongly forward scattering than spherical particles of the same mass, leading to substantially lower simulated upwelling microwave radiances at the higher-frequency GMI channels. The impact is to reduce CMB V05 algorithm-estimated snow water contents, since less snow is required to produce the same signal at the higher frequency channels. Mixed-phase particles are still described using spherical geometry models in V05.

The prescribed uncertainty of any observation in the CMB algorithm represents both the noise in the observation as well as the error in the simulation of that observation by the algorithm's forward model, and therefore it determines the degree to which the observation impacts estimates produced by the ensemble filter. As previously mentioned, the prescribed uncertainties of Ka-band reflectivities and Ku- and Ka-band path-integrated attenuations are modified in CMB V05. In addition, attenuated σ^0 observations are also introduced, and these observations are assigned uncertainties based on the variances of σ^0 for the given earth surface type, incidence angle, and wind conditions based upon a climatology of σ^0; see Munchak et al. (2016).

The prescribed uncertainties of Ka-band reflectivities are reduced from 3 dB in V04 to 2 dB in CMB V05. The uncertainty of Ku-band path-integrated attenuations is reduced from 4 dB to 3 dB. If path-integrated attenuation at Ka-band is available, the difference of the path-integrated attenuations (Ka – Ku) is used as an observable, with a prescribed uncertainty reduced from 4 dB to 2 dB in V05. This reduction of uncertainty is in recognition of the fact that the Ka-Ku path-integrated attenuation difference in non-precipitation situations provides a more stable reference relative to that of either one of the two channels. Over open water surfaces, the uncertainties of the σ^0 at Ku and Ka band are set to the climatological variabilities of σ^0 in those bands, given the 10-m wind speed derived from reanalysis data. For other surfaces, the uncertainty of Ku σ^0 is also derived from its climatological variability, but it is limited to values above 2 dB, while the uncertainty of the Ka σ^0 is limited to values above 4 dB. Uncertainties in brightness temperatures are maintained at the V04 values of 5 K (at or below 37 GHz) and 6.1 K (above 37 GHz).

Grecu, M., W. S. Olson, S. J. Munchak, S. Ringerud, L. Liao, Z. S. Haddad, B. L. Kelley, and S. F. McLaughlin, 2016: The GPM Combined Algorithm. *J. Atmos. and Oceanic Tech.*, **33**, 2225-2245.

Kuo, K.-S., W. S. Olson, B. T. Johnson, M. Grecu, L. Tian, T. L. Clune, B. H. van Aartsen, A. J. Heymsfield, L. Liao, and R. Meneghini, 2016: The microwave radiative properties of falling snow derived from nonspherical ice particle models. Part I: An extensive database of simulated pristine crystals and aggregate particles, and their scattering properties. *J. Appl. Meteor. and Climatol.*, **55**, 691-708.

Munchak, S. J., R. Meneghini, M. Grecu, and W. S. Olson, 2016: A coupled emissivity and surface backscatter cross-section model for radar-radiometer retrieval of precipitation over water surfaces. *J. Atmos. Oceanic Technol.*, **33**, 215-229.

Olson, W. S., L. Tian, M. Grecu, K.-S. Kuo, B. T. Johnson, A. J. Heymsfield, A. Bansemer, G. M. Heymsfield, J. R. Wang, and R. Meneghini, 2016: The microwave radiative properties of falling snow derived from nonspherical ice particle models. Part II: Initial testing using radar, radiometer and in situ observations. *J. Appl. Meteor. Climatol.*, **55**, 709 – 722.