GPM Ground Validation: Strategy and Efforts

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1. Strategy

The validation of satellite products is classically defined as a ground-based observing strategy intended to assess whether satellite products meet their stated accuracy requirements and objectives. In the case of the Tropical Rainfall Measurement Mission (TRMM), this philosophy was translated to the quasi-continuous operation of four ground radar sites for which TRMM satellite sensor-based and ground-based rainfall products were compared. The findings from these four sites revealed that TRMM products generally met their stated objectives. In addition, a number of lessons have also been learned in the course of these efforts: (a) quality control and careful construction of ground validation datasets is very labor intensive, but methods that make calibration and quality control techniques more efficient continue to improve; (b) despite every effort, ground validation data has its own set of uncertainties, consisting of both biases (currently ~ 5%) and random errors that are difficult to quantify on short time/space scales such as a single satellite overpass; and (c) direct comparison between rainfall estimates from the TRMM Precipitation Radar (PR) and microwave imager (TMI) reveal that instrument differences have regional and seasonal components that require validation results to be interpreted in a similar fashion.

In addition to incorporating lessons learned from TRMM, Global Precipitation Measurement mission (GPM) validation has a unique set of challenges introduced by the merits and objectives of the core and constellation satellites. The GPM core satellite is expected to generate products of a very high quality - indeed likely higher then most surface observations of instantaneous rainfall. This accuracy, combined with the relatively narrow swath of the dual frequency radar, requires either a very large number of very accurate surface observation sites or a physical approach, recommended here. In the physical approach, the rainfall validation is separated into a component related to validating satellite observables (i.e. reflectivity Z, brightness temperatures etc.) and a component designed to assess the uncertainty in translating these observables into surface rainfall products. Validation of the GPM constellation rainfall products, inferred from passive microwave sensors of varying capabilities, has distinct challenges related to the many applications envisioned for the GPM program. A combination of the core satellite and existing surface observations will meet the basic error characterization but can add little to GPM's effort to develop more physically based algorithms over land. These algorithms are essential to improving the fidelity of radiometer based rainfall estimates over land at short time and space scales. A physically based algorithm approach requires greater insight into the properties and behavior of both ice microphysics and land surface processes. The validation effort for the GPM constellation thus devotes significant effort and resources to improve the basic understanding needed for physically based algorithms.

Looking ahead it is becoming apparent that the future of precipitation research is probably not one in which satellite data are used in isolation. Instead, integration of satellite precipitation measurements with ground observations, cloud resolving models (CRMs), and land surface data assimilation systems (LDAS) is likely to replace satellite-only precipitation products, particularly for forecasting and hydrological applications that require precipitation as input. This is already apparent in the analyzed precipitation products over the continental US, and similar activities in Japan. Hence within this context, GPM validation activities should consider not only the satellite products, but the merged precipitation products based upon GPM data that embrace cloud resolving models and coupled land surface/cloud resolving models used in hydrologic applications. Such modeling components are also needed to improve the physical formulation of the radiometer algorithm over land and thus serve a dual role in the efforts described here.

The above strategy, discussed in greater detail within the following sections focuses upon two critical objectives that GPM validation must accomplish. *The first is the quantitative assessment of the rainfall uncertainties from the core satellite.* To the extent that the core satellite is used as a calibration standard for the constellation radiometers, it is imperative that uncertainties in the operational products be fully quantified and compared together with uncertainties in the conventional rainfall products. *The second overarching objective is the collection of data required to advance present-day empirical radiometer algorithms over land to a physical level approaching that currently available over oceans.* While it is recognized that that oceanic retrieval algorithms are still imperfect, advancement of the algorithms over land is seen as a critical step towards generating products with fidelity at storm scales (instead of the current climatological scales) envisioned for many GPM applications. To achieve these objectives, a system using operational radars, a specially instrumented GPM validation site designed to observe cloud microphysics and surface rainfall with high fidelity, a sequence of aircraft field experiments, and cloud- and coupled land/atmosphere models will be employed. In order to fully satisfy the above requirements it is also clear that the infrastructure must be deployable. This will ensure that validation results are robust and not related to a specific meteorological regime. In this same vein, it is clear that if/where specific meteorological regimes are not easily accessible from surface instruments, airborne measurements should be available. This is equally true for some parameters that simply require *in- situ* observations of cloud properties. Prudence thus calls for reserving resources to carry out at least one or possibly two airborne campaigns to address such issues.

The report does not deal equally with all potential validation needs but hopes not to preclude any additional activities related to the improvement of algorithms or better understanding of rainfall processes that can be leveraged against the proposed infrastructure with little additional cost and potentially great benefits. This, however, is viewed more as a Principal Investigator (PI) led activity.

2. Objectives[1]

[1] A complete validation effort must include those efforts related to validating the basic measurements – radiances in the case of the radiometers and measured reflectivity factors in the case of radar. Because these efforts encompass both scientific efforts as well as engineering and spacecraft considerations, they are included in a separate statement – Appendix A, in order to leave this document to deal with the Science Team activities related to rainfall validation.

2.1 Core Satellite Error Characterization

The GPM core satellite, with a dual frequency radar and state of the art radiometer is expected to produce very high quality rainfall products to be used as a reference for the radiometer constellation as well as climate studies. Comparisons against surface rainfall observations are useful to confirm performance goals of 5-10% in estimates of instantaneous rainfall rate over areas of O[100 x 100 km^2]. However, difficulties associated with operational sites, coupled with problems related to infrequent overpasses of the core satellite sensors over any given validation site when raining, require that additional efforts be undertaken to properly validate the GPM core satellite products. While a physical approach intended to validate algorithm components is feasible, it is not possible to perform a fully comprehensive validation effort. There are simply too many parameters whose measurement is difficult and for which we cannot afford to collect robust statistics. Instead, the validation paradigm will be seen to be incremental – first establishing the physical validation framework and then iteratively improving upon this framework as uncertainties are reduced.

As outlined in the strategy section, the validation of GPM radar and/or radiometer algorithms is difficult because the narrow swath of the Ka band radar precludes many overpasses over an individual validation site while the high accuracy expected from the spaceborne sensors precludes any but the most sophisticated sites to be useful for validation. Fortunately, the Core-satellite radar algorithm or the combined radar/radiometer algorithm may be simpler to validate than the radiometer-only algorithms because the primary validation tool is a similar instrument - namely a multi-parameter airborne or ground-based radar. Of course even given a "similar" measurement type, both the characteristics and operation mode of the radar platform must be judiciously chosen so as to appropriately validate targeted parameters of interest (e.g., attenuation, surface rainfall, precipitation profiles etc.). This is true even for combined radar-radiometer rainfall algorithms since the radiometer in the algorithm must be viewed as a tool to constrain the radar solution instead of providing an independent means of retrieving rainfall. From a validation perspective, the radiometer-only solution is equivalent to the constellation algorithms and it discussed in that section.

In order to quantify core-satellite radar uncertainties, a two-step approach to using existing WSR-88D radars (polarimetric or not) is to first compare on a common grid the radar reflectivities from the ground and space radars at altitudes of 6 km or above, and then to compare reflectivity values near the surface. At a 6 km height, the Ku-band (13.6 GHz) DPR frequency and the ground-based S-band radar experience little attenuation. These comparisons thus provide information on the relative calibration accuracy of the space and ground-based radars. If good agreement in the reflectivity fields can be established at this altitude over the course of a number of satellite overpasses, then subsequent comparisons of the S- and Ku-band reflectivity fields near the surface provides a way to assess the accuracy of spaceborne radar attenuation correction algorithms. Similar considerations apply to comparisons of the S- and Ka-band (35.5 GHz) data sets although in this case, effects of Mie scattering at the high frequency must be accounted for in the comparisons. To the extent that systematic differences are identified between the DPR and WSR-88D datasets, these differences could be investigated and corrected through experimentation with DPR algorithm assumptions.

By the time of GPM, it is further expected that a significant number of WSR-88D radars will have been upgraded to include polarimetric capabilities. Polarimetric radar observations will provide an internally consistent means to verify overall WSR-88D calibration and will provide additional information about the near surface raindrop size distribution - specifically the median volume diameter, D_0. This value can also be compared to that derived from the spaceborne algorithm. While both the reflectivity and the median volume diameter are seen as essential components needed to infer surface rainfall, there are of course additional variables related to the details of the drop size distribution and air motions that determine the rainfall reaching the ground.

The final step in assessing uncertainties in the operational product is thus to establish the relation between the satellite observable Z and retrieved D_0 that can be evaluated at a number of operational sites, and the surface rainfall. This will be accomplished at the US GPM Validation Site via dedicated multi-frequency polarimetric radar and a large number of distributed rain gauges. The occasional core satellite overpasses will be useful to verify the procedures at this location, but not required once the validation of satellite observables is separated from the relationship between these and the surface rainfall. All data (not just from the overpasses) from the validation site are therefore useful and will be used to examine if the relationships between Z and D_0 and the surface rainfall exhibit any meteorological regime dependence. In addition, the large number of rain gauges will be used to assess area average rainfall uncertainties to serve as a benchmark for areas with fewer gauges. An important component of GPM validation will thus be the contrasting of GPM core satellite uncertainties with those in common use by the applications community. Redundant D_0 information will be collected from profilers and disdrometers in order to have confidence in the D_0 determined from polarimetric radar and to assess its own uncertainty needed for the error propagation studies.

Key to the above error characterization effort is an *early* set of tests designed to verify the strategy prior to its full implementation. While DPR data must wait for the launch of the satellite, it is nonetheless possible to simulate the system using airborne dual frequency radar and existing polarimetric ground based radar. For studies of rainfall, rain gauges can be deployed at the GPM Validation Site(s) early. It is thus recommended that this activity be carried out at the earliest possible opportunity.

Validation of snow would be performed in the same manner although it remains to be established that an equivalent D_0 in snow can be defined from both spaceborne and ground based polarimetric radars. It is recommended that high frequency radiometer and DPR retrievals of snowfall characteristics are studied using high frequency radar (W, Ka and Ku or combinations thereof), in-situ aircraft measurements, and ground based measurements of snow particle size distributions and snow density.

2.1.1 Key infrastructure summary

- WSR-88D radars – some with polarimetric capabilities

- o Multi-frequency polarimetric radar, wind profilers, dense rain gauge array and redundant D_0 measurements at one location - referred to here as US GPM Validation Site. The site should have significant meteorological regime variability and frequent precipitation
- o Aircraft multi-parameter radar with attendant radiometers and microphysical instrumentation
- o Meteorological observations (e.g., profiles of wind and thermodynamic parameters) needed for quantifying changes in meteorological forcings

2.2 Constellation Satellites Validation

The core satellite is the ideal validation tool for instantaneous rainfall retrievals from the radiometers comprising the GPM constellation. This effort thus requires only the core satellite products during satellite coincidences and the research efforts associated with the analysis and interpretation of the comparison results. This effort, however, represents only a portion of the validation requirements as the constellation must also provide validated rainfall accumulations over multiple space/time domains needed for hydrologic applications. Over land, this can be accomplished by direct comparisons with existing networks and analyses such as the NOAA Stage-4 rainfall product over the US or the AMeDAS network in Japan. Over oceans, this is more difficult as surface-based observing infrastructure is scarce. Access to and utilization of data sets over ocean areas supplied by international partners should be fully explored; one example would be the Japanese site at Okinawa. There is also a need to validate winter precipitation regimes over open mid-latitude oceans, a task that will likely require an in situ field campaign involving aircraft (cf. Sec. 3). The utility of *any operating* radar/rain gauge networks for establishing random and systematic errors in rainfall relative to the GPM core satellite over oceanic domains for identified scales of interest should be fully explored.

While the validation of constellation radiometer products will rely heavily on global comparisons against the core satellite products, the largest challenge to GPM is the absence to date of a robust physically derived algorithm over land that will be necessary in the GPM time frame. Because the TRMM TMI land rainfall is still largely empirical, it is applicable primarily in a climate sense and not expected to perform particularly well over the storm scales relevant to the GPM science applications. A physically derived algorithm consistent with the more mature oceanic version of the radiometer algorithm must therefore be viewed as a top priority for GPM. The two main difficulties are the lack of good physical information relating ice microphysics and thus radiometric scattering signals to surface rainfall and a good surface model that can predict multi-channel radiances based upon soil conditions. These two shortcomings will be addressed using airborne and ground observations combined with Cloud Resolving Models, and a Coupled Land/Atmosphere modeling effort respectively. These modeling efforts will be seen to require nearly the same validation infrastructure envisioned for the core satellite but greatly expand the scientific scope of the GPM science. They are separated into individual sections of this report only because the expertise in modeling is found in slightly different communities albeit part of the GPM science team.

2.2.1 Infrastructure requirements for radiometer rainfall algorithm validation

- o Core satellite rainfall estimates

- GV site multi-parameter radar (polarimetric, vertically profiling)/composite national radar, rain gauge products
- Aircraft and island-based radiometer and microphysical instrumentation

2.3 Physical Models to Derive Uncertainties in GPM Products

A complimentary approach to observing uncertainties is to construct error models that propagate any uncertainties in the algorithm assumptions to derive a theoretical uncertainty in the final product. This requires knowledge about hydrometeor characteristics as well as the intervening atmosphere and surface properties. For example, nature of snow crystals, the vertical distribution of cloud water relative to rain water, the freezing level height, and the frequency of mixed phase conditions all affect the final precipitation products but are currently assumed. The role of the Ground Validation Program in these cases is to provide reliable statistics for parameters such as the above that can be used to construct the theoretical error model.

2.3.1 Snow crystals

The higher orbital inclination of GPM relative to that of TRMM implies that a greater proportion of the precipitation encountered by GPM will be in the form of snow. To improve radiometric snow retrievals, especially over land, 166 GHz and 183 GHz channels will be added to the GMI. The importance of snow in northern latitude water budgets and the need to establish the capabilities of the high frequency radiometric channels makes snow validation experiments a high priority item. Specifically, data sets are needed to (1) develop and validate models that convert the physical properties (shape, size distribution, density, ice-air-water ratio) of single snowflakes to their radiative properties (asymmetry factor, and absorption, scattering, and backscattering coefficients); and (2) relate the bulk layer radiative properties (summation of the single particle radiative properties over a discrete vertical layer) to calculated and observed passive microwave radiances and radar reflectivities. These models are central to the development of physically-based snowfall retrieval methods, as well as the characterization of likely retrieval uncertainties. In the past, the microwave community has used a number of approximate models all giving different results based on choices of parameters and assumptions.

To date, there has been only one field campaign dedicated to comprehensive ground, air, and in-situ measurement of snowfall (Wakasa Bay, Japan, Jan.-Feb. 2003). This data set was taken near the Sea of Japan and included six reported days of snowfall events, though some of the remote sensors had calibration issues. A key advantage of the Wakasa Bay dataset is the frequency ranges of the collocated airborne radar (13, 36, and 94 GHz) and passive microwave (10 – 340 GHz) remote sensing data collected. Such high spatial resolution data are valuable for obtaining more specific information on ice particle single-scattering properties and vertical distributions that may later be incorporated into algorithm models. Additional and more accurate snowfall ground and airborne data sets are needed for winter season continental and lake effect snow events to assist with retrievals over land surfaces[2].

2.3.2 Cloud Water

Relative to intervening cloud properties the microwave emission/attenuation properties of cloud water are problematic, but reasonably well known being primarily a function of mass content. For the radiometers the critical issues are: what are the relative proportions of cloud and rainwater and their geometries (depth of liquid water column and horizontal distribution) within the radiometer footprint? Attenuation in cloud-water is also an issue for the Ka and Ku-band frequencies of the DPR. The DPR can supply rain geometry information at coarse resolution, but the relative proportions of cloud and rain are difficult to untangle. Parameterizations of cloud and rainwater proportions have so far been supplied by CRM simulations, making it possible to include the effects of cloud in combined radar-radiometer and radiometer-only algorithms. Hence, validation of cloud/rain parameterizations, although difficult, could be a worthy goal of GPM ground validation, since in light rain situations the relative proportion of cloud liquid water can have a significant impact on observed microwave radiances. At least one to two airborne field campaigns will likely be required to address this aspect of the validation activity (cf. Sec. 3).

2.2.3 Mixed Phase

Mixed-phase precipitation is perhaps the most difficult entity to properly parameterize in radar or radiometer algorithms, since particle geometry, particle density, and meltwater distribution can influence particle single-scattering properties. However, at least in stratiform precipitation situations, ice-phase precipitation distributions above the melting layer and raindrop size distributions below supply constraints on the evolution of melting particles in between. Airborne X- and Ka-band observations have been used in the past to give a best estimate of the density of ice-phase precipitation that eventually melted to produce stratiform rain below. As in the case of ice-phase precipitation, combinations of airborne or ground-based radars and microwave radiometers, in combination with coincident *in situ* microphysics observations, are suited to derive the properties of mixed-phase precipitation. In addition, microwave link observations through melting layers, combined with observations from disdrometers placed at intervals along the link, could provide insight into the attenuation of melting precipitation as a function of directly observed particle size distributions and habits, at least in stratiform situations.

2.4 CRM Validation Activities

CRMs can serve a number of roles in GPM: (1) Establishing physical relationships between the cloud vertical hydrometeor profiles and expected radiometric signals as a function of the cloud environment, (2) as space/time interpolators between GPM satellite overpasses, and (3) a conduit

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[2] The planned participation of the NASA Precipitation Measurement Mission and GPM Project in the Canadian CloudSat/CALIPSO Validation Project (C3VP; winter 2006-7) will provide one such opportunity.

for linking atmospheric regime forcing variability to cloud physical processes and associated latent heating structure. Forward thinking also dictates consideration of the space/time integrator role that operational CRMs may play in future high-resolution re-analysis systems.

CRMs are generally applied to the study of precipitation processes using two distinct approaches. The first approach, termed "cloud ensemble modeling", allows many clouds of various sizes and stage of lifecycle to be present at any simulation time. For this approach large-scale “forcing” (advective effects, lift etc.) must be imposed into the model and is typically derived from quality controlled observational networks (e.g., sounding arrays) or reanalyses. The second approach uses initial temperature and water vapor profiles having significant convective available potential energy (CAPE). Modeled clouds are subsequently initialized with cool pools, warm bubbles or land or ocean surface fluxes to simulate specific types of clouds or convective systems. For this approach no large-scale advective forcing is required. Both of these approaches have been applied to the Goddard Cumulus Ensemble model (GCE), and both could be used for GV. For shallow convection and stratiform clouds, large-eddy simulation models (LES), rather than CRMs, are generally used in cloud process studies, owing to requirements for higher resolution in simulating these cloud systems. Since GPM will place more emphasis on higher-latitude cloud systems than TRMM, it may be necessary to employ LES if CRMs are unable to meet the success criteria discussed below.

Perhaps the most important criteria for measuring the utility and/or success of CRMs in the GPM framework are (a) do they reproduce the climatological relationship between surface rainfall and ice scattering observed by the GPM core satellite, and (b) if so, can they be used to establish storm-specific relationships based upon the meteorological regime and temporal evolution of the storm system? Success in the latter would add significantly to the ability of passive microwave algorithm to retrieve precipitation over land needed by a host of applications envisioned for GPM. One other measure of CRM consistency and a potential success metric would be the ability to replicate the gross characteristics of cloud system *latent heating structure* (Q1-QR; magnitude, heating peak altitude, shape etc.); a parameter of interest to GPM. Note that these criteria are *statistical* in nature and thus do not depend upon the exact location, time, or evolution of any particular storm. The microphysics process site is viewed as ideal for this effort.

If CRMs fail to meet the above success criteria, there are several avenues to be pursued as remedies. For shallow cumulus and stratiform clouds, LES simulations may be required. For both CRMs and LES, there remain many possibilities for improvement related by use of advanced microphysics methods (multiple moments and bin methods), should current approaches prove inadequate. Treatments of sub-grid-scale diffusion and numerical methods are also at issue for both CRMs and LES and would be targets of investigation should these models fail to meet success criteria. Outside the models themselves, the possibility of deficient forcing could also require consideration.

2.4.1 Infrastructure required for CRM validation

a. Initialization

- Frequent (accurate) soundings and/or large scale forcing from sounding arrays (possibly re-analyses) for model initialization; these also provide diagnostic budgets for heating and moistening. Note sounding arrays also provide a "gold standard" for diagnosing heating and moisture budgets.
- Cloud condensation and ice nuclei measurements if possible. A combination of ground and/or in situ airborne sampling could provide useful information for initializing model microphysical formulations which rely on aerosol characteristics to initiate nucleation processes prior to precipitation formation.

b. Validation

- Detailed cloud structures including both kinematic and dynamic over the entire life cycle for various cloud types; i.e., measurements from dense sounding networks and well-coordinated Doppler radar observations.
- The statistical relationship between simulated and radiometer-observed ice scattering versus the surface rainfall simulated by the model or observed by the GV infrastructure.
- Microphysical properties over the life cycle of clouds, cloud systems, and cloud-system types (convective, stratiform) such as: drop size distributions (DSDs) at various layers; gamma or exponential distributions for cloud water, rain, cloud ice, snow, and graupel; 3D liquid and ice water contents and median diameters; mixed phase information; particle density and number concentrations for cloud ice, snow, graupel and hail; aerial ratios (ice habits); and the liquid water fraction of melting snow, graupel and hail. These observations are limited to select IOPs consisting of both airborne and ground based operations designed to improve the understanding of cloud processes and the modeling system.
- Latent heating (LH) structure. Validation of CRM-diagnosed LH structures (i.e., magnitude, profile shape and altitude of the profile peak) follows logically from the validation of CRM microphysics and cloud structures. Perhaps more importantly, the majority of satellite-based LH retrieval algorithms currently rely on ensembles of CRM-generated heating profiles (as in the case of hydrometeor retrievals). Here the validation effort should not be viewed in terms of measuring an "instantaneous" LH profile, but rather assessing the degree to which CRM ensemble heating characteristics represent nature over longer time and spatial scales (e.g., daily to monthly, $\Delta x \geq 200$ km; TBD). For this effort dense sounding networks with frequent sampling (once every 4-6 hours) would be most desirable- consistent with datasets required to force CRM simulations. However, it is also possible that radar-derived divergence profiles will be useful. Algorithm development and interpretation of LH at various time and space scales have now just reached a stage of routine application. The activity and the science *are* considered important. We suggest that PMM and GPM science interests work to further advance this validation activity (e.g., collaboration with/leveraging of international field campaign opportunities).

2.5 Coupled CRM/LSM and closure of the water cycle:

Hydrological applications demand accurate rainfall and snowfall estimates over land. However, satellite-based microwave retrievals of precipitation over land areas are complicated by uncertainty in background emissivity and the spatiotemporal variability of surface radiance. This uncertainty and variability is largely due to surface characteristics and states, including soil and vegetation types and properties, soil moisture content, and surface skin temperature. Because these surface states (and therefore the GPM retrieval errors) vary as a coupled system, the GPM GV program will benefit from the deployment of a coupled CRM/LSM approach, both to understand the tight interactions between the microphysics and terrestrial physics, but also to leverage the integrating power of the land surface for water budget analyses that will provide additional diagnostics of GPM performance.

Accordingly, the key science questions that could be addressed by a coupled CRM/LSM approach for GPM GV include:

- *How are retrievals over land affected by uncertainty in the surface emissivity and spatiotemporal variability in surface radiance?*

- *How well can we estimate the water budget over land using space-based rainfall estimates, and how are hydrologic fluxes and states such as runoff, evapotranspiration, soil moisture, and groundwater recharge affected by changing precipitation patterns?*

A coupled CRM/LSM system for GPM GV must be able to represent both tropical and midlatitude microphysical processes as well as the proper coupling dynamic terrestrial water and energy balance processes. Recent long term integrations with the coupled Land Information System/Goddard Cumulus Ensemble Model (LIS/GCE) system over the ARM region indicate that the land surface has a major impact on cloud and precipitation processes especially for less-organized convective clouds. The Land Information System (LIS; http://lis.gsfc.nasa.gov;), which contains several mature LSMs including Noah, CLM and VIC, and the GCE model has been shown to represent both tropical and midlatitude microphysical processes. Other recent work with the LIS/Weather Research and Forecasting (LIS/WRF) coupled system has shown that the frequency of coupling radiation, clouds and the land can have a profound impact on the prediction of clouds and precipitation. While the above models are showing promise, a fully coupled CRM/LSM that can predict microwave surface emissivity characteristics does not yet exist. However, based on these recent works, we recommend that a coupled CRM/LSM with adaptive representation of vegetation be deployed at all GPM GV sites to serve as a benchmark for retrievals and a pathway to understanding errors over land.

A key unresolved science issue related to the hydrologic cycle over land is how changing precipitation patterns at multiple scales will translate into changes in hydrologic fluxes and states, such as runoff, evapotranspiration, soil moisture, and groundwater recharge. Recent analysis demonstrated a significant amplification of uncertainty in using precipitation fields from commonly applied global precipitation products (6 including TRMM) fields to determine spatially-distributed runoff, which ultimately is the source of renewable freshwater resources. The global geography of runoff source areas shows nearly 20% of humankind with little or no access to renewable supply, a high degree of water scarcity, and economic hardship. Accurate assessment of renewable freshwater resources is critical to economic and social development and the entry point for making such estimates is accurate precipitation measurement.

Understanding and predicting these changes is a key goal of the Global Land Data Assimilation System (GLDAS), which uses TRMM-based multi-satellite data as input into several hydrological models. Unfortunately, the desired progression to finer scales in rainfall retrievals is counter-balanced by the increasing multi-dimensionality of error, which has a consequentially complex effect on propagation through land surface-atmosphere interaction simulations. In essence, this represents a competing trade off between lowering the rain retrieval error and modeling land-vegetation-atmosphere processes at the finest scale possible. The propagation of uncertainty in remote sensing precipitation estimates and also the absence of small-scale (of the order of 4 km or less) variability of precipitation forcing in coupled land-atmosphere models results in biased hydrometeorological predictions at regional or continental scales due to significant nonlinearities in the coupled system. Recent studies have suggested that using ancillary information related to the water balance can be useful for constraining hydrologic fluxes, although the uncertainties in the water balance over land are still well over 10% in many areas. Using GPM products as input to these models and assessing their water budget errors will provide another critical diagnostic of GPM performance.

2.5.1 Key observational requirements

- Those necessary for the CRM analysis described in the previous section,
- Land surface water and energy budget terms, including surface energy fluxes (downward shortwave, longwave and net radiation, sensible, latent and ground heat),
- Surface water fluxes (stream flow)
- State variables such as soil moisture and temperature profiles, groundwater levels, and land cover, vegetation properties, and soil properties.

3. Synergies and Additional Needs

Five broad efforts have been described above: Core Satellite Quality Assessment, Improved physical basis for the Constellation "land" algorithm, Algorithm Uncertainties, CRM Validation, and Coupled Models/water budget closure. These emphases are all closely interconnected with each other as well as with related efforts by operational agencies. Below is a summary of perhaps the most evident of such connections:

Core Satellite Quality Assessment and the National radar/rain gauge network: The effort to quantify the quality of the GPM core satellite is based upon matching vertical reflectivity profiles to measure attenuation and an effort to assess how well the derived DSD parameters (such as D_o) relate to the surface rainfall. The first part is equally important to assess the quality of the national radar network, while the second is likely to help provide uncertainties not only for the GPM core satellite, but for polarimetric rain estimates from the national radar network as well.

Radiometer/Radar algorithm uncertainties and the CRM modeling effort: Algorithm uncertainties are caused primarily by those parameters that cannot be sensed directly but that are nonetheless known to impact the derived rainfall products in some fashion. The parameters are explicitly modeled by the CRM effort and thus the CRMs form a first estimate of their natural variability.

Verifying these at a well-instrumented site thus helps not only the algorithm validation, but the CRM efforts as well.

Core satellite quality assessment and Radar/radiometer algorithm uncertainties: These two efforts are closely linked in that if the algorithm is correctly formulated, the uncertainties derived in the quality assessment portion of this plan should reflect the same uncertainties derived independently from the error model developed as part of the algorithm uncertainty work. Having independent checks of the overall uncertainty is likely to help both efforts.

Development of physically based radiometer algorithms over land and CRMs: Because the observed radiances over land are primarily a reflection of the ice scattering, which is not a unique measure of the surface precipitation, the CRMs will be critical to help guide a physically based radiometer algorithm over land. Aside from its role in providing forecast guidance, the CRMs thus form an integral part of the constellation algorithm development. Verifying that the CRMs properly reproduce the radiometer scattering signal, and produce this signal for the right reasons, simultaneously helps constrain the CRM microphysics.

Constellation satellite algorithm and Coupled models: As with the CRMs, the radiometer algorithm over land requires surface characteristics that are currently not well understood. Aside from the important validation work related to closing the water budget, the couple land/atmosphere models thus also constitute an integral part of the constellation algorithm development via radiative transfer modeling.

Core Satellite Quality Assessment and Coupled Models: These two components, through the closure of the water budget, form yet another independent means of assessing the overall uncertainty in the rainfall products.

CRMs and Coupled Models: While one first effort has historically focused upon microphysical parameterizations and atmospheric forcings, the latter has focused upon surface forcings, the overlap in the atmospheric portion of the coupled models is self evident.

A final and important synergy, which is an integral part of this planning process, is related to the regional dependence of satellite products and models upon meteorological regimes. While the satellite has greater insight into the actual realization of a storm event, the satellite lacks information about the background meteorological condition. This is precisely what the models add and what the GV program is designed to validate. Together, the physical validation that involves models capable of diagnosing fundamental changes in forcing is therefore an integral part of the validation process.

Nonetheless, not all physical variables can be measured adequately from the ground. As noted above, profilers and polarimetric radars do not provide estimates of cloud water or water vapor and give only semi-quantitative information on snow, graupel and mixed-phase hydrometeors. Ground-based dual-wavelength radars such as a Ku/Ka-band combination have some attractive features but their maximum range, particularly in rain, is limited. Furthermore, it is often difficult with ground-based measurements to separate the scattering, emission, and absorption processes contributing to the observed spaceborne radar and radiometer measurements. Airborne multi-wavelength radar and radiometer measurements on high altitude aircraft with similar viewing geometries to the satellite sensors along with in-situ microphysical measurements from low-altitude and medium-altitude aircraft are generally recognized as the best combination of measurements for understanding the scattering physics contributing to the observed satellite observables. In-situ aircraft provide the only robust means of quantifying the DSD of various ice habits needed for the CRM validation as well understanding of Radar/Radiometer algorithm uncertainties. Therefore, in situ aircraft observations will play an important role in GPM validation activities.

The TRMM field campaigns were focused on the tropics and sub-tropics and there have been few field campaigns in the higher latitudes covered by GPM. The meteorology for these higher latitudes is significantly different than the tropics in that it will include extratropical weather systems with significant regions of snow and mixed phase precipitation. The algorithms for these higher latitudes will also be different because of differences in the hydrometeor phase and also likely differences in the microphysics that so greatly affect the satellite measurements. It is therefore anticipated that at least one and possibly two or more aircraft field campaign(s), addressing precipitation over both ocean and land, will be required at higher latitudes to help in understanding and improving the spaceborne algorithms.

Appendix A: Calibration Issues (to be completed by "calibration WG")