Precipitation estimation using combined active/passive sensor information within the GPM framework

Arthur Y. Hou

NASA Goddard Space Flight Center

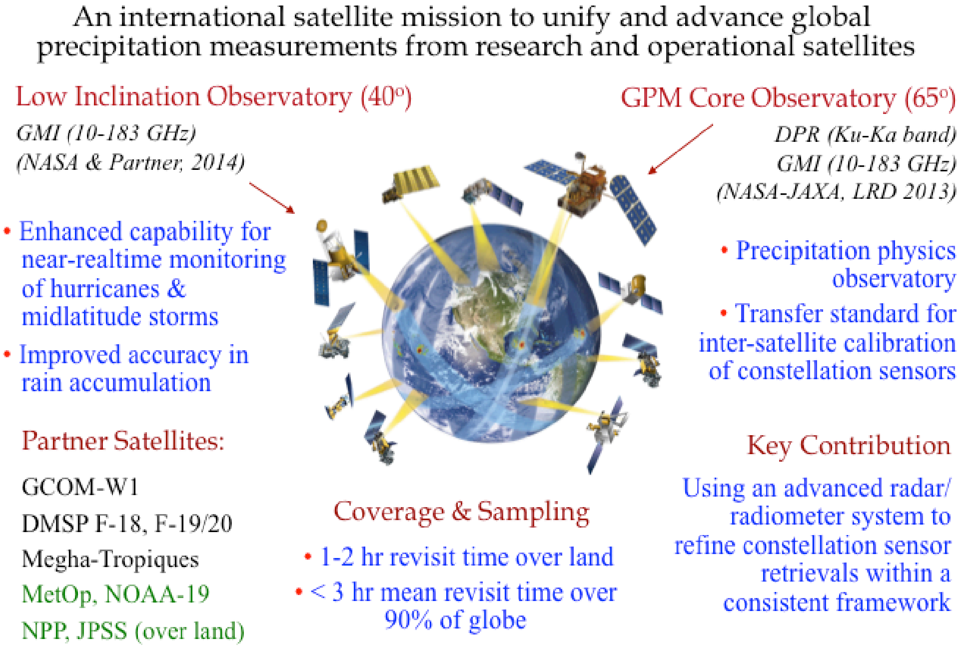
Forward

Global Precipitation Measurement (GPM) is an international satellite mission specifically designed to unify and advance precipitation estimates from a constellation of microwave sensors to provide next-generation global precipitation products for scientific research and societal applications (Hou et al., 2011). The GPM measurement strategy relies on the use of an active microwave sensor to obtain 3D precipitation structures, a network of passive microwave sensors for global coverage, and combined active/passive sensor measurements provided by a reference satellite for improving precipitation estimates from all constellation sensors. This presentation provides an overview of the mission and considers potential areas of science collaboration between the remote sensing and data assimilation communities.

1. GPM mission concept

The GPM mission was initiated by the National Aeronautics and Space Administration (NASA) of the United States and the Aerospace and Exploration Agency (JAXA) of Japan as a follow-on to the U.S.-Japan Tropical Rainfall Measuring Mission (TRMM), which was launched in 1997 and is currently in its 13th year of operation. NASA and JAXA will deploy a GPM "Core Observatory" in a non-Sun-synchronous orbit at 65° inclination carrying a Dual-frequency Precipitation Radar (DPR) operating at Ku and Ka bands and a multi-frequency (10-183 GHz) conically-scanning GPM Microwave Imager (GMI). The role of the Core Observatory is to serve as a "physics observatory" to provide 3D precipitation structure information together with associated radiometric signatures, which can then be used as a reference standard for improving precipitation estimates from passive microwave sensors.

For global coverage, GPM relies on a constellation of microwave imagers and sounders on research and operational satellites, which include the U.S. Defense Meteorological Satellite Program (DMSP) F-Series, Japan's Global Change Observation Mission-Water 1 (GCOM-W1), the French-Indian Megha-Tropiques, the National Oceanic and Atmospheric Administration (NOAA)-19, the European MetOp Series, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP), and the NASA-NOAA Joint Polar Satellite System (JPSS). NASA will also provide a second GMI on a partner-provided "Low Inclination" Observatory (LIO) at 40° inclination to provide additional observations from a non-Sun-synchronous orbit. It was recognized from the inception of GPM that it would be difficult to achieve accurate estimates of time-integrated rain accumulation by relying solely on observations at fixed local times by a number of polar orbiting satellites. The GPM Core and LIO will together provide "asynoptic" observations from non-Sun-synchronous orbits to reduce the temporal gaps in-between overpasses by polar-orbiters. NASA and JAXA have completed in 2009 a formal partnership agreement to implement GPM. Additional agreements to formalize the participation of NOAA and space agencies of France, India, Brazil, and the European community are in various stages of development. The GPM mission concept of using combined DPR+GMI measurements from the Core Observatory to refine precipitation estimates from all constellation satellites is summarized in Fig. 1.



An international satellite mission to unify and advance global precipitation measurements from research and operational satellites

Low Inclination Observatory (40°)

GMI (10-183 GHz)
(NASA & Partner, 2014)

- Enhanced capability for near-realtime monitoring of hurricanes & midlatitude storms
- Improved accuracy in rain accumulation

GPM Core Observatory (65°)

DPR (Ku-Ka band)
GMI (10-183 GHz)
(NASA-JAXA, LRD 2013)

- Precipitation physics observatory
- Transfer standard for inter-satellite calibration of constellation sensors

Partner Satellites:

GCOM-W1
DMSP F-18, F-19/20
Megha-Tropiques
MetOp, NOAA-19
NPP, JPSS (over land)

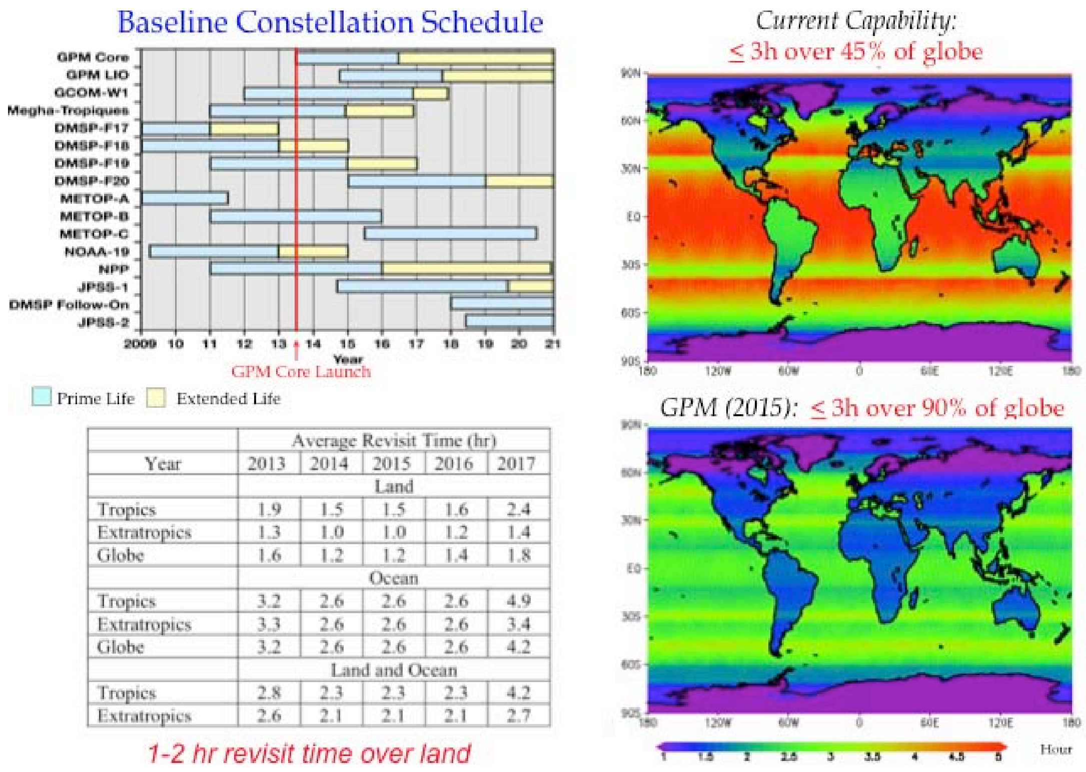
Coverage & Sampling

- 1-2 hr revisit time over land
- < 3 hr mean revisit time over 90% of globe

Key Contribution

Using an advanced radar/ radiometer system to refine constellation sensor retrievals within a consistent framework

Figure 1. GPM Mission Concept



	Average Revisit Time (hr)				
Year	2013	2014	2015	2016	2017
	Land				
Tropics	1.9	1.5	1.5	1.6	2.4
Extratropics	1.3	1.0	1.0	1.2	1.4
Globe	1.6	1.2	1.2	1.4	1.8
	Ocean				
Tropics	3.2	2.6	2.6	2.6	4.9
Extratropics	3.3	2.6	2.6	2.6	3.4
Globe	3.2	2.6	2.6	2.6	4.2
	Land and Ocean				
Tropics	2.8	2.3	2.3	2.3	4.2
Extratropics	2.6	2.1	2.1	2.1	2.7

Figure 2 GPM constellation launch schedule based on current estimates (upper left) and mean revisit times of the baseline GPM microwave sampling that includes humidity sounder observations over land.

The spatial and temporal sampling capability of the GPM constellation will vary as a function of the partner-provided on-orbit assets. The upper left panel in Fig. 2 shows the launch schedules and expected mission lifetimes of the constellation members based on information that is currently available. Given the known issues with microwave humidity sounders in warm rain detection over ocean (Vila et al., 2007), NASA currently plans to use sounder measurements only over land for microwave-based global precipitation products. Figure 2 shows that this constellation sampling translates into mean revisit times between 1 to 2 hours over land but longer over oceans. The preset-day mean revisit times shown in Fig. 2 are based on observations by the TMI, AMSR-E on Aqua, SSM/I F13 and F14 over ocean and land – augmented with observations by AMSU-B's on NOAA-15, NOAA-16, and NOAA-17 over land. Overall, in 2015 the GPM constellation is expected to double the coverage on the globe where the mean revisit time is less than 3 hours.

For near real-time numerical weather prediction (NWP) or hydrological applications, both the GPM Core and LIO will provide GMI radiance as well as precipitation products within 3 hrs of observation, which have been shown by TRMM to be valuable for monitoring rapidly developing storms and the initial position fix for cyclone track prediction (NRC 2005).

2. Core Observatory capabilities

The GPM Core Observatory will carry two precipitation sensors: the DPR provided by JAXA and the GMI provided by NASA. The instrument scanning patterns and swath widths are illustrated in Fig. 3.

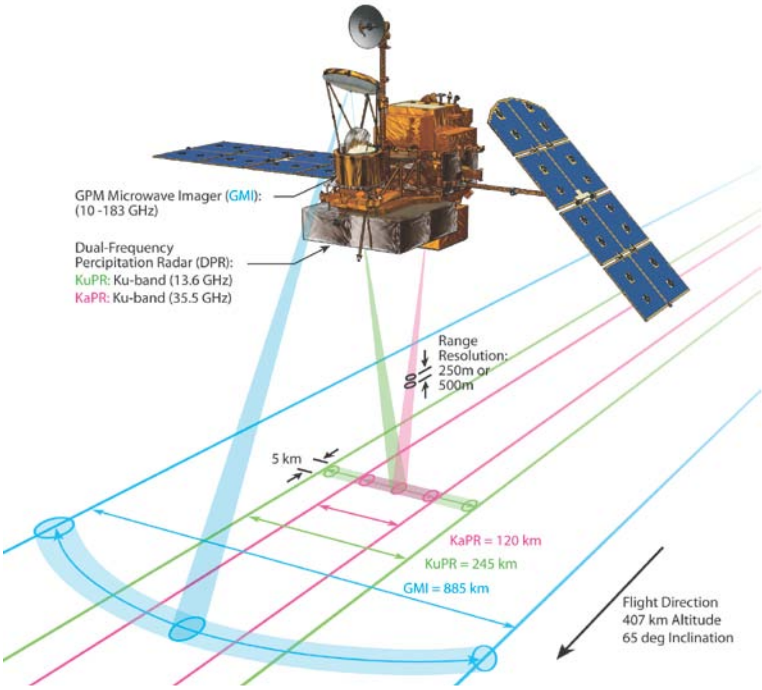
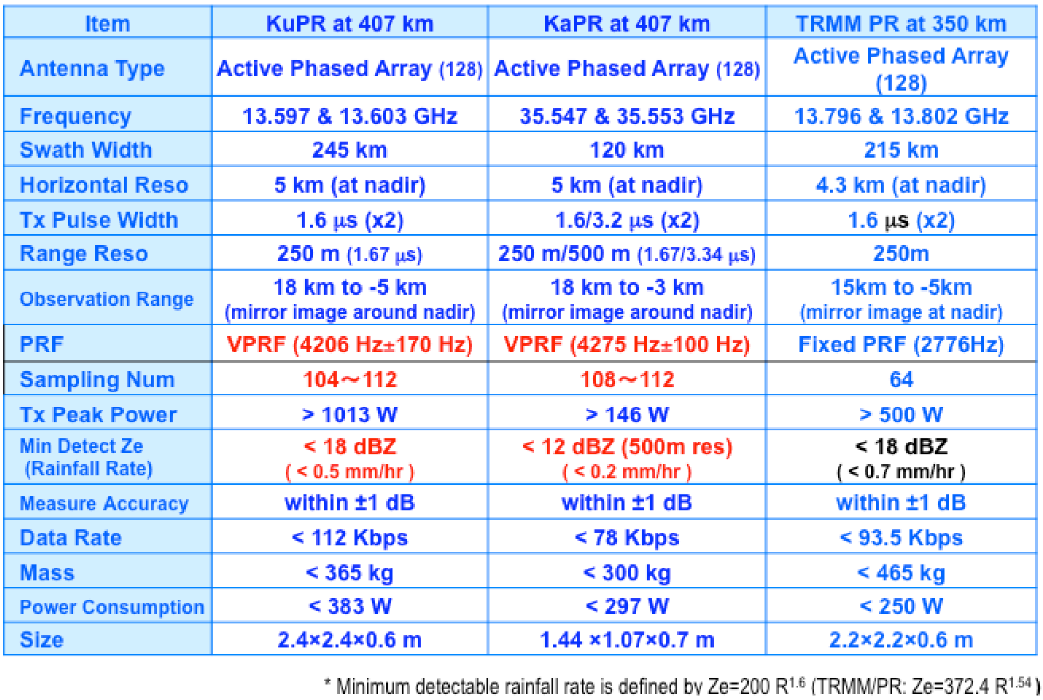


Figure 3. GPM Core Observatory

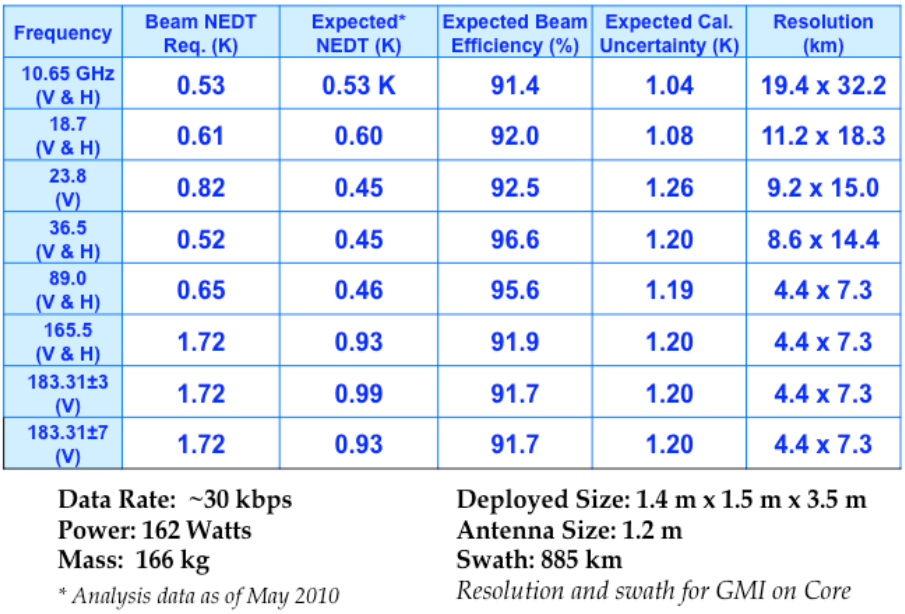
Though nearly identical to the TRMM Precipitation Radar (PR), the Ku-band channel of the DPR will have higher precision because of a greater number of independent samples (used to form the average return power) and greater sensitivity due to higher transmitted peak power, achieving a minimum detection threshold of 0.5 mm/hr (or 18 dBZ). The Ka-band channel will further extend the DPR sensitivity range to detect lighter precipitation rates down to 0.2 mm/hr (12 dBZ). Detailed instrument characteristics for both sensors are listed in Figs. 4 and 5.



Item	KuPR at 407 km	KaPR at 407 km	TRMM PR at 350 km
Antenna Type	Active Phased Array (128)	Active Phased Array (128)	Active Phased Array (128)
Frequency	13.597 & 13.603 GHz	35.547 & 35.553 GHz	13.796 & 13.802 GHz
Swath Width	245 km	120 km	215 km
Horizontal Reso	5 km (at nadir)	5 km (at nadir)	4.3 km (at nadir)
Tx Pulse Width	1.6 μs (x2)	1.6/3.2 μs (x2)	1.6 μs (x2)
Range Reso	250 m (1.67 μs)	250 m/500 m (1.67/3.34 μs)	250m
Observation Range	18 km to -5 km (mirror image around nadir)	18 km to -3 km (mirror image around nadir)	15km to -5km (mirror image at nadir)
PRF	VPRF (4206 Hz±170 Hz)	VPRF (4275 Hz±100 Hz)	Fixed PRF (2776Hz)
Sampling Num	104～112	108～112	64
Tx Peak Power	> 1013 W	> 146 W	> 500 W
Min Detect Ze (Rainfall Rate)	< 18 dBZ (< 0.5 mm/hr)	< 12 dBZ (500m res) (< 0.2 mm/hr)	< 18 dBZ (< 0.7 mm/hr)
Measure Accuracy	within ±1 dB	within ±1 dB	within ±1 dB
Data Rate	< 112 Kbps	< 78 Kbps	< 93.5 Kbps
Mass	< 365 kg	< 300 kg	< 465 kg
Power Consumption	< 383 W	< 297 W	< 250 W
Size	2.4×2.4×0.6 m	1.44 ×1.07×0.7 m	2.2×2.2×0.6 m

* Minimum detectable rainfall rate is defined by $Ze=200 R^{1.6}$ (TRMM/PR: $Ze=372.4 R^{1.54}$)

Figure 4. GPM Dual-frequency Precipitation Radar (DPR) Characteristics



Frequency	Beam NEDT Req. (K)	Expected* NEDT (K)	Expected Beam Efficiency (%)	Expected Cal. Uncertainty (K)	Resolution (km)
10.65 GHz (V & H)	0.53	0.53 K	91.4	1.04	19.4 x 32.2
18.7 (V & H)	0.61	0.60	92.0	1.08	11.2 x 18.3
23.8 (V)	0.82	0.45	92.5	1.26	9.2 x 15.0
36.5 (V & H)	0.52	0.45	96.6	1.20	8.6 x 14.4
89.0 (V & H)	0.65	0.46	95.6	1.19	4.4 x 7.3
165.5 (V & H)	1.72	0.93	91.9	1.20	4.4 x 7.3
183.31±3 (V)	1.72	0.99	91.7	1.20	4.4 x 7.3
183.31±7 (V)	1.72	0.93	91.7	1.20	4.4 x 7.3

Data Rate: ~30 kbps
Power: 162 Watts
Mass: 166 kg

** Analysis data as of May 2010*

Deployed Size: 1.4 m x 1.5 m x 3.5 m
Antenna Size: 1.2 m
Swath: 885 km

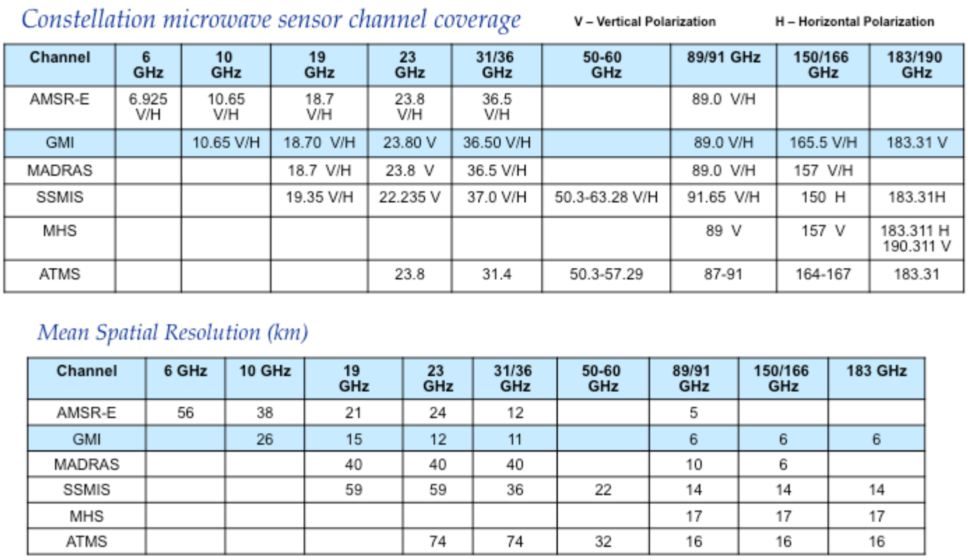
Resolution and swath for GMI on Core

Figure 5. GPM Microwave Imager (GMI) Instrument Characteristics

In addition to offering higher sensitivity to light rain rates, a key advancement of the GPM DPR over the TRMM PR is the ability to provide, for the first time from space, quantitative estimates of the precipitation particle size distribution (PSD) from the combination of reflectivity factors at Ku and Ka bands. This information is key to refining physical-based precipitation retrieval algorithms (see section 4).

3. Inter-satellite calibration of constellation radiometers

The GPM constellation consists of a network of microwave radiometers that are similar but not identical. As a first step in developing uniform precipitation estimates from this heterogeneous set of sensors, the differences in central frequency, spatial resolution, and viewing geometry must be reconciled (see Fig. 6).



Constellation microwave sensor channel coverage

V – Vertical Polarization

H – Horizontal Polarization

Channel	6 GHz	10 GHz	19 GHz	23 GHz	31/36 GHz	50-60 GHz	89/91 GHz	150/166 GHz	183/190 GHz
AMSR-E	6.925 V/H	10.65 V/H	18.7 V/H	23.8 V/H	36.5 V/H		89.0 V/H		
GMI		10.65 V/H	18.70 V/H	23.80 V	36.50 V/H		89.0 V/H	165.5 V/H	183.31 V
MADRAS			18.7 V/H	23.8 V	36.5 V/H		89.0 V/H	157 V/H	
SSMIS			19.35 V/H	22.235 V	37.0 V/H	50.3-63.28 V/H	91.65 V/H	150 H	183.31H
MHS							89 V	157 V	183.311 H 190.311 V
ATMS				23.8	31.4	50.3-57.29	87-91	164-167	183.31

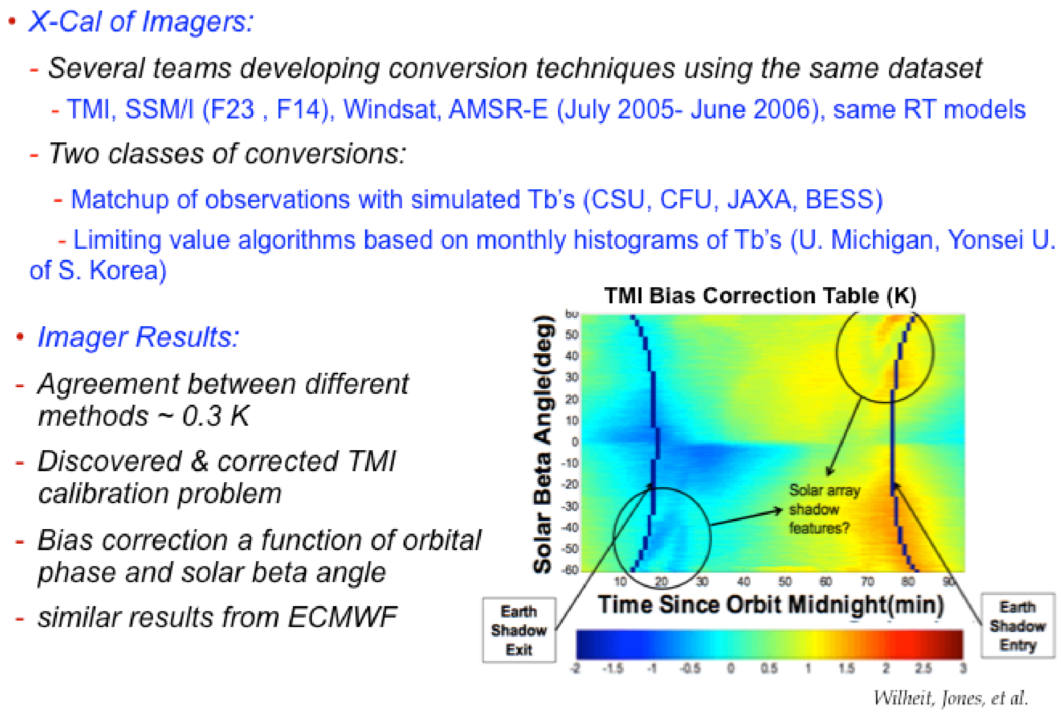
Mean Spatial Resolution (km)

Channel	6 GHz	10 GHz	19 GHz	23 GHz	31/36 GHz	50-60 GHz	89/91 GHz	150/166 GHz	183 GHz
AMSR-E	56	38	21	24	12		5		
GMI		26	15	12	11		6	6	6
MADRAS			40	40	40		10	6	
SSMIS			59	59	36	22	14	14	14
MHS							17	17	17
ATMS				74	74	32	16	16	16

Figure 6. Radiometer characteristics in the GPM era

In coordination with the Global Space-based Inter-Calibration System (GSICS) sponsored by the World Meteorological Organization, GPM has established an international "x-cal" working group to quantify and reconcile differences between microwave radiometers and to develop a consensus algorithm to unify radiometric measurements within a consistent framework. The working group members currently include university/government participants from Argentina, China, EUMETSAT, France, Japan, South Korea, and the United States. The ultimate goal is to remove relative biases in brightness temperatures of the constellation radiometers to provide a self-consistent input dataset for precipitation retrieval. GPM will designate this bias-adjusted radiometric dataset as Level 1C, which does not replace the official Level 1B sensor products.

For conical-scanning radiometer imagers (with channels up to 90 GHz), the strategy is to convert observations of one satellite to virtual observations of another using a non-Sun-synchronous satellite as a transfer standard (*e.g.*, TMI or GMI). Recent activities in microwave imager intercalibration are summarized in Fig. 7.

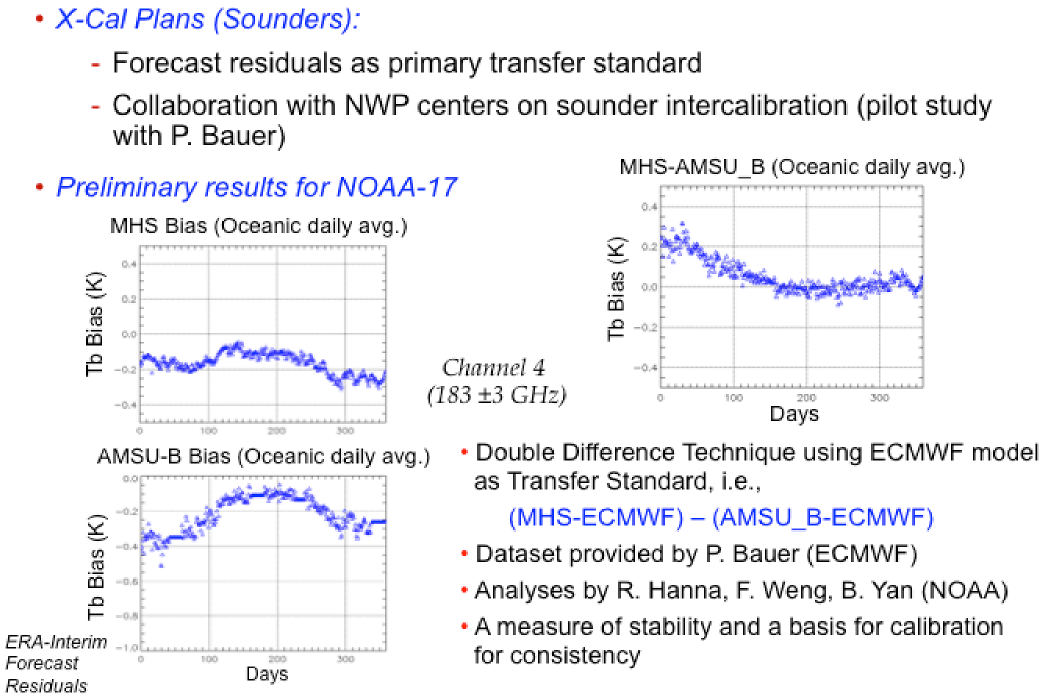


- *X-Cal of Imagers:*
  - *Several teams developing conversion techniques using the same dataset*
    - TMI, SSM/I (F23 , F14), Windsat, AMSR-E (July 2005- June 2006), same RT models
  - *Two classes of conversions:*
    - Matchup of observations with simulated Tb's (CSU, CFU, JAXA, BESS)
    - Limiting value algorithms based on monthly histograms of Tb's (U. Michigan, Yonsei U. of S. Korea)
- *Imager Results:*
  - *Agreement between different methods ~ 0.3 K*
  - *Discovered & corrected TMI calibration problem*
  - *Bias correction a function of orbital phase and solar beta angle*
  - *similar results from ECMWF*

Wilheit, Jones, et al.

Figure 7. Status of microwave imager intercalibration activities

For intercalibration of cross-track-scanning microwave humidity sounders, GPM plans to build upon the bias removal diagnostics used at operational forecasting centers. The near-term strategy is to experiment with a "Double Difference" Technique using NWP forecast residuals as the transfer standard. Results from a pilot study using ERA-Interim Forecast Residuals are shown in Fig. 8.



- *X-Cal Plans (Sounders):*
  - Forecast residuals as primary transfer standard
  - Collaboration with NWP centers on sounder intercalibration (pilot study with P. Bauer)
- *Preliminary results for NOAA-17*

- Double Difference Technique using ECMWF model as Transfer Standard, i.e.,
  (MHS-ECMWF) – (AMSU_B-ECMWF)
- Dataset provided by P. Bauer (ECMWF)
- Analyses by R. Hanna, F. Weng, B. Yan (NOAA)
- A measure of stability and a basis for calibration for consistency

Figure 8. Intercalibration of microwave sounders: Initial results from the Double Difference Technique using ERA-Interim Forecast Residuals.

4. Precipitation retrievals

At the heart of the GPM Mission are the radar and radiometer measurements provided by the Core Observatory. Along with the associated radar-radiometer algorithms, these data should provide more detailed and accurate information on the characteristics of the precipitation than has previously been possible. The GPM Level-2 precipitation retrievals consist of (1) DPR-only retrieval, (2) Combined DPR+GMI retrieval, and (3) Radiometer retrieval that uses an *a priori* hydrometeor database constrained by Core sensor measurements. Each of these retrievals is briefly described below.

DPR retrievals. The Dual-frequency Precipitation Radar (DPR), to be deployed on the GPM Core Satellite, will be the first of its kind in space. The instrument offers several improvements relative to its single-frequency counterpart. These include improvements in hydrometeor identification, particularly in convective rain, higher accuracy in the estimates of rain rate and water content, and information on the particle size distribution in both rain and snow. With regard to the PSD, the DPR will provide a characteristic size parameter (such as the median mass diameter, D_0) estimated from the difference (in dB) between Ku- and Ka-band attenuation-corrected radar reflectivity factors for a reasonable range of assumed gamma distribution shape parameters or snow mass densities. A characteristic number concentration of the PSD can then be found from D_0 and the radar equation. Attenuation correction, which is key to the success of any radar algorithm at these frequencies, can be accomplished either by the use of the surface as reference target or by an iteration where the PSD itself is used in a step-wise correction procedure (e.g., Meneghini et al. 1997, Mardiana et al. 2004, Rose and Chandrasekar 2006). Systematic evaluations of the algorithms as well as of potentially more robust formulations (e.g. Grecu et al. 2010.) are currently being performed using dual-frequency airborne precipitation radar. The outcome of these evaluations will determine the Day-1 DPR algorithm.

Combined DPR+GMI retrievals. While the DPR algorithms represent a major advancement over the TRMM PR by providing not only estimates of the 3D precipitation structure but also estimates of the PSD characteristics, ambiguities still exist as a result of a number of assumptions. These assumptions include the vertical profiles of water vapor and cloud liquid water as well as the ‘shape’ parameter, μ, of the size distribution and the mass densities of snow aggregates and graupel. The purpose of the combined DPR+GMI retrieval is to use the multi-channel GMI radiances as additional constraints on the DPR profiling algorithm over the radar swath. Specifically, some of the above-mentioned assumptions can be constrained by using variational procedures that minimize departures between simulated and observed brightness temperatures, or by using filtering approaches which determine an ensemble of radar solutions that are consistent with the brightness temperatures and their uncertainties. Thus, the resulting combined precipitation retrievals are consistent with both DPR reflectivity profiles and multi-channel GMI radiances within the framework of maximum-likelihood estimation. The combined retrieval methodology will be based on approaches developed and tested within the TRMM mission (e.g. Haddad et al. 1998, Grecu et al. 2004, Masunaga and Kummerow 2005). Several improvements, such as the incorporation of a more complex radar-only retrieval algorithm, the optimization over an extended set of assumptions, and the inclusion of uncertainty estimates in the final products are planned. The combined DPR+GMI retrievals, which are expected to provide the highest quality precipitation estimates, will be used to construct an *a priori* database that relates hydrometeor profiles to microwave radiances over the range of observed brightness temperatures. The advantage of databases constructed directly from combined observations over cloud-model derived databases has been already demonstrated (e.g. Grecu and Olson 2006). This database will be applicable not only to the Core GMI retrieval but also to constellation radiometer retrievals.

"Radar-enhanced" radiometer retrievals. Following the TRMM heritage, GPM will employ a Bayesian algorithm for precipitation retrieval from all constellation radiometers. But, unlike TRMM-era radiometer retrievals, which use a model-generated *a priori* hydrometeor database, GPM radiometer retrievals will use an observation-constrained global database consistent with GPM Core sensor measurements, as described in the previous section. Since the common hydrometeor database used for constellation radiometer retrievals contain DPR information, GPM radiometer retrievals may be characterized as "radar enhanced". A prototype GPM radiometer retrieval using a tropical cloud database constrained by TRMM PR reflectivities and TMI radiances over ocean has been developed to demonstrate the efficacy of this technique. Results show excellent match (apart from spatial resolutions) between the PR rain retrieval in the radar swath and TMI rain retrieval over the wider radiometer swath (see Kummerow's paper in the workshop proceedings). Since the construction of an observation-constrained database requires on-orbit DPR and GMI data, it is anticipated that GPM radar-enhanced radiometer products will be available after 6 months of the completion of on-orbit calibration of the Core instruments.

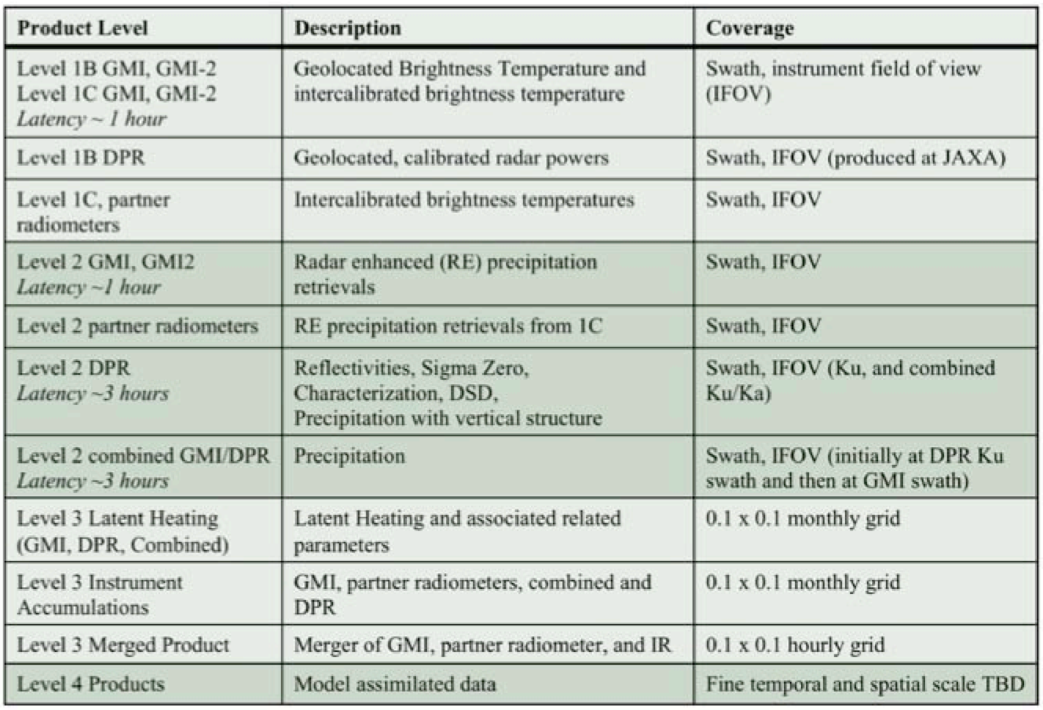
5. Synergy between retrieval algorithm development and data assimilation

In taking on the challenge of developing physical-based algorithms to retrieve liquid and solid precipitation over land, GPM relies on ground validation (GV) field experiments to improve the characterization of surface emissivity and variability, and to better define the highly nonlinear, under-constrained relationships between physical properties of precipitation particles and their microwave signatures. During the GPM pre-launch phase, NASA is conducting a series of field experiments to refine the assumptions and physical parameters of retrieval algorithms in collaboration with a number of domestic and international partners. In March 2010, NASA and the National Institute for Space Research (INPE) of Brazil jointly conducted the Pre-CHUVA field campaign in Alcantara, Brazil, targeting warm rain retrieval over land. In collaboration with the Finnish Meteorological Institute, NASA CloudSat and GPM missions conducted the Light Precipitation Validation Experiment (LPVEx) focusing on light precipitation with shallow melting layers over the Gulf of Finland during a 6-week period in September-October 2010. NASA and the U.S. Department of Energy will jointly conduct a major field campaign known as the Mid-latitude Continental Convective Cloud Experiment (MC3E) in April-May 2011 over the DOE-Atmospheric System Research (ASR) Central Facility in central Oklahoma. In early 2012, NASA and the Environment Canada will conduct the GPM Cloud-season Precipitation Experiment (GCPEX) to focus issues concerning retrievals of falling snow in Ontario, Canada.

In several of these experiments, NASA and partners will deploy multiple aircraft to provide both *in situ* microphysical measurements and high-altitude observations by airborne radar-radiometer simulators, as well as a surface network of radars, disdrometers, profilers, and sounding arrays, etc. GPM algorithm developers and GV scientists have been working as an integrated team to define and implement these experiments, and a matrix table that relates specific retrieval algorithm parameters to GV measurements has been developed to guide field campaign design and to track precipitation algorithm improvements using GV measurements. Since precipitation retrieval and assimilation of satellite precipitation data in NWP systems both require detailed knowledge of microphysical properties of precipitating particles through an atmospheric column, GPM GV measurements will also be useful for improving observation operators to make more effective use of satellite precipitation information in operational forecasting systems. In particular, field campaign data can be used to improve radiative transfer modeling of non-spherical ice particles, melting layers, etc., and to improve characterizations of land surface variability and emissivity.

6. Concluding remarks

GPM is an international satellite mission specifically designed to provide “next generation” global precipitation products from a constellation of research and operational satellites. These products will be derived from a set of self-consistent constellation radiometeric input data and a unified retrieval scheme that uses a common hydrometeor database constrained by combined radar-radiometer measurements. NASA and JAXA will produce a hierarchy of precipitation data products (Fig. 9), which can be used for forecast verification and/or assimilation in operational NWP.



Product Level	Description	Coverage
Level 1B GMI, GMI-2 Level 1C GMI, GMI-2 *Latency ~ 1 hour*	Geolocated Brightness Temperature and intercalibrated brightness temperature	Swath, instrument field of view (IFOV)
Level 1B DPR	Geolocated, calibrated radar powers	Swath, IFOV (produced at JAXA)
Level 1C, partner radiometers	Intercalibrated brightness temperatures	Swath, IFOV
Level 2 GMI, GMI2 *Latency ~1 hour*	Radar enhanced (RE) precipitation retrievals	Swath, IFOV
Level 2 partner radiometers	RE precipitation retrievals from 1C	Swath, IFOV
Level 2 DPR *Latency ~3 hours*	Reflectivities, Sigma Zero, Characterization, DSD, Precipitation with vertical structure	Swath, IFOV (Ku, and combined Ku/Ka)
Level 2 combined GMI/DPR *Latency ~3 hours*	Precipitation	Swath, IFOV (initially at DPR Ku swath and then at GMI swath)
Level 3 Latent Heating (GMI, DPR, Combined)	Latent Heating and associated related parameters	0.1 x 0.1 monthly grid
Level 3 Instrument Accumulations	GMI, partner radiometers, combined and DPR	0.1 x 0.1 monthly grid
Level 3 Merged Product	Merger of GMI, partner radiometer, and IR	0.1 x 0.1 hourly grid
Level 4 Products	Model assimilated data	Fine temporal and spatial scale TBD

Figure 9. GPM data product categories

The NASA GPM Program is devoting considerable resources to developing radiometer intercalibration techniques and conducting ground validation field experiments to refine satellite algorithms. Given the synergy between the remote sensing and NWP communities in a range of research areas such as radiometer intercalibration, observation operator development, and model physics improvement, scientific collaboration between the two communities would be of significant benefits to both. The NASA Precipitation Measurement Missions (PMM) Program is accepting proposals from international investigators to conduct collaborative research that complements existing science team activities on the basis of no exchange of funds. Investigators on successful proposals will be members of the NASA PMM Science Team with full access to data and facilities available to the team as well as opportunities to participate in all team activities. Currently, the NASA PMM Science Team has 19 International Principal Investigators from 12 nations. For more information, please contact the author by email at: arthur.y.hou@nasa.gov.

Acknowledgements

The author would like to thank Robert Meneghini, Mircea Grecu, Bill Olson, Tom Wilheit, Fuzhong Weng, and Peter Bauer for contributions to the results and discussions presented in sections 3 and 4.

References

Grecu, M., W. S. Olson, and E. N. Anagnostou, 2004: Retrieval of precipitation profiles from multiresolution, multifrequency active and passive microwave observations. *J. Appl. Meteor*, **43**, 562–575.

Grecu, M., and W. S. Olson, 2006: Bayesian estimation of precipitation from satellite passive microwave observations using combined radar–radiometer retrievals. *J. Appl. Meteor. Climatol*., 45, 416–433.

Grecu M., L. Tian, W. S. Olson, and S. Tanelli, 2010: A robust dual-frequency radar profiling algorithm, *J. Appl. Meteor. Clim.*, submitted.

Hou, A., R. Kakar, S. Neeck, A. Azarbazin, C. Kummerow, M. Kojima, R. Oki, K. Nakamura, and T. Iguchi, 2011: The Global Precipitation Measurement (GPM) Mission, *Bull. Amer. Meteorol. Soc.*, submitted.

Mardiana, R., T. Iguchi and N. Takahashi, 2004: A dual-frequency rain profiling method without the use of a surface reference technique. *IEEE Trans. Geosci. Remote Sens.*, **42**, 2214-2225.

Meneghini, R., H. Kumagai, J.R. Wang, T. Iguchi, and T. Kozu, 1997: Microphysical retrievals over stratiform rain using measurements from an airborne dual-wavelength radar-radiometer. *IEEE Trans. Geosci. Remote Sens*., **35**, 487-506.

NRC (National Research Council), 2005: *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission*, National Academies Press, Washington, DC, 103 pp.

Rose, C, and V. Chandrasekar, 2006: A GPM dual-frequency retrieval algorithm: DSD profile-optimization method. *J. Atmos. Oceanic Technol.*, **23**, 1372–1383.

Vila, D., R. Ferraro, and R. Joyce, 2007: Evaluation and improvement of AMSU precipitation retrievals, *J. Geophys. Res*., **112**, D20119, doi:10.1029/2007JD008617.