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

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ECMWF-JCSDA Workshop on Cloud/Precipitation Assimilation for NWP, 15-17 June 2010

Outline

- Measurement strategy:
  - *active sensor for details, passive sensors for coverage*
- GPM mission concept
  - *Making use of combined information from active & passive sensors to improve retrieval accuracy over either sensor alone*
- Core Observatory capabilities
- Algorithm development & supporting field campaigns
- Next-generation global precipitation products
  - *inter-satellite calibration of radiometric measurements*
  - *precipitation retrievals within a unified framework*
- Synergy between retrieval and assimilation
- Summary

GPM Mission Concept

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

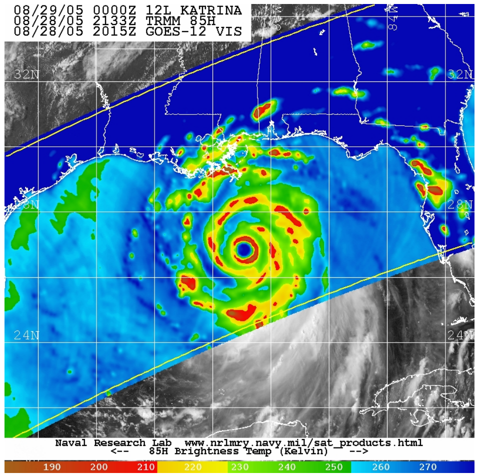
Key Contribution

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

GPM Observations from Non-Sun-Synchronous Orbits

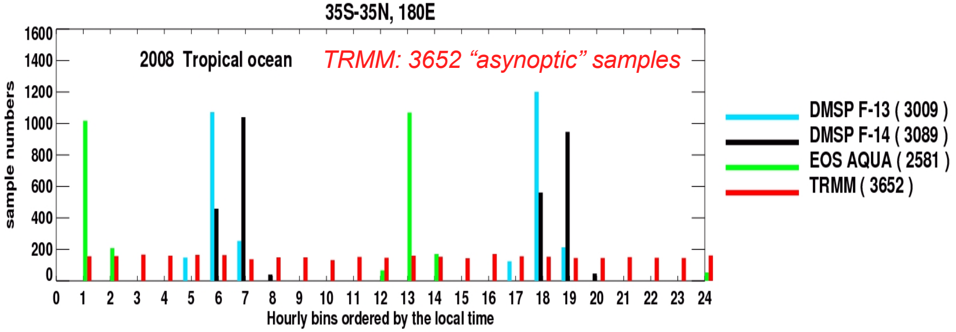
Near real-time observations filling gaps between those of polar orbiters at fixed time of the day for:

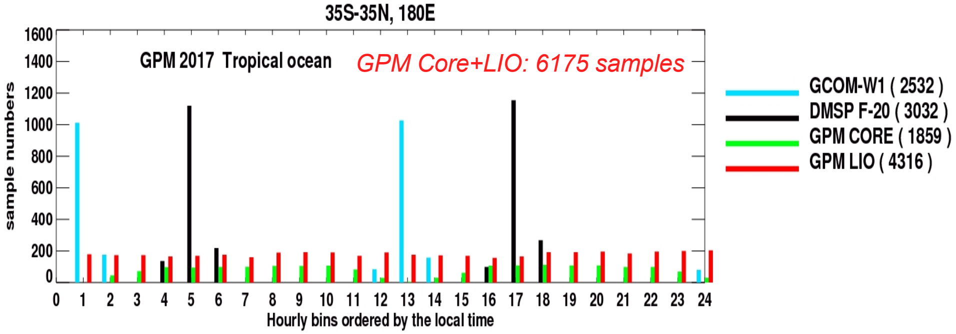
- Intercalibration of polar-orbiting sensors over wide range of latitudes
- Near real-time monitoring of hurricanes & midlatitude storms
- Improved accuracy of rain volume estimation
- Resolving diurnal variability in rainfall climatology

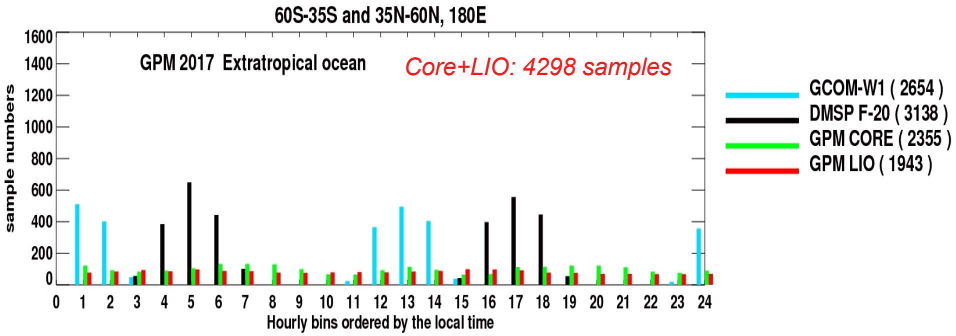


Monthly Samples as a Function of the Time of the Day

(1º x 1º Resolution)







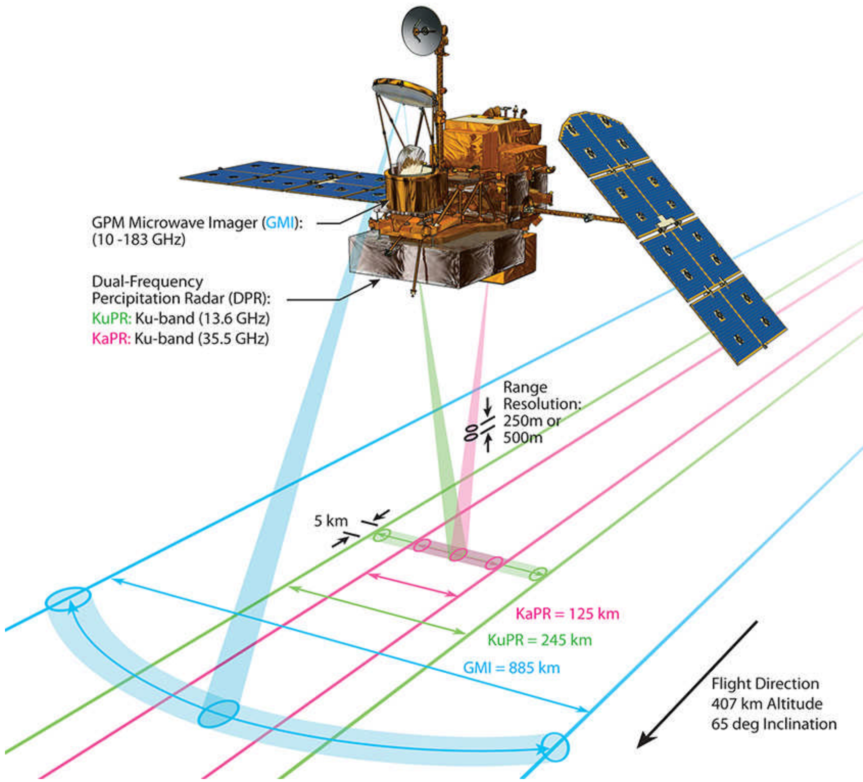
GPM Core Observatory Capabilities

Dual-Frequency (Ku-Ka band) Precipitation Radar (DPR):

- *Increased sensitivity (~12 dBZ) for light rain and snow detection relative to TRMM*
- *Better measurement accuracy with differential attenuation correction*
- *Detailed microphysical information (DSD mean mass diameter & particle no. density) & identification of liquid, ice, and mixed-phase regions*

Multi-Channel (10-183 GHz) GPM Microwave Imager (GMI):

- *Higher spatial resolution (IFOV: 6-26 km)*
- *Improved sensitivity to light rain*
- *Improved signals of solid precipitation over land (especially over snow-covered surfaces)*
- *4-point calibration for nonlinearity removal and backup calibration reference during hot load anomalies*



Combined Radar-Radiometer Retrieval

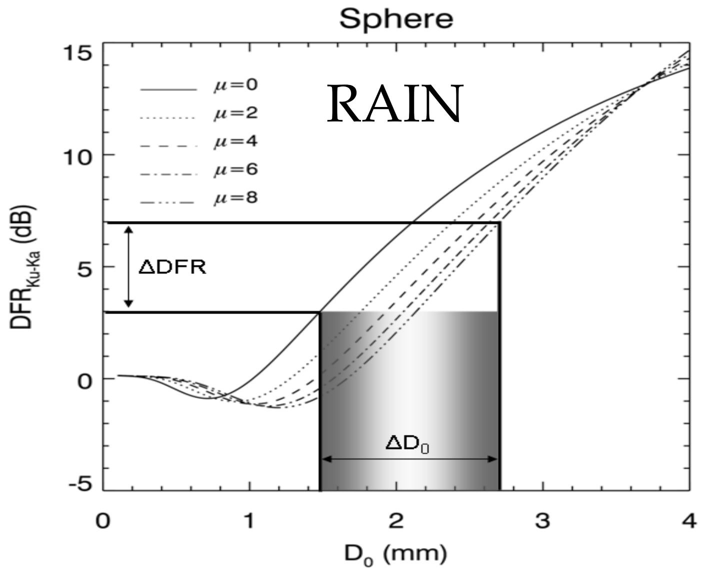
- *DPR & GMI together provide greater constraints on possible solutions to improve retrieval accuracy*
- *Observation-based a-priori cloud database for constellation radiometer retrievals*

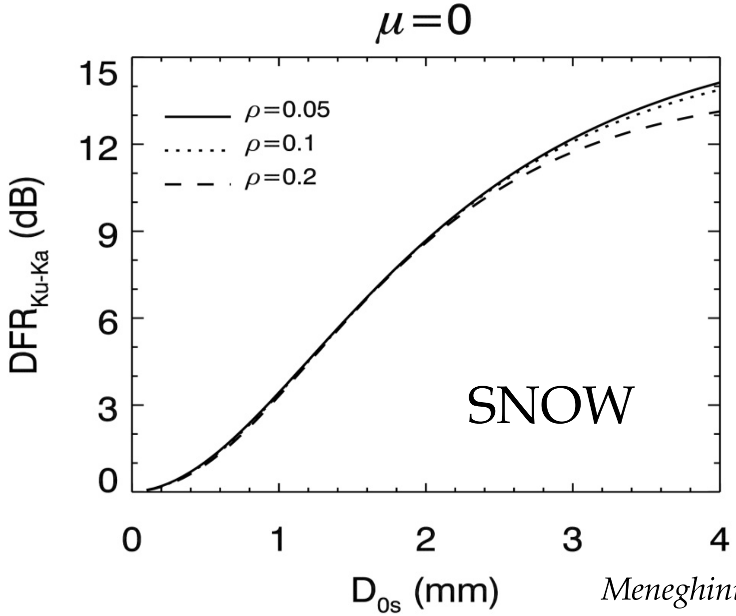
DPR Instrument Characteristics

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: $Ze=372.4\,R^{1.54}$)

Estimation of PSD & Precipitation Rate from the DPR





Meneghini et al.

- A characteristic size parameter (D_0) of the PSD can be estimated from the difference (in dB) between Ku- and Ka-band radar reflectivity factors
- Ambiguities include unknown shape parameter (μ) of the gamma PSD distribution and the snow mass density (ρ)
- Characteristic number concentration of PSD is found from D_0 and the radar equation
- Step-by-step estimation of attenuation correction based on PSD estimates
- Precipitation rate and the equivalent water content are derived from the PSD for an assumed velocity distribution

GMI Instrument 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

Combined DPR+GMI retrievals

- Using GMI radiance measurements as additional constraints on the DPR profiling algorithm:

  Assumptions regarding the particle size distribution, ice microphysics, cloud water and water vapor vertical distribution are refined – using a variational procedure that minimizes departures between simulated and observed brightness temperatures (according to the sensitivity of simulated brightness temperatures to assumptions in DPR retrievals).

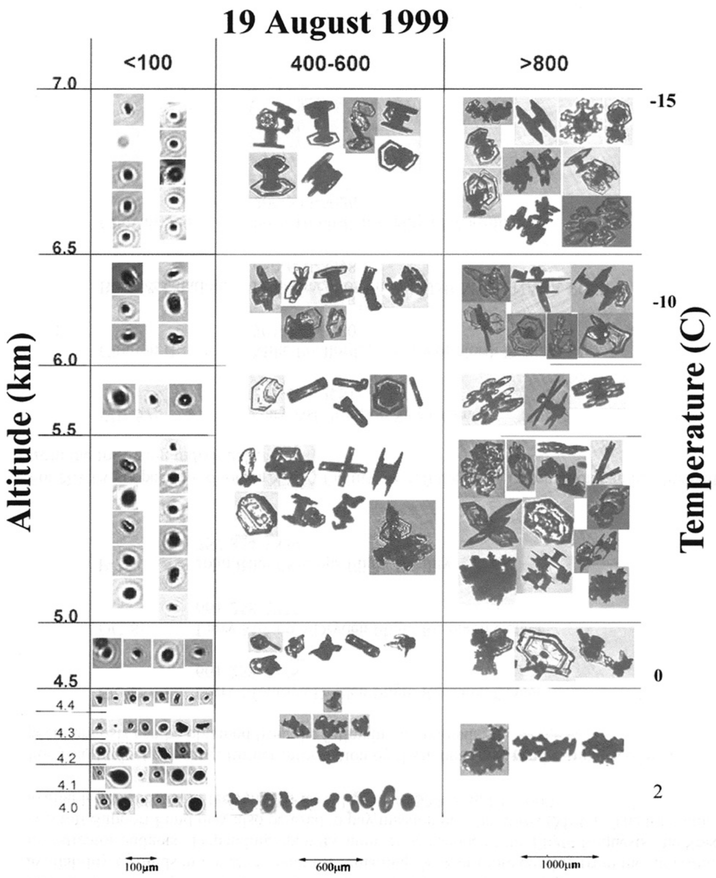
- Retrievals are consistent with both DPR reflectivities and GMI radiances within a maximum-likelihood estimation framework.

- Results enable the construction of an *a priori* database that relates hydrometeors to brightness temperatures over the range of observed T_b values for precipitation retrievals from constellation radiometers.

Frontiers in precipitation retrieval

Solid precipitation

Frozen Particle Variability
(Non-Spherical Shapes)

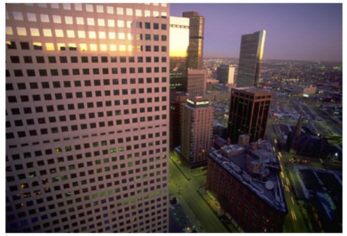


← Melting particles

CPI *in situ* images, A. Heymsfield

Physical retrieval over land

Surface Variability/Emissivity



Modeling of nonlinear, under-constrained relationships between physical characteristics of precipitation particles and microwave observations

GPM Ground Validation

Pre-launch algorithm development & post-launch product evaluation

- Refine algorithm assumptions & parameters
- Characterize uncertainties in satellite retrievals & GV measurements

Three complementary approaches:

- *Direct statistical validation (surface):*

  - Leveraging off operational networks to identify and resolve first-order discrepancies between satellite and ground-based precipitation estimates

- *Physical process validation (vertical column):*

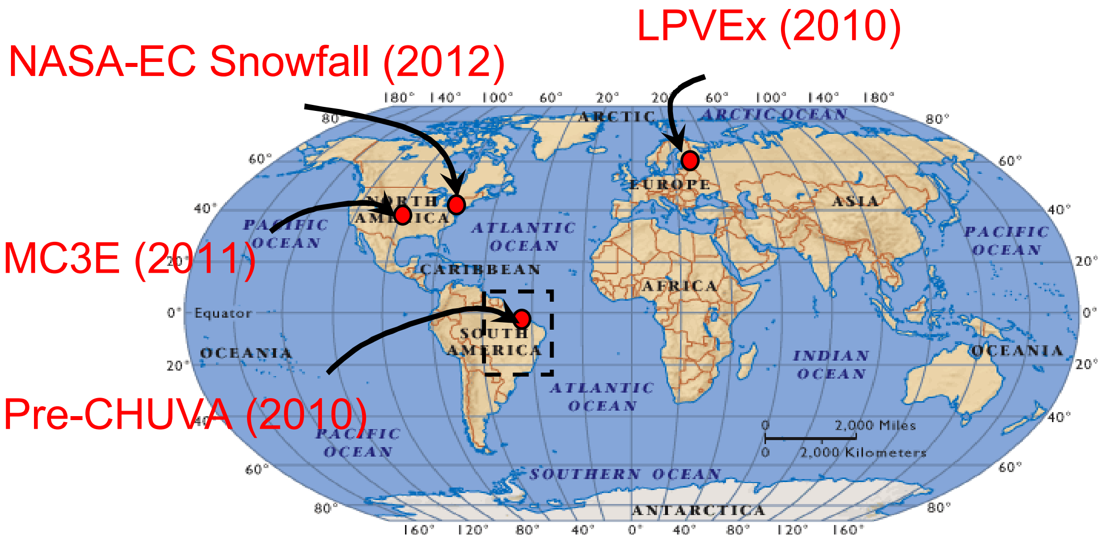
  - Cloud system and microphysical studies geared toward testing and refinement of physically-based retrieval algorithms

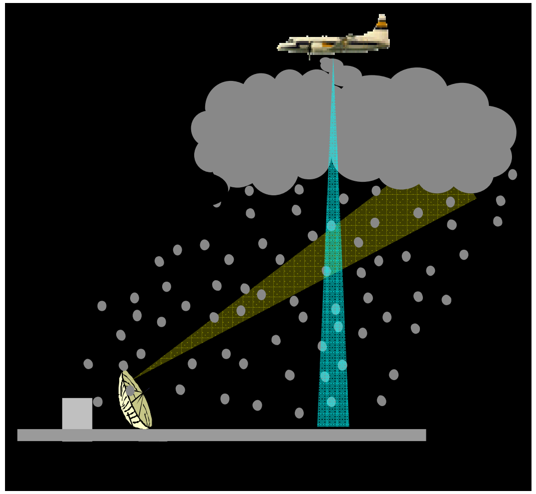
- *Integrated hydrologic validation/applications (4-dimensional):*

  - Identify space-time scales at which satellite precipitation data are useful to water budget studies and hydrological applications; characterization of model and observation errors

"Truth" is estimated through the convergence of satellite and ground-based estimates

Physical Validation: Field Campaigns (2010-2012)





- Pre-CHUVA: GPM-Brazil & NASA field campaign targeting warm rain retrieval over land, Alcântara Launching Center, 3-24 March 2010
- Light Precipitation Validation Experiment (LPVEx): CloudSat-GPM light rain in shallow melting layer situations, Helsinki Testbed & Gulf of Finland, Sept-Oct 2010
- Mid-Latitude Continental Convective Clouds Experiment (MC3E): NASA-DOE field campaign at DOE-ASR Central Facility in Oklahoma, Apr-May 2011
- High-Latitude Cold-Season Snowfall Campaign: GPM-Environment Canada campaign on snowfall retrieval, Ontario, Canada, Jan-Feb 2012

International Collaboration on GPM Ground Validation

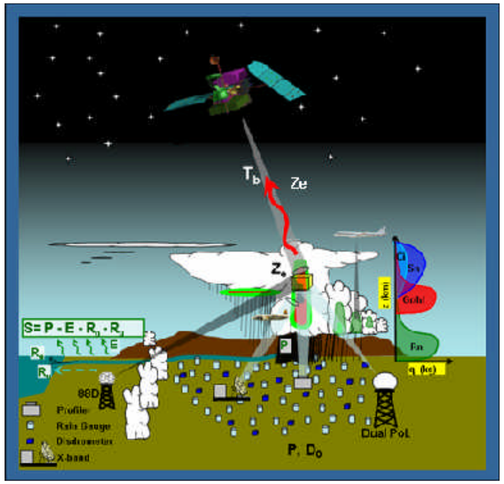
- *Joint field campaigns*
- *National networks and other ground assets (radar, gauges, etc.)*
- *Hydrological validation sites (streamflow gauges, etc.)*

Active Projects

- Argentina (U. Buenos Aires)
- Australia (BOM)
- Brazil (INPE)
- Canada (EC)
- Ethiopia (AAU)
- Finland (FMI)
- France (CNRS)
- Germany (U. Bonn)
- Israel (Hebrew U. Jerusalem)
- Italy (CNR-ISAC)
- Italy (Sapienza U. Rome)
- South Korea (KMA)
- Spain (UCLM)
- United Kingdom (U. Birmingham)

Proposals in Development

- Cyprus (CMS)
- Germany (MPI)
- Spain (Barcelona)
- India (ISRO)
- Taiwan



4th International Workshop for GPM Ground Validation hosted by the Finish Meteorological Institute, 21-23 June 2010, Helsinki, Finland

Constellation Radiometer Characteristics

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

Characteristics are similar but not identical

Different center frequency, viewing geometry, and spatial resolution need be reconciled

Inter-Satellite Calibration of Microwave Radiometers (1/3)

- *Objective:* Quantify and reconcile differences between microwave radiometers to produce self-consistent global precipitation estimates
- *Context:*
  - *Calibration of individual instruments: Instrument manufacturers*
  - *Cross-calibration to remove relative biases among instruments: GPM X-Cal*
  - *Statistical comparison at rain retrieval level: GPM Science Team*
- *GPM X-Cal (Imagers):* Convert observations of one satellite to virtual observations of another using non-Sun-synchronous satellite as a transfer standard (*e.g*. TMI or GMI)
  - Develop techniques for comparing similar but not identical MW radiometers
  - Develop implementation strategy for routine intercalibration of constellation radiometers
  - Develop corrections for recurring instrument errors
  - Total transparency (logic, models, results, numbers will be publicly available online)

GPM International X-Cal Working Group (CMA, CNRS, CONAE, EUMETSAT, GIST, JAXA, NASA, NOAA, & universities) in coordination with WMO/CGMS Global Space-based Inter-Calibration System (GSICS)

Inter-Satellite Calibration of Microwave Radiometers (2/3)

- *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)

TMI Bias Correction Table (K)

- *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*

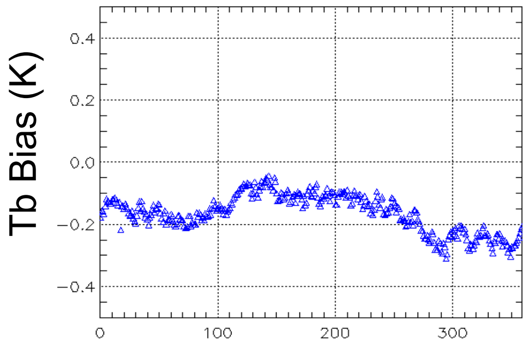
Wilheit, Jones, et al.

Inter-Satellite Calibration of Microwave Radiometers (3/3)

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

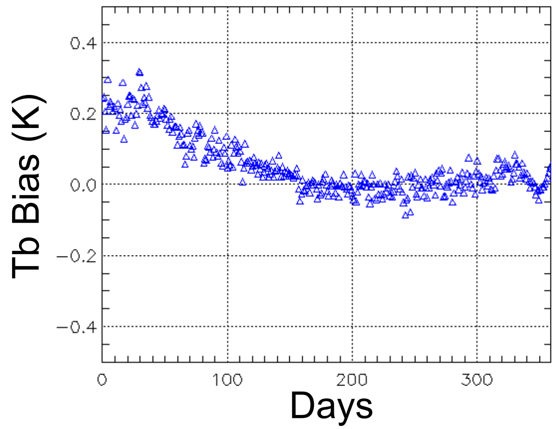
- *Preliminary results for NOAA-17*

MHS Bias (Oceanic daily avg.)

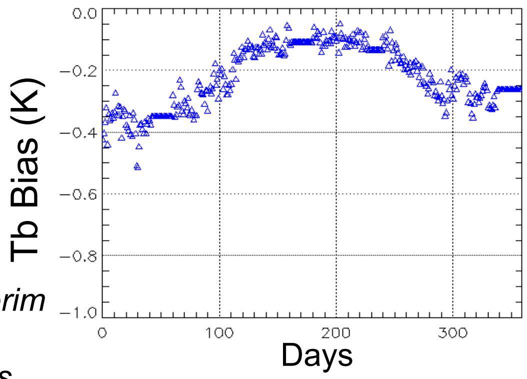


Channel 4
(183 ±3 GHz)

MHS-AMSU_B (Oceanic daily avg.)



AMSU-B Bias (Oceanic daily avg.)



ERA-Interim Forecast Residuals

- Double Difference Technique using ECMWF model as Transfer Standard, i.e.,

  (MHS-ECMWF) – (AMSU_B-ECMWF)

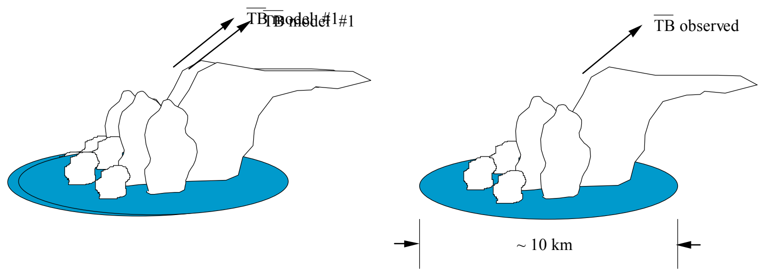
- Dataset provided by P. Bauer (ECMWF)
- Analyses by R. Hanna, F. Weng, B. Yan (NOAA)
- A measure of stability and a basis for calibration for consistency

Next-Generation Global Precipitation Products

- Intercalibrated constellation radiometric data (differences in center frequency, viewing geometry, resolution, reconciled)
- Unified precipitation retrievals using a common hydrometeor database constructed from combined DPR+GMI measurements

Matching observed T_b with simulated T_b using an a priori cloud database

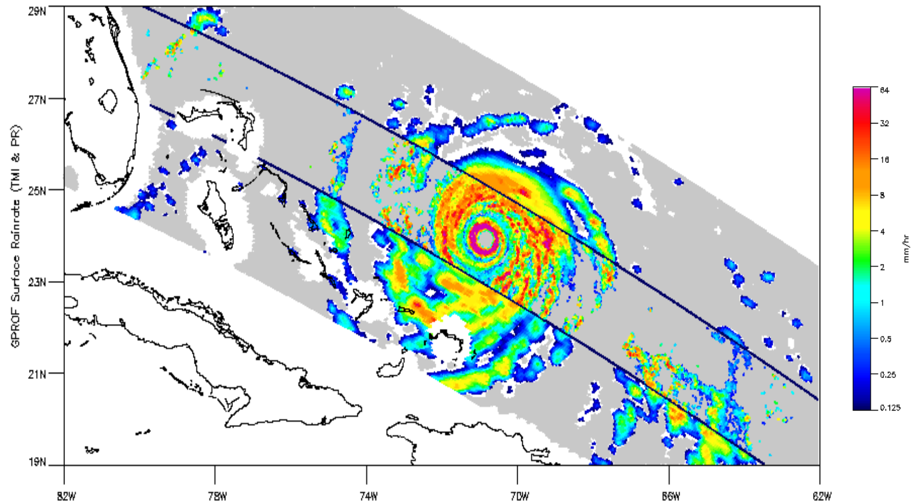
Simulated T_b *Observed T_b*



TRMM uses a model-generated cloud database

GPM will use an observation-constrained database

Prototype GPM Radiometer Retrieval



Comparison of TRMM PR surface rain with TMI rain retrieval using an observational cloud database consistent with PR reflectivity

Kummerow et al.

GPM Data Products

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, Ka, 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

Synergy Between Retrieval and Assimilation

GPM

Radiance observations

Obs.-constrained cloud database	RT model

↓

Retrieval algorithm

Selection of profiles	Output: Composite rain profiles

↓

Precipitation retrieval

Pixel scale

- Free of forecast model errors
- Validated with high-quality GV data
- Useful for assimilation or verification
- At observation time/location

NWP

Radiance observations

Model forecast	Obs. operator

↓

Assimilation procedure

Minimization	Output: Model state

↓

Precipitation analysis/forecast

Model resolution

- Consistent with model state and other variables
- Uniform global coverage

Areas of Common Interest and Endeavor

- Satellite data product assessment:

  GPM data available for assimilation and/or forecast verification -

  - *Interclibrated MW radiances*
  - *Radar reflectivities*
  - *Precipitation retrievals (Radar-only, Combined Radar-Radiometer, & "Radar-Enhanced" Radiometer)*

- Development of satellite simulators and observation operators:

  GPM field campaign data for –

  - *Radiative transfer modeling of non-spherical ice particles, melting layer, etc.*
  - *Characterizations of land surface variability and emissivity*

- Model physics evaluation and improvement using GPM 3D hydrometeor database:

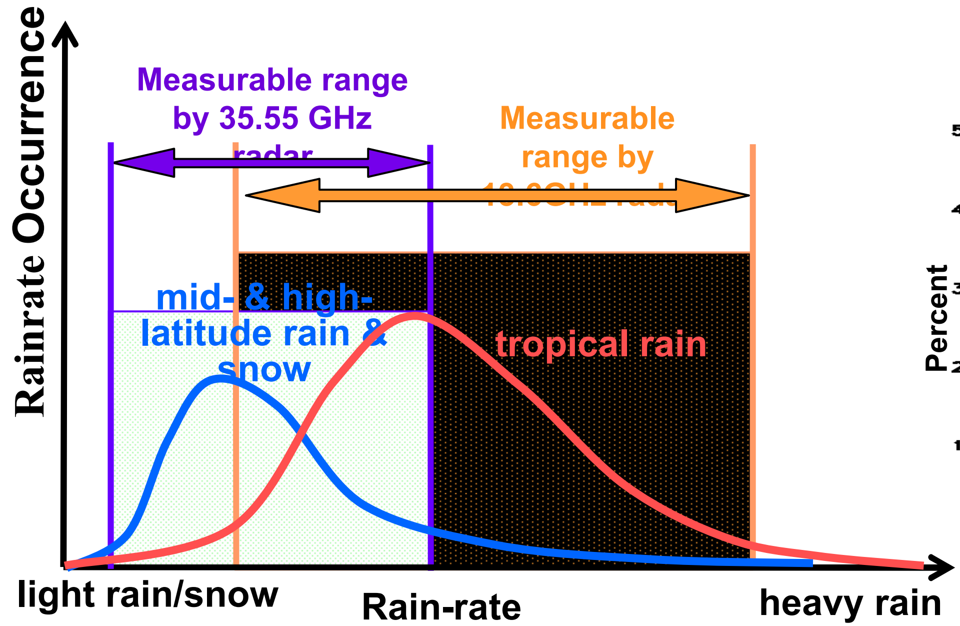
  - *High-resolution cloud profiles consistent with DPR reflectivities and GMI multi-channel radiances*

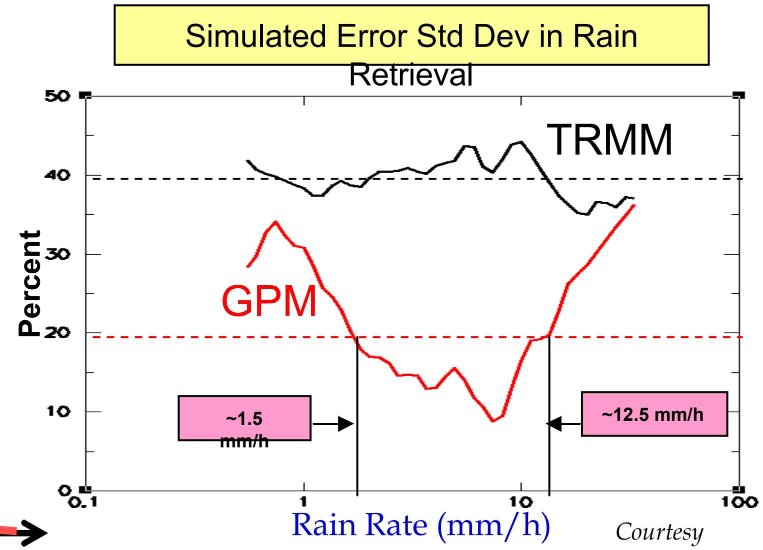
Summary

- GPM is an international satellite mission specifically designed to unify and advance precipitation measurements from a constellation of microwave sensors for research and applications.
- Next-generation constellation-based global precipitation products built on intercalibrated microwave radiances and unified retrievals using a common hydrometeor database consistent with combined radar/ radiometer measurements
- A hierarchy of data products for assimilation or forecast verification
- Synergy with future satellite missions:
    - *Cloud/aerosol/light rain processes (e.g., EarthCARE, ACE)*
    - *Land surface characterization & modeling (e.g., SMOS, SMAP)*
    - *Ocean salinity (e.g., Aquarius)*
- Synergy with NWP:
    - *radiometer intercalibration, observation operator development, and model physics refinement using precipitation inofrmation*

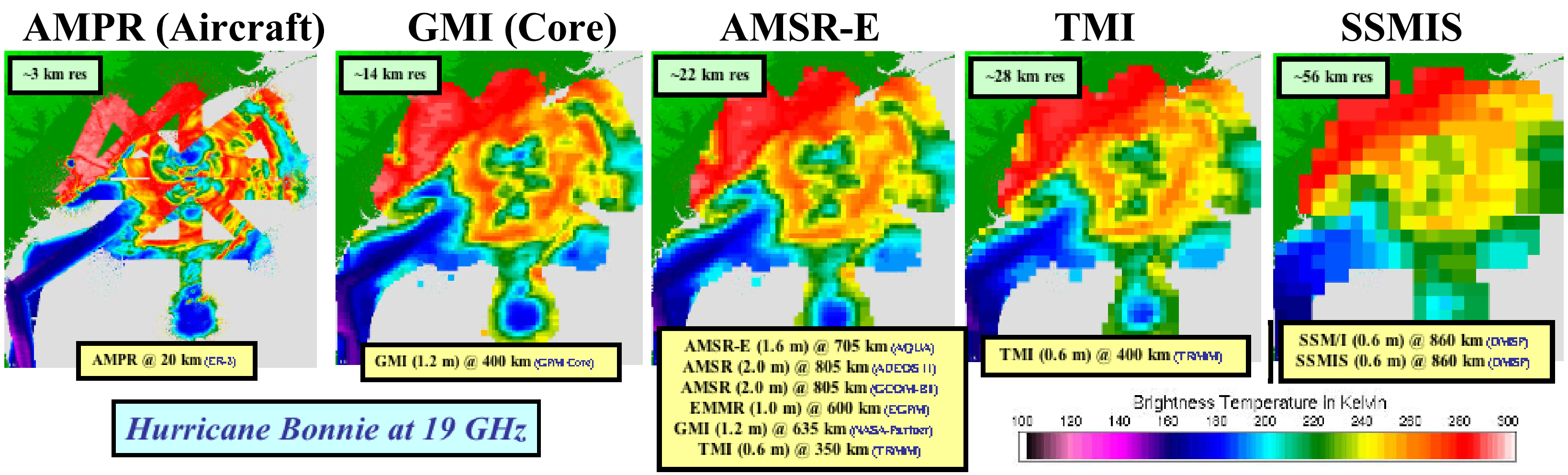
Additional Slides

Improvements over TRMM





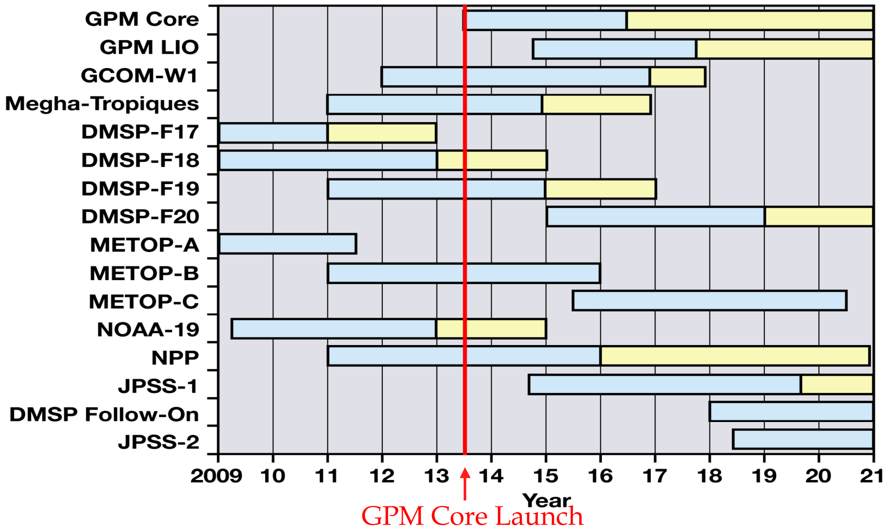
Courtesy
Z. Haddad



Synthesized Brightness Temperatures (R. Hood NASA/MSFC)

GPM Constellation Sampling and Coverage

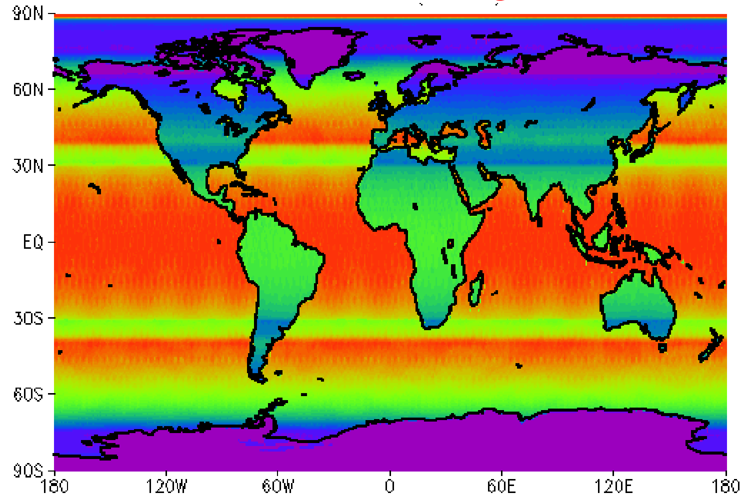
Baseline Constellation Schedule



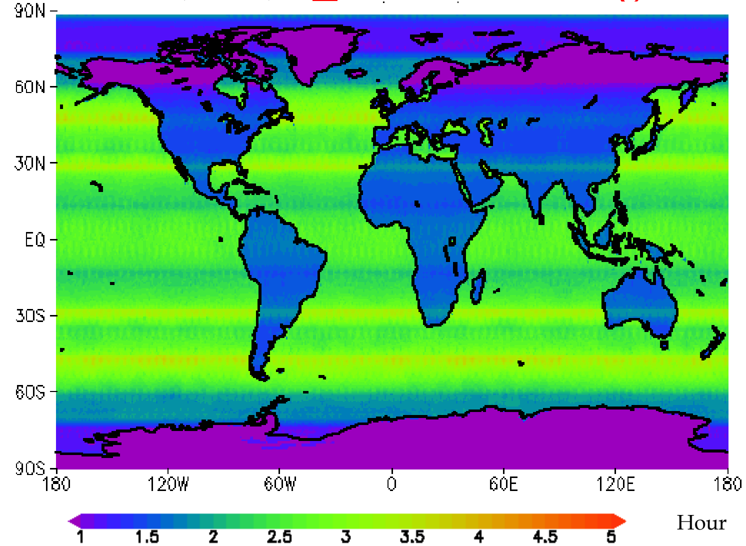
Year	Average Revisit Time (hr) 2013	2014	2015	2016	2017
	Land				
Tropics	1.9	1.5	1.5	1.6	2.4
Extratropics	1.3	1.0	1.0	1.2	1.4
Globe	1.6	1.2	1.2	1.4	1.8
	Ocean				
Tropics	3.2	2.6	2.6	2.6	4.9
Extratropics	3.3	2.6	2.6	2.6	3.4
Globe	3.2	2.6	2.6	2.6	4.2
	Land and Ocean				
Tropics	2.8	2.3	2.3	2.3	4.2
Extratropics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

1-2 hr revisit time over land

Current Capability:
$\leq$ 3h over 45% of globe



GPM (2015): $\leq$ 3h over 90% of globe



LPVEx Field Campaign (Sept. 15 – Oct. 24, 2010)

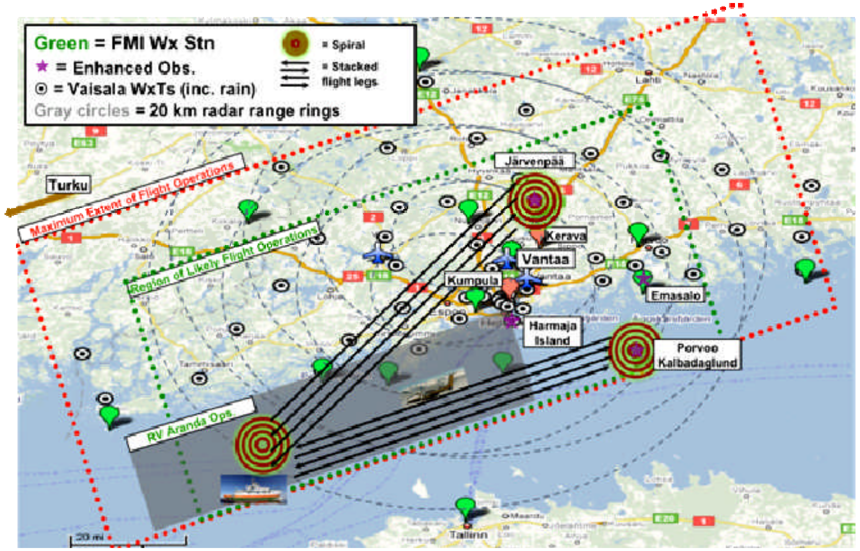
Target: Light rain in cold low altitude melting layer environment

GV Science:

a) Quantify column DSD/precip variability over inland, coastal, sea regimes
b) Melting layer physics coupled to water below and ice above
c) Reconstructed Ka-Ku band (DPR) data for DFR algorithm testing
d) Observationally-validated model databases for radiometer algorithms

Approach:

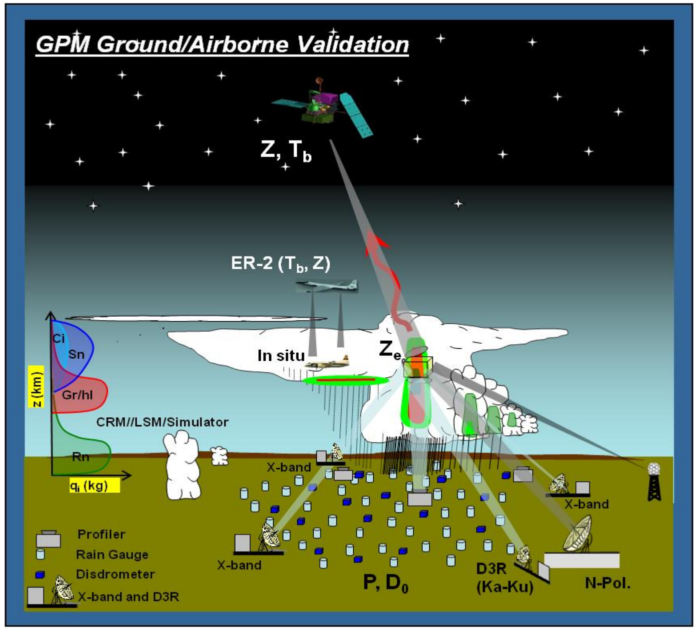
- Heavily instrument surface sites + 1 Ship under radar/aircraft/satellite coverage at Järvenpää (*inland*), Harmaja (*Island)*, Emasalo (*coast*), and R/V Aranda (*sea*)
- 3 Dual-pol radars, 6-8 disdrometers/4-MRRs/ADMIRARI radiometer/3 POSS U. Wyoming King Air Airborne microphysics + W-band radar



Helsinki-Testbed & Gulf of Finland

MC3E Field Campaign (April 15 – May 31, 2011)

Target: Mid-latitude convective and stratiform rainfall over land



Location: DOE-ASR Central Facility, Oklahoma

GV Science Priorities

1. **Coordinated Airborne [high altitude/in situ]**
   a. High altitude Ka/Ku-band radar, multi-freq. radiometer with in-situ ice microphysics
   b. Pre/post storm surface properties
2. **3-D Mapping of *hydrometeor distribution/type***
   a. Unified framework for retrieving 3-D DSD
   b. Sub pixel scale DSD variability
   c. Cross validation/comparison of multi-frequency (Ka-Ku) and dual-pol. retrievals
3. **Satellite *simulator models (CRM/LSM/RT)***
   a. High quality sounding-based forcing data
   b. Microphysical and kinematic validation.
   c. Land surface impacts

Confirmed Instruments:

- Aircraft: ER-2, UND Citation (microphysics)
- Radars: NPOL, D3R, DOE X-band(s),
  C-band, Ka/W, S/UHF profiler
- Surface: Dense disdrometer/gauge net.
  ASR surface met, radiometer, flux
  and, aerosol instruments
- Soundings: ASR array 6 – 8 launches/day

Status: Pre-field deployment sampling and logistics planning

NASA-EC Snowfall Campaign (Jan.-Feb. 2012)

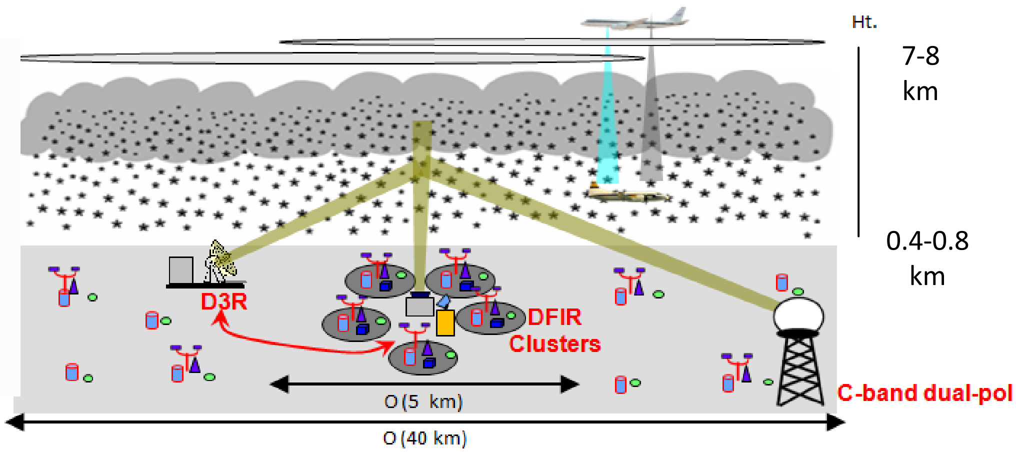
Target: Snowfall retrieval algorithms

GV Science

1. Radiometer/DPR Snowfall measurement sensitivities to snow type, rate, surface and tropospheric characteristics
2. Physics of snowfall in the column and relation to extinction characteristics
3. Model databases for forward modeling and retrieval development.

Approach

- Network observations of SWE and PSD
- In-situ and high-altitude airborne sampling
- Ground-based radar/profiling components
- Soundings for column T and Water Vapor



Status: Planning phase

Site chosen: Environment Canada CARE site in Ontario, Canada

Instruments planned: DC-8 (Ka-Ku band radar, CoSMIR radiometer), microphysics aircraft (TBD), D3R Ka-Ku radar, C-band dual-pol radar, numerous snow-gauge/disdrometer clusters, profiling radars at S/UHF, X, K, and W-bands.