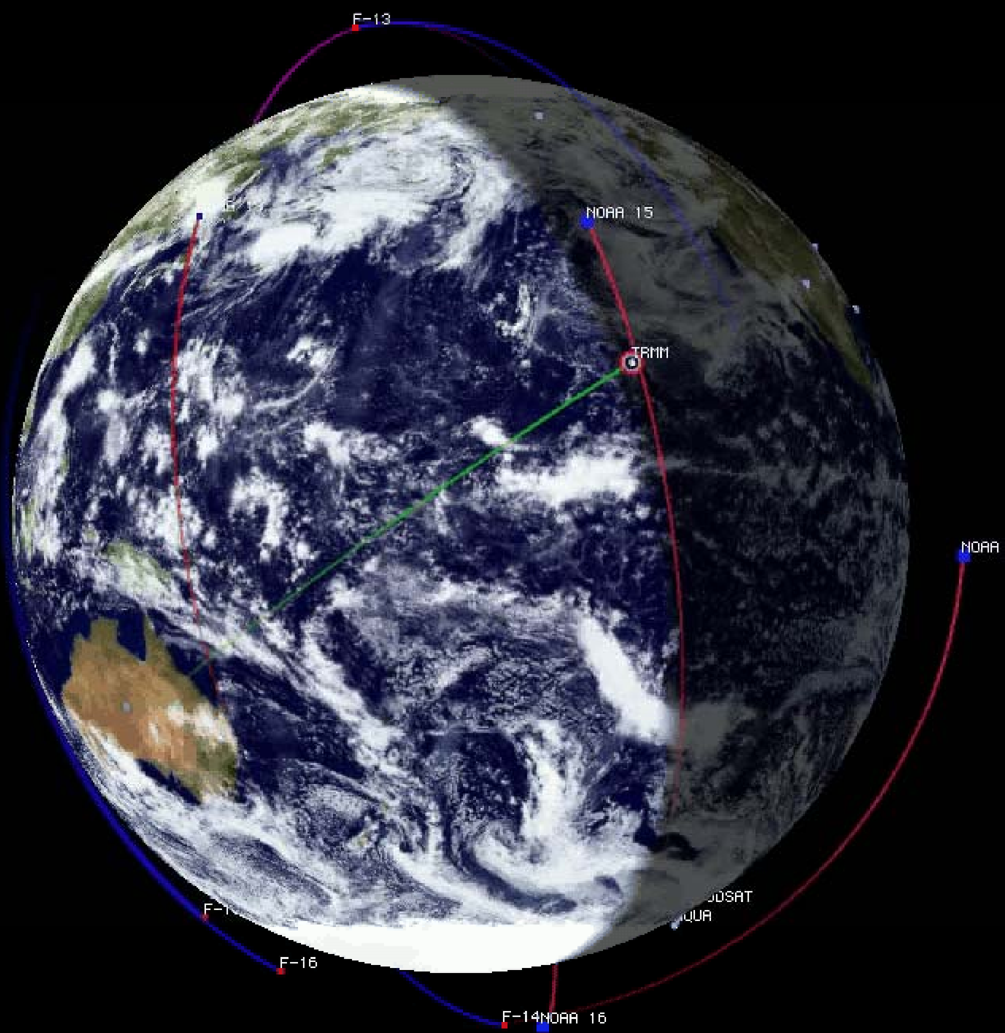
Current and Future Satellite Observations of Precipitation

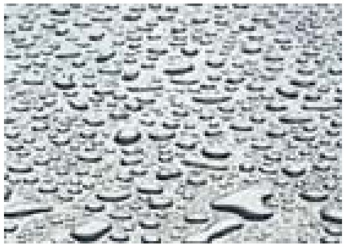


Joe Turk
Jet Propulsion Laboratory
jturk@jpl.nasa.gov

Characteristics of Precipitation

- Wide variability in space, time, and intensity
  - Discontinuous; wide range of extremes; intermittent
  - Controlled across scales from microscale (microphysics), mesoscale (sea breezes), synoptic (fronts)

- Spaceborne measurement of precipitation:
  - Constrained by observing system limitations (revisit, resolution, frequency, swath, noise)
  - More challenging over land than over ocean
  - Used by an increasingly broad and diverse user community
  - Not straightforward to validate

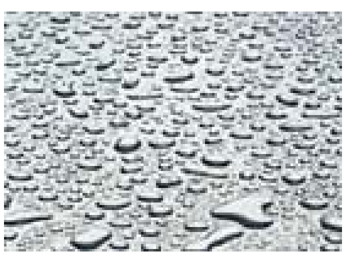



Topics that I will discuss

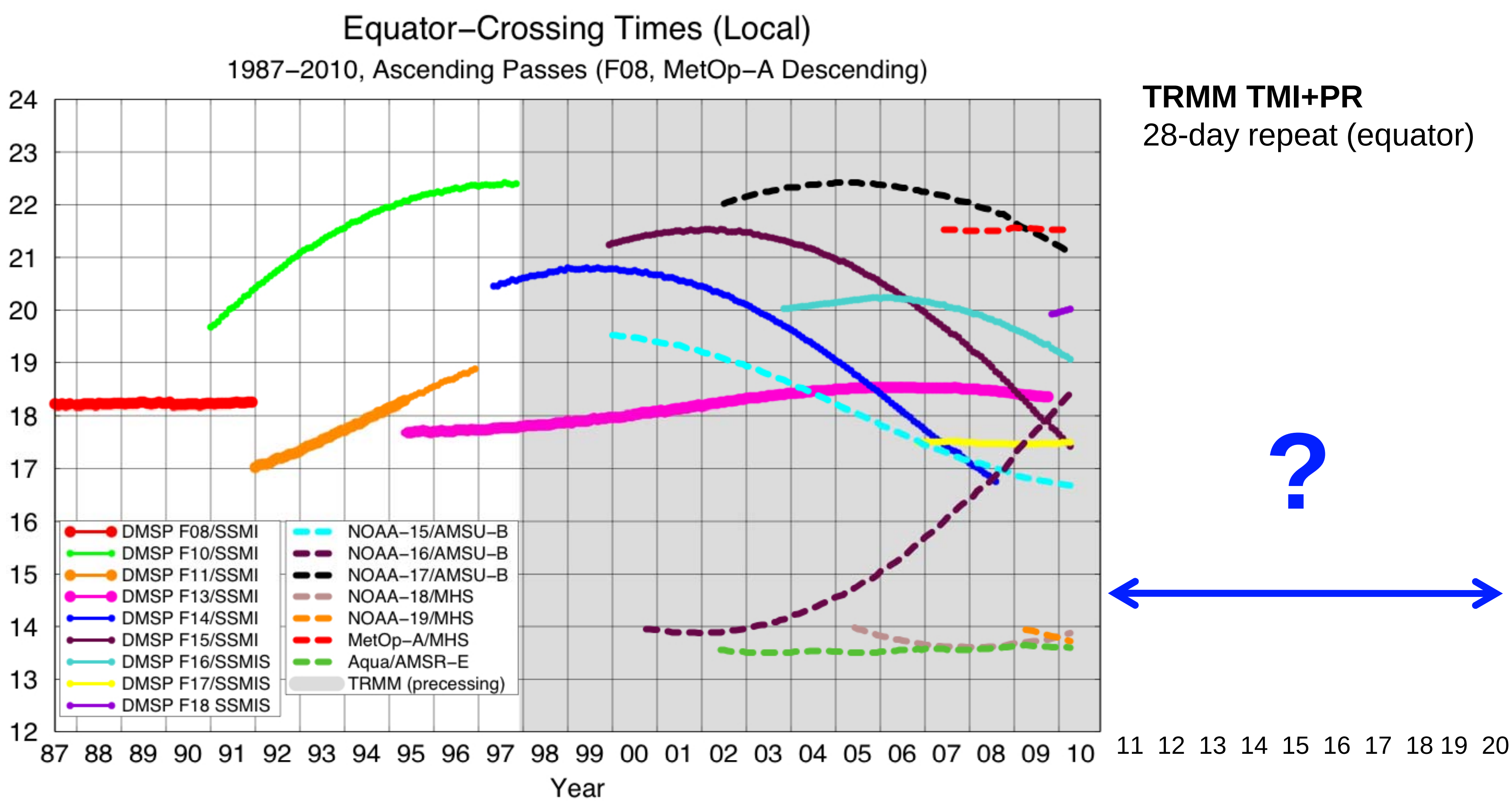
- ➢ Satellite Platforms with Precipitation-Relevant Capabilities
- ➢ General issues with current datasets and products
- ➢ Focus on GPM and what it will do differently from TRMM
- ➢ A few unique proposed mission concepts

Topics that I will not have time to discuss

- ➢ Sensor Intercalibration (X-CAL)
- ➢ Microwave Surface Emissivity Modeling (over-land precipitation)
- ➢ Radar/Combined Retrieval Algorithms
- ➢ Latent Heat Products
- ➢ Cloud Resolving Models & Ground Validation



Local Time of Observations

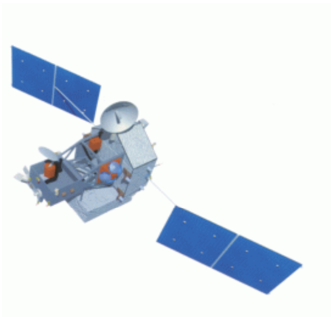


Thickest lines denote GPCP calibrator.

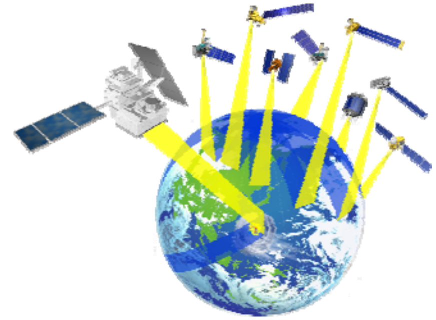
Image by Eric Nelkin (SSAI), 19 April 2010, NASA/Goddard Space Flight Center, Greenbelt, MD.

TRMM launch Nov 1997
F14 only direct-broadcast since 24 Aug 2008
F15 RADCAL beacon activated 14 Aug 2006

F18 launch: Oct 2009
F13 only direct-broadcast since 9 Nov 2009
FY-3A launch: May 2008



TRMM and GPM

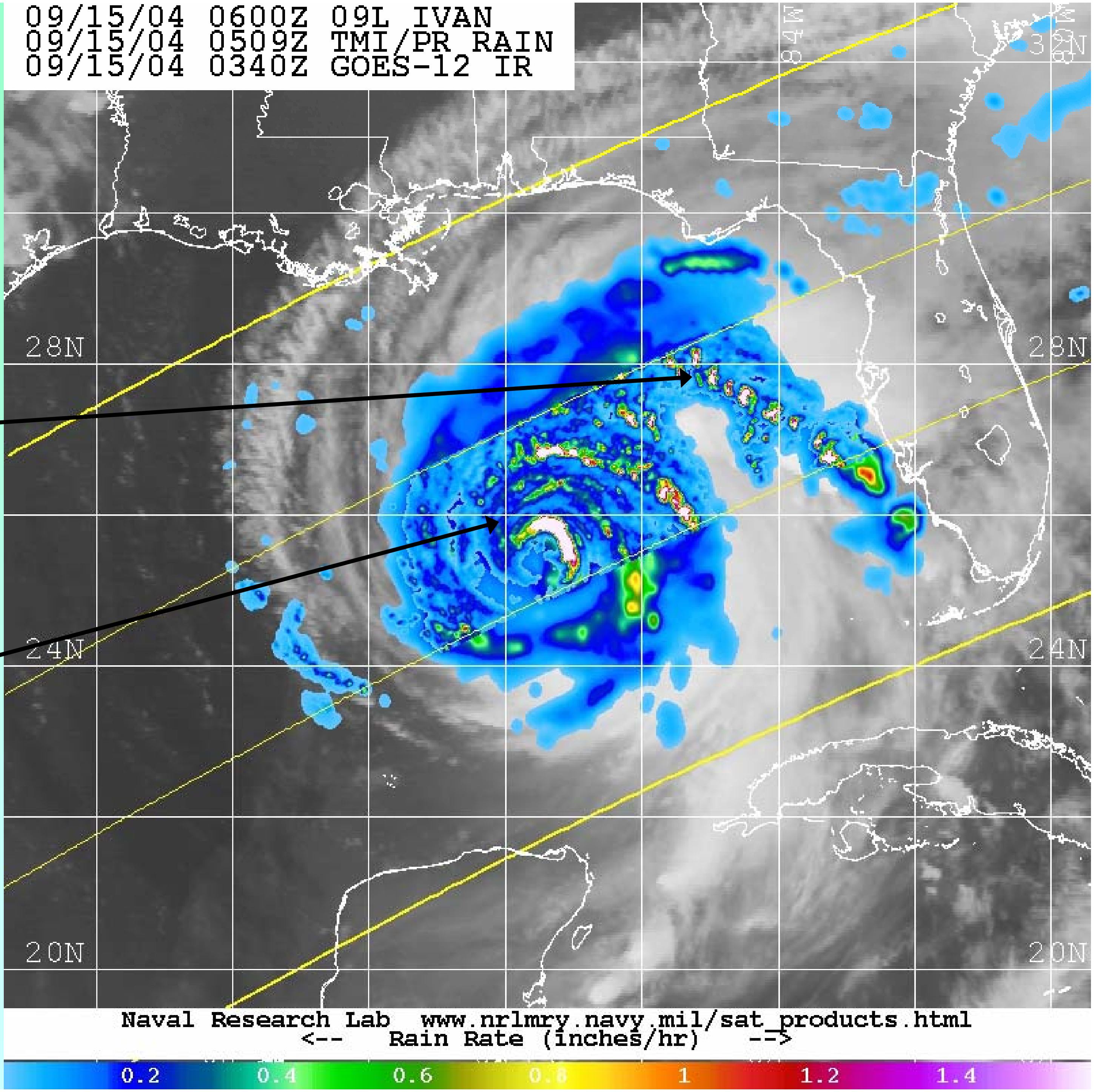


- TRMM: Tropical Rainfall Measuring Mission (11/97-current)
  - single satellite mission
  - science oriented
- GPM: Global Precipitation Measurement (7/2013)
  - constellation-based, multiple partner satellite mission
  - applications **and** science in scope
- Both of them:
  - Carry conically scanning microwave radiometers
  - Carry radar and observe 3-D structure of precipitation systems
  - LEO satellites (core satellite about 400-km orbit)
    - narrow swath, low sampling frequency
  - US-Japan joint missions

TRMM TMI/PR 15 Sep 2004 0509 UTC Over-Ocean

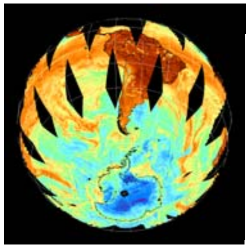
TMI can't delineate fine-scale structure

PR-estimated precip is displaced from the TMI-estimated precip due to parallax



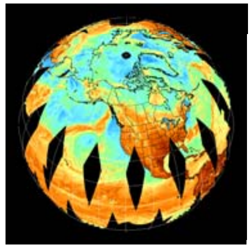
satellite motion

Multi-Sensor & Techniques



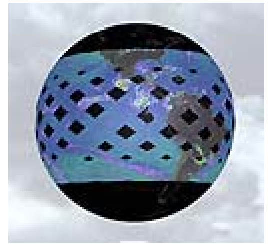
DMSP orbits

+



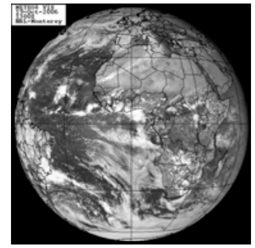
Aqua (AMSR)

+



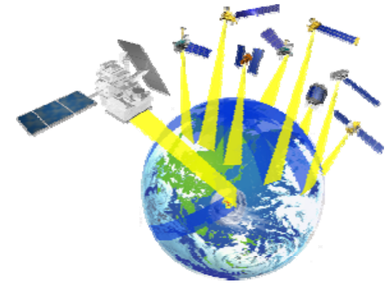
TRMM (TMI+PR)

+



geostationary

=



Across-track scanning microwave sounders (15-50 km)

Conically scanning microwave imagers (5-70 km)

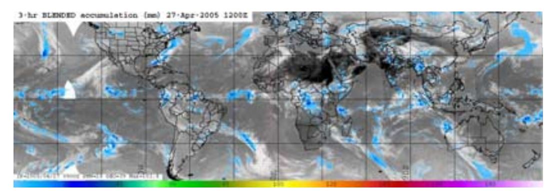
Space Radars (5 km)

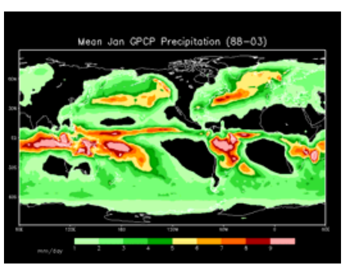
TRMM 2A12

Instantaneous swath-level precipitation product (L2)

CMORPH
TRMM 3B42

Blend/tracking with geostationary VIS/IR (25 km, 3-hourly)
"High resolution" precipitation products HRPP





GPCP
CMAP
HOAPS
etc

Raingauge analyses
(1-deg, daily)
(2.5-deg, monthly

Seasonal Performance Australia Tropics

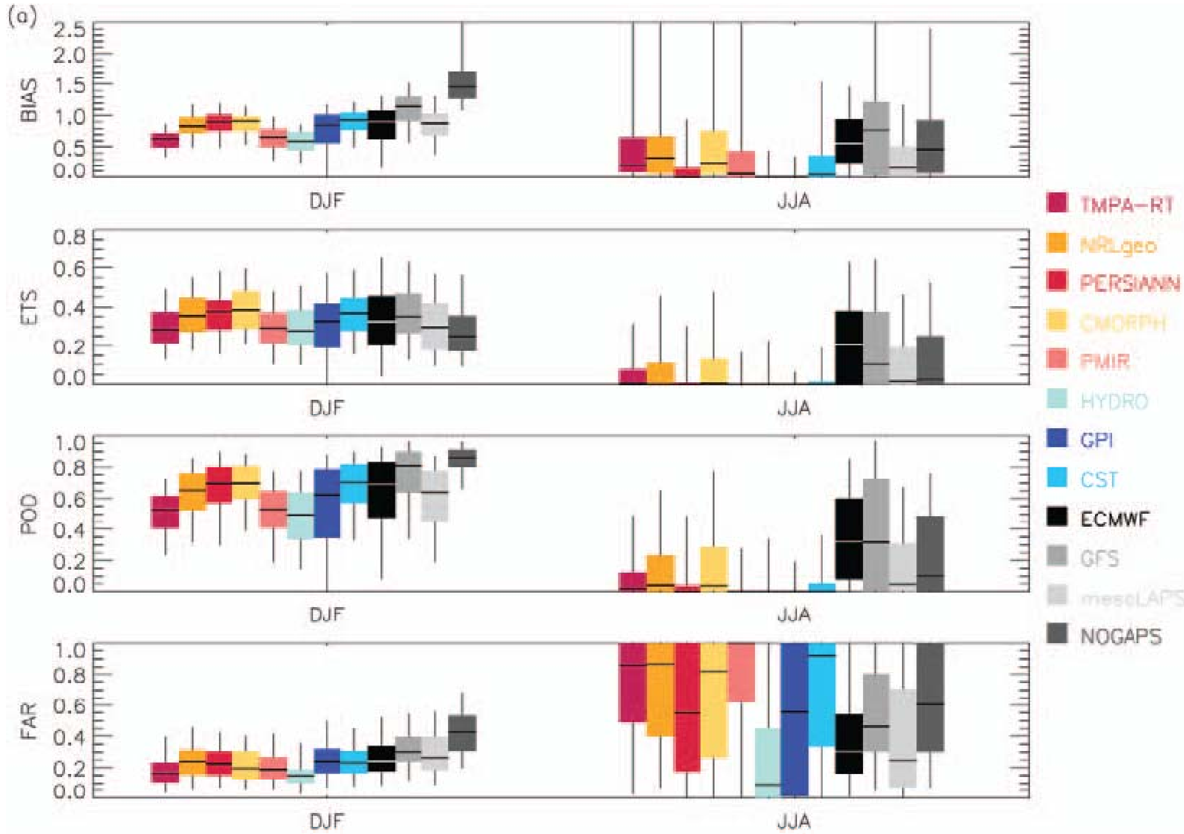
Over-land validation of 12 HRPPs and 4 NWP) models

Daily, 25-km

Ebert et. al, 2007
Ongoing

HRPPs (colors)
NWP Models (grays)

summer **winter**



Bias

Equitable Threat Score

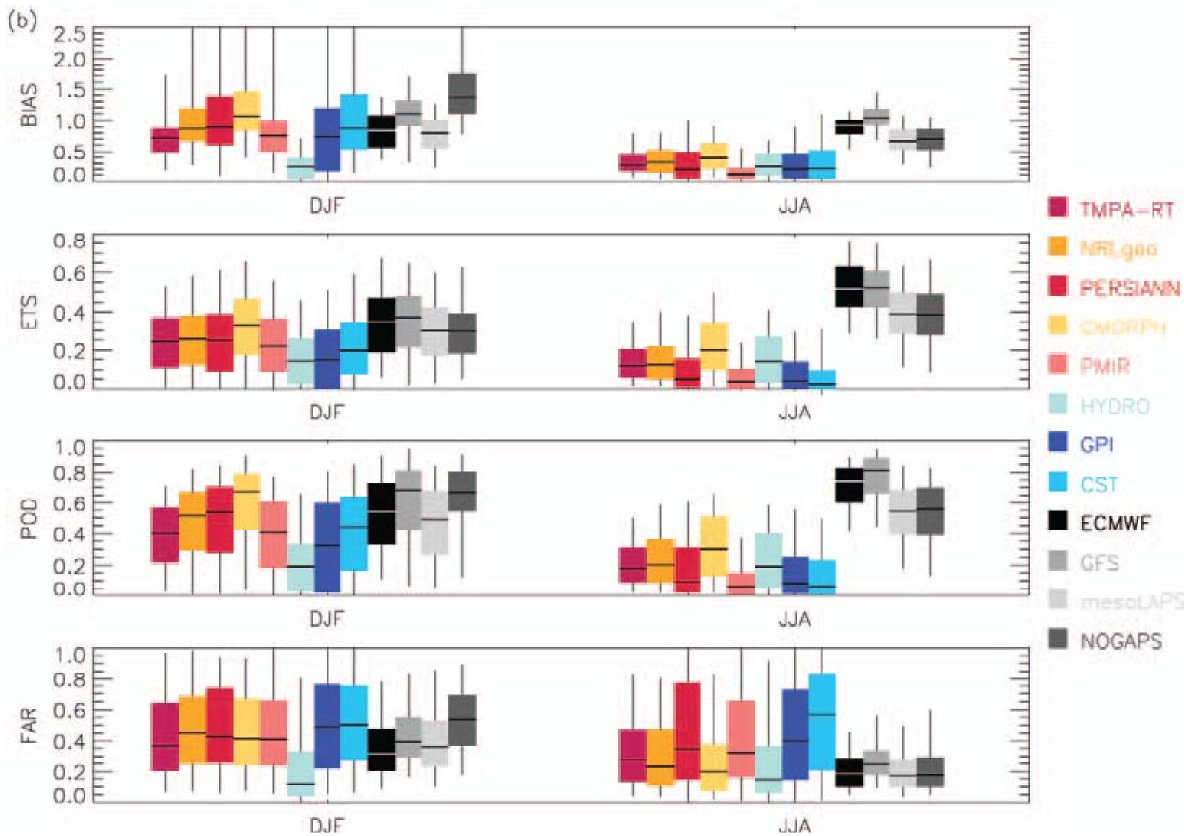
Probability of Detection

False Alarm Rate

1. HRPP-derived occurrence and amount are most accurate during summer and lower latitudes
2. NWP models exhibit superior performance during winter months and higher latitudes
3. HRPP estimates showed improved performance compared to NWP models for convective type precipitation (and opposite behavior for lighter, stratiform precipitation)

Seasonal Performance Australia Mid-Latitudes

summer **winter**



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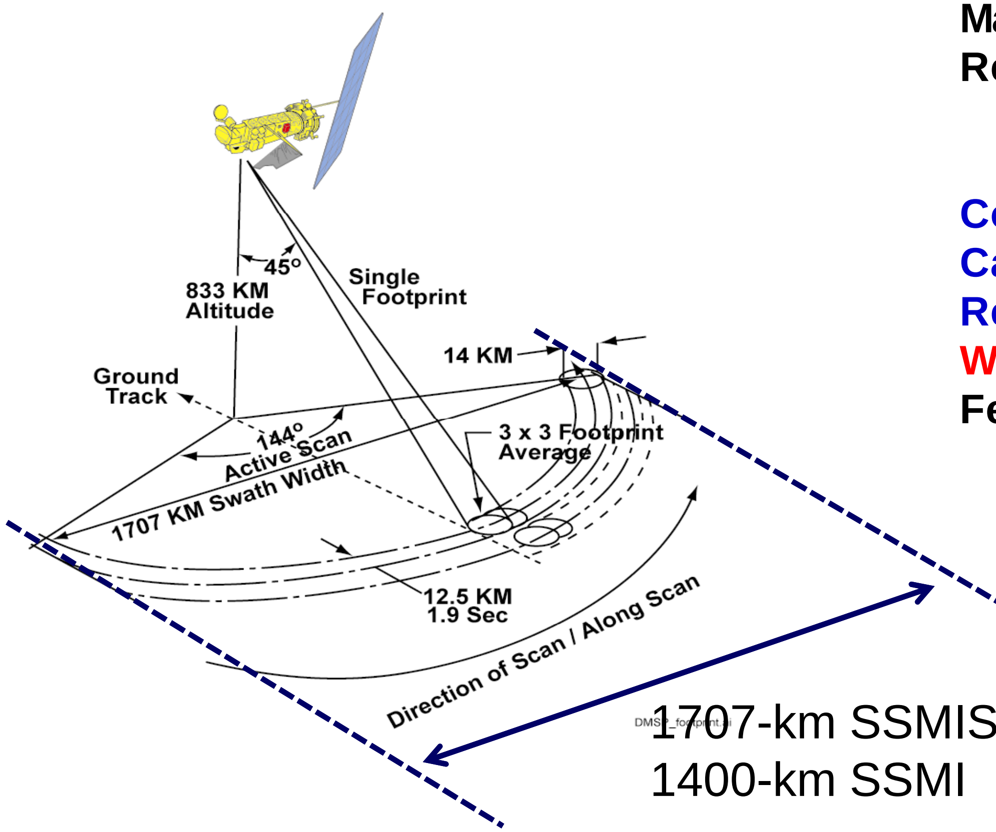
Precipitation-Related Missions Between 2010-2020

Year	Mission	Instrument
2010	FY-3B (CMA)	
2011	Aquarius (US+CONAE)	L-band scatterometer + 24/37 GHz radiometer
	GCOM-W1 (JAXA)	AMSR-2
	Megha-Tropiques (CNES+ISRO)	MADRAS radiometer + MW sounder
2012	NPP (US)	ATMS (no MW imager)
	DMSP F-19 (US)	SSMIS
	FY-3C (CMA)	
2013	GPM core (US+JAXA)	GMI+DPR
2014	GPM constellation (US+partner)	GMI copy
	FY-3D (CMA)	
2015	SMAP (US)	L-band radar/radiometer
	DMSP F-20 (US)	SSMIS
2016	FY-3E (CMA)	
2017	DWSS-MIS ? (US)	
2018	FY-3F (CMA)	
2019		
2020	Post-EPS (EUMETSAT)	

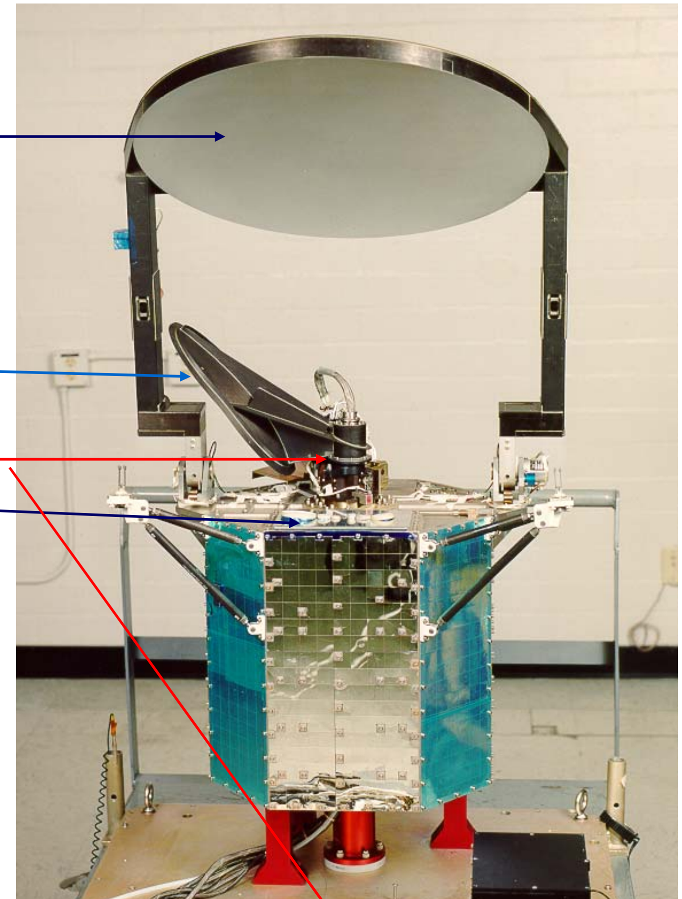
Not inclusive

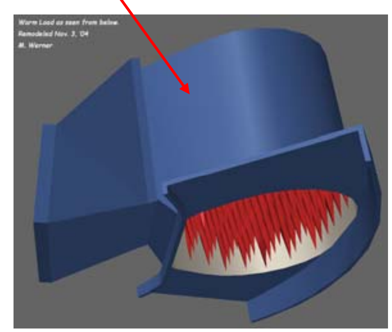
Approximate launch dates

SSMIS Scan Geometry



1707-km SSMIS
1400-km SSMI





180 samples/scan (91, 150, 183 GHz)
90 samples/scan (19-37 GHz)
60 samples/scan (lower sounding)
30 samples/scan (upper sounding)

SSMIS: 24 Channels

imaging environmental lower-atmos upper-atmos

SSMIS Channel	Center Frequency (GHz)	RF BW (MHz)	Receive Polarization	3-dB resolution (km) @ 833-km	Sample spacing (km)	Samples per scan
1	50.3	380.0	H	37.7 x 38.8	37.5	60
2	52.8	388.8	H	37.7 x 38.8	37.5	60
3	53.596	380.0	H	37.7 x 38.8	37.5	60
4	54.4	382.5	H	37.7 x 38.8	37.5	60
5	55.5	391.3	H	37.7 x 38.8	37.5	60
6	57.29	330.0	RC	37.7 x 38.8	37.5	60
7	59.4	238.8	RC	37.7 x 38.8	37.5	60
8	150 ± 1.25	3284.0	H	13.2 x 15.5	12.5	180
9	183.31 ± 6.6	1025.0	H	13.2 x 15.5	12.5	180
10	183.31 ± 3	2038.0	H	13.2 x 15.5	12.5	180
11	183.31 ± 1	3052.0	H	13.2 x 15.5	12.5	180
12	19.35	355.0	H	43.5 x 73.6	25	90
13	19.35	356.7	V	43.5 x 73.6	25	90
14	22.235	407.5	V	43.5 x 73.6	25	90
15	37.0	1615.0	H	43.5 x 73.6	25	90
16	37.0	1545.0	V	43.5 x 73.6	25	90
17	91.655 ± 0.9	2836.0	V	13.2 x 15.5	12.5	180
18	91.655 ± 0.9	2822.0	H	13.2 x 15.5	12.5	180
19	63.283248 ± 0.285271	1.35 (2)	RC	75.2 x 75	75	30
20	60.792668 ± 0.357892	1.35 (2)	RC	75.2 x 75	75	30
21	60.792668 ± 0.357892 ± 0.002	1.3 (4)	RC	75.2 x 75	75	30
22	60.792668 ± 0.357892 ± 0.0055	2.6 (4)	RC	75.2 x 75	75	30
23	60.792668 ± 0.357892 ± 0.016	7.35 (4)	RC	75.2 x 75	75	30
24	60.792668 ± 0.357892 ± 0.050	26.5 (4)	RC	37.7 x 38.8	37.5	30

SSMIS Calibration Issues

Post-launch F16/F17 SSMIS Cal/Val efforts together with data assimilation monitoring at NWP centers have uncovered two main calibration issues:

Warm load intrusion: Direct or reflected sunlight heats the warm calibration target, increasing the apparent gain, and resulting in anomalously cold observations

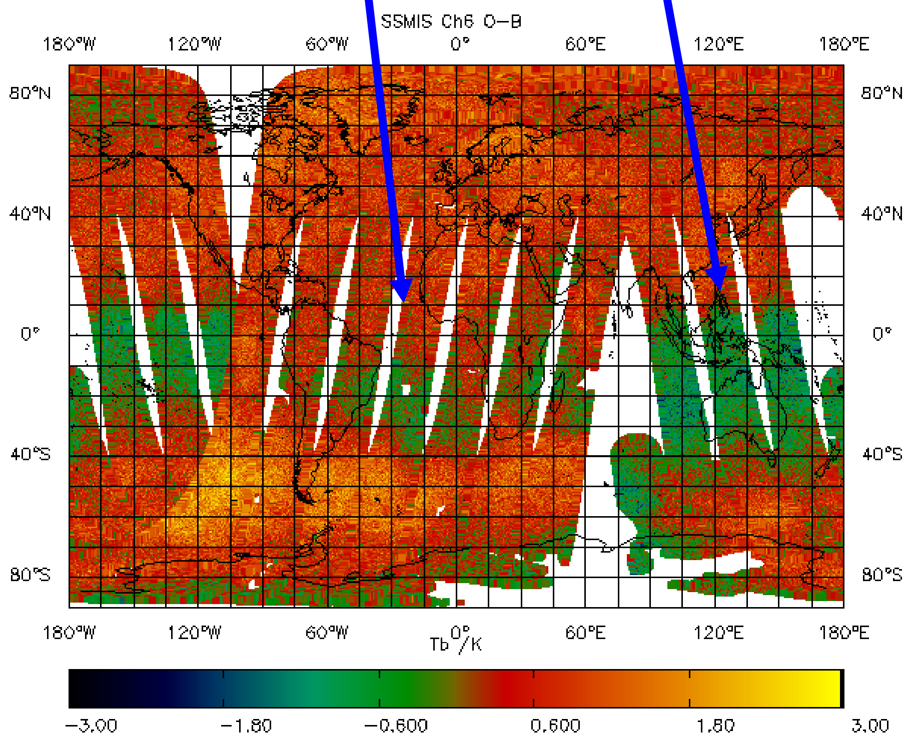
Reflector emission: The temperature of the main reflector varies between 220-300 K during orbit, and the anomalous emissivity of 0.01-0.05 contaminates the scene temperature

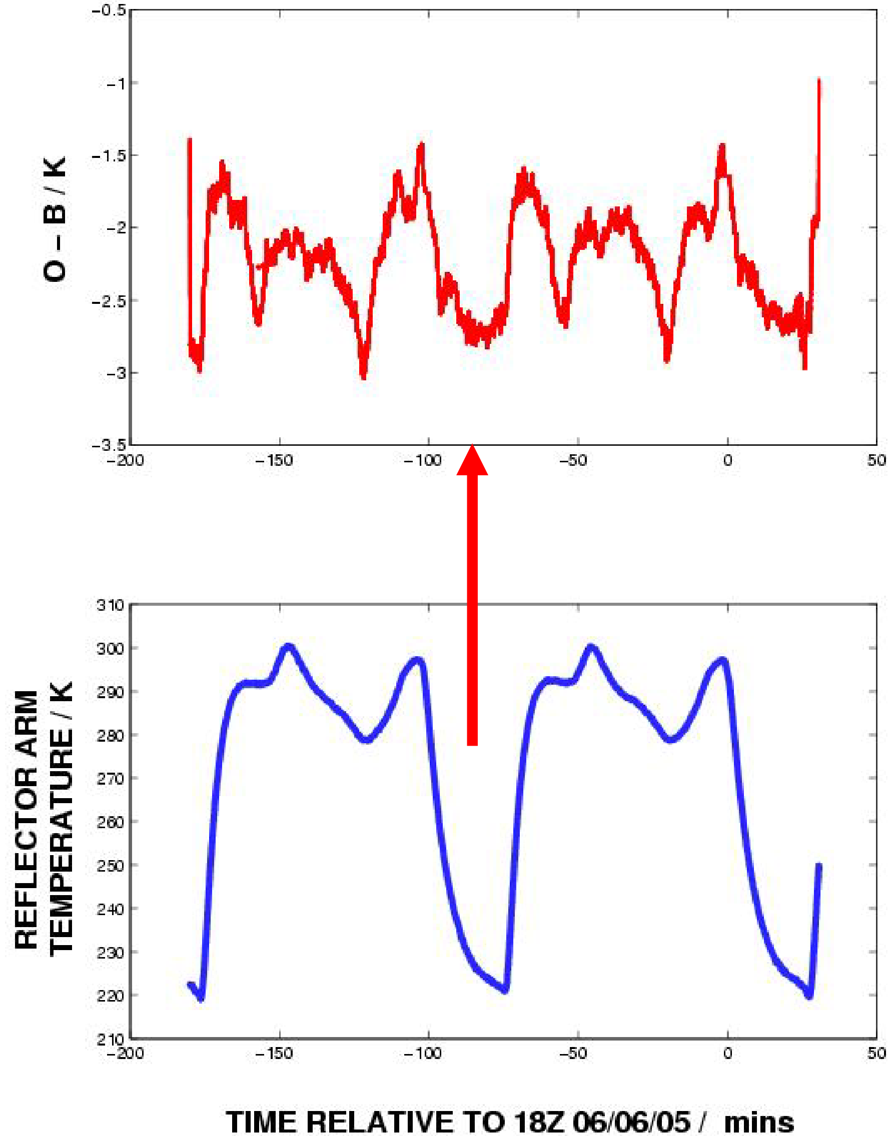
The reflector for F18 was replaced prior to launch to mitigate the reflector emission issue (also for F19 and F20)

Reflector emission

Less evident in descending (in sunlight)

Problems in ascending (in shadow)





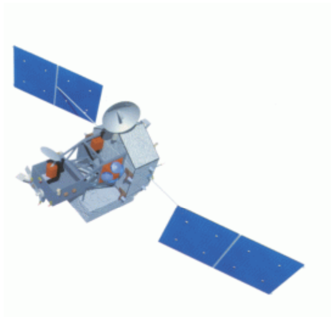
Reflector Rim Temperature Cycle Dominated by Earth and Spacecraft Shadowing

Patterns Show Frequency Dependent Reflector Emissivity

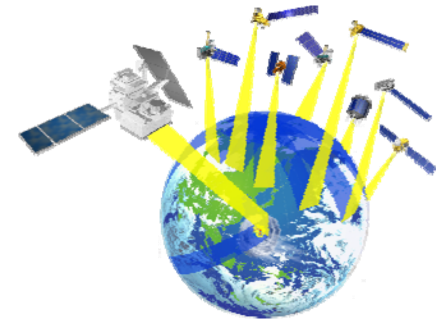
1.5–2K Obs-BG jump at 50-60 GHz

5-7K Obs-BG jump at 183 GHz

courtesy Bill Bell, ECMWF



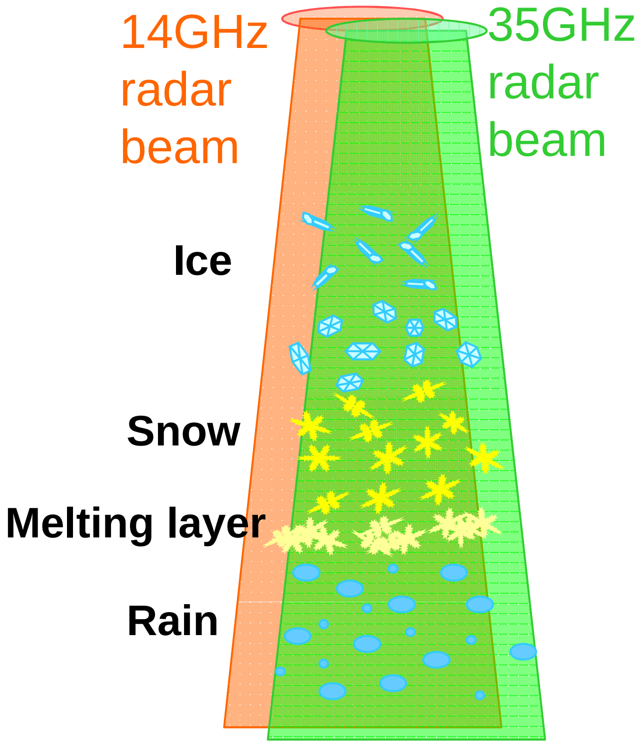
TRMM and GPM

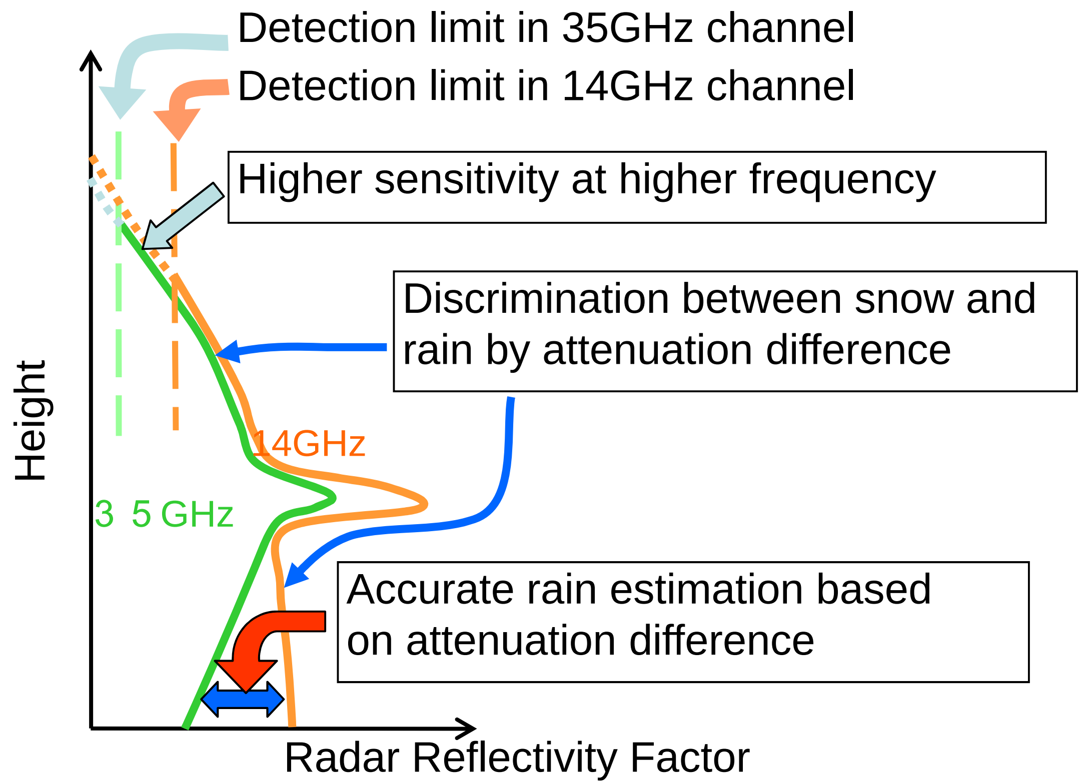


	TRMM	GPM
Orbit	38-deg NSS[1], 405-km	65-deg NSS, 410-km
Launch	H-2 (JAXA)	HY-2 (JAXA)
Radar	Single frequency, ±17^o scan	Dual frequency/interlaced
Radiometer	TMI (SSMI + 10 GHz)	GMI (TMI + 157/183 GHz)
Revisit	Sufficient sampling to study tropical climate	Aggregate 3-hr revisit with partner satellites
Data System	TSDIS (now PPS) Realtime was afterthought and “best effort”	PPS Realtime essential role

[1] Non Sun Synchronous

Dual Frequency Precipitation Radar (DPR)





Roles of DPR

Accurate 3D measurements of precipitation as TRMM, but with better sensitivity

Improvement of estimation accuracy

Identification of hydrometer type, phase state

Improvement of MWR algorithms

Simultaneous measurements with GPM Microwave Imager (GMI)

Courtesy T. Iguchi, NICT

Courtesy T. Iguchi, NICT

Main Characteristics of DPR

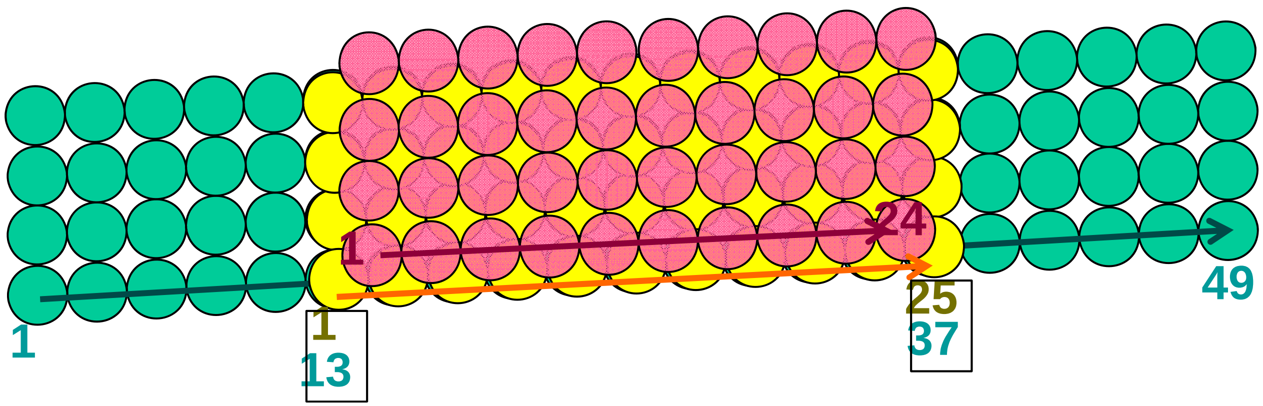
Item	KuPR	KaPR	TRMM PR
Antenna Type	Active Phased Array (128)	Active Phased Array (128)	Active Phased Array (128)
Frequency	13.597 & 13.603 GHz	35.547 & 35.553 GHz	13.796 & 13.802 GHz
Swath Width	245 km	120 km	215 km
Horizontal Reso	5 km (at nadir)	5 km (at nadir)	4.3 km (at nadir)
Tx Pulse Width	1.6 us (x2)	1.6/3.2 us (x2)	1.6 us (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: $Ze=372.4 R^{1.54}$)

Courtesy T. Iguchi, NICT

Concept of the DPR antenna scan

- *KuPR footprint* : *Δz = 250 m*
- *KaPR footprint (Matched-beam with KuPR)* : *Δz = 250 m*
- *KaPR footprint (High-sensitivity beam)* : *Δz = 500 m*



KaPR: 120 km (24 beams)

KuPR: 245 km (49 beams)

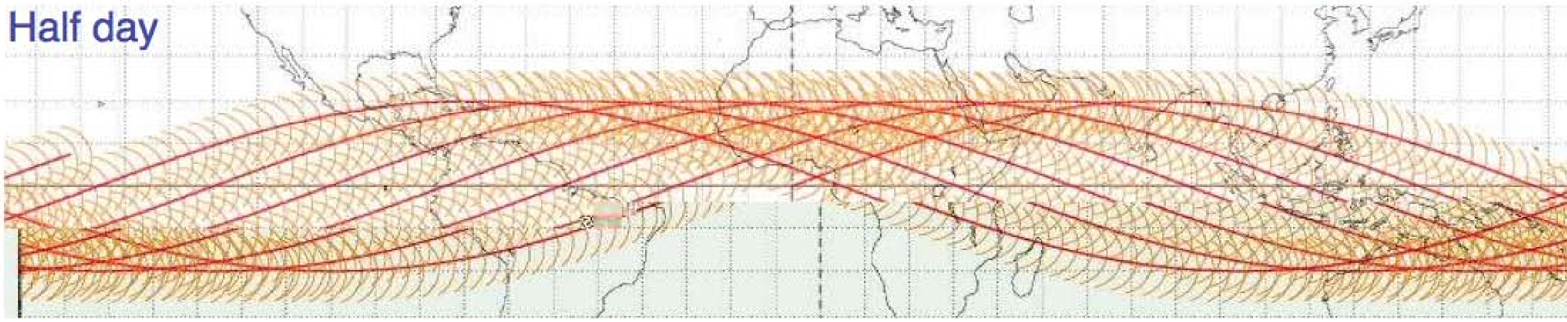
In the interlacing scan area ( ), the KaPR can measure snow and light rain in a high-sensitivity mode with a double pulse width.

The synchronized matched beam ( ) is necessary for the dual-frequency algorithm.

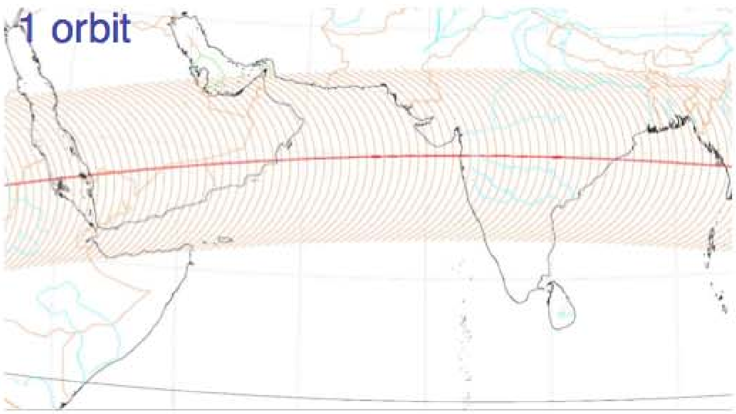
The Megha-Tropiques mission

Orbit (1/1)

Half day

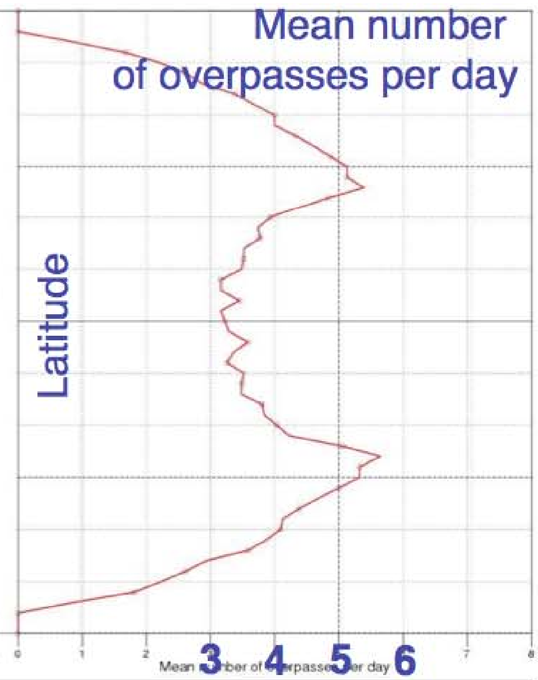


1 orbit

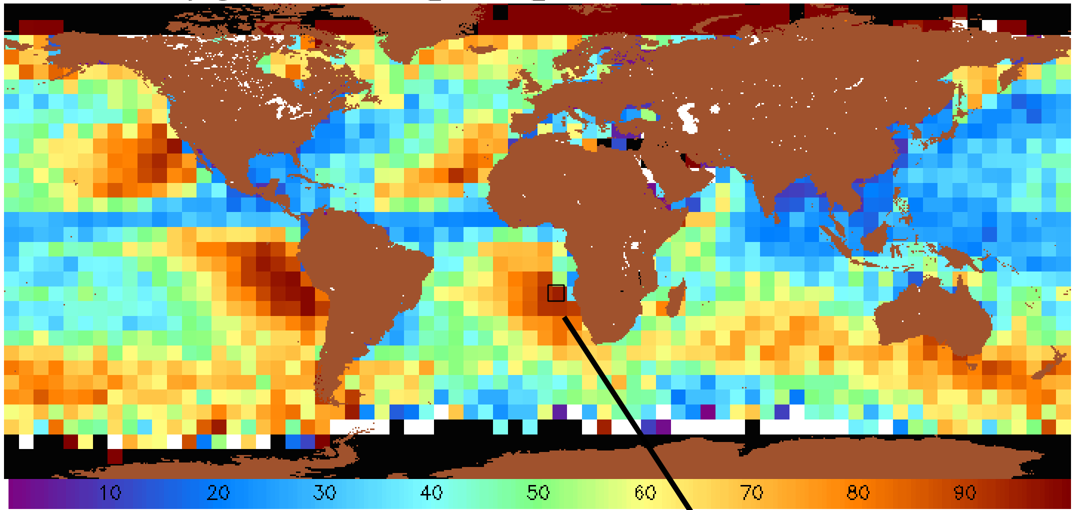


MADRAS sampling over 20°S-20°N
Min 3 per day
Max 5 per day

DAYS 1	6	11	16	21	26	31	Tot	Mean	Day1
0	0	0	0	0	0	0	0	0.0	0
2	2	2	1	2	2	1	52	1.7	31
3	2	3	3	2	2	3	81	2.6	31
3	4	3	3	4	4	3	105	3.4	31
4	4	4	4	4	4	4	124	4.0	31
4	4	4	5	4	4	5	134	4.3	31
5	4	5	5	5	5	5	151	4.9	31
5	6	5	5	5	5	5	159	5.1	31
5	6	5	4	5	5	5	150	4.8	31
4	4	4	4	4	4	4	122	3.9	31
4	4	4	4	3	3	4	117	3.8	31
4	2	4	4	3	3	4	109	3.5	31
3	4	3	3	3	4	3	98	3.2	31
4	4	4	2	4	4	3	107	3.5	31
3	4	3	3	3	3	3	100	3.2	31
4	2	4	4	3	3	4	111	3.6	31
3	3	3	4	3	3	3	101	3.3	31
4	5	3	3	4	4	3	106	3.5	31
4	5	4	3	4	4	3	118	3.8	31
4	5	4	4	4	4	4	125	4.0	31
5	5	5	6	5	4	5	157	5.1	31
5	6	5	6	5	5	5	165	5.3	31
5	6	5	5	5	5	5	155	5.0	31
4	6	4	4	5	5	4	136	4.4	31
4	5	4	4	4	4	4	127	4.1	31
3	3	4	4	3	3	4	111	3.6	31
3	3	3	2	3	3	2	81	2.6	31
2	1	2	2	2	1	2	56	1.8	31
0	0	0	0	0	0	0	0	0.0	0



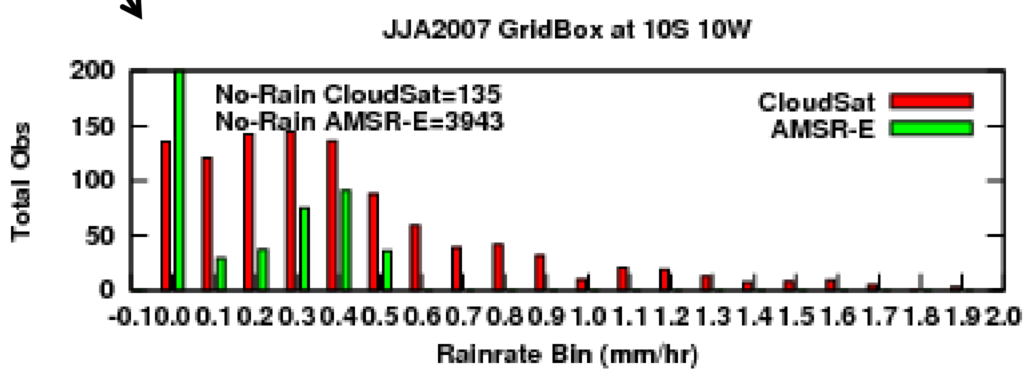
CloudSat –vs- AMSRE (Passive) Precipitation Detection



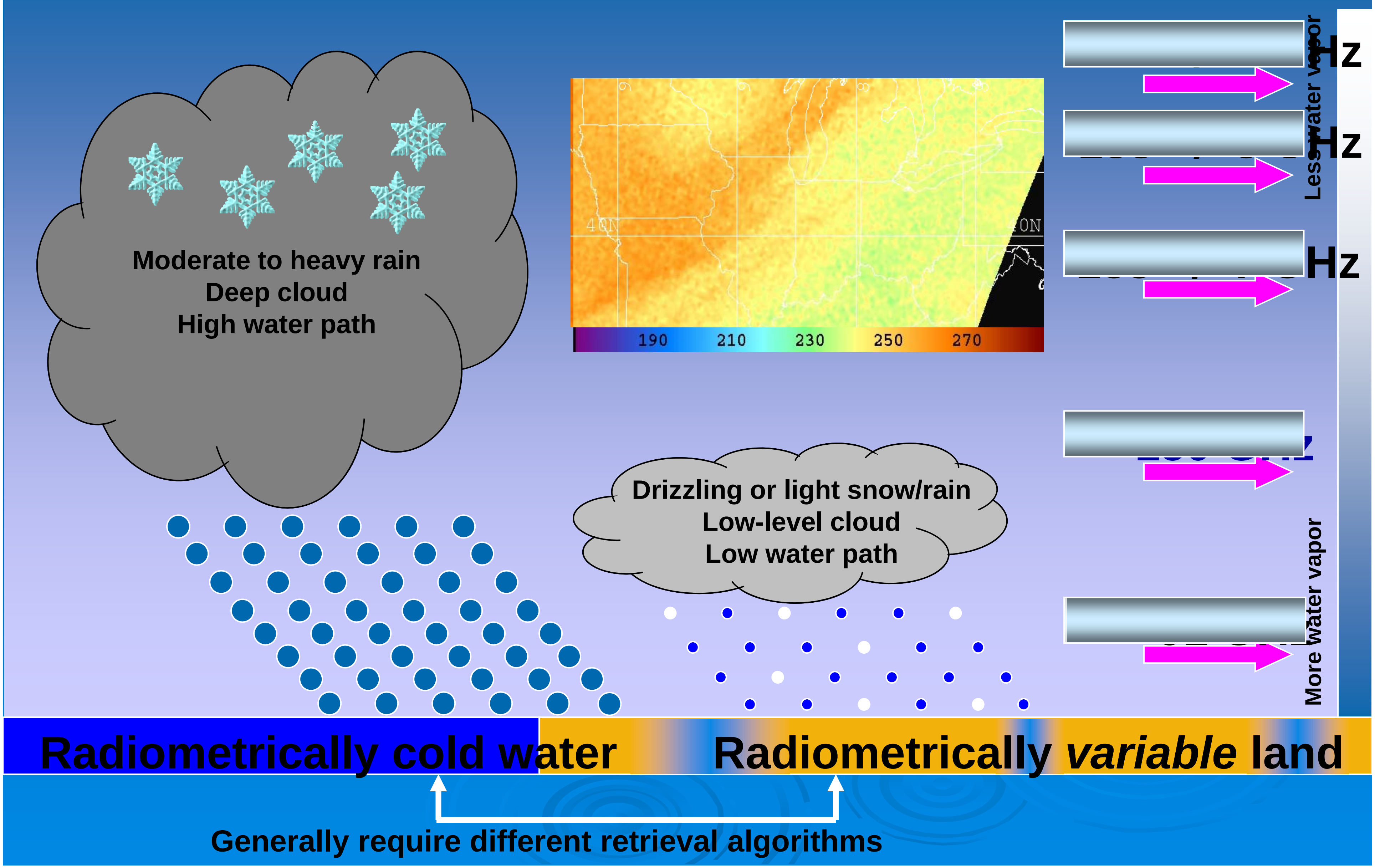
Colors represent percentage of coincident observations where CloudSat flags rain and AMSRE does not

5-degree gridbox centered at 10S 10W

Drop off in the low end of the passive precipitation distribution



Microwave Sounder Observations Above 90 GHz

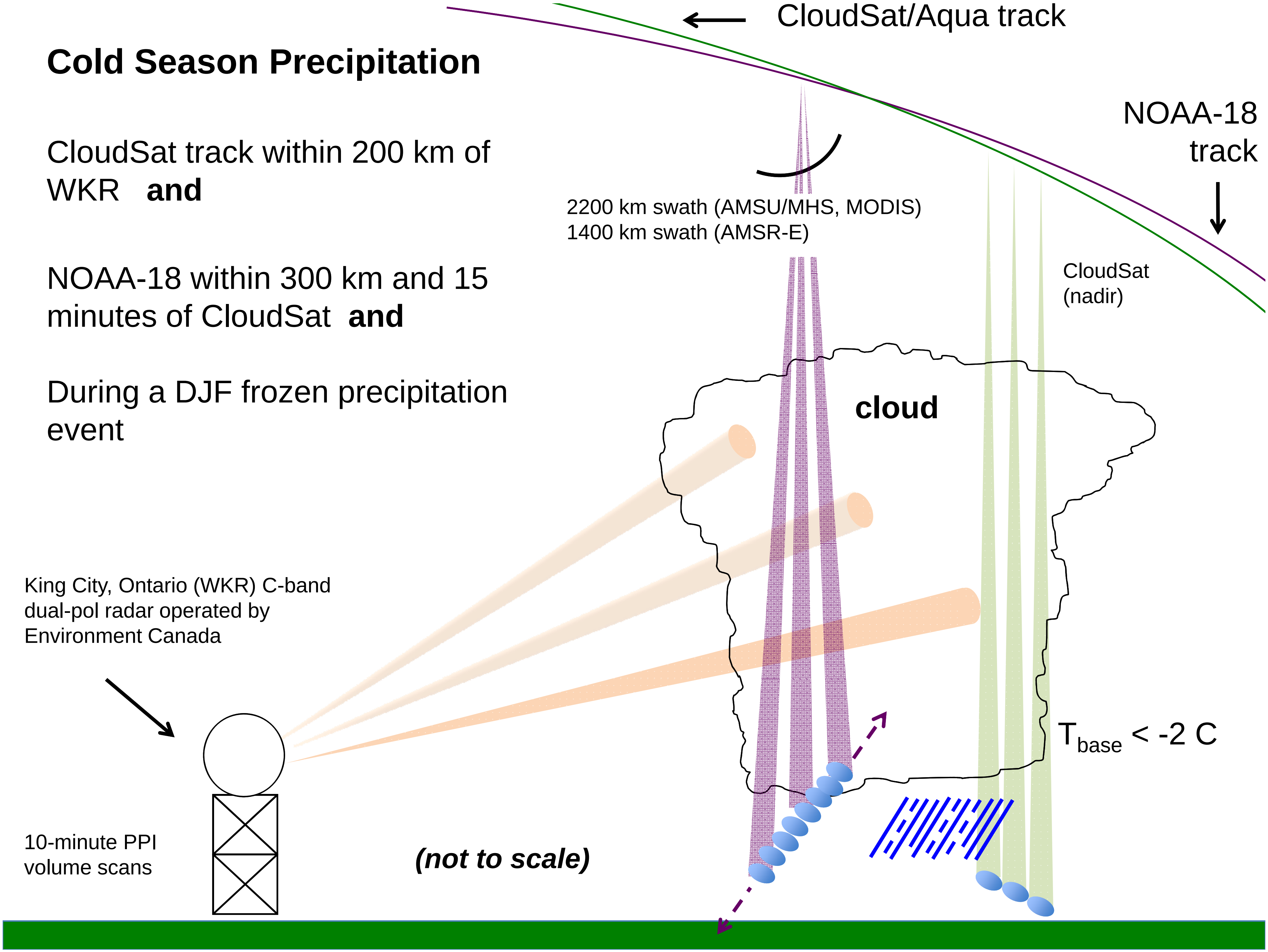


Cold Season Precipitation

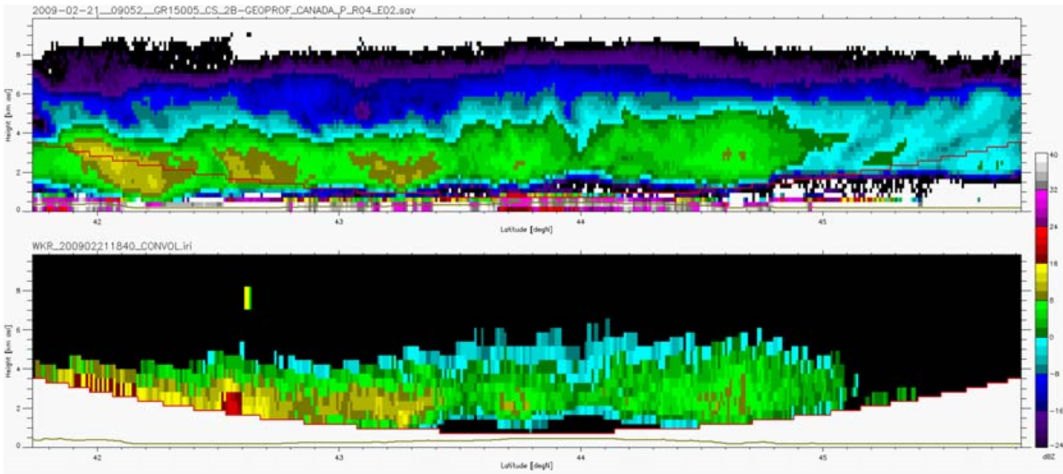
CloudSat track within 200 km of WKR **and**

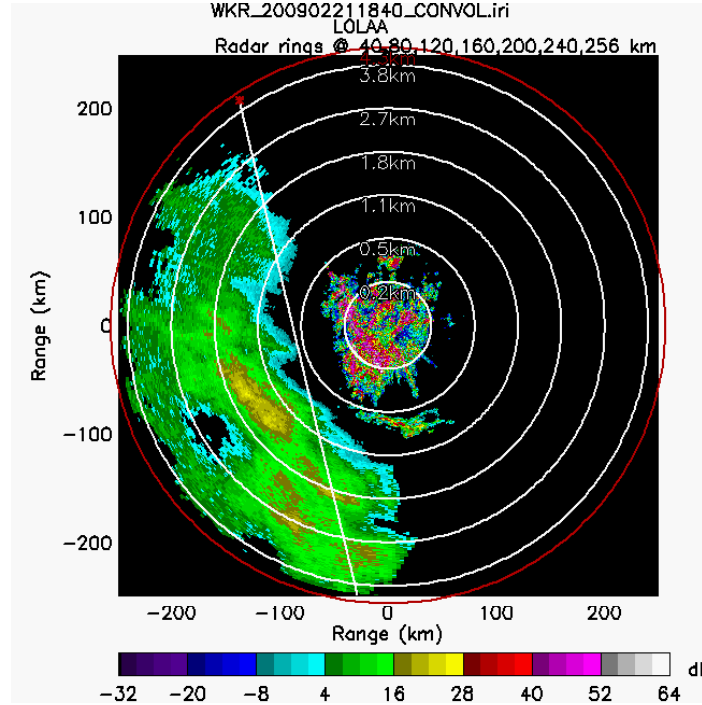
NOAA-18 within 300 km and 15 minutes of CloudSat **and**

During a DJF frozen precipitation event

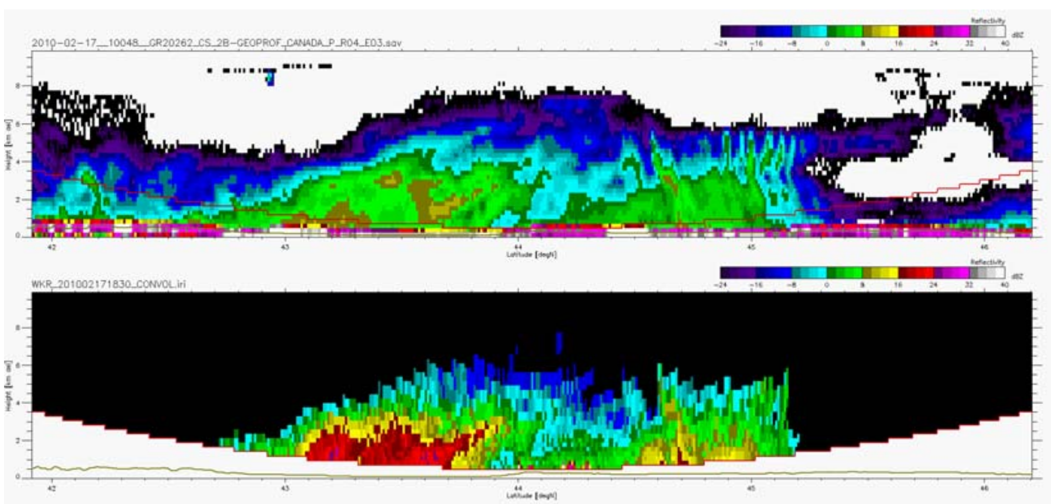


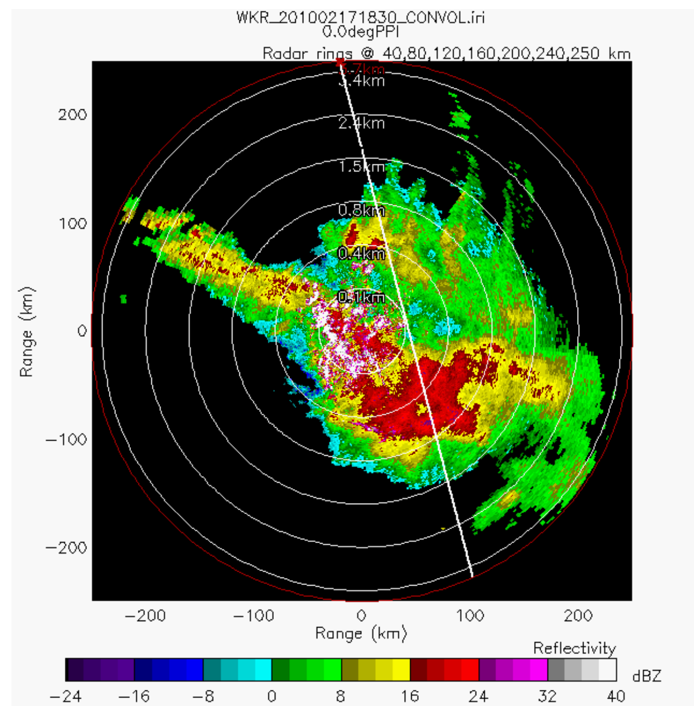
Case 5 2009/02/21
Ascending over Lake Ontario and Lake Huron





Case 6 2010/02/17
Ascending over Lake Ontario





Simulated C-band Cumulative Contour Frequency by Altitude (CCFAD) diagrams under the CloudSat track

All 6 Cases Together

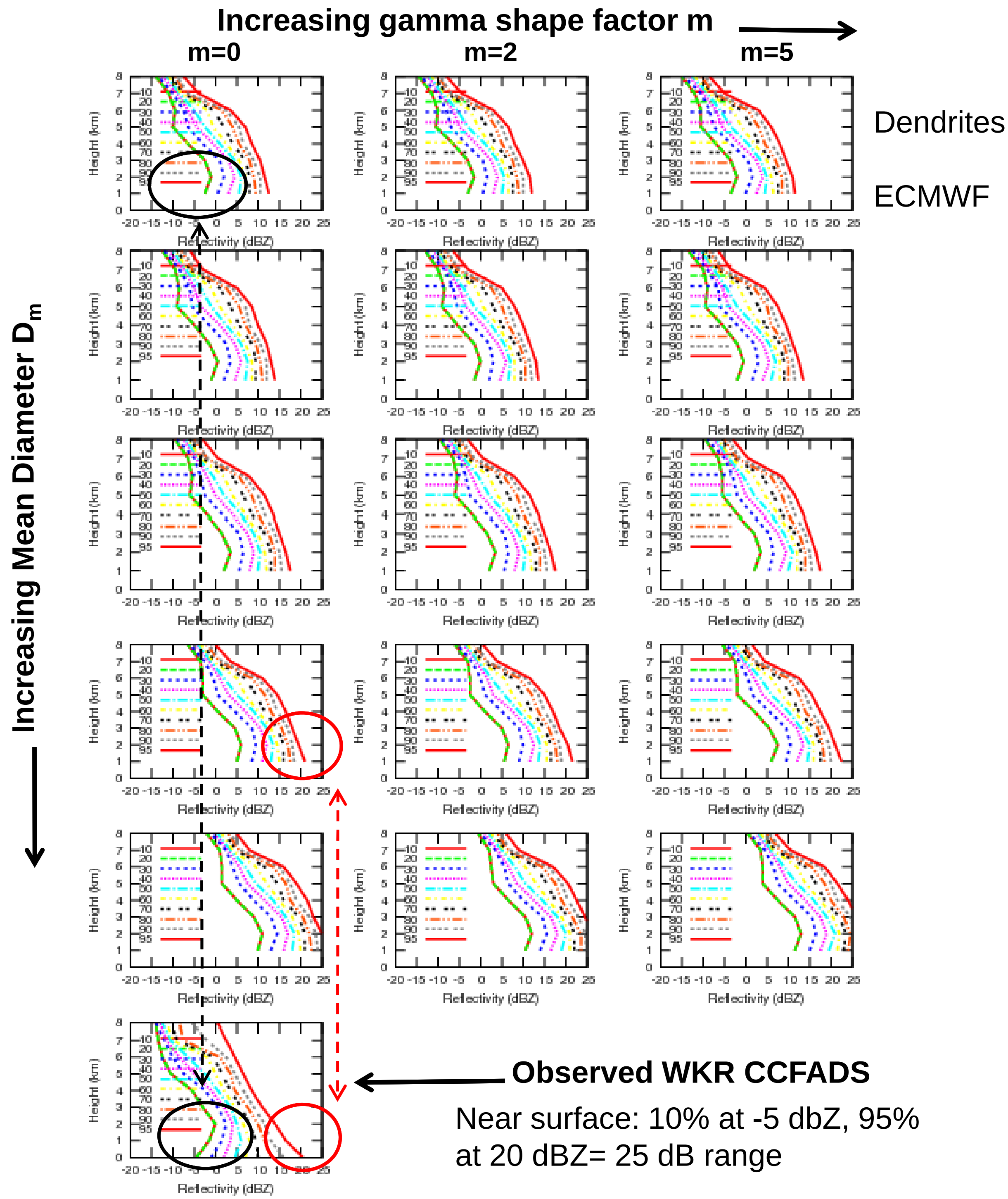
Intervals of 10%

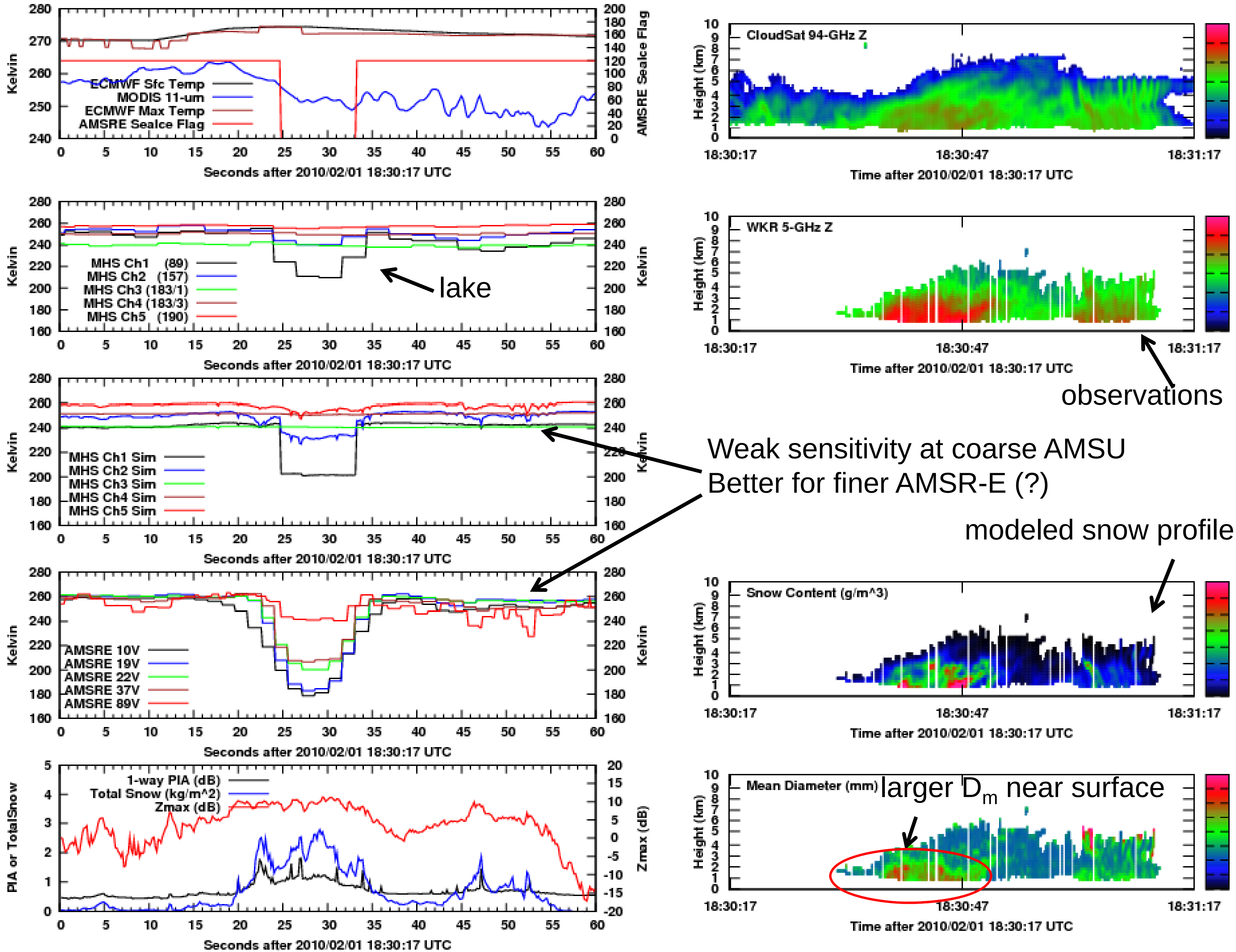
1-km and higher (CloudSat has no cloud data below 1-km)

Near the surface, observed CCFADS cover a 25 dB range, but simulated only about 15 dB

Near the surface, lower reflectivities better replicated **(black ellipses)** than the higher reflectivities **(red ellipses)**

Consistent with aggregation of biggest particles and larger D^6




ECMWF Sfc Temp
MODIS 11-um
ECMWF Max Temp
AMSRE Sealce Flag
Kelvin
AMSRE Sealce Flag
Seconds after 2010/02/01 18:30:17 UTC
MHS Ch1 (89)
MHS Ch2 (157)
MHS Ch3 (183/1)
MHS Ch4 (183/3)
MHS Ch5 (190)
lake
MHS Ch1 Sim
MHS Ch2 Sim
MHS Ch3 Sim
MHS Ch4 Sim
MHS Ch5 Sim
AMSRE 10V
AMSRE 19V
AMSRE 22V
AMSRE 37V
AMSRE 89V
1-way PIA (dB)
Total Snow (kg/m^2)
Zmax (dB)
PIA or TotalSnow
Zmax (dB)
CloudSat 94-GHz Z
WKR 5-GHz Z
Height (km)
Time after 2010/02/01 18:30:17 UTC
18:30:17
18:30:47
18:31:17
observations
Weak sensitivity at coarse AMSU
Better for finer AMSR-E (?)
modeled snow profile
Snow Content (g/m^3)
Mean Diameter (mm)
larger D$_m$ near surface

MOTIVATION

- **IS X-SAR REALLY AN "ALL WEATHER" SENSOR ?**
  - **The SAR frequency at** X band **(9.6 GHz) is not too far from** Ku band **(14 GHz), frequency of the TRMM Precipitation Radar**
  - **Rainfall signatures have been already revealed by** previous X-SARs measurements **(e.g. SAR-X SIR-C in 1994).**

- **POTENTIAL OF X-SAR FOR RAIN RETRIEVAL**
  - **The** high spatial resolution **(~100 m) of SAR sensors might provide new insights into the structure of precipitating clouds from space.**
  - **The measurement of** highly-resolved precipitation **over land** where spaceborne microwave radiometers have had limited success.
    - **X-SAR precipitation retrievals will be especially valuable** over mountainous terrain **(where ground based radars are obstructed), but also** over ocean **with different problems to be solved.**
  - Near-future SAR satellites **will also measure the** co-polar and cross-polar polarized backscattering.

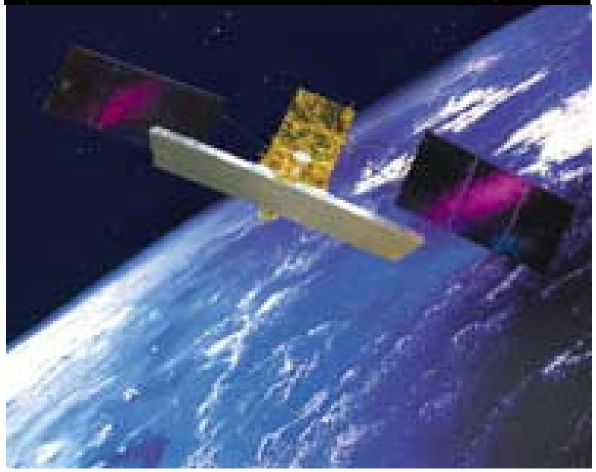
INTERNATIONAL CONTEXT ON X-SARs

- **X-band SAR current missions**
  - **Satellite missions implemented by some European space agencies.**

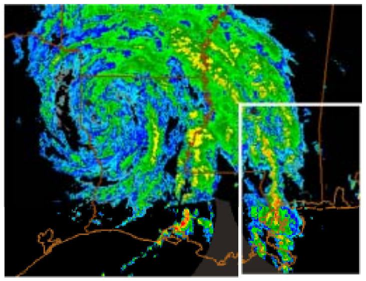
1. **The** TerraSAR-X (TSX) **has been launched by the Deutsches Zentrum f. Luft u. Raumfahrt (DLR) on June 15, 2007**
2. **The** Constellation of 4 Small Satellites for Mediterranean basin Observations (COSMO-SkyMed) **have been launched by the Agenzia Spaziale Italiana (ASI) on June 7, 2007, Dec. 2007 and Oct. 2008**
   - X-band polarimetric SAR
   - Stripmap mode **(Himage res.: 3 m, scene: 40x40 km²)**
   - Polarimetric mode **(select. HH-HV, VV-HV, HH-VV, res.: 15 m, scene: 30x30 km²)**
   1. ScanSAR mode **(res.: <30-100 m, scene: 100x100 or 200x200 km²)**

- **CoReH$_2$O mission proposed to ESA**
  - **dual-band X/Ku band SAR**

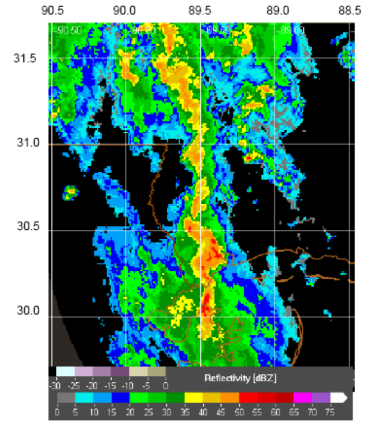
COSMO SkyMed satellite system



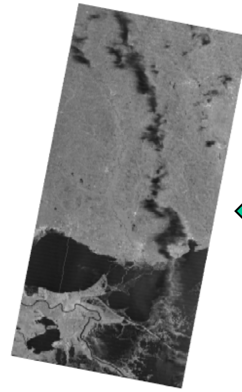
Rainfall Measurements from the TerraSAR-X Satellite

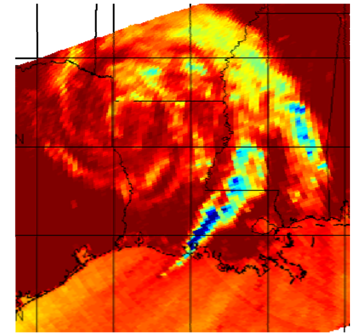


Hurricane Gustav
2 Sep 2008 1200 UTC



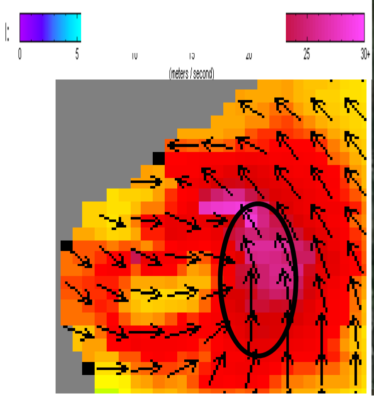
NEXRAD 1200 UTC



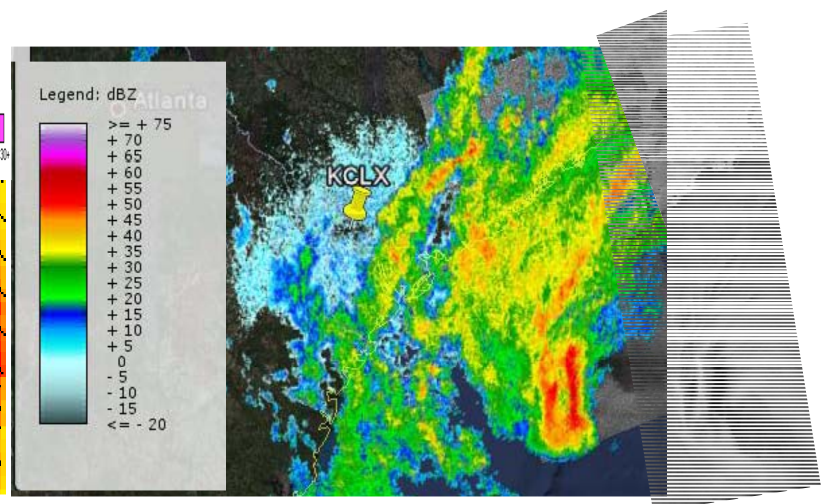


TRMM 85H 1648 UTC

Wind Speed

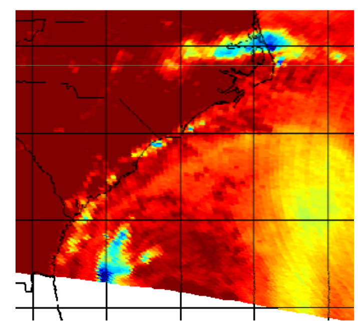


QuikSCAT wind vectors
5 Sep 2008 2136 UTC



Charleston, SC NEXRAD
2330 UTC

TerraSAR-X 2315
UTC



TRMM 85H 1722 UTC

Courtesy F. Marzano, Univ-Rome

Mori, S., F. Marzano, and J.A.Weinman, 2010: Evidence of rainfall signatures on X-Band synthetic aperture radar imagery over land, *IEEE Trans. Geosci. Rem. Sensing*, **48**, 950- 964.