Current and Future Satellite Observations of Precipitation

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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

Equator–Crossing Times (Local)
1987–2010, Ascending Passes (†08, MetOp–A Descending)

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)

Blend/tracking with geostationary VIS/IR (25 km, 3-hourly)

“High resolution” precipitation products HRPP

CMORPH
TRMM 3B42

GPCP
CMAP
HOAPS etc

Raingauge analyses
(1-deg, daily)
(2.5-deg, monthly)
Over-land validation of 12 HRPPs and 4 NWP models

Daily, 25-km

_Ebert et. al, 2007_

Ongoing

HRPPs (colors) NWP Models (grays)

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)
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)
# Precipitation-Related Missions Between 2010-2020

## 2010
- FY-3B (CMA)
- Aquarius (US+CONAE)
- GCOM-W1 (JAXA)
- Megha-Tropiques (CNES+ISRO)
- NPP (US)
- DMSP F-19 (US)
- FY-3C (CMA)
- GPM core (US+JAXA)
- GPM constellation (US+partner)
- FY-3D (CMA)
- SMAP (US)
- DMSP F-20 (US)
- FY-3E (CMA)
- DWSS-MIS ? (US)
- FY-3F (CMA)

## 2011
- L-band scatterometer + 24/37 GHz radiometer
- AMSR-2
- MADRAS radiometer + MW sounder
- ATMS (no MW imager)
- SSMIS
- GMI+DPR
- GMI copy

## 2012
- SMAP (US)
- L-band radar/radiometer
- SSMIS

## 2013
- Not inclusive

## 2014
- Approximate launch dates
SSMIS Scan Geometry

- **Main Reflector**
- **Cold Calibration Reflector**
- **Warm Load**
- **Feedhorns**

**Ground Track**
- 1707 km Swath Width
- 144° Active Scan
- 3 x 3 Footprint Average
- 12.5 km 1.9 Sec
- Direction of Scan / Along Scan

**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

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

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

\(^1\) 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
## Main Characteristics of DPR

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

*Minimum detectable rainfall rate is defined by Ze=200 R^{1.6} (TRMM/PR: Ze=372.4 R^{1.54})
Concept of the DPR antenna scan

- **KuPR footprint**: $\Delta z = 250 \text{ m}$
- **KaPR footprint (Matched-beam with KuPR)**: $\Delta z = 250 \text{ m}$
- **KaPR footprint (High-sensitivity beam)**: $\Delta z = 500 \text{ m}$

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

Mean number of overpasses per day

Latitude

S Cloché et al, MT Overview, Helsinki, June 2010
CloudSat –vs- AMSRE (Passive) Precipitation Detection

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

Drop off in the low end of the passive precipitation distribution.
Microwave Sounder Observations Above 90 GHz

- Moderate to heavy rain
  - Deep cloud
  - High water path

- Drizzling or light snow/rain
  - Low-level cloud
  - Low water path

- More water vapor
- Less water vapor

- Radiometrically cold water
- Radiometrically variable land

Generally require different retrieval algorithms.
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

King City, Ontario (WKR) C-band dual-pol radar operated by Environment Canada

10-minute PPI volume scans

(not to scale)

CloudSat/Aqua track

NOAA-18 track

2200 km swath (AMSU/MHS, MODIS)
1400 km swath (AMSR-E)

T_{base} < -2°C
Case 5  2009/02/21
Ascending over Lake Ontario and Lake Huron

Case 6  2010/02/17
Ascending over Lake Ontario
Increasing gamma shape factor m

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 $D^6$

Observed WKR CCFADS

Near surface: 10% at -5 dBZ, 95% at 20 dBZ = 25 dB range
Weak sensitivity at coarse AMSU
Better for finer AMSR-E (?)
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)
  • CoReH₂O mission proposed to ESA
    • dual-band X/Ku band SAR
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