Lecture 1

Principle of Microwave Radiometry

Dr. Fuzhong Weng
Center for Satellite Applications and Research
National Environmental Satellites, Data and Information Service
National Oceanic and Atmospheric Administration

2012 Update
Outline

1. Solar Radiation Spectrum
2. Microwave Radiometry System
3. History of Microwave Instruments
4. Calibration and Validation
5. Microwave Data, Products and Applications
6. Future Challenges
7. Summary
Electromagnetic (EM) Spectrum

The Sun produces a continuous spectrum of energy from gamma rays to radio waves that continually bathe the Earth in energy.

The visible portion of the spectrum may be measured using wavelength in unit of \( \mu m \), nm, or eV (electron volts). All units are interchangeable.
Blackbody Radiation Curves

Relative Radiation Energy

Wavelength (µm)

6000 K Sun
3000 K Tungsten filament
800 K Red hot object
300 K Earth
150 K Dry ice
79 K Liquid air

Visible light

Visible light ———> Wavelength (µm)
Advantages of Microwave Remote Sensing from Space

1. Penetration through non-precipitating clouds

2. Highly stable instrument calibration

3. Radiance is linearly related to temperature (i.e. the retrieval is nearly linear)

4. $O_2$ concentration is uniformly distributed in the atmosphere

5. Major impacts on NWP and climate research
# Microwave Radiometers

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Center Frequencies (GHz)</th>
<th>Nadir 1FOV (km)¹</th>
<th>Primary Application²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmos-243 1969</td>
<td>-</td>
<td>3.5, 8.8, 22.2, 37</td>
<td>13 (nadir)</td>
<td>V, L, F, T, S</td>
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<tr>
<td>Cosmos-384 1970</td>
<td>-</td>
<td>3.5, 8.8, 22.2, 37</td>
<td>13 (nadir)</td>
<td>V, L, F, T, S</td>
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<tr>
<td>Nimbus-5 1972</td>
<td>NEMS</td>
<td>22.23, 31.40</td>
<td>200 (nadir)</td>
<td>t, V, L</td>
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<tr>
<td>Nimbus-6 1975</td>
<td>SCAMS</td>
<td>22.23, 31.65</td>
<td>53.65, 54.90, 58.80</td>
<td>t, V, L</td>
</tr>
<tr>
<td>Nimbus-6 1975</td>
<td>EMSR</td>
<td>37.0 (V+H)</td>
<td>52.85, 53.85, 55.45</td>
<td>V, L, F, W</td>
</tr>
<tr>
<td>Nimbus-7 1978</td>
<td>SMMR</td>
<td>6.6, 10.69, 18.0 (V+H)</td>
<td>25 (c-scan)</td>
<td>F, S, R, C</td>
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<tr>
<td>TIROS 1978-1995</td>
<td>MSU</td>
<td>21.0, 37.0 (V+H)</td>
<td>50, 30, 53.74, 54.96, 57.95</td>
<td>20-100 (c-scan) V, L, W, T</td>
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<tr>
<td>DMSP 1979-</td>
<td>SSM/T</td>
<td>50, 50, 53.20, 54.35, 54.90</td>
<td>110 (x-scan)</td>
<td>t, L</td>
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<tr>
<td>DMSP 1979-</td>
<td>SSM/I</td>
<td>58.40, 58.82, 59.40</td>
<td>175 (x-scan)</td>
<td>t, L</td>
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<tr>
<td>MOS-1 1987</td>
<td>MSR</td>
<td>23.80, 31.40</td>
<td>23-32 (x-scan)</td>
<td>V, L, F, W</td>
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<tr>
<td>DMSP 1987-</td>
<td>SSM/T2</td>
<td>19.35, 37.0, 85.5 (V+H)</td>
<td>15-60 (c-scan)</td>
<td>F, R, C, V</td>
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<tr>
<td>DMSP 1991-</td>
<td>SSM/T2</td>
<td>22.235 (V)</td>
<td>183±3, 183±1</td>
<td>L, W</td>
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<td>NOAA 1998-</td>
<td>AMSU/A</td>
<td>90.0, 150.0, 183±7</td>
<td>50 (x-scan)</td>
<td>v, V, R</td>
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<tr>
<td>NOAA 1998-</td>
<td>AMSU/B</td>
<td>23.8, 31.4, 89.0, 50.3</td>
<td>50 (x-scan)</td>
<td>t, v, F, R, C, V, L, I, R</td>
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<tr>
<td>NOAA 1998-</td>
<td>AMSU/B</td>
<td>52.8, 53.6, 54.4, 59.54</td>
<td>55.50, F = 57.29</td>
<td>t, v, F, R, C, V, L, I, R</td>
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<tr>
<td>NOAA 1998-</td>
<td>AMSU/B</td>
<td>F±0.217</td>
<td>v, V, I, R</td>
<td></td>
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<tr>
<td>NOAA 1998-</td>
<td>AMSU/B</td>
<td>F±0.322±0.048</td>
<td>15 (x-scan)</td>
<td>v, V, I, R</td>
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<tr>
<td>NOAA 1998-</td>
<td>AMSU/B</td>
<td>F±0.322±0.022</td>
<td>183±3, 183±1</td>
<td>v, V, I, R</td>
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<tr>
<td>TRMM 1998-</td>
<td>TMI</td>
<td>10.7, 19.35, 37.0, 85.5</td>
<td>5-30 (c-scan)</td>
<td>R, V, T, L</td>
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<tr>
<td>Navy 2002</td>
<td>WINDSAT</td>
<td>6.7, 10.6, 19.35, 37.0, 85.5 (V+H), 23.8 (V)</td>
<td>30-60 (c-scan)</td>
<td>T, S, L, V, R, W, D</td>
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<tr>
<td>DMSP 1987-</td>
<td>SSM/IS</td>
<td>6.9, 10.7 (V+H), 23.8 (V)</td>
<td>18.7, 37 (Stokes)</td>
<td>50 (x-scan) F, R, C, V</td>
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<tr>
<td>NPP 2009</td>
<td>ATMS</td>
<td>19.35, 37.0, 91.6 (V+H)</td>
<td>15-75 (c-scan)</td>
<td>L, W, t, v, t, F, R, L, V</td>
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<tr>
<td>NPP 2009</td>
<td>ATMS</td>
<td>22.23 (V) + SSM/T &amp; T2</td>
<td>t, F, R, L, V</td>
<td>15 (x-scan) v, R, C, I</td>
</tr>
</tbody>
</table>

¹ x-scan: cross-track scanner, c-scan: conical scanner
Microwave Radiometry System

- Emission from the reflector
- Contamination on calibration targets
- Non-linearity factor
- Spill-over effects (e.g. side lobe, cross-pol)
What are calibration and validation?

- **Calibration** is a process of quantitatively defining the system or instrument response to known, controlled signal inputs.

- **Validation** is a process of assessing the quality of the data products derived from the system outputs by independent means.
Calibration
Including Non-Linearity Effect

\[ V = a_1 I + a_2 I^2 + a_3 I^3 + a_4 I^4 \]

\[ I^2 = \text{KBG} \left[ R(T_A) + R(T) \right] \]

\[ V = b_0 + b_1 R(T_A) \left[ 1 + \mu R(T_A) \right] \]
Microwave Radiometry Calibration

\[ R_A = R_C + S(C_A - C_C) + \mu S^2 (C_A - C_C)(C_A - C_W) \]
Microwave Instrument Calibration Components

- Energy sources entering feed for a reflector configuration
- Earth scene component
- Reflector emission
- Sensor emission viewed through reflector
- Sensor reflection viewed through reflector
- Spacecraft emission viewed through reflector
- Spacecraft reflection viewed through reflector
- Spillover directly from space
- Spillover emission from sensor
- Spillover reflected off sensor from spacecraft
- Spillover reflected off sensor from space
- Spillover emission from spacecraft
Traits: Accuracy, Precision and Uncertainty
(After Stephens, 2003)

\[ u = \sqrt{a^2 + p^2} \]
Accuracy, Precision, Stability (after Stephens)

**Accuracy** = True y - mean y

**Precision** = standard deviation of y

**Stability** = change of accuracy with time
F13 provided a stable and longest time series for inter-sensor calibration!
Conical vs Cross Track Sounding

- Narrow scan swath with orbit gap
- FOV size is the same everywhere but varies with frequencies
- Same pol for all scan positions

- Large scan swath width (no orbit gap)
- Same resolution for all frequencies
- Mixing pol as scan from nadir to limb
- Res varies with scan angle
Microwave Temperature Sounding
Vertical Resolution

MSU+SSU (1978-2007)

AMSU-A
SSMIS
ATMS
• Requirements for current system (AMSU/MHS)
  – Accuracy: 1.0 K
  – Precision (NEDT): 0.25 – 1.2K
  – Stability: None
• Requirements for future system
  – Accuracy: 0.5 K
  – Precision (NEDT): <0.1K
  – Stability: 0.04K
Physical Basis:

Microwave Measurements

Scattering $T_B < \varepsilon_S T_S$

Emission $T_B > \varepsilon_S T_S$

\[ V \Rightarrow \varepsilon_V = \varepsilon_S + \Delta \varepsilon \]
Physical Basis and Phenomenology

• In microwave region, surface emissivity over oceans is typically low and therefore emits less thermal radiation

• Clouds and raindrops in atmosphere absorb the emitted radiation from surface and re-emit higher radiation

• A retrieval of a lower amount of cloud liquid water is significantly affected by sea surface conditions

• The absorption coefficient of cloud liquid water is dependent on cloud temperature

• Accuracy in remote sensing of cloud retrieval over land is poor due to large variability of emissivity
Microwave Sounding Principle Under All Weather Conditions

- Satellite microwave radiation at each sounding channel primarily arises from a particular altitude, indicated by its weighting function.

- The vertical resolution of sounding is dependent on the number of independent channel measurements.

- Lower tropospheric channels are also affected by the surface radiation which is quite variable over land.
Advanced Microwave Sounding Unit
Window Channels

23.8 GHz
AMSU-A Antenna Temperature at 23.8 GHz
2000-10-05

31.4 GHz
AMSU-A Antenna Temperature at 31.4 GHz
2000-10-05

89 GHz
AMSU-B Antenna Temperature at 89.0 GHz
2000-10-05

150 GHz
AMSU-B Antenna Temperature at 150 GHz
2000-10-05
Advanced Microwave Sounding Unit
Sounding Channels

52.8 GHz

53.7 GHz

183+/-1 GHz

183+/-3 GHz
Cloud Emission and Scattering (over Oceans)
US Polar Missions with MW Sensors for Operational Uses

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>DMSP 13</td>
</tr>
<tr>
<td>2005</td>
<td>DMSP 17</td>
</tr>
<tr>
<td>2006</td>
<td>DMSP SSMI/S</td>
</tr>
<tr>
<td>2007</td>
<td>DMSP 19</td>
</tr>
<tr>
<td>2008</td>
<td>DMSP 20</td>
</tr>
<tr>
<td>2009</td>
<td>NOAA 17</td>
</tr>
<tr>
<td>2010</td>
<td>NOAA 18</td>
</tr>
<tr>
<td>2011</td>
<td>NOAA: AMSU-A/MHS</td>
</tr>
<tr>
<td>2012</td>
<td>METOP-A</td>
</tr>
<tr>
<td>2013</td>
<td>METOP-B</td>
</tr>
<tr>
<td>2014</td>
<td>METOP: AMSU-A/MHS</td>
</tr>
<tr>
<td>2015</td>
<td>METOP-C</td>
</tr>
<tr>
<td>2016</td>
<td>NPP: ATMS</td>
</tr>
<tr>
<td>2017</td>
<td>JPSS: ATMS</td>
</tr>
</tbody>
</table>
From AMSU/MHS to ATMS

AMSU-A1
- 73x30x61 cm
  - 67 W
  - 54 kg
  - 3-yr life

AMSU-A2
- 75x70x64 cm
  - 24 W
  - 50 kg
  - 3-yr life

MHS
- 75x56x69 cm
  - 61 W
  - 50 kg
  - 4-yr life

Reduce the volume by 3x
- 70x40x60 cm
  - 110 W
  - 85 kg
  - 8 year life

From Bill Blackwell, MIT
Content

• Long-Term Monitoring System for Suomi NPP/JPSS Operational CalVal

• Suomi NPP SDR Product Maturity

• CalVal Results and New Sciences

• Summary and Conclusions

Vern Suomi

Suomi NPP satellite was successfully launched on October 28, 2011!!!
Suomi NPP Instruments  (the Same as JPSS-1)

<table>
<thead>
<tr>
<th>JPSS Instrument</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATMS</strong> - Advanced Technology Microwave Sounder</td>
<td>ATMS and CrIS together provide high vertical resolution <strong>temperature</strong> and <strong>water vapor information needed to maintain and improve forecast skill</strong> out to 5 to 7 days in advance for extreme weather events, including hurricanes and severe weather outbreaks</td>
</tr>
<tr>
<td><strong>CrIS</strong> - Cross-track Infrared Sounder</td>
<td></td>
</tr>
<tr>
<td><strong>VIIRS</strong> – Visible Infrared Imaging Radiometer Suite</td>
<td>VIIRS provides many <strong>critical imagery products</strong> including snow/ice cover, clouds, fog, aerosols, fire, smoke plumes, vegetation health, phytoplankton abundance/chlorophyll</td>
</tr>
<tr>
<td><strong>OMPS</strong> - Ozone Mapping and Profiler Suite</td>
<td>Ozone spectrometers for <strong>monitoring ozone</strong> hole and recovery of stratospheric ozone and for UV index forecasts</td>
</tr>
<tr>
<td><strong>CERES</strong> - Clouds and the Earth’s Radiant Energy System</td>
<td>Scanning radiometer which supports studies of Earth Radiation Budget</td>
</tr>
</tbody>
</table>
Summary of Suomi NPP TDR/SDR Algorithm Schedule

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Beta</th>
<th>Provisional (planned)</th>
<th>Validated (planned)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CrIS</td>
<td>May 7, 2012</td>
<td>October, 2012</td>
<td>2013</td>
</tr>
<tr>
<td>OMPS</td>
<td>March 12, 2012</td>
<td>March, 2013</td>
<td>2013</td>
</tr>
<tr>
<td>VIIRS</td>
<td>May 2, 2012</td>
<td>October, 2012</td>
<td>2013</td>
</tr>
</tbody>
</table>

NPP SDR Product Maturity Levels

1. **Beta**
   - Early release product.
   - Initial calibration applied.
   - Minimally validated and may still contain significant errors (rapid changes can be expected. Version changes will not be identified as errors are corrected as on-orbit baseline is not established)
   - Available to allow users to gain familiarity with data formats and parameters
   - Product is not appropriate as the basis for quantitative scientific publications studies and applications

2. **Provisional**
   - Product quality may not be optimal
   - Incremental product improvements are still occurring as calibration parameters are adjusted with sensor on-orbit characterization (versions will be tracked)
   - General research community is encouraged to participate in the QA and validation of the product, but need to be aware that product validation and QA are ongoing
   - Users are urged to contact NPOESS NPP Cal/Val Team representatives prior to use of the data in publications

3. **Validated/Calibrated**
   - On-orbit sensor performance characterized and calibration parameters adjusted accordingly
   - Ready for use by the Centrals and in scientific publications
   - There may be later improved versions
   - There will be strong versioning with documentation
Satellite Integrated Calibration / Validation System (ICVS)

ATMS Channel NEdT
- All Channel Snapshot ▶ Display

ATMS Channel Gain
- All Channel Snapshot ▶ Display

ATMS Cold Calibration Count
- All Channel Snapshot ▶ Display

ATMS Warm Calibration Count
- All Channel Snapshot ▶ Display

ATMS 2-Wire PRT (27 PRTs)
- K-Band Receiver Front End Temperature ▶ Display

ATMS 4-Wire PRTs
- K/Ka/V-Band Sensor ▶ Display

ATMS Receiver Shelf 2-Wire PRTs
- K-Band ▶ Display

ATMS Health/Status Analog Parameters (35 Index)
- Signal Processing Assembly +5V Secondary Voltage ▶ Display

NPP ATMS K, Ka, V-Band 4-Wire PRTs
Science RDR

(Updated at Thu Mar 15 18:30:56 2012 UTC)
NPP Spacecraft Monitoring Example

- Instrument temperatures obtained from S/C telemetry (right)

- S/C PUMA Battery 1 Voltage real time variation during the last 24 hours and LTM trending since launch (below)
NPP ATMS Channel Space View Count (10 Days)

- NPP ATMS space view calibration counts are stable
- NPP ATMS warm load calibration counts and gain are also stable (not shown)
ATMS Calibration Target Monitoring

- Lunar intrusion effects on ATMS space view readings and channels are different (right)
- ATMS 4-Wire PRTs anomalies are observed in individual readings of all bands (below)
ATMS Bias Monitoring

- ATMS angular dependent bias character obtained from RTM (right)
- ATMS daily global images (below) and data quality distribution
ATMS Data Types

Raw Data Record (RDR): digital counts with full calibration and geo-location information for all 22 channels at the original field of view (FOV)

Antenna Data Record (TDR): brightness temperatures at all 22 channels at the original field of view (FOV) derived from two-point calibration with non-linearity correction and geolocation

Sensor Data Record (SDR): brightness temperatures with all 22 channels at their original field of view resolution with corrections of antenna gain and side-slope effects to TDR data

Remap Sensor Data Record (RSDR): SDR data at each channel other than ch 1 and 2 are resampled to the CrIS field of regard (3x3 field of views) which is equivalent to about AMSU-A antenna beam width (3.3 degree)
ATMS Scanning Characteristics

Nadir

Start of Earth Scan

End of Earth Scan

Cold

4 beams @ 1.11°

Hot

4 beams @ 1.11°

+Z

Nadir

-+Y

+Z

Scan Direction

96 beams @ 1.11°

-+Y

Start of Earth Scan

-+Z
Spectral Differences

ATMS has 22 channels and AMSU/MHS have 20, with polarization differences between some channels

- QV = Quasi-vertical polarization vector is parallel to the scan plane at nadir
- QH = Quasi-horizontal polarization vector is perpendicular to the scan plane at nadir
On-orbit ATMS noise magnitudes are about twice as large as those AMSU-MHS but much lower than specification. The re-sampled ATMS data within CrIS FOR or equivalent AMSU-A FOV would result in noise much lower than that of AMSU-A/MHS.
Building High Quality NPP SDR Products for Science Community: Or-Orbit ATMS Absolute Calibration Using COSMIC and LBL RT Model

1. High vertical resolution
2. No contamination from clouds
3. No system calibration required
4. High accuracy and precision:

The global mean differences between COSMIC and high-quality reanalyses is ~0.65K between 8 and 30km (Kishore et al. 2008)
The precision of COSMIC GPS RO soundings is ~0.05K in the upper troposphere and lower stratosphere (Anthes et al. 2008)
NPP Data Collocation with COSMIC

• **Time period of data search:**
  
  January, 2012

• **Collocation of CloudSat and COSMIC data:**
  
  Time difference < 0.5 hour
  
  Spatial distance < 30 km
  
  (GPS geolocation at 10km altitude is used for spatial collocation)

3056 collocated measurements

*Courtesy of Lin Lin, STAR*
MonorTM

- Perform a line by line radiative transfer calculation
- Accurate atmospheric spectroscopy data base
- Only gaseous absorption
- Vertical stratification

Microwave sounding channels at 50-60 GHz O₂ absorption band can be best simulated under a cloud-free atmosphere using line by line calculation
Effects of ATMS Spectral Response Function

- Ch01
- Ch02
- Ch03
- Ch04
ATMS Bias Obs (TDR) - GPS Simulated

Ch 6

Ch 7

Ch 10

Ch 11
ATMS Bias Obs (TDR) - GPS Simulated
Shown is the means bias of ATMS simulations using boxcar to the measured SRF and the standard deviation of the bias. The simulations are computed from GPSRO profiles and LBLRTM.
On-orbit ATMS calibration accuracy is quantified using GPSRO data as input to RT model and is better than specification for most of sounding channels.

Courtesy of Xiaolei Zou, FSU/STAR
Impacts of ATMS Spatial Re-sampling on NWP O-B

ATMS Field of View Size for the beam width of 2.2° – black line

ATMS Resample to the Field of View Size for the beam width of 3.3°- blue line
Scene-Temperature Dependence of Biases

Notice the differences between ATMS raw and remap data:

- Dynamics range
- Biases
- Noises
ATMS SDR Global Biases and Standard Deviations

Within 60S-60N, clear-sky, ocean only, 20-27 December 2011
ATMS Pitch Maneuver February 20, 2012

ATMS Cross Track Spot

ATMS Down Track Scan
ATMS Pitch Maneuver Antenna
Temperature Model

A smile pattern QV- antenna temperature:

\[ T_a^{vq} = (\eta_m^{vv} + \eta_m^{hv})T_b^c + \beta_0^v + \beta_1^v \sin^2 \theta \]

A frown pattern QH- antenna temperature:

\[ T_a^{hq} = (\eta_m^{hh} + \eta_m^{vh})T_b^c + \beta_0^h + \beta_1^h \cos^2 \theta \]

\( \beta \): the slope and scale parameters related to spacecraft emission and reflection. It is not well understood in the past. NPP pitch maneuver offers a unique opportunity for us to characterize the term for better characterizations of the earth view bias along the scanline.
ECMWF and UK Met Office provided clear evidence of increased NWP benefit of microwave measurements from two versus only one polar orbiting AMSU. 500 hPa geopotential showing one day increase in forecast skill over Europe at 5 days with two AMSU over none in 50 cases.
## Microwave Environmental Data Records

<table>
<thead>
<tr>
<th>SDR/EDR</th>
<th>POES/METOP AMSU-A/B; MHS</th>
<th>DMSP SSMIS</th>
<th>NPOESS ATMS/MIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiances</td>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temp. profile</td>
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<tr>
<td>Moist. profile</td>
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<tr>
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<td>Snow water equivalent*</td>
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<td>Ice water*</td>
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<td>Land emis*</td>
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<td>Soil moisture/Wetness Index</td>
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</table>
NESDIS SSM/I Climate Data Records
Since 1987

SSM/I Monthly Composite Products

Cloud Liquid Water  Rain Rate  Snow Cover  Sea Ice  Vegetation/Moisture

November 1987

Satellite Research Laboratory
Microwave Products from NOAA Operational Sensor: AMSU

Monthly Hydrological Product Composite Derived from N-15 AMSU 2001-01
Comparison of SSM/I Monthly Oceanic Rain-free TDR Trend

Before Calibration

After Calibration
Large TPW biases between F10-F11 and F10-F13 are obvious. Since TPW = 232.89 - 1.486*TV19 - 0.3695*TV37 - (1.8291 - 0.006193*TV22)*TV22, (Alishouse et al., 1991), any radiance biases in lower SSM/I frequencies will be directly translated into TPW biases.
The inter-sensor TPW biases become much smaller and consistent between different sensors. The averaged absolute bias after calibration is reduced by 75% and 21% over global ocean and over tropical ocean, respectively.
Future Advances in Microwave Technology in Space

1. Probe higher atmosphere by adding more sounding channels

2. Polarization or polarimetry for microwave imager

3. Combination of sounder and imager in a single scanning mode

4. Low instrument noise and high instrument stability

5. Longevity (5-10 years) beyond the mission life span
Technology Barriers in Microwave Instrument Developments

1. Course spatial resolutions from uses of solid aperture antenna

2. Slow progress in using low noise amplifier for lower frequencies

3. Difficult uses of microwave imager data in NWP systems through direct radiance assimilation
Summary

1. **Microwave thermal radiation** from the Earth is of much smaller magnitude, compared to VIS/IR
2. **Satellite Microwave Observations** are critical for atmospheric sounding and imaging under all weather conditions
3. **Microwave Sensor Calibration** converts analog signal to physical quantity using both linear and nonlinear systems
4. **Climate Data Record** can be obtained from satellites through cross sensor calibrations that remove inter-sensor biases
5. **Microwave Sensing Principle** is based on imaging clouds over ocean with lower emissivity, and sounding atmosphere from $O_2$ and $H_2O$ absorption lines