Satellite Microwave Sounding System: Past, Present and Future

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Outline

• Evolution of Microwave Sounding System
• Microwave Instrument Calibration
• Applications of Microwave Sounding Products
• Calibration Requirements for Future Systems
• Summary
Evolution of Passive Microwave Sensors

The instruments with a bold font contain temperature sounding channels

* GPM also contains water vapor sounding channels
US Polar Missions with MW Sensors for Operational Uses

- **Early-AM Orbit**
  - DMSP 13
  - DMSP 17
  - DMSP SSMI/S
  - DMSP 19
  - DMSP 20

- **Mid-AM Orbit**
  - DMSP 16
  - NOAA 17
  - DMSP 18
  - METOP-A
  - METOP-B
  - METOP: AMSU-A/MHS
  - METOP-C

- **PM Orbit**
  - NOAA 16
  - NOAA: AMSU-A/MHS
  - NOAA 18
  - NOAA 19
  - EOS AQUA AMSR-E
  - JPSS: ATMS
  - NPP: ATMS
  - DoD MIS?
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
Conical vs Cross Track Sounding

- Narrow scan swath width with orbit gap
- FOV size is the same for all positions 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

Pressure (hPa)

Weighting function

Altitude [km]

[km^2]
MSU/AMSU/MHS Calibration Precision & Accuracy & Stability

• 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
A Schematic Microwave Radiometry System

Major Error Sources Affecting MW Calibration Accuracy

- Emission from the reflector
- Contamination on calibration targets
- Non-Linearity factor
- Spill-over effects (e.g. side lobe, cross-pol)
A Typical Microwave Antenna Subsystem

1. **Earth Scene Radiation**
2. Reflector emission
3. Sensor emission viewed through reflector,
4. Sensor reflection viewed through reflector,
5. Spacecraft emission viewed through reflector,
6. Spacecraft reflection viewed through reflector,
7. Spillover directly from space,
8. Spillover emission from sensor,
9. Spillover reflected off sensor from spacecraft,
10. Spillover reflected off sensor from space,
11. Spillover emission from spacecraft
SSMIS Anomalies at LAS Channels
( Observation – Simulation )

54.4 GHz V

55.5 GHz V
A Two-Point Calibration System

Two Point Radiometer
Linear Calibration:

\[ R_{e,L} = R_c + S(C_e - C_c) \]

\[ S = \frac{R_w - R_c}{C_w - C_c} \]

Two Point Radiometer with
Nonlinear Calibration Correction:

\[ R_e = R_{e,L} + \mu Z - \delta R \]

where \( \delta R \) is the post-launch bias caused by factors other than non-linearity

\[ Z = S^2 (C_e - C_c)(C_e - C_w) \]
Nonlinearity
Spec:
Ch.1, 2, 15: 0.5 K
Ch.3-14: 0.375 K
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.
SSMIS Impacts on Weather Forecasts

- The Defense Meteorological Satellite Program (DMSP) successfully launched the first of five Special Sensor Microwave Imager/Sounder (SSMIS) on 18 October 2003.

- The SSMIS measures partially polarized radiances in 24 channels covering a wide range of frequencies (19 – 183 GHz)

- Shown are the impacts from assimilating SSMIS 50-60 GHz temperature sounding channels compared with the impacts from cross-track scanning system (AMSU-A)
NOAA Microwave Products from AMSU/MHS

Monthly Hydrological Product Composite Derived from N-15 AMSU
2001-01
CDRs Constructed from Series of Overlapping Satellites
Consistent Mid-Tropospheric Trend by Combining MSU and AMSU-A

MSU2/AMSU5—mid-tropospheric temperature

Multiple MSUs and AMSUs are cross-calibrated using Simultaneous Overpassing

From Cheng-Zhi Zou, 2010 NOAA CDR Workshop
Trends in T trends

- UAH 2009 shows increasing warming with time
- Compare UAH 2009 with earlier versions
- Compare UAH and other MSU
- More warming in recent (adjusted) radiosonde datasets
- Consistency of surface datasets
- Overall convergence

From Climate Signal to Satellite Instrument Requirements (ASIC3, Ohring 2008)

Decadal Climate Signal

Data Set Requirements for Accuracy and Stability (1/5 of Signal)

Satellite Instrument Requirements
Modelled trends in the mid-troposphere are 0.2 - 0.4 K/decade.

The IPCC Fourth Assessment report (2007) drew upon two types of measurement of atmospheric temperature: Radiosondes and microwave radiances from satellite sounding instruments. Microwave Sounding Unit (1979-2006) and Advanced Microwave Sounding Unit (1998 -today) cover more than 30 years of period.

For understanding climate: accuracy critical, stability appears to be less difficult to achieve in satellite instruments. 1/5 of decadal climate signal (somewhat arbitrary) is typically required.
## Instrument Requirements: MW Sounder & Imager

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
<th>Accuracy</th>
<th>Stability (decadal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Troposphere</td>
<td>MW or IR radiometer</td>
<td>0.5 K</td>
<td>0.04 K</td>
</tr>
<tr>
<td>Stratosphere</td>
<td>MW or IR radiometer</td>
<td>1 K</td>
<td>0.08 K</td>
</tr>
<tr>
<td>Water vapor</td>
<td>MW radiometer</td>
<td>1.0 K</td>
<td>0.08 K</td>
</tr>
<tr>
<td></td>
<td>IR radiometer</td>
<td>1.0 K</td>
<td>0.03 K</td>
</tr>
<tr>
<td>Precipitation</td>
<td>MW radiometer</td>
<td>1.25 K</td>
<td>0.03 K</td>
</tr>
</tbody>
</table>
“In order to build confidence in the detection of a trend, one wishes to acquire an estimate of a slope \( m \) greater than the uncertainty of its estimate by a factor of \( S \), the signal-to-noise ratio”

(Williams, 1959; von Storch and Zwiers, 2001)

\[
m = \left( \sum_{i=1}^{N} (t_i - \bar{t})^2 \right)^{-1} \sum_{i=1}^{N} T_i (t_i - \bar{t})
\]

\[
\langle (\delta m)^2 \rangle = \frac{12(\sigma_v^2 + \sigma_m^2)}{(1\text{yr})^2 (N^3 - N)}
\]

The standard deviation of the natural variability is \( \sigma_v \), the measurement uncertainty is \( \sigma_m \), and both are uncorrelated from year to year, then the squared uncertainty in the determination of the slope.
“Hyperspectral” measurements allow the determination of the Earth’s tropospheric temperature with vertical resolution exceeding 1km
  – ~100 channels in the microwave

Hyperspectral infrared sensors available since the 90’s
  – Clouds substantially degrade the information content
  – A hyperspectral microwave sensor is therefore highly desirable

Several recent enabling technologies make HyMW feasible:
  – Detailed physical/microphysical atmospheric and sensor models
  – Advanced, signal-processing based retrieval algorithms
  – RF receivers are more sensitive and more compact/integrated

The key idea: Use RF receiver arrays to build up information in the spectral domain (versus spatial domain for STAR systems)
Temperature profiles from microwave sounding meets the requirements while water vapor profile is out of spec due to limited channels. Hyperspectral microwave sounding system may be required.
Geostationary Synthetic Thin Array Radiometeor (GeoSTAR) - JPL

- **All-weather soundings @ 2-4 km vertical resolution**
  - Full hemisphere @ ≤ 50/30 km every 30-60 min (continuous) - easily improved
  - Standalone soundings; Also complements any GEO IR sounder
- **Rain**
  - Full hemisphere @ ≤ 30 km every 30 min (continuous) - easily improved
  - Measurements: scattering from ice associated with precipitating cells
  - Real time: full hemispheric snapshot every 30 minutes or less
- **Tropospheric wind profiling**
  - Surface to 300 mb; adjustable pressure levels
  - Primarily horizontal wind vectors (at pressure levels)
  - Very high temporal resolution possible
  - Vertical winds may also be feasible (requires some research)
- **Rapid-cycle NRT storm tracking**
  - Scattering signal from hurricanes/convection detectable in < 5 minutes
  - Switch to detect/track mode -> Update every 5 minutes (continuous)
Development of New MW Sounding Technology is Very Slow, Comparing to IR Sounders

- NOAA HIRS with 20 channels from 1978 to today
- 3 IR hyperspectral sounding systems
  - EOS Aqua/AIRS in 1:30 pm orbit
  - METOP-A/IASI in 9:30 am orbit (July 2006)
  - 4 times/day
  - JPSS/CrIS in 1:30 pm orbit (2011)
AIRS, IASI and CrIS System:
Hyperspectral Sounding in Operations

AIRS 15 µm (650-800 cm\(^{-1}\)) band

\[ K = \frac{dR}{dT} \]

AIRS 6.7 µm (1200-1600 cm\(^{-1}\)) band

\[ K = \frac{dR}{dq} \]
WMO GSICS Uses AIRS/IASI as a reference satellite to cross calibrate geostationary infrared channels (Mitch Goldberg, GSICS Executive Chair)
Summary

- MSU/AMSU-A is recommended by IPCC as one of the best observing systems for monitoring the tropospheric temperature trend primarily due to its stable performance.
- In general, the cross-track scanning sounding system is better calibrated than the conical one through its end-end capability.
- Satellite observations from cross-track and conical microwave sounding systems are vital for improving weather forecasts and climate monitoring.
- 70-80% of measurements from satellite microwave sounding data can be directly assimilated into NWP systems.
- Today, NWP forecast temperature in troposphere is close or better than one obtained by any single observing system. New microwave sounding technology needs to focus on better instrumentation and to achieve NEDT better than 0.2K.
- The retrieval accuracy of water vapor profiles in mid-troposphere from is in general out of specifications due to limited channels in the current sounding system.
- Developments of new microwave sounding system are significantly falling behind, comparing to satellite infrared sounding technology.