ATMOSPHERIC SOUNDING – MOTIVATION AND APPROACH

Think – Pair – Share

- Design your own passive atmospheric sensing system that is measuring water vapor distribution using microwave signals:
  - Measurement principle: Passive systems measure emissions at specific frequencies. How would you design your system to be able to measure water vapor concentrations across the atmospheric column?
  - Observation geometry: We will talk about both nadir-looking and limb-sounding geometries. Which one would you choose to map atmospheric water vapor and why?
About Microwave Sounding Instruments

- Microwave Sounders are measuring emissions of the earth's atmosphere to develop understanding of global atmospheric processes.

- Typically monitored parameters:
  - Temperature, pressure, and wind
  - Distribution of atmospheric gases (water vapor, ozone, chlorine monoxide, ...)

- Atmospheric gases have specific absorption/emission lines at very specific frequencies (see figure on right).

- General principle: Measure atmospheric emissions at molecule-specific absorption lines.

Microwave Sounders Of Most Value for Middle Atmosphere

- Microwave sounders of most value for measuring middle atmosphere (e.g., ozone concentration).

- Middle atmosphere marked in red in figure.

Measurement Principle of Microwave Sounders

- Many atmospheric constituents have rotational and vibrational spectral absorption lines between 10GHz and 300GHz (e.g., $\text{H}_2\text{O}$, $\text{O}_3$, $\text{ClO}$, $\text{SO}_2$, ...).

- We also know from Kirchoff's law that good absorbers are also good emitters, corresponding to $\varepsilon = \sigma$.

- Principle: measure emissivity $\varepsilon$ at absorption line of specific molecule $\leftrightarrow$ convert to absorptance $\sigma$ $\leftrightarrow$ quantify molecule abundance.

- Advantages of Microwave sounders over optical systems:
  - High penetration into the atmosphere $\rightarrow$ middle to lower troposphere can be analyzed
  - Passive sensor $\rightarrow$ no external illuminator required $\rightarrow$ 24/7 operation possible
  - Besides gas concentrations, microwave sounders also simultaneously measure atmospheric temperature and pressure (we will see why on slide 8).
More Details on Measurement Principle

- **Original measurement:** Brightness temperature at emission lines corresponding to key constituents.
- **Problem:** Emissivity is a function of two things: (1) concentration of constituent AND (2) atmospheric temperature.
- **Solution Two-Step Approach to Measuring Gas Concentrations:**
  1. Measure emissivity at uniformly mixed gases such as O or CO₂, which hardly vary in time and space → abundance constant → derive temperature
  2. Measure emissivity at constituent of interest (e.g., H₂O) ideally at several emission lines → derive constituent abundance
- **Additionally, we can measure atmospheric pressure:**
  - Sample a few bands around emission line → derive shape of emission peak → derive atmospheric pressure (next slide shows the connection between pressure and shape of line)

Pressure Broadening of Spectral Absorption Lines

- Shape of Absorption Line at 50km / 0.5 hPa
- Shape of Absorption Line at 20km / 50 hPa
- Shape of Absorption Line at 10km / 200 hPa

Increased pressure leads to line broadening → atmospheric pressure from line shape

Spatial Resolution of Microwave Sounders is Generally Poor

- **Problem:** Sufficient amount of radiation is required for successful operation of radiometers and sounders, yet, emission energy is low
- **Solution 1:** Long integration time (maximize dwell time) → often not a good approach for instruments on aircraft or spacecraft
- **Solution 2:** Integrate over large area to lift signal over noise level → radiometers tend to have low angular (spatial) resolution
- **Low resolution usually not a big problem for atmospheric remote sensing but significant limitation for other applications of radiometers**
What is a Forward Model?

• Forward model $F$ is a mathematical expression describing the relationship between a physical attribute of an observed object and measured signal.

• The forward model can also be seen as a simulation of the measurements given the physical attributes of, e.g., the atmosphere.

• Here we will express the forward model in terms of measured $T_2$ values.

• Forward model allows us to derive physical meaning of observations.

In atmospheric sounding, the forward model has to include:

- Knowledge of EM radiation being measured (discussed in Lecture 3).
- Understanding of how EM waves interact with natural objects (see Lecture 4).
- Behavior of the instrument (see Lecture 5).

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- Understanding of how EM waves interact with natural objects (see Lecture 4).
- Behavior of the instrument (see Lecture 5).

Formal Representation of a Forward Model

• Vector $y$ represents measured values and vector $x$ physical attributes:

$$y = F(x, b_e, b_o) + \epsilon_y$$

where vector $b_e$ describes how $x$ maps into $y$, $b_o$ represents instrument influence, and $\epsilon_y$ represents noise or random error.

Due to a large number of physical parameters, $F(\ldots)$ often is an integral in remote sensing:

$$y_j = \int_{a_j}^{b_j} K(y_j, x, d) \, dx + \epsilon_j$$

where $f(x)$ is function describing physical properties and $K(y_j, x)$ is generally known as kernel function that is determined by the observation setup being modeled.

Kernel $K(y_j, x)$ transforms input variables into a set of output variables.
Further Notes on the Forward Model

- The forward model is often nonlinear, meaning that the equation on the bottom of previous page is only a linearized approximation of reality.
- Also, we usually don’t know \(K, b_0,\) and \(b_1\) precisely, resulting in model errors.

The Forward Model of Atmospheric Sounding

- Measurement by radiometer is top of atmosphere (TOA) brightness including contributions from atmospheric layers and surface.
- Hence, ideal conditions for measuring atmosphere are where transmissivity is low so that \(T_{TOA} \approx T_{up}\) (yet, then signal mostly comes from upper atmosphere).
- To include observation geometry (off-nadir angle \(\theta\)), we rephrase \(\Upsilon\) using opacity \(\tau\) to:
  \[
  \Upsilon = \exp\left(-\tau \cos \theta \right)
  \]
- We can also write \(T_{up}\) according to previous radiative transfer model:
  \[
  T_{up} = \frac{1}{\cos \theta} \int_{\text{TOA}}^{\text{Top}} \sigma(T) \cdot T dz \cdot \exp\left(-\Upsilon \cos \theta \right) dz
  \]

Solving the Inverse Problem

- Model inversion (or retrieval) is process of trying to figure out the atmosphere from a set of satellite measurements.
- To simplify model on previous page use a matrix equivalent of the integral (approximating integration with a summation).
- We use kernel matrix \(K\) a discrete matrix version of the forward model:
  \[
  y = Kx + e
  \]
- Such inverse problems are usually ill-posed, meaning that there are an infinite number of possible solutions that fulfill the data.

Goal of inverse modeling: Find the most appropriate solution out of all possible solutions (GEOS 627 “Inverse Problems”).
Measuring Vertical Distribution of Atmospheric Gases

- Multi-frequency radiometers can map vertical profile of atmospheric gases
- How? Signal at different frequency lines is dominated by particular layers of atmosphere
- Sensitivity range of a specific frequency is described by weighting function (see figure)
- E.g., channel 9 has peak sensitivity around 90mb
- Weighting functions are expressed through kernel $K$

We Distinguish Two Generic Viewing Geometries in Atmospheric Sounding

- Nadir Sounding
  - Effective for regular measurements of atmosphere
  - Provides good horizontal resolution
  - Vertical resolution defined by width of weighting functions and generally poor
  - Good for observing upper atmosphere

- Limb Sounding
  - Poorer horizontal resolution
  - Good vertical resolution
  - Not affected by surface emissions
  - Better for observing middle atmosphere

Observation Geometries
Observation Equation of Nadir Sounding

- Top of Atmosphere brightness temperature equation:
  
  \[ T_{\text{TOA}} = T(\gamma_{\text{SURF}} + \gamma_{\text{SC}}) + T_{\text{SP}} \]

  - Background term from Slide 14 now contains radiation from surface \( T_{\text{SURF}} \) plus downwelling radiation from atmosphere that is scattered by the surface \( T_{\text{SC}} \).

- If we know the Emissivity \( \varepsilon \) of the surface we can rewrite \( T_{\text{SURF}} \) and \( T_{\text{SC}} \) to:

  \[ T_{\text{SURF}} = \varepsilon T_{\text{SP}} \]

  \[ T_{\text{SC}} = (1 - \varepsilon) T_{\text{SP}} \]

  where \( T_{\text{SP}} \) is physical temperature of surface and \( T_{\text{SP}} \) is downwelling radiation.

- Allowing for small off-nadir angles if the final observation equation is:

  \[ T_{\text{TRO}} = \varepsilon T_{\text{SP}} + (1 - \varepsilon) T_{\text{SP}} + (1 - \varepsilon) T_{\text{SP}} \cos^2 \theta \]

  \[ + \frac{1}{c_{\text{g}}} \int_{z_{\text{top}}}^{z} T_{\text{SP}}(z) - T_{\text{SP}} \exp \left( -\frac{T_{\text{SP}}}{c_{\text{g}}} \right) \frac{dz}{c_{\text{g}}} \]

Observation Equation of Limb Sounding

- Background term in limb sounding is cold space (3K temperature) rather than earth surface:

  \[ T_{\text{TRO}} = T_{\text{SP}} + T_{\text{SP}} \]

  Compact Version of observation equation

- Advantage:
  - Background term \( T_{\text{TOP}} \) is small, very homogeneous, and easy to characterize.
  - Vertical resolution of around 1.5km is achievable.

PASSIVE MICROWAVE SYSTEMS FOR SOIL MOISTURE APPLICATIONS
Microwave Systems for Soil Moisture Mapping

- **SMAP (NASA)**
  - L-band
  - 40 km
  - Observations every 3 days
  - [https://nsidc.org/data/smap/smapdata.html](https://nsidc.org/data/smap/smapdata.html)

- **SMOS (European Space Agency)**
  - L-band
  - 40 km
  - Observations every 3 days

- **ASCAT (EUMETSAT)**
  - C-band
  - 50 km
  - Observations every 2 days
  - [https://www.ospo.noaa.gov/Products/atmosphere/ascat/](https://www.ospo.noaa.gov/Products/atmosphere/ascat/)

Operational L-band Radiometers For Soil Moisture

- **SMOS-ESA Satellite**
  - Launched: Nov 2009
  - L-band radiometer
  - Spatial resolution: 40 km
  - Temporal resolution: 3 days
  - Sensing depth: ~5 cm

- **SMAP Satellite**
  - Launched: Jan 2015
  - L-band radiometer
  - Spatial resolution: 40 km
  - Temporal resolution: 3 days
  - Sensing depth: ~5 cm

Uniqueness of SMAP
- Aggressive approach to radio-frequency interference (RFI) Detection and Mitigation
- Constant incidence angle

Relationship between L-band Brightness Temperature and Surface Soil Moisture

- We know that:
  - Increasing soil moisture increases radar cross section \( \sigma \)
  - Due to Kirchhoff's Law, this means that increasing moisture reduces \( T_b \)

- See plot of \( T_b \) vs. soil moisture from Jackson & O'Neill (1987)
Measurement Approach (Passive vs Active)

- What do Active and Passive Microwave Sensors see:
  - Contributions from (1) soil (roughness and moisture), vegetation, and soil/vegetation interaction
  - To measure soil moisture, original measurements are corrected for impacts of vegetation, surface roughness, and temperature.

Ancillary Data needed for Soil Moisture Retrieval

- Ancillary data are used to estimate the key unknown parameters:
  - surface temperature (= surface air temp. at 6 a.m.),
  - vegetation opacity,
  - surface roughness, and
  - soil texture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description/Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Air Meteorology</td>
<td>Data assimilation (GEOS/DAO), Forecast models (NCEP and ECMWF)</td>
</tr>
<tr>
<td>Vegetation Opacity</td>
<td>VIS/IR satellite-derived NDVI, LAI, Landcover (MODIS, IGBP-DIS), Historical phenology (AVHRR)</td>
</tr>
<tr>
<td>Surface Topography</td>
<td>Digital elevation models (SRTM, SGM)</td>
</tr>
<tr>
<td>Soil Texture</td>
<td>Soil databases (Dakota, NSIDC, US, STS/GSD)</td>
</tr>
<tr>
<td>Land/Water Boundaries</td>
<td>Coastal boundaries and inland water bodies (NSIDC)</td>
</tr>
</tbody>
</table>

3-Day SMAP Soil Moisture Composite
**Back to the Atmosphere: Sensor and Sensor Parameters**

- **SMMR** (on Nimbus-7) – Scanning Multichannel Microwave Radiometer
- **AMSR-E** (on AQUA) – Advanced Microwave Scanning Radiometer-EOS
- **TRMM** – Tropical Rainfall Measuring Mission
- **AMSU** – Atmospheric Sounding Instrument (on many weather satellites)
- **SMOS** – Soil Moisture and Ocean Salinity
- **SSM/I** – Special Sensor Microwave Imager
- **SMAP** – Soil Moisture Active Passive

**Nimbus-7: Spacecraft Overview**

- Launched 1978 and operated by NOAA and NASA
- Seven instruments for atmospheric monitoring including Scanning Multichannel Microwave Radiometer (SMMR)
- **SMMR goals:**
  - low altitude winds, water vapor, cloud liquid water, rainfall rates, sea surface temperature, sea ice concentration
- **SMMR design:**
  - 10 channels with two orthogonal polarizations @ f = 37.03, 22.06, 18.07, 10.71 and 6.61 GHz

[http://nsidc.org/data/docs/daac/nimbus-7_platform.gd.html](http://nsidc.org/data/docs/daac/nimbus-7_platform.gd.html) Nimbus-7 Observatory
Nimbus-7: The SMMR Sensor

- Sensor design and operation:
  - Parabolic antenna 79 cm in diameter reflected microwave emissions into five-frequency feed horn
  - Antenna was forward-viewing and rotated equally (±25°) about satellite subtrack
  - The 50° scan provided a 780 km swath of the Earth’s surface.

AMSR-E: Sensor Description

- Advanced Microwave Scanning Radiometer-EOS (AMSR-E)
- One of several instruments on NASA AQUA satellite
- Launched in 2002

- Sensor characteristics:
  - 6 frequencies with two orthogonal polarizations @ f = 89.0, 36.5, 23.8, 18.7, 10.7 and 6.9 GHz
  - Conical scan of 55° creates elliptical footprint
  - Swath width of 1445 km
  - 10 km resolution at nadir

- Products:
  - Brightness temperatures; rain rate; rain type; sea surface temperature; near-surface wind speed; water vapor; liquid water; soil moisture …

AMSR-E Multi-Frequency Data Example

- Examples of all 12 channels are shown. Blue is low brightness temperature; red is high brightness temperature
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**About the AMSR-E Data on Previous Slide**

- The higher the frequency, the higher the sensitivity to water vapor and ice crystals.
- The images are blurrier at the lower channels due to decreased resolution.
- The microwave radiation from any given footprint reaching the AMSR-E is influenced by complex combinations of emission and scattering from all objects in the FOV.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Footprint Size</th>
<th>Mean Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.9</td>
<td>73 x 43 km</td>
<td>66 km</td>
</tr>
<tr>
<td>10.7</td>
<td>51 x 29 km</td>
<td>58 km</td>
</tr>
<tr>
<td>18.7</td>
<td>51 x 29 km</td>
<td>21 km</td>
</tr>
<tr>
<td>23.8</td>
<td>27 x 16 km</td>
<td>11 km</td>
</tr>
<tr>
<td>36.5</td>
<td>14 x 8 km</td>
<td>12 km</td>
</tr>
<tr>
<td>39.2</td>
<td>5 x 2 km</td>
<td>6.4 km</td>
</tr>
</tbody>
</table>

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**AMSR-E Product Specifications**

<table>
<thead>
<tr>
<th>Product</th>
<th>Base Resolution</th>
<th>Valid Range</th>
<th>Other Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain Rate (liquid water)</td>
<td>5.4 km</td>
<td>0 – 50 mm/hr</td>
<td>constrained to a maximum of 50 mm/hr</td>
</tr>
<tr>
<td>Rain Type</td>
<td>5.4 km</td>
<td>0 – 100 percent</td>
<td></td>
</tr>
<tr>
<td>Sea Surface Temp 1</td>
<td>56 km</td>
<td>-3.0 – 34.5 °C</td>
<td>based on 6.9 GHz, ~1 mm depth</td>
</tr>
<tr>
<td>Sea Surface Temp 2</td>
<td>38 km</td>
<td>-3.0 – 34.5 °C</td>
<td>based on 10.7 GHz, ~1 mm depth</td>
</tr>
<tr>
<td>Wind Speed 1</td>
<td>36 km</td>
<td>0 – 70 m/s-1</td>
<td>based on 10.7, 10m above surface</td>
</tr>
<tr>
<td>Wind Speed 2</td>
<td>21 km</td>
<td>0 – 30 m/s-1</td>
<td>based on 18.7, 10m above surface</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>21 km</td>
<td>0 – 75 mm</td>
<td>based on 10.7, vertically integrated</td>
</tr>
<tr>
<td>Cloud Liquid Water</td>
<td>12 km</td>
<td>0 – 2.5 mm</td>
<td>based on 96%, vertically integrated</td>
</tr>
<tr>
<td>Wet Beef</td>
<td>56 km</td>
<td>0 – 150 g cm-2</td>
<td>based on 96% (a)</td>
</tr>
<tr>
<td>Vegetation Water Amt.</td>
<td>56 km</td>
<td>0 – total g cm-2</td>
<td>based on 4 g (b)</td>
</tr>
<tr>
<td>Surface Topography</td>
<td>56 km</td>
<td>1 – 16</td>
<td>utilizes USGS databases</td>
</tr>
</tbody>
</table>

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**AMSR-E Rain Rate Product**

- 5.4 km resolution
- Data range is 0 – 1 inches/hour
- Reaches beyond the range of ground-based radar and does not suffer from attenuation
- Instantaneous estimate (not time averaged)
- Example shows hurricane Irene (2011/08/26; 17:29UTC)
AMSR-E Integrated Water Vapor Product

- Derived from 18.7GHz channel resulting in 21km resolution
- Example: Typhoon No. 1 [Sudal] in 2004 captured by AMSR-E

The TRMM Sensor

- Launched 1997
- Multi-sensor platform including two microwave instruments
  1. Precipitation Radar (PR)
  2. TRMM Microwave Imager (TMI)
  3. Visible & Infrared Scanner (VIRS)
  4. Lightning Imaging Sensor (LIS)
  5. CERES

The TRMM Orbit Configuration

- Precessing low-inclination (35°) low-altitude (360 km) orbit to achieve high spatial resolution and capture the diurnal variation of tropical rainfall
The TRMM Microwave Imager (TMI)

- NASA, TRMM
  - launched November 27, 1997
- Sensor Characteristics
  - 10 channel microwave radiometer with 5 frequencies from 10.7 to 85.5 GHz
  - with both vertical and horizontal polarization
  - conical scan mirror with 55° incident angle at Earth’s surface
  - spatial resolutions:
    - 4.4 km (85.5 GHz)
    - 45 km (10.7 GHz)
  - swath width of 760 km
  - mass of 65 kg
  - power of 50 W

TRMM Rain Rate Products

- Derived from combination of 10.7GHz and 85GHz channels
- Vertical precipitation structure is provided

Example: Typhoon Dan approaching China in Oct.99

- 10.7GHz is used only over oceans due to ground contamination over land areas → data of less value over land

- Relatively low orbit of TRMM provides higher resolution (~6km) but less frequent coverage
AMSU – Atmospheric Sounding Instrument

- Composed of two instruments: AMSU-A (15 channels) and AMSU-B (5 channels)
- Atmospheric sounding instrument flown on many satellites including NOAA-15 – 18 and Aqua

<table>
<thead>
<tr>
<th>Channel</th>
<th>Frequency (GHz)</th>
<th>Polarizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.8</td>
<td>89.0</td>
</tr>
<tr>
<td>2</td>
<td>31.4</td>
<td>157.0</td>
</tr>
<tr>
<td>3</td>
<td>50.3</td>
<td>183.3</td>
</tr>
<tr>
<td>4</td>
<td>52.8</td>
<td>183.3</td>
</tr>
<tr>
<td>5</td>
<td>53.6</td>
<td>183.3</td>
</tr>
<tr>
<td>6</td>
<td>54.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>54.9</td>
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<tr>
<td>8</td>
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<td>9</td>
<td>57.2</td>
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<td>10</td>
<td>57.29</td>
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<td>12</td>
<td>57.29</td>
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<tr>
<td>13</td>
<td>57.29</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>57.29</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>89.0</td>
<td></td>
</tr>
</tbody>
</table>

Channels with same frequency but different polarization

AMSU – Channel Weighting Functions

- Weighting functions determine the sensitivity range of different channels
- Therefore, they determine vertical resolution of system

AMSU – Total Precipitable Water Content (TPW)

- Calculated from a combination of AMSU-B (channels 3-5; 183.3 GHz) and AMSU-A (channel 1; 23.8 GHz)
- Due to reliance on low frequency channel AMSU-A-1, strong background contamination over land
  → mostly useful over water where TPW is very high
AMSU – Total Precipitable Water Content (TPW)

- 30 Day global variation of TPW from a combination of AMSU and SSM/I

http://amsu.cira.colostate.edu/

Black areas are no data areas due to low atmospheric signal and/or high background signal

Reading Assignment

- To prepare for next lecture, please read:
  
  
  pp. 221 – 250

  “Active Systems and Radar Altimeters”