GEOS 657 – MICROWAVE REMOTE SENSING

GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

Lecturer:
Franz J Meyer, Geophysical Institute, University of Alaska Fairbanks, Fairbanks; fjmeyer@alaska.edu

Lecture 6: Atmospheric Sounding Using Passive Microwave Systems

UAF Course GEOS 657

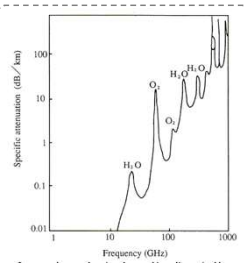
ATMOSPHERIC SOUNDING – MOTIVATION AND APPROACH

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

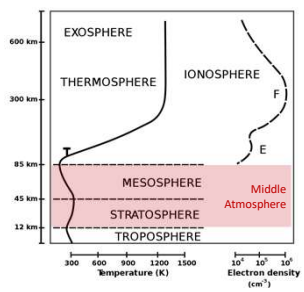
- Microwave Sounders are measuring emissions of the earth's atmosphere to develop understanding of global atmospheric processes
- **Typically monitored parameters**:
  - Temperature, pressure, and wind
  - Distribution of atmospheric gases (water vapor, ozone, chlorine monoxide, …)
- Atmospheric gases have specific absorption/emission lines at very specific frequencies (see figure on right)
- **General principle:** Measure atmospheric emissions at molecule-specific absorption lines



Some atmospheric absorption lines in the microwave spectrum

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., H_2O, O_3, ClO, SO_2 …)
- We also know from Kirchoff's law that good absorbers are also good emitters, corresponding to: $\kappa = \epsilon$

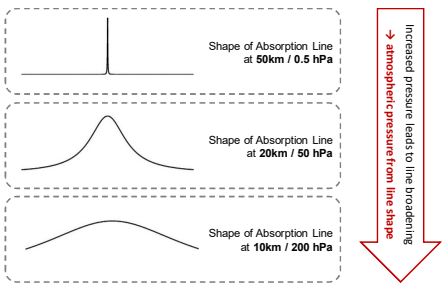
Principle: measure emissivity ϵ at absorption line of specific molecule → convert to absorptance κ → quantify molecule abundance

- **Advantages of Microwave sounders over optical systems:**
  - High penetration into the atmosphere → middle to lower troposphere can be analyzed
  - Passive sensor → no external illuminator required → 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 function of **two** things, **(1)** concentration of constituent *AND* **(2)** atmospheric temperature!
- **Solution is Two Step Approach to Measuring Gas Concentrations:**
  1. measure emissivity at uniformly mixed gasses such as O or CO_2, which hardly vary in time and space → abundance constant → derive temperature
  2. Measure emissivity at constituent of interest (e.g. H_2O) [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



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

THE FORWARD MODEL OF ATMOSPHERIC SOUNDING

What is a Forward Model?

- **Forward model** F is mathematical expression describing the relationship between a physical attribute of 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_B 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)

Formal Representation of a Forward Model

- **Vector y represents measured values and vector x physical attributes**:

$$y = F(x, b_M, b_i) + \epsilon_y$$

where vector b_M describes the physics of how x maps into y, b_I represents instrument influence, and ϵ_y represents noise or random error

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

$$y_i = \int_a^b K_i(x)\, f(x)\, dx + \epsilon_i$$

where $f(x)$ is function describing physical properties and $K_i(x)$ is generally known as *kernel* of *kernel function* that is determined by the observation setup being modeled

- Kernel $K_i(x)$ 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 $K_i(x)$, b_M, and b_i 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**

$$T_{TOA} = \Upsilon T_{BG} + T_{UP}$$

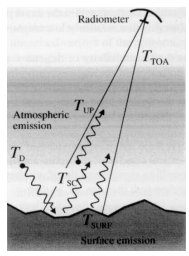
Transmissivity of entire atmosphere — Background signal — Upwelling signal from atmosphere

- **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 θ), we rephrase Υ using opacity τ to:

$$\Upsilon = exp\left(-{}^{\tau}/_{cos\theta}\right)$$

- We can also write T_{UP} according to previous radiative transfer model:

$$T_{UP} = \frac{1}{cos\theta}\int_0^{TOA} \kappa_f(z) \cdot T(z) \cdot exp\left(-{}^{\tau(z)}/_{cos\theta}\right) dz$$



Woodhouse (2006)

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:

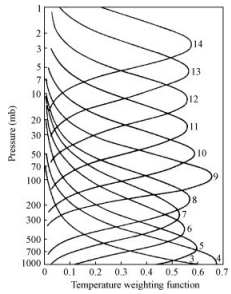
$$y = Kx + \epsilon_y$$

- 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

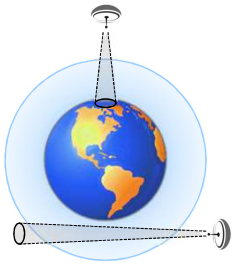
- **Multi-frequency radiometers can map vertical profile of atmospheric gases**
- **How?** Signal at different frequency lines is dominated by particular layers of atmosphere
- Sensitivity range of a specific frequency is described by **weighting function** (see figure)
- E.g., channel 9 has peak sensitivity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



OBSERVATION GEOMETRIES

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 Equation of Nadir Sounding

- **Top of Atmosphere brightness temperature equation:**
  - Background term from Slide 14 now contains radiation from surface T_{SURF} **plus** downwelling radiation from atmosphere that is scattered by the surface T_{SC}

$$T_{TOA} = \Upsilon(T_{SURF} + T_{SC}) + T_{UP}$$

Compact Version of observation equation

- **If we know the Emissivity ϵ of the surface we can rewrite T_{SURF} and T_{SC} to:**

$$T_{SURF} = \epsilon T_s \qquad T_{SC} = (1-\epsilon)T_D$$

where T_s is physical temperature of surface and T_D is downwelling radiation

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

$$T_{TOA} = \underbrace{\Upsilon[\epsilon T_s + (1-\epsilon)T_D]}_{\text{Background term}} + \underbrace{\frac{1}{cos\theta}\int_0^{TOA} \kappa_f(z)\cdot T(z)\cdot exp\left(-{}^{\tau(z)}/_{cos\theta}\right)dz}_{\text{Atmospheric Radiation}}$$

Observation Equation of Limb Sounding

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

$$T_{TOA} = \Upsilon_{limb} T_{3K} + T_{UP}$$

Compact Version of observation equation

- **Advantage:**
  - Background term $\Upsilon_{limb} T_{3K}$ is small, very homogeneous, and easy to characterize
  - Vertical resolution of around 1.5km is achievable

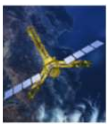
PASSIVE MICROWAVE SYSTEMS FOR SOIL MOISTURE APPLICATIONS

Microwave Systems for Soil Moisture Mapping

- **SMAP (NASA)**
  - L-Band
  - 40 km
  - Observations every 3 days
  - https://nsidc.org/data/smap/smapdata.html
- **SMOS (European Space Agency)**
  - L-Band
  - 40 km
  - Observations every 3 days
  - http://bit.ly/2ocXevG
- **ASCAT (EUMETSAT)**
  - C-band
  - 50 km
  - Observations every 2 days
  - 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

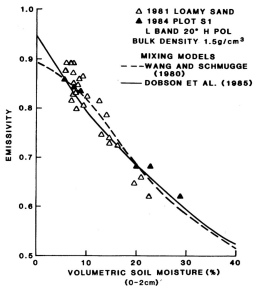
- Launched: Jan 2015
- L-band radiometer
- Spatial resolution: 40 km
- Temporal resolution: 3 days
- Sensing depth: ~5 cm

Uniqueness of SMAP

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

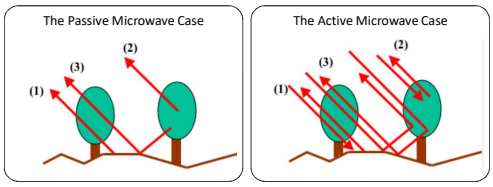
Relationship between L-band Brightness Temperature and Surface Soil Moisture

- We know that:
  - Increasing soil moisture increases radar cross section σ
  - 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.

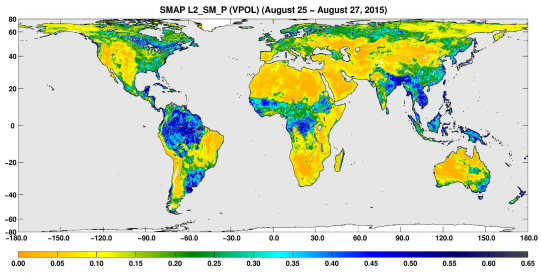


Ancillary Data needed for Soil Moisture Retrieval

- **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

Parameter	Description/Source
Surface Air Meteorology	• Data assimilation (GEOS/DAO) • Forecast models (NCEP and ECMWF)
Vegetation Opacity	• Vis/IR satellite-derived NDVI, LAI, Landcover (MODIS, IGBP-DIS) • Historical phenology (AVHRR)
Surface Topography	• Digital elevation models (USGS and SRTM)
Soil Texture	• Soils databases (Global, NGDC; US, STATSGO)
Land/Water Boundaries	• Coastal boundaries and inland water bodies (NGDC)

3-Day SMAP Soil Moisture Composite

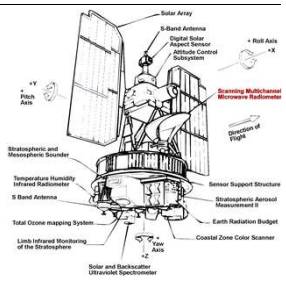


BACK TO THE ATMOSPHERE: SENSOR AND SENSOR PARAMETERS

- **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

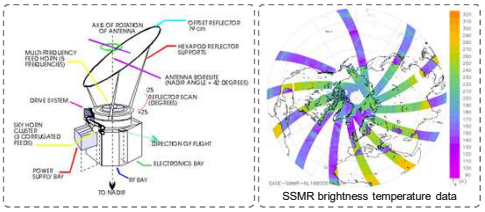
- Launched 1978 and operated by NOAA and NASA
- Seven instruments for atmospheric monitoring including Scanning Multichannel Microwave Radiometer (SMMR)
- **SMMR goals**:
  - low altitude winds, water vapor, cloud liquid water, rainfall rates, sea surface temperature, sea ice concentration
- **SMMR design**:
  - 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 **Nimbus-7 Observatory**

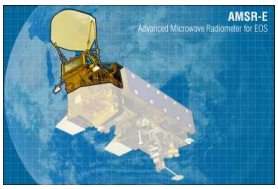
Nimbus-7: The SMMR Sensor

- **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 ($\pm 25°$) 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 1445km
  - 10km resolution at nadir

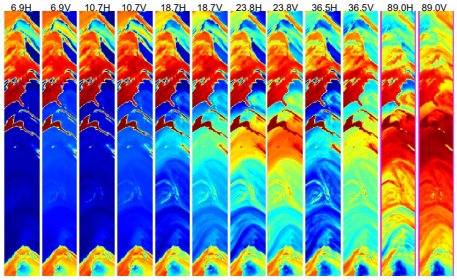


AMSR-E on AQUA

- **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



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

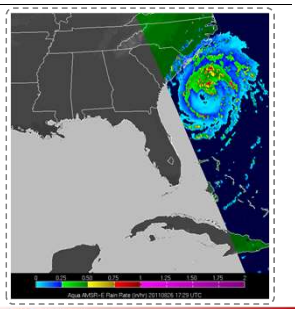
Frequency	Footprint Size	Mean Resolution
6.9	75 x 43 km	56 km
10.7	51 x 29 km	38 km
18.7	51 x 29 km	21 km
23.8	27 x 16 km	21 km
36.5	14 x 8 km	12 km
89.0	6 x 4 km	5.4 km

AMSR-E Product Specifications

Product	Base Resolution	Valid Range	Other Information
Rain Rate (liquid water)	5.4 km	0 – 50 mm/hr	restrained to a maximum of 50 mm/hr
Rain Type	5.4 km	0 – 100 percent	convective rain percentage
Sea Surface Temp 1	56 km	-3.0 – 34.5 C	based on 6.9 GHz, ~1 mm depth
Sea Surface Temp 2	38 km	-3.0 – 34.5 C	based on 10.7 GHz, ~1 mm depth
Wind Speed 1	38 km	0 – 50 m s-1	based on 10.7, 10m above surface
Wind Speed 2	21 km	0 – 50 m s-1	based on 18.7, 10m above surface
Water Vapor	21 km	0 – 75 mm	based on 18.7, vertically integrated
Cloud Liquid Water	12 km	0 – 2.5 mm	based on 36.5, vertically integrated
Soil Moisture	56 km	15 – 500 g cm-3	based on 6.9 GHz
Vegetation Water Amt.	56 km	0 – 1000 kg m-2	based on 6.9 GHz
Surface Topography	56 km	1 – 16	utilizes USGS databases

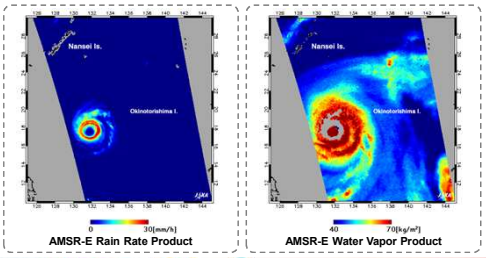
AMSR-E Rain Rate Product

- 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)



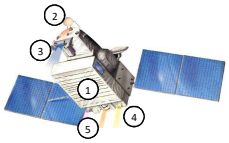
AMSR-E Integrated Water Vapor Product

- 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

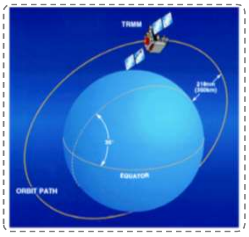


1: Precipitation Radar (PR)
2: TRMM Microwave Imager (TMI)
3: Visible & Infrared Scanner (VIRS)
4: Lightning Imaging Sensor (LIS)
5: CERES

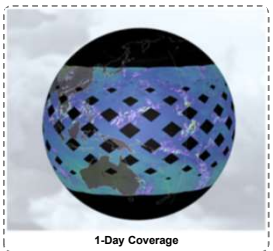
- Precipitation Radar (PR)
  - 13.8 GHz radar with 215 km swath width and 4.3 km footprint
- TRMM Microwave Imager (TMI)
  - Conically scanning, passive microwave radiometer with 760 km swath (10.7-85.5 GHz)
- Visible & Infrared Scanner (VIRS)
- Lightning Imaging Sensor (LIS)
- CERES

The TRMM Orbit Configuration

- Precessing low-inclination (35°) low-altitude (350 km) orbit to achieve high spatial resolution and capture the diurnal variation of tropical rainfall



TRMM Coverage

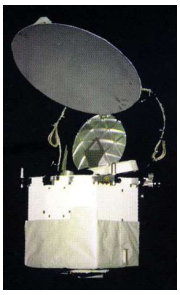


1-Day Coverage

2-Day Coverage

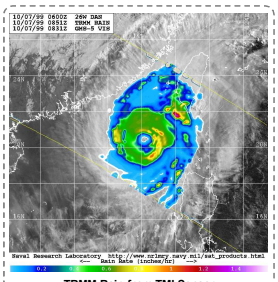
The TRMM Microwave Imager (TMI)

- **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



TRMM Rain from TMI Sensor

AMSU – Atmospheric Sounding Instrument

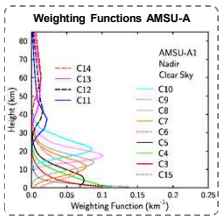
- Composed of two instruments: AMSU-A (15 channels) and AMSU-B (5 channels)
- Atmospheric sounding instrument flown on many satellites including NOAA-15 – 18 and Aqua

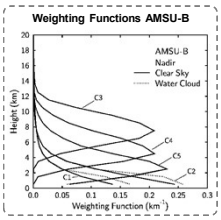
Channel	Frequencies (GHz) and Polarizations	Frequencies (GHz) and Polarizations
1	23.8	89.0
2	31.4	157.0
3	50.3	183.3
4	52.8	183.3
5	53.6	183.3
6	54.4	
7	54.9	
8	55.5	
9	57.2	
10	57.29	
11	57.29	
12	57.29	
13	57.29	
14	57.29	
15	89.0	

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





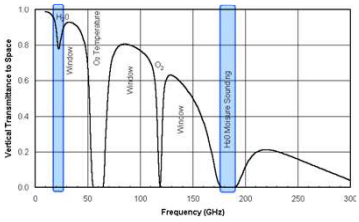
http://amsu.cira.colostate.edu/

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

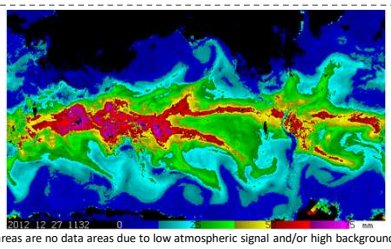
→ **mostly useful over water of where TPW is very high**



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

AMSU – Total Precipitable Water Content (TPW)

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



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

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

Reading Assignment

- To prepare for next lecture, please read:

Woodhouse (2006), "Introduction to Microwave Remote Sensing"

pp. 221 – 250

"Active Systems and Radar Altimeters"