Topic 7: PASSIVE MICROWAVE SYSTEMS

GOALS:

At the end of this Section you should be able to:

1. Define the effective wavelength range of microwave systems, and specify the advantages and disadvantages of shorter vs. longer wavelengths.

2. Recognize that passive microwave sensing is similar to thermal sensing in that it observes radiative emission from the earth.

3. Describe the Rayleigh-Jeans approximation and understand the relationship between emittance, wavelength, emissivity and temperature – especially the increased importance of emissivity.

4. List properties that affect the emissivity

5. Contrast passive microwave radiation with thermal radiation in terms of the relationship between emissivity and temperature, radiometric sensitivity, and spatial resolution.

6. Know that emissivity of a material is inversely proportional to its dielectric constant and its electrical conductivity.

7. Understand the relationship between absolute (surface) and apparent (radiative) temperature in the microwave and how it differs from the thermal.

8. Have a basic understanding of antennas:
   a. Know the difference between beamwidth and bandwidth.
   b. Be able to describe how microwave antennas focus a beam.
   c. Recognize the difference between parabolic, horn and phased array antennas.

There is an excellent short course on microwave systems in general and passive microwave systems in particular. There is both a video and print version available on this web site. You will need to create an account (free) to use the site.

http://www.meted.ucar.edu/npoess/microwave_topics/resources/index.htm

\[
\frac{30}{x \text{ cm}} = y \text{ GHz} \Rightarrow 3 \text{ cm} \rightarrow 10 \text{ GHz}
\]

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\]
Microwave Radiometry

- **Passive**: Emission from the earth
- **Wavelengths**: 1 mm – 10 cm
- **Frequency**: 300 GHz - 3 GHz
- **Atmosphere**:
  - Essentially opaque for $\lambda < 1$ mm primarily due to H$_2$O and O$_2$
  - Atmospheric attenuation very low for 14 $\mu$m > $\lambda$ > 3 cm
- **Low energy ➔ Large FOV**
- **Brightness Temperature** (apparent temperature) is the temperature of a blackbody with the same temperature.

Blackbody Radiation

**Planck's Formula** describes the magnitude and spectral distribution of radiation emitted by a blackbody source.

$$M_\lambda = \frac{2\pi hc^2}{\lambda^5 \left[ \exp \left( \frac{hc}{\lambda kT} \right) - 1 \right]}$$

where:
- $M_\lambda$ = exitance at wavelength $\lambda$
- $h$ = Planck's constant = $6.625 \times 10^{-34}$ J-sec
- $c$ = speed of light in a vacuum = $2.997 \times 10^8$ m/sec
- $k$ = Boltzmann's constant = $1.38 \times 10^{-23}$ J/°K
- $T$ = absolute temperature in degrees Kelvin

Recall that, integrated over all wavelengths, thermal emission is proportional to $T^4$ (Boltzmann’s Law: $M_{\text{tot}} = \sigma T^4$). Since the bulk of the earth’s radiation occurs within the 8-14 $\mu$m window, this strong sensitivity to temperature is apparent with thermal sensing.
Topic 7: Passive Microwave Systems

Atmospheric Transmission in the microwave

Dotted line: oxygen contribution,
Dash-dotted line: water contribution,
Solid line: contribution from all resonance lines in atmosphere.

Passive microwave imaging: Shafter Airport, Bakersfield CA

Image collected using a plastic lens to focus 3 mm radiation onto an array of miniature receivers.

Characteristics of Passive Microwave
- All weather
- Day/night
- Daily or better coverage
- Multi-channel (atmospheric sounding)
- Long record
- Low energy / Large footprint (FOV)

Rayleigh-Jeans Approximation
\[ M_\lambda = \frac{2\pi hc^2}{\lambda^5 \left[ \exp \left( \frac{hc}{\lambda kT} \right) - 1 \right]} \]

Taylor Series Expansion:
\[ \exp \left( \frac{hc}{\lambda kT} \right) = 1 + \left( \frac{hc}{\lambda kT} \right) + \frac{1}{2!} \left( \frac{hc}{\lambda kT} \right)^2 + \frac{1}{3!} \left( \frac{hc}{\lambda kT} \right)^3 + \cdots \]

For \( \frac{hc}{\lambda kT} \ll 1 \):
\[ \exp[hc/\lambda kT] \sim 1 + hc/\lambda kT \]

\[ \Rightarrow \text{Rayleigh-Jeans Approximation:} \quad M_\lambda = \frac{2\pi ck}{\lambda^4} T \]

Thus, emission from real objects on the earth's surface in the microwave region is then:
\[ M_\lambda = \varepsilon_\lambda M_{bb\lambda} = (2\pi c k/\lambda^4) \varepsilon_\lambda T_{bb} \]
- Linear dependence on temperature
- Much more sensitive to emissivity differences than in the thermal range.

Brightness Temperature: \( T_B = \varepsilon_\lambda T_{bb} \)
- There is a large variation in emissivity of different materials at microwave wavelengths.
- Note that ice will appear relatively warm, water relatively cold, even when water is at 0°C.
- Low energy ==> poor spatial resolution

http://www.meted.ucar.edu/lobjects/npoess/microwave_topics/resources/9_7/
Emissivity in the microwave:

Emissivity is a function of several variables:
- Dielectric properties (e.g., electrical conductivity).
  - Inherent conductivity
  - Water content
  - Salinity
  - Frequency (wavelength)
- Viewing angle
- Non-Lambertian emission
  - Surface roughness
  - Polarization

**NOTE:** A blackbody source will be Lambertian and unpolarized.

Salinity measurements by NASA’s Aquarius instrument require adjustments for the sea surface temperature and roughness, the intervening atmosphere and ionosphere, and galactic signals reflected off the sea surface.

Moisture in the top 5 centimeters (2 inches) of soil as observed in August 2013

**SMOS satellite (ESA)** [https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos](https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos)

**SMAP satellite (NASA)** [https://smap.jpl.nasa.gov/](https://smap.jpl.nasa.gov/)
### Dielectric properties

**Earth Conductivity & Dielectric Constant**

- **Emissivity**, $\varepsilon$, in the microwave range is inversely proportional to the relative permittivity, $\varepsilon_r$:
  \[ \varepsilon \propto \frac{1}{\varepsilon_r} \]

- **Relative permittivity** is a measure of a material's ability to transmit (or "permit") an electric field and consists of a real (scattering) component, the dielectric constant, $\varepsilon'$, and an imaginary (absorption) component, $\varepsilon''$.
  \[ \varepsilon_r = \varepsilon'_{\text{scattering}} + i\varepsilon''_{\text{absorption}} \]

- The **dielectric constant**, $\varepsilon'$, is a measure of the ability of a material to store a charge from an applied electromagnetic field and then transmit that energy.

- The absorption term is generally negligible for most environmental remote sensing applications

- Most earth materials have a dielectric constant in the range of 1 to 4 (air~1, veg~3, ice~3.2). The dielectric constant of liquid water is 80 ⇒ moisture content will lower the brightness temperature

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**Sensitivity to water content of bare soil**

- Emissivity decreases as soil moisture increases.

- Emissivity is highly wavelength dependent.

**In general:**

- high dielectric constant ⇒ low emissivity
  - water: $80 \quad \sim0.50$
  - bare soil: $1 - 4 \quad \sim0.95$
**Polarization notation**

The direction of polarization is specified relative to the plane containing the incident, reflected and refracted rays.

- **H** = horizontal polarization (perpendicular polarization) → the electric field is perpendicular to the vertical plane.
- **V** = vertical polarization (parallel polarization) → the electric field is parallel to the vertical plane.

**Emissivity Variables**

- Water content
- Polarization
- Salinity
- Angle of incidence
- Frequency

![Emissivity graph](image)

![Polarization diagram](image)
Atmospheric effects: Brightness temperature from a reflecting surface

The atmosphere as a source: for an opaque surface and a detector just above the surface:

\[ T_B = \varepsilon_s T_s + \rho_s T_i(\theta) = \varepsilon_s T_s + (1-\varepsilon_s)T_i(\theta) \]

- if \( \varepsilon_s \approx 1 \) there will be very little influence on the observed brightness by reflectance from other sources of moderate brightness temperature
- if \( \varepsilon_s \) is low, reflectance from other sources can have a strong effect.
- There is a wide range of emissivities in the \( \mu \)-wave
  - fresh water \( < 0.5 \)
  - ice \( \approx 1 \)
  - ocean water \( \approx 0.4 \)
  - earth \( > 0.85 \)

Atmosphere as a filter: brightness temperature observed through an absorbing medium

Absorption:
- for \( \lambda < 1 \) mm, \( H_2O \) and \( O_2 \) are strong absorbers
- for \( \lambda > 3 \) cm the air is quite clear
- Clouds (water vapor, liquid water) both absorb and re-emit radiation.

- Atmospheric transmittance = \( \tau_a \)
  \[ \alpha_a + \rho_a + \tau_a = 1 \]
- atmospheric absorption:
  \[ \alpha_a = (1 - \tau_a) = \varepsilon \text{ if } \rho_a = 0 \]
  [ in \( \mu \)-wave, \( \rho_a \approx 0 \) ]
- for thermal equilibrium, \( \alpha_a T_a = \varepsilon_a T_a \)

\[ T_B = \tau_a \left( \varepsilon_s T_s \right) + \left( 1 - \tau_a \right) \varepsilon_a T_a \]

\( T_B \) = attenuated brightness temperature of the surface
\( \varepsilon_a T_a \) = energy absorbed and re-radiated in the optical path

\[ T_B = \{ \tau_1 T_i + (1 - \tau_1) T_{a1} \} \rho + \varepsilon T_s \} \tau_2 + (1 - \tau_1) T_{a2} \]

\( T_B \) = energy emitted by the atmosphere at temp \( T_s \)
\( T_{a2} \) = energy absorbed and re-radiated by the atmosphere at temp
Microwave sensors - radiometers:
A microwave radiometer is a passive sensor. The detector for microwave radiation is an antenna. The apparent temperature observed at the antenna -- the antenna temperature -- is related to the brightness temperature, $T_B$, by:

$$T_{ant} = \int_{\lambda \Omega} T_B \ G \ d\Omega \ d\lambda$$

where $\Omega$ is the IFOV of the system and $G$ is the antenna gain.

The amount of radiation obtained is limited by:
- the antenna bandwidth ($\Delta \lambda$ or $\Delta \nu$)
- the beamwidth (solid angle viewed by the antenna)

The bandwidth is the wavelength or frequency range over which the antenna is sensitive.
The beamwidth is the angular interval over which the antenna's power pattern exceeds one-half of its maximum value ("half-power" beamwidth). (This is the "IFOV" of the microwave system)

Microwave systems use antennas to focus and direct radiation.
- Antennas, like lenses, are diffraction limited.
- The angular resolution of a diffraction limited system will be on the order of $\lambda/d$, where $d$ is the aperture size (i.e., length or diameter).
- In the optical range $\lambda/d \sim 10^{-5}$ and the effects are subtle.
- In the microwave, $\lambda/d \sim 10^{-1}$ and diffraction effects are much more significant, producing side lobes in the detection pattern.

A dipole is the simplest antenna, and forms the core of many more complex antennas.

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Horns are also used as feeds for reflector antennas.

Since dipole and horn antennas are not well-focused, most narrow beam antennas employ reflectors that are generally a paraboloid of revolution.

Phased array antennas may be used to produce multiple beams or for electronic steering.

Microwave sensors – Dipole Antennas
A dipole antenna is a straight electrical conductor measuring 1/2 wavelength from end to end and connected to a radio-frequency (RF) feed line. Although this antenna is one of the simplest, it is often the primary RF radiating and receiving element in more sophisticated antennas.
A horn antenna derives its name from the characteristic flared appearance. The flared portion can be square, rectangular, or conical. A horn antenna must be a certain minimum size relative to the wavelength of the incoming or outgoing electromagnetic field. If the horn is too small or the wavelength is too large (the frequency is too low), the antenna will not work efficiently.

Like the dipole antenna, the horn antenna is frequently used as the main receiving or transmitting element of a more sophisticated antenna. It has the advantage of being able to accommodate a relatively broad bandwidth.

The widest dimension of a waveguide is called the "a" dimension and determines the range of operating frequencies.

The narrowest dimension determines the power-handling capability and is called the "b" dimension. (see: https://en.wikipedia.org/wiki/Horn_antenna)

**Dipole Antennas: polarization**

A half-wave dipole antenna consists of two quarter-wavelength conductors placed end to end for a total length of approximately \( L = \lambda/2 \).

The polarization of a dipole antenna is determined by its orientation. A dipole antenna erected horizontally (or a horn antenna with it's "a" dimension oriented horizontally) is "horizontally polarized".

**Dipole Antennas: beam pattern**

A vertical dipole antenna is responsive to **vertically polarized** radiation (of the appropriate wavelength) in all azimuthal directions (\( \phi \)). The response in the zenith direction (\( \theta \)) decreases as the sin of \( \theta \).

Placing a reflector behind the antenna will improve the sensitivity in one direction.

A horn antenna is inherently more directional, but is not necessarily well-focused.
**Microwave antennas – Antenna Focus**
Antenna focusing can be accomplished with a parabolic dish which restricts the direction of waves detected by the dipole (or horn) antenna at the focus.

- The larger the antenna, the more narrow the major lobe will be;
- The beamwidth will be $\sim \lambda/d$ where $d$ is the diameter of the dish.

**Microwave antennas – Dish antenna (paraboloid)**
- Dipole and horn antennas are commonly used as the active element in a dish antenna.
- The dipole or horn is pointed toward the center of the dish.

  The use of a horn, rather than a dipole antenna, at the focal point of the dish minimizes loss of energy (leakage) around the edges of the dish reflector. It also minimizes the response of the antenna to unwanted signals not in the favored direction of the dish.

**Microwave antennas – Truncated paraboloid**
- The reflector is parabolic in the horizontal plane $\Rightarrow$ focused into a narrow beam horizontally.
- The reflector is truncated vertically $\Rightarrow$ the beam spreads out vertically instead of being focused.
- This **fan-shaped beam** is used for the accurate determination of **bearing**.
  - Since the beam is spread vertically, it will detect aircraft at different altitudes without changing the tilt of the antenna.
  - The truncated paraboloid also works well for surface search radar applications to compensate for the pitch and roll of the ship.

**Power in decibels**
Relative power, can be expressed in decibels as ten times the base-10 logarithm of the ratio of the measured quantity, $P$, to the reference level, $P_0$. Thus, the ratio of measured power, $P$, to the reference power, $P_0$, is represented by $L_P$, that ratio expressed in decibels, which is calculated using the formula:

$$L_P = \frac{1}{2} \ln \left( \frac{P}{P_0} \right) N_P = 10 \log_{10} \left( \frac{P}{P_0} \right) dB$$

The base-10 logarithm of the ratio of the two power levels is the number of bels. The number of decibels is ten times the number of bels (equivalently, a decibel is one-tenth of a bel).

<table>
<thead>
<tr>
<th>Name</th>
<th>Shape</th>
<th>Gain (over isotropic)</th>
<th>Beamwidth -3 dB</th>
<th>Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropic</td>
<td><img src="image" alt="Isotropic" /></td>
<td>0 dB</td>
<td>360</td>
<td><img src="image" alt="Isotropic Pattern" /></td>
</tr>
<tr>
<td>Dipole $\lambda/2$</td>
<td><img src="image" alt="Dipole" /></td>
<td>2.14 dB</td>
<td>55</td>
<td><img src="image" alt="Dipole Pattern" /></td>
</tr>
<tr>
<td>Folded Dipole $\lambda/2$</td>
<td><img src="image" alt="Folded Dipole" /></td>
<td>5.64 dB</td>
<td>45</td>
<td><img src="image" alt="Folded Dipole Pattern" /></td>
</tr>
<tr>
<td>Yagi $\lambda/2$</td>
<td><img src="image" alt="Yagi" /></td>
<td>7.14 dB</td>
<td>25</td>
<td><img src="image" alt="Yagi Pattern" /></td>
</tr>
<tr>
<td>Parabolic Dipole $D = 5\lambda/2$</td>
<td><img src="image" alt="Parabolic Dipole" /></td>
<td>14.7 dB</td>
<td>20</td>
<td><img src="image" alt="Parabolic Dipole Pattern" /></td>
</tr>
<tr>
<td>Horn $3\lambda$</td>
<td><img src="image" alt="Horn" /></td>
<td>15 dB</td>
<td>15</td>
<td><img src="image" alt="Horn Pattern" /></td>
</tr>
</tbody>
</table>
Microwave sensors - radiometers:
Increasing the sensitivity of microwave radiometers:
- increasing the IFOV (beamwidth)
  (A common solution. The spot size of a typical satellite microwave radiometer is many kilometers.)
- increasing the bandwidth
  (can probably be effective for some applications but is often not a realistic option.)
- integrating over longer periods
  (good for ground systems, not very useful for aircraft or satellite systems)

Types of microwave scanner

The conical scan insures a constant incidence angle at the surface \( \Rightarrow \) removes one variable of emissivity.

Note that the scan line is not perpendicular to the nadir path \( \Rightarrow \) the scan rate is relatively slow.

Microwave antennas – dipole phased arrays
Adapted from: http://www.haarp.alaska.edu/haarp/ant3.html

- Whenever two or more simple antenna elements (e.g. dipoles) are brought together and driven from a source of power (a transmitter) at the same frequency, the resulting antenna pattern becomes more complex due to interference between the signals transmitted/detected separately from each of the individual elements.
- At some points, this interference may be constructive causing the transmitted signal to be increased. At other points, the interference may be destructive causing a decrease or even a cancellation of transmitted energy in that direction.

Here two dipole antennas are placed close to each other and excited with a single receiver.

The resulting antenna pattern is narrower or sharper in the broadside (T1) direction and the signal off-broadside (T2) is weaker than it would have been for either dipole alone.

The ratio of the strength of the signal at the pattern maximum (i.e. at T1) to the signal for a single antenna element is called the pattern
gain. Pattern gain is accomplished at the expense of power transmitted in other directions.

Adding additional antenna elements can result in further narrowing of the pattern.

Four dipole antennas placed near each other and monitored by a receiver set to receive in-phase signals results in a narrower pattern than that for the 2-dipole case.

The resulting antenna pattern is narrower or sharper in the broadside (T3) direction.

Sidelobes also appear in the total antenna pattern:

- characteristic feature of most complex antenna arrays.
- generally an undesirable characteristic of an antenna system
- It is theoretically possible to suppress side lobes completely in an array of antenna elements if the excitation of each element is controllable.
- The process of shaping the antenna pattern so as to eliminate sidelobes is called tapering.
- Eliminating sidelobes results in less total gain at the pattern maximum, however, and it yields a broader main lobe.

The angle at which the pattern maximum occurs can be changed by adjusting the phase of the signals received from each of the antenna elements.

- With all elements in-phase, the pattern maximum will occur broadside to the array.
- By adjusting the relative phase, the peak of the main lobe can be shifted (or steered) to a new angle relative to broadside.
- In general, the maximum signal strength at the new pointing angle (T4 in Figure 3 to the left) is close to but less than the broadside case.

When the pattern is steered to a new direction, the shape and direction of the sidelobes change.

If the pattern is steered too far relative to the element spacing, a new lobe (called a grating lobe) will appear with a peak in its pattern nearly equal to the main lobe.

The point where this occurs is the maximum useful steering angle.

**Airborne L-band radiometer**

An L-Band (~20 cm) Radiometer Mapping System for small aircraft

**Applications:**

- ocean surface temperature and salinity
- soil water content
- mapping of ice extent
**TMI - TRMM Microwave Imager**

**Tropical Rainfall Measuring Mission**

<table>
<thead>
<tr>
<th>Observation Frequency</th>
<th>10.7, 19.4, 21.3, 27 and 85.5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polarization</strong></td>
<td>Vertical/Horizontal (21.3 GHz Channel: H only)</td>
</tr>
<tr>
<td><strong>Horizontal Resolution</strong></td>
<td>6 - 50 km</td>
</tr>
<tr>
<td><strong>Swath Width</strong></td>
<td>About 760 km</td>
</tr>
<tr>
<td><strong>Scan Mode</strong></td>
<td>Conical Scan (49 deg)</td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td>Designed to provide quantitative rainfall information over a wide swath: water vapor, cloud water, and rainfall intensity.</td>
</tr>
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</table>

**AMSU- Advance Microwave Sounding Unit**

**AMSU-A**
- 15-channel total power microwave radiometer
- 23.8 GHz to 89.0 GHz

**AMSU-B**
- 5-channel total power microwave radiometer
- two channels centered nominally at 89 GHz and 150 GHz
- three channels centered around the 183.31 GHz water vapor line

Operates with either a 48 km or 16 km resolution
Measures total precipitable water, rain rate, cloud liquid water, snow cover, sea ice, total precipitable water, and cloud liquid water

Individual AMSU-A channels are carefully chosen to detect microwave radiation from a discrete layer within the earth's atmosphere.

This allows the development of a tropospheric water vapor profile.

[http://amsu.ssec.wisc.edu/explanation.html](http://amsu.ssec.wisc.edu/explanation.html)
WATER: AMSR-E SST & Surface winds

• SST fields are shown as gray contours in this figure superimposed on the ASMR-E wind field.

• Emissivity varies with surface roughness which, in turn, varies with wind speed.

• Because the different frequencies interact differently with different roughness scales it is possible to estimate wind speed independently of temperature.

• Over the cold Malvinas Current, the wind speed is lower than over the warm Brazil Current waters.

• This is an example of the close coupling that exist between the surface wind and SST due momentum fluxes in the marine boundary layer.

WATER: AMSU Surface air temperature

Comparing brightness temperatures from frequencies – some of which do not penetrate all the way to the ground – allows estimates of the temperature above the water surface.

http://pm-esip.msfc.nasa.gov/cyclone/
Comparing brightness temperatures from frequencies that reach to different altitudes also allows estimates of water vapor content at selected altitudes.

**ATMOSPHERE: water vapor profiles**

*TRMM*  

*ATMOSPHERE: Katrina rainfall profile*
**ATMOSPHERE: water vapor**


Comparison of rawinsonde and NOAA-15 AMSU retrievals for 2000. 13289 matchups. A) Temperature and (B) Mixing ratio. Different colored lines indicate rawinsonde, retrieval, retrieval with zenith angle less than 15 degrees, and retrieval with cloud liquid water less than 0.03 mm, respectively. Temperature retrieval first guess error from the NESDIS statistical algorithm also shown.

**ATMOSPHERE: Global precipitation estimates**

3 Hourly Global Rainfall

Week of Global Rainfall Accumulation

These images represent a merger of all available SSM/I and TMI *microwave* precipitation estimates plus estimates from geostationary infrared satellites.