Physical Principles of Passive Microwave Radiometry. Soil Moisture

Passive Microwaves. Introduction
Rayleigh-Jeans Law. Background
Factors Affecting Emissivity
Polarization
Estimation of Soil Moisture

Ernesto López Baeza
with contributions from Mike Schwank and Jean-Pierre Wigneron
What is remote sensing:
Observing an object with an instrument that is in a certain distance to this object.

Applications of remote sensing:
- soil sciences
- climate, meteorology
- hydrolgy
- geology
- cartography
- astronomy

Why remote sensing:
- large scale
- accessibility
- areal statistics
- costs

Goal of SMOS mission:
Global water content and ocean salinity data. $\theta [m^3m^{-3}]$

Spring | Summer | Autumn | Winter
Introduction

Passive Sensors
Use reflected (external source) or emitted by the system energy
Different illumination and observation angle
Do not alter the conditions of the system
Sensitive to illumination conditions
Much simpler, less expensive

Active Sensors
Use reflected (own source) energy
Same illumination and observation angle
May alter the conditions of the system
Non sensitive to illumination conditions
More complex, more expensive because they need plenty of energy to work

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Optical / IR remote sensing
- Uses the VIS / IR parts of the electromagnetic spectrum
- Human eye, cameras, telescopes, radiometers
- Problems with clouds, rain, fog, snow, smoke, smog, etc.
- Only from surface. Cannot penetrate soil, vegetation, snowpack, ice
- Relies on ambient light sources (e.g., sunlight)

Microwave remote sensing is less than 100 years old
- Uses the microwave and RF parts of the spectrum
- Radars and radiometers
- Is largely immune to clouds, precipitation, smoke, etc.
- Penetrates sand, soil, rock, vegetation, dry snow, ice, etc.
- Does not rely on sunlight – radar provides its own illumination, radiometers use the target’s thermal emission

Data from microwave sensors complement data from optical sensors
Why this is interesting:

The global water cycle is the “motor” of the global climate.

Solution:

Microwave (L-band) measurements from a satellite. Soil Moisture and Ocean Salinity mission (SMOS) launched on November 2th 2009.
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Factors Affecting Emissivity

Polarization

Estimation of Soil Moisture
How it works:

The electromagnetic radiance $T_B$ (brightness temperature) of an object is determined by:
- Temperature $T$ and emissivity $E$.
- $E$ depends on the dielectric constant $\varepsilon$ of the object, and therefore on the water content $\theta$.

| measurement: $T_B$ | model: Radiative transfer $T_B = f(T_i, E_i)$ and $E_i = f(\varepsilon_i)$  

Dielectric mixing model $\varepsilon = f(\theta)$ | result: $T_B \Rightarrow \theta$ |

Radiative components in case of a soil covered with vegetation

M. Schwank
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Microwaves have wavelengths that can be measured in centimeters! The longer microwaves, those closer to a foot (30 cm) in length, are the waves which heat our food in a microwave oven.

Microwaves are good for transmitting information from one place to another because microwave energy can penetrate haze, light rain and snow, clouds, and smoke. Shorter microwaves are used in remote sensing. These microwaves are used for radar like the doppler radar used in weather forecasts. Microwaves, used for radar, are just a few inches (1 inch = 2.54 cm) long.
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The Microwave Spectrum

Microwave band codes

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength, cm</th>
<th>Frequency, GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_a</td>
<td>0.75-1.18</td>
<td>40.0-26.5</td>
</tr>
<tr>
<td>K</td>
<td>1.19-1.67</td>
<td>26.5-18.0</td>
</tr>
<tr>
<td>K_u</td>
<td>1.67-2.4</td>
<td>18.0-12.5</td>
</tr>
<tr>
<td>X</td>
<td>2.4-3.8</td>
<td>12.5-8.0</td>
</tr>
<tr>
<td>C</td>
<td>3.9-7.5</td>
<td>8.0-4.0</td>
</tr>
<tr>
<td>S</td>
<td>7.5-15.0</td>
<td>4.0-2.0</td>
</tr>
<tr>
<td>L</td>
<td>15.0-30.0</td>
<td>2.0-1.0</td>
</tr>
<tr>
<td>P</td>
<td>30.0-100</td>
<td>1.0-0.3</td>
</tr>
</tbody>
</table>

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Canada Centre for Remote Sensing

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**What do Microwaves show us?**

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Microwave Image" /></td>
<td>Because microwaves can penetrate haze, light rain and snow, clouds and smoke, these waves are good for viewing the Earth from space. The ERS-1 satellite sends out wavelengths about 5.7 cm long (C-band). This image shows sea ice breaking off the shores of Alaska.</td>
</tr>
<tr>
<td><img src="image2.jpg" alt="Microwave Image" /></td>
<td>The JERS satellite uses wavelengths about 20 cm in length (L-band). This is an image of the Amazon River in Brazil.</td>
</tr>
<tr>
<td><img src="image3.jpg" alt="Microwave Image" /></td>
<td>This is a radar image acquired from the Space Shuttle. It also used a wavelength in the L-band of the microwave spectrum. Here we see a computer enhanced radar image of some mountains on the edge of Salt Lake City, Utah.</td>
</tr>
</tbody>
</table>

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Most weather satellites use the visible and infrared regions of the electromagnetic spectrum to collect data on the Earth and atmosphere. Visible channels use reflected sunlight to create images. In the infrared and microwave, satellites sense Earth-emitted energy to create images. The graph shows that Earth-emitted energy drops off sharply beyond the infrared region of the electromagnetic spectrum.

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... and this is the order of energy that we want to measure ...

\[ W = \sigma T B \ \text{order of} \ 10^{-13} \ \text{W} \]

\[
\sigma = 1.380658 \cdot 10^{-23} \ \text{J} \ \text{K}^{-1} \text{ (Boltzmann constant)}
\]

\[
T = \text{Physical temperature (K)}
\]

\[
B = 27 \text{ MHz (bandwidth)}
\]

This decrease of energy with increasing wavelength continues into the microwave regions. Indeed, the energy per unit area in the microwave region is several orders of magnitude less than in the infrared.

Since we often use frequency units (Hertz) rather than wavelength when referring to microwave energy, we note that energy decreases as frequency decreases.

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Available Energy for Passive Sensors

We can see how passive sensing of microwave energy impacts sensor resolution by looking at the five channels on WindSat. The lower the frequency (longer the wavelength) of the channel, the less energy available per unit area, and therefore larger fields-of-view are necessary to collect enough information to create imagery and derived products.

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Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures

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Wien’s Law

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Wien’s Law

6000 K ♯ VIS (0.4 μm)

300 K ♯ IR (10 μm)

??? K ♯ μwaves (ex. 20 cm)

the answer is coming up soon …
Passive Microwaves. Introduction

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Polarization

Estimation of Soil Moisture
Temperature Sensitivity of $B(\lambda, T)$ for typical earth scene temperatures

$B(\lambda, T) / B(\lambda, 273K)$

Temperature (K)

Temperature Sensitivity

$B \propto T$

microwave

4μm

6.7μm

10μm

15μm

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Rayleigh – Jeans Approximation

\[ B(\lambda, T) = \frac{c_1}{\lambda^5} \left[ \exp\left(\frac{c_2}{\lambda T}\right) - 1 \right] \]

In the microwave region (\( \lambda \) from 1 mm to 1 m),

\[ \frac{c_2}{\lambda T} \ll 1, \text{ so that} \]

\[ \exp\left(\frac{c_2}{\lambda T}\right) = 1 + \frac{c_2}{\lambda T} + \text{second order} \]

and classical Rayleigh – Jeans equation originates

\[ B_\lambda(T) \approx \left(\frac{c_1}{c_2}\right) \left(\frac{T}{\lambda^4}\right) \]

\[ \Rightarrow \text{radiance is a linear function of brightness temperature} \]
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The COBE (Cosmic Background Explorer) satellite made very careful measurements of the shape of the spectrum of this emission. It is a perfect blackbody at a temperature of 2.728 K; it is often termed the "3K background".

(From R. McCray)

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The 3K radiation is remarkably uniform in all directions. The temperature in one direction is the same as in 180 deg the opposite direction to an accuracy of 1 part in 100,000! Here is a map of the whole sky from COBE, scaled so blue would be 0 K and red 4 K. The fact that it is all the same colour shows how uniform the 3K radiation is. This is why passive microwave radiometers can be calibrated against this temperature.

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Satellite remote sensing is an important complementary tool for observing Earth’s land and ocean surfaces, especially where in-situ observations are scarce or nonexistent. Microwave remote sensing from polar-orbiting satellites plays a unique role:

- 1. polar-orbiting satellites offer the unique capability to provide global coverage
- 2. microwave radiation penetrates most clouds and allows for observation of surface features in the vast majority of weather conditions. This is especially important over the oceans, where cloud cover averages nearly 70%
- 3. two important properties that impact microwave radiation, polarization and emissivity, vary depending on both wavelength/frequency and characteristics of the emitting material

As a result, satellite observation of microwave radiation and its variability makes it possible to identify and characterize specific surface properties important to weather and climate, such as soil moisture, snow cover and water equivalent, sea ice cover and age, and SST.
Example of polarization dependent transmissivity:
Background of L-band Microwave Radiometry

Direct Methods:
The demanded quantity is directly measured.
E.g. the soil water content results from the mass loss measured after drying a soil sample.

Indirect Methods:
An other physical quantity (a proxy-quantity) which can be related to the demanded quantity is deduced.
E.g. the dielectric constant (permittivity) is the well suited proxy for deriving soil moisture.

The Pros and Cons:
Direct methods are generally more accurate, but also more laborious.
Direct methods are important for calibrating indirect methods.
Indirect methods often require models.
Indirect methods allow for remote sensing of quantities.
Permittivity; Dielectric Constant

The permittivity of water is $\varepsilon_W \approx 80$ at frequencies $< 2$ GHz. This is significantly larger than the permittivities of all the other soil components.

- dry soil matrix: $\varepsilon_M \approx 2.5$
- Air: $\varepsilon_A \approx 1$
- Ice: $\varepsilon_{\text{Ice}} \approx 3$

The soil permittivity $\varepsilon_S$ is highly sensitive with regard to changes in the soil water content. Therefore $\varepsilon_S$ is the suited proxy for determining the volumetric soil moisture $\theta$ in units of m$^3$m$^{-3}$.

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Water Molecule

Liquid Water

IceWater

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Greatly Enlarged Water Molecule

Water Molecule

Water Molecules at the Surface in a Glass of Water

Cloud Drops within a Cloud

Water in the Soil

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Permittivity; Dielectric Constant

A dipole experiences a torque $M$ when a constant electric field $E$ is applied.

This causes the dipole to align along the field direction.

As the H$_2$O-molecule is highly polar, $M$ is large and therefore:

$\Rightarrow$ strong interaction with $E$

$\Rightarrow \varepsilon_W$ is large!
### Dielectric Constants for Various Materials

<table>
<thead>
<tr>
<th>Common naturally occurring materials</th>
<th>Typical Dielectric Constants between ~1 to 100 GHz $\varepsilon'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, vacuum</td>
<td>1.00059, 1.0 (by definition)</td>
</tr>
<tr>
<td>Ice (fresh, sea)</td>
<td>3.2, 4-8</td>
</tr>
<tr>
<td>Snow (dry, wet)</td>
<td>1.3-1.6, 1.4-1.9</td>
</tr>
<tr>
<td>Permafrost</td>
<td>4-8</td>
</tr>
<tr>
<td>Water (fresh)</td>
<td>80 ($20^\circ\text{C}$, $&lt; 3$ GHz), ↓15-25 ($\sim 3$ GHz) and decreasing with frequency</td>
</tr>
<tr>
<td>Sea water</td>
<td>78 ($20^\circ\text{C}$, $&lt; 3$ GHz), decreasing with frequency</td>
</tr>
<tr>
<td>Sandy soil (dry, wet)</td>
<td>2.5-5, 15-30</td>
</tr>
<tr>
<td>Loamy soil (dry, wet)</td>
<td>4-6, 10-20</td>
</tr>
<tr>
<td>Clayey soil (dry, wet)</td>
<td>4-6, 10-15</td>
</tr>
<tr>
<td>Silts</td>
<td>5-30</td>
</tr>
<tr>
<td>Granite</td>
<td>4-6</td>
</tr>
<tr>
<td>Limestone</td>
<td>4-8</td>
</tr>
<tr>
<td>Salt</td>
<td>4-7</td>
</tr>
</tbody>
</table>
L-band “strategically” positioned

\[ \varepsilon_r = \varepsilon' + i\varepsilon'' \]

where:

\[ \varepsilon_r = \text{complex relative permittivity/complex dielectric constant} \]

\[ \varepsilon' = \text{real component/scattering term or “dielectric constant”} \]

\[ \varepsilon'' = \text{imaginary component/absorption or loss term} \]
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Microwave Dielectric Behaviour of Wet Soil

Evaluates the microwave dielectric behaviour of soil-water mixtures as a function of water content, temperature, and soil textural composition. Results of dielectric constant measurements conducted for five different soil types at frequencies between 1.4 and 18 GHz.

<table>
<thead>
<tr>
<th>No.*</th>
<th>Designation</th>
<th>Soil Type</th>
<th>Soil Texture (%)</th>
<th>Soil Specific Surface, m²/g</th>
<th>Cation Exchange Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Field 1</td>
<td>Sandy Loam</td>
<td>51.51</td>
<td>35.06</td>
<td>13.43</td>
</tr>
<tr>
<td>2</td>
<td>Field 2</td>
<td>Loam</td>
<td>41.96</td>
<td>49.51</td>
<td>8.53</td>
</tr>
<tr>
<td>3</td>
<td>Field 3</td>
<td>Silt Loam</td>
<td>30.63</td>
<td>55.89</td>
<td>13.48</td>
</tr>
<tr>
<td>4</td>
<td>Field 4</td>
<td>Silt Loam</td>
<td>17.16</td>
<td>63.84</td>
<td>19.00</td>
</tr>
<tr>
<td>5</td>
<td>Field 5</td>
<td>Silty Clay</td>
<td>5.02</td>
<td>47.60</td>
<td>47.38</td>
</tr>
</tbody>
</table>

Waveguide Transmission System: 1.4, 4.0, 4.5, 5.0, 5.5, 6.0 GHz
Free-Space Transmission System: 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0, 18.0 GHz
Microwave Dielectric Behaviour of Wet Soil

Comparison of soil dielectric measurements made by the waveguide and free-space techniques at 6 GHz.

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Good agreement achieved for both $\varepsilon'$ and $\varepsilon''$ over the range of $m_v$. 
Soil-moisture content is commonly expressed in gravimetric or volumetric units. Electromagnetically, the volumetric measure is preferred because the dielectric constant of the soil-water mixture is a function of the water volume fraction in the mixture.

Measurements made for two soil samples with approximately the same $m_v$ but significantly different bulk densities resulted in significantly different values for $\varepsilon'$ and $\varepsilon''$, but samples with the same $m_v$ and different bulk densities resulted in approximately the same values for $\varepsilon'$ and $\varepsilon''$. 

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Fig. 6. Measured dielectric constant for five soils (see Table I for textural composition of the indicated soil types) at (a) 1.4 GHz, (b) 5 GHz, (c) 10 GHz, and (d) 18 GHz.
The behavior of $\varepsilon''$ can be explained by two phenomena. At the low end of the frequency range, i.e., at frequencies of less than $\approx 5.0\ \text{GHz}$, the effective ionic conductivity of the soil solution is dominant, whereas at higher frequencies, the dielectric relaxation of water is the principal mechanism contributing to loss. The effective conductivity is due to the presence in the soil liquid of salts composed primarily of calcium. The concentration of these salts increases with the clay fraction of the soil; hence, the soil having the greatest clay fraction (Field 5) has the highest $\varepsilon''$ at 1.4 GHz. For a given soil, the volume fraction of bound water is proportional to the soil specific surface, which increases from about 50 $\text{m}^2/\text{g}$ for Fields 1 and 2 to 252 $\text{m}^2/\text{g}$ for Field 5. If bound water possesses dielectric properties significantly lower than those of bulk water (for example, ice with $\varepsilon' = 3.15$ and $\varepsilon'' \ll 0.1$), then at higher frequencies, where the contribution of conductivity to $\varepsilon''$ is no longer significant, $\varepsilon''$ will be proportional to the volume fraction of bulk water. Since Fields 1 and 2 have the lowest specific surface, they will have the least bound water and conversely the most bulk water at a given $m_v$ compared to Field 5; consequently, $\varepsilon''$ is highest for Field 5 at frequencies $\geq 8.0\ \text{GHz}$.

In Fig. 6, sandy soils are shown to have the highest $\varepsilon'$ at all frequencies. This is to be expected from the standpoint of both bound water and soil salinity, since $\varepsilon'$ of bound water is less than $\varepsilon'$ of bulk water, and $\varepsilon'$ of saline water is less than $\varepsilon'$ of pure water. Of the soils measured, the soils highest in sand content have the least specific surface and hence the lowest bound-water volume fraction; they also have the lowest cation exchange capacity, which is related to the effective salinity of the soil solution.
Fig. 7. Measured dielectric constant at 4, 10, and 18 GHz for (a) Field 1, (b) Field 3, and (c) Field 5. Polynomial regression fits are also shown.
C. Frequency Behavior

The frequency behavior of the dielectric constant of moist soils is shown in Fig. 7 at frequencies of 4, 10, and 18 GHz for Fields 1, 3, and 5 as measured by the free-space system. For all soils, the results indicate that $\varepsilon'$ decreases and $\varepsilon''$ increases with increasing frequency from 4 to 18 GHz. At frequencies of less than 4 GHz, the conductivity term becomes increasingly important. This effect is shown in Fig. 8, in which the measured dielectric constant of Field 2 (loam) is plotted as a function of frequency for various soil-moisture conditions. Fig. 8 includes data at 1.4 GHz measured by the waveguide technique and at 3 GHz measured by the free-space technique, and shows a minimum in $\varepsilon''$ in the vicinity of 3 GHz. The precise location of this minimum cannot be determined without additional waveguide measurements between 2 and 4 GHz. For $\varepsilon'$ at all frequencies and $\varepsilon''$ above 3 GHz, the dielectric constant varies with frequency at a rate similar to that of pure water, which is shown in Fig. 8 for reference.
Effective Media Models (dielectric mixing approaches):

Such models are used to represent the effective permittivity “seen” by a electromagnetic field with a wavelength considerably larger than the dimension of the dielectric inhomogenities.

These methods can be used to model effective permittivities of:
- Canopies (Grass)
- Leaf litter
- Transition layers (roughness)
- Clouds
- Rain
- Effective media approaches can be applied in the regime of physical optics.

- Physical optics is an intermediate method between geometric optics, which ignores wave effects, and full wave electromagnetism, which is a precise theory.
Example of a physical mixing model for the effective permittivity of a moist soil:

Three phases: Spherical air bubbles and grains embedded in water:

Maxwell-Garnett formula:

\[ \varepsilon_s = \varepsilon_w + 3\varepsilon_w \frac{(1-\eta) \frac{\varepsilon_M - \varepsilon_w}{\varepsilon_M + 2\varepsilon_w} + (\eta - \theta) \frac{\varepsilon_A - \varepsilon_w}{\varepsilon_A + 2\varepsilon_w}}{1 - (1-\eta) \frac{\varepsilon_M - \varepsilon_w}{\varepsilon_M + 2\varepsilon_w} + (\eta - \theta) \frac{\varepsilon_A - \varepsilon_w}{\varepsilon_A + 2\varepsilon_w}} \]

- \( \eta \) = porosity
- \( \theta \) = volumetric water content
- \( \varepsilon_A, \varepsilon_w, \varepsilon_M \), permittivities of air, water, and matrix (grains)

Not only the fractional amount of the phases determines the effective permittivity, but also the structure of phases!!
Example of empirical mixing models for the effective permittivity of a moist soil:

Polynomial fit to $\varepsilon_S$ measured for soils with different moisture $\theta$

Topp et al. (1980): \[
\theta = 4.3 \cdot 10^{-6} \varepsilon_S^3 - 5.5 \cdot 10^{-4} \varepsilon_S^2 + 2.92 \cdot 10^{-2} \varepsilon_S - 5.3 \cdot 10^{-2}
\]

Semi-empirical relation (three phases, parameter $\alpha = 0.46$)

Roth et al. (1990): \[
\varepsilon_S = \left[ \theta \cdot \varepsilon_w^\alpha + (1-\eta) \cdot \varepsilon_M^\alpha + (\eta - \theta) \cdot \varepsilon_A^\alpha \right]^{1/\alpha}
\]
Brightness Temperature $T_B^p (p = H, V)$

The brightness temperature $T_B^p$ of

- a black body ($e = 1$) is: $T_B^p = T$
- a gray body ($0 < e < 1$) is: $T_B^p = e \cdot T$
- a perfectly reflecting body ($e = 0$) is: $T_B^p = 0$

In thermal equilibrium emissivity and reflectivity are related via:

$$e = 1 - r$$

Reflectivity of a specular surface is given by the Fresnel equations:

$$r^H (\theta) = \left| \frac{\cos \theta - \sqrt{e - \sin^2 \theta}}{\cos \theta + \sqrt{e - \sin^2 \theta}} \right|^2$$

$$r^V (\theta) = \left| \frac{e \cos \theta - \sqrt{e - \sin^2 \theta}}{e \cos \theta + \sqrt{e - \sin^2 \theta}} \right|^2$$

This is why $T_B^p = (1 - r^p) \cdot T$

depends on the permittivity $e$ which serves e.g. as a proxy for water content.

Nature is much more complex

$\Rightarrow$ sophisticated models for $r^p$ and $T$ are needed!
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Estimation of Soil Moisture
The amount of microwave radiation emitted by the Earth’s surface depends on interactions between energy and the various characteristics and elements that make up the surface.

The two properties that have a significant impact on emitted microwave radiation are polarization and the dielectric effect. Each property varies by wavelength and the physical characteristics of the emitting and/or reflecting material. This makes it possible to discriminate between solid, liquid, and frozen elements on both land and ocean surfaces.
For open regions with relatively sparse vegetation, the moisture content of the surface soil is the dominant factor in the surface emission of microwave radiation. One of the more important electromagnetic properties of a surface in the microwave region is the **dielectric effect**. The dielectric effect accounts for the majority of the reflection and scattering as radiation interacts with the surface molecules, and is commonly quantified by a term known as the **dielectric constant**.

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How does a Wet vs. Dry Surface Appear from Space?

Dry vs. Wet Surface

The introduction of water to soil results in a dramatic increase in the dielectric constant, and correspondingly a decrease in soil emissivity. This is easily detectable by a passive microwave remote sensor as a relatively cold brightness temperature, as we will see later in this section.
How does a Wet vs. Dry Surface Appear from Space?

Dry vs. Wet Surface

If we isolate the dry land, wet land, and sea water curves for a moment, we see dramatic differences between the three surface types. Emissivity over land can vary strongly, with surface type and frequency in the microwave between 10 and 100 GHz. Notice how much the emissivity is reduced for wet surfaces compared to dry land, especially at the lower frequencies.

Adapted from Dr. Norman C. Grody

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How does a Wet vs. Dry Surface Appear from Space? Dry vs. Wet Surface

This graph plots emissivity for vertically polarized radiation as a function of different magnitudes of surface wetness. The curves help illustrate two important points. First, as more water is introduced to a surface, the smaller its emissivity, and second, the effect is more pronounced at lower frequencies. We should note that emissivity increases with increasing frequency and that this trend is especially pronounced for a wet surface. Most algorithms that compute some measure of surface wetness, like a wetness index, take advantage of the change in microwave emissivity as water is introduced.

This can be accomplished by calculating brightness temperature differences between high and low frequencies, or by comparing how a single frequency responds when compared to a reference observation for dry conditions. Derivation of soil moisture content is a more complex process that typically involves models and climatology information of the soil layer itself.

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How does a Wet vs. Dry Surface Appear from Space?

Dry vs. Wet Surface

Soil moisture signature observed ~150 km NNW of Des Moines, Iowa on July 4, 2002 using the NOAA PSR/CX imaging radiometer. Area shown was imaged using the C-band (6-8 GHz) radiometer.
How does a Wet vs. Dry Surface Appear from Space?

Dry vs. Wet Surface

Soil Penetration Depth as a Function of Frequency

<table>
<thead>
<tr>
<th>Frequency (GHz), Wavelength (cm)</th>
<th>Dry Soil Penetration Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8 to 7 GHz, ~4.3 cm</td>
<td>4.5</td>
</tr>
<tr>
<td>10 GHz, 3 cm</td>
<td>3</td>
</tr>
<tr>
<td>19, 23.8 GHz, ~ 1.3 cm</td>
<td>1.4</td>
</tr>
<tr>
<td>85, 89 GHz, ~0.34 cm</td>
<td>0.34</td>
</tr>
</tbody>
</table>

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How does a Wet vs. Dry Surface Appear from Space? 

Dry vs. Wet Surface

Soil Penetration Depth as a Function of Moisture Content

By increasing soil moisture content, the penetration depth decreases. Recall that a relatively wet layer of soil scatters and reflects more energy and thus has a lower emissivity than dry soil. This increased scattering and reflection blocks a portion of the radiation from reaching the surface so that a satellite senses less and less energy from progressively deeper layers.

Note that the figure also reinforces the advantage of using lower frequencies (longer wavelengths) because of their ability to penetrate deeper into the soil.

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Surface Roughness Effects on Brightness Temperature

Surface roughness increases the emissivity of natural surfaces, and is caused by increasing scattering due to the increase in surface area of the emitting surfaces.
Soil Type Effects
Soil dielectric constant as a function of soil moisture for three generic soils

The basis for microwave remote sensing of soil moisture follows from the large contrast in $\varepsilon$ for dry soil (~4) and water (~80) and the resulting dielectric properties of soil-water mixtures (~4 - 40) and their effect on the natural emission from the soil

$\varepsilon'$ (real part) determines propagation characteristics of the energy as it passes upward through the soil

$\varepsilon''$ (imaginary part) determines energy losses
Passive Microwaves. Introduction
Rayleigh-Jeans Law. Background
Factors Affecting Emissivity
Polarization
Estimation of Soil Moisture
Microwave Dielectric Behaviour of Wet Soil

Polarization Effects
Soil emissivity at H and V at a frequency of 6.6 GHz and an incidence angle of 50°

While the emissivity is lower at H pol, the sensitivity to changes to SM is significantly greater than at V pol
One property important in the microwave region of the electromagnetic spectrum is **polarization**. Microwave remote sensing instruments take advantage of how materials differentially polarize microwave energy to observe and characterize atmospheric constituents like clouds and precipitation, land, and ocean surfaces.

**Example of polarization dependent transmissivity**
Polarization refers to the orientation of the electric field vector of an electromagnetic wave as it is emitted, reflected, or transmitted by a material or medium such as a gas. This graphic shows microwave energy polarized in a vertical orientation. Microwave energy can be emitted in six polarization states, vertical, horizontal +45 and -45 deg, and right hand and left hand circular. Observing the polarization state and how it changes provides important information to build a variety of products such as ocean surface wind speed, snow and ice cover, and to help distinguish between surface features such as soil moisture and vegetation.
Brightness temperature for September with the same incidence angle of $\theta = 55^\circ$ and with H polarization (left) and V polarization (right)
Polarization: Additional useful information to obtain geophysical variables

Pellarin et al.,

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Most naturally emitted microwave energy is essentially unpolarized. That is, the electric field vector traces the motion of the electromagnetic wave, which oscillates randomly in all directions as it passes along the Z-axis. Energy can become partially polarized through interaction with various elements in the Earth-Atmosphere system. In other words, the oscillation of the electric field vector exhibits a predictable pattern of behavior that can be observed and used to infer specific properties of that element.

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Vertically polarized electromagnetic energy is characterized by an electromagnetic wave where the wave and its electric field vector, shown by the arrow, oscillate in only one plane, shown here as the Y direction.

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For **horizontally polarized electromagnetic energy**, the wave and its electric field vector oscillate in a single horizontal plane, shown here in the X direction.

Horizontal and Vertical Polarization

http://www.meted.ucar.edu/npoess/microwave_topics/resources/s8flyout.htm

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Polarization:
Additional useful information to obtain geophysical variables
Polarization

additional useful information to obtain geophysical quantities

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Vegetation
Vegetation
Figura 17
Relación entre la emisividad y el contenido en humedad volumétrico para una arena desnuda y muy poco rugosa a 1.4 GHz.

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Passive Microwaves. Introduction
Rayleigh-Jeans Law. Background
Factors Affecting Emissivity
Polarization
Estimation of Soil Moisture
Generalized Microwave Soil Moisture Retrieval Process

- Moisture
- Dielectric constants

Soil model

- Vegetation
- Soil type
- Depth
- Stratification
- Surface roughness

Soil Moisture Product

* AMSR-E Land Soil Moisture 28 Aug 2006
* NOAA / NESDIS

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Figure 7
Schematic overview of factors influencing the brightness temperature of a complex, vegetation covered surface (from: Van de Griend and Owe, 1993b).