Physical Principles of Passive Microwave Radiometry. Soil Moisture

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

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with contributions from Mike Schwank and Jean-Pierre Wigneron

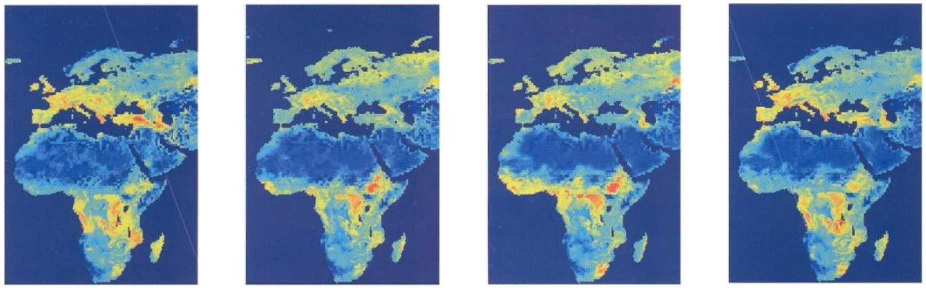
What is remote sensing:
Observing an object with an instrument that is in a certain distance to this object.

Applications of remote sensing:
soil sciences | **climate, meteorology** | **dydrology**
geology | **cartography** | **astronomy**

Why remote sensing:
large scale | **areal statistics**
accessibility | **costs**

Goal of SMOS mission:
Global water content and ocean salinity data.

θ [$m^3 m^{-3}$]



Spring *Summer* *Autumn* *Winter*

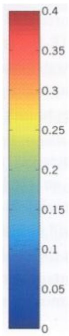
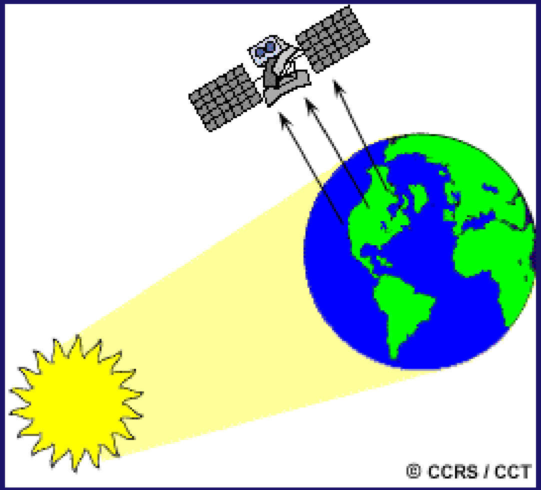


photo
Apollo 17, 1972

Introduction

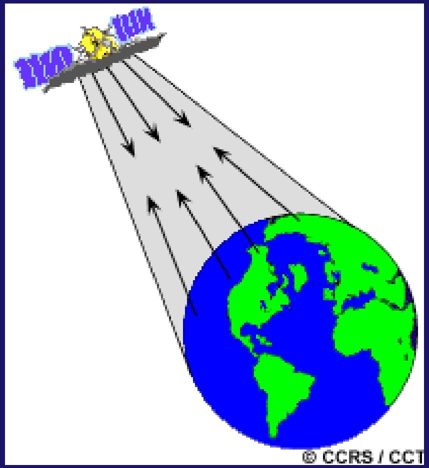
Passive Sensors

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



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)

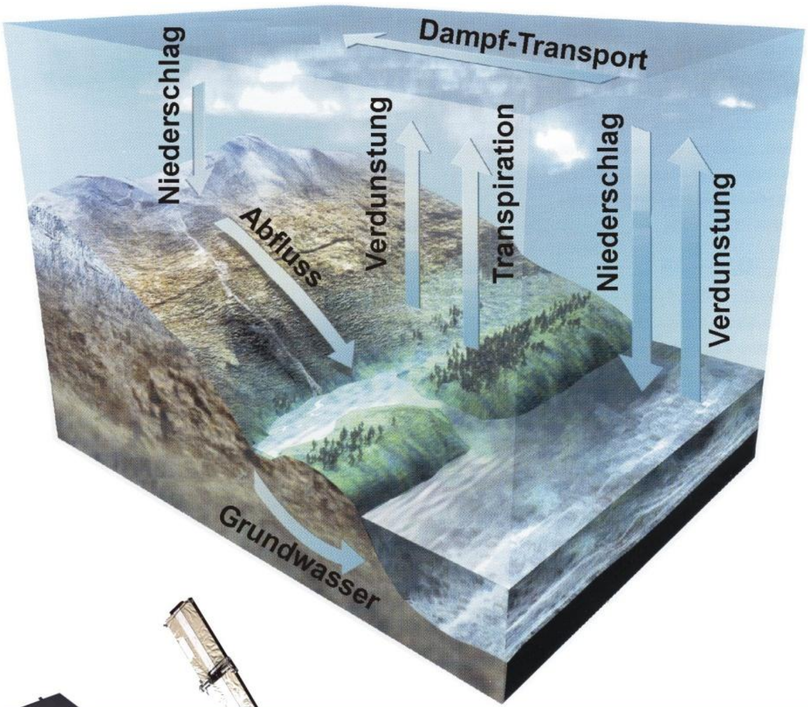
Microwave remote sensing is less than 100 years old

- 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

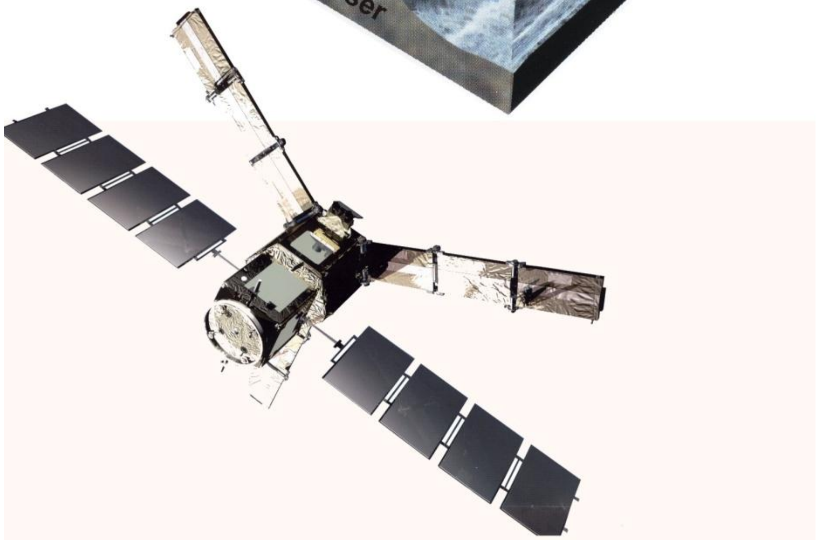
Why this is interesting:

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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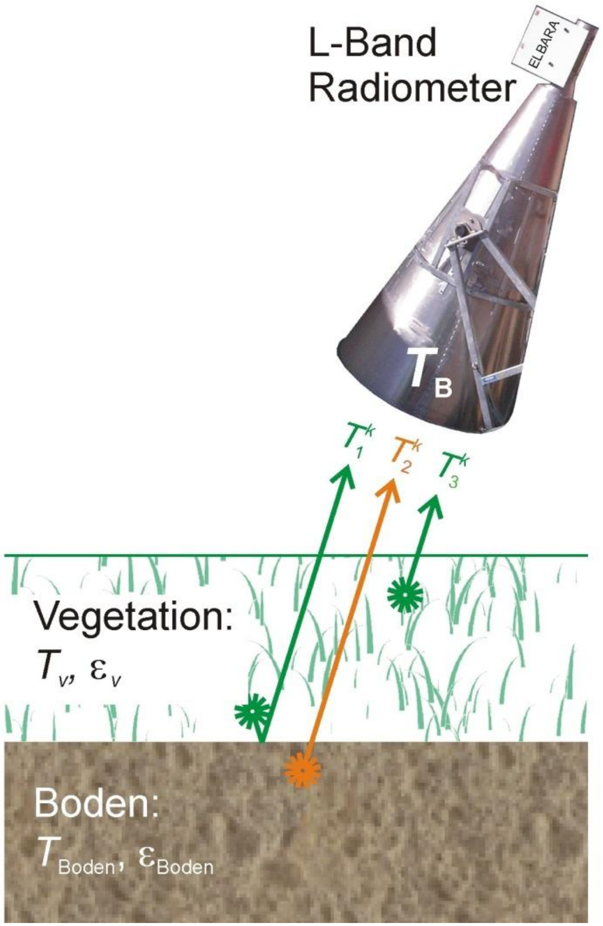
How it works:

The electromagnetic radiance T_B (brightness temperature) of an object is determined by:

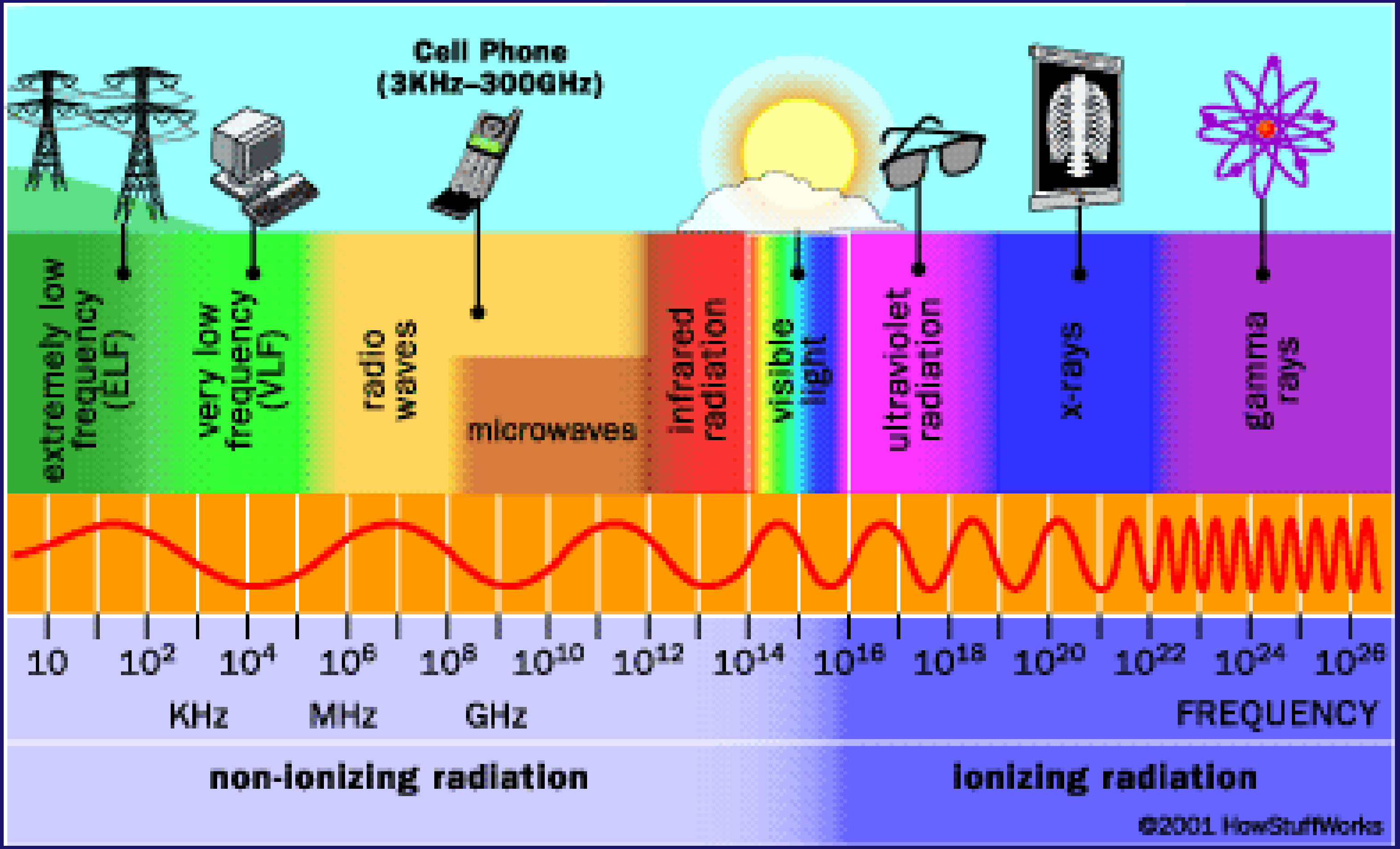
Temperature T and emissivity E.

E depends on the dielectric constant ε of the object, and therefore on the water content θ.

measurement:		model:		result:
T_B	⇨	**Radiative transfer** $T_B = f(T_i, E_i)$ and $E_i = f(\varepsilon_i)$ **Dielectric mixing model** $\varepsilon = f(\theta)$	⇨	$T_B \Rightarrow \theta$



Radiative components in case of a soil covered with vegetation


Cell Phone
(3KHz–300GHz)
extremely low frequency (ELF)
very low frequency (VLF)
radio waves
microwaves
infrared radiation
visible light
ultraviolet radiation
x-rays
gamma rays
10 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22} 10^{24} 10^{26}
KHz MHz GHz
FREQUENCY
non-ionizing radiation
ionizing radiation
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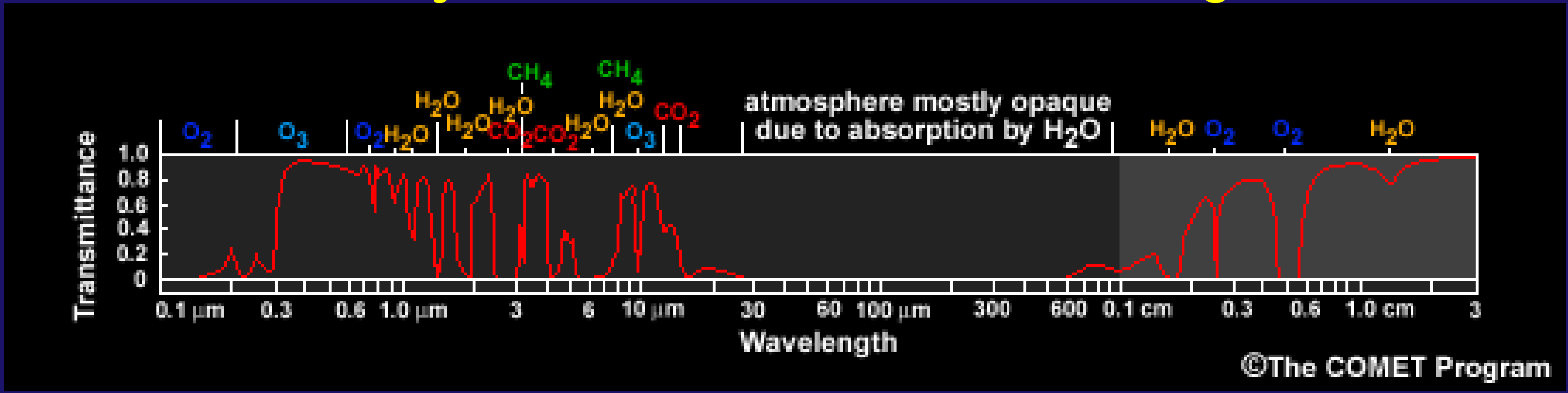
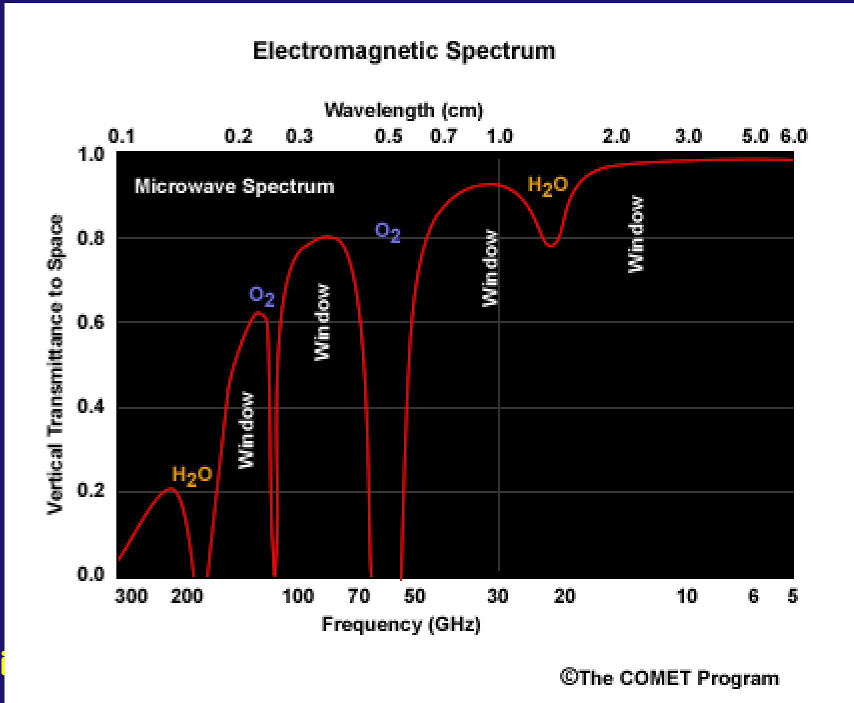
Why Use Microwaves in Remote Sensing?

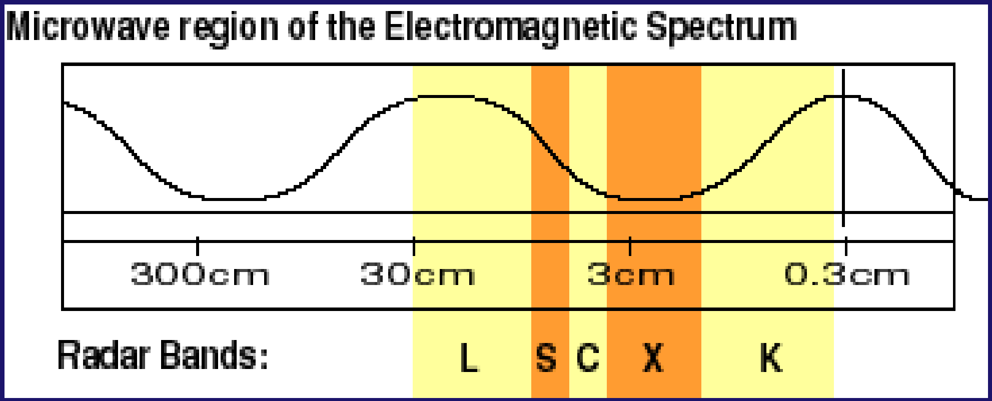


A relatively small portion of the energy is emitted at microwave wavelengths.

"Passive" microwave sensors or radiometers are designed to measure microwave energy at frequencies typically between 6 and 200 GHz (6 to 0.15 cm).

The relatively wide frequency range covered by various remote sensing instruments provides data for a broad range of Earth remote sensing applications. These include detection of cloud microphysics and precipitation, as well as atmospheric and surface applications.

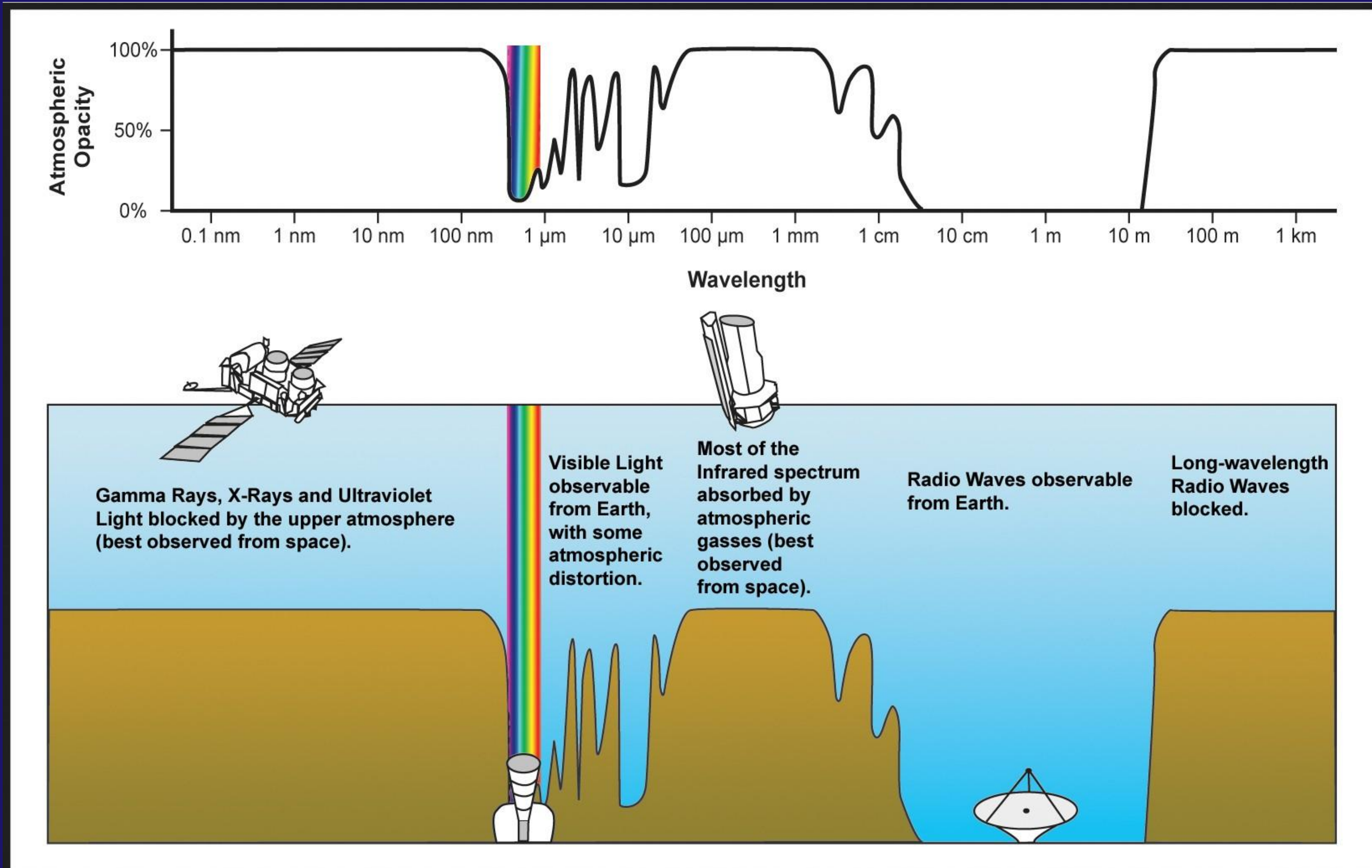




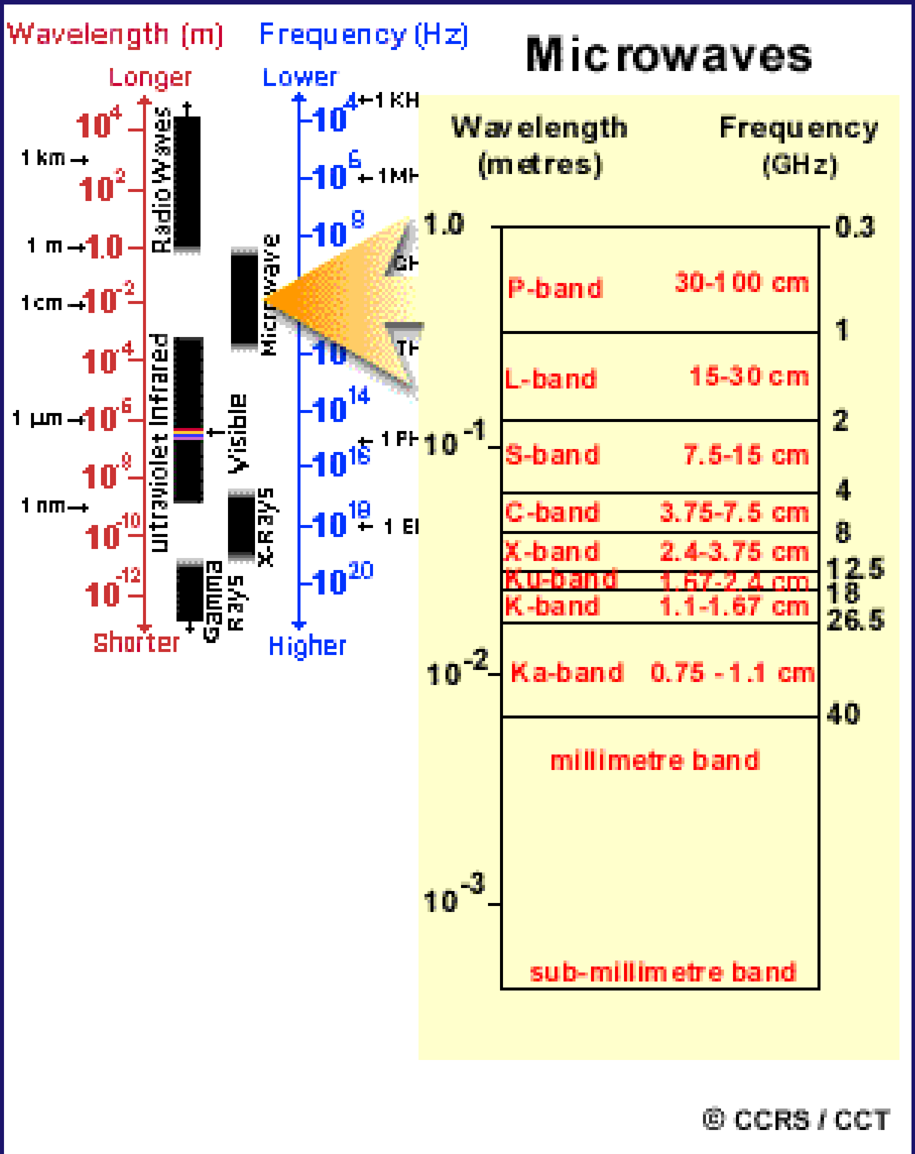
Microwaves have wavelengths that can be measured in centimeters! The longer microwaves, those closer to a foot (30 cm) in length, are the waves which heat our food in a microwave oven.

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.


Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.

The Microwave Spectrum

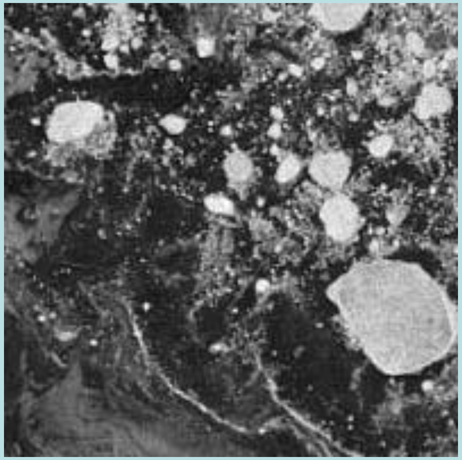


Microwave band codes

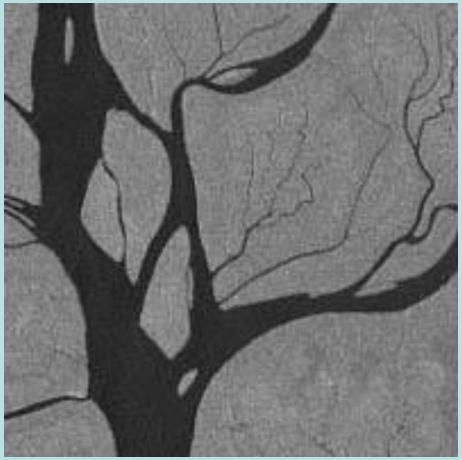
Band	Wavelength, cm	Frequency, GHz
K_a	0.75-1.18	40.0-26.5
K	1.19-1.67	26.5-18.0
K_u	1.67-2.4	18.0-12.5
X	2.4-3.8	12.5-8.0
C	3.9-7.5	8.0-4.0
S	7.5-15.0	4.0-2.0
L	15.0-30.0	2.0-1.0
P	30.0-100	1.0-0.3

Canada Centre for Remote Sensing

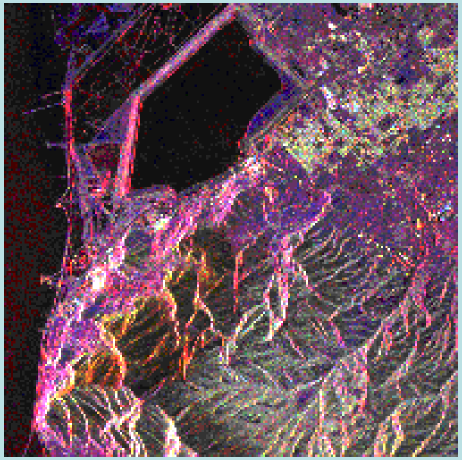
What do Microwaves show us?



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.



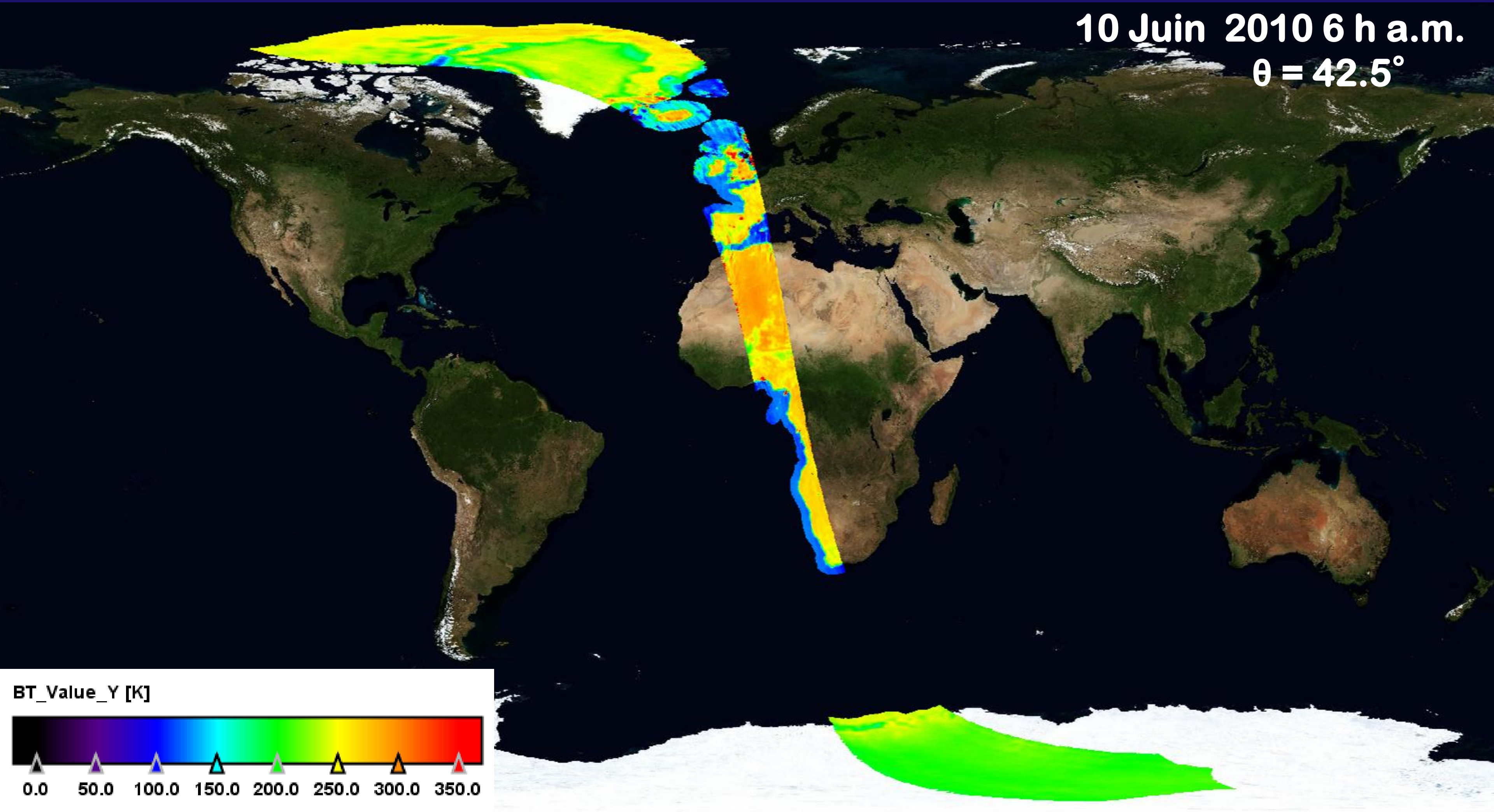
The JERS satellite uses wavelengths about 20 cm in length (L-band). This is an image of the Amazon River in Brazil.



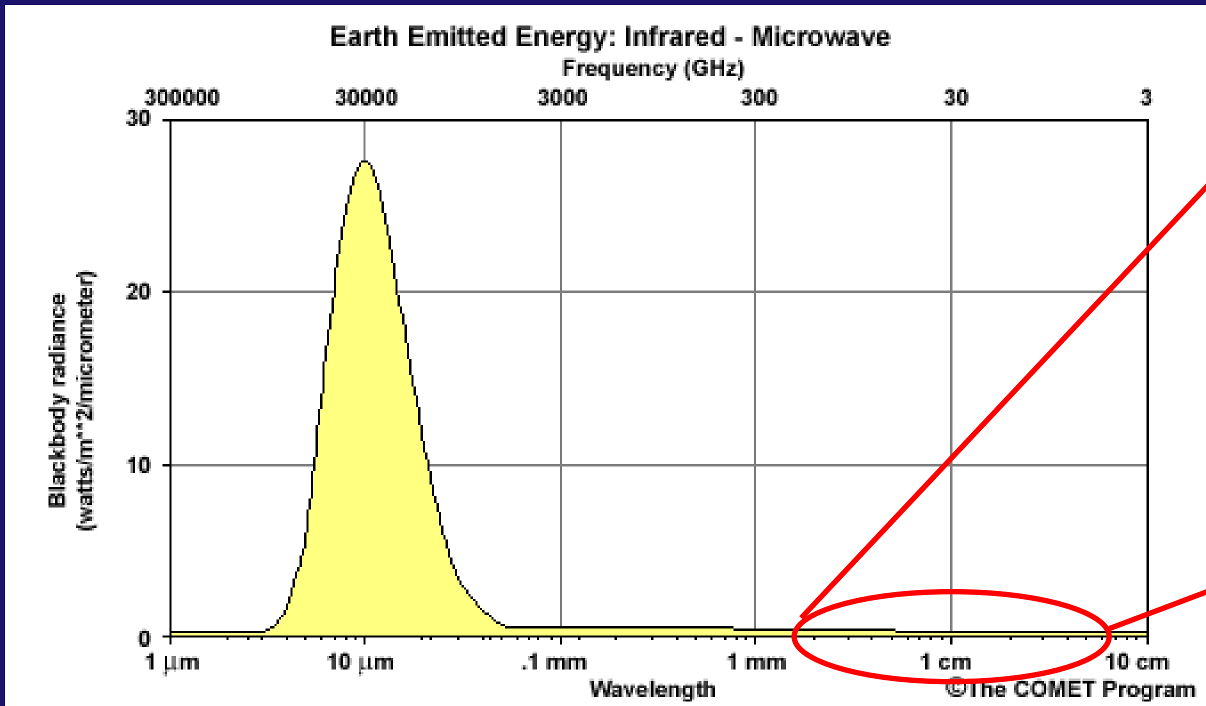
This is a radar image acquired from the Space Shuttle. It also used a wavelength in the L-band of the microwave spectrum. Here we see a computer enhanced radar image of some mountains on the edge of Salt Lake City, Utah.

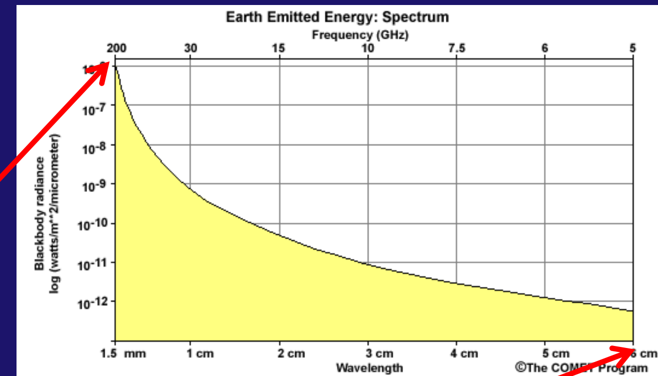
Température de brillance – produit SMOS (S. Juglea)

TB > 230 K : surfaces continentales sèches
180 K < TB < 230 K : surfaces continentales humides
TB < 120 K : eau

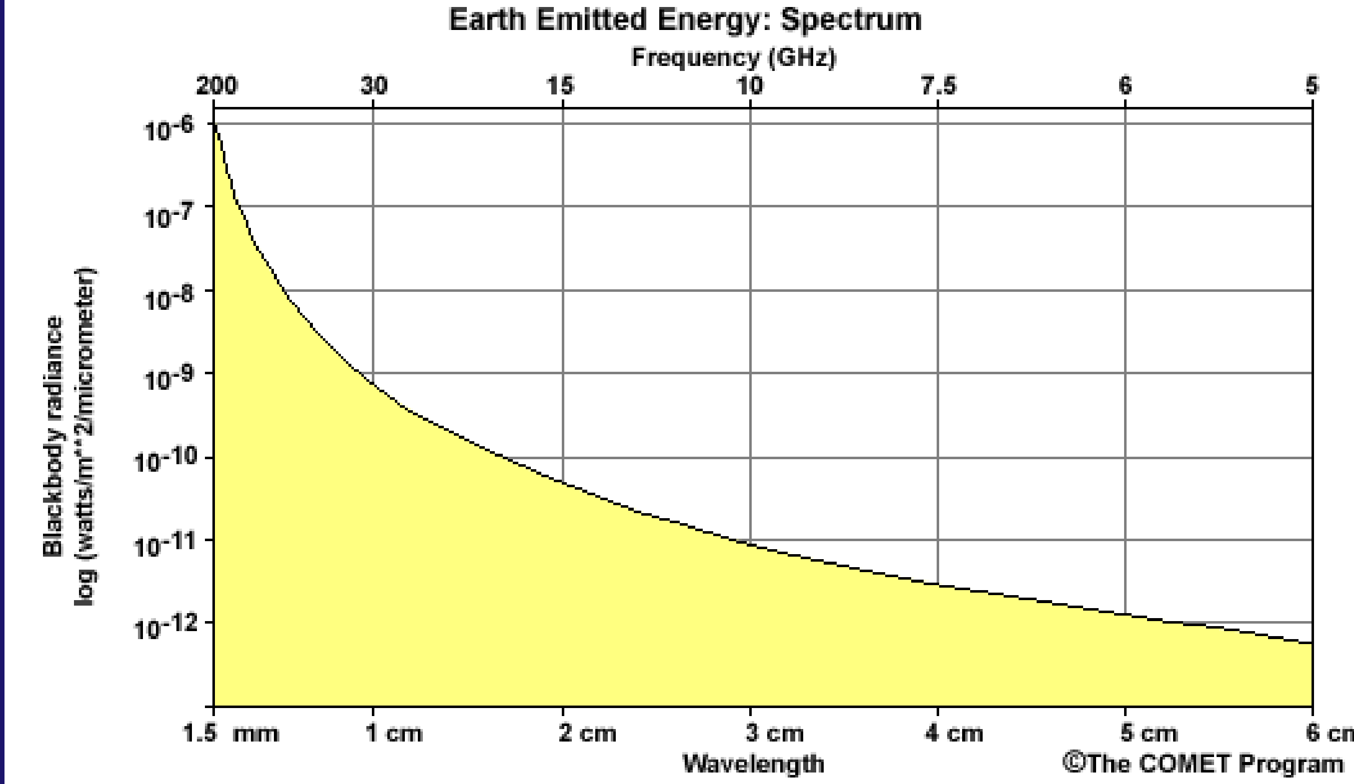


Available Energy for Passive Sensors





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.



Available Energy for Passive Sensors

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

$W = \sigma T B$ → order of 10^{-13} W !!!

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

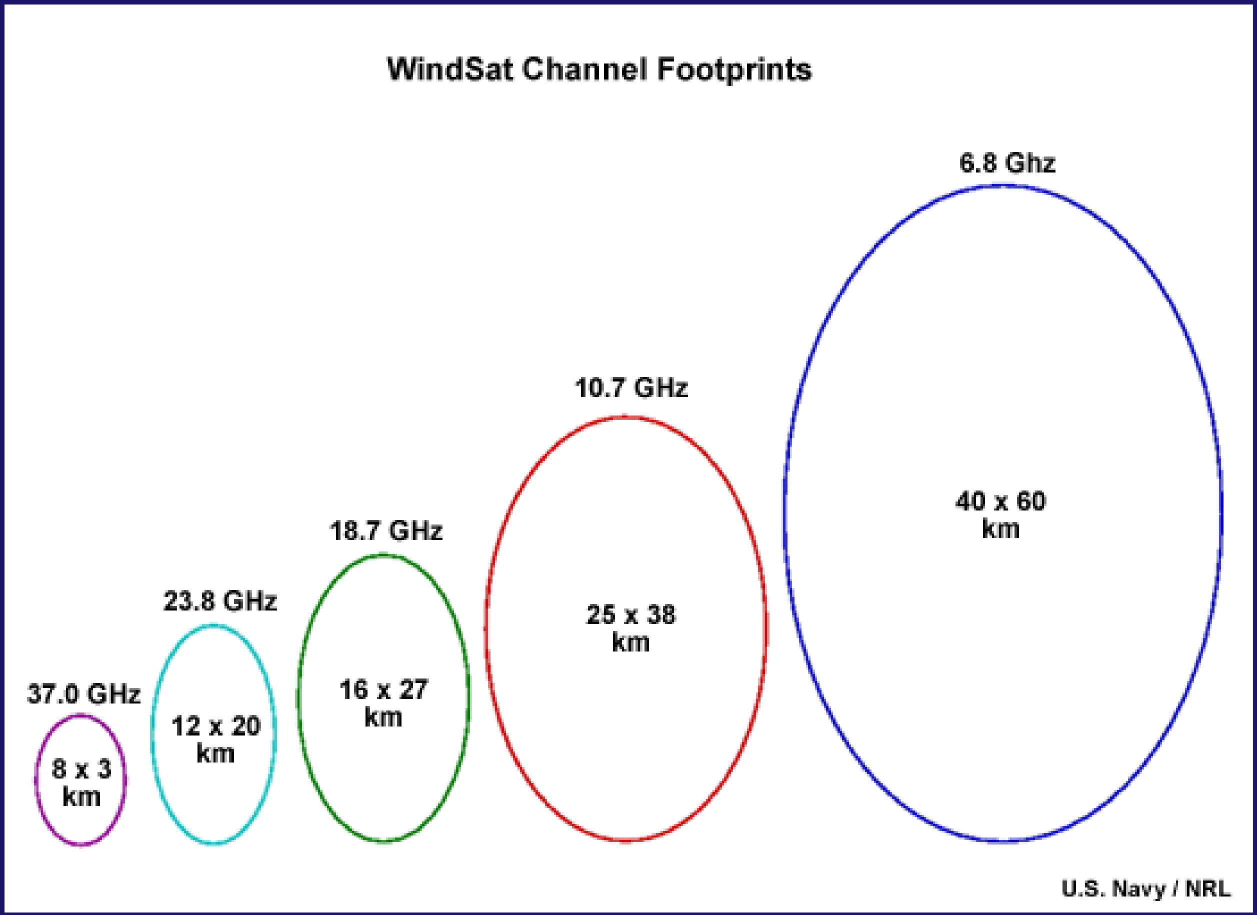
T = Physical temperature (K)

B = 27 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

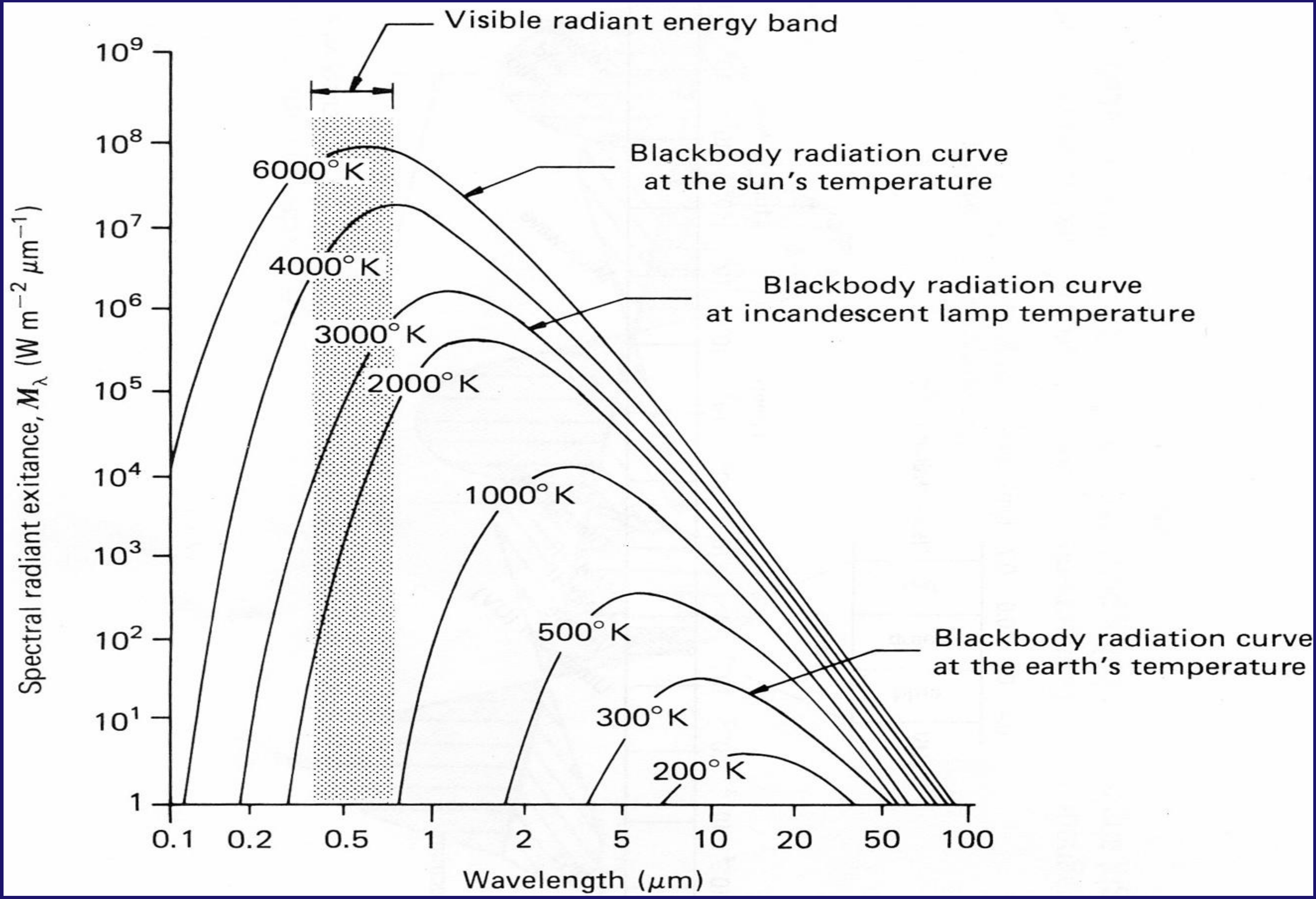
Available Energy for Passive Sensors



The relatively small amount of emitted microwave energy available to passive satellite sensors requires large fields-of-view to collect sufficient energy for a measurement. Thus, in contrast to visible or infrared sensors, where there is sufficient energy for relatively small fields-of-view on the scale of meters (hyperspectral) or kilometers, passive microwave sensors require larger fields-of-view on the scale of 10 km or more.

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.

Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures

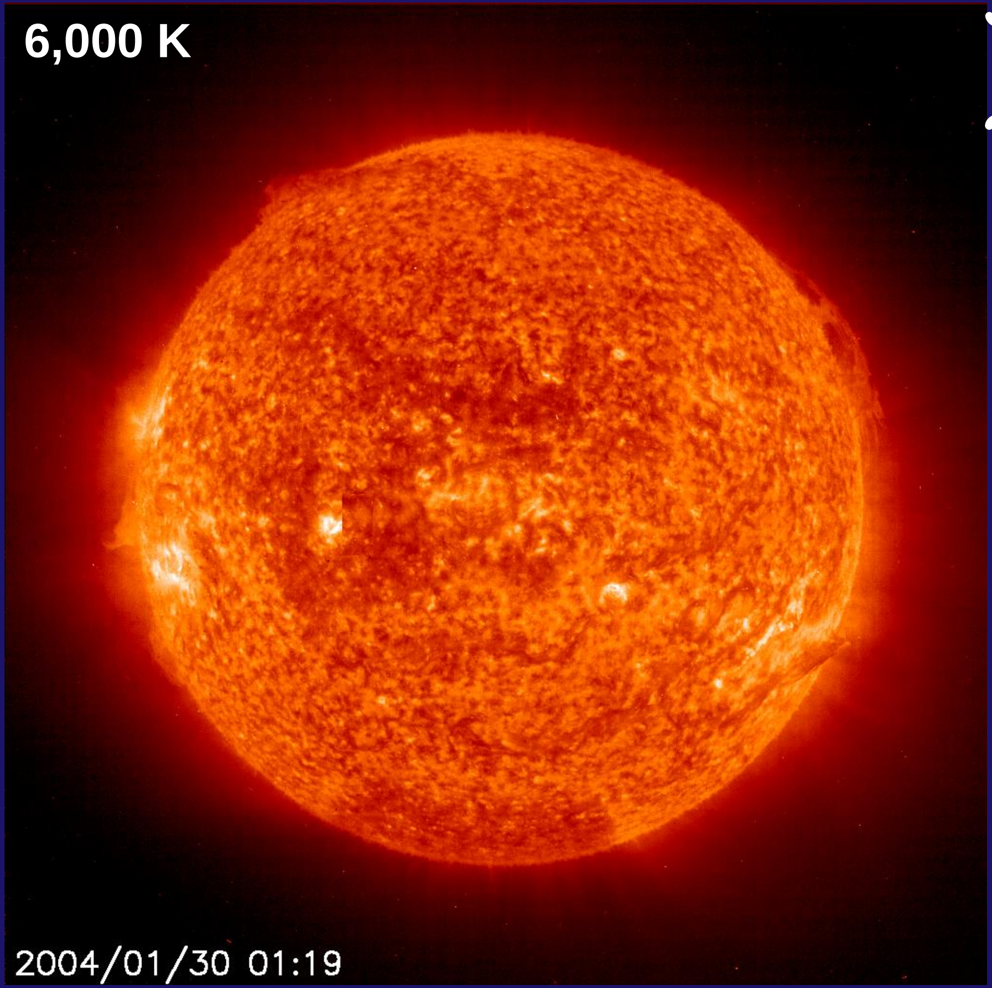


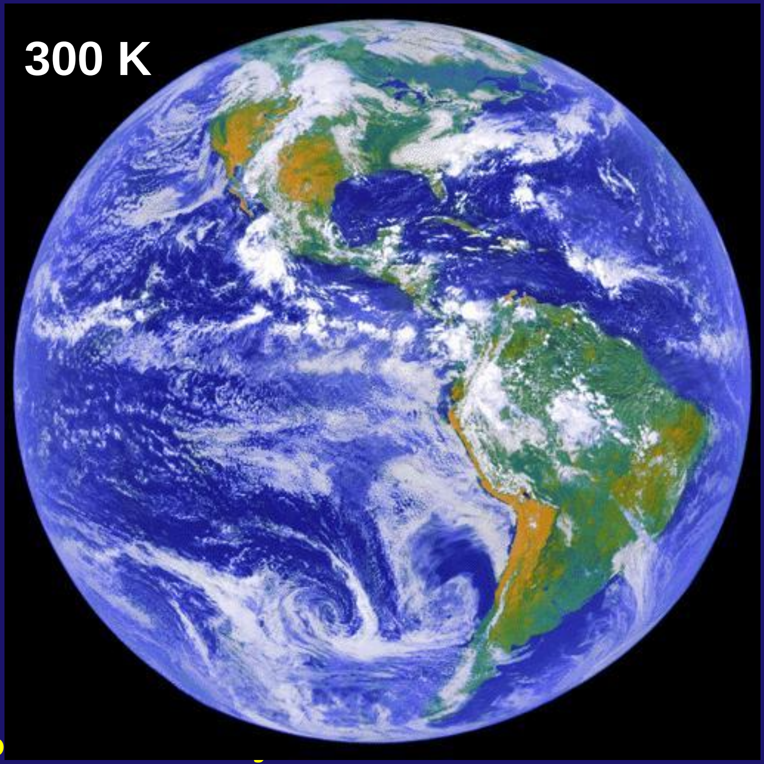
Wien's Law

6000 K → VIS (0.4 μm)

300 K → IR (10 μm)

??? K → μwaves (ex. 20 cm)





the answer is coming up soon …

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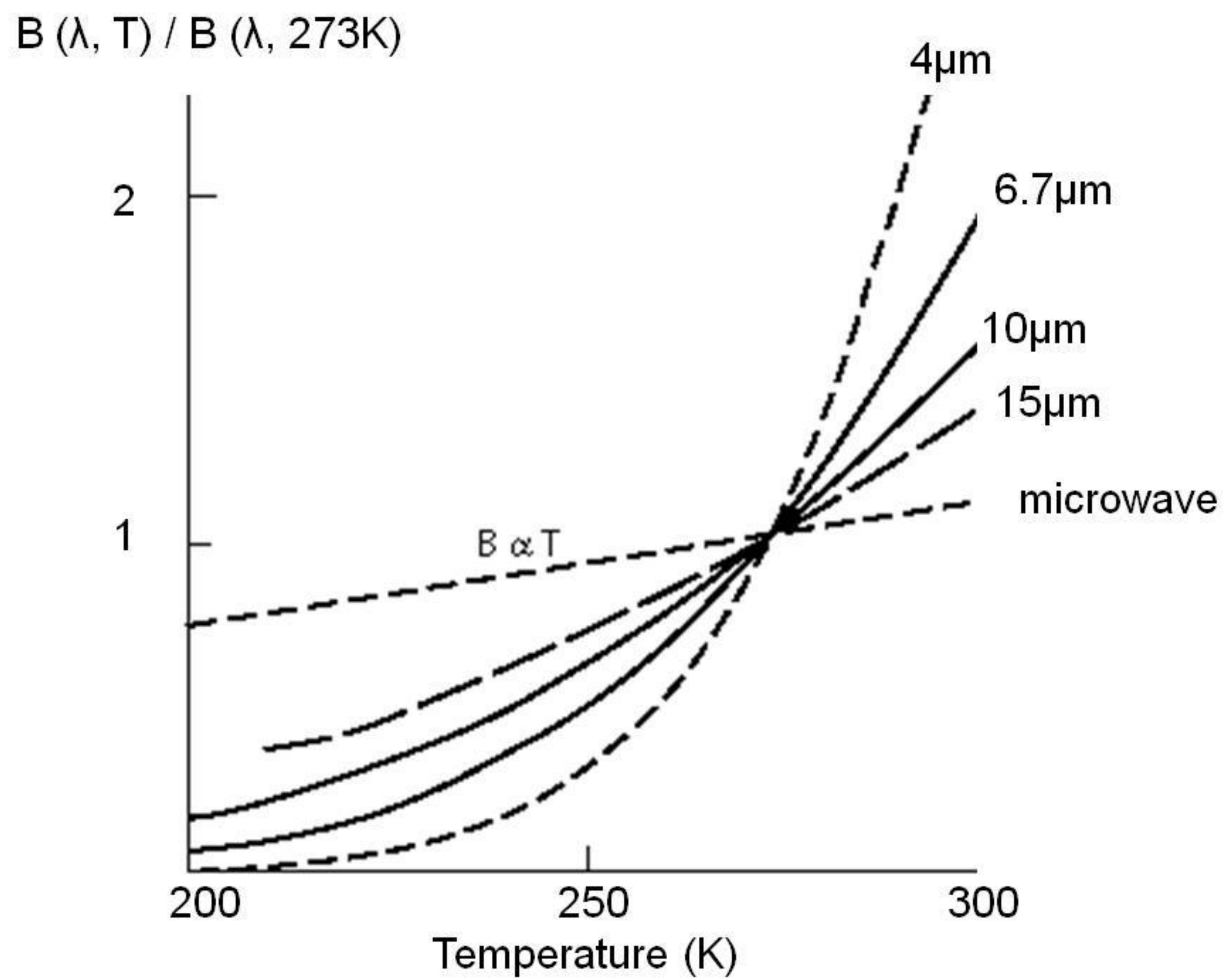
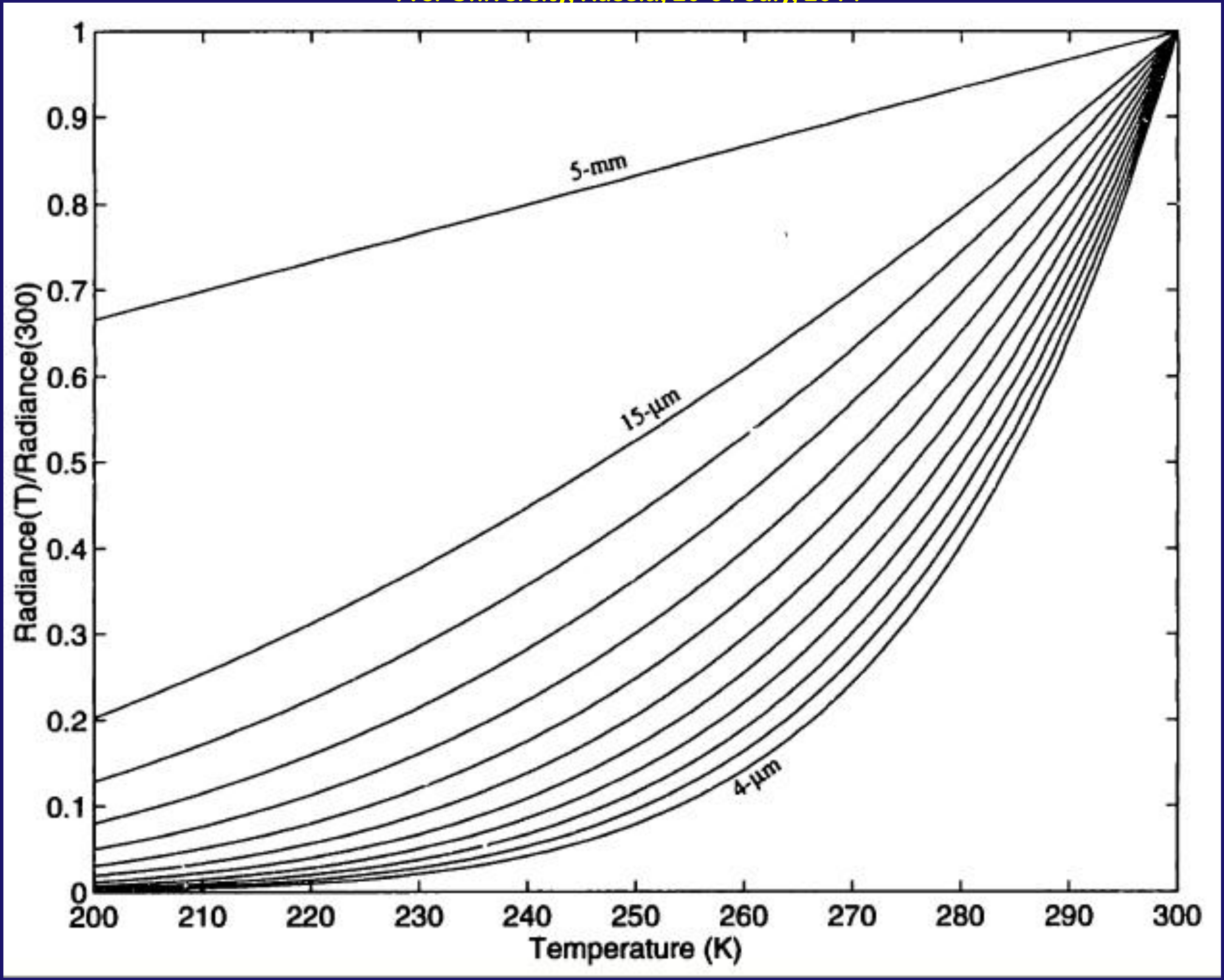
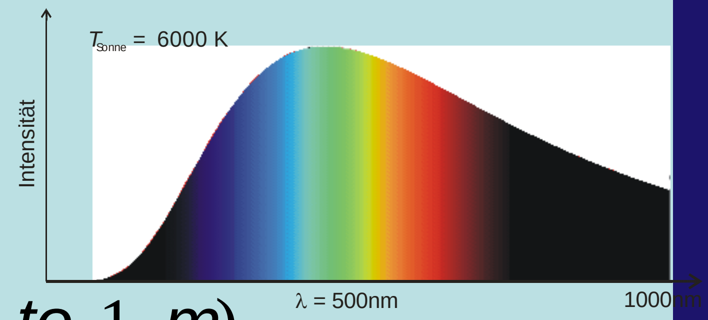
Temperature Sensitivity of B(λ,T) for typical earth scene temperatures




5-mm
15-µm
4-µm
Radiance(T)/Radiance(300)
Temperature (K)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
200
210
220
230
240
250
260
270
280
290
300

Rayleigh – Jeans Approximation



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

In the μwave region (λ from 1 mm to 1 m),

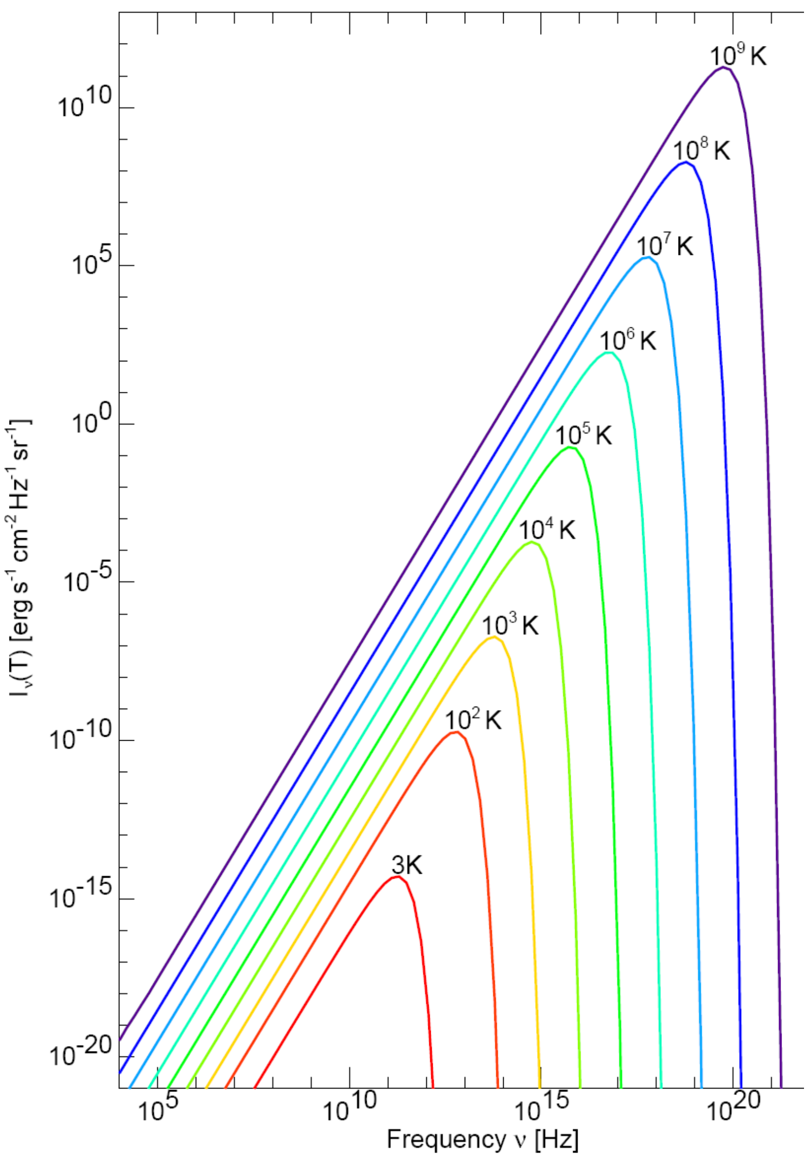
$$c_2 / \lambda T \ll 1, \text{ so that}$$

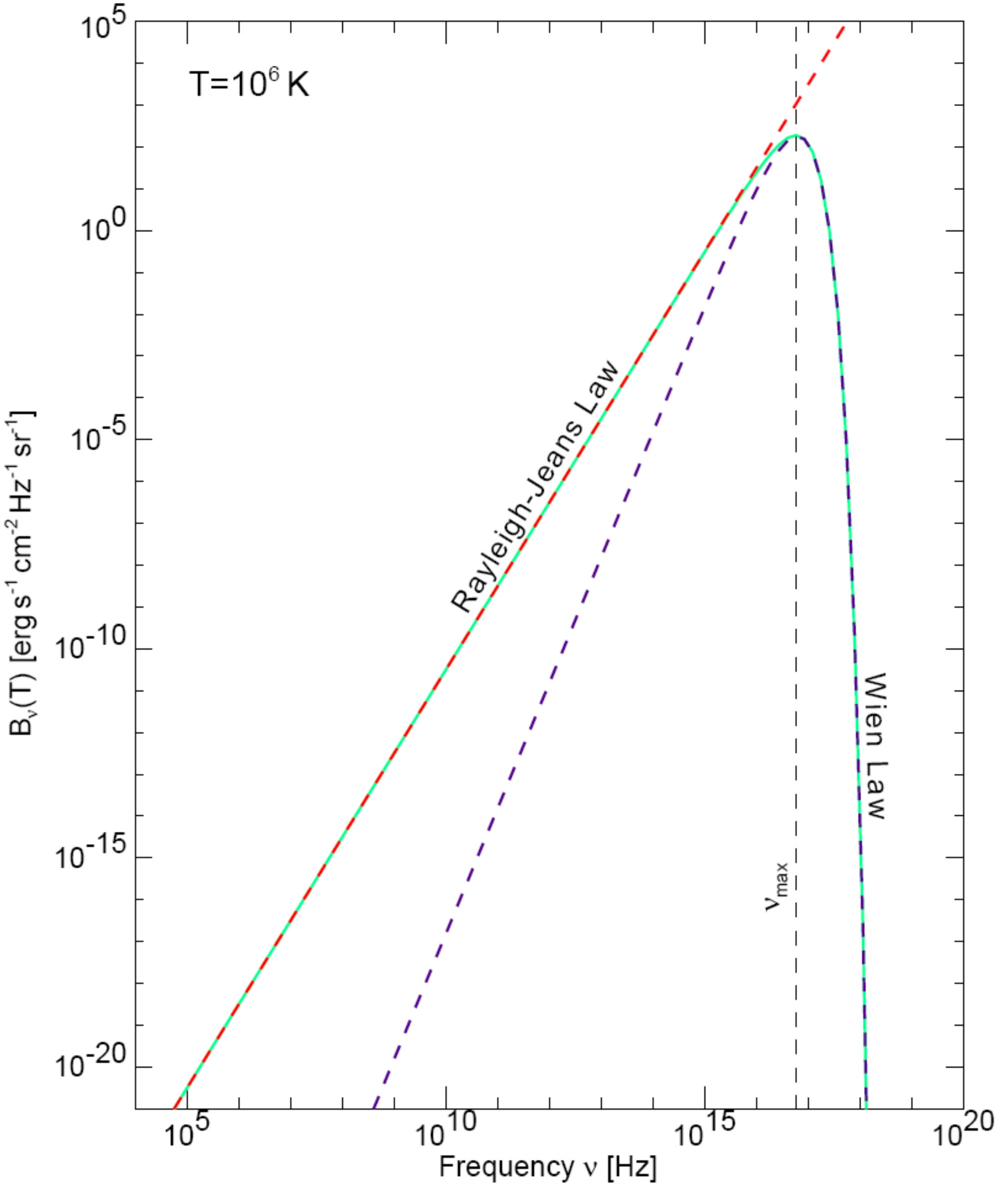
$$\exp\left(\frac{c_2}{\lambda T} \right) = 1 + \frac{c_2}{\lambda T} + \text{second order}$$

and classical Rayleigh - Jeans equation originates

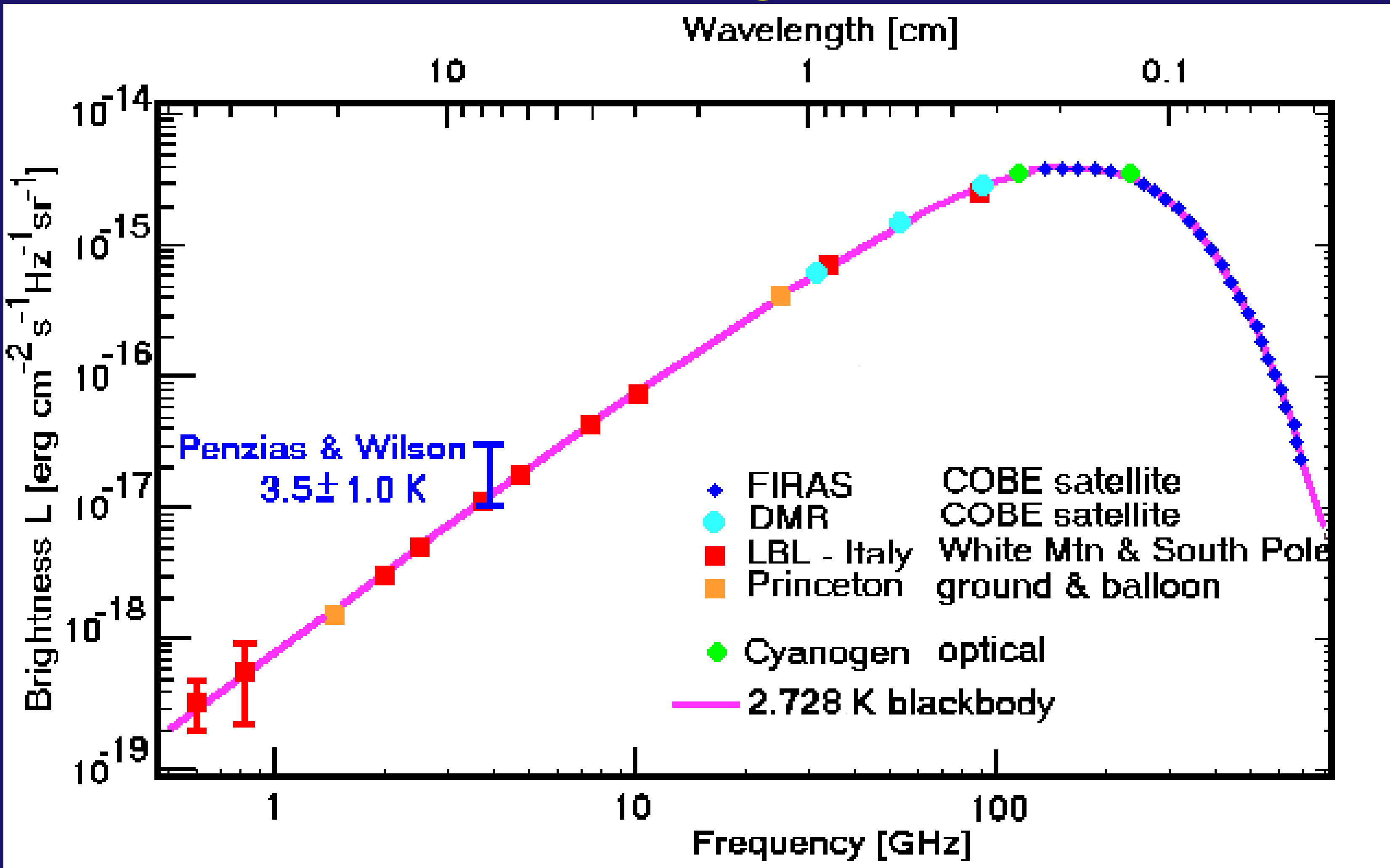
$$B_\lambda(T) \cong \left(\frac{c_1}{c_2} \right) \left(\frac{T}{\lambda^4} \right)$$

$\Rightarrow$ *radiance is a linear function of brightness temperature*


10^9 K
10^8 K
10^7 K
10^6 K
10^5 K
10^4 K
10^3 K
10^2 K
3K
$I_\nu(T)$ [erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}]
Frequency ν [Hz]

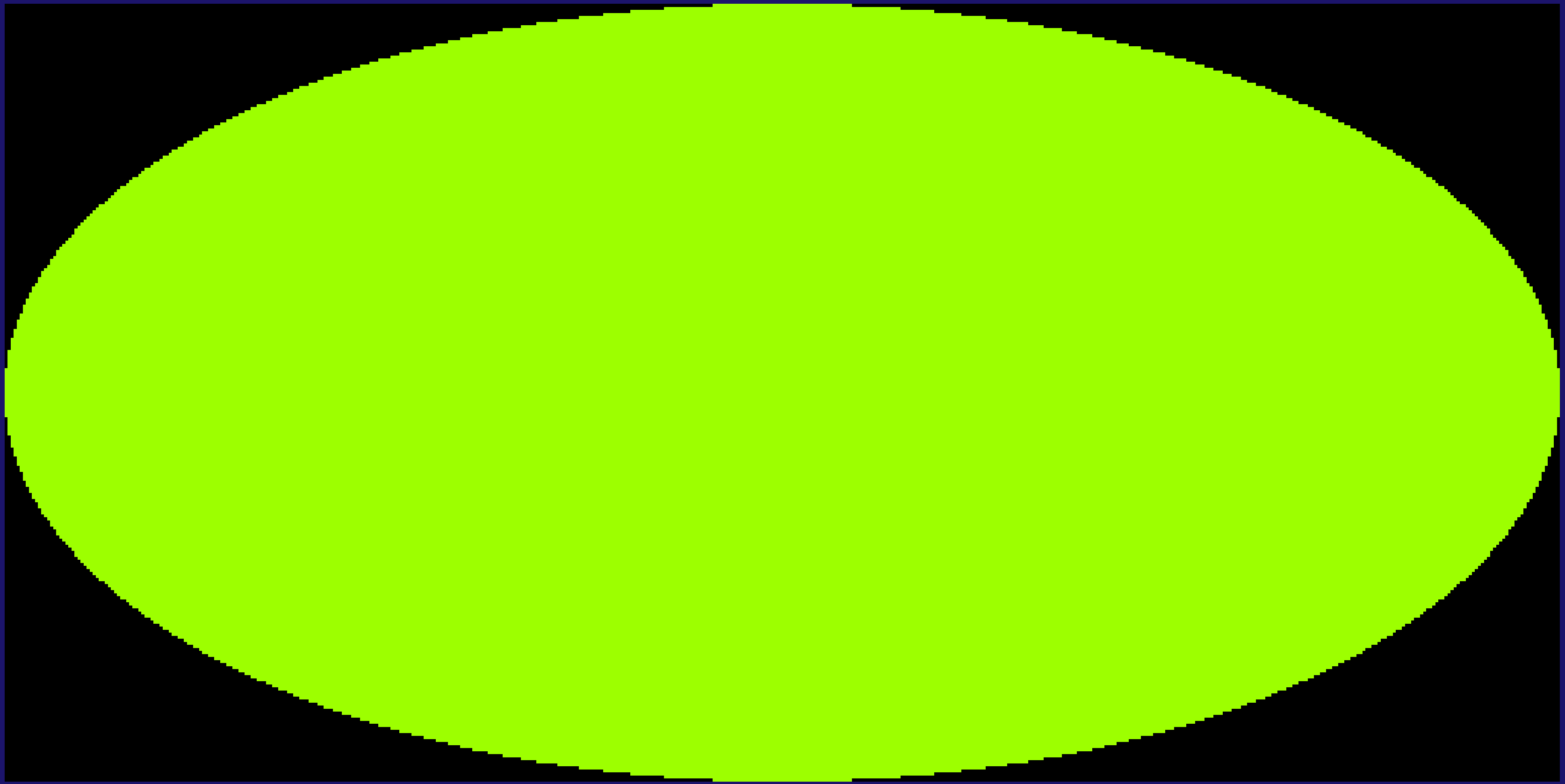

T=10^6 K
Rayleigh-Jeans Law
Wien Law
ν_{max}
$B_\nu(T)$ [erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}]
Frequency ν [Hz]

The 3K Cosmic Background Radiation



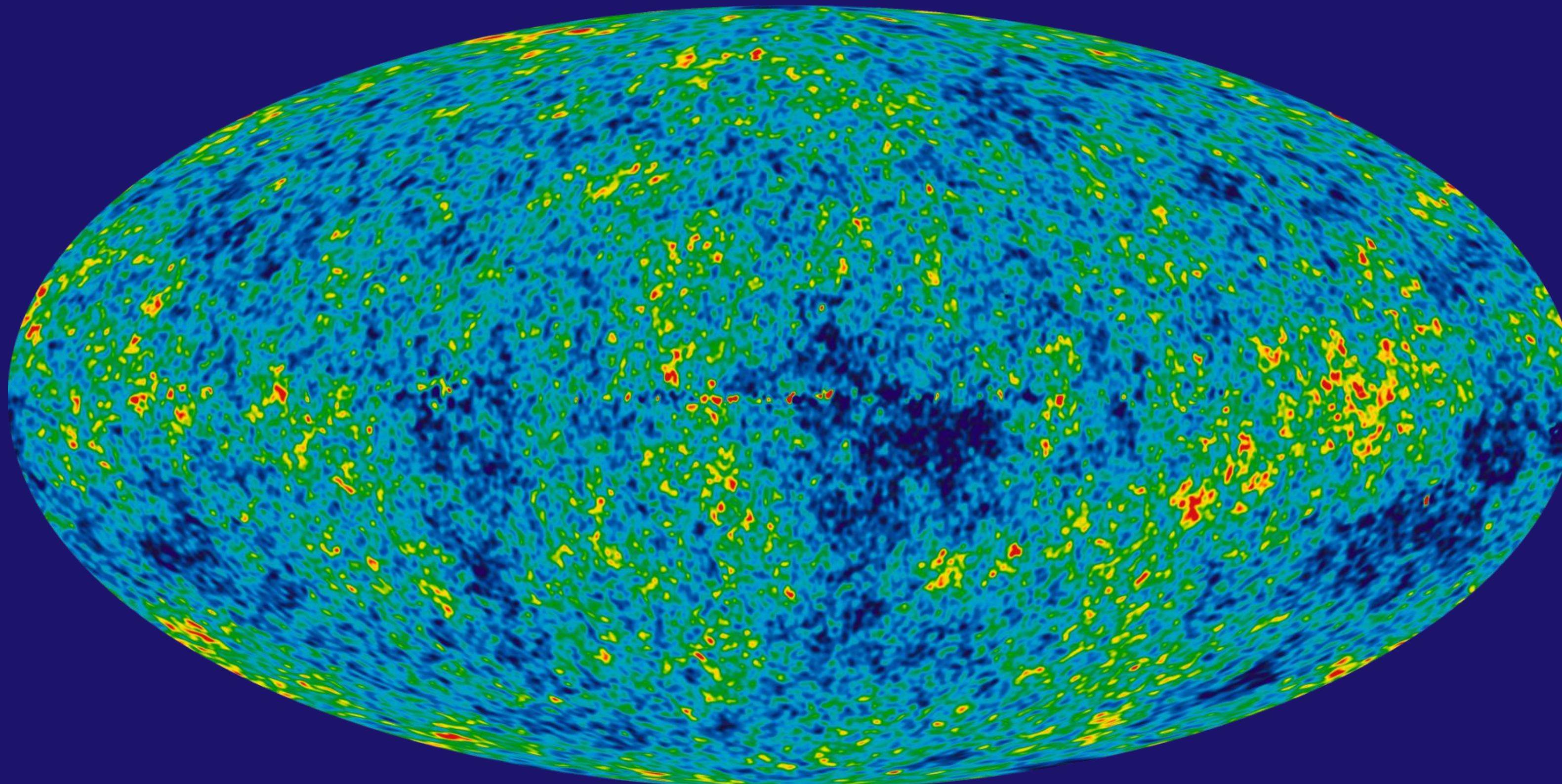
The COBE (*Cosmic Background Explorer*) satellite made very careful measurements of the shape of the spectrum of this emission. It is a perfect blackbody at a temperature of 2.728 K; it is often termed the "3K background". (From R. McGray)

The 3K Cosmic Background Radiation



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 μwave radiometers can be calibrated against this temperature

The 3K Cosmic Background Radiation



The detailed, all-sky picture of the infant universe created from seven years of WMAP data. **The image reveals 13.7 billion year old temperature fluctuations** (shown as color differences) that correspond to the seeds that grew to become the galaxies. The signal from our Galaxy was subtracted using the multi-frequency data. **This image shows a temperature range of ± 200 microKelvin.**

The 3K Cosmic Background Radiation

This Thursday, scientists will unveil the best image yet of the cosmic microwave background – the ‘afterglow’ of the Big Bang – by ESA’s Planck space telescope.

Planck was launched on 14 May 2009 and the mission’s first all-sky image, shown here, was presented in July 2010.

The main disc of our Milky Way Galaxy runs across the centre of the image with streamers of cold dust reaching above and below, tracing out a web of forming stars.

Behind the Milky Way lies the mottled backdrop of the cosmic microwave background (CMB), the oldest light in our 13.7 billion-year-old Universe. It blankets the entire Universe and is even responsible for a tiny fraction of static on analogue television sets.

The CMB was frozen into the sky when the Universe was just 380 000 years old. As the Universe expanded, the CMB signal was stretched out to microwave wavelengths, equivalent to a temperature of just 2.7 degrees above absolute zero.

The mottled pattern represents minute differences in temperatures that correspond to regions of slightly different densities at very early times in the Universe’s history, representing the seeds of all future structure: the stars and galaxies of today.

From this map, scientists can learn about the composition and evolution of the Universe from its birth to the present day and beyond.

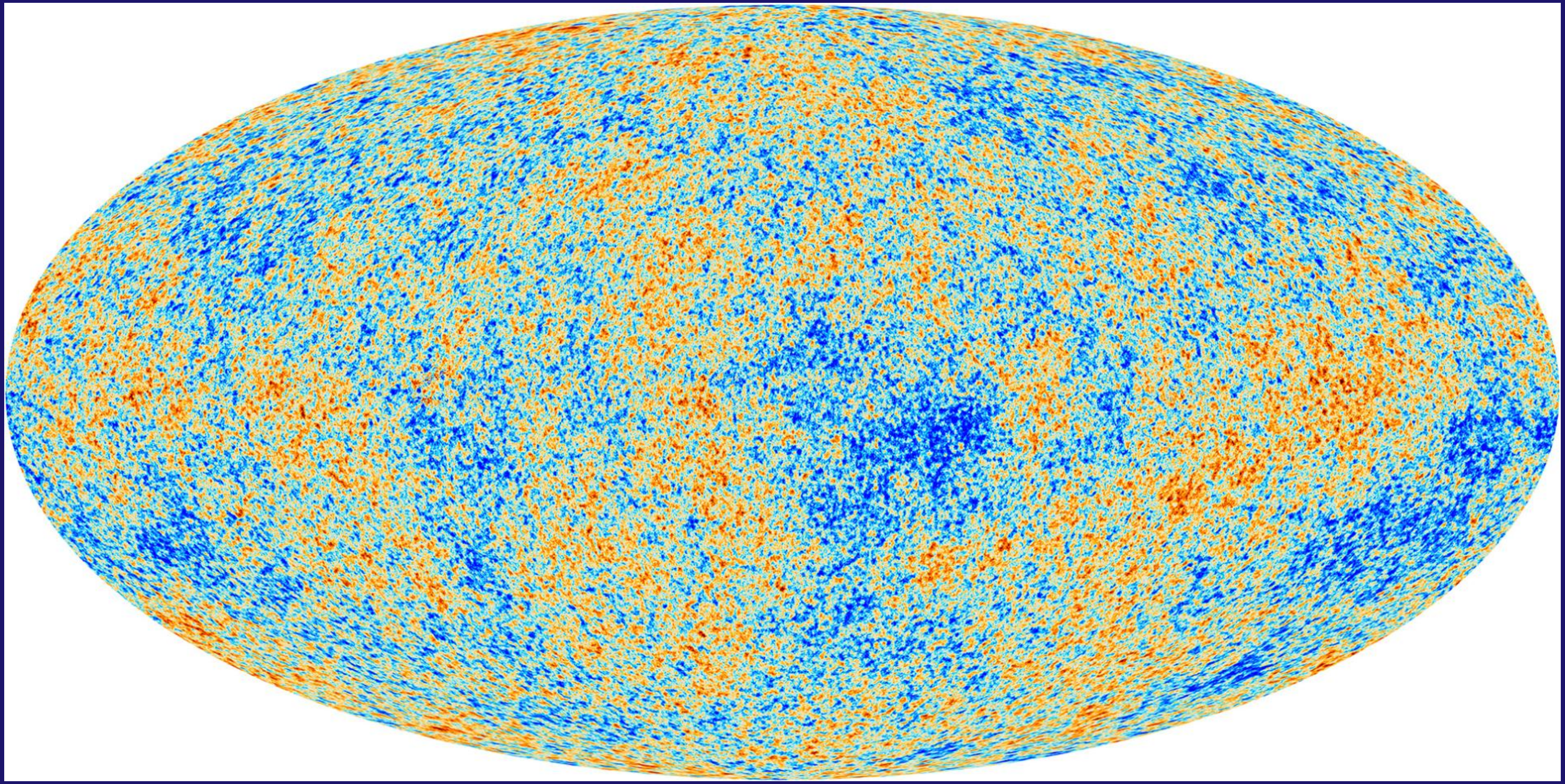
The first space mission to study the CMB was NASA’s Cosmic Background Explorer, launched in 1989. NASA’s second-generation Wilkinson Microwave Anisotropy Probe was launched in 2001 to study the CMB fluctuations in much more detail. All-sky CMB maps from these missions are shown here in black and white, as the animation peels back the progressively more detailed views of the Big Bang afterglow.

Now Planck has ‘tuned in’ to this background radiation with even greater precision, extracting and removing the foreground emissions to reveal the CMB in the highest detail yet.

The new map will be presented and discussed at a dedicated press conference held at ESA Headquarters on Thursday at 10:00 CET.

http://www.esa.int/Our_Activities/Space_Science/Coming_soon_Planck_unveils_the_cosmic_microwave_background

Planck reveals an almost perfect Universe

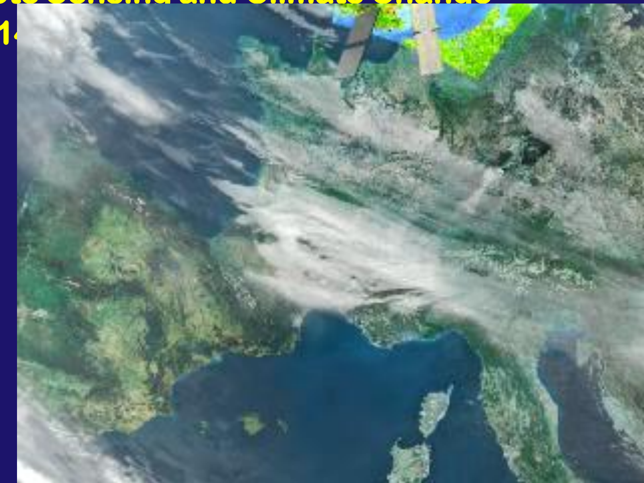


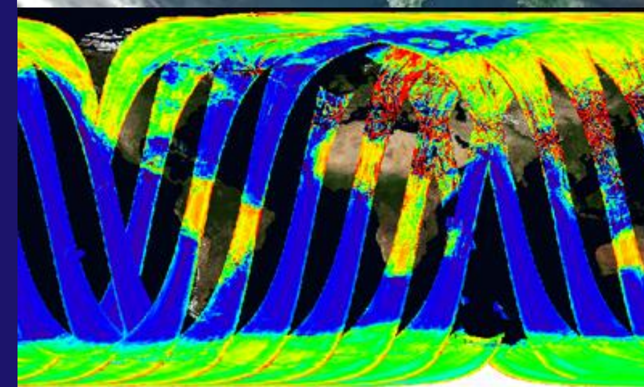
Acquired by ESA's Planck space telescope: the most detailed map ever created of the cosmic microwave background – the relic radiation from the Big Bang – reveals the existence of features that challenge the foundations of our current understanding of the Universe.
The image is based on the initial 15.5 months of data from Planck and is the mission's first all-sky picture of the oldest light in our Universe, imprinted on the sky when it was just 380 000 years old.

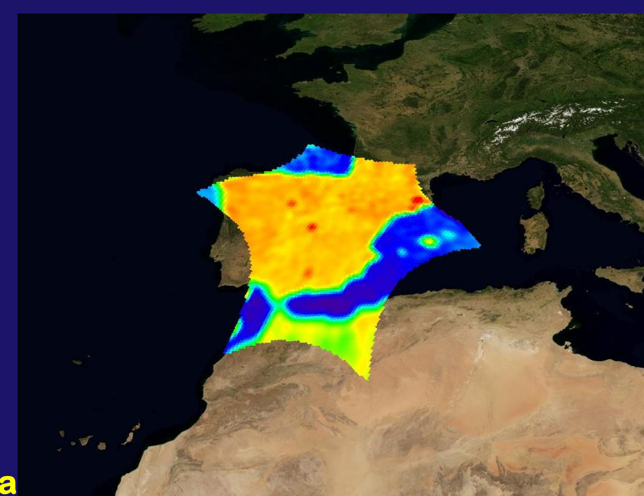
Satellite remote sensing is an important complementary tool for observing Earth's land and ocean surfaces, especially where in-situ observations are scarce or nonexistent. Microwave remote sensing from polar-orbiting satellites plays a unique role:

- •1. polar-orbiting satellites offer the unique capability to provide global coverage
- •2. μwave 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 μwave radiation, polarization and emissivity, vary depending on both wavelength/frequency and characteristics of the emitting material

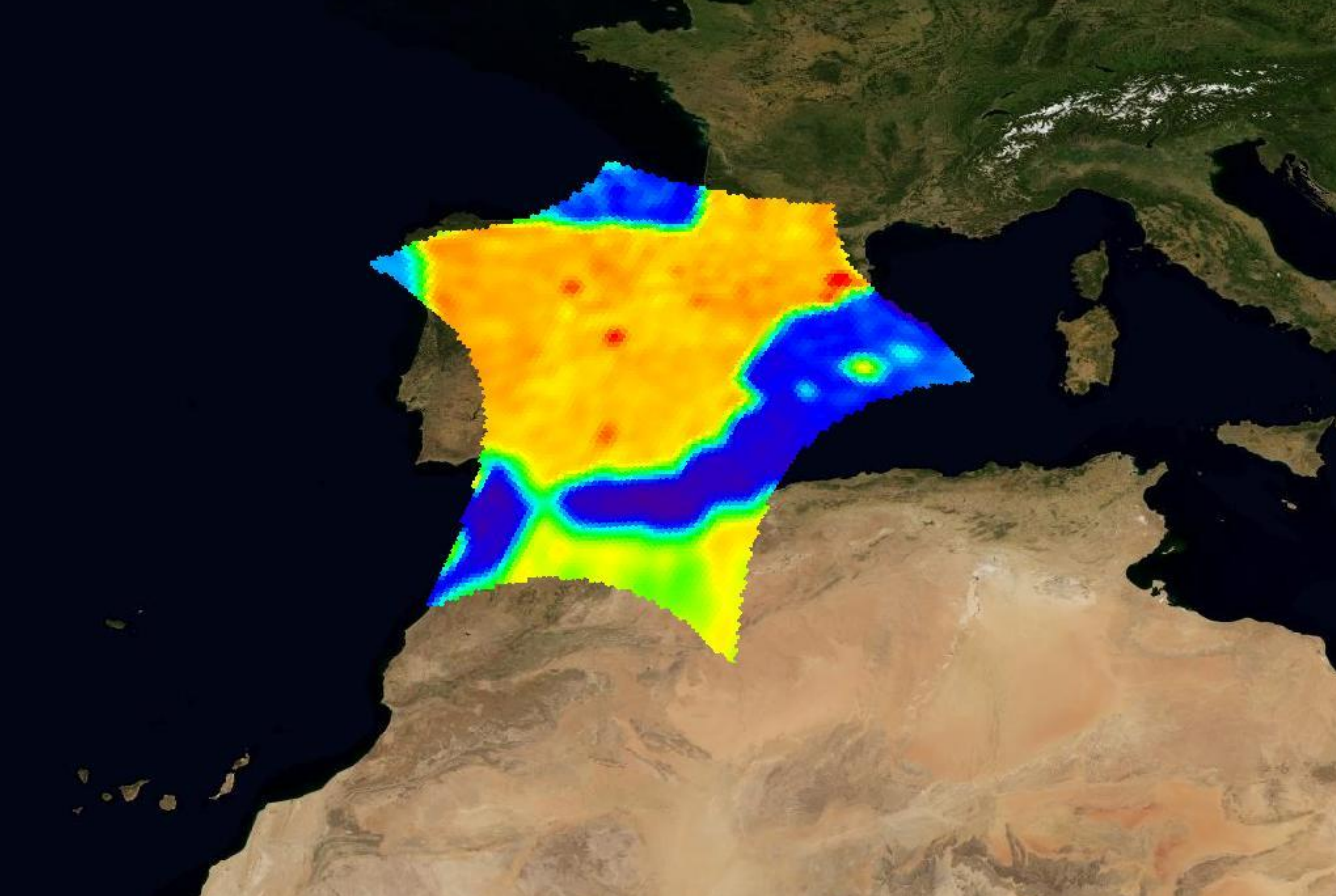
As a result, satellite observation of μwave radiation and its variability makes it possible to identify and characterize specific surface properties important to weather and climate, such as soil moisture, snow cover and water equivalent, sea ice cover and age, and SST







7th July 2010!!!



Example of polarization dependent transmissivity:

M. Schwank

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:

Another 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.

M. Schwank

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:	$\varepsilon_{Ice} \approx 3$

The soil permittivity ε_S is highly sensitive with regard to changes in the soil water content.

Therefore ε_S is the suited proxy for determining the volumetric soil moisture θ in units of m^3m^{-3}.

ε

El. material property

measures the "strength" of the interaction between the electric field and the material

complex quantity
$\varepsilon = \varepsilon' + j\,\varepsilon''$

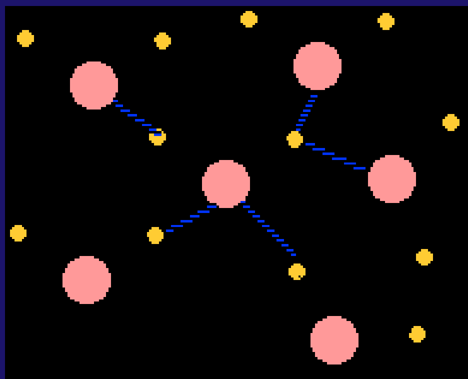
propagation speed: $n = \sqrt{\varepsilon'}$

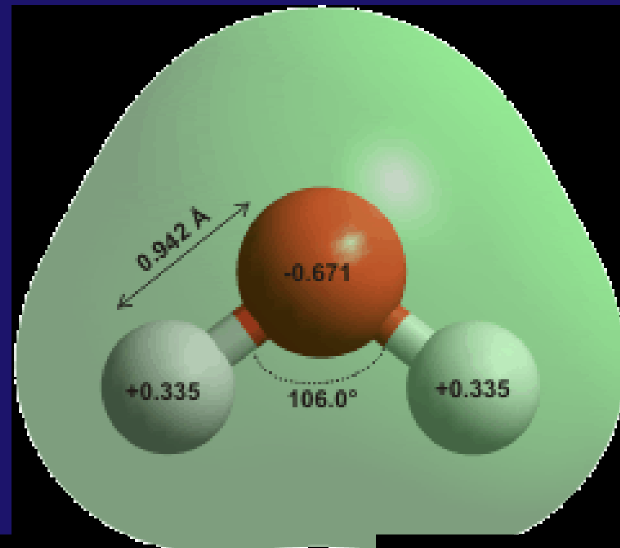
absorbtion (losses): $\gamma = \frac{2\pi}{\lambda} \cdot \varepsilon''$

M. Schwank

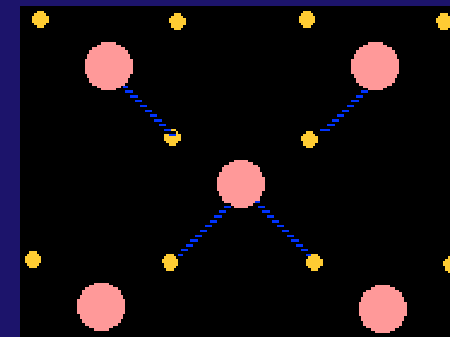
Water Molecule

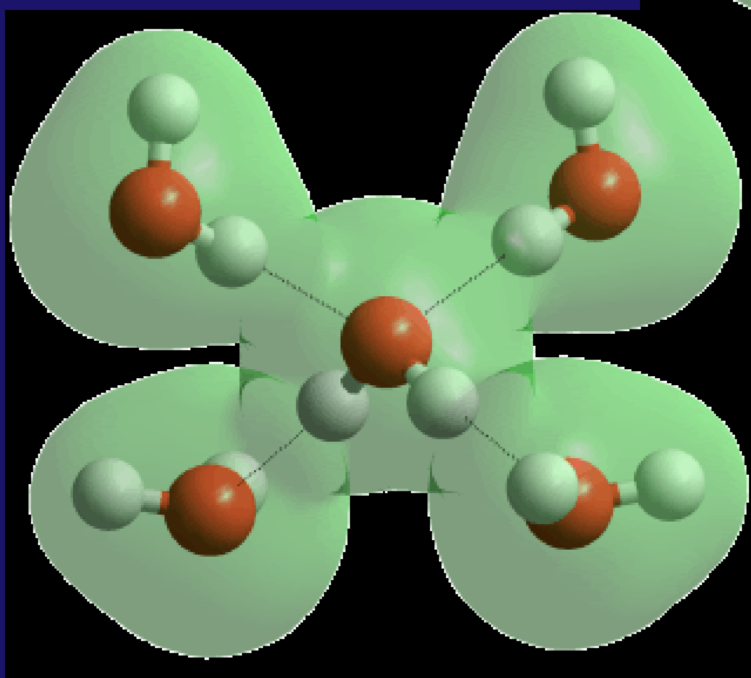
Liquid Water

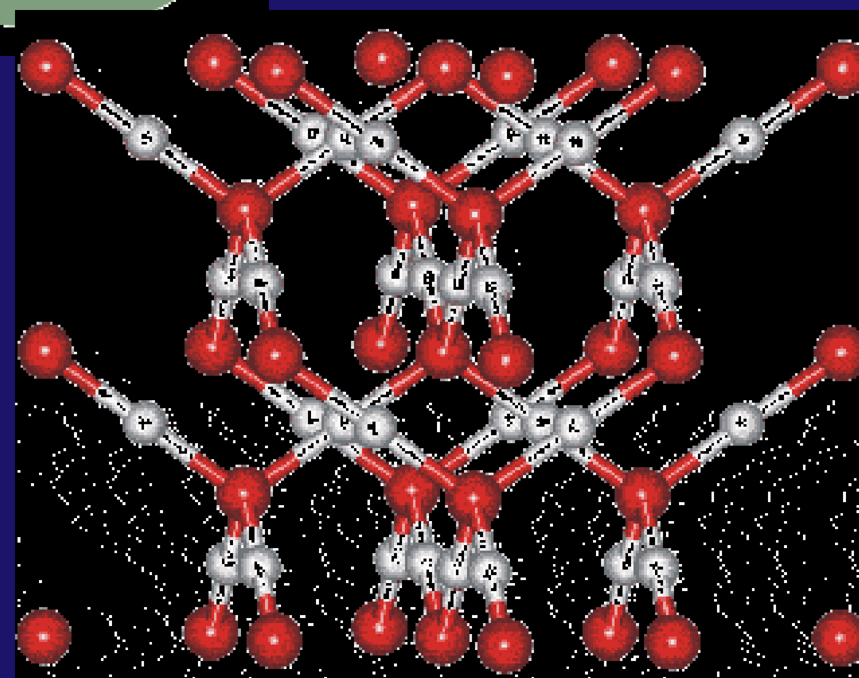




IceWater

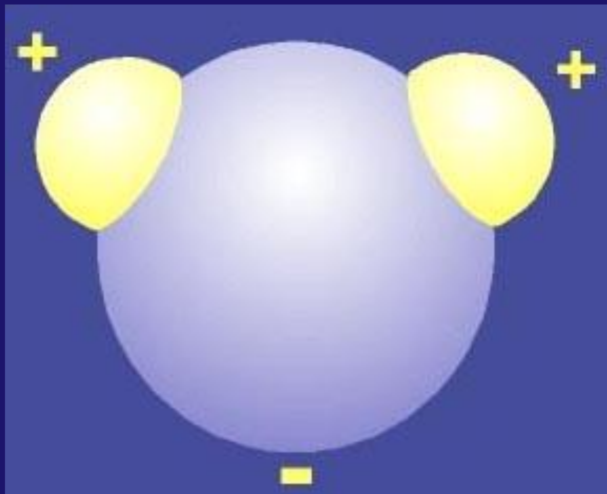






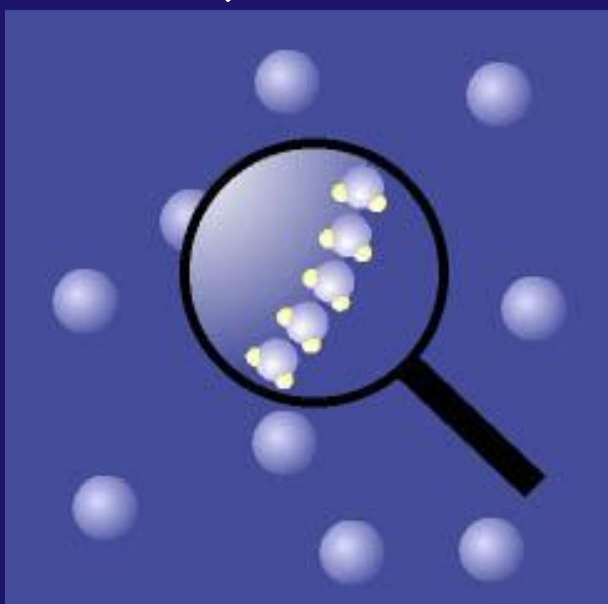
Water Molecule

Greatly Enlarged Water Molecule

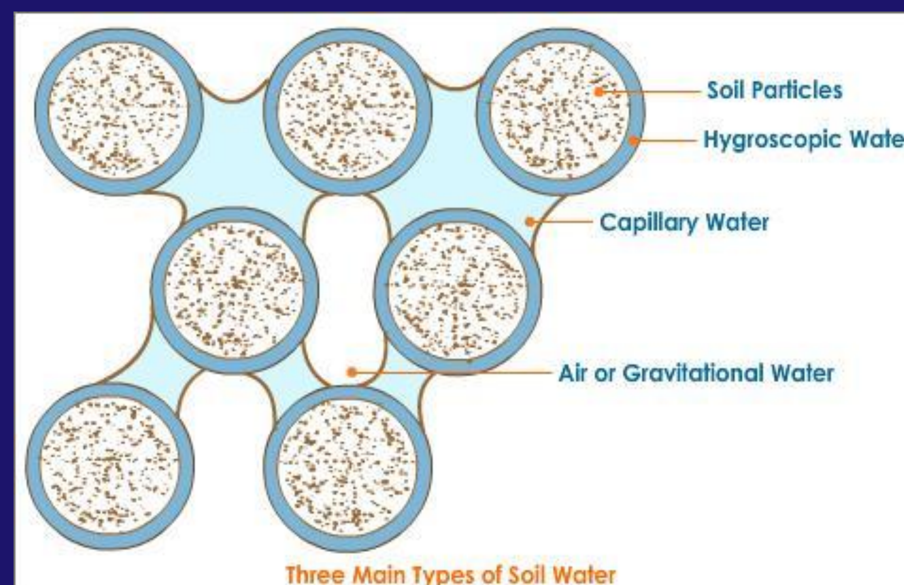


Water Molecules at the Surface in a Glass of Water

Cloud Drops within a Cloud

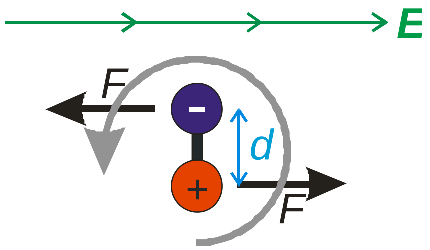


Water in the Soil



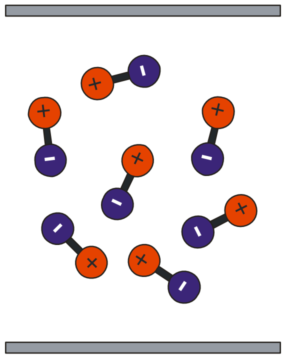
Permittivity; Dielectric Constant

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



$M = F \times d$

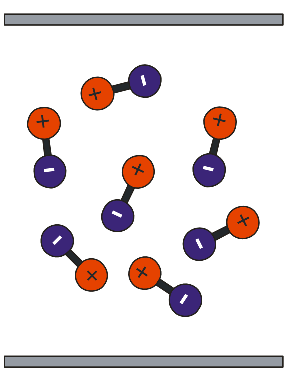
This causes to align the dipole along the field direction.

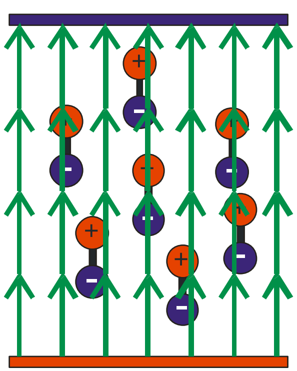


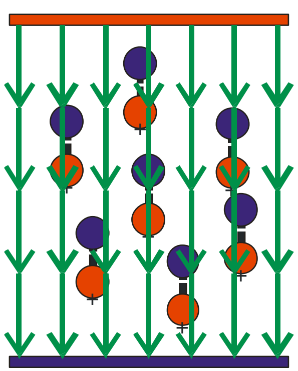
As the H_2O-molecule is highly polar, *M* is large and therefore:

$\Rightarrow$ strong interaction with ***E***

$\Rightarrow$ ε_W is large!

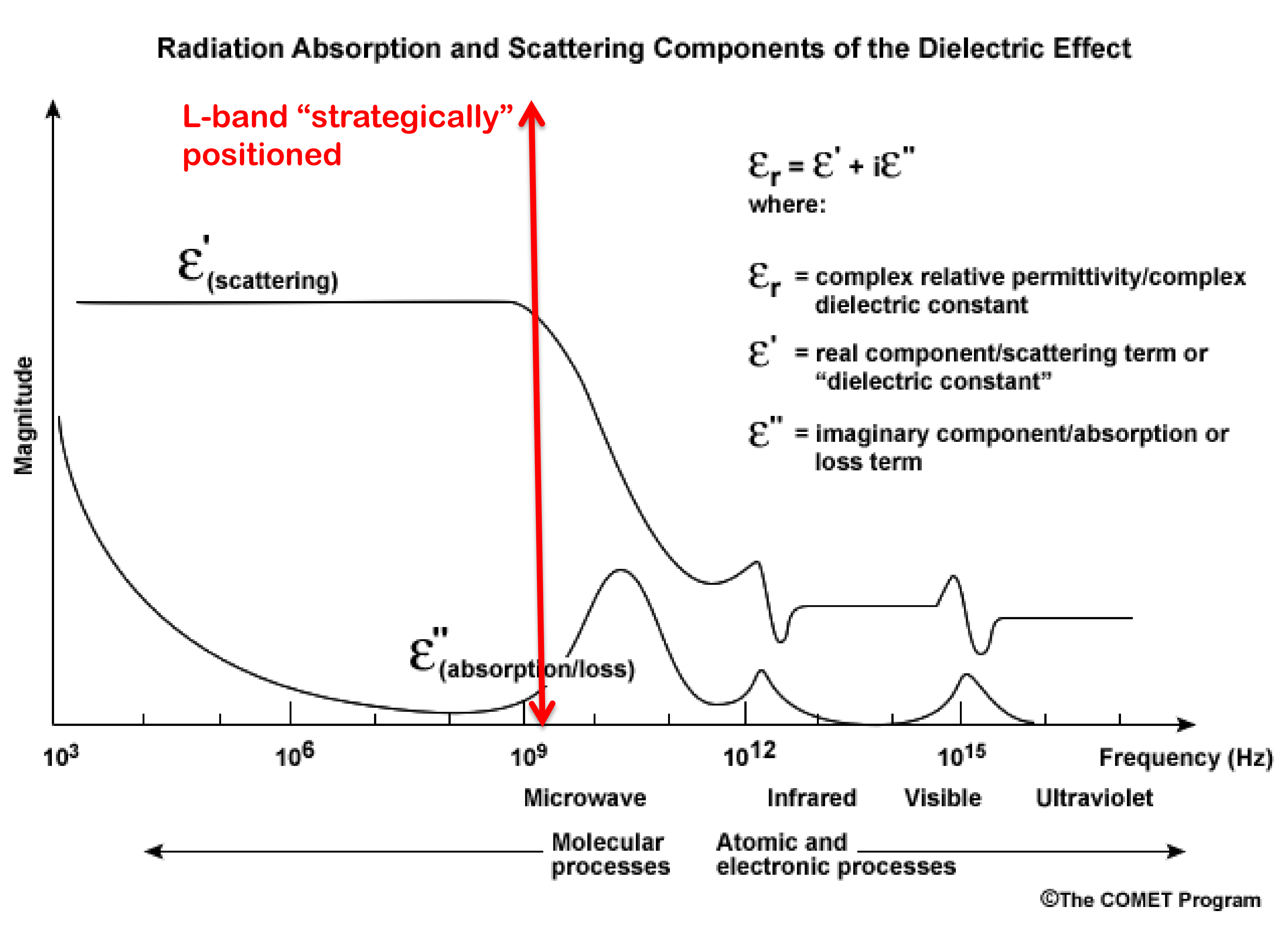






Dielectric Constants for Various Materials

Common naturally occuring materials	Typical Dielectric Constants between ~1 to 100 GHz ε'
Air, vacuum	1.00059, 1.0 (by definition)
Ice (fresh, sea)	3.2, 4-8
Snow (dry, wet)	1.3-1.6, 1.4-1.9
Permafrost	4-8
Water (fresh)	80 (20°C, <3 GHz), ↓15-25 (~3 GHz) and decreasing with frequency
Sea water	78 (20°C, <3 GHz), decreasing with frequency
Sandy soil (dry, wet)	2.5-5, 15-30
Loamy soil (dry, wet)	4-6, 10-20
Clayey soil (dry, wet)	4-6, 10-15
Silts	5-30
Granite	4-6
Limestone	4-8
Salt	4-7


Radiation Absorption and Scattering Components of the Dielectric Effect
L-band "strategically" positioned
$\varepsilon_r = \varepsilon' + i\varepsilon''$
where:
ε_r = complex relative permittivity/complex dielectric constant
ε' = real component/scattering term or "dielectric constant"
ε'' = imaginary component/absorption or loss term
$\varepsilon'_{(scattering)}$
$\varepsilon''_{(absorption/loss)}$
Magnitude
10^3
10^6
10^9
10^{12}
10^{15}
Frequency (Hz)
Microwave
Infrared
Visible
Ultraviolet
Molecular processes
Atomic and electronic processes
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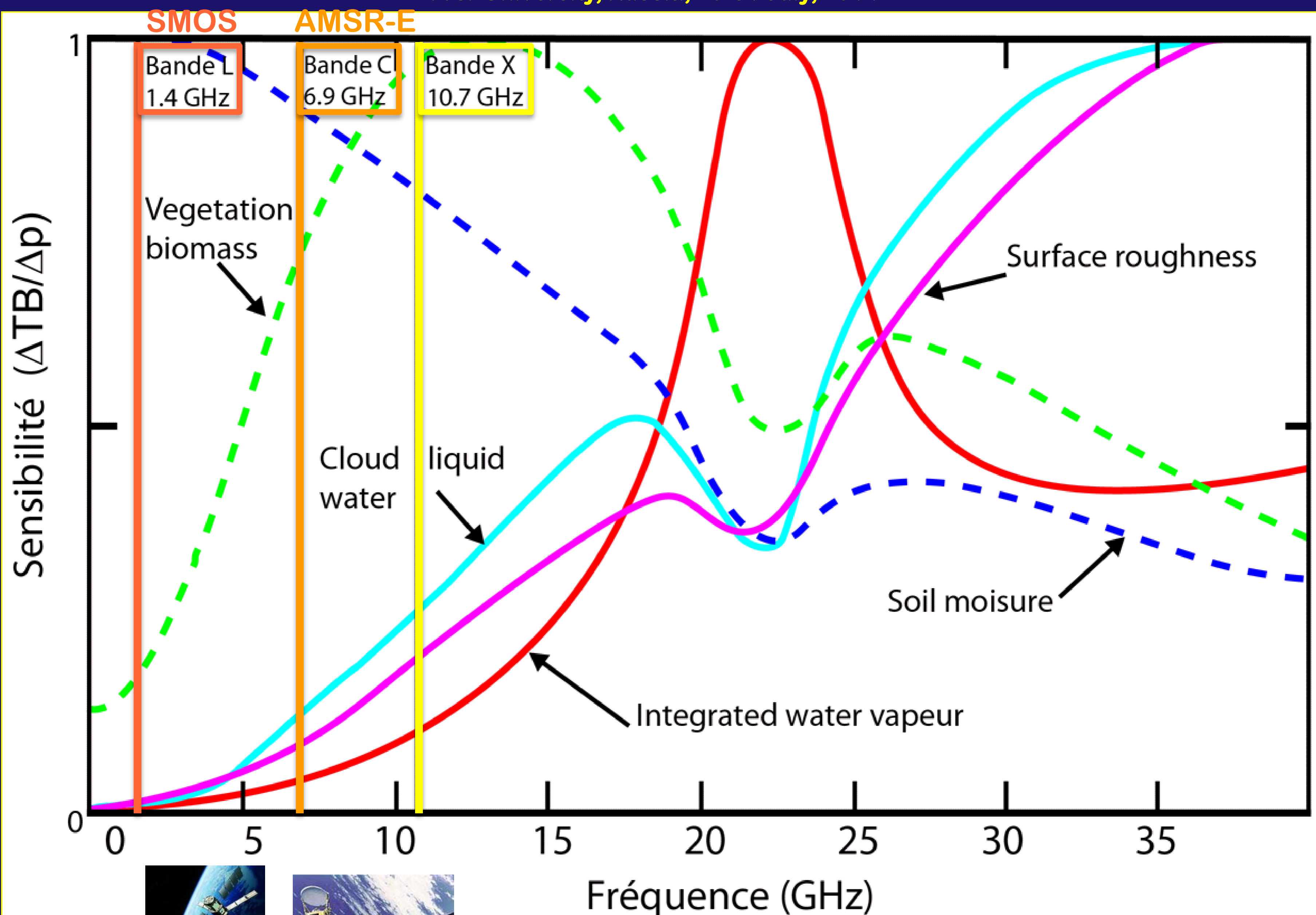
Joint COSPAR – WMO Capacity Building Workshop on Satellite Remote Sensing and Climate Change
Tver University, Russia, 20-31 July, 2014



z-E l Principles of Passive Microwave Radiometry. Soil Moisture

ESA Bulletin

Microwave Dielectric Behaviour of Wet Soil

acting on a water molecule decrease rapidly with distance away from the soil-particle surface, water molecules located several molecular layers away from soil particles are able to move within the soil medium with relative ease, and hence are referred to as "free." Dividing the water into bound and free fractions describes only approximately the actual distribution of water molecules within the soil medium and is based on a somewhat arbitrary criterion for the transition point between

Manuscript received January 13, 1983; revised April 11, 1984. This

dielectric behavior [5], [6], [16], [17] through the use of dielectric mixing formulas. A close examination of these investigations leads to the following observations:

1) Inconsistencies exist between experimental measurements reported by different investigators, both in terms of the absolute level of the relative dielectric constant ϵ (versus water content) for similar soil textures and in terms of the dependence of ϵ on soil texture. Hoekstra and Delaney [5] and Davis *et al.* [14], for example, conclude that on the basis of their respective measurements, soil textural composition has a very minor

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.

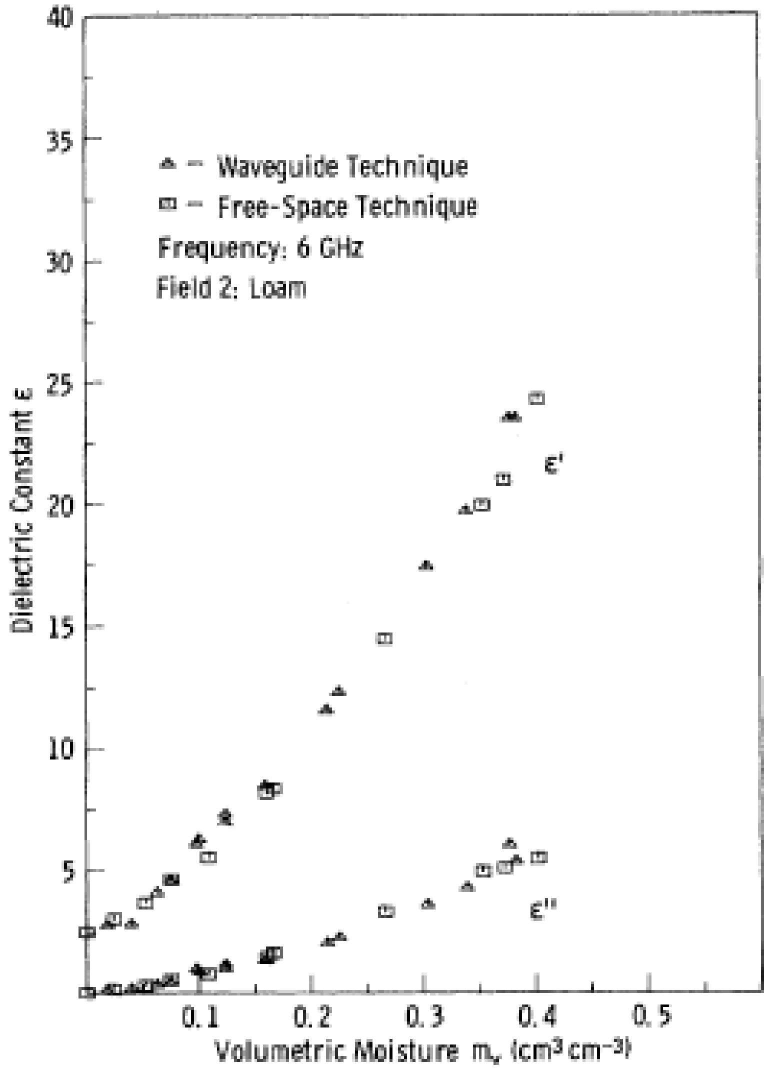
TABLE I
SOIL TEXTURE SAMPLES AND FREQUENCIES AT WHICH DIELECTRIC MEASUREMENTS WERE OBTAINED

No.*	Designation	Soil Type	Soil Texture (%) Sand	Silt	Clay	Soil Specific Surface, m^2/g	Cation Exchange Capacity
1	Field 1	Sandy Loam	51.51	35.06	13.43	52	8.2
2	Field 2	Loam	41.96	49.51	8.53	49	7.6
3	Field 3	Silt Loam	30.63	55.89	13.48	66	11.4
4	Field 4	Silt Loam	17.16	63.84	19.00	119	20.5
5	Field 5	Silty Clay	5.02	47.60	47.38	252	34.8

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 wave-guide and free-space techniques at 6 GHz.

good agreement achieved for both ε' and ε'' over the range of m_v

Microwave Dielectric Behaviour of Wet Soil

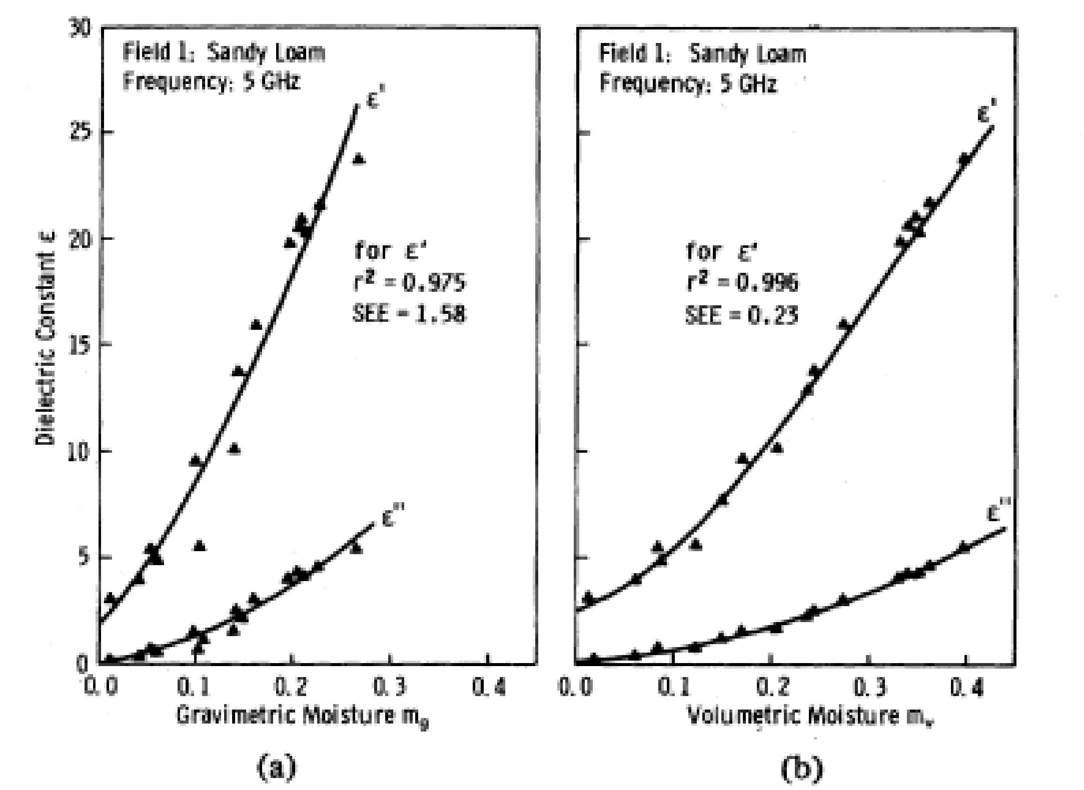


Fig. 5. Comparison of soil dielectric constants plotted as a function of (a) gravimetric moisture content and (b) volumetric moisture content.

Bulk Density Effects

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_g but significantly different bulk densities resulted in significantly different values for ε' and ε'', but samples with the same m_v, and different bulk densities resulted in approximately the same values for ε' and ε''.

Microwave Dielectric Behaviour of Wet Soil

Soil Texture Effects

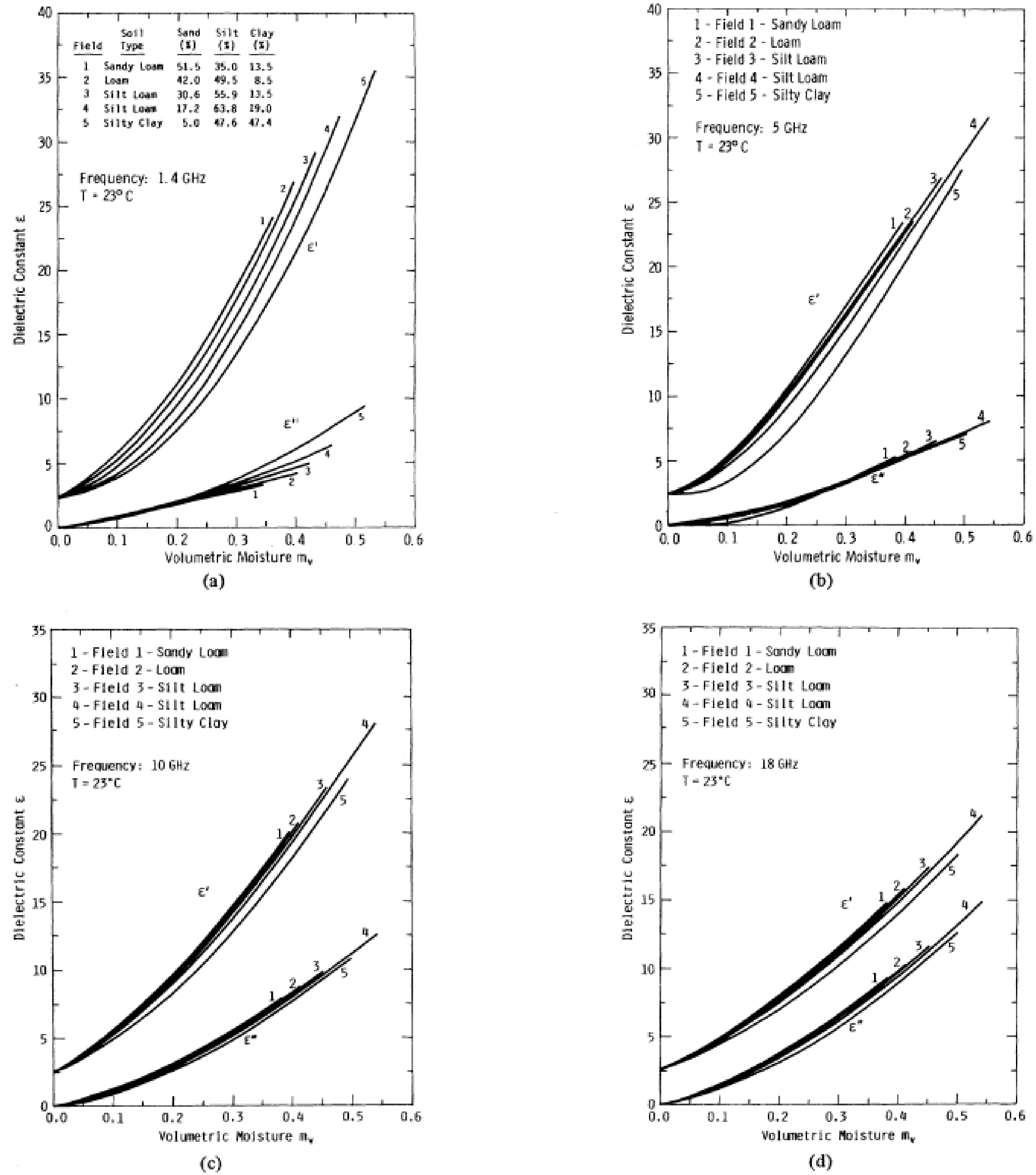


Fig. 6. Measured dielectric constant for five soils (see Table I for textural composition of the indicated soil types) at (a) 1.4 GHz, (b) 5 GHz, (c) 10 GHz, and (d) 18 GHz.

Microwave Dielectric Behaviour of Wet Soil

Soil Texture Effects

Fig. 6 shows the moisture dependence of the dielectric constant for each soil at frequencies of 1.4, 5, 10, and 18 GHz. The indicated moisture range for each soil extends between $m_v \simeq 0$ and the highest moisture content that can be supported by that soil type without drainage taking place. At each frequency, all the curves for ϵ' and similarly for ϵ'' have approximately the same intercept at $m_v = 0$ and exhibit the same general shape but have different curvatures for different soil types.

At any given moisture content and at all frequencies, ϵ' was found to be roughly proportional to sand content (and inversely proportional to clay content). Thus ϵ' was shown to be soil-texture dependent in the same fashion at all frequencies from 1.4 to 18 GHz, although the magnitude of the effect was found to decrease with frequency.

The effect of soil texture on ϵ'' is more complicated. At 1.4 GHz, ϵ'' was shown to increase with soil clay content for $m_v \geqslant 0.2\ \text{cm}^3 \cdot \text{cm}^{-3}$. At 4.0–6.0 GHz, ϵ'' is nearly independent of soil texture at all soil moisture conditions. At frequencies of 8.0 GHz and above, ϵ'' was observed to decrease with soil clay fraction (the reverse of the behavior observed at 1.4 GHz); furthermore, the magnitude of this behavior increases with frequency.

The behavior of ϵ'' can be explained by two phenomena. At the low end of the frequency range, i.e., at frequencies of less than $\simeq 5.0$ 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 ϵ'' 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 m^2/g for Fields 1 and 2 to 252 m^2/g for Field 5. If bound water possesses dielectric properties significantly lower than those of bulk water (for example, ice with $\epsilon' = 3.15$ and $\epsilon'' \ll 0.1$), then at higher frequencies, where the contribution of conductivity to ϵ'' is no longer significant, ϵ'' 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, ϵ'' is highest for Field 1 at frequencies $\geqslant 8.0$ GHz.

In Fig. 6, sandy soils are shown to have the highest ϵ' at all frequencies. This is to be expected from the standpoint of both bound water and soil salinity, since ϵ' of bound water is less than ϵ' of bulk water, and ϵ' of saline water is less than ϵ' 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.

Microwave Dielectric Behaviour of Wet Soil

Frequency Behaviour

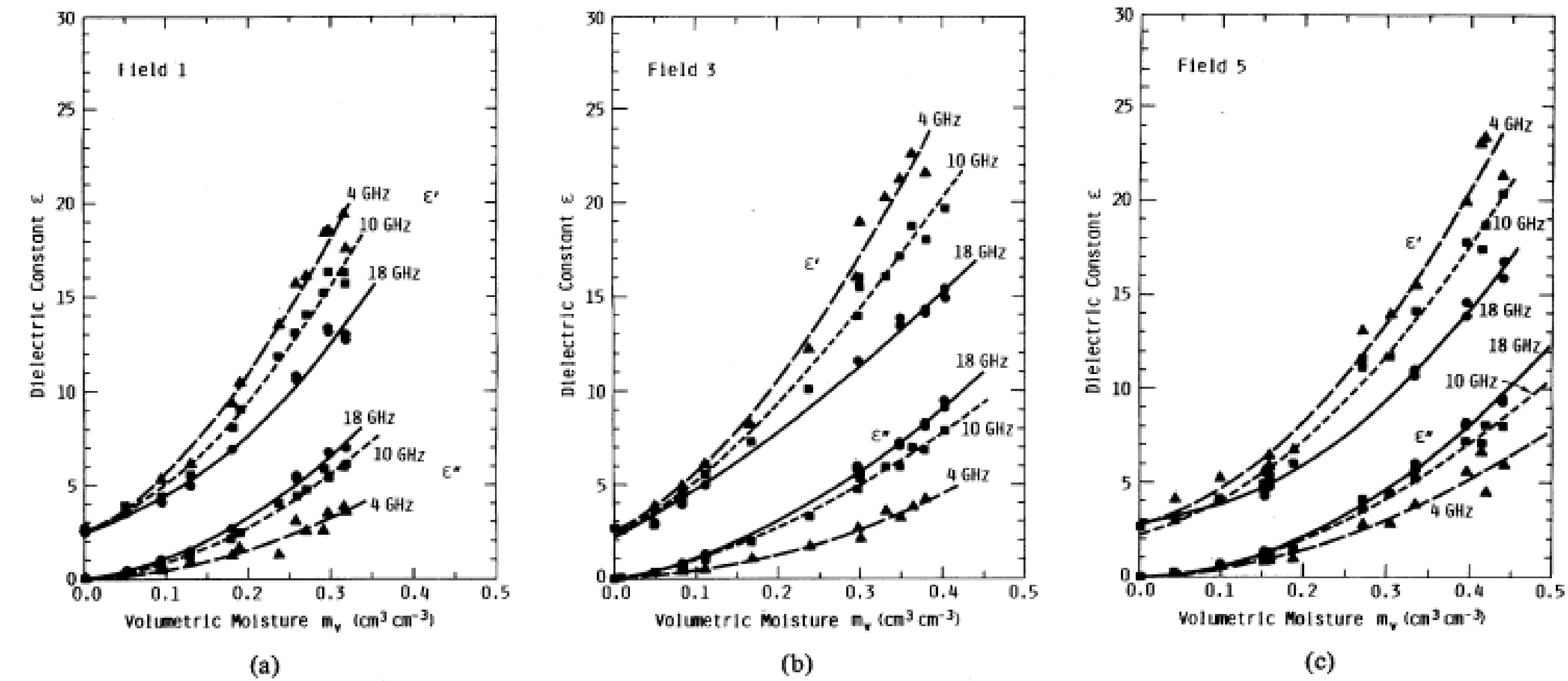


Fig. 7. Measured dielectric constant at 4, 10, and 18 GHz for (a) Field 1, (b) Field 3, and (c) Field 5. Polynomial regression fits are also shown.

Microwave Dielectric Behaviour of Wet Soil

Frequency Behaviour

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 ϵ' decreases and ϵ'' 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 ϵ'' 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 ϵ' at all frequencies and ϵ'' 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.

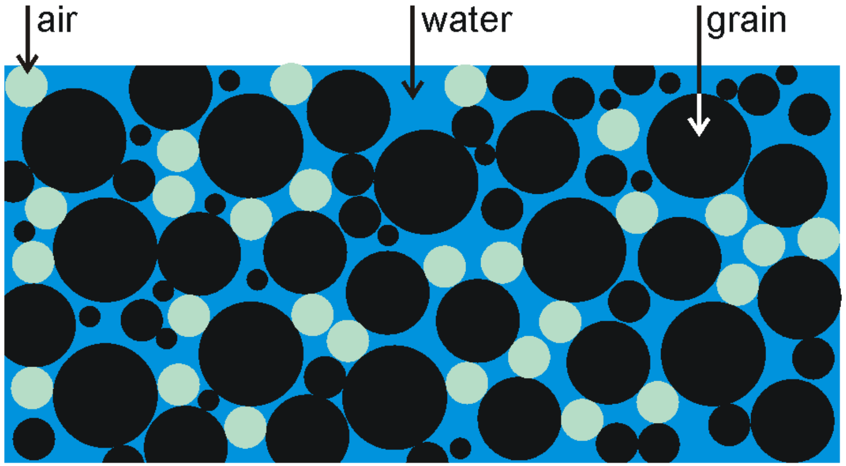
These methods can be used to model effective permittivities of:

- 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:

$$\varepsilon_S = \varepsilon_W + 3\varepsilon_W \frac{(1-\eta)\frac{\varepsilon_M-\varepsilon_W}{\varepsilon_M+2\varepsilon_W} + (\eta-\theta)\frac{\varepsilon_A-\varepsilon_W}{\varepsilon_A+2\varepsilon_W}}{1-\left[(1-\eta)\frac{\varepsilon_M-\varepsilon_W}{\varepsilon_M+2\varepsilon_W} + (\eta-\theta)\frac{\varepsilon_A-\varepsilon_W}{\varepsilon_A+2\varepsilon_W}\right]}$$

η = porosity

θ= volumetric water content

ε_A, ε_W, ε_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!!

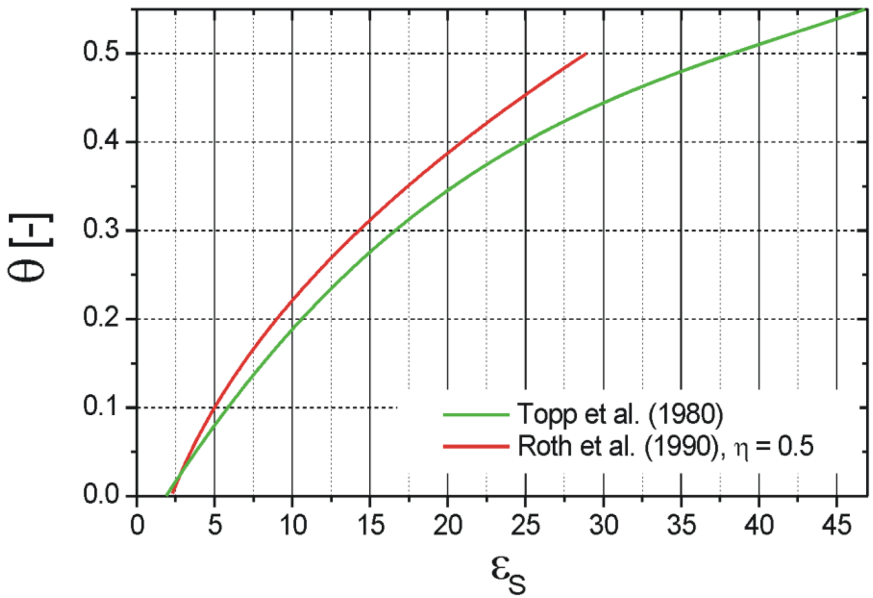
Example of empirical mixing models for the effective permittivity of a moist soil:

Polynomial fit to ε_S measured for soils with different moisture θ

Topp et al. (1980): $$\theta = 4.3\cdot10^{-6}\varepsilon_S'^3 - 5.5\cdot10^{-4}\varepsilon_S'^2 + 2.92\cdot10^{-2}\varepsilon_S' - 5.3\cdot10^{-2}$$

Semi-empirical relation (three phases, parameter α =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: $T_B^p = e\,T$

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:

$$r^H(\vartheta) = \left| \frac{\cos\vartheta - \sqrt{\varepsilon - \sin^2\vartheta}}{\cos\vartheta + \sqrt{\varepsilon - \sin^2\vartheta}} \right|^2 \qquad r^V(\vartheta) = \left| \frac{\varepsilon\cos\vartheta - \sqrt{\varepsilon - \sin^2\vartheta}}{\varepsilon\cos\vartheta + \sqrt{\varepsilon - \sin^2\vartheta}} \right|^2$$

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

depends on the permittivity ε 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!

Passive Microwaves. Introduction

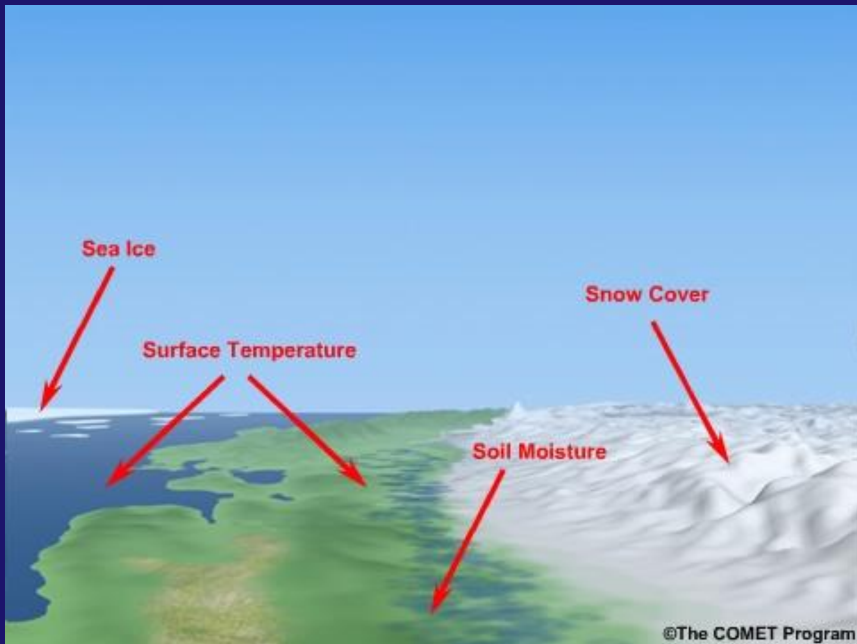
Rayleigh-Jeans Law. Background

Factors Affecting Emissivity

Polarization

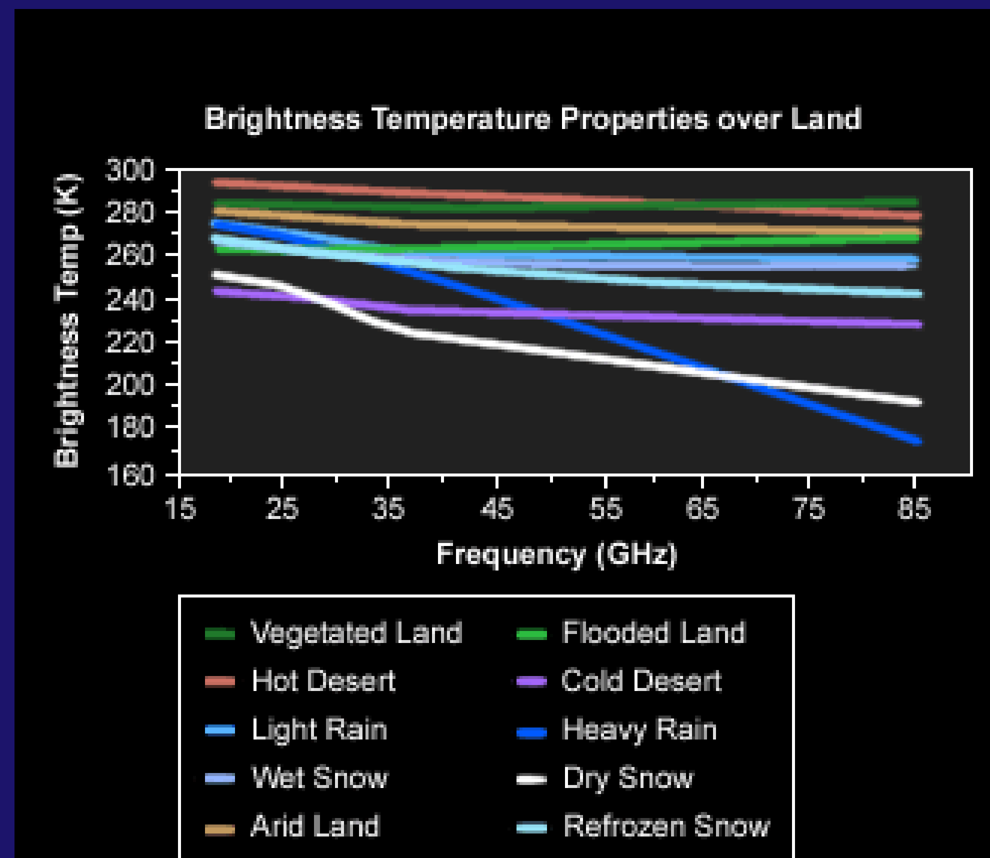
Estimation of Soil Moisture

Microwave Emissivity

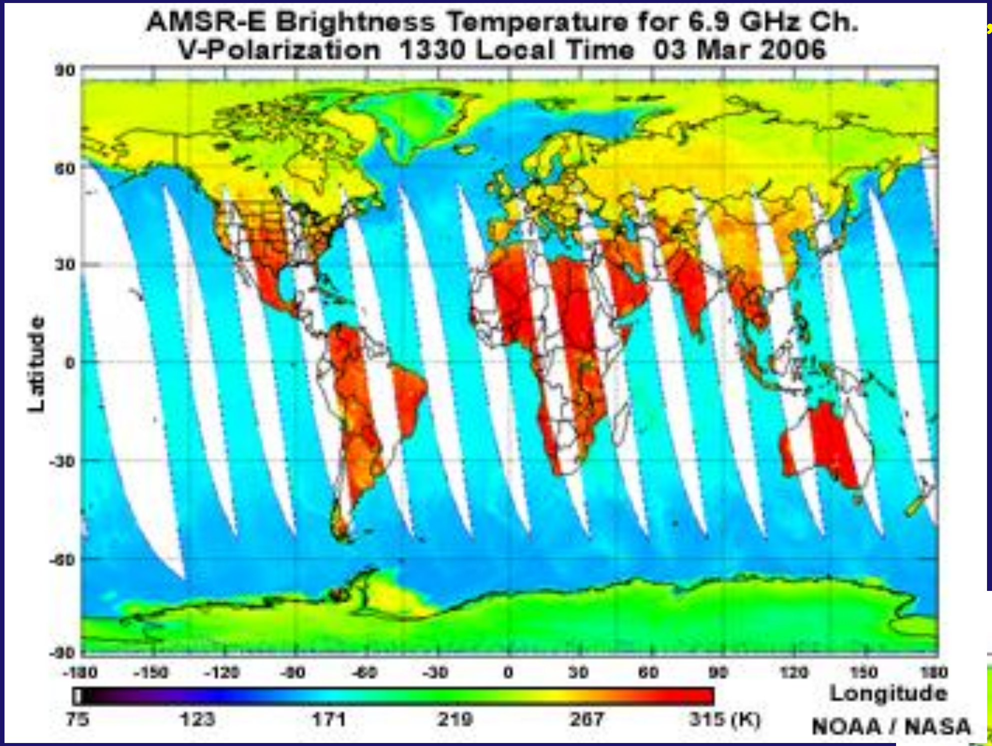


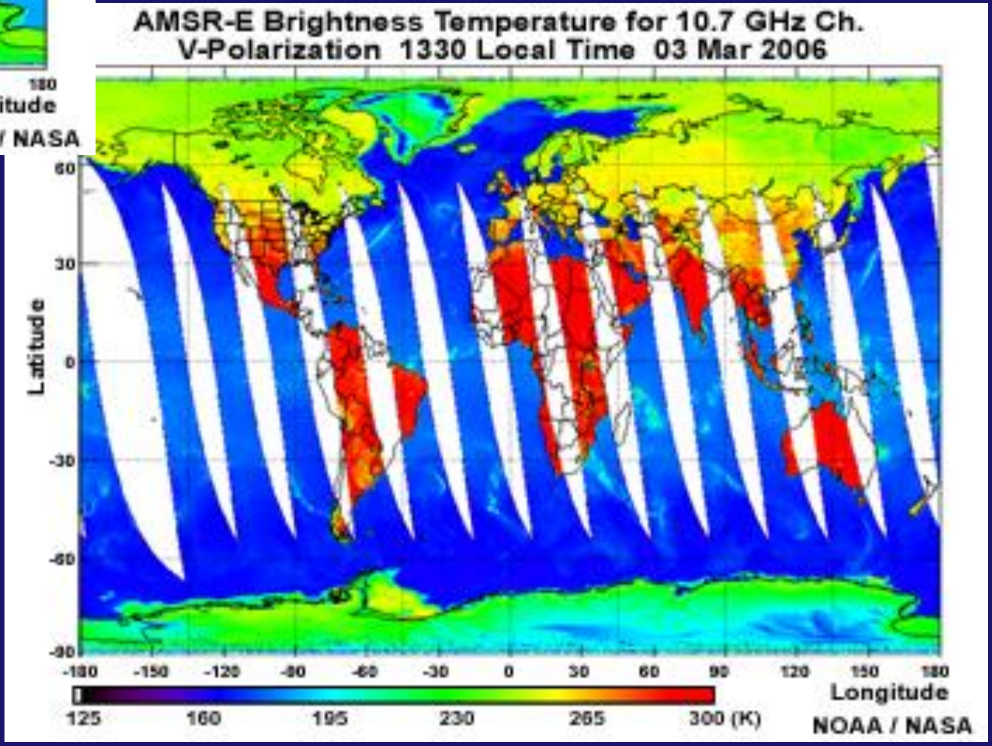
The amount of microwave radiation emitted by the Earth's surface depends on interactions between energy and the various characteristics and elements that make up the surface.

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.

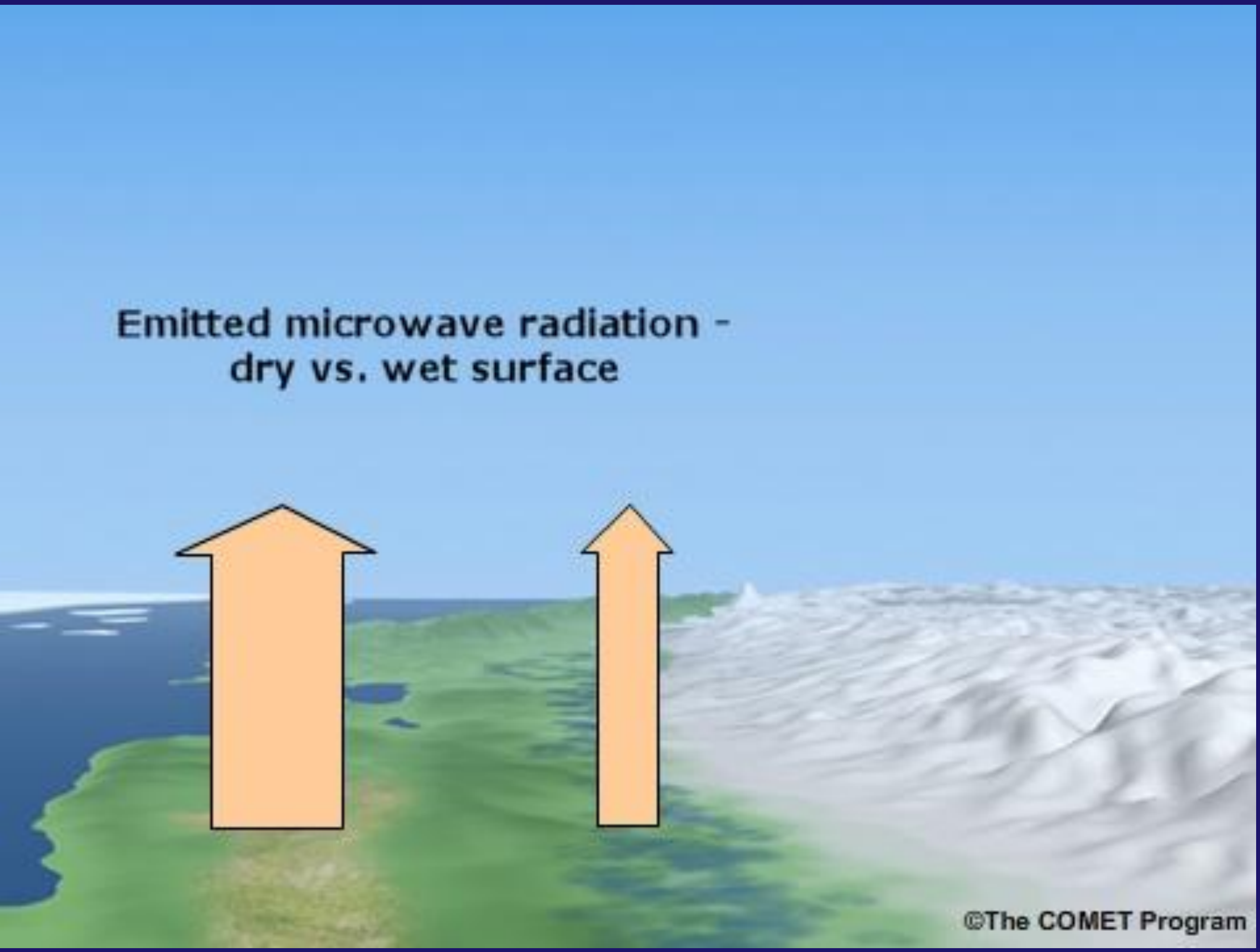


Adapted from R. Ferraro, 1999


AMSR-E Brightness Temperature for 6.9 GHz Ch.
V-Polarization 1330 Local Time 03 Mar 2006
Latitude
Longitude
75 123 171 219 267 315 (K)
NOAA / NASA


AMSR-E Brightness Temperature for 10.7 GHz Ch.
V-Polarization 1330 Local Time 03 Mar 2006
Latitude
Longitude
125 160 195 230 265 300 (K)
NOAA / NASA

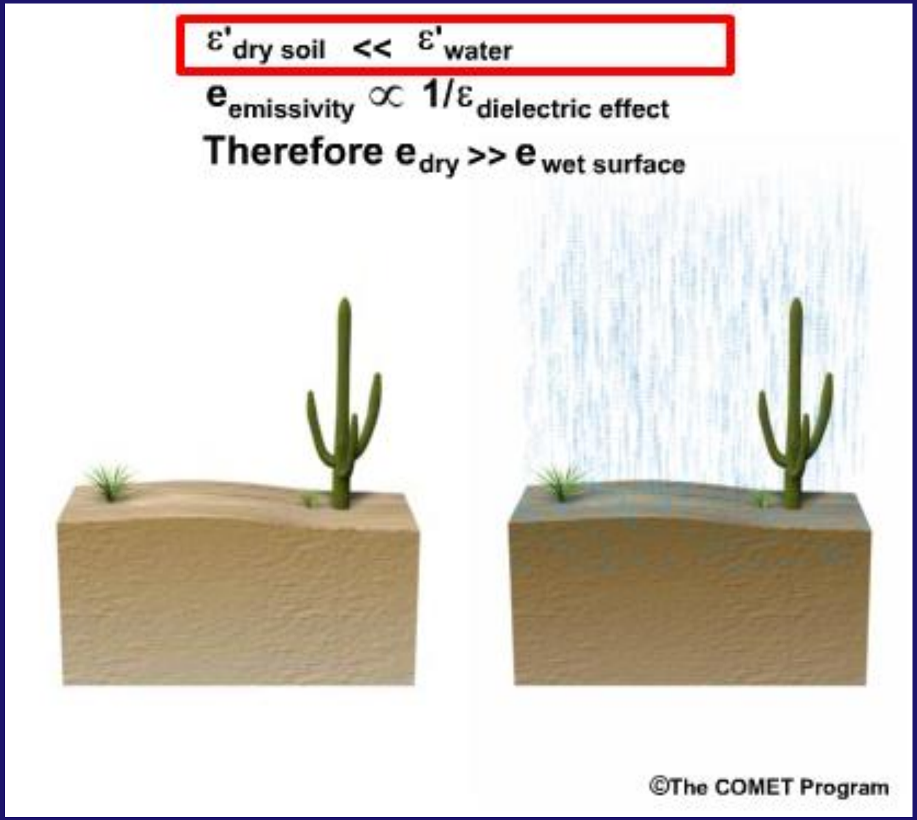
How does a Wet vs. Dry Surface Appear from Space? Dry vs. Wet Surface

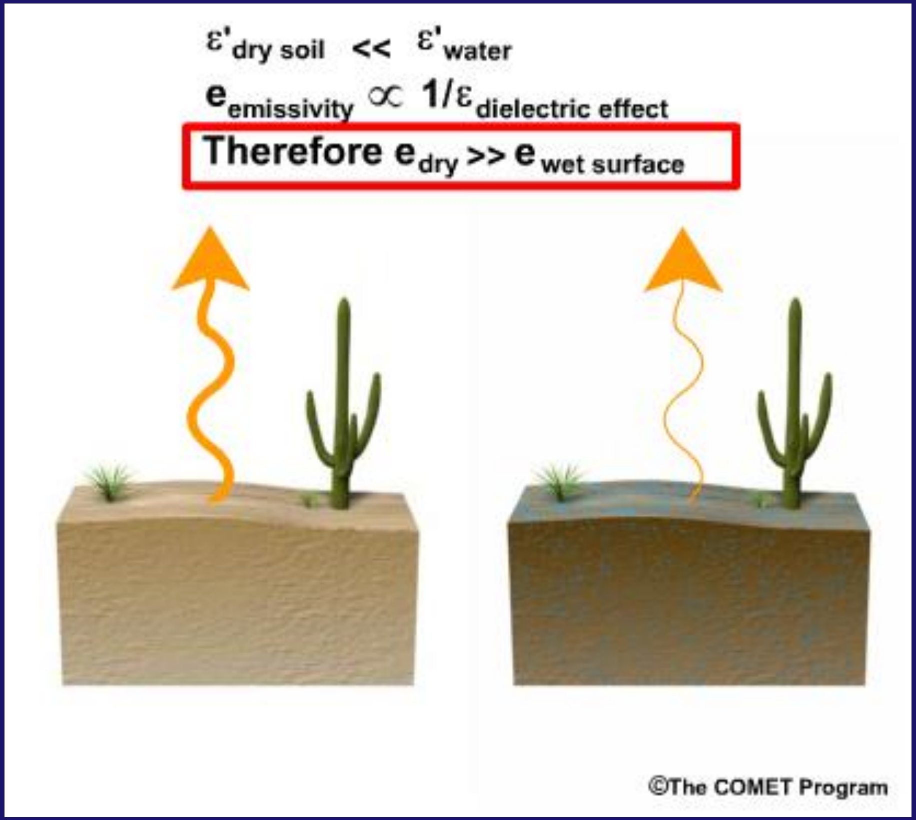


For open regions with relatively sparse vegetation, the moisture content of the surface soil is the dominant factor in the surface emission of microwave radiation.

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**.

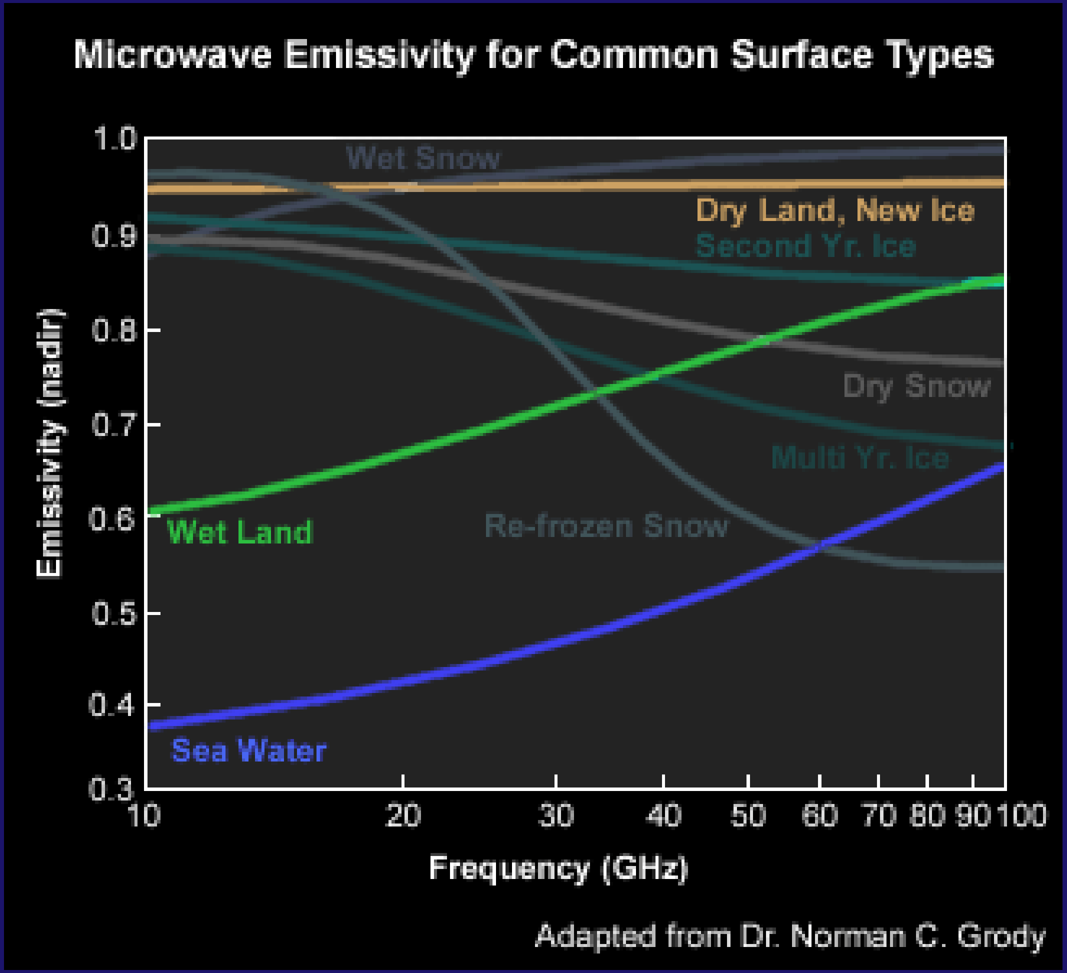
How does a Wet vs. Dry Surface Appear from Space?
Dry vs. Wet Surface





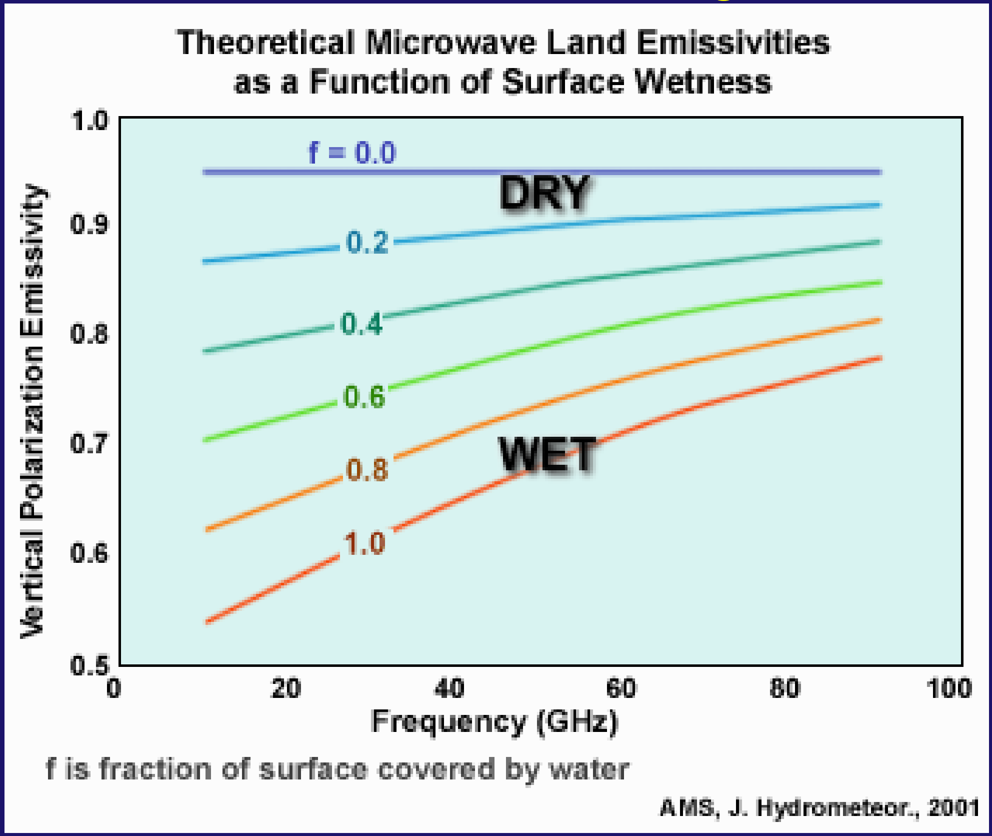
The introduction of water to soil results in a dramatic increase in the dielectric constant, and correspondingly a decrease in soil emissivity. This is easily detectable by a passive microwave remote sensor as a relatively cold brightness temperature, as we will see later in this section.

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.

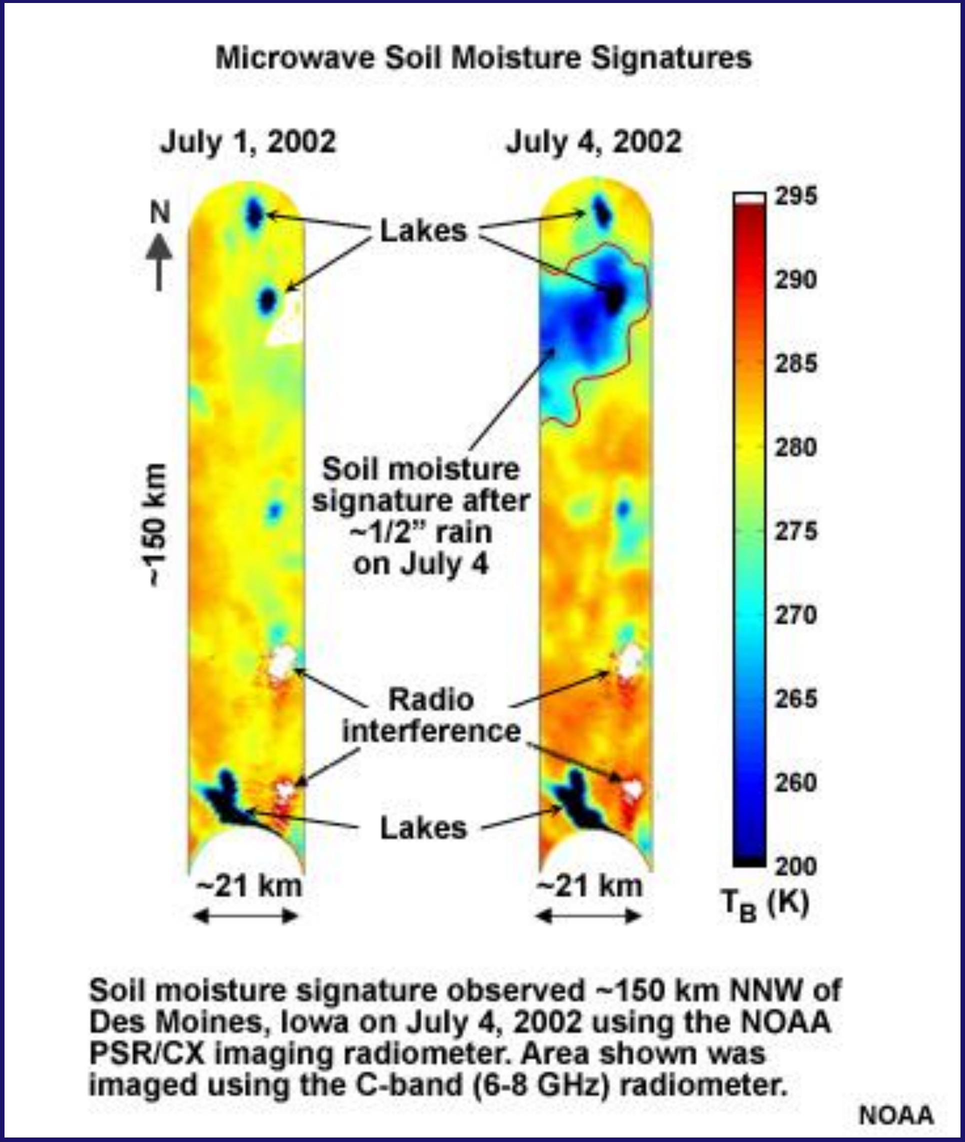
How does a Wet vs. Dry Surface Appear from Space?
Dry vs. Wet Surface

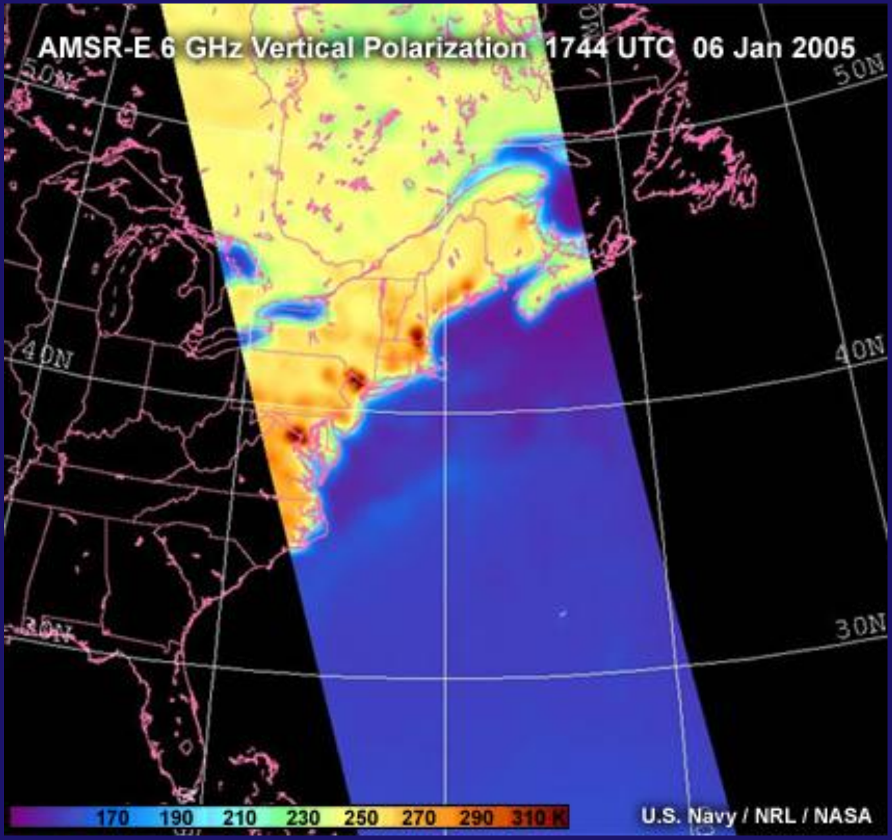


This graph plots **emissivity** for vertically polarized radiation **as a function of** different magnitudes of **surface wetness**. The curves help illustrate two important points. First, **as more water is introduced to a surface, the smaller its emissivity**, and second, **the effect is more pronounced 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.

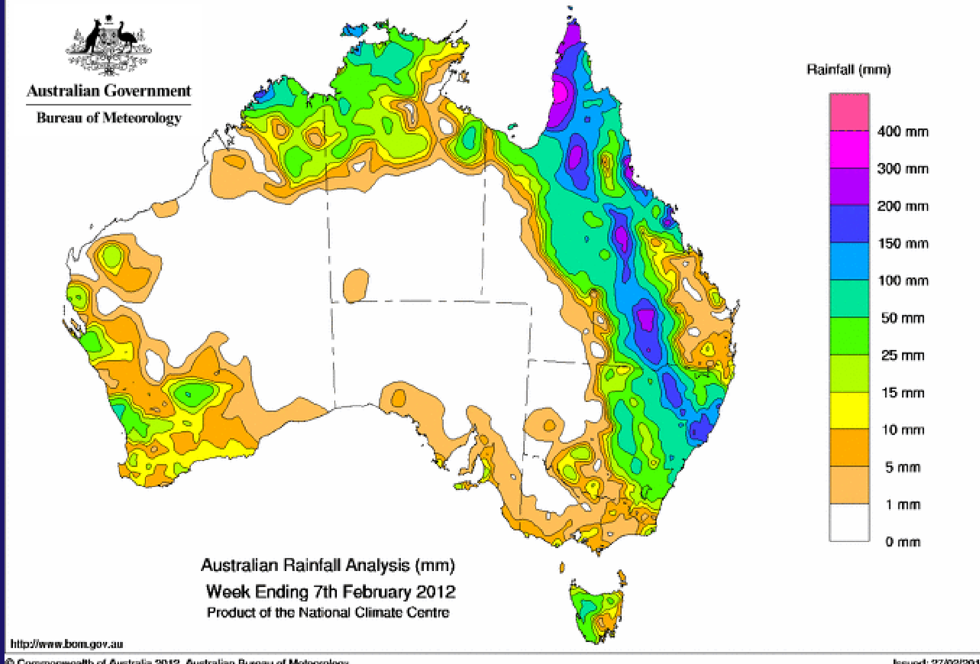
This can be accomplished by calculating brightness temperature differences between high and low frequencies, or by comparing how a single frequency responds when compared to a reference observation for dry conditions. Derivation of soil moisture content is a more complex process that typically involves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

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





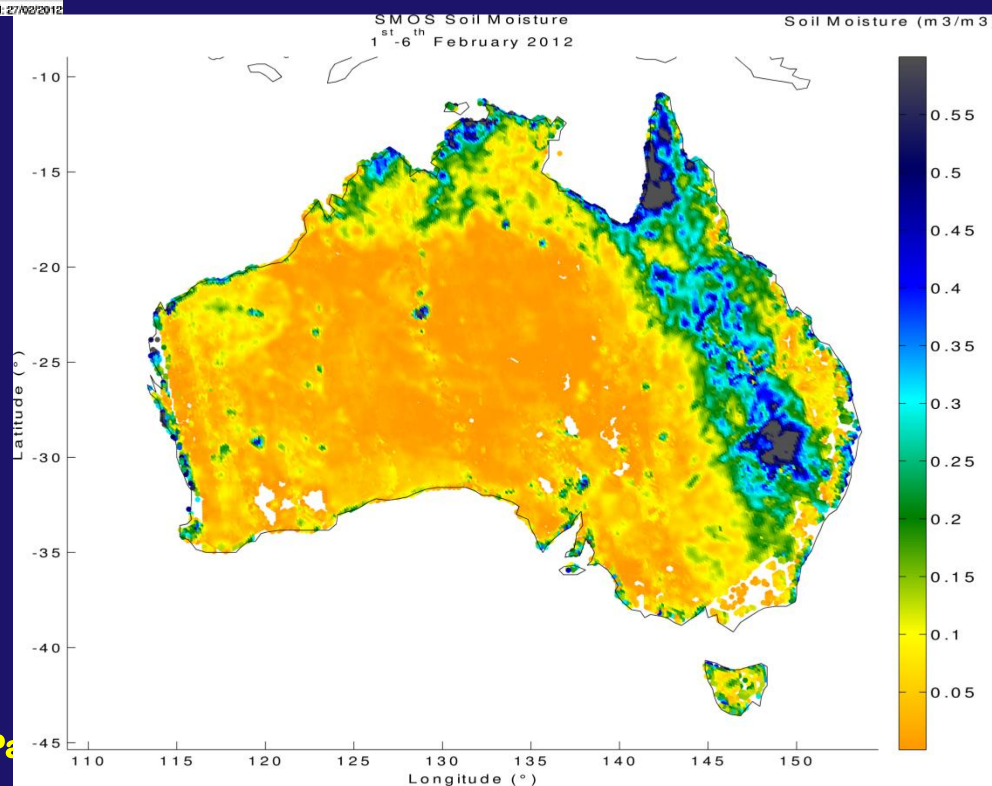
How does a Wet vs. Dry Surface Appear from Space? Dry vs. Wet Surface



SMOS Blog

Important precipitations in Australia

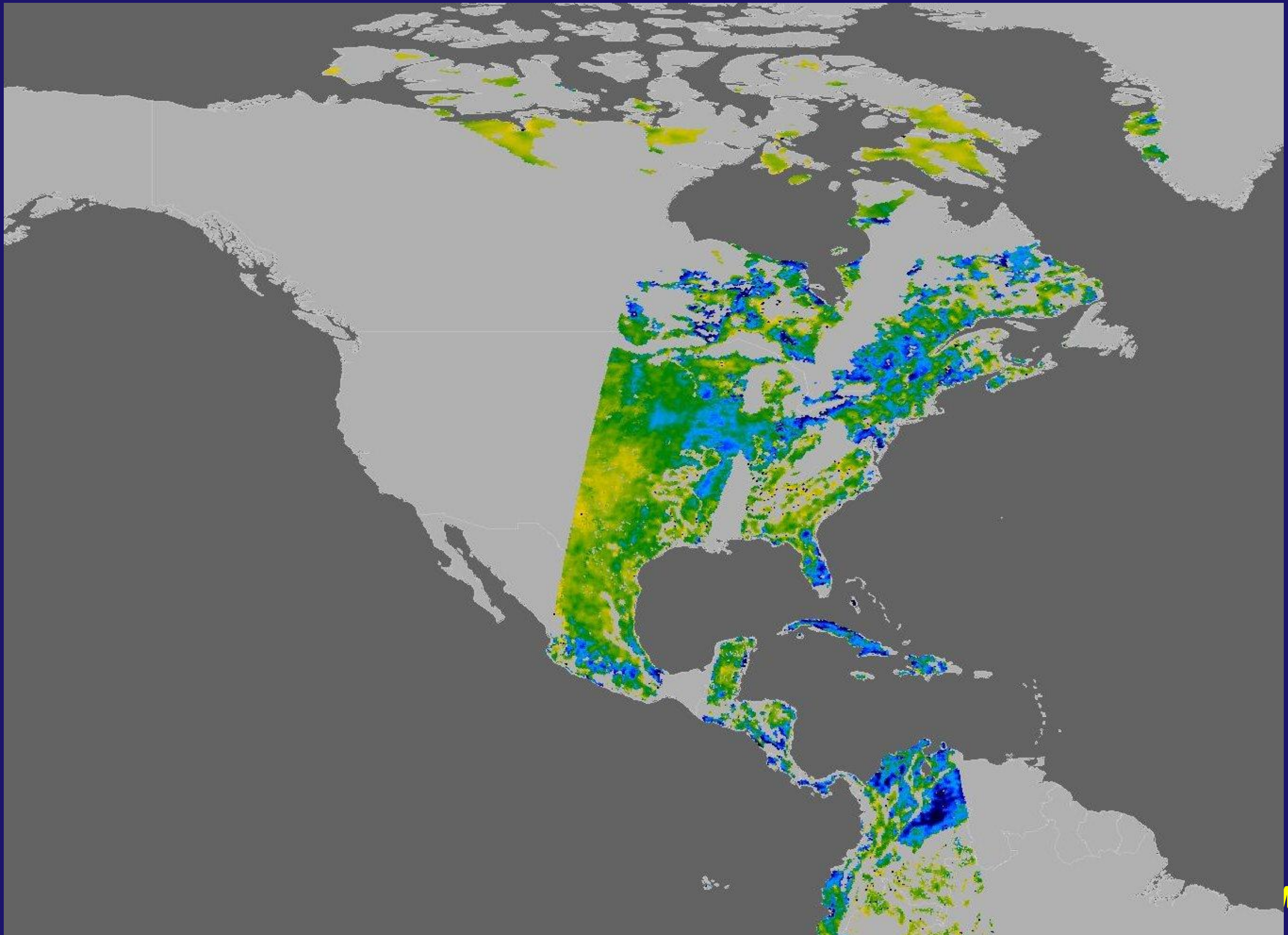
The SMOS mission clearly sees these events. The following figure represents the average SM for the first week of February. Only ascending overpasses are selected, meaning that the soil moisture is measured at about 6 a.m. local solar time. The afternoon overpasses present the same pattern. The area with a soil moisture higher than 0.5 m3/m3 (dark blue / grey) depict flooded areas or saturated soil. Note that the pattern of the precipitations and the SMOS soil moisture are well correlated (R=0.72).



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

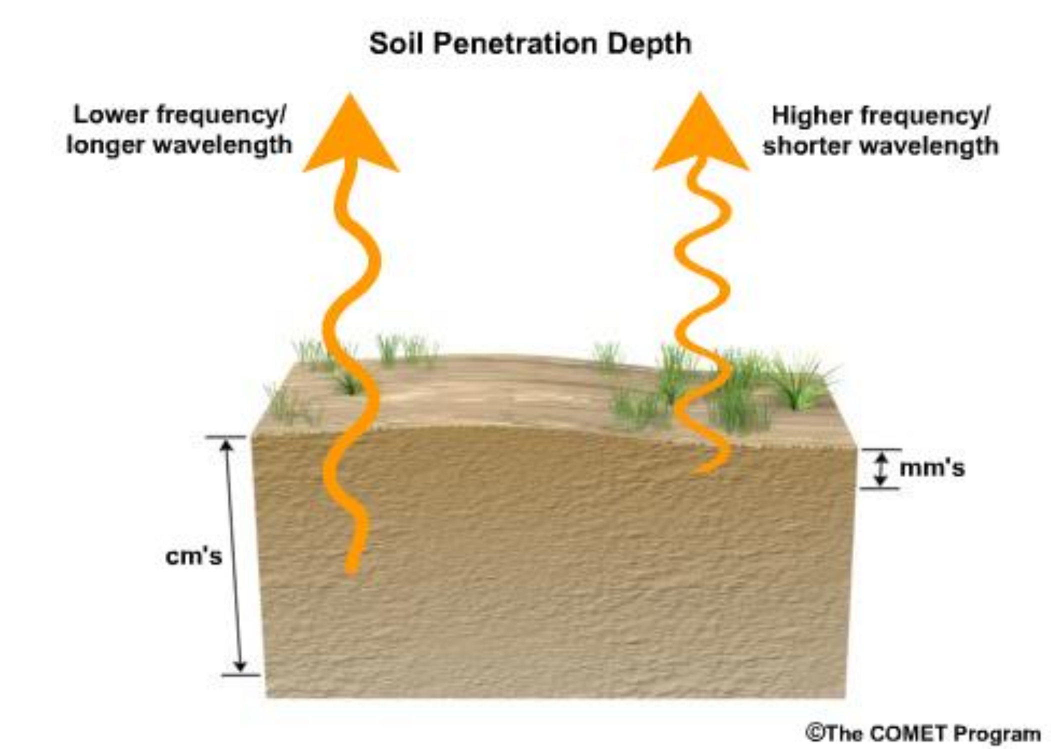
Huricane Sandy

- http://www.esa.int/esaCP/SEM28Q62Q8H_Spain_1.html
- and SMOS Blog



Moisture

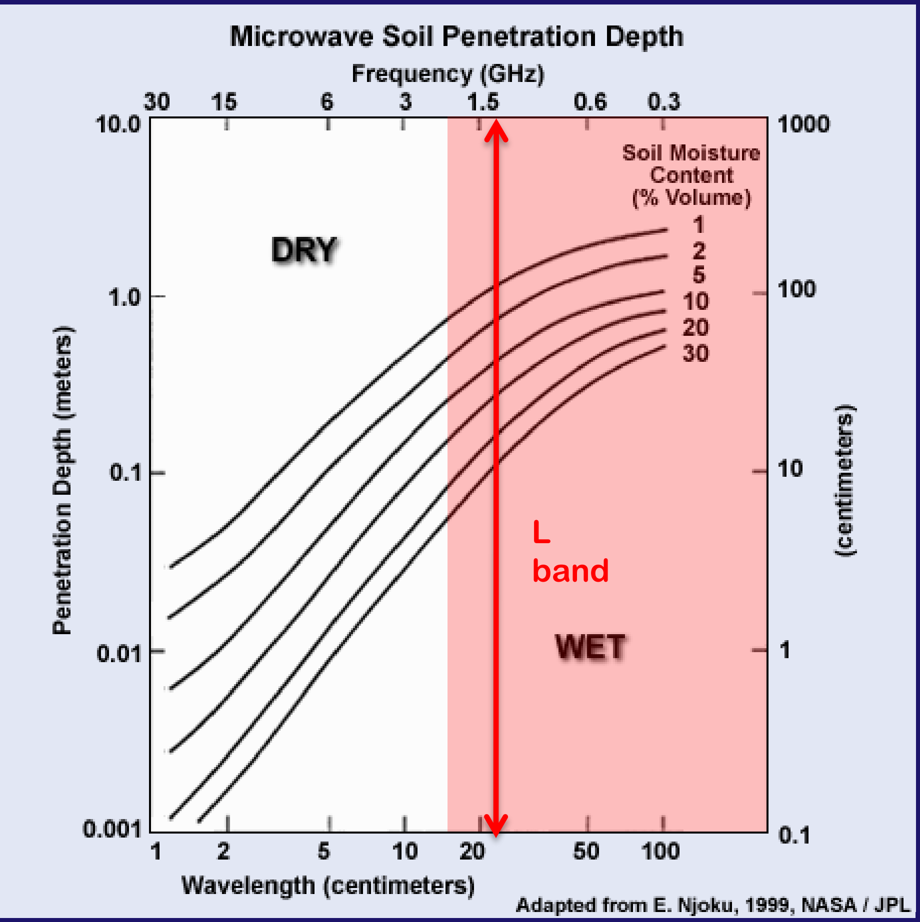
How does a Wet vs. Dry Surface Appear from Space?
Dry vs. Wet Surface



Soil Penetration Depth as a Function of Frequency

SSM/I, SSMIS, AMSR-E, TMI, WindSat Frequency (GHz), Wavelength (cm)	Dry Soil Penetration Depth (cm)
6.8 to 7 GHz, ~4.3 cm	4.5
10 GHz, 3 cm	3
19, 23.8 GHz, ~ 1.3 cm	1.4
85, 89 GHz, ~0.34 cm	0.34

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

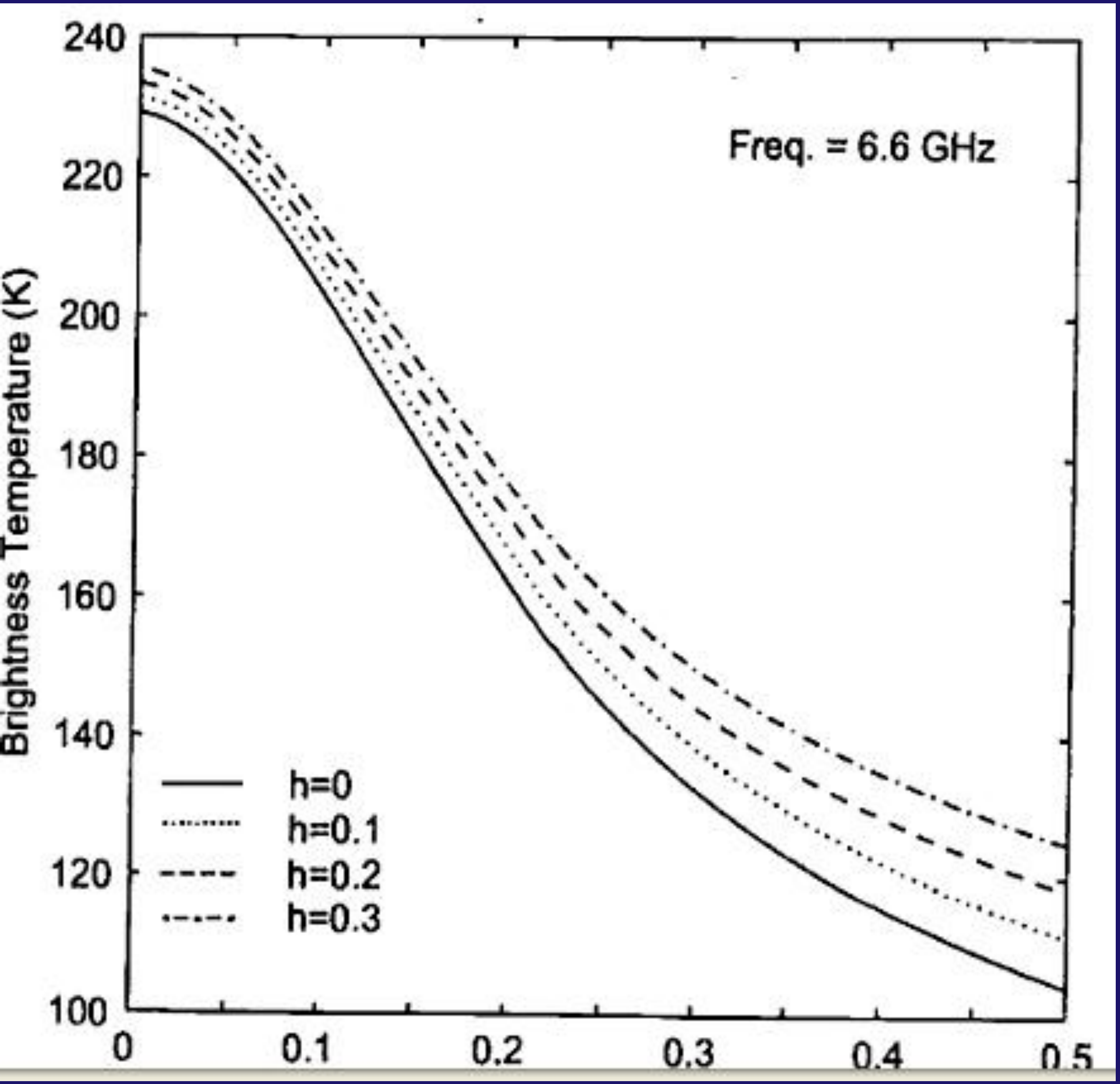


Soil Penetration Depth as a Function of Moisture Content

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.

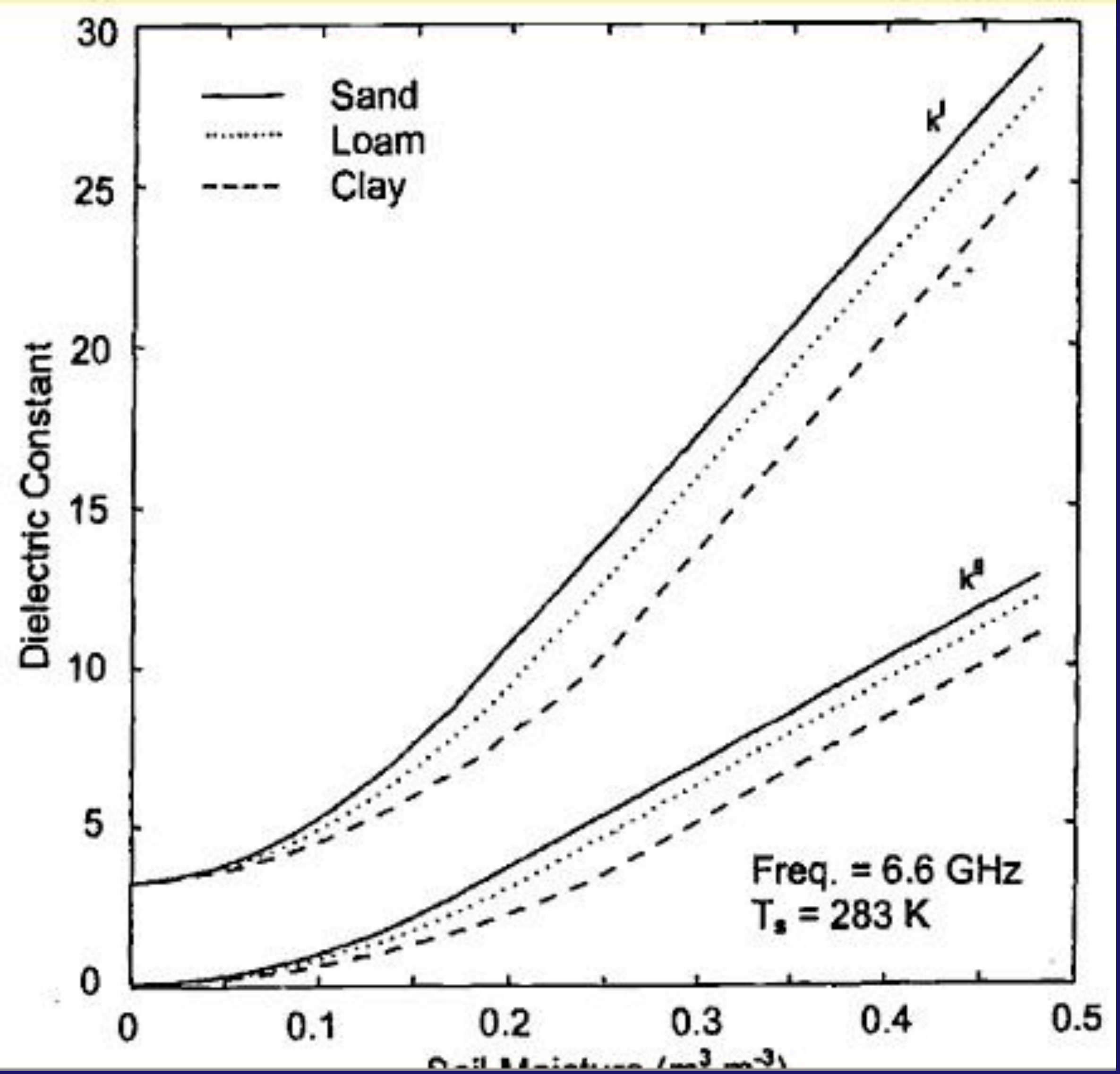
Microwave Dielectric Behaviour of Wet Soil



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

Microwave Dielectric Behaviour of Wet Soil



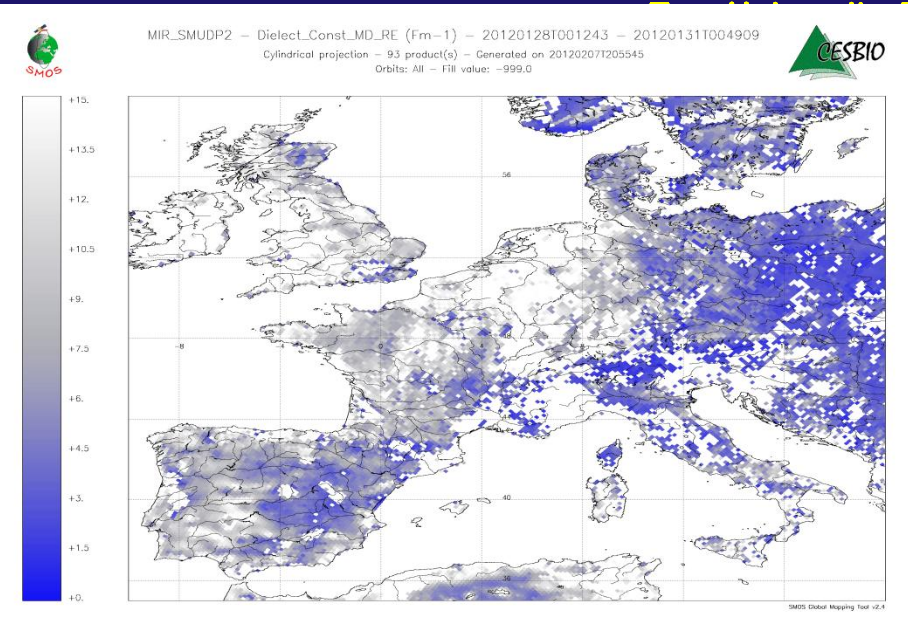
Soil Type Effects

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 ε 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

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

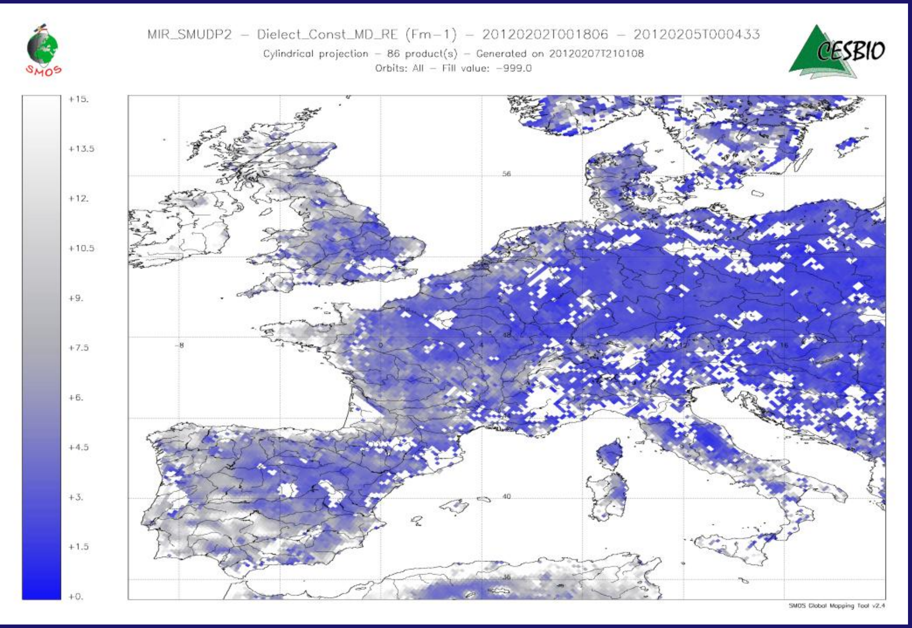
ε'' (imaginary part) determines energy losses



c Behaviour of Wet Soil

Soil Type Effects

January 28 to 31, 2012: Western Europe is grayish white hence high dielectric constant values



February 2-5, 2012. Western Europe is under snow or frozen, … much lower values of the dielectric constant.

Al Bitar and al, CESBIO

Passive Microwaves. Introduction

Rayleigh-Jeans Law. Background

Factors Affecting Emissivity

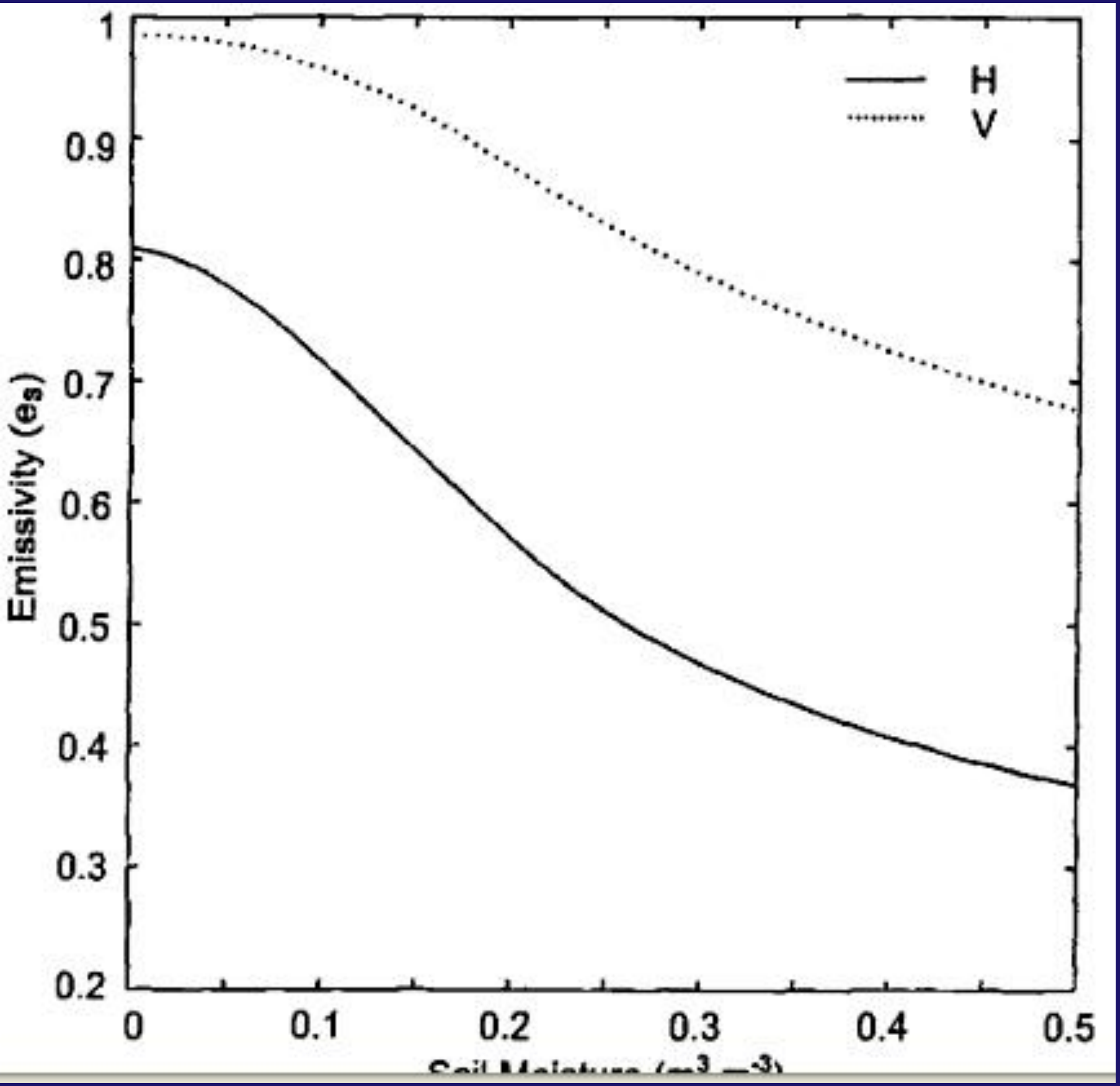
Polarization

Estimation of Soil Moisture

Foto Wikipedia

http://www.europapress.es/ciencia/noticia-realizan-primeras-mediciones-directas-estados-polarizacion-luz-20130303194355.html?utm_source=boletin&utm_medium=email&utm_campaign=usuariosboletin

Microwave Dielectric Behaviour of Wet Soil

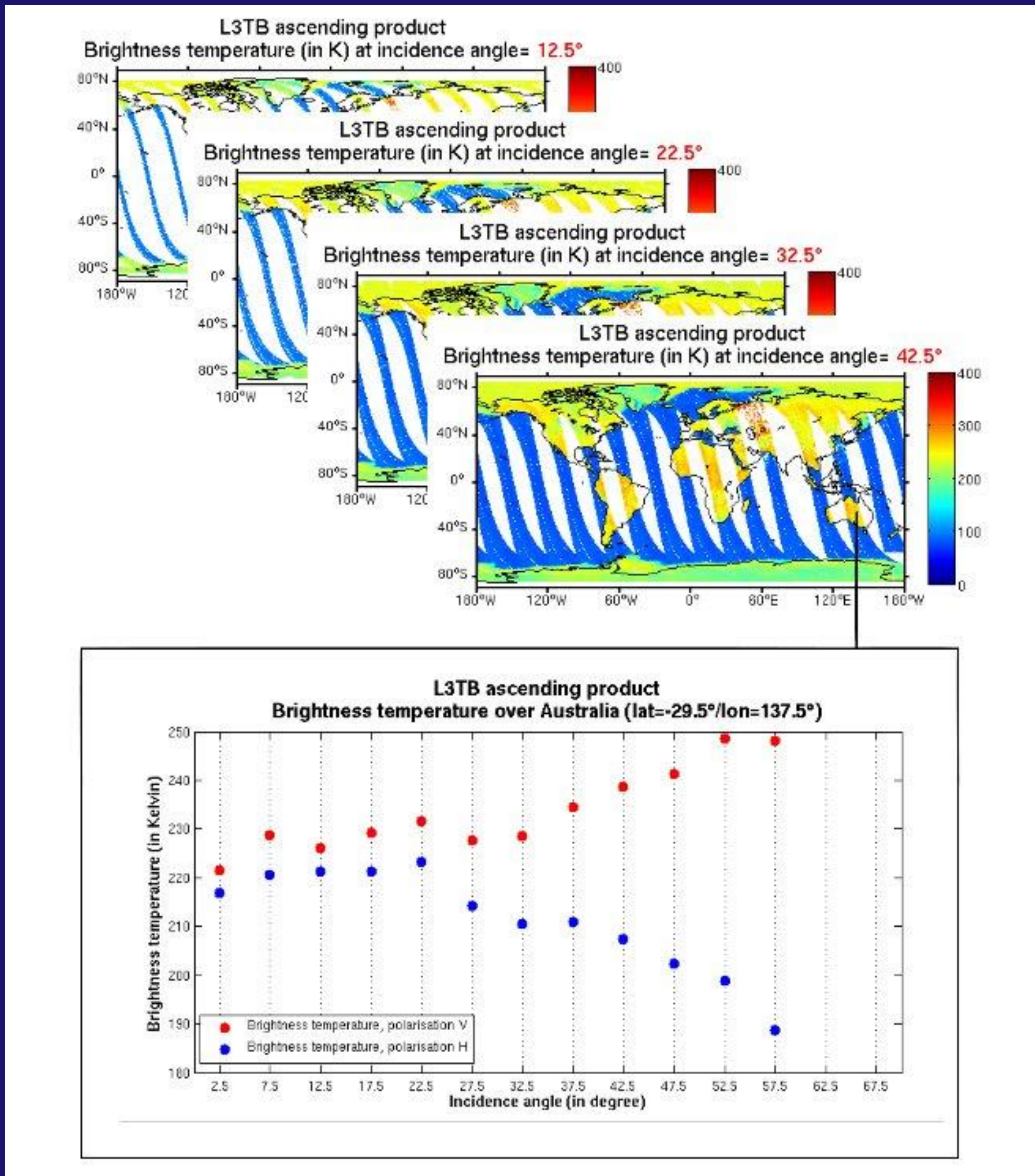


Polarization Effects

Soil emissivity at H and V at a frequency of 6.6. GHz and an incidence angle of 50º

While the emissivity is lower at H pol, the sensitivity to changes to SM is significantly greater than at V pol

Microwave Dielectric Behaviour of Wet Soil

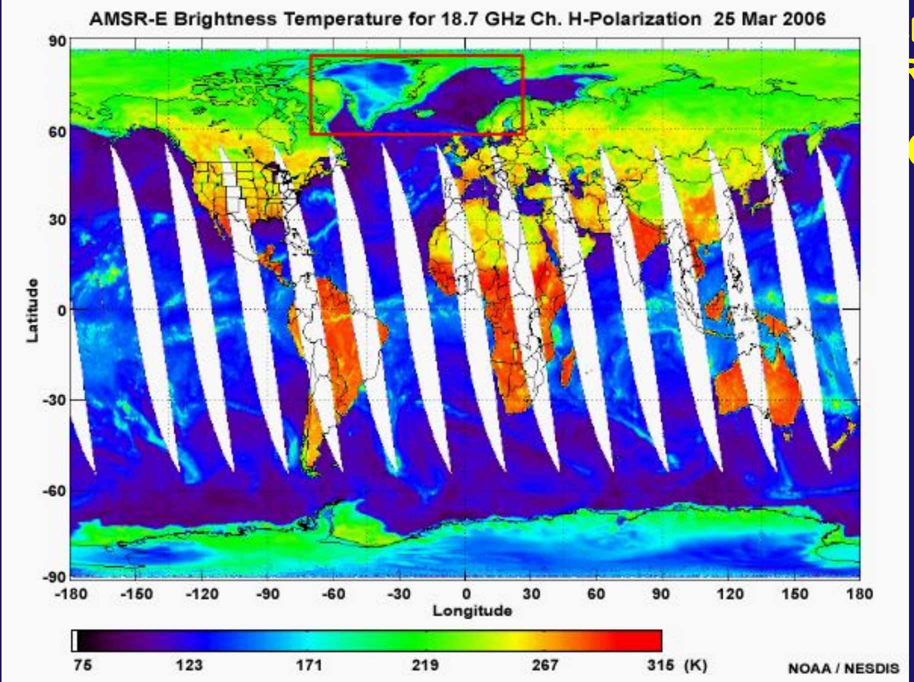


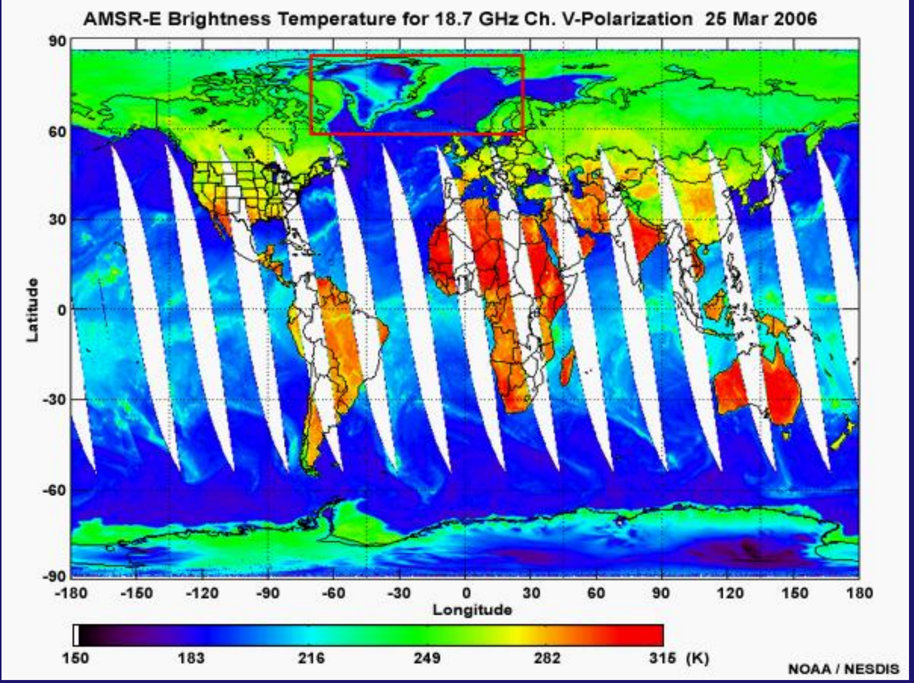
Polarization Effects

SMOS blog

c Behaviour of Wet Soil

Polarization Effects





Microwave Dielectric Behaviour of Wet Soil

Polarization Effects

Normalized Polarization Ratio a

$$= \frac{(T_{bv} - T_{bh})}{(T_{bv} + T_{bh})}$$

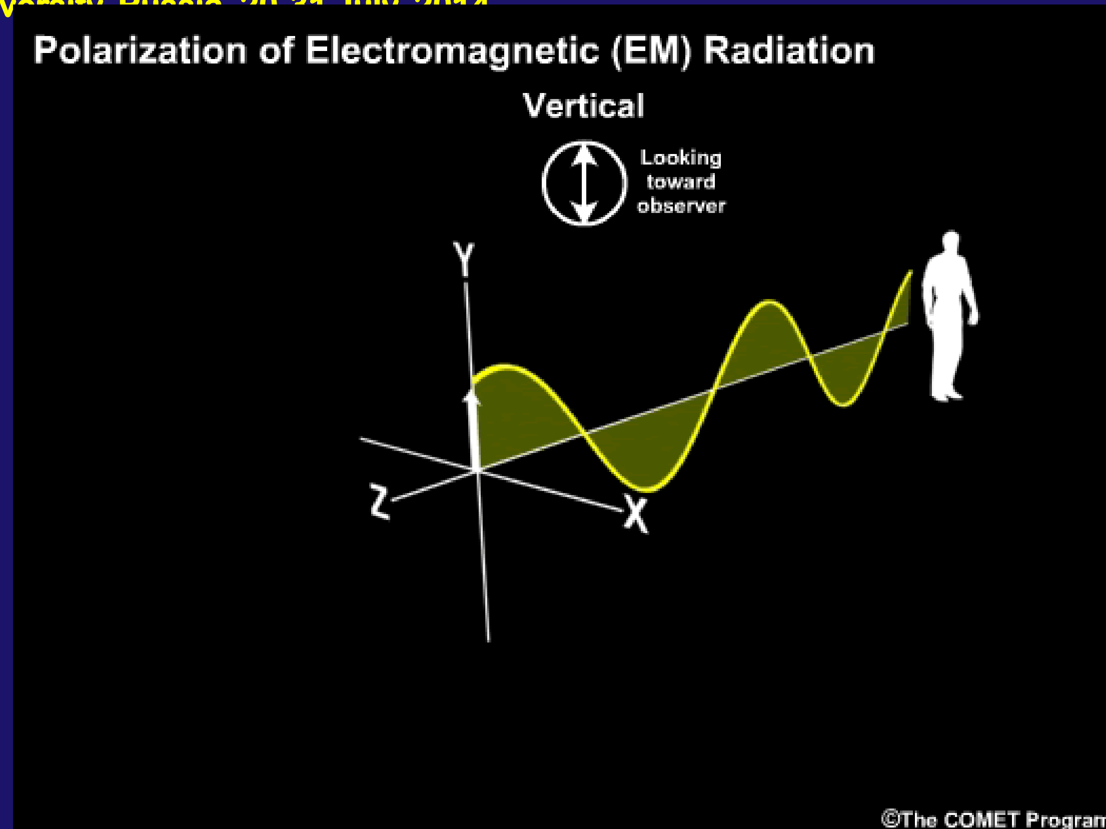
Polarization

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.

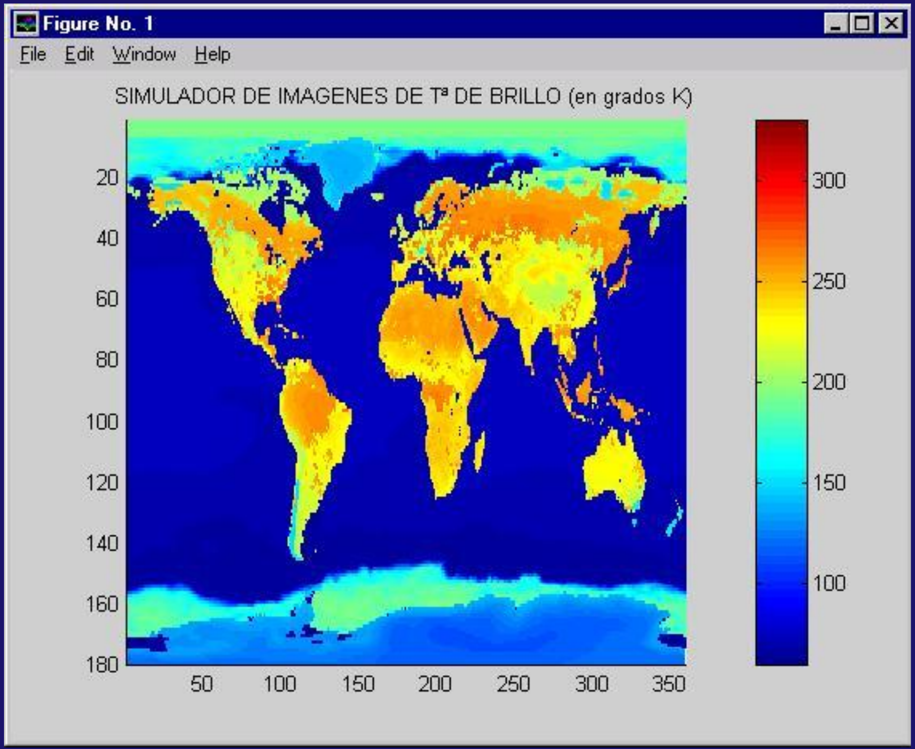
Example of polarization dependent transmissivity

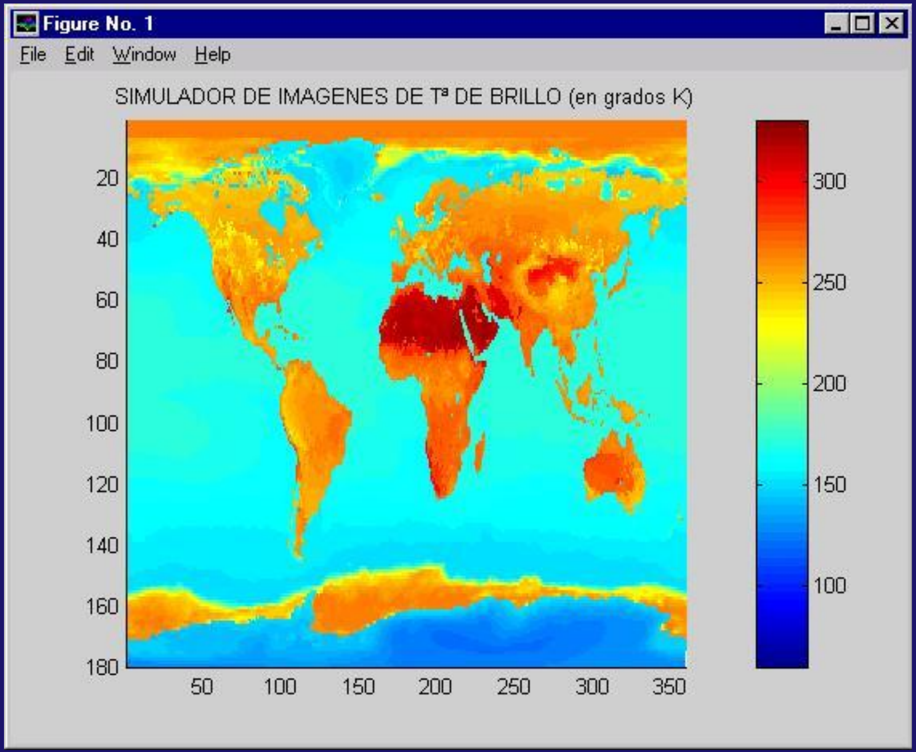
M. Schwank

Polarization



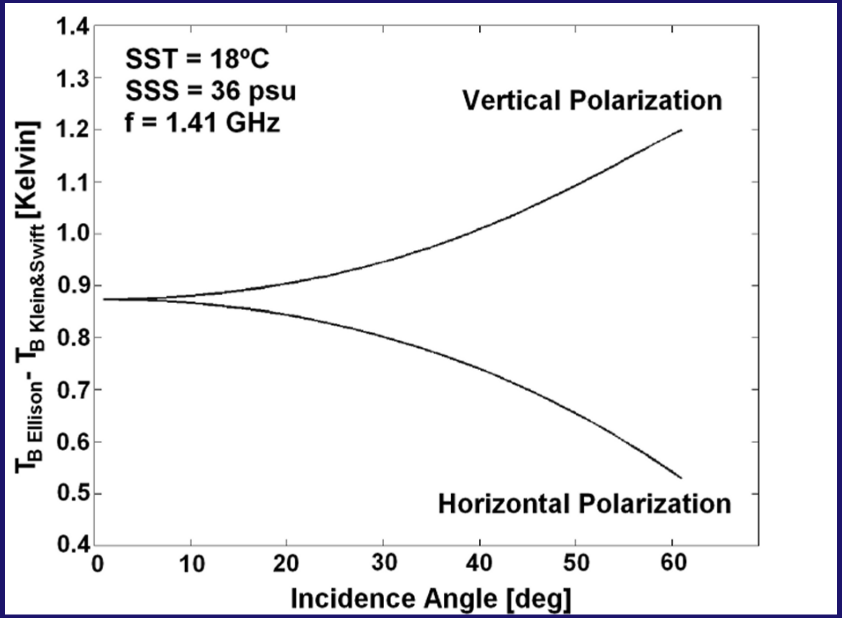
Polarization refers to the orientation of the electric field vector of an electromagnetic wave as it is emitted, reflected, or transmitted by a material or medium such as a gas. This graphic shows microwave energy polarized in a vertical orientation. Microwave energy can be emitted in six polarization 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.

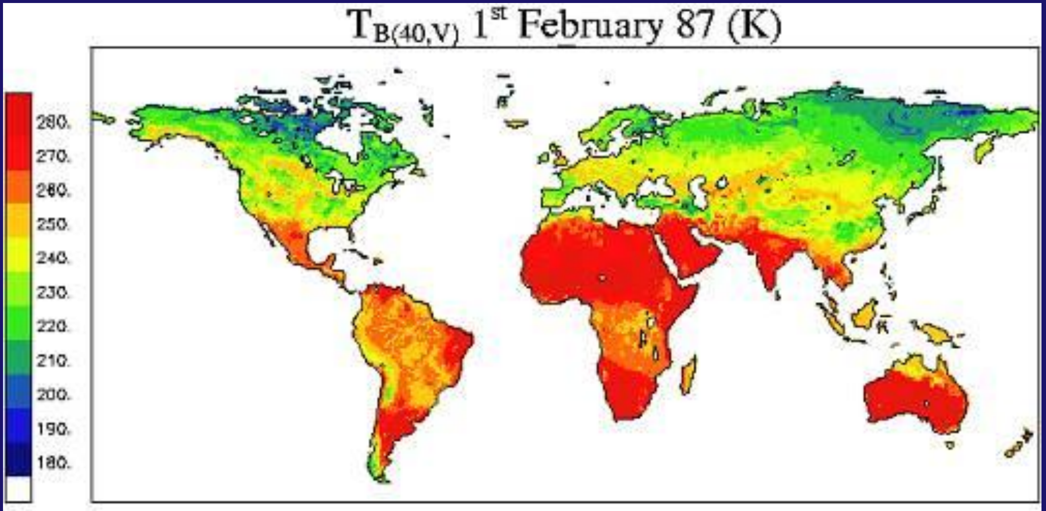


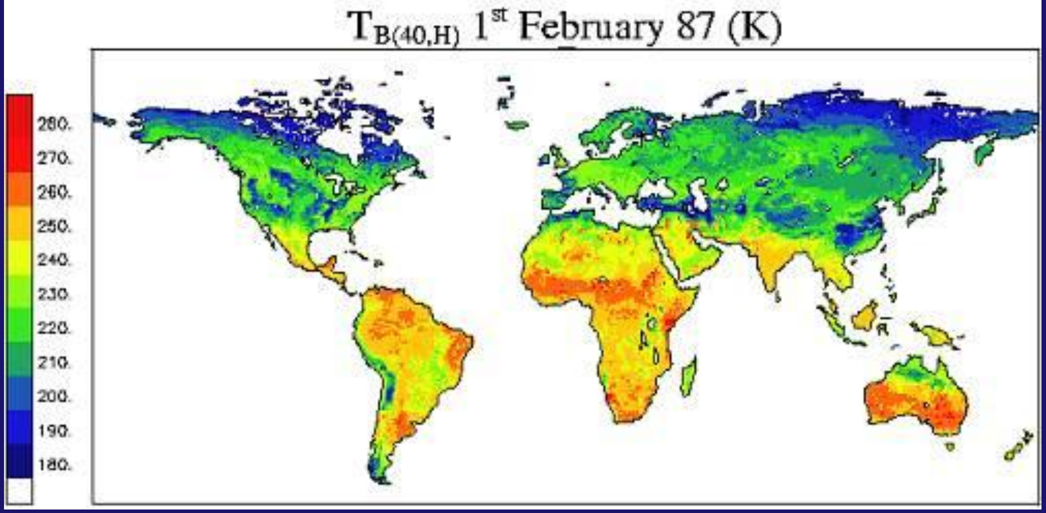


Brightness temperature for September with the same incidence angle of θ = 55° and with H polarization (left) and V polarization (right)

Polarization: Additional useful information to obtain geophysical variables

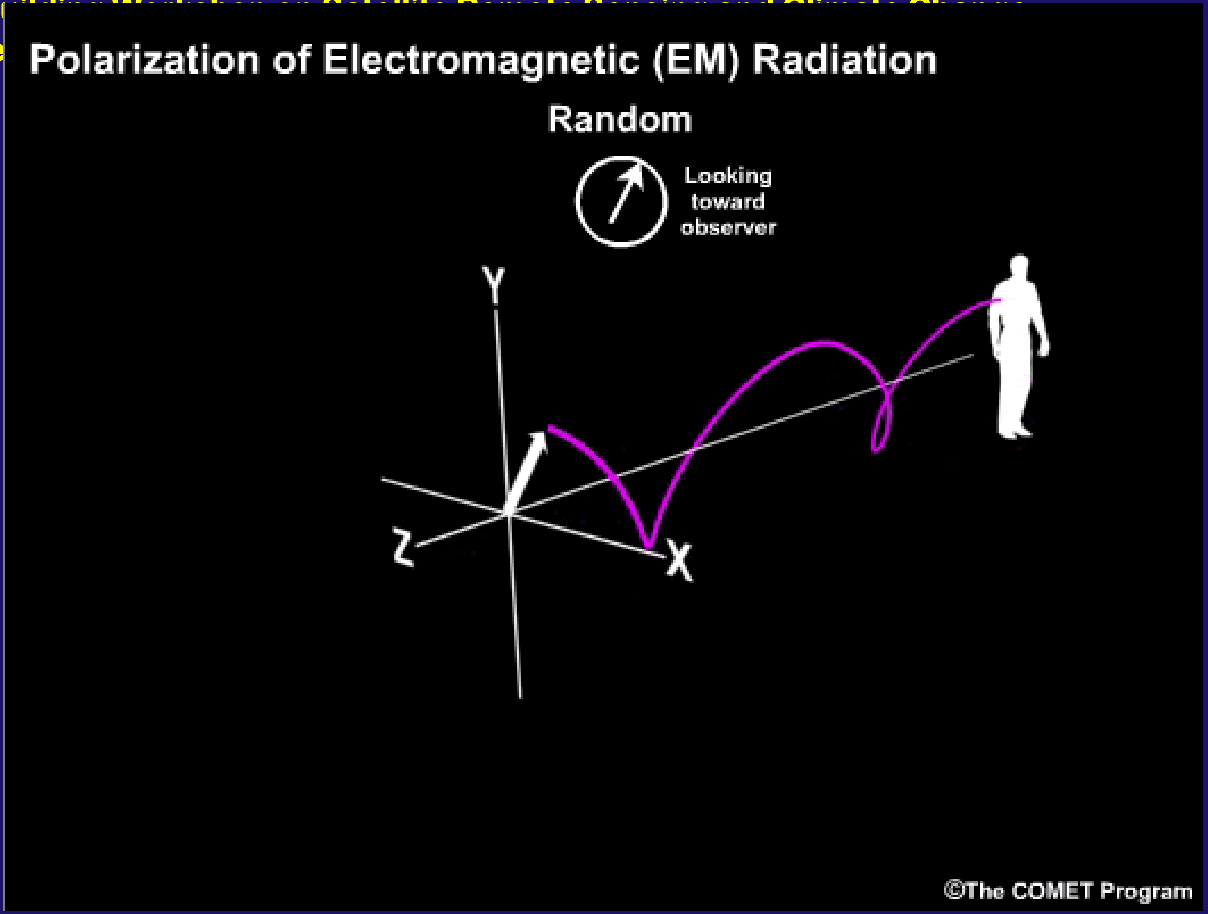






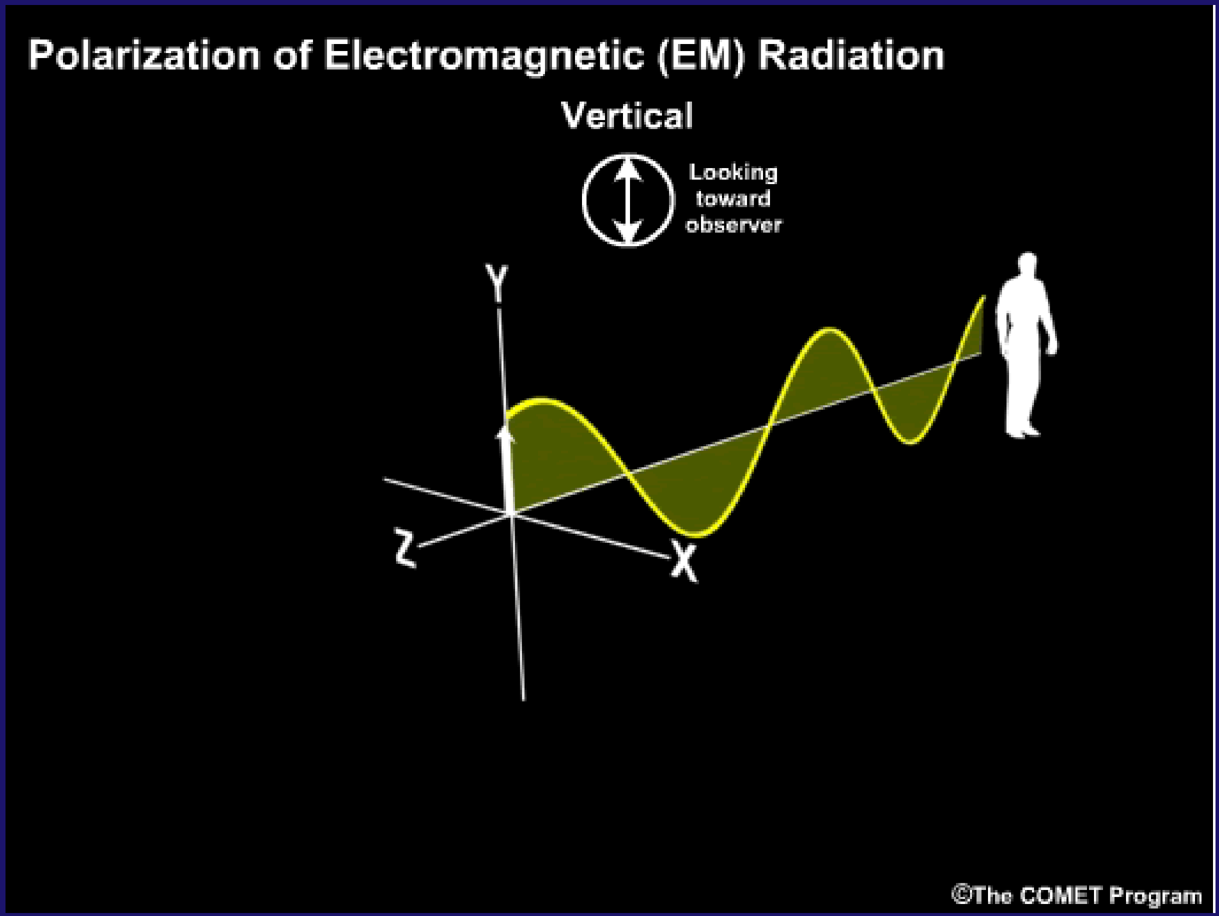
Pellarin et al.,

Random Polarization



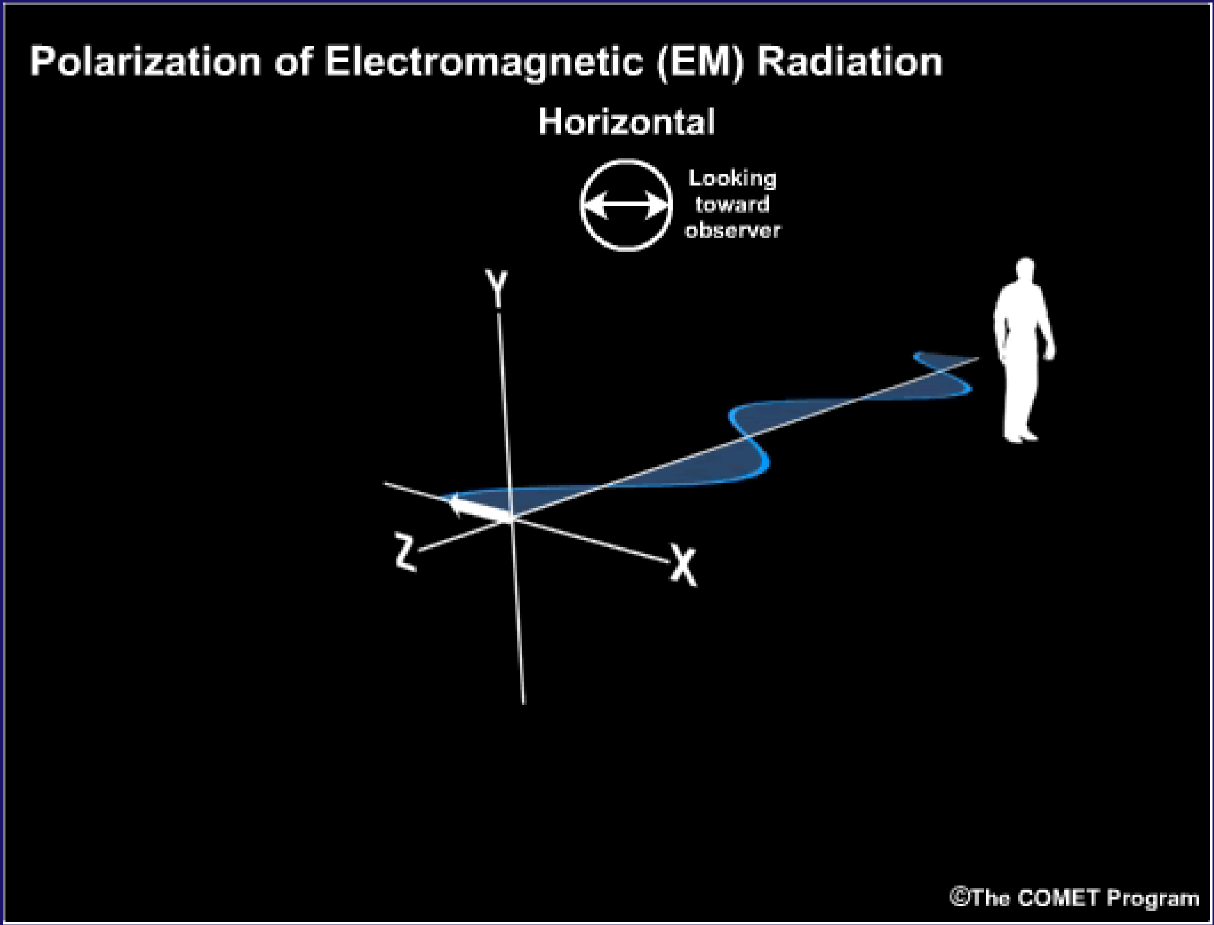
Most naturally emitted microwave energy is essentially unpolarized. That is, the electric field vector traces the motion of the electromagnetic wave, which oscillates randomly in all directions as it passes along the Z-axis. Energy can become partially polarized through interaction with various elements 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.

Horizontal and Vertical Polarization



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.

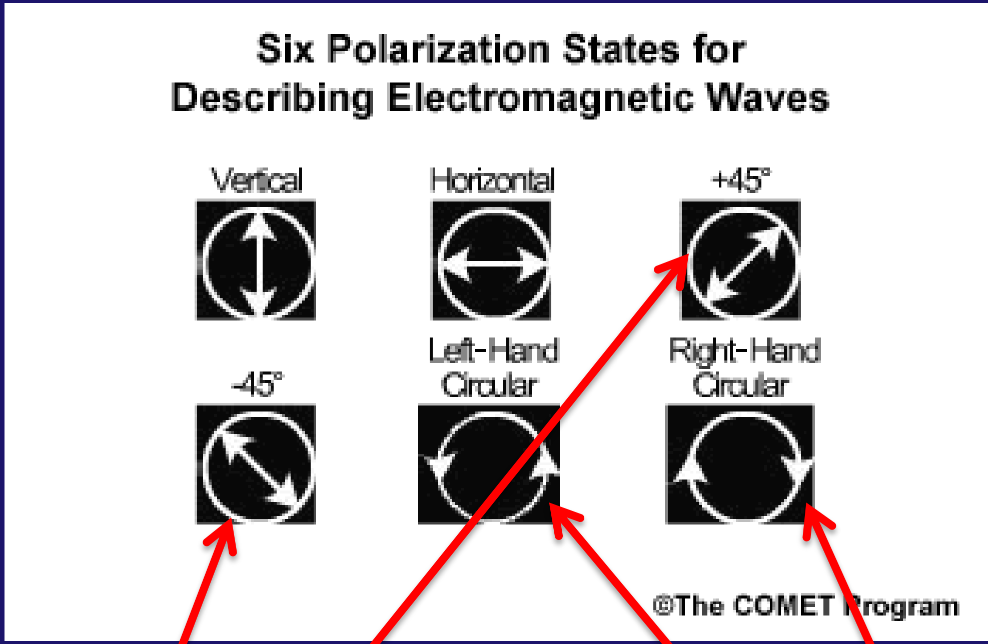
Horizontal and Vertical Polarization



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

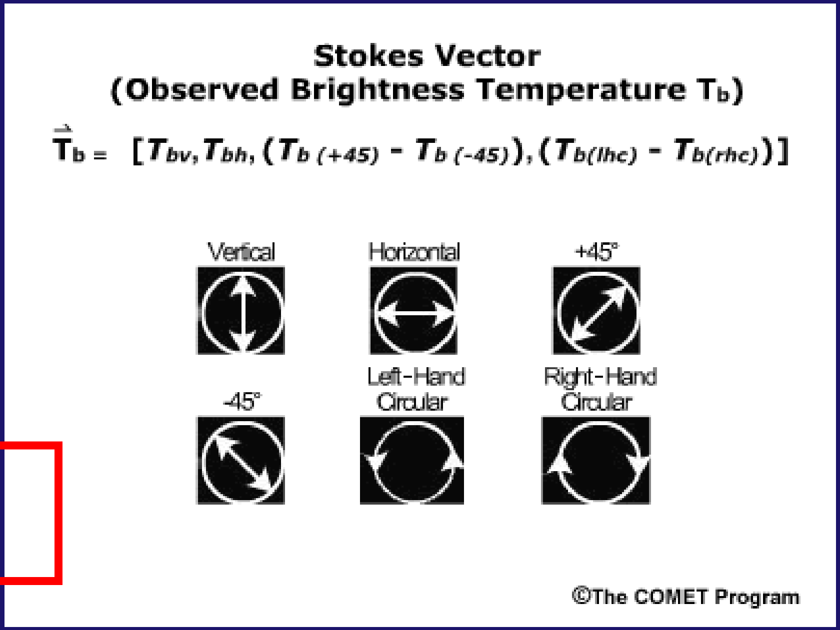
Horizontal and Vertical Polarization

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



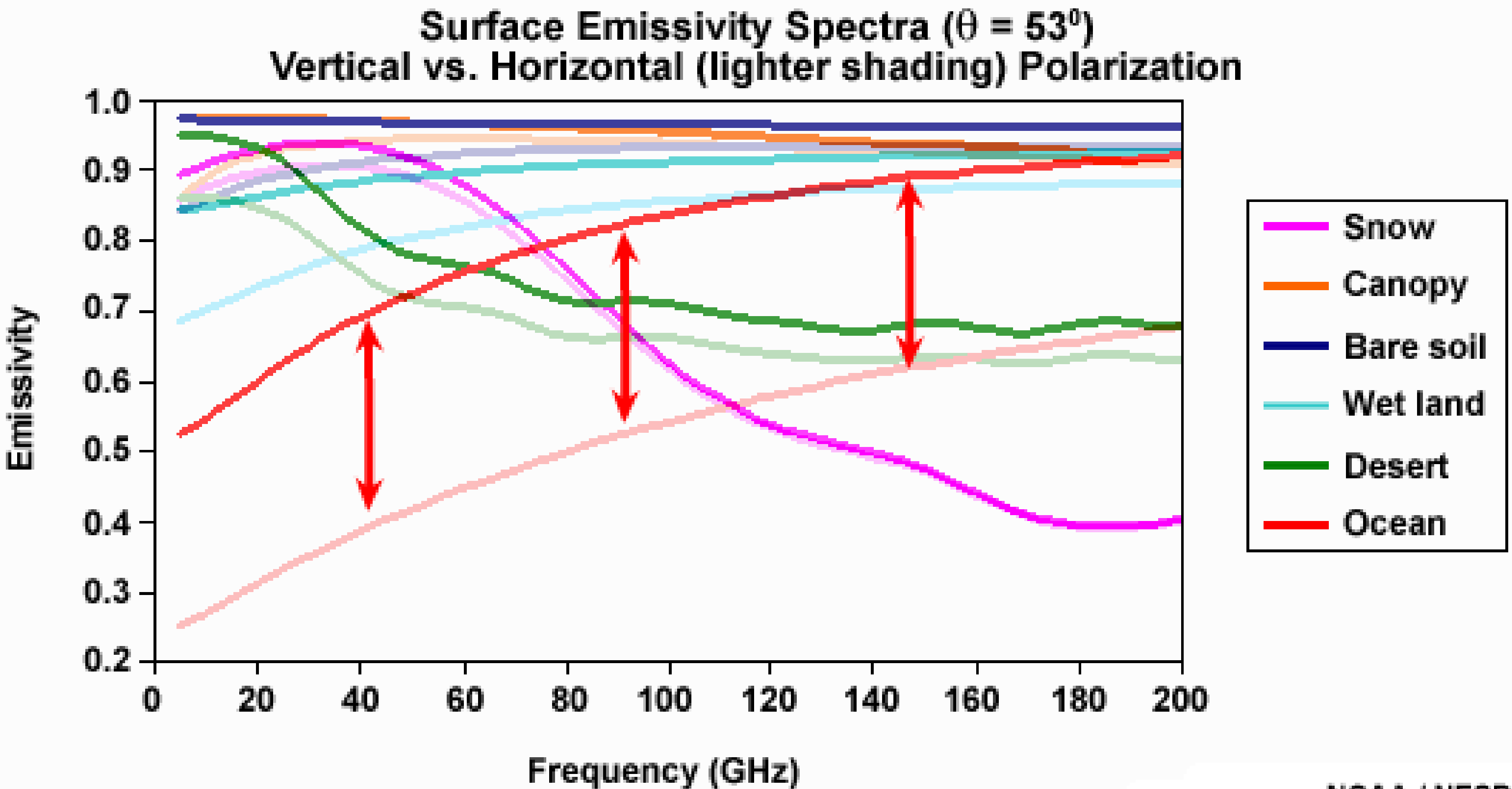
H and V composition on phase

H and V composition with 90 deg phase difference



Polarization:

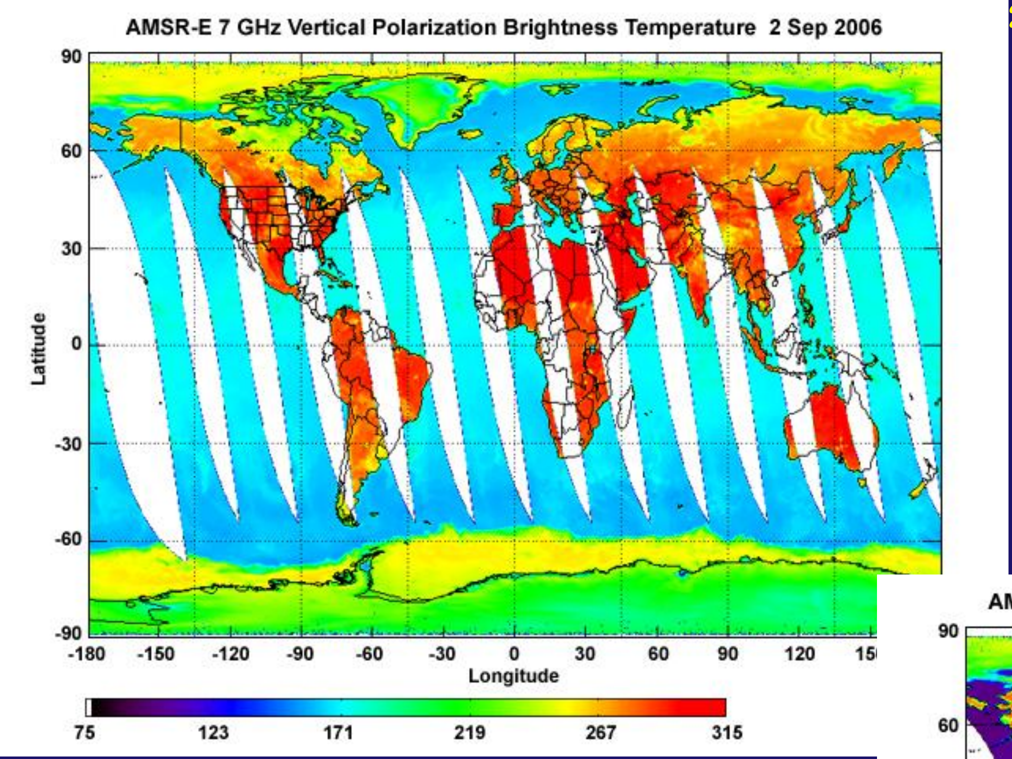
Additional useful information to obtain geophysical variables

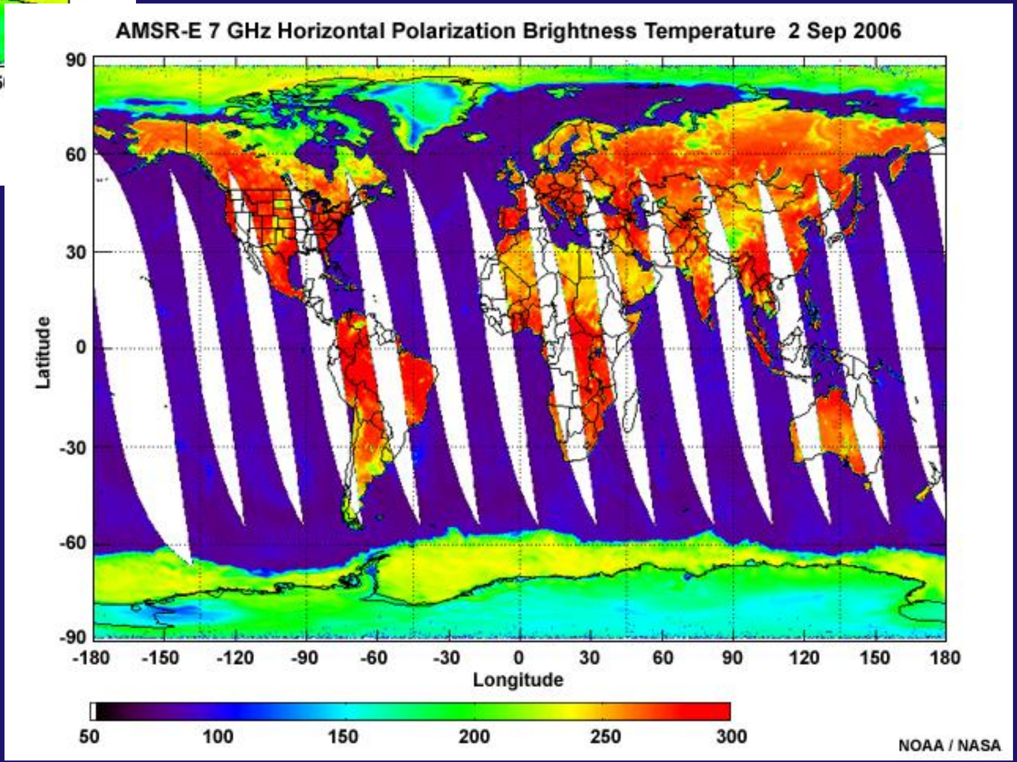


NOAA / NESDIS

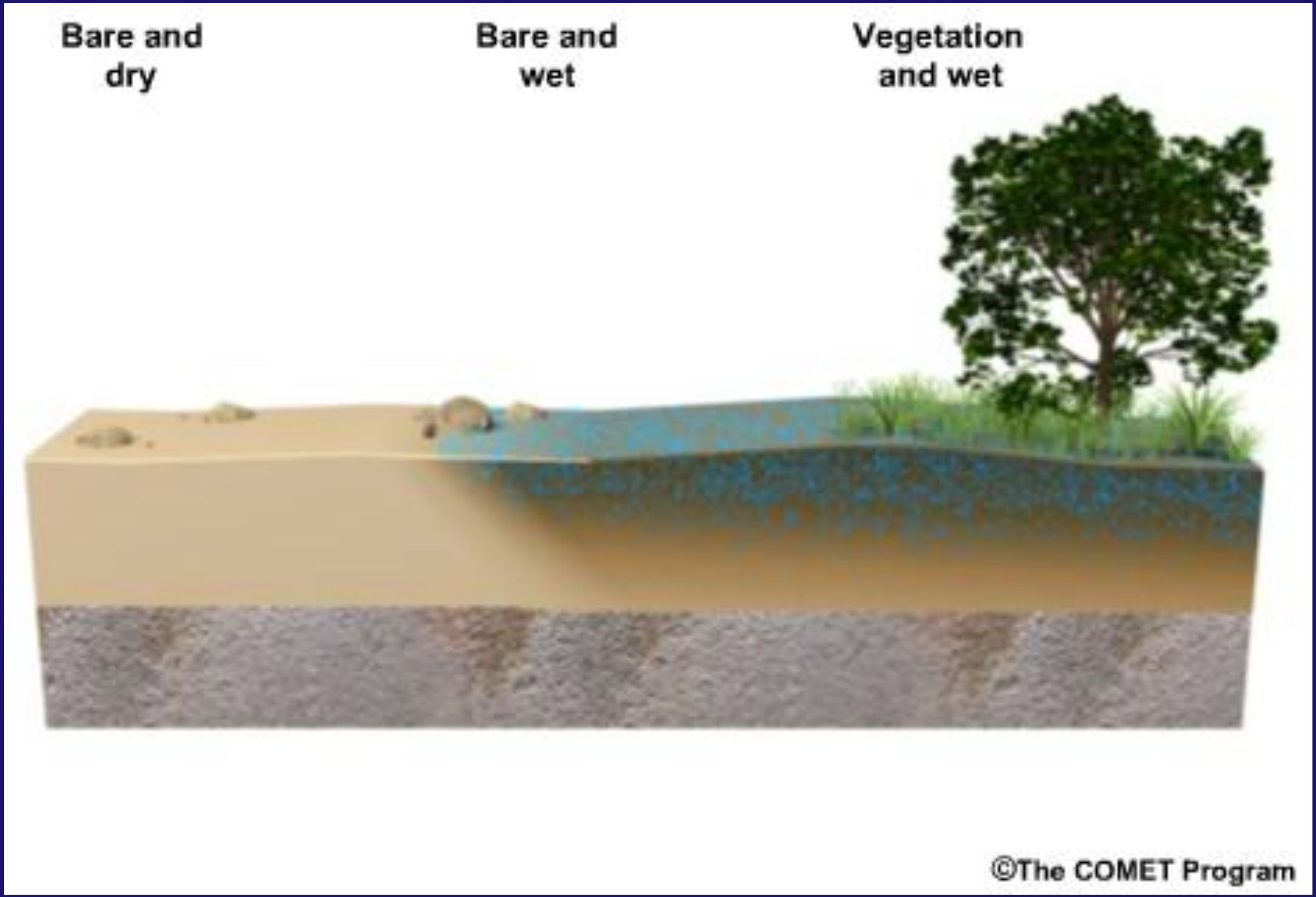
Polarization

additional useful information to obtain geophysical quantities

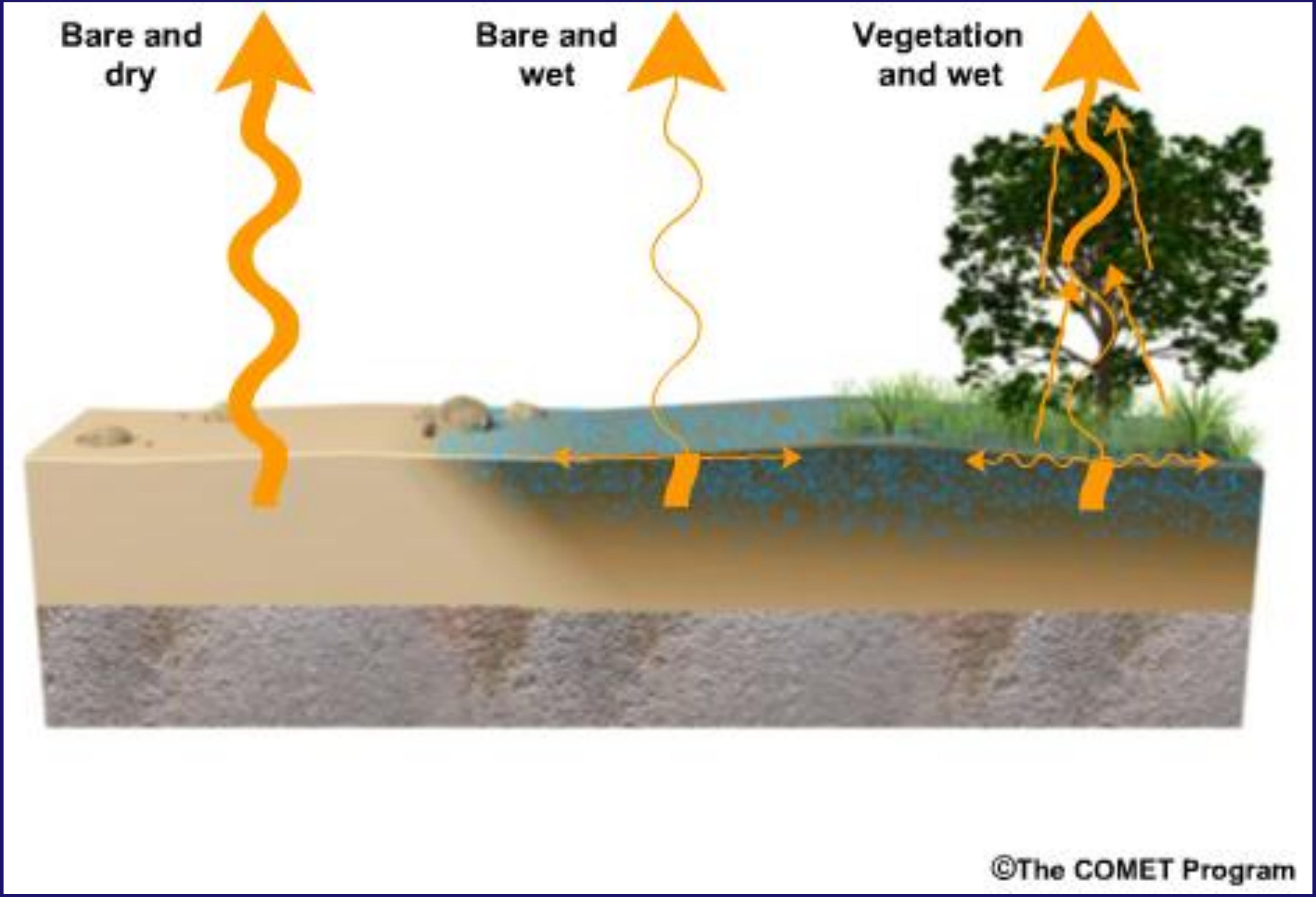




Vegetation


Bare and dry
Bare and wet
Vegetation and wet
©The COMET Program

Vegetation


Bare and dry
Bare and wet
Vegetation and wet
©The COMET Program

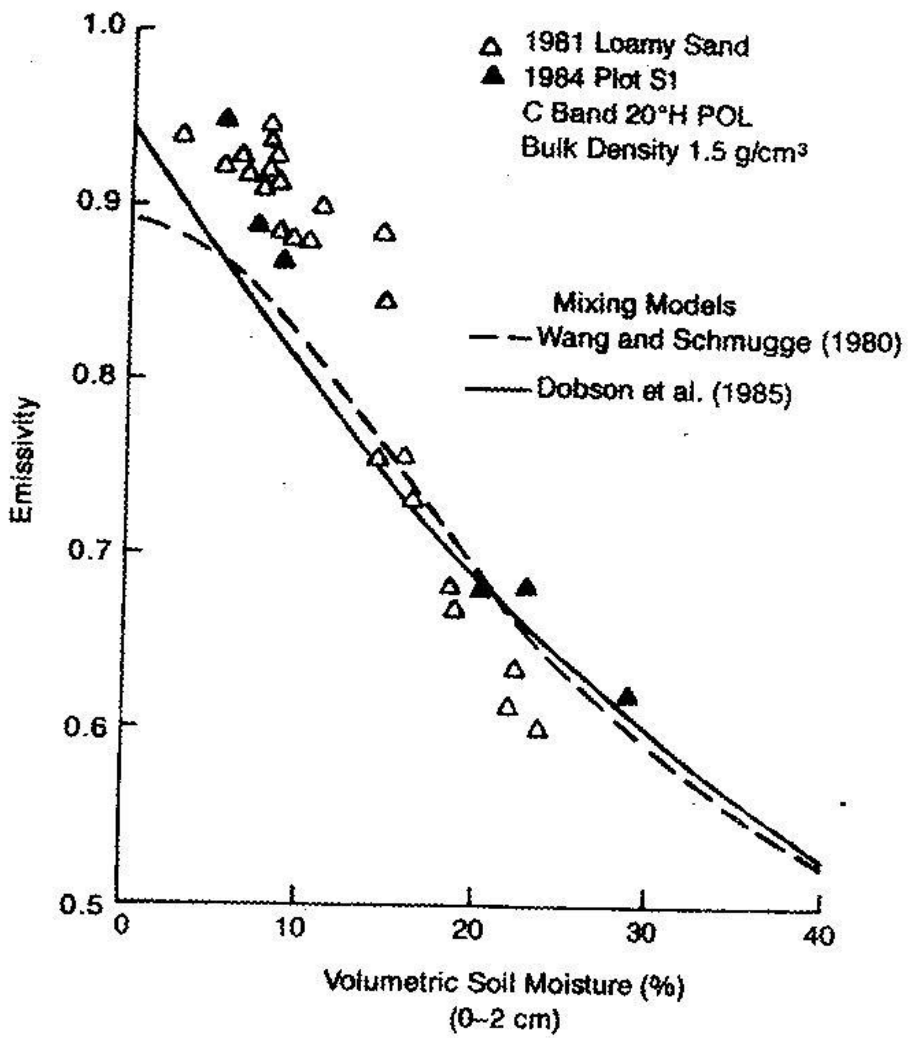
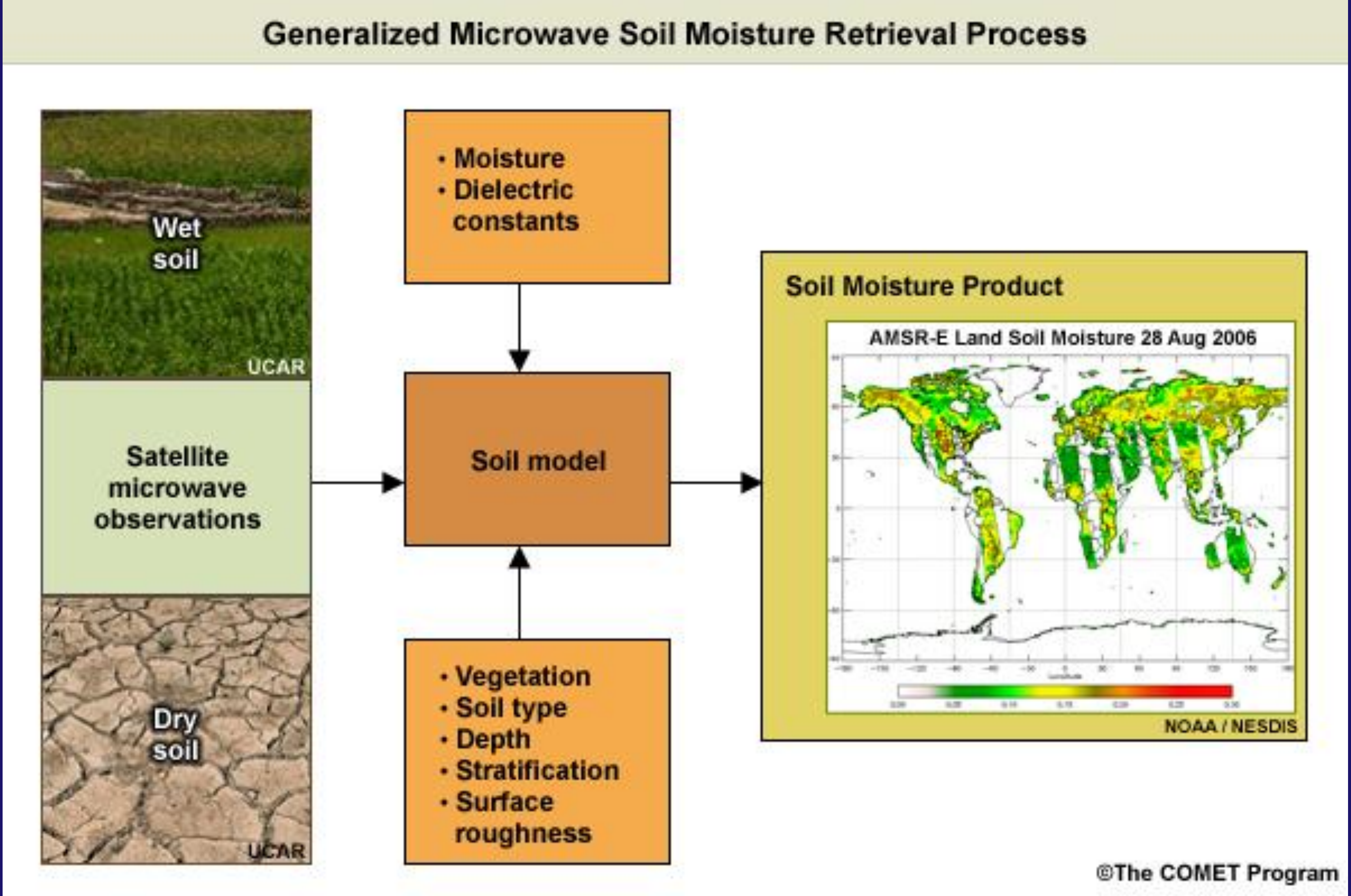


Figura 17

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

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


Generalized Microwave Soil Moisture Retrieval Process
Wet soil
UCAR
Satellite microwave observations
Dry soil
UCAR
• 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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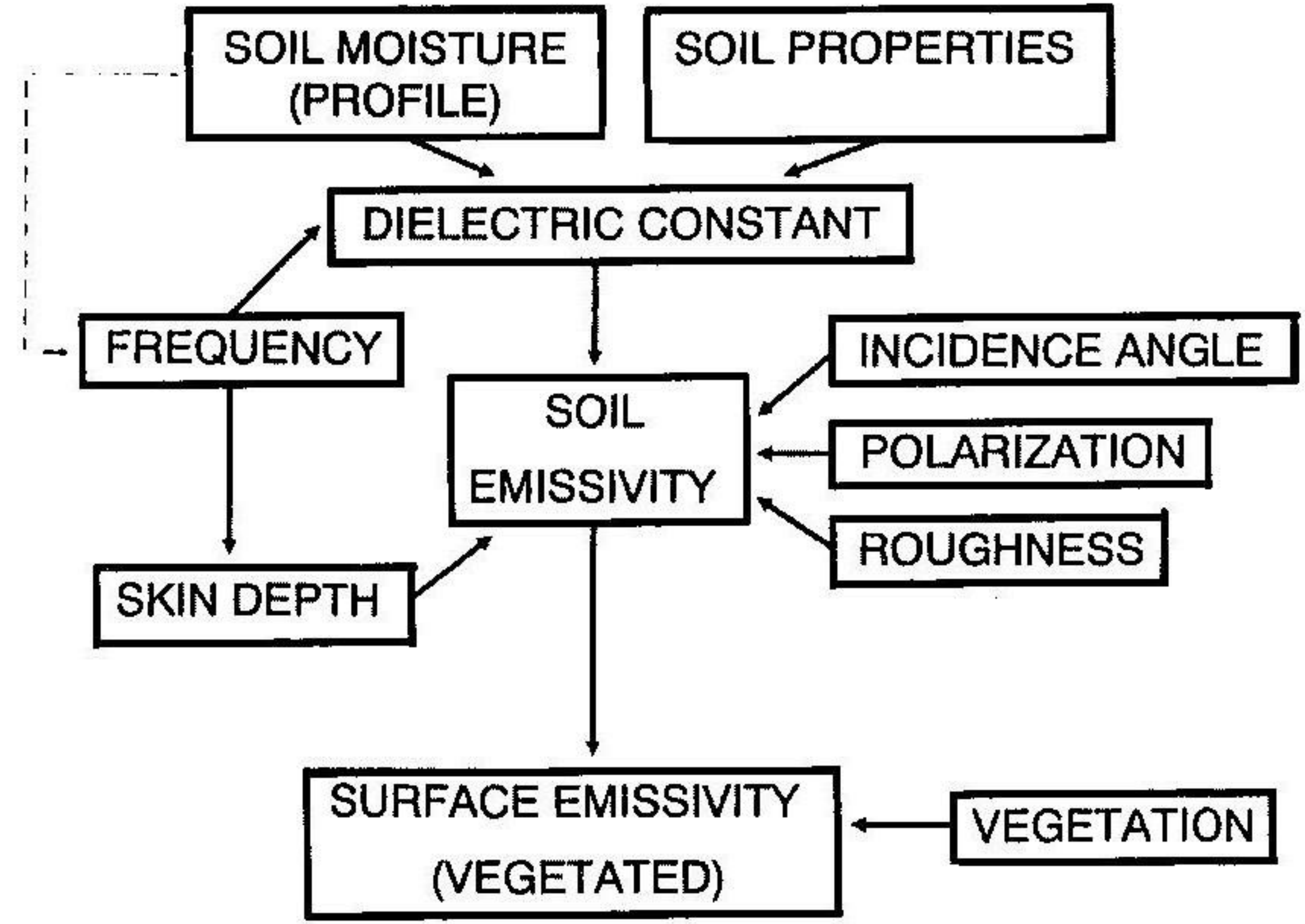

Figure 7

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

L-band Microwave Emission of the Biosphere (L-MEB)

J.-P- Wigneron

Objectives

To perform the validation on the capabilities of the participating land surface schemes in simulating the brightness temperature in those areas where field- and aircraft-based measurements are available.

J.-P- Wigneron

L-MEB Input Variables

Variable Description	Unit
Landmask	-
Sand%	-
Clay%	-
Elevation	m
Vegetation type	-
Air temperature (2m)	K
Leaf Area Index (LAI)	m^2m^{-2}
Surface soil temperature (0 ~ 5cm)	K
Deep soil temperature (50 or 100cm)	K
Vegetation canopy temperature	K
Surface soil moisture	m^3m^{-3}
Surface frozen soil moisture	m^3m^{-3}
Canopy water interception	kgm^{-2}
Snow temperature	K
Snow depth	m
Snow water equivalent	kgm^{-2}
Snow covered fraction	-
Liquid water content of the snow	m^3m^{-3}

J.-P- Wigneron

L-MEB Model Characteristics/Capabilities

- Brightness temperature simulation for
  - Single frequency (1.4 GHz)
  - Dual polarization (H and V)
  - Multiple incidence angles
  - Various land cover types (and subgrid heterogeneity)
    - Water bodies / Bare soil / Herbaceous canopies / shrubland / forest types
  - A variety of climatological conditions
    - No snow / frozen soil / snow overlaying vegetation

J.-P- Wigneron

Vegetation Cover Effects (τ-ω Model)

- τ-ω model is based on two parameters
  - Optical depth (τ)
    - To parameterize the vegetation attenuation properties
    - $\tau = bW_c$ where Wc is the total vegetation water content.
  - Single scattering albedo (ω)
    - To parameterize the scattering effects within the canopy

τ-ω Model Parameters for Common land cover types

Land cover Type	ω	b	Wc
Water bodies			0.0
Bare soil			0.0
Crops	0.05	0.15	0.5*LAI
Grasslands	0.05	0.20	0.5*LAI
Shrubland	0.00	0.15	2 kgm^{-2}
Rainforests	0.15	0.33	6 kgm^{-2}
Deciduous forests	0.15	0.33	4 kgm^{-2}
Conifer forests	0.15	0.33	3 kgm^{-2}

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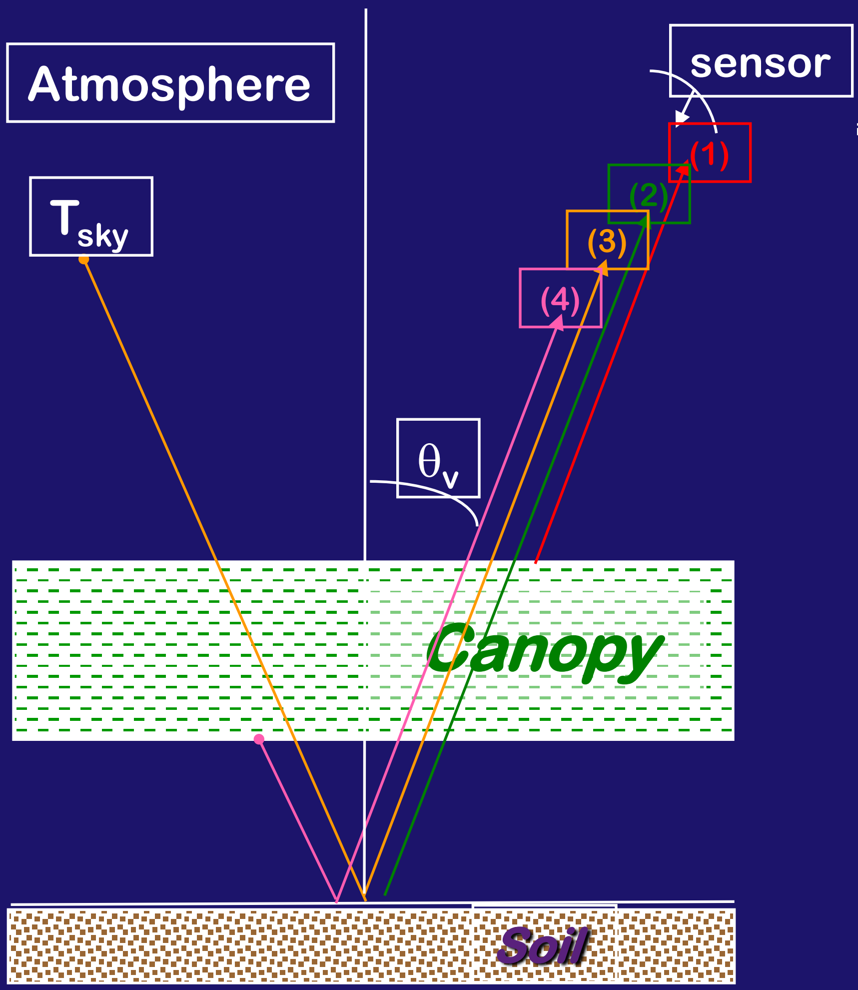
τ-ω Model (con't)



Radiation Components in a Vegetation Layer

- The direct vegetation emission (1)
- Soil-surface emission attenuated by the canopy (2)
- Downward cosmic background and atmospheric radiation attenuated by the canopy (3)
- The vegetation emission reflected by the soil and attenuated by the canopy (4)

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Snow-covered Surface (HUT Snow Model)

- Snow overlaying herbaceous vegetation canopies (soil/vegetation/ snow/ atmosphere medium)
  - Soil/vegetation emission (τ-ω model)
  - Soil/vegetation emission is treated as that of the soil which is overlaid by snow (HUT model)
- Snow under forest /shrubland canopies (soil/snow/forest or shrubland/atmosphere medium)
  - Soil/snow cover emission (HUT model)
  - Soil/snow cover emission is treated as that of the soil which is overlaid by forest or shrubland canopies (τ-ω model)

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Other Issues

- Subgrid heterogeneity
  - Brightness temperature of the mixed pixel is simulated as a linear combination of each cover fraction and its respective brightness temperature.
- Treat soil as stratified dielectric instead of uniform dielectric.
- Account for the topography effects (right now only for atmosphere).
- Some improvements are necessary for the emission simulation over snow-covered surface (HUT model is an approximate approach).

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Sensitivity Studies

- Comparison between different models using the same forcing (baseline runs)
- Comparison of different forcings on the same model.
- What will produce the best results? Can we say why??