Soil Moisture Estimation using Radiometers

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Some Definitions

✓ **Surface Soil Moisture**: is the water in that is in the upper 10 cm of the soil.

✓ **Root Zone Soil Moisture**: is the water that is available to plants, which is considered to be in the upper 200 cm of soil.

✓ **Radiometers**: instruments that measures the intensity of microwave emission from the soil, which is proportional to the brightness temperature.

$$m_v = \frac{\text{Water Volume}}{\text{Total Volume}}$$

![Soil profile diagram](image)
Why remote sensing of Soil Moisture?

✓ Soil moisture plays a vital role in the Earth’s water cycle.
✓ Direct impacts on human health, safety, agriculture and the economies of the world.

✓ Soil moisture is a key player in understanding, modeling, and predicting land surface hydrology, ecosystems, weather and climate.
Why remote sensing of Soil Moisture?

✓ Knowing the moisture content of the Earth’s layer of topsoil is critical to monitoring crop conditions.

✓ Knowing the moisture content in deeper sub-soil layers is important for agricultural planning and water resource management.

✓ Low levels of soil moisture can lead to drought and conditions conducive to wildland fire.

✓ Excessive amounts together with precipitation may increase the risk of flooding.
Why Measure Soil Moisture from Satellites?

✓ Soil moisture exhibits extremely high spatial variability on both small and large scale.

Due to variability of precipitation and the heterogeneity of land surface (vegetation, soil texture, topography, etc.)

✓ In situ measurement are representative only of a relative small area immediately surrounding the sample location
Why Measure Soil Moisture from Satellites?

✓ Recent technological advances in satellite remote sensing have shown that soil moisture can be measured by a variety of remote sensing techniques, each with its own strengths and weaknesses.

✓ Microwave remote sensing can detect variations in the Earth’s microwave emissions regardless of lighting conditions.

✓ Microwaves can penetrate most cloud cover and allows for observation of surface features in the vast majority of weather conditions.

✓ Several studies had showed that passive microwave remote sensors can be used to monitor surface soil moisture over land surfaces, specially at lower frequency (Eagleman and Lin, 1976; Ulaby et al., 1986; Schmugge and Jackson, 1994; Jackson et al., 1995; Wigneron et al., 2004).
Basic Principles of Radiometers

✓ Passive microwave remote sensing is based on the measurement of thermal radiation from land surface. This radiation is determined by the physical temperature and the emissivity of the radiation body, and may be approximated by

\[ T_B \approx \varepsilon_p \cdot T \]

✓ Soil emission at microwave frequencies is related to the soil water content by the \textit{dielectric constant}.

✓ The dielectric effect accounts for the majority of the reflection and scattering as radiation interacts with the surface molecules, and is commonly quantified.
The dielectric constant of water is much larger than that of dry soil and there is a strong correlation between the dielectric effect and reflection (and therefore emissivity). Emissivity is inversely proportional to the dielectric effect.

Dielectric constant as a function of volumetric soil moisture for five soils with different textural composition at 1.4 GHz (Ulaby, 1986).
Basic Principles of Radiometers

- Satellite brightness temperature observations can be used to quantify emissivity and extract information about various surface parameters.

- Important differences between dry land and wet land curve.

- Emissivity is reduced for wet surfaces compared to dry land, especially at the lower frequencies.
Basic Principles of Radiometers

- Emissivity for vertically polarized radiation as a function of different magnitudes of surface wetness.

- As more water is introduced to a surface, the smaller its emissivity and the effect is more pronounced at lower frequencies.

- Emissivity increases with increasing frequency and that this trend is especially pronounced for a wet surface.
Soil moisture also influence the microwave penetration depth.

Define as the uppermost layer of top soil from which 63% of the Earth’s emitted radiation originates at a given frequency or wavelength.

The penetration depth is deeper for lower microwave frequencies (1-10 GHz for example) because the longer wavelengths are less absorbed and scattered by the soil.

Penetration depth is significantly less at higher frequencies (only convey information about the top few millimeters of soil).
Basic Principles of Radiometers

- Increasing soil moisture content, the penetration depth decreases.

- A wet layer of soil scatters and reflects more energy and thus has a lower emissivity than dry soil.

- The figure also reinforces the advantage of using lower frequencies (longer wavelengths) because of their ability to penetrate deeper into the soil.
Basic Principles of Radiometers

- The figure illustrates the effect of soil roughness on the microwave emission from bare soils.

- Surface roughness increases the emissivity of natural surfaces and reduces the differences between V and H polarization.

- Sensitivity of emissivity to soil moisture variations decreases significantly as the surface roughness increases, since it reduces the range in measurable emissivity from dry to wet soil conditions.

Emissivity vs. incidence angle at 1.4GHz for three bare soil fields with different surface roughness (Newton and Rouse, 1980)
Basic Principles of Radiometers

✓ When Soil is covered by vegetation, emission is affected by canopy layer:
  ✓ Absorbs and scatters the radiation emanating from the soil
  ✓ Adds its own contribution

✓ Magnitud of the absorption depends upon wavelength, vegetation water content:
  ✓ Longer wavelength have greater penetration of vegetation.
Surface Emission Models

a. Soil Emission Model

Q/H model describes the bare soil surface emission as a function of the surface roughness and dielectric properties (Choudhury et al, 1979)

\[ \varepsilon_p = 1 - R_p^e = [(1 - Q) \cdot r_p + Q \cdot r_q] \cdot H \]

- \( R_p^e \) and \( \varepsilon_p \) are the surface effective reflectivity and emissivity at polarization p
- \( r \) is the surface reflectivity for flat surface.
- Roughness parameter Q describes the energy emitted in orthogonal polarization due to the surface roughness effects.
- H is a measure of the roughness effect on surface effective reflectivity.
- Q and H are determined empirically from experimental data
Surface Emission Models

b. Emission model for vegetation cover areas

Vegetation cover effects can be approximated by a simple radiative transfer model, commonly referred to as the $\tau\omega$ model (Wigneron et al., 2003).

Model based on two parameters:

- optical depth $\tau$ → Vegetation attenuation properties
- single scattering albedo $\omega$ → Scattering effects within canopy layer
Surface Emission Models

b. Emission model for vegetation cover areas

Several studies found that $\tau_c$ can be estimated through its relationship to the total vegetation water content $W_c$ (kg/m²) given by:

$$\tau_c = \frac{b \cdot W_c}{\cos \theta}$$

The $b$ parameter can be calibrated for each crop type or for large categories of vegetation (leaf-dominated, steam-dominated, grass). Also depends on polarization and incident angle, especially for vegetation with a dominant vertical.

At 1.4 GHz a value of $0.12\pm0.03$ was found to be representative for most agricultural crops.
Surface Emission Models

b. Emission model for vegetation cover areas

Using the $\tau \sim \omega$ model, the brightness temperature $T_b$ of a soil and vegetation layer is the sum of three terms:

1. Canopy attenuated soil emission
2. Direct vegetation emission
3. Vegetation emission reflected by the soil and attenuated by the canopy.

$$T_b = T_s \cdot \varepsilon_p \cdot \exp(-\tau_c) + \tau_c \cdot (1 - \omega) \cdot [1 - \exp(-\tau_c)] + T_c \cdot (1 - \varepsilon_p) \cdot (1 - \omega)[1 - \exp(-\tau_c)] \cdot \exp(-\tau_c)$$

- $T_s$ and $T_c$ are the physical temperatures (K) of the soil and vegetation canopy
- $\varepsilon_p$ is the surface emissivity
- $\tau_c$ is the vegetation optical depth
- $\omega$ is the single scattering albedo.
b. Emission model for vegetation cover areas

✓ The $\tau - \omega$ model can be applied successfully if other factors that influence the brightness temperature, such as instrument configuration and target characteristics, are invariant for a particular locality (Schmugge, 1983).

✓ Spatial variability of the soil texture and temperature, surface roughness and vegetation from one locality to another complicates the application of this technique.

_Polarization Indexes:_ to monitor soil moisture and vegetation development, as the microwave signatures of soil and vegetation exhibit distinct response to polarization effects.

$$MPDI = \frac{T_{BV} - T_{BH}}{T_{BV} + T_{BH}}$$
Soil Moisture Retrieval

- The brightness temperatures of land covers is influenced by many variables, the most important being soil moisture, soil roughness and vegetation characteristics such as albedo $\omega$ and opacity $\tau$.

- The challenge of retrieval or inversion techniques is to reconstruct the environmental parameters from the measured signal by using a minimum of auxiliary data.
Many approaches have been developed to retrieve soil moisture from microwave radiometric measurements, which can be grouped into three main categories:

a. **Statistical Techniques**: empirical relationship between the geophysical variables and the radiative transfer equation through a regression technique. Simple and efficient, but are site-specific.

b. **Forward Model Inversion**: a model is first selected to simulate the microwave radiometric measurements on the basis of land surface parameters. Then a method is developed to invert this model by minimizing the root mean square error (RMSE) between the forward model simulations and observed brightness temperature values.

Other methods suggest the use of look up tables (LUT) or neural network (NN).
Current and near future missions
Special Sensor Microwave Imager (SSM/I)

- Launched in 1987 on board the United State Air Force Defense Meteorological satellite Program (DMSP).

- Instrument measures atmospheric ocean and terrain microwave brightness temperature.

- **Products:**
  - Microwave Rain Rate
  - Sea Ice Concentration
  - Soil Moisture
  - Snow Depth
  - Water Vapor
  - etc.

- Mapped Resolution: 25 Km
- Frequency: Daily

http://www.osdpd.noaa.gov/ml/spp/
Tropical Rainfall Measuring Mission (TRMM/TMI)

- Launched in 1997, its a join mission between NASA and JAXA.
- Designe to monitor and study tropical precipitation and the associative release of energy.
- Microwave Imager (TMI) is a radiometer with multichannel in dual polarization.

Jackson et al., use the low frequency (10.65 GHz, X-band) radiometer with a land surface microwave emission model to retrieval land soil moisture.
WindSat

- Launched in 2003 on board the Coriolis platform. Developed by the Naval Research Laboratory for the U.S. Navy.
- Derived products include soil moisture and sea ice.
- Daily Global data of: surface soil moisture (data range 0 – 0.5 cm³/cm³), land surface temperature, land classification
Advance Microwave Scanning Radiometer for EOS (AMSR-E)

✓ Belong to the Aqua Mission, a major satellite mission of the Earth Observing System (EOS)

✓ Is a six frequency microwave radiometer system with dual polarization

✓ AMSR-E instrument provides measurements of terrestrial, oceanic, and atmospheric parameters for the investigation of global water and energy cycles, including:
  - precipitation rate
  - sea surface temperature
  - snow water equivalent
  - soil moisture
  - wind speed
  - etc.
Advance Microwave Scanning Radiometer for EOS (AMSR-E)

✓ Soil moisture product is a daily global composite of day and night time orbits produced by NASA.

✓ Relatively dry regions appear as orange and shades of red while relatively wet areas recently impacted by precipitation or snow melt appear as shades of green.
Soil Moisture Ocean Salinity (SMOS)

✔ Launched on 2009, is the first satellite ever attempted to globally measure the Earth’s soil moisture and ocean salinity by means of L-band microwave radiometry.

✔ SMOS is expected to provide global maps of soil moisture every 3 days, with a ground resolution better than 50 km, and an accuracy of 0.04 m³/m³ volumetric humidity (ESA, 2003).
Soil Moisture Ocean Salinity (SMOS)

First map of global soil moisture retrievals, released on June 30th of 2010.
Aquarius/ SAC-D

✓ Joint international science mission, between the NASA and CONAE, launched on June 10, 2011.

✓ Aquarius/SAC-D provides opportunities to explore new approaches to soil moisture retrieval. It’s the first space borne data that can be used to assess the synergy of L-band passive and active observation for improving remote sensing of soils and vegetation.

✓ The two main instruments of the mission are: the Aquarius, which is an integrated L-band radiometer/scatterometer and the Microwave Radiometer (MWR), a three channel radiometer measures surface brightness temperature in one polarization at 23.8 GHz (H-pol) and a 36.5 GHz frequency in both polarizations.

✓ Soil moisture retrieval algorithm are being develop by Jackson and Karszenbaum using data obtained from both sensors (plus auxiliary data)
Soil Moisture Active Passive (SMAP) Mission

- Developed by NASA, is scheduled for launch in the 2014–2015 timeframe.
- The SMAP mission will utilize a combination of radiometer high resolution radar with multiple polarizations in L-band to provide high resolution and high-accuracy global maps of soil moisture and freeze/thaw state every two to three days.
Latest Works

SMOS Barcelona Expert Centre on Radiometric Calibration and Ocean Salinity (SMOS-BEC)

Joint initiative of the Spanish Research Council and the Universitat Politècnica de Catalunya to contribute to the ground segment of the SMOS mission of the ESA

Developed high resolution (resolution 1 Km x 1 Km) soil moisture maps now available in near real-time by optimally merging SMOS and MODIS NDVI data using the downscaling algorithm (Piles et al., 2011).

1 km Soil Moisture, from July 7, 2012 (6 am)
Centre d'Etudes Spatiales (CESBIO)

Join partner of the SMOS mission, has developed the Drought Root Zone Soil index and is part of the level 4 SMOS products, which are end-level products.

This index represents the available water in the root zone.
SMOS Africa Root zone Index (SARI) is a joint project with the Land Surface Hydrology group at Princeton.

The SMOS L4 SARI has been integrated into the web-based interface and will be a great added value to the population touched by the drought, as they have an easy complete tool to follow the drought.

![African Drought Monitor](image-url)
International Soil Moisture Network

http://www.ipf.tuwien.ac.at/insitu/
Conclusions

✓ Microwave remote sensing is an effective technique for soil moisture estimation, with advantages for all-weather observations and solid physics.

✓ The current state of the art indicates that surface soil moisture measurements from space are feasible in regions of bare soil or low vegetation cover using sensor with frequencies in the range 1-5 GHz.

✓ Measurements, acquired on a global and repetitive basis, would be extremely useful for hydrologic and climate studies.

✓ Passive microwave has more potential for large-scale soil moisture monitoring but has a low spatial resolution.

✓ For future soil moisture retrieval algorithms, a lot of effort is being put in integrating the space borne measurements from multiple sensors, especially high resolution SAR images with radiometric data like the SMAP mission.