SAR applications in Soil Moisture (SM) estimation: Potential of RISAT-1 Polarimetric SAR data

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Objectives

• To get an overview on soil and soil moisture
• To get introduced to relevant physical basics
• To get an overview of approaches for soil moisture retrieval from SAR with a focus on soil moisture retrieval using RISAT-1 SAR data—why?
  – Operational data sets can be used (single frequency/wavelength, single polarization)
  – No additional field measurements required for model calibration
  – Most promising method

Soil and soil moisture

– Weathered and fragmented outer layer of the earth’s terrestrial surface
– Formed initially through disintegration, decomposition, and re-composition of mineral material contained in exposed rocks by physical, chemical, and biological processes
– Further conditioned by the activity of numerous organisms (plants and animals)
– Culminates in the formation of a characteristic soil profile

Fig.: Hypothetical Soil Profile

Soil and Soil Moisture

– Soil (as defined in Hillel, 2003):
  – Weathered and fragmented outer layer of the earth’s terrestrial surface
  – Formed initially through disintegration, decomposition, and re-composition of mineral material contained in exposed rocks by physical, chemical, and biological processes
  – Further conditioned by the activity of numerous organisms (plants and animals)
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Fig.: Hypothetical Soil Profile (Hillel, 2003)
Soil and Soil Moisture

• Soil moisture:
  – Volume fraction of water held in the soil against gravity (Hillel, 2003)
  – Amount of water which evaporates within 24 hours when drying soil samples at 105°C (Koorevaar et al., 1999)
  – Soils in fact are a mixture of solid, liquid and gaseous constituents (minerals, organic matter, water, air)
  – Under natural conditions, nearly every soil contains water

Fig.: Cross-section of a soil sample with solid soil particles (a), a liquid phase (b) and a gaseous phase (c) (Koorevaar et al. 1999)

Soil and Soil Moisture

• Soil moisture can vary between:
  – Oven dryness
  – Pore space saturation

• For hydrological and agronomic purposes two intermediate states are more important:
  – Permanent wilting point (PWP) = water content from which plant roots are unable to retrieve water from the soil as the forces attracting water to the soil particles exceeds the plant roots suction
  – Field capacity (FC) = maximum amount of water a soil can hold against gravity; is reached usually after an already wetted soil has been drained with water for at least two days

Importance of Soil Moisture

• Soil moisture makes up only 0.05% of the Earth’s fresh water resources but plays an important role in water, energy, and carbon cycle, in climatology and meteorology

• Hydrology and water management
  – Wetland management
  – Flood forecasting
  – Hydrological modelling

• Meteorology & Climate
  – Climate models
  – Weather forecasting
  – Global/regional anomalies

• Land cover and disturbances
  – Agriculture (droughts/crop yield)
  – Vegetation growth
  – Occurrence of fires

• Soils
  – Carbon sequestration
  – Dust
  – Desertification
  – Salinity

Fig.: Links between soil moisture and climate (Entekhabi et al., 1996)

Importance of Soil Moisture

• Soil moisture controls partitioning of:
  – Precipitation into infiltration and surface runoff
  – Incoming solar radiation into sensible and latent heat fluxes
In-situ measurement techniques

- **Direct measurements**
  - Measure soil moisture directly
  - Example:
    - Volumetric measurement
    - Gravimetric measurement

- **Indirect measurements**
  - Measure another soil property and relate to soil moisture content
  - Examples:
    - TDR/FDR
    - Tensiometer
    - Neutron probe

In-situ measurements:
- Time consuming
- Expensive
- Maybe destructive
- Point measurements in space and time of a temporal and spatial highly variable phenomenon
- Does not account for spatial and temporal variability of soil moisture

Direct in-situ measurement techniques

- Most common standard methods for soil moisture measurement in the laboratory
  - Gravimetric measurement: $m_w (\text{grav.}) = \frac{m_w - m_d}{m_w - m_{	ext{damp}}} \cdot 100$
    - $m_w$ = mass of wet soil sample (including sample container)
    - $m_d$ = mass of dry soil sample (including sample container)
    - $m_{	ext{damp}}$ = mass of empty sample container
  - Volumetric measurement: $m_w (\text{vol.}) = \frac{m_w - m_d}{V} \cdot 100$
    - $m_w$ = mass of wet soil sample
    - $m_d$ = mass of dry soil sample
    - $V$ = volume of sample container
  - Water volume per unit total volume

Indirect in-situ measurement techniques

- Dielectric measurement
  - Based on relation of dielectric permittivity of a medium to its water content
  - Time Domain Reflectometry (TDR)
    - Measurement of signal travel time of an EM wave along the length of the needles of a probe (high dielectric permittivity slows down propagation of EMR in soil) which then is related to water content of the soil

Fig.: TDR soil moisture measurement (©EOS 2013)
Indirect in-situ measurement techniques

- Dielectric measurement
  - Capacitance/Frequency Domain Reflectometry (FDR)
    - Soil as dielectric medium
    - Needles of the probe of the FDR device form large capacitor
    - Electrical capacitance of the capacitor measured
    - Charge of the capacitor related to water content of the soil

Spatio-temporal Variability of Soil Moisture

- Soil moisture as property and process is highly variable in space and time!
  - May vary within a few meters as much as within kilometers!
  - Spatial patterns follow:
    - Topography
    - Geological substrates/soil texture/water holding capacity
    - Vegetation cover
  - Temporal patterns mainly follows precipitation as main driving force.

Remote Sensing of Soil Moisture

- Why remote sensing for soil moisture estimation?
  - Yields repeatable measurement and area extensive data
  - Possibility of acquiring global soil moisture
    - To compensate for lack of in-situ soil moisture measurement networks
    - To better understand climate and climate change
    - To cope with consequences of climate change
    - To support sustainable water resources management
  - Remote sensing of soil moisture possible in different regions of the EM spectrum
Remote Sensing of Soil Moisture

- Visible and infrared reflectance ($\lambda = 0.3 – 3$ µm)
  - Spectral information related to $m_s$ as function of spectral absorption features
  - Water absorption bands at 1.4, 1.9 and 2.7 µm
  - Increase in $m_s$ leads to decrease in soil reflectance
  - Pros: high spatial resolution, multiple satellite systems available
  - Cons: weak relation to $m_s$, minimal surface and vegetation penetration, influence of atmospheric conditions

![Absorption of the Sun’s incident electromagnetic energy in the region from 0.1 to 30 µm by various atmospheric gases (Jensen, 2007)](image)

Remote Sensing of Soil Moisture

- Thermal infrared emissivity ($\lambda = 7 – 15$ µm)
  - Surface energy balance affected by soil moisture
  - Emissivity increases with increasing soil moisture
  - Pros: high spatial resolution, multiple satellite systems available, strong correlation to $m_s$
  - Cons: minimal surface and vegetation penetration, influence of atmospheric conditions

Radar remote sensing of soil moisture

- Radiometers (passive)
  - Brightness temperature $T_B = e \times T_s$, where $e$ is the emissivity and $T_s$ is the surface temperature

- Scatterometer/SAR (Active)
  - Backscattering coefficient $\sigma^0$, a measure of the reflectivity of the Earth Surface

- Passive and active methods are interrelated through Kirchhoff’s law:
  - $e = 1 – r$, where $e$ is the emissivity and $r$ is the reflectivity
  - Increase in soil moisture content leads to
    - Increasing backscatter (reflectivity)
    - Decreasing emissivity

Nature of electromagnetic radiation

- EMR exhibits both wave and particle properties
  - Wave model
    - Based on Maxwell’s equations
    - Describes generation, propagation of EMR and interaction of EMR with media
  - Particle model
    - At very short wavelengths some wave interaction with media better described by particle model
    - Originates from quantum mechanics
Basic principle of active radar remote sensing

- Radar antenna
  - Parallel to flight direction
  - Sends out short pulses of microwaves perpendicular to flight path diagonally downwards
  - Receives signals scattered back by Earth's surface

Short review of scattering

- "...redirection of electromagnetic radiation by an object..." (Woodhouse, 2006)
- Radar wave impinging on a boundary of two semi-infinite media* will be partly scattered back and partly transmitted forward into medium.
  - * two media with a common boundary, from there they extend to infinity in the direction away from the boundary

Short review of scattering

- Backscattering from natural surfaces can be divided into:
  - Surface scattering
  - Volume scattering

- Surface scattering occurs for:
  - Water
  - Wet snow
  - (Very) wet soil
- Volume scattering occurs for:
  - Vegetation canopies
  - Dry snow
  - Dry soil
- Bare soil surfaces:
  - For short wavelengths/low penetration depths volume scattering part becomes negligible
Controls on Radar Backscatter

- Backscattering governed by a number of parameters

Geometric Properties/Surface Roughness

- Surface roughness
  - Quantification of surface roughness always dependent on wavelength
  - Backscatter increases with surface roughness
  - Can be described by
    - RMS height $s$ to describe the vertical roughness component
    - Its autocorrelation function and correlation length $l$ for the horizontal roughness component

Surface Roughness

- RMS height $s$: standard deviation of random surface components from a mean reference surface

$$s = \sqrt{\frac{1}{N} \left( \sum_{i=1}^{N} z_i^2 \right) - \bar{z}^2}$$

Fig.: RMS height $s$ as standard deviation from a mean reference height (Dobson & Ulaby, 1998)

Surface Roughness

- Correlation functions describes the degree of correlation between a single roughness components $z$ at a distance $\xi$.
  - Two commonly used autocorrelation functions:
    - Gaussian:
      $$\rho(\xi) = \exp\left( -\frac{\xi}{\rho} \right)$$
    - Exponential:
      $$\rho(\xi) = \exp\left( -\frac{\xi}{\rho} \right)$$
  - Correlation length $l$ describes distance, at which the random surface components are statistically independent.
Surface Roughness

- Rayleigh criterion:
  \[ n > \frac{\lambda}{8 \cos \theta} \]
  - Surface is rough if phase difference is larger than \( \pi/2 \)

- Fraunhofer criterion:
  \[ n > \frac{\lambda}{32 \cos \theta} \]
  - Surface is rough if phase difference is larger than \( \pi/8 \)

- When is a surface rough?
  - Depends on wavelength \( \lambda \) and phase difference \( \Delta \phi \)

\[ \Delta \phi = 4 \pi \frac{\Delta h \cos \theta}{\lambda} \]

- Criteria to qualify roughness:
  - Rayleigh criterion
  - Fraunhofer criterion

- How does roughness influence radar backscatter?
  - Surface scattering - incident waves partially reflected in the specular direction (reflected component) and partially scatter back towards the sensor (scattered component)

Given a fixed incidence angle, signal strength of the reflected component decreases and the strength of scattered component increases with increasing surface roughness.
Dielectric Properties

- Microwave soil moisture retrieval based on large contrast between dielectric properties of dry soil and water
  - $\varepsilon_r$ of soil:
    - Mixture of dielectric constants of its constituents (soil particles, free and bound water, air)
    - Depends on frequency, temperature, salinity, volumetric water content, fractions of bound and free water
  - Dry soil: $\varepsilon_r \approx 2$ - 4
  - Water: $\varepsilon_r \approx 73$ (at 5 GHz [C-band] and 20°C)

Fig. Relationship between soil moisture and dielectric constant (Woodhouse, 2006)

Dielectric Properties

- With increasing soil moisture, the dielectric constant of the soil is increasing and thus leads to an enhanced radar backscatter also towards the sensor.

Fig. Effect of soil moisture on backscattering behavior

Dielectric Properties

- Penetration depth depending on
  - Dielectric constant/soil moisture content
  - Wavelength

Vegetation

Dry soil

Dry snow/ice

Fig. Relationship between penetration depth and wavelength (Albertz, 1991)

Need for Backscatter Model?

- To understand the overall information provided by remote sensing data and images, not only empirically or qualitatively, but also quantitatively
- To understand information fully, we must study and understand the interaction in remote sensing, and develop the quantitative mathematical-physical models and numerical approaches.
Modeling in Natural Sciences

- Modeling is used to find solutions to a problem.
- Problem:
  - Greek word meaning task or matter of dispute
  - Question/challenge/difficulty that needs to be solved
- Well-posed problem
  1. There is a solution to the problem.
  2. The solution is unique.
  3. The solution depends continuously on the data.
- Ill-posed problem
  - It is not well posed

Modeling in Natural Sciences

- Model:
  - Abstraction of reality/representation of an object or phenomenon
- Backscatter models try to describe radar backscatter with mathematics by means of the involved physics.
- Soil moisture retrieval using models deals with an inverse problem:
  - Use indirect measurements to make statements about the object or system under investigation.

Backscatter Modeling

- Based on observations, a model is formulated which contains a soil moisture related term (forward model)
- Use the inverted model (=rearranged equation to solve for soil moisture) to determine soil moisture from radar backscatter
- Calculated soil moisture should correspond to measured soil moisture

Backscatter Modeling

- Furthermore, retrieving soil moisture is an so-called ill-posed problem
  - There is an infinite number of possible solutions giving the same observables
  - Usually not as many number of observables as parameters controlling radar backscatter (unknowns)
Backscatter Modeling

• Basic assumption:
  – Radar backscatter is a function of a soil’s moisture content!
  • Simple model for bare soil
    \[ \sigma^0 = f(m_s, R) \]
  • That means, that \( \sigma^0 \) contains ambiguous information:
    Soil moisture \( m_s \) and surface roughness \( R \)!
  • Presence of vegetation complicates the problem

Moran et al., 2006

• Presence of vegetation complicates the problem

Moran et al., 2006

• Previous slides showed various influences on radar backscatter
• Goal of backscatter modeling: Describe controls on backscatter and isolate soil moisture information!

Backscatter Modeling

• Basic assumption:
  • Model including vegetation:
    \[ \sigma^0 = \tau^2 \cdot \sigma^0_s + \sigma^0_{veg} + \sigma^0_{multi} \]
    \( \tau^2 \) = two-way attenuation of vegetation layer (varies between \( \tau^2 = 0 \) for dense vegetation and \( \tau^2 = 1 \) for sparse vegetation)
    \( \sigma^0_s \) = bare soil backscatter contribution
    \( \sigma^0_{veg} \) = vegetation layer backscatter contribution
    \( \sigma^0_{multi} \) = multiple scattering contribution
  
Moran et al., 2006

• Short review of wave propagation and interaction with matter

• Radar waves are impinging on a boundary of two semi-infinite media
• Maxwell’s equations provide explanation on how electromagnetic waves are created and propagate
• Fresnel reflectivity describes the amount of energy scattered back from the boundary

Backscatter Modeling

• Backscatter models try to provide a solution to an inverse, ill-posed, problem
• Model types:
  – Bare soil backscatter models
    • Theoretical models (white-box model)
    • Semi-empirical models (grey-box model)
    • Regression models (black-box model)
  – Vegetation backscatter models (also at different levels of sophistication)
### Comparison between different Model based approach

<table>
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<tr>
<th>Model based Approach</th>
<th>Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td><strong>Empirical Model</strong></td>
<td>Regression fits between in situ measurements and σ₀</td>
<td>Simple and straightforward</td>
<td>No physical basis behind the model. Usually only valid for the area under investigation or site dependent.</td>
<td>[1-4]</td>
</tr>
<tr>
<td><strong>Semi-empirical Model</strong></td>
<td>Based on Theoretical models but have been extended according to empirical observations.</td>
<td>Offer a good compromise between the simplicity of empirical and complexity of theoretical models.</td>
<td>Each model has certain validity ranges. Generally only valid for bare soil surfaces.</td>
<td>[5-8]</td>
</tr>
<tr>
<td><strong>Theoretical (Physical) Forward model</strong></td>
<td>Simulates σ₀ as a function of m, and rms height and known radar configurations.</td>
<td>Well defined physical basis. Not site dependent. Not sensor specific; Wide range of validity, external parameterization is possible.</td>
<td>Only accounts for single scattering terms and needs to evolve with ground observation. Many input parameters required making model implementation extremely complex.</td>
<td>[9-10]</td>
</tr>
</tbody>
</table>

### Theoretical Models

- **But:** Natural conditions do not fit assumptions!
  - Soil surface: randomly rough surfaces, roughness may be much larger than wavelength
  - Roughness description does not account for three-dimensional character of natural surfaces
  - Soils are dielectrical inhomogeneous media sometimes behaving like volume scatterer sometimes like surface scatterer
  - Consequence: Models only valid in certain ranges of validity!

### Advantage of Theoretical physical models (electromagnetic scattering Model)

- To provide a reliable theoretical basis and guidance for data prediction and analysis
- Utility for parameter retrieval techniques
- Provide inputs for improving and developing new remote sensors and novel approaches

### Modeling (mathematical-physical) approach for natural media

- Natural targets and environment in remote sensing (Atmosphere, cloud and precipitation, soil, vegetation canopy, snow and ice, ocean etc.) are usually modeled as a random discrete scatterers or a continuous random media with dielectric fluctuation.
- The dielectric properties, scatterer size, shape, orientation and distribution, multi-layered structures, smooth or rough boundary surface, correlation function consists of the characteristic parameters of random media modeling.
- By studying the mathematical physics of electromagnetic scattering and transmission in random media and by developing numerical approaches, Polarimetric response can be simulated and then established quantitatively their dependence on the dielectric, geometric and other characteristics parameters of the target and the environment.
### Different Cases: Modeling approach

- Bare Surface/Sparsely Vegetated surface
- crop covered soil
- Forest

### Exiting Bare surface models

- **Empirical Model**
  - Linear regression model
  - Modified Linear relationship (Addition of vegetation function)
  - (Ulaby, 1974; Ulaby et al., 1981; Bernard et al., 1982; Wood et al., 1993; Meade et al., 1999; Quinney et al., 2000; Moeremans et al., 2002; Génin et al., 2002; Srivastava et al., 2003; Kasischke et al., 2003)

- **Semi-Empirical Model**
  - Oh Model (Oh et al., 1992)
  - Dubois Model (Dubois et al., 1995)

- **Theoretical (Physical) Model**
  - IEM model (Fung et al., 1992)

Mainly used for bare soil surface and vegetation effect is not considered here.

### Vegetation backscatter models

- **Backscatter from vegetated surfaces**
  - Direct backscatter from plants
  - Direct backscatter from underlying soil
  - Multiple scattering between vegetation and soil
  - Multiple scattering between leaves, stalks, branches, etc.

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**IEM Forward scattering model: Bare surface**

\[ \sigma^2 = f(F, \theta_i, pp, m_v, \sigma_s, L_s, ACF) \]

*Where F = Operating SAR Frequency
* \( \theta_i \) = Incidence Angle
* pp = Polarization (HH, VV or HV)
* \( m_v \) = Volumetric soil moisture
* \( \sigma_s \) = RMS Height (cm)
* \( L_s \) = Correlation Length (cm)
* ACF = Auto-correlation Function

- A Scattering model based on an approximate solution of integral equations for the tangential surface fields.
- Surface backscattering from a bare soil depends on its dielectric constant and surface roughness which is described by an auto-correlation function and standard deviation of surface roughness height.
- Most natural terrain have a small rms slope, single scattering will dominate over the multiple scattering in most situations.

Flow chart for modeling, simulation and validation of Model

Soil Parameters

- Volumetric soil moisture (%)
  - $R^2$: 0.96
  - Bias: 0.04 (%)
  - RMSE: 3.32 (%)

- RMS soil roughness (cm)
  - $R^2$: 0.93
  - Bias: 0.003 (cm)
  - RMSE: 1.7 (cm)

Performance of ANN based retrieval algorithm on Synthetic Data

Validation of ANN based retrieval algorithm for bare soil using Synthetic Data

Performance of ANN retrieved algorithm on RISAT-1 Data

Soil moisture estimation using Hybrid Polarimetric SAR data of RISAT-1

The capabilities of hybrid polarimetric synthetic aperture radar are investigated to estimate soil moisture on bare and vegetated agricultural soils.

References


Thank you!