Microwave Remote Sensing of Soil Moisture

Wolfgang Wagner
ww@ipf.tuwien.ac.at

Institute of Photogrammetry and Remote Sensing (I.P.F.)
Vienna University of Technology (TU Wien)
www.ipf.tuwien.ac.at
Soil Moisture

- Definition, e.g.
  \[ \theta = \frac{\text{Water Volume (m}^3\text{)}}{\text{Total Volume (m}^3\text{)}} \]

- Average
  \[ \langle \theta \rangle = \frac{1}{\text{Area} \cdot \text{Depth}} \int \int \theta(x, y, z) \, dz \, dx \, dy \]
Scaling Issues

- The term “scale” refers to a
  - characteristic length
  - characteristic time
- The concept of scale can be applied to
  - Process scale = typical time and length scales at which a process takes place
  - Measurement scale = spatial and temporal sampling characteristics of the sensor system
  - Model scale = Mathematical/physical description of a process

Ideally: Process = measurement = model scale

- Microwave remote sensing offers a large suit of sensors
  - Scaling issues must be understood in order to select the most suitable sensors for the application
Soil Moisture Scaling Properties

- High variability in time
  - Remotely sensed layer exposed to atmosphere
- Distinct but temporally stable spatial patterns

- Temporal stability means that spatial patterns persist in time
  - Vachaud et al. (1985)
    - Practical means of reducing an in-situ soil moisture network to few representative sites
  - Vinnikov and Robock (1996)
    - Large-scale atmosphere-driven soil moisture field
    - Small-scale land-surface soil moisture field
In-Situ Soil Moisture Time Series

Mean (red) and station (black) in-situ soil moisture time series. REMEDHUS network in Spain. © University of Salamanca
Time-Invariant Linear Relationship

Regional scale soil moisture
\[ \theta_r(t) = \frac{1}{A_r} \int \int \theta_p(x', y', t) dx' dy' = c_{rp}(x, y) + d_{rp}(x, y) \theta_p(x, y, t) \]

Local scale soil moisture

Linear scaling coefficients

Model Error \( \approx 5\% \)
Satellite Sampling Requirements

- Sampling requirements driven by
  - High temporal variability of soil moisture
  - Spatial resolution is of secondary concern

- Preference is for long-term, temporally dense data
  - Wide swath width
  - 100 % duty cycle
  - No conflicting modes
Daily Global Coverage of ASCAT and ASAR Global Monitoring Mode

- **METOP ASCAT**
  - 2 swath with each 500 km
  - 25 km resolution
  - 100 % duty cycle
  - 82 % daily global coverage

- **ASAR Global Monitoring Mode**
  - 405 km swath
  - 1 km resolution
  - Potentially 100 % duty cycle
  - Background mission
Daily Global Coverage of ASAR Wide Swath and Image Modes

- **ASAR Wide Swath Mode**
  - 450 km swath
  - 150 m
  - Max. 30 % duty cycle
    - 20 min for descending orbit
    - 10 min for ascending orbit

- **ASAR Imaging Mode**
  - 100 km swath
  - 30 m resolution
  - Max. 30 % duty cycle
Geophysical Parameter Retrieval

- Abstraction of complex objects and measurement processes
  - Empirical models
  - Semi-empirical models
  - Theoretical models

- Inversion
  - Direct inversion
  - Least-square matching
  - Lookup tables and neural networks
Underdetermination and Ambiguity

- Problem is underdetermined when $N(X) \gg N(Y)$

- For complex models, two sets of input parameters $X_1$ and $X_2$ may result in very similar modelled $Y$ values

$$ Y_j = f(X_1) \approx f(X_2) $$

Schematic representation of a vegetation scattering model. Kurum et al. (2009) TGRS
Equifinality

Two models are equifinal if they lead to an equally acceptable or behavioral representation of the observations.

- The term is due to Karl Ludwig von Bertalanffy (1901-1972)
  - Biologist and philosopher borne in Vienna
  - Founder of General Systems Theory
Falsifiability

A theory should be considered scientific if and only if it is falsifiable.

- Karl Popper (1902-1994)
  - Austrian/British philosopher
  - Borne in Vienna
  - "Logik der Forschung" in 1934
Approaches to Remote Sensing of Soil Moisture

- Measurement principles
  - No direct measurement of $\theta$ possible, only indirect techniques

- Optical to Mid-Infrared (0.4 – 3 $\mu$m)
  - Change of “colour”
  - Water absorption bands at 1.4, 1.9 and 2.7 $\mu$m

- Thermal Infrared (7-15 $\mu$m)
  - Indirect assessment of soil moisture through its effect on the surface energy balance (temperature, thermal inertia, etc.)

- Microwaves (1 mm – 1 m)
  - Change of dielectric properties
Microwaves

- Microwaves (1 mm – 1 m wavelength)
  - All-weather, day-round measurement capability
  - Very sensitive to soil water content below relaxation frequency of water (< 10 GHz)
  - Penetrate vegetation and soil to some extent
    - Penetration depth increases with wavelength

The dipole moment of water molecules causes “orientational polarisation”, i.e. a high dielectric constant.

Dielectric constant of water
Measurement Principles

- **Radars** measure the energy scattered back from the surface.
- **Radiometers** measure the self-emission of the Earth’s surface.

**Active Sensors**
- ERS-1/2
- SAR
- SCAT

**Passive Sensor**
- EMISSION FROM SPACE
- ATMOSPHERIC EMISSION
- SURFACE EMISSION

SAR und scatterometer on European Remote Sensing Satellites ERS-1 and ERS-2
Active and passive microwave sensors for long-term soil moisture monitoring
Observed Quantities

- **Radar**
  - Backscattering coefficient $\sigma^0$; a measure of the reflectivity of the Earth Surface

- **Radiometers**
  - Brightness temperature $T_B = e \times T_s$ where $e = \text{emissivity}$ and $T_s = \text{temperature}$

- Active measurements are somewhat more sensitive to roughness and vegetation structure than passive measurements, but
  - are not affected by surface temperature (above 0°C)
  - have a much better spatial resolution

- Despite these differences both active and passive sensors measure essentially the same variables:
  - Passive and active methods are interrelated through Kirchhoff’s law:
    - $e = 1 - r$ where $r$ is the reflectivity
  - Increase in soil moisture content
    - backscatter $\uparrow$
    - emissivity $\downarrow$
European C-Band Scatterometers

- **ERS Scatterometer**
  - $\lambda = 5.7$ cm
  - VV Polarization
  - Resolution: 50 / 25 km

- **Data availability**
  - ERS-2: since 1995
    - gaps due to loss of gyros (2001) and on-board tape recorder (2003)
  - Operations conflict with ERS SAR

- **METOP Advanced Scatterometer**
  - $\lambda = 5.7$ cm
  - VV Polarization
  - Resolution: 50 / 25 km

- **Data availability**
  - At least 15 years
  - METOP-A: since 2006

Daily global scatterometer coverage: ERS (left) and METOP (right)
ENVISAT ASAR

- ENVISAT
  - Launched March 1, 2002
  - Sun-synchronous, near-polar orbit
  - Altitude of 795 km
  - 14 orbits per day and nominal repeat rate 35 days

- ASAR
  - C-band SAR
    - $\lambda = 5.67 \text{ cm} / f = 5.331 \text{ GHz}$
  - ScanSAR modes
    - Wide Swath Mode
    - Global Mode (background mission)
ASAR Global Monitoring Mode Coverage
Radar Equation

\[ P_r = P_t \cdot G_t \cdot \frac{1}{4\pi R^2} \cdot \sigma \cdot \frac{1}{4\pi R^2} \cdot A_r \]

Ulaby et al. (1982)
Cross Section and Backscattering Coefficient

- Radar scattering cross section $\sigma$
  - Describes the scattering properties of the targets
  - Depends on geometry and dielectric properties of targets
  - Given in $m^2$

- Radar backscattering coefficient $\sigma^0$
  - Used for area-extensive targets
  - Given in $m^2m^{-2}$ or Decibels (dB)

\[
\sigma^0[m^2m^{-2}] = \frac{\sigma}{A}
\]
\[
\sigma^0[\text{dB}] = 10 \log_{10} \sigma^0[m^2m^{-2}]
\]
Backscatter from Vegetated Surfaces

- Except for dense forest canopies, backscatter from vegetation is due to surface-, volume- and multiple scattering.

\[ \sigma^0_{total} = \sigma^0_{volume} + \sigma^0_{surface} + \sigma^0_{interaction} \]
Bare Soil Backscatter Models

- Modelling of rough surface backscatter is still a problem
  - Models like Fung’s IEM are believed to work "in theory"
  - Restricted validity ranges
  - Problem of correct statistical description of surface roughness still not solved

- The problem can be circumvented if a change detection approach is chosen
  - Scale must be taken into account

Comparison of different bare soil backscatter models using the same roughness parameters
Vegetation Backscatter Models

- Vegetation elements can be larger, comparable, and smaller than the wavelength
  - Simplifying, yet reasonable assumptions difficult to find
- Wide range of models
  - Cloud Model $\rightarrow$ MIMICS

Cross section of a sphere

MIMICS backscatter model of a tree
3D Backscatter Measurements of Vegetation

„significant disagreements between measurements and models“
„attenuation [in radiative transfer models] is significantly overestimated“

3D radar measurements of a 58 cm high wheat canopy

TU Wien Change Detection Approach

- Change detection
  - Accounts indirectly for surface roughness and land cover

\[ m_s(t) = \frac{\sigma^0(t) - \sigma^0_{dry}(t)}{\sigma^0_{wet}(t) - \sigma^0_{dry}(t)} \]
Semi-Empirical Mixed Pixel Model

- First-order radiative transfer solution
  - “Cloud Model” + Vegetation-Surface Interaction term
  - “Linear” bare soil backscatter model

\[
\sigma^0 = (1 - A_{nt}) \cdot \sigma^0_{tr} + A_{nt} \cdot \sigma^0_{nt}
\]

\[
\sigma^0_{nt} = \frac{\omega_{nt} \cos \theta}{2}
\]

\[
\sigma^0_{tr} = \frac{\omega_{tr} \cos \theta}{2} (1 - e^{-\frac{2\tau_{tr}}{\cos \theta}}) + \sigma^0_s(\theta)e^{-\frac{2\tau_{tr}}{\cos \theta}} + 2\chi\Gamma_0 \omega_{tr} \tau_{tr} e^{-\frac{2\tau_{tr}}{\cos \theta}}
\]

\[
\sigma^0_s = \sigma^0_{s,dry}(40) + \sigma_s' \cdot (\theta - 40) + S_s m_s \quad \text{in dB}
\]
Model Simulations

Simulations performed with a radiative transfer mixing model.

- **Grassland & agriculture**: 30% forest cover
- **Dense Forest**: 100% forest cover

Graphs showing backscattering coefficient $\sigma^0$ as a function of incidence angle $\theta$ for different conditions (wet, dry, winter, summer) and forest cover percentages.
TU Wien Model

- Formulated in decibels (dB) domain
- Linear relationship between backscatter (in dB) and soil moisture
- Empirical description of incidence angle behaviour
- Seasonal vegetation effects cancel each other out at the "cross-over angles"
  - dependent on soil moisture

ERS Scatterometer measurements

Incidence angle behaviour is determined by vegetation and roughness roughness

Changes due to soil moisture variations
A new study by Wade Crow using his data assimilation approach reveals:

- 30% reduction in soil moisture retrieval skill from near to far range
- TU Wien (WARP 5) models vegetation effects with varying incidence angle quite well (better than with IEM + Cloud Model)

Historically Driest and Wettest Conditions

- Dry backscatter reference at 40° incidence angle
Wet Backscatter Reference

- In deserts saturated conditions are not reached (corrections necessary)
Sensitivity

- The sensitivity describes the signal response to soil moisture changes and depends strongly on land cover.
ASAR Backscatter Model

- Simplified version of the SCAT backscatter model

\[ \sigma^0(t, \theta) = \sigma_{dry}^0(30) + S \cdot m_s(t) + \beta(\theta - 30) \]

ASAR backscatter model parameters and land cover map of Oklahoma, USA.
SCAT Noise from Error Propagation
ASAR Noise from Error Propagation
SCAT Seasonal Soil Moisture Dynamics

Mean ERS scatterometer surface soil moisture (1991-2007)
Model parameters are estimated off-line in the Reprocessing Facility and fed into the near-real-time (NRT) processor.
Operational NRT METOP ASCAT Product

- EUMETSAT processes and delivers global 25 km ASCAT surface soil moisture data to user within 130 minutes after sensing

http://www.ipf.tuwien.ac.at/radar/dv/ascat/
First SMOS Soil Moisture Image
Sentinel-1

- With two satellites and a fixed acquisition scenario (IWS mode in HH polarisation over land) Sentinel-1 can overcome all shortcomings of ENVISAT ASAR GM mode!
Soil Moisture Active Passive (SMAP)

- Launch in 2014/15
- Active/passive microwave instrument in L-band
- Rotating antenna with $\varnothing = 6$ m
Literature


