Soil moisture and biomass retrieval over forest areas using low frequency polarimetric SAR data

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Objective: is it possible to estimate soil moisture under forest?

• Introduction

• Presentation of the model

• Inversion process

• Sensitivity analysis of the inversion process with simulated data

• Application with real data

• Explanation of field measurements
• Synthetic aperture radar
• Low frequency
• Soil moisture
Forward model expression

- Simplification of the distorted Born approximation
  - complex
  - requires detailed information about vegetation structure

\[
\begin{align*}
\sigma_{\text{HH}}^0 &= A_{\text{HH}} \cos \theta_0 W^{\alpha_{\text{HH}}} (1 - \exp(-B_{\text{HH}} W^{\beta_{\text{HH}} \sec \theta_0})) + C_{\text{HH}} \Gamma_{\text{HH}} W^{\delta_{\text{HH}}} \sin \left(\theta_0\right) \exp(-B_{\text{HH}} W^{\beta_{\text{HH}} \sec \theta_0}) + S_{\text{HH}} \exp(-B_{\text{HH}} W^{\beta_{\text{HH}} \sec \theta_0}) \\
\sigma_{\text{VV}}^0 &= A_{\text{VV}} \cos \theta_0 W^{\alpha_{\text{VV}}} (1 - \exp(-B_{\text{VV}} W^{\beta_{\text{VV}} \sec \theta_0})) + C_{\text{VV}} \Gamma_{\text{VV}} W^{\delta_{\text{VV}}} \sin \left(\theta_0\right) \exp(-B_{\text{VV}} W^{\beta_{\text{VV}} \sec \theta_0}) + S_{\text{VV}} \exp(-B_{\text{VV}} W^{\beta_{\text{VV}} \sec \theta_0}) \\
\sigma_{\text{HV}}^0 &= A_{\text{HV}} \cos \theta_0 W^{\alpha_{\text{HV}}} (1 - \exp(-B_{\text{HV}} W^{\beta_{\text{HV}} \sec \theta_0})) + C_{\text{HV}} \Gamma_{\text{HV}} W^{\delta_{\text{HV}}} \sin \left(\theta_0\right) \exp(-B_{\text{HV}} W^{\beta_{\text{HV}} \sec \theta_0}) + S_{\text{HV}} \exp(-B_{\text{HV}} W^{\beta_{\text{HV}} \sec \theta_0})
\end{align*}
\]

W is the biomass (Mg/ha)
\( \Gamma_{pq} = R_p R_q^* \exp\left(-4k^2s^2 \cos^2(\theta_0)\right) \)
\( s \) is the rms height
K is the wavenumber
R_p and R_q being the Fresnel reflection coefficients of the ground for polarization p and q
S_{HH}, S_{VV} and S_{HV} being the scattering term from a rough surface model
\( \theta_0 \) is the local incidence angle
\( \alpha_{pq}, \beta_{pq}, \delta_{pq} \) are structural parameters
A_{pq}, B_{pq} and C_{pq} are calibration factors
Training the model to site data

\[ \sigma^0_{HH} = A_{HH} \cos \theta_0 W^{α_{HH}} (1 - \exp(-B_{HH} W^{β_{HH}} \sec \theta_0)) + C_{HH} \Gamma_{HH} W^{δ_{HH}} \sin(\theta_0) \exp(-B_{HH} W^{β_{HH}} \sec \theta_0) + S_{HH} \exp(-B_{HH} W^{β_{HH}} \sec \theta_0) \]
\[ \sigma^0_{VV} = A_{VV} \cos \theta_0 W^{α_{VV}} (1 - \exp(-B_{VV} W^{β_{VV}} \sec \theta_0)) + C_{VV} \Gamma_{VV} W^{δ_{VV}} \sin(\theta_0) \exp(-B_{VV} W^{β_{VV}} \sec \theta_0) + S_{VV} \exp(-B_{VV} W^{β_{VV}} \sec \theta_0) \]
\[ \sigma^0_{HV} = A_{HV} \cos \theta_0 W^{α_{HV}} (1 - \exp(-B_{HV} W^{β_{HV}} \sec \theta_0)) + C_{HV} \Gamma_{HV} W^{δ_{HV}} \sin(\theta_0) \exp(-B_{HV} W^{β_{HV}} \sec \theta_0) + S_{HV} \exp(-B_{HV} W^{β_{HV}} \sec \theta_0) \]

- Calibrated SAR data
- Use average soil moisture and roughness for the site
- Use plot level biomass values
- Create a series of points to estimate coefficients \( A_{pq}, B_{pq}, C_{pq} \)

Biomass: \( \{W_0, \ldots, W_n\} \)
Soil moisture: \( \{m_{v0}, \ldots, m_{vn}\} \)
Roughness: \( \{s_0, \ldots, s_n\} \)

Training backscatter data
\( \sigma_{HH}, \sigma_{VV}, \sigma_{HV} \)

Fitting process
\( \sigma_{pq} = f(W, m_v, s) \)
Model shape – tropical data

<table>
<thead>
<tr>
<th></th>
<th>HH</th>
<th>VV</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>0.016819935</td>
<td>0.0142891</td>
<td>0.00504441</td>
</tr>
<tr>
<td>R²</td>
<td>0.930469068</td>
<td>0.933139812</td>
<td>0.955186855</td>
</tr>
</tbody>
</table>
Shape of each scattering

Backscattering (power) vs. W (Mg/ha)

- Total
- Volume
- Double-bounce
- Surface
- Measurements
Incidence angle effect
Soil moisture sensitivity

\[ W = 150 \text{ Mg.ha}^{-1} \]
\[ s = 3 \text{ cm} \]
\[ W' = \frac{S(W, \varepsilon, s)}{n} = \sum_{i=1}^{n} \left[ \sigma_{pq} - f(W, \varepsilon, s) \right]^2 \]

Inversion process
Levenberg-Marquardt algorithm:

\[ \sqrt{W} = a_0 + a_1 \sigma_{HH} + a_2 \sigma_{HV} + a_3 \sigma_{VV} \] (1)

\[ s_0 = \begin{cases} 
  \text{surface} & \text{mean}(s) \\
  \text{vegetated areas} & \text{mean}(s) 
\end{cases} \]

\[ m_{v_0} = \begin{cases} 
  \text{surface} & \text{mean}(m_v) \\
  \text{vegetated areas} & \text{mean}(m_v) 
\end{cases} \]

Initial data & bounds
- \(-W_0, M_{v_0} (\varepsilon_0), s_0\)
- \(-0 < \varepsilon' < 80\)
- \(-0 < W' < 300\)
- \(-0 < s' < 0.1\)

With time series measurements

\[
W_0d1, \varepsilon_{0d1}, s_{0d1}
\]

\[
W_0d2, \varepsilon_{0d2}, s_{0d2}
\]

\[
W_0d3, \varepsilon_{0d3}, s_{0d3}
\]

\[
W_1, m_{v1}, s_1
\]

\[
W_2, m_{v2}, s_2
\]

\[
W_3, m_{v3}, s_3
\]

\[
W=(W_1+W_2+W_3)/3
\]

\[
s=(s_1+s_2+s_3)/3
\]
Sensitivity analysis

\[ \sqrt{W} = a_0 + a_1 \sigma_{HH} + a_2 \sigma_{HV} + a_3 \sigma_{VV} \]

**SM:**

\[ \sigma_{HH}^0 = A_{HH} \cos \theta_0 W^{\alpha_{HH}} (1 - \exp(-B_{HH}W^{\beta_{HH} \sec \theta_0})) + C_{HH} \Gamma_{HH} W^{\delta_{HH}} \sin(\theta_0) \exp(-B_{HH}W^{\beta_{HH} \sec \theta_0}) + S_{HH} \exp(-B_{HH}W^{\beta_{HH} \sec \theta_0}) \]

\[ \sigma_{VV}^0 = A_{VV} \cos \theta_0 W^{\alpha_{VV}} (1 - \exp(-B_{VV}W^{\beta_{VV} \sec \theta_0})) + C_{VV} \Gamma_{VV} W^{\delta_{VV}} \sin(\theta_0) \exp(-B_{VV}W^{\beta_{VV} \sec \theta_0}) + S_{VV} \exp(-B_{VV}W^{\beta_{VV} \sec \theta_0}) \]

\[ \sigma_{HV}^0 = A_{HV} \cos \theta_0 W^{\alpha_{HV}} (1 - \exp(-B_{HV}W^{\beta_{HV} \sec \theta_0})) + C_{HV} \Gamma_{HV} W^{\delta_{HV}} \sin(\theta_0) \exp(-B_{HV}W^{\beta_{HV} \sec \theta_0}) + S_{HV} \exp(-B_{HV}W^{\beta_{HV} \sec \theta_0}) \]

**CM:**

\[ W_0 = W + k \]

\[ m_{v0} = m_v + l \]

\[ S_0 = s + m \]

\[ k \in [-0.5 ; 0.5] \times W \]

\[ l \in [-0.5 ; 0.5] \times m_v \]

\[ m \in [-0.5 ; 0.5] \times s \]
Sensitivity analysis - results

RMSE = 50 Mg/ha
88% of pixels have a relative error ~ 0

RMSE = 4.35 %
90% of pixels have a relative error ~ 0
Application

AirSAR data - Howland forest – Maine - October 1994

$\sigma_{VV}; \sigma_{HV}; \sigma_{HH}$

Pixel Size: 1 arcsec
Aboveground Vegetation Biomass

0 < W < 300 Mg/ha
Mean(W) = 64 Mg/ha
Soil moisture map

0 < mv < 50%
Ground measurement = 18.4%
Estimated value on this particular point = 21.5%
Soil penetration depth

\[ d = \frac{-\log_e(0.1) \lambda}{2\pi n_i}; \quad n_i = \text{Im}\left(\sqrt{\varepsilon_r}\right) \]

Depth = \( d \cos \theta_2 \), \( \sin \theta_2 \sqrt{\varepsilon_2} = \sin \theta_1 \sqrt{\varepsilon_1} \)

0 < d < 75 m
Mean(d) = 50 cm
La Selva – Costa Rica

AirSAR data - La Selva - Costa Rica – March 6\textsuperscript{th}, 2004

\[ \{\sigma_{VV} ; \sigma_{HV} ; \sigma_{HH}\} \]
La Selva volumetric soil moisture in 2004
Results on tropical forest - La Selva/Costa Rica

RMSE = 30.5 Mg/ha

28.3% < m_v < 58.7%
Average(m_v) = 45.2%
P2: m_v = 48.8%, m_v' = 50.8%
L2: m_v = 47.4%, m_v' = 43.9%
Field campaigns
Sampling Strategy

1 km transects with sampling at 50m intervals with GPS at each location

Collect 5 parallel 50 m transects With sampling at 10m intervals with GPS at each location
Soil Moisture TDR Sensors

2 units

6050X1 TRASE SYSTEM I
Soil Moisture TDR Sensors
Field measurements examples
Spatial variation of soil moisture

- Distance (m)
- %

The graph illustrates the spatial variation of soil moisture across different distances. The color gradient on the right side indicates the percentage of moisture, with darker colors representing higher moisture levels.
Summary & Perspectives

• Semi-empirical model
  – Is a simplification of the distorted Born model
  – Requires ground measurements to set up calibration coefficients
  – Is sensitive to:
    • Biomass
    • Soil moisture
    • Incidence angle

• Inversion process
  – Uses LM method to invert the forward model
  – Needs initialization and constraints
  – Shows good results over simulated data
    • Biomass: RMSE = 50Mg/ha for a biomass level up to 500 Mg/ha
    • Soil moisture: RMSE = 4.35% for soil moisture up to 40%
  – Estimates soil moisture and biomass with AirSAR P-band data acquired over
    • Howland forest in October 1994 with an absolute error of 3%.
    • La Selva forest in March 2004 with a RMSE of 30.5 Mg/ha for a biomass level up to 300 Mg/ha
      and soil moisture in the expected range.

• Field measurements show the spatial variation of soil moisture.

• Future works: topographic effect, using AirMOSS SAR data
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