AirMOSS soil moisture retrieval: From forest to backscatter to soil moisture

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Outline

- Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) mission and objective
- From forest to backscatter
  - Derivation of parameters from FIA data: relationship of biomass with diameter at breast height (DBH), tree height, and tree diameter
  - Finding fit parameters
- From backscatter to soil moisture
- Field campaign
Uncertainty in Annual and Seasonal Net Ecosystem Exchange Estimates over North America

Based on spatial resolution of ~ 0.5 degree
Uncertainty in Annual and Seasonal Net Ecosystem Exchange Estimates over North America

**Bottom-up scaling**

- **North America water and carbon fluxes**
- Reduce uncertainty of continental Scale fluxes
- AIRMOSS model integration over North American Biomes
- Extrapolate between biomes using stats derived at 50km scale
- AirMOSS data over modeling sub-grid: 2500 km²
- Spatial and temporal distribution of RZSM @ 100m; capture seasonal & interannual variability (ED-2 NEE & land hydrology model runs)
- Tower site footprint
  - 1km x 1km
  - Currently used to calculate NEE by routine scaling up; RZSM assumed homogeneous
- Plot Level
  - (0-50m)

**Scientific Approach (2)**

**Based on spatial resolution of ~ 0.5 degree**
Forward model expression

Distorted Born approximation model

\[ \sigma_{pq}^o = \sigma_{pq \_direct}^o + \sigma_{pq \_double\_boundary}^o + \sigma_{pq \_surface}^o \]

\[ \sigma_{pq \_direct}^o = \sigma_{pq \_crown}^o + \sigma_{pq \_trunk}^o \]

\[ \sigma_{pq \_double\_boundary}^o = \sigma_{pq \_crown\_ground}^o + \sigma_{pq \_trunk\_ground}^o \]

\[ \sigma_{pq \_crown}^o = (\rho_1 \sigma_{pqld} + \rho_b \sigma_{pqld} + \rho_{b2} \sigma_{pqbd2}) \left[ 1 - \exp\left( -2 \text{Im}\left\{ K_{pq} + K_{qc} \right\} d_c \right) \right] \frac{2 \text{Im}\left\{ K_{pc} + K_{qc} \right\}}{2 \text{Im}\left\{ K_{pc} + K_{qc} \right\}} \]

\[ \sigma_{pq \_trunk}^o = (\rho_1 \sigma_{pqld} + \rho_b \sigma_{pqld} + \rho_{b2} \sigma_{pqbd2}) \left[ 1 - \exp\left( -2 \text{Im}\left\{ K_{pq} + K_{qc} \right\} d_c \right) \right] \exp\left( -2 \text{Im}\left\{ K_{pc} + K_{qc} \right\} d_c \right) \]

\[ \sigma_{pq \_surface}^o = \sigma_{pqg} \exp\left( -2 \text{Im}\left\{ K_{pc} + K_{qc} \right\} d_c \right) \left( K_{pt} + K_{qt} \right) \]

\[ \sigma_{pq \_crown\_ground}^o = (\rho_1 \sigma_{pqld} + \rho_b \sigma_{pqld} + \rho_{b2} \sigma_{pqbd2}) \left[ 1 - \exp\left( -2 \text{Im}\left\{ K_{pc} - K_{qc} \right\} d_c \right) \right] \frac{2 \text{Im}\left\{ K_{pc} - K_{qc} \right\}}{2 \text{Im}\left\{ K_{pc} - K_{qc} \right\}} \]

\[ \sigma_{pq \_trunk\_ground}^o = (\rho_1 \sigma_{pqld} + \rho_b \sigma_{pqld} + \rho_{b2} \sigma_{pqbd2}) \left[ 1 - \exp\left( -2 \text{Im}\left\{ K_{pc} - K_{qc} \right\} d_c \right) \right] \frac{2 \text{Im}\left\{ K_{pc} - K_{qc} \right\}}{2 \text{Im}\left\{ K_{pc} - K_{qc} \right\}} \]

\[ r_g = \exp\left( -4k_o^2s^2 \cos^2 \theta \right) \]

\[ \Gamma_p = R_p \exp\left( 2i \left[ K_{pc} d_c + K_{pc} d_l \right] \right) \]

\[ \sigma_{pqad} = 4\pi \left( f_{pqad} \right)^2, \sigma_{pqad1} = 4\pi \left( f_{pqad1} \right)^2, \sigma_{pqad2} = 4\pi \left( f_{pqad2} \right)^2, \sigma_{pqad12} = 4\pi \left( f_{pqad1} f_{pqad2} \right)^2 \]

\[ K_{pq} = k_o \cos \theta + \frac{2\pi}{k_o \cos \theta} \left[ \rho_1 f_{pqf}^f + \rho_{b1} f_{pqf}^f b_1 + \rho_{b2} f_{pqf}^f b_2 \right] \]

\[ K_{qf} = k_o \cos \theta + \frac{2\pi}{k_o \cos \theta} \left[ \rho_1 f_{qpf}^f \right] \]
Forward model expression

Simplification of the distorted Born approximation

Born approximation model requires detailed information about vegetation structure

\[ 0_{HH} = A_{HH} \cos W_{HH} \left( 1 - \exp( -B_{HH} W_{HH} \sec \theta_0 ) \right) + C_{HH} W_{HH} \sin \left( \theta_0 \right) \exp( -B_{HH} W_{HH} \sec \theta_0 ) + S_{HH} \exp( -B_{HH} W_{HH} \sec \theta_0 ) \]

\[ 0_{VV} = A_{VV} \cos W_{VV} \left( 1 - \exp( -B_{VV} W_{VV} \sec \theta_0 ) \right) + C_{VV} W_{VV} \sin \left( \theta_0 \right) \exp( -B_{VV} W_{VV} \sec \theta_0 ) + S_{VV} \exp( -B_{VV} W_{VV} \sec \theta_0 ) \]

\[ 0_{HV} = A_{HV} \cos W_{HV} \left( 1 - \exp( -B_{HV} W_{HV} \sec \theta_0 ) \right) + C_{HV} W_{HV} \sin \left( \theta_0 \right) \exp( -B_{HV} W_{HV} \sec \theta_0 ) + S_{HV} \exp( -B_{HV} W_{HV} \sec \theta_0 ) \]

\( W \) is the biomass (Mg/ha)
\( s \) is the rms height
\( k \) is the wavenumber
\( R_p \) and \( R_q \) are the Fresnel reflection coefficients
\( S_{HH}, S_{VV} \) and \( S_{HV} \) are the scattering term from bare soil surface
\( \theta_0 \) is the local incidence angle

\( \alpha_{pq}, \beta_{pq}, \delta_{pq} \) are structural parameters

\( A_{pq}, B_{pq} \) and \( C_{pq} \) are calibration factors
Deriving structure parameters

- Forest Inventory Agency (FIA) data provides
  - Tree species
  - Tree height
  - Tree diameter
  - Density of tree and more
- We find fits for these information as a function of above ground biomass (AGB)
- Using the information for fits, we simulate backscatter and its component (direct, direct reflect, and the exponential decay factor) using distort Born model
- We capture information on average for each forest in ‘structure parameters’ $\alpha_{pq}$, $\beta_{pq}$, $\delta_{pq}$ as a function of biomass
Deriving structure parameters

• Trunk parameter
  – Use data for these relationship:
    • AGB with Basal Area (BA)
    • AGB with total tree Height (H)
    • AGB with average Diameter (D)
  – Tree Per Hectare (TPH) = 4BA/(\pi*D^2)
  – Use Jenkin’s eq. to get Biomass of Trunk (Bt)
  – Height of Trunk (Ht) = 4BT/(gt*TPH*\pi*D^2)
    where gt is the specific gravity of trunk
  – Crown height = H – Ht

• Branch parameter
  – Use Jenkin’s eq to get Biomass of branch -> Bb
  – Interpolate branch length using relationship of AGB and trunk height * a factor (0.2)
  – Interpolate branch diameter using relationship of AGB and trunk diameter * a factor (0.2)
  – Branch density (BPH) = 4*Bb/(gb*\pi*Db^2*Lb)
    where gb is the specific gravity of branch
Structure parameter fit

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<tr>
<td>HH</td>
<td>0.16499</td>
<td>0.95334</td>
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<tr>
<td>VV</td>
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<td>0.91384</td>
<td>1.9728</td>
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<tr>
<td>HV</td>
<td>0.2568</td>
<td>1.7575</td>
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Training the model to site data

- 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 $A_{pq}$, $B_{pq}$, $C_{pq}$

$$
\begin{align*}
0_{HH} &= A_{HH} \cos \left( W_{HH} \right) (1 - \exp(-B_{HH}W_{HH} \sec \theta_0)) + C_{HH} \sin \left( W_{HH} \right) \exp(-B_{HH}W_{HH} \sec \theta_0) + S_{HH} \exp(-B_{HH}W_{HH} \sec \theta_0) \\
0_{VV} &= A_{VV} \cos \left( W_{VV} \right) (1 - \exp(-B_{VV}W_{VV} \sec \theta_0)) + C_{VV} \sin \left( W_{VV} \right) \exp(-B_{VV}W_{VV} \sec \theta_0) + S_{VV} \exp(-B_{VV}W_{VV} \sec \theta_0) \\
0_{HV} &= A_{HV} \cos \left( W_{HV} \right) (1 - \exp(-B_{HV}W_{HV} \sec \theta_0)) + C_{HV} \sin \left( W_{HV} \right) \exp(-B_{HV}W_{HV} \sec \theta_0) + S_{HV} \exp(-B_{HV}W_{HV} \sec \theta_0)
\end{align*}
$$
Backscatter model vs data

HH

VV

HV

total
double-bounce
volume
surface
measurements
Inversion process

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

Initial data & bounds
- \(W_0, M_{v0} (\varepsilon_0), s_0\)
- \(-0 < \varepsilon' < 80\)
- \(-0 < W' < 300\)
- \(-0 < s' < 0.1\)

Inversion process
Levenberg-Marquardt algorithm:

\[
S(W, \varepsilon, s) = \sum_{i=1}^{n} \left[ \sigma_{pq} - f(W, \varepsilon, s) \right]^2
\]

\(\{R;G;B\} = \{\sigma_{VV}; \sigma_{HV}; \sigma_{HH}\}\)

classification

\(s_0 = \text{mean}(s) \quad \text{vegetated areas}\)

\(m_{v0} = \text{mean}(m_v) \quad \text{vegetated areas}\)

Application

AirSAR data - Howland forest – Maine – October 1994

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

Pixel Size: 1 arcsec
0 < mv < 50%
Ground measurement = 18.4%
Estimated value on this particular point = 21.5%
Field campaign

Howland forest – October 2012
Soil Moisture TDR Sensors
Data 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
Field measurements examples
THANK YOU! QUESTIONS?