RADAR RESPONSE OF VEGETATION:
AN OVERVIEW

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- Vegetation Classes
- Soil Scattering: (1) Backscatter
  (2) Forward Scattering
- Radar Response
  - Vegetation Biomass
  - Vegetation Structure
- Temporal Variations: (1) Short Term (hours to days)
  (2) Long Term (Seasonal)
- Effect of Rain
- Emergence of a User Community
- Concluding Remarks
<table>
<thead>
<tr>
<th>Growth Form</th>
<th>Herbaceous</th>
<th>Woody</th>
<th>Trees</th>
<th>Columnar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade-like</td>
<td>Broadleaf</td>
<td>Shrubs</td>
<td>Excurrent</td>
<td>Decurrent</td>
</tr>
<tr>
<td>(i.e., grass, corn)</td>
<td>(i.e., soybeans)</td>
<td>(i.e., alder)</td>
<td>(i.e., pine and spruce)</td>
<td>(i.e., oak and maple)</td>
</tr>
<tr>
<td>Structural Characteristics</td>
<td>none</td>
<td>none</td>
<td>conical layered dielectric</td>
<td>cylindrical, forked layered dielectric</td>
</tr>
<tr>
<td>Trunks</td>
<td>some non-woody stalks or stems</td>
<td>some non-woody stems</td>
<td>branch size and orientation varies with height, large branches, planophile, many small stems, erectophile branches tend to be long and thin</td>
<td>many forked with few horizontal elements branches tend to be short and thick</td>
</tr>
<tr>
<td>Branches</td>
<td>blade-like erectophile</td>
<td>broad leaves</td>
<td>blade-like or broadleaves</td>
<td>needies</td>
</tr>
<tr>
<td>Foliage</td>
<td>low to moderate $\sigma^0$ dominated by surface scattering</td>
<td>moderate $\sigma^0$, $\sigma^0(f, \omega, \theta)$ dependent upon trunks &amp; branches uniform $\Delta \phi$</td>
<td>very high like-polarized $\sigma^0$, moderate $\sigma^\text{pp}$, dominated by ground-trunk and few large branches $\sigma^\text{pp} \geq \sigma^\text{VV}$, $\sigma^\text{HH} / \sigma^\text{VV} = f$ (branch biomass) broad distributions of $\Delta \phi$</td>
<td>high $\sigma^0$ dominated by large branches, $\sigma^\text{HH} \geq \sigma^\text{VV}$</td>
</tr>
<tr>
<td>General Scattering Properties</td>
<td>$f &lt; 5$ GHz: $\sigma^\text{VV} \geq \sigma^\text{HH} \gg \sigma^\text{HV}$ zero mean $\Delta \phi$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f &gt; 5$ GHz: moderate to high $\sigma^0$ dominated by vegetation $\sigma^\text{VV} \geq \sigma^\text{HH} \geq \sigma^\text{HV}$ stem orientation and leaf size very important</td>
<td>high $\sigma^0$ dominated by branches and stems</td>
<td>mod. to very high $\sigma^0$ can vary seasonally with foliage and stem properties</td>
<td>high $\sigma^0$ determined by crown</td>
<td></td>
</tr>
</tbody>
</table>
- Direct Ground Backscatter
- Vegetation-Ground Bistatic Scattering
  - Trunks
  - Leaves (needles)
  - Branches
- Direct Crown Backscatter
SOIL BACKSCATTERING

A. Theoretical Models

- Small Perturbation Model
- Physical Optics Model
- Geometric Optics Model
- Phase Perturbation Method
- Full Wave Model
- Integral Equation Model

Models agree with experimental observations only under certain conditions. Overall, models not useful.

B. Michigan Empirical Model

- Frequency Range: 1-10 GHz
- Angular Range: 20° - 70°
- Roughness range: s = 0.32 cm to s = 4.0 cm
  (expected validity for any s >0.3 cm)
- Moisture range: 0.05 g/cm³ to 0.31 g/cm³

Moisture Sampling Depth

L-Band (1.25 GHz): Average Moisture of Top 10 cm layer
C-Band (5.3 GHz): Average Moisture of Top 3 cm layer
X-Band (9.5 GHz): Average Moisture of Top 1 cm layer

\[ \text{Sampling Depth} = \frac{\lambda}{3} \]
Model Verification For A smooth Surface ($s=0.4$ cm)

1.5 GHz

$s = 0.4$ cm
$m_v = 0.29$

- $\sigma_w^o$, Model
- $\sigma_{lh}^o$, Model
- $\sigma_{lm}^o$, Model
- $\sigma_{wl}^o$, Measured
- $\sigma_{lw}^o$, Measured
- $\sigma_{wm}^o$, Measured

4.75 GHz

9.5 GHz
MOD-3

correl. coeff. = 0.98

1990 meas.

1991 meas.

Measured ks

Estimated ks

rms height

soil moisture

Measured $m_v$

Estimated $m_v$

correl. coeff. = 0.97

1990 meas.

1991 meas.

156
Inversion Algorithm

If radar measures $\sigma_{vv}^0$, $\sigma_{hh}^0$, and $\sigma_{hv}^0$ at a given frequency and angle, both $s$ and $m_v$ can be determined from the ratios:

\[
p = \frac{\sigma_{hh}^0}{\sigma_{vv}^0}
\]
\[
q = \frac{\sigma_{hv}^0}{\sigma_{vv}^0}
\]

Note: $p(dB) = 10 \log \left( \frac{\sigma_{hh}^0}{\sigma_{vv}^0} \right) = \sigma_{hh}^0(dB) - \sigma_{vv}^0(dB)$

$q(dB) = \sigma_{hv}^0(dB) - \sigma_{vv}^0(dB)$. 
ERS-1 SAR Response

\( \theta = 23^\circ \)

vv Polarization

![Graph showing backscattering coefficient vs. moisture content](image-url)
Coherent Reflectivity

Reflection Coefficient $\Gamma$ (dB)

Incidence Angle $\theta$ (degrees)

$\epsilon=3+j0$  $ks<0.2$
Reduction of Reflectivity by Surface Roughness at L-band

Incidence Angle $\theta$ (degrees)
RADAR RESPONSE TO VEGETATION

• OBJECTIVES
  • To Discriminate/Classify Vegetation Classes
  • To Estimate Biomass
  • To Estimate LAI
  • To Estimate Soil Moisture
  • To Monitor Changes (deforestation, growth, stress, etc.)
  • Other

• VEGETATION CANOPY
  • Structure: (1) Macro (tree or plant scale): Tree height, density, ground cover
    (2) Micro (wavelength scale): Leaves, branches
  • Dielectric Properties
  • Ground Cover (soil, debris, undergrowth, etc.)

• TOOLS
  • Wavelength
  • Polarizations
  • Phase Statistics
  • Incidence Angle
  • Time

• APPROACH
  • Theory
  • Observations
    • Lab
    • Field
    • Air SAR
    • Satellite
DIURNAL VARIATION IN $\sigma^0$

Humid Temperate Forest Loblolly Pines at Duke Forest

While $\varepsilon^*$ of trunks are found to vary by 30%,

$\sigma^0$ varies by only $\approx 1$ dB

Calibration accuracy is 1 dB
Calibrated AIRSAR Response at L-Band to Standing Forest Biomass

\[ y = -13.43 + 4.6x - 0.76x^2 \quad R^2 = 0.90 \]  
HH polarization

\[ y = -22.22 + 7.24x - 1.48x^2 \quad R^2 = 0.97 \]  
HV polarization

\[ y = -14.48 + 4.17x - 0.70x^2 \quad R^2 = 0.92 \]  
VV polarization

- Loblolly pine (Duke Forest, USA)
- Maritime pine (Landes, France)
- Non-forested
Backscatter From Loblolly and Maritime Pines
Aboveground Biomass (tonnes/ha)

Duke Forest
Michigan Forests
Landes
L-band, HV-polarization

Backscatter Coefficient (dB)

Aboveground Biomass (tonnes/ha)

- Lobolly pine
- Maritime pine
- Red pine
- Jack pine
- Bigtooth aspen
- Red maple swamp
- White cedar swamp
- Non-forested
- Grass (dry soil)
- Grass (wet soil)
- Clear-cut

Grass (dry soil)
6. L-BAND SAR OBSERVATIONS IN ALASKA

\[ \sigma^0 \text{ (dB) observed} \]

\[ \sigma^0 \text{ (dB) MIMICS} \]

- White Spruce -- Thawed
- White Spruce -- Frozen
- Black Spruce -- Thawed
- Black Spruce -- Frozen
- Balsam Poplar -- Thawed
- Balsam Poplar -- Frozen
- Alder -- Thawed
- Alder -- Frozen
Pellston $\Delta \sigma^0$, July 8 – July 10, HH-polarization

GRASS      ASPEN      PINES

P band

L band

C band
June 14, 1983
Winter Wheat
10.2 GHz

\[ \sigma_{\text{can}}^0 \]

Leaf Surface Water
VW Polarization
\( \theta = 50^\circ \)
ERS-1 RESULTS

- Class Statistics
- Observation *versus* Theory (MIMICS)
- Biomass Response (Deciduous and Coniferous)
- Seasonal Variation (LAI)
  - Deciduous
  - Coniferous
ERS-1 Class Statistics for 3x3 Pixel Averages

Normalized Frequency

-30  -25  -20  -15  -10  -5  0
\( \sigma^0 (\text{dB}) \)

Cover Type

Inland Lakes  Concrete  Prairie  Hay fields  Red Pine  Jack pine  Northern Hardwoods  Lowland Conifers
Comparison of SAR Observations with MIMICS Simulations
C-band, VV-polarization

Observed Backscatter Coefficient (dB)

Simulated Backscatter Coefficient (dB)
ERS-1 Backscatter Modeled by MIMICS for Northern Michigan Forests in August 1991

Dominant Mechanisms in Radar Backscattering by Forests

<table>
<thead>
<tr>
<th>Dominant Specie</th>
<th>Percent of Total Return</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Crown</td>
</tr>
<tr>
<td>Red maple</td>
<td>95.5</td>
</tr>
<tr>
<td>Sugar maple</td>
<td>96.4</td>
</tr>
<tr>
<td>Jack pine</td>
<td>100</td>
</tr>
<tr>
<td>Red Pine</td>
<td>41.3</td>
</tr>
<tr>
<td>grass</td>
<td>0.03</td>
</tr>
</tbody>
</table>
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Dependence Upon Above Ground Forest Biomass

\[ y = -21.82 + 4.79 \log(x) \quad R^2 = 0.62 \]

- Backscatter Coefficient (dB)
- Dry Biomass (tonnes/ha)

- Red pine
- Jack pine
- Spruce bog
- Bigtooth aspen
- Red maple
- Red oak
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Backscatter vs. LAI for Deciduous Forests

Backscatter Coefficient (dB)

Leaf Area Index (m^2/m^2)
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Backscatter vs. LAI for Closed-Canopy Conifer Forests

\[ y = -19.248 + 9.9315 \times \log(x) \quad R^2 = 0.708 \]
CONCLUSIONS & RECOMMENDATIONS

I. SURFACE SCATTERING

1. Retrieval of Soil Moisture and Surface Roughness
   - L-Band Quad-Pol for bare soil
   - P-Band Quad-Pol: extends to agricultural crops

2. Effects of Organic Debris
   - Extinction depends on size / λ
     At P and L-Bands, only trunks and large branches are significant

II. VEGETATION SCATTERING

1. In general σ° = f (biomass, structure)

2. Extinction by crown layer increases with frequency

3. Scattering by foliage and small branches:
   - negligible at P and L Bands
   - dominates at C and X Bands

4. Scattering by trunks and large branches:
   - dominates at P and L Bands
CONCLUSIONS & RECOMMENDATIONS

- Even P-Band is insensitive to high biomass forests (Pacific NW ≅ 500 tons/ha)

6. Innundation under Forest Cover

   L-Band HH

7. Effects of Intercepted Precipitation

   - negligible at P Band
   - ≅ 1 dB increase or decrease at L-Band
   - ≅ 2 dB increase at C-Band

8. Freezing of Vegetation Leads to

   Significant changes in $\sigma^0$ at all Bands

9. Deforestation Readily Detectable at

   P and L-Band

10. LAI Foliar Biomass Estimation

    C-Band Quad or X-Band

11. Multi-Date Observations: Very Powerful Tool

    - Requires good Relative Calibration (Stability) $\equiv \pm 1$ dB
    - Requires good Absolute Calibration $\equiv \pm 1$ dB

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