Determination of Soil Moisture Beneath a Stalk or Trunk Dominated Canopy

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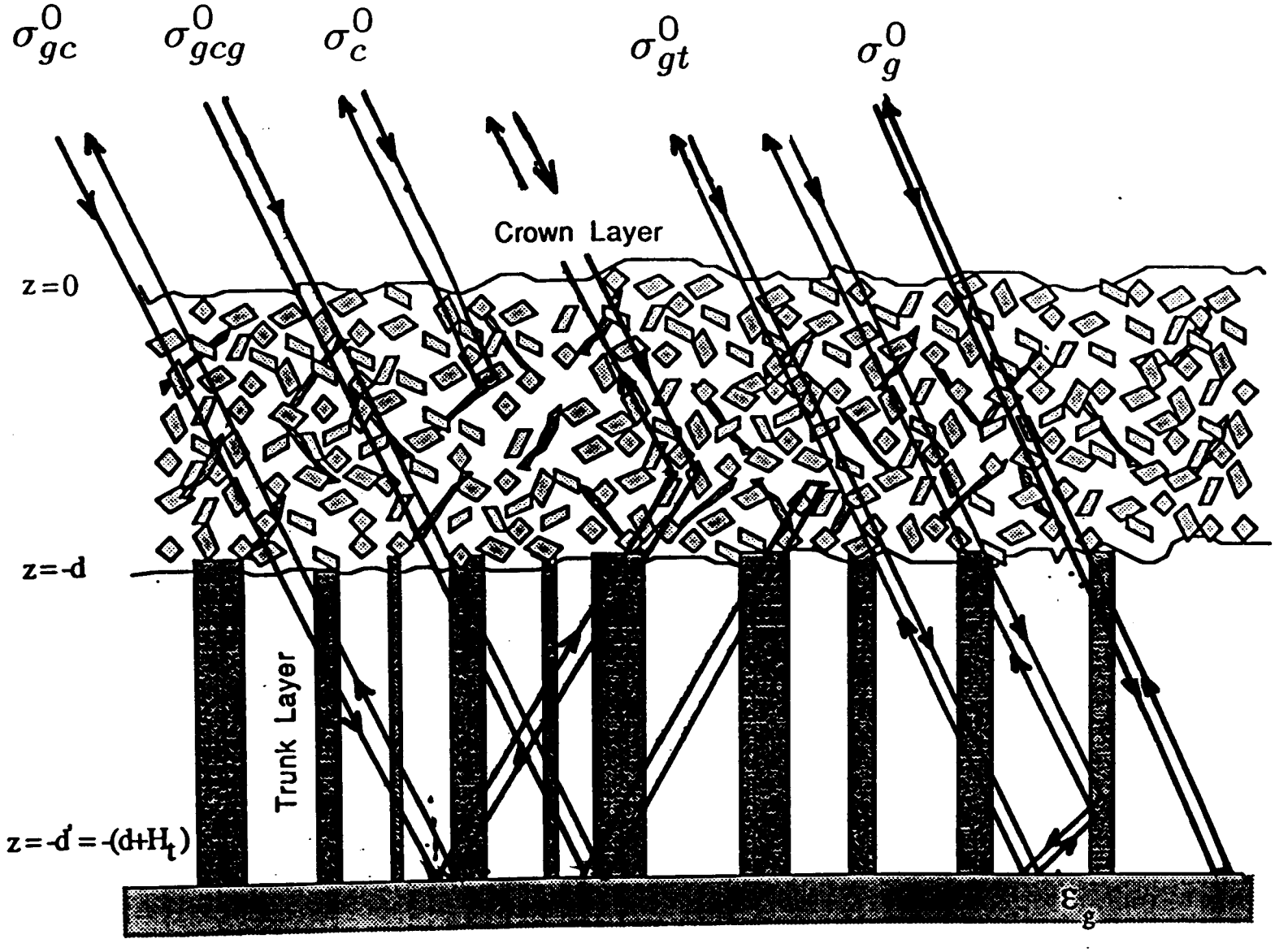
This work was supported by the National Aeronautics and Space Administration under Contract NAG5-480.

OVERVIEW

1. Radiative transfer model
    - Simplified L-Band MIMICS model
    - $\sigma^0_{HH}, \sigma^0_{VV}$ and $\Delta\phi_{HH-VV}$
2. Example model computations
    - Dominant backscatter contributions
3. Application of the model to determining soil moisture
    - Inversion of backscatter data



$$\sigma_t^0 = \sigma_c^0 + \sigma_g^0 + \sigma_{gt}^0 + \sigma_{gc}^0 + \sigma_{gcg}^0$$

- Direct Crown Backscatter

$$\sigma_c^0 = \frac{\sigma_v \cos\theta}{2\kappa_e}\left[1 - \exp\left(-\frac{2\kappa_e H_c}{\cos\theta}\right)\right]$$

$$\sigma_v = \frac{3}{2}\omega \simeq \frac{3}{2}(0.1)$$

$$\kappa_e^p = \kappa_l + \kappa_t^p$$

$$\kappa_l = \mathrm{Im}\left[\frac{4\pi}{\lambda}\sqrt{1 + \frac{v_l}{3}(\epsilon_l - 1)\left(2 + \frac{1}{\epsilon_l}\right)}\right]$$

$$\kappa_t^p = -N\frac{2\lambda}{\pi}\mathrm{Re}\left[\sum_{n=-\infty}^{\infty} C_n^p(\theta_0)\right]$$

$$p = v \text{ or } h$$

- Direct Ground Backscatter

  - Small Perturbation Model

$$\sigma_g^0 = \sigma_{s,p}^0 \exp\left(-2\kappa_e^p \sec\theta\right)$$

$$\sigma_{s,p}^0 = 4\,(ks)^2\,(kl)^2 \cos^4\theta\,|\alpha_{pp}|^2\, e^{-(kl\sin\theta)^2}$$

$$\alpha_{hh} = \frac{\cos\theta - \sqrt{\epsilon_s - \sin^2\theta}}{\cos\theta + \sqrt{\epsilon_s - \sin^2\theta}}$$

$$\alpha_{vv} = (\epsilon_s - 1)\frac{\sin^2\theta - \epsilon_s\left(1 + \sin^2\theta\right)}{\left[\epsilon_s\cos\theta + \sqrt{\epsilon_s - \sin^2\theta}\right]^2}$$

Validity Conditions

$$s \leq 0.05\lambda$$
$$m = \sqrt{2}\frac{s}{l} \leq 0.3$$
$$l \leq 0.5\lambda$$

Recommended Conditions

$$l \leq 0.25\,\lambda$$
$$s \leq 0.05\lambda$$

- Ground-Trunk (Stalk) Interaction

$$\sigma^0_{gt,pp} = 4Ne^{-2\kappa_e^p H_c \sec\theta} |R_p(\theta)|^2 \sigma_p^t$$

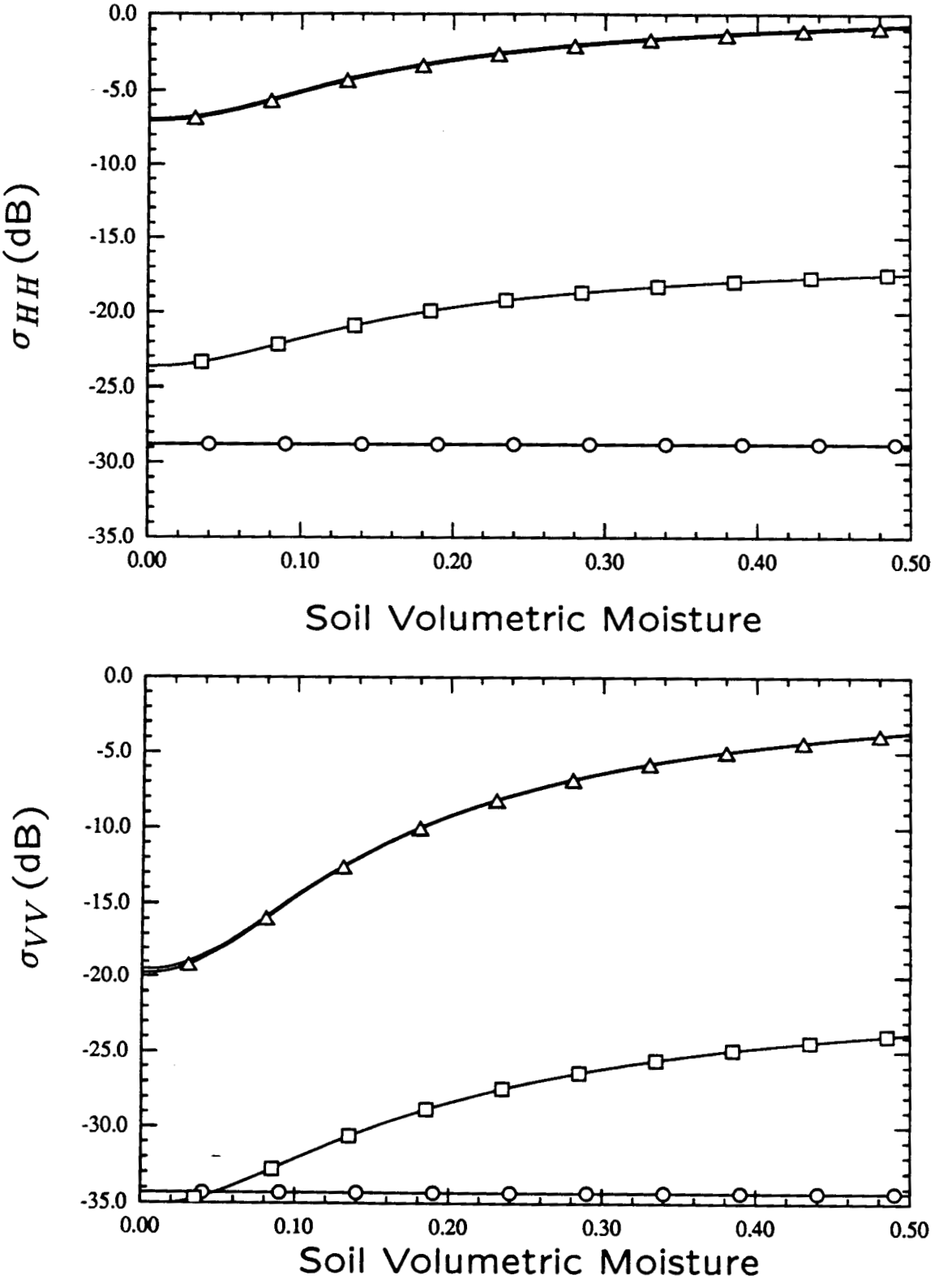
$$\sigma_p^t(\theta) = \frac{16H_t^2}{\pi} \left| \sum_{n=-\infty}^{\infty} (-1)^n C_n^p \right|^2$$

$$p = v \text{ or } h$$

Validity Conditions:

- $H_t \gg \lambda$
- Specular forward scatter from soil

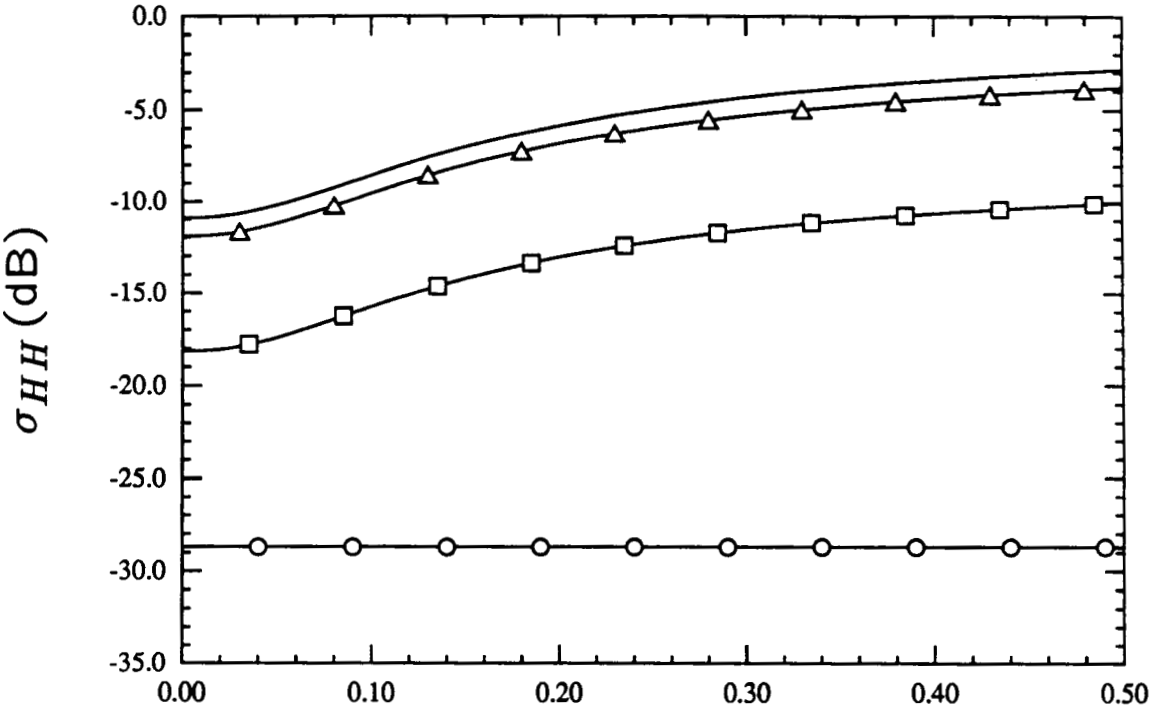
Backscatter Contributions, θ = 50 Degrees

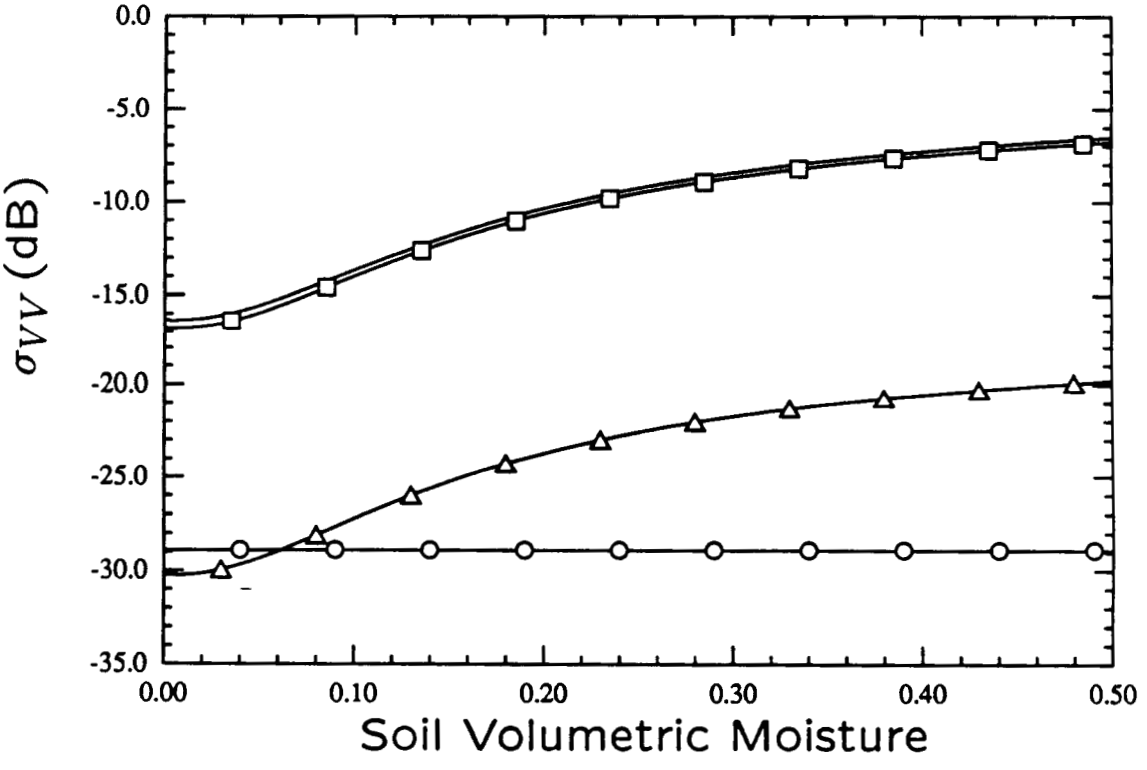


— Total Backscatter
○ Direct Crown
□ Direct Ground
△ Ground-Stalk

Stalk Moisture = 0.5

Backscatter Contributions, θ = 30 Degrees





— Total Backscatter
○ Direct Crown
□ Direct Ground
△ Ground-Stalk

Stalk Moisture = 0.2

Polarization Phase Difference

$$\Delta\phi_{(HH-VV)gs} = 2\Delta\phi_p + \Delta\phi_{g,s} + \Delta\phi_{tr}$$
$$\Delta\phi_{(HH-VV)g} = 2\Delta\phi_p + \Delta\phi_{g,b}$$

- Propagation Phase Difference

$$\Delta\phi_p = \frac{2NH_t}{k}\tan\theta\left[\mathrm{Im}\left\{A_h(\theta,\pi)\right\} - \mathrm{Im}\left\{A_v(\theta,\pi)\right\}\right]$$

$$A_p(\theta,\pi) = \sum_{n=-\infty}^{\infty} C_n^p(\theta), \qquad p = v \text{ or } h$$

- Trunk Scatter Phase Difference

$$\Delta\phi_t = \tan^{-1}\left\{\frac{\mathrm{Im}\left[A_h/A_v\right]}{\mathrm{Re}\left[A_h/A_v\right]}\right\}$$

$$A_p(\theta,0^o) = \sum_{n=-\infty}^{\infty}(-1)^n C_n^p(\theta)$$
$$p = v \text{ or } h$$

- Ground Scatter Phase Difference
  - Specular Scatter

$$\Delta\phi_{g,s} = \tan^{-1}\left\{\frac{\mathrm{Im}\,(R_h/R_v)}{\mathrm{Re}\,(R_h/R_v)}\right\} - 180^o$$

  - Backscatter

$$\Delta\phi_{g,b} = \tan^{-1}\left\{\frac{\mathrm{Im}\,(\alpha_{hh}/\alpha_{vv})}{\mathrm{Re}\,(\alpha_{hh}/\alpha_{vv})}\right\}$$

Total Phase Difference

$$\begin{bmatrix} |S_{VV}|^2 & 0 & 0 & 0 \\ 0 & |S_{HH}|^2 & 0 & 0 \\ 0 & 0 & \mathrm{Re}\,(S_{VV}S_{HH}^*) & -\mathrm{Im}\,(S_{VV}S_{HH}^*) \\ 0 & 0 & \mathrm{Im}\,(S_{VV}S_{HH}^*) & \mathrm{Re}\,(S_{VV}S_{HH}^*) \end{bmatrix}$$

where:

$$\begin{aligned} |S_{VV}|^2 &= \sigma^0_{gt,VV} + \sigma^0_{g,VV} \\ |S_{HH}|^2 &= \sigma^0_{gt,HH} + \sigma^0_{g,HH} \\ \mathrm{Re}\,(S_{VV}S_{HH}^*) &= \mathrm{Re}\left[\sqrt{\sigma_{gt,VV}}\sqrt{\sigma_{gt,HH}}e^{i\Delta\phi_{gs}}\right] \\ &\quad + \mathrm{Re}\left[\sqrt{\sigma_{g,VV}}\sqrt{\sigma_{g,HH}}e^{i\Delta\phi_{g}}\right] \\ \mathrm{Im}\,(S_{VV}S_{HH}^*) &= \mathrm{Im}\left[\sqrt{\sigma_{gt,VV}}\sqrt{\sigma_{gt,HH}}e^{i\Delta\phi_{gs}}\right] \\ &\quad + \mathrm{Im}\left[\sqrt{\sigma_{g,VV}}\sqrt{\sigma_{g,HH}}e^{i\Delta\phi_{g}}\right] \end{aligned}$$

Dielectric Bevahior of Constituents

- Vegetation - Ulaby and El-Rayes (1987)

$$\epsilon_{mg} = A + B\left(4.9 + \frac{\epsilon_s - \epsilon_\infty}{1 + j\frac{f(\text{Hz})}{f_o}} - \frac{22.74}{f(\text{GHz})}\right) + C\left(2.9 + \frac{55}{1 + \sqrt{j\frac{f(\text{GHz})}{0.18}}}\right)$$

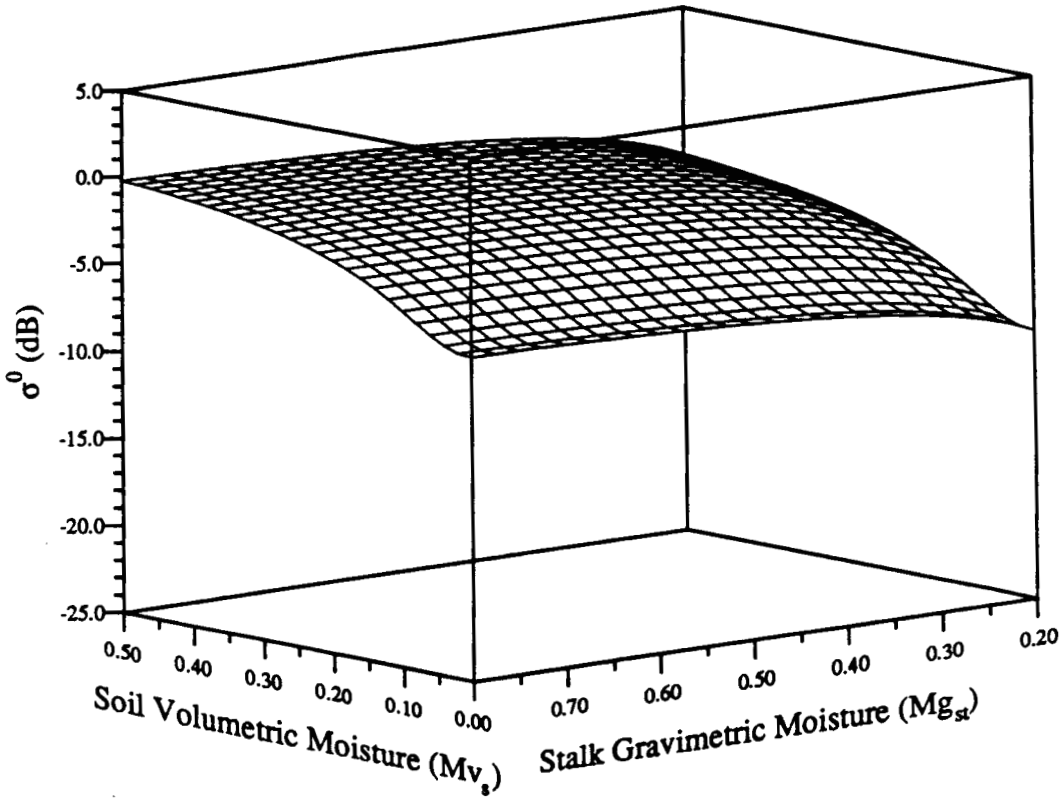
- Soil - Hallikainen et al. (1985)

$$\epsilon_{mv} = \epsilon_s' - j\epsilon_s''$$

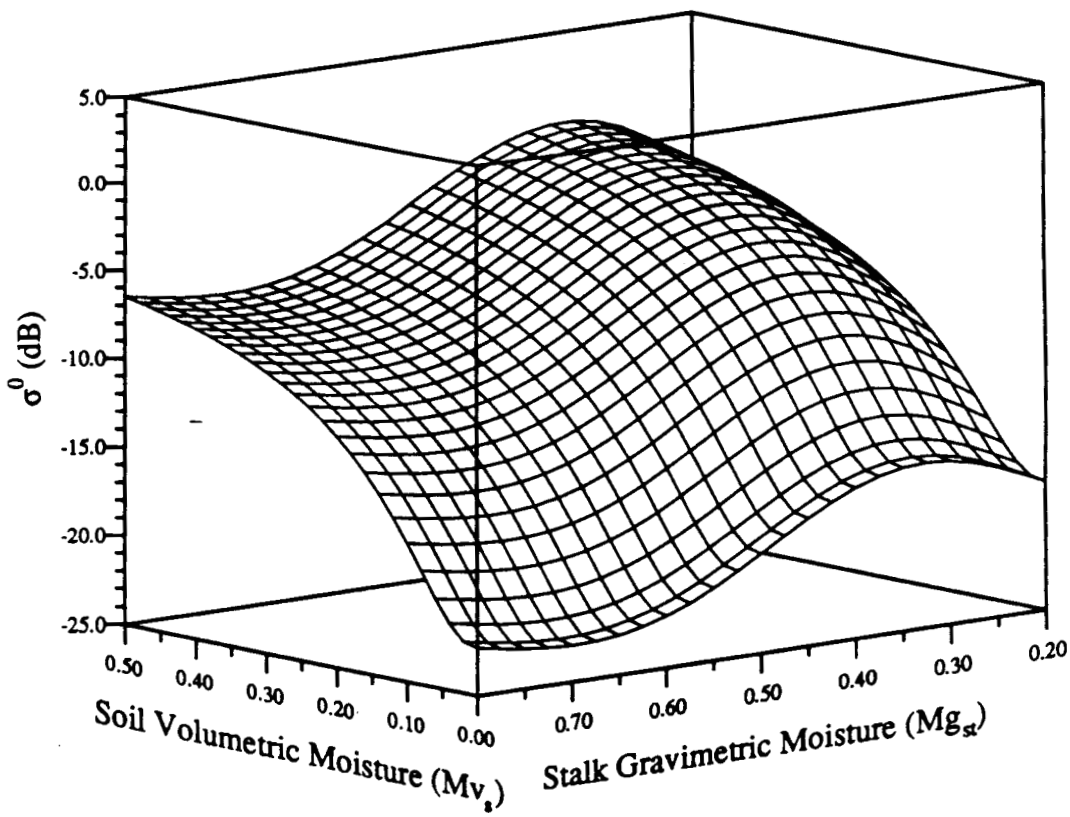
$$\epsilon = (a_0 + a_1 S + a_2 C) + (b_0 + b_1 S + b_2 C)\, m_v + (c_0 + c_1 S + c_2 C)\, m_v^2$$

$$\epsilon = \epsilon_s' \text{ or } \epsilon_s''$$

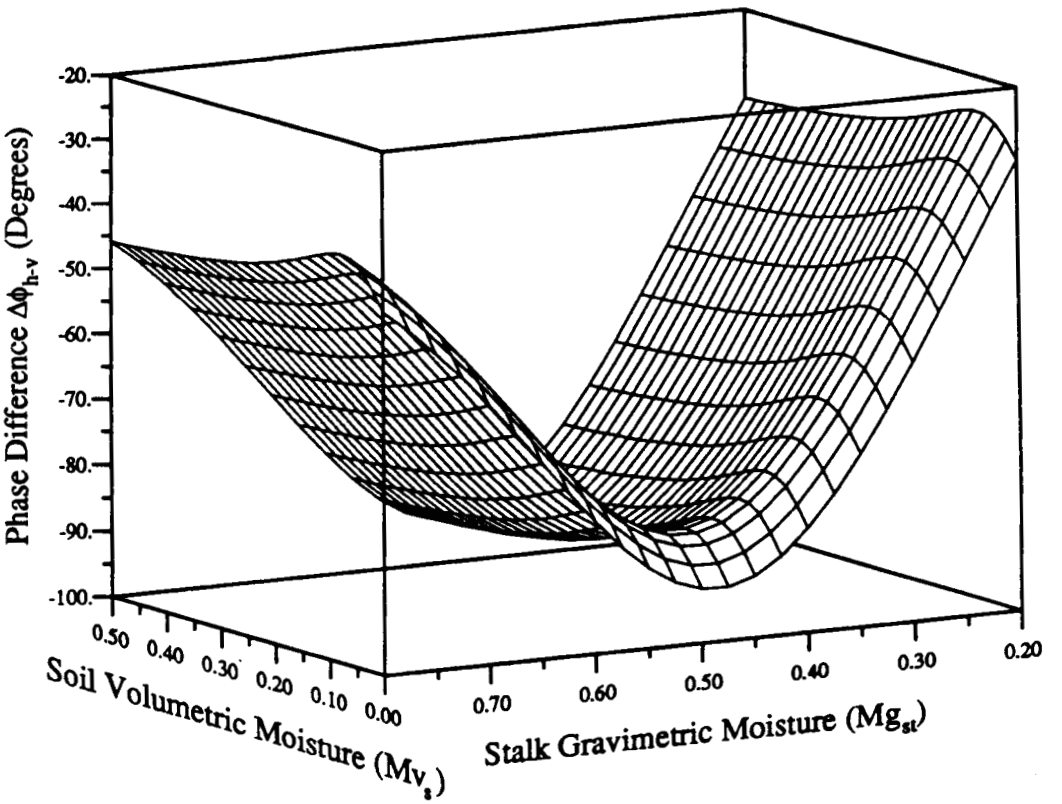
Canopy Backscatter, $\theta=50^{o}$, HH Pol.



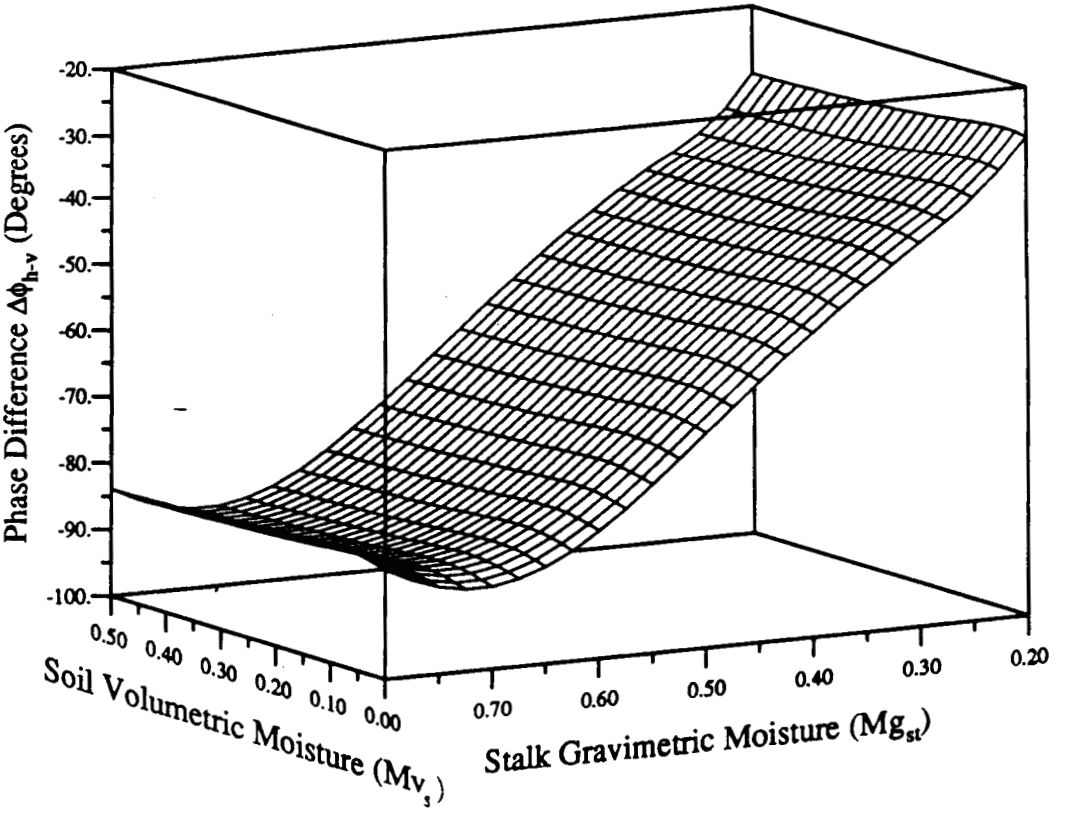
Canopy Backscatter, $\theta=50^{o}$, VV Pol.



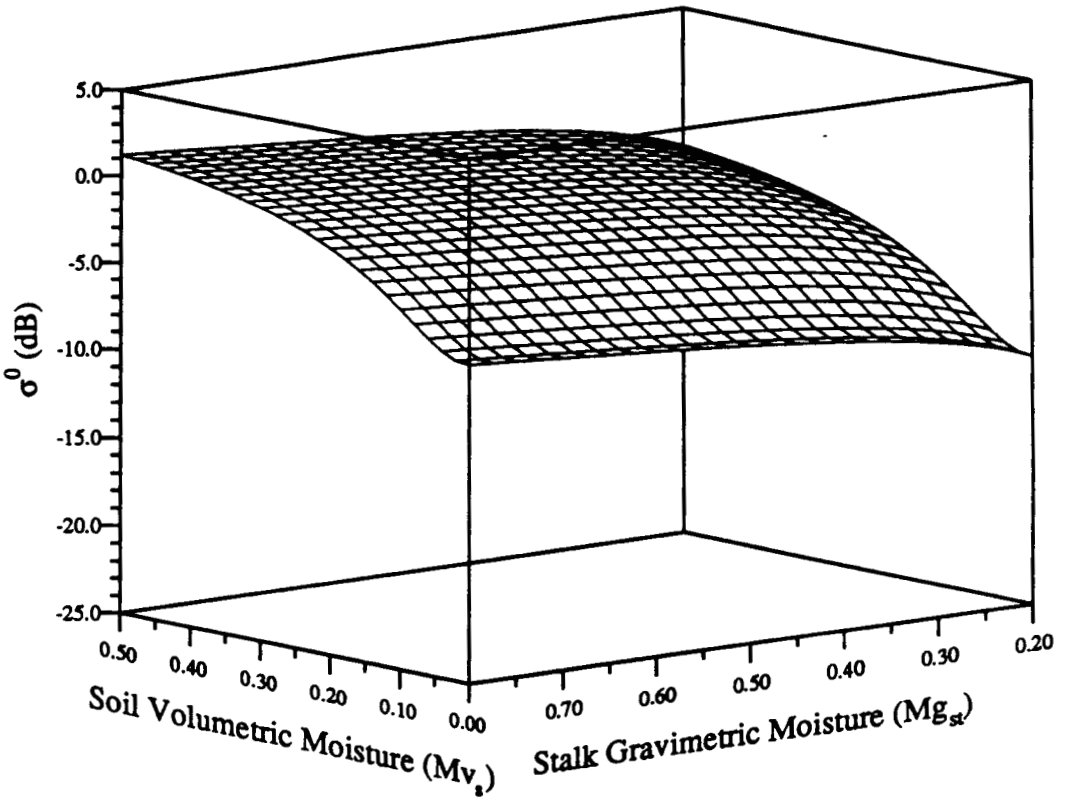
Polarization Phase Difference, $\theta=50^{o}$



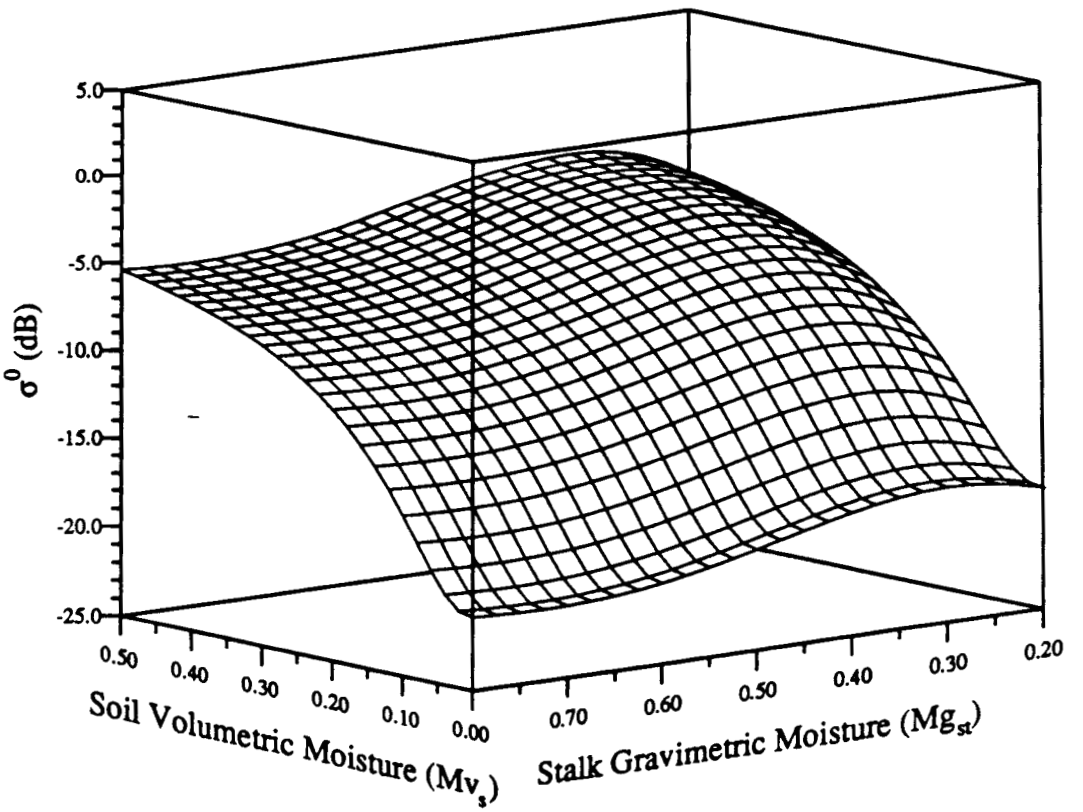
Polarization Phase Difference, $\theta=30^{o}$



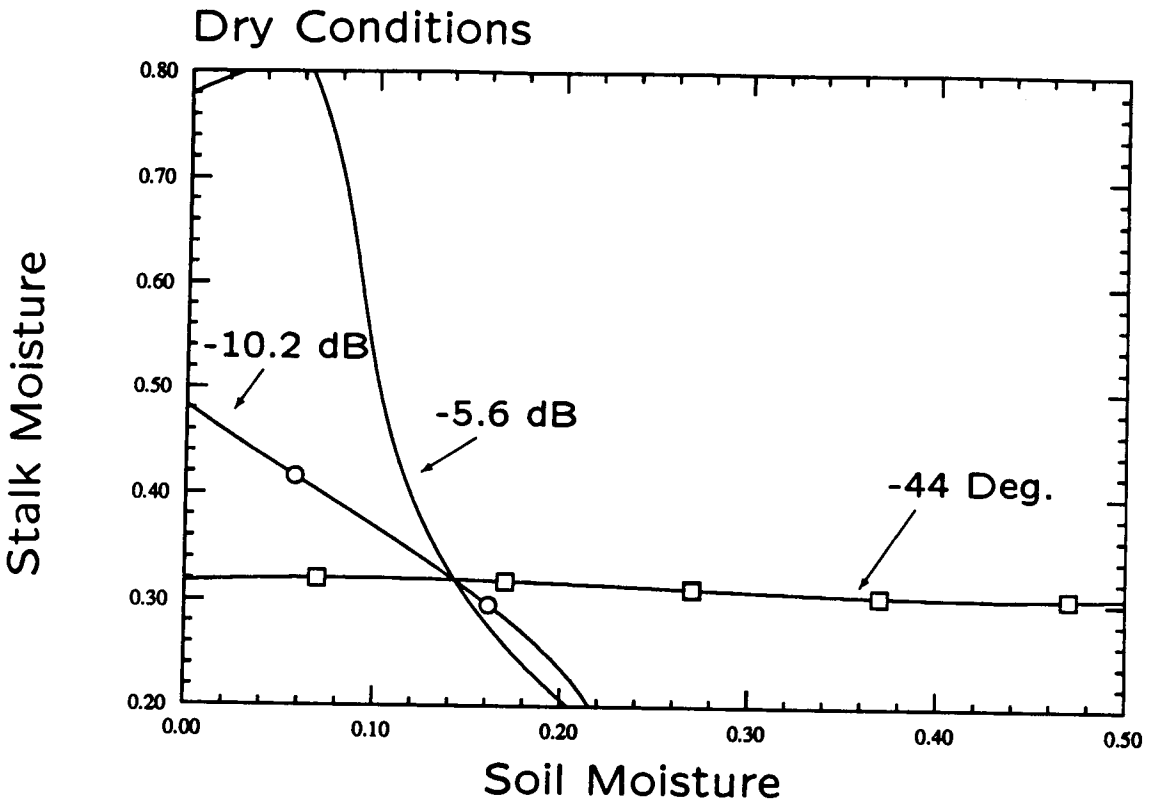
Canopy Backscatter, $\theta=30^{o}$, HH Pol.

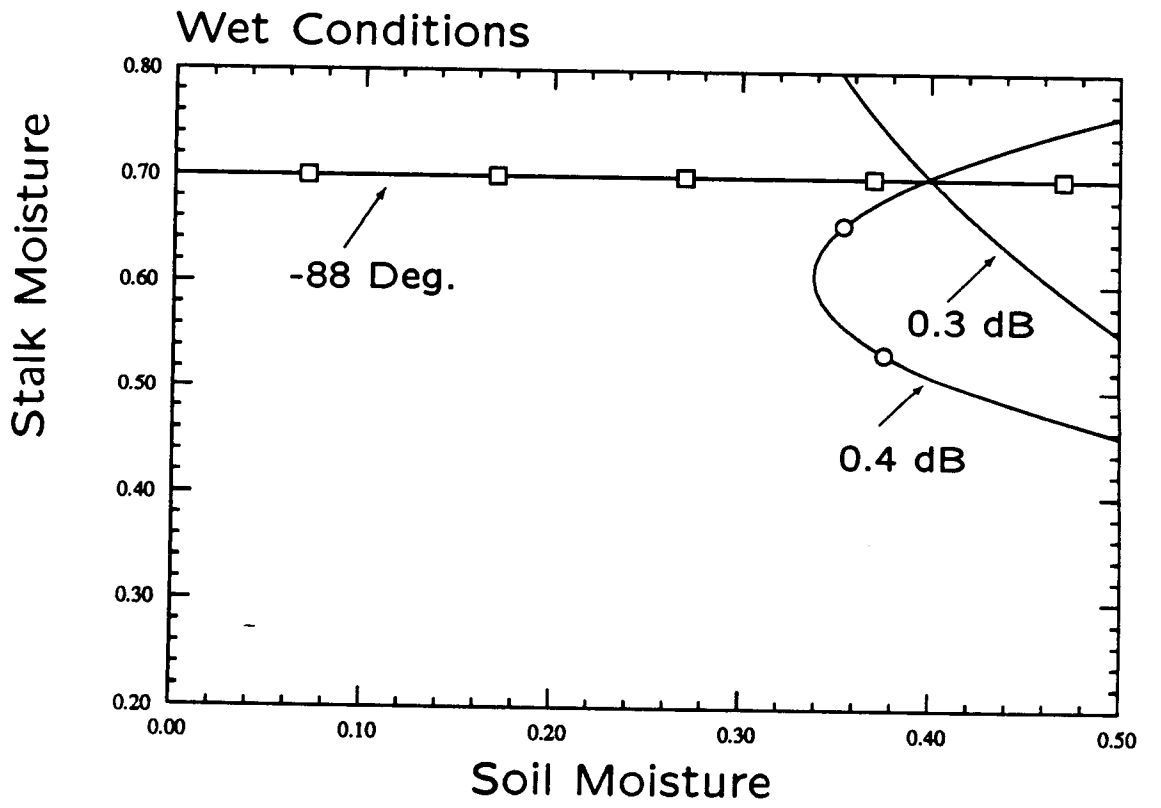


Canopy Backscatter, $\theta=30^{o}$, VV Pol.

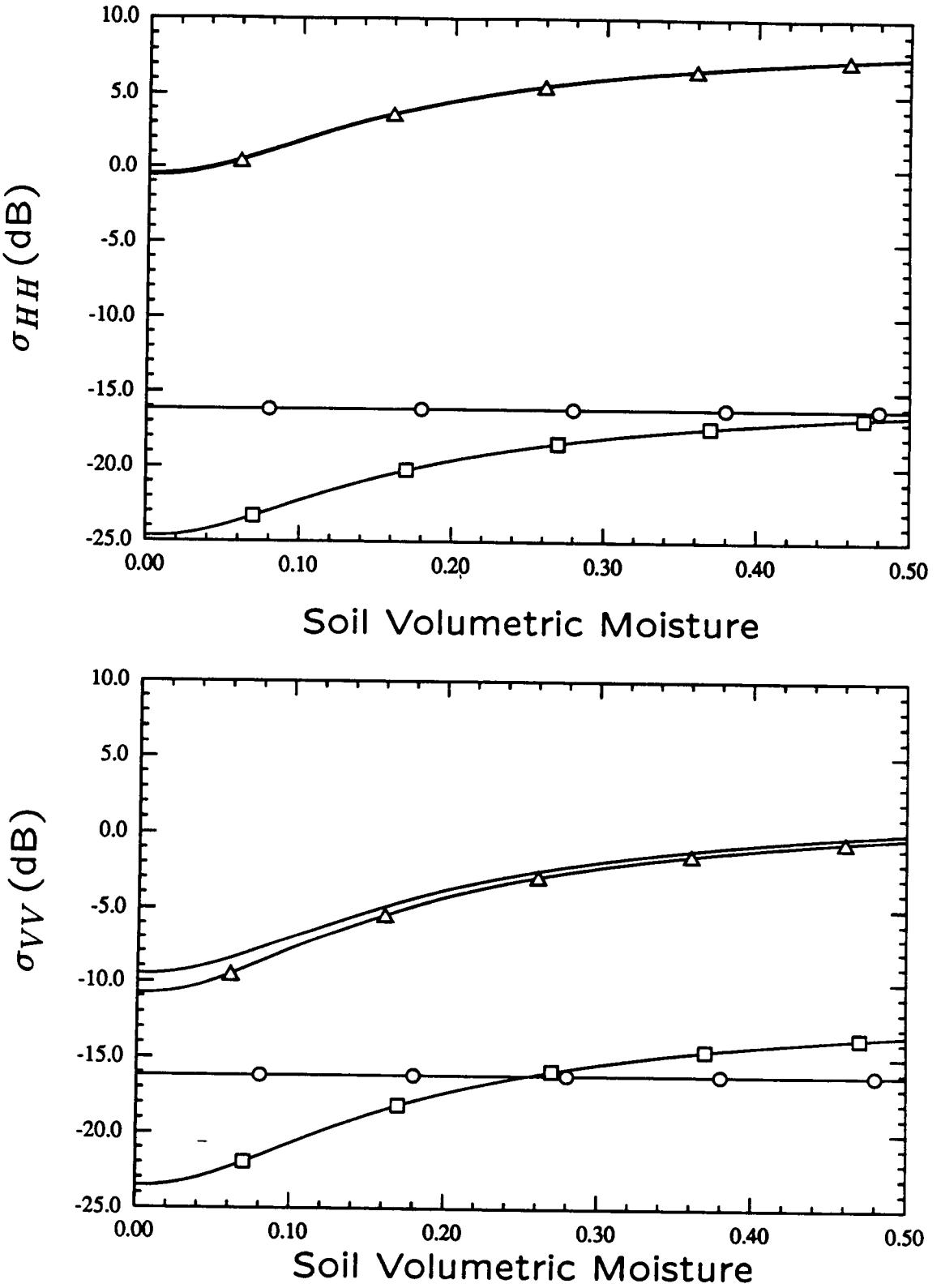


Moisture Parameters, $\theta = 30$ Degrees

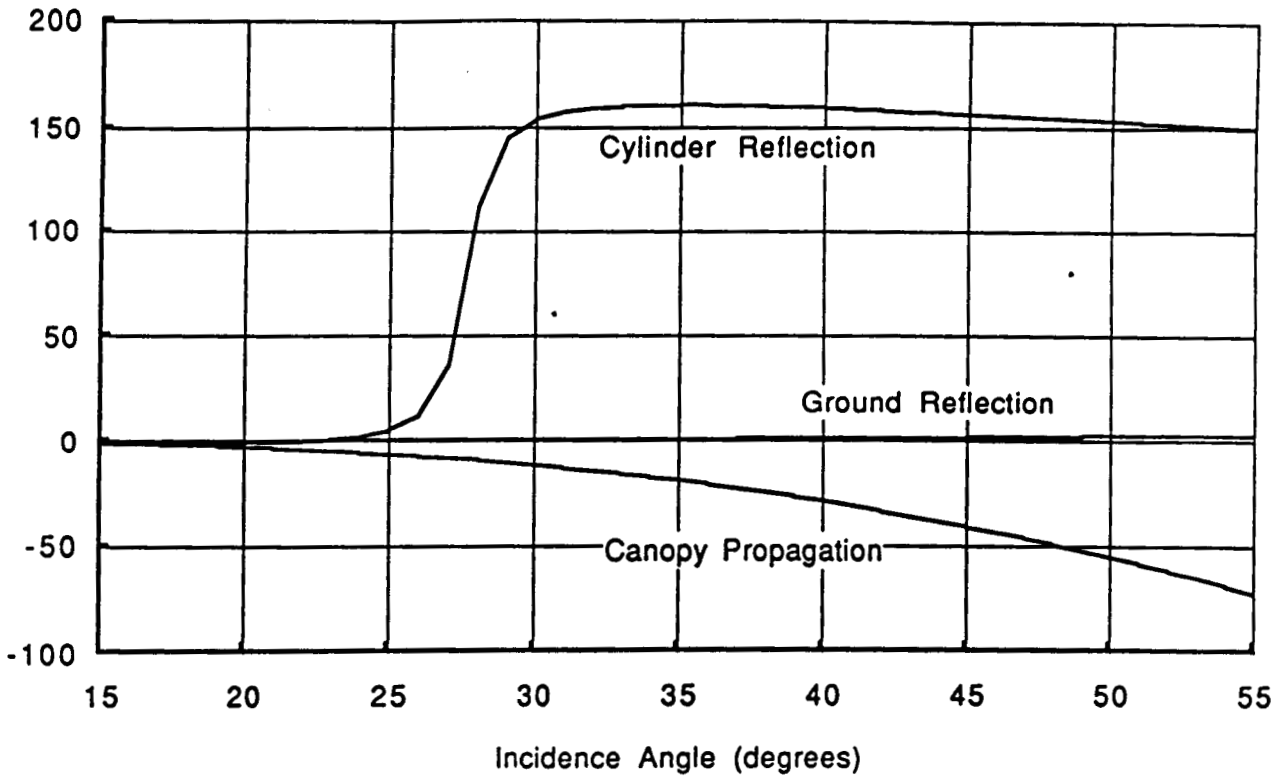




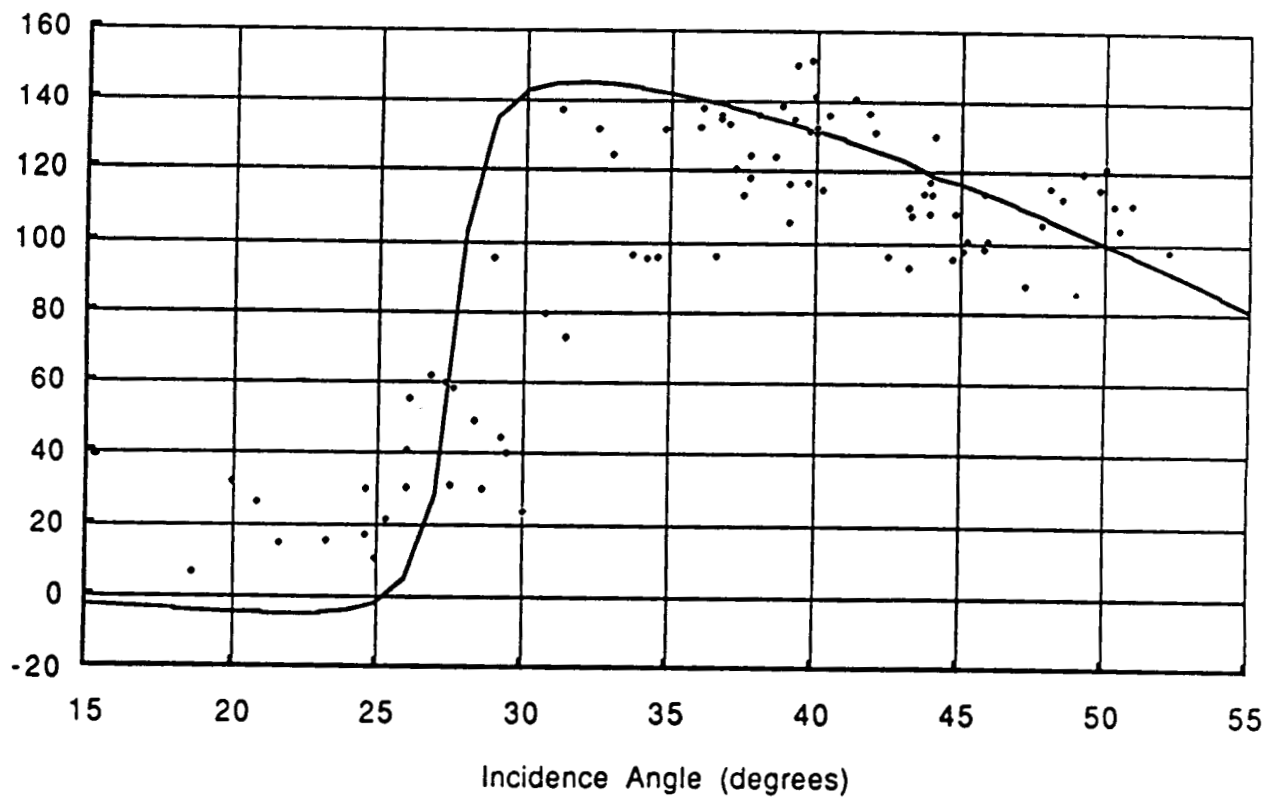
— σ_{HH}
○ σ_{VV}
□ $\Delta\phi_{HH-VV}$


Aspen Canopy, θ = 30 Degrees
σHH (dB)
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
0.00
0.10
0.20
0.30
0.40
0.50
Soil Volumetric Moisture
σVV (dB)
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
0.00
0.10
0.20
0.30
0.40
0.50
Soil Volumetric Moisture
Total Backscatter
Direct Crown
Direct Ground
Ground-Trunk

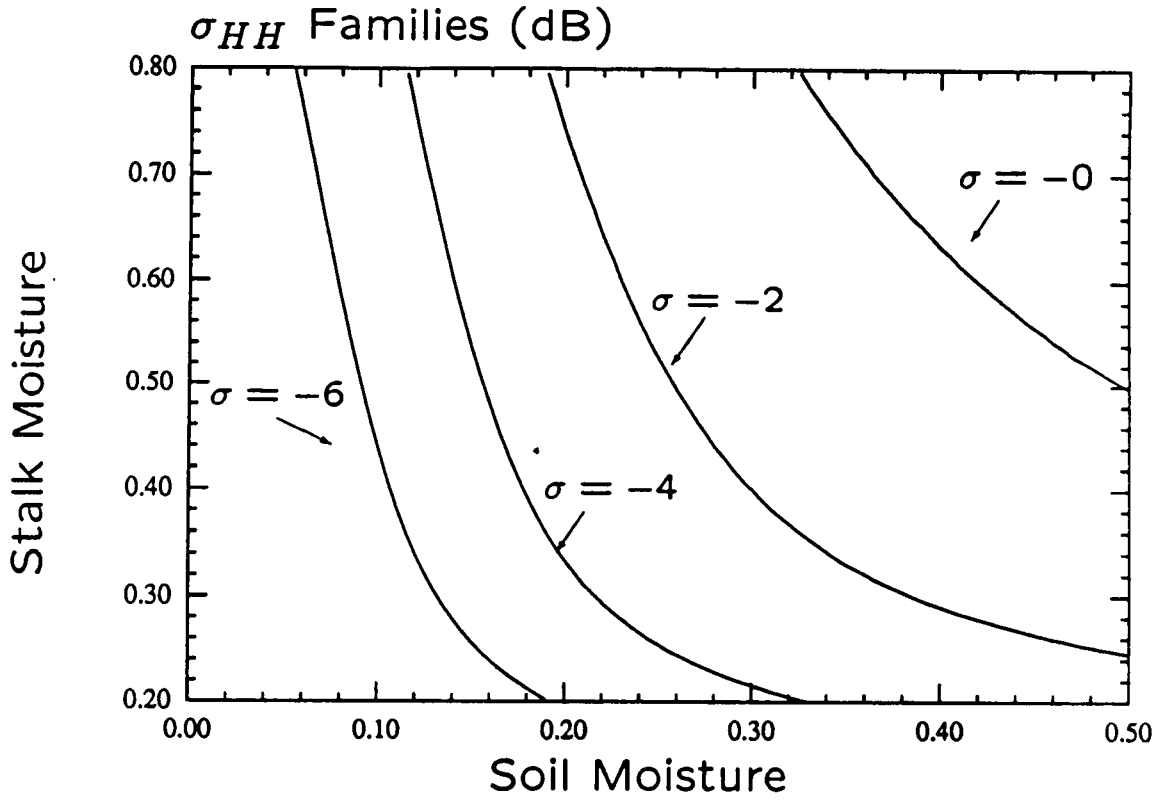
CALCULATED PHASE DIFFERENCE

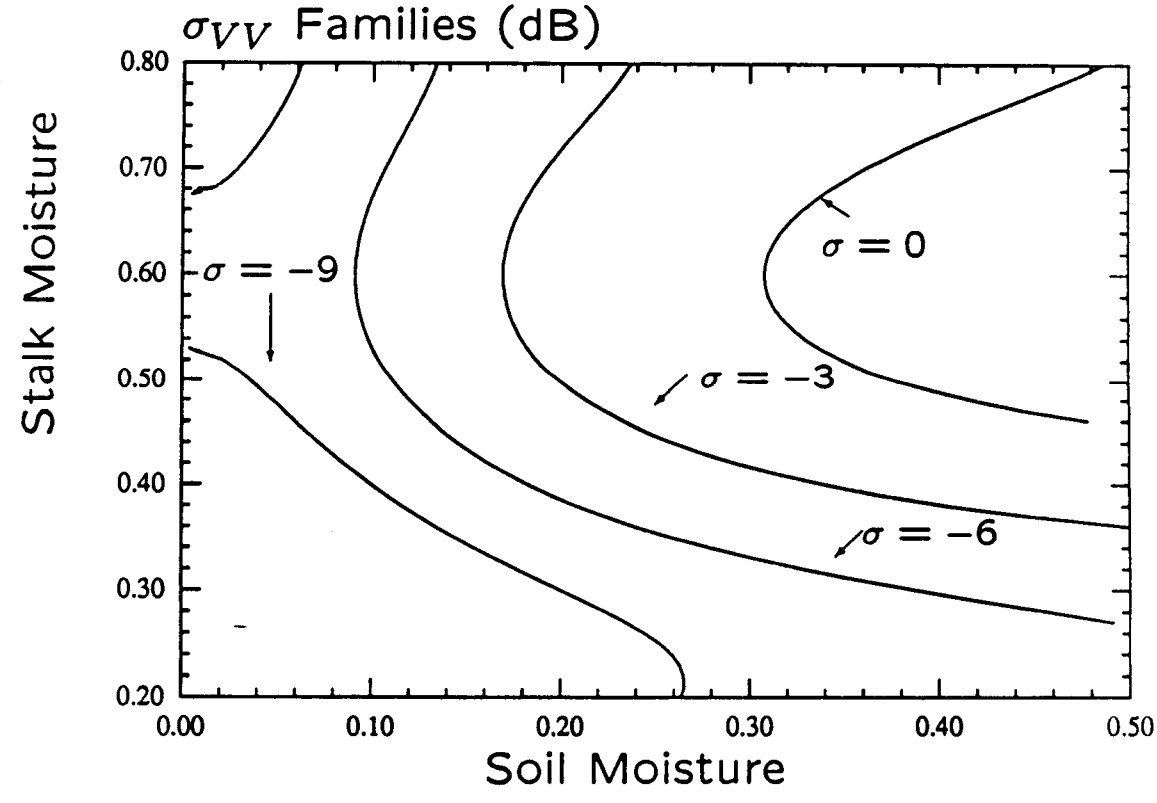


CALCULATED AND MEASURED PHASE DIFFERENCE

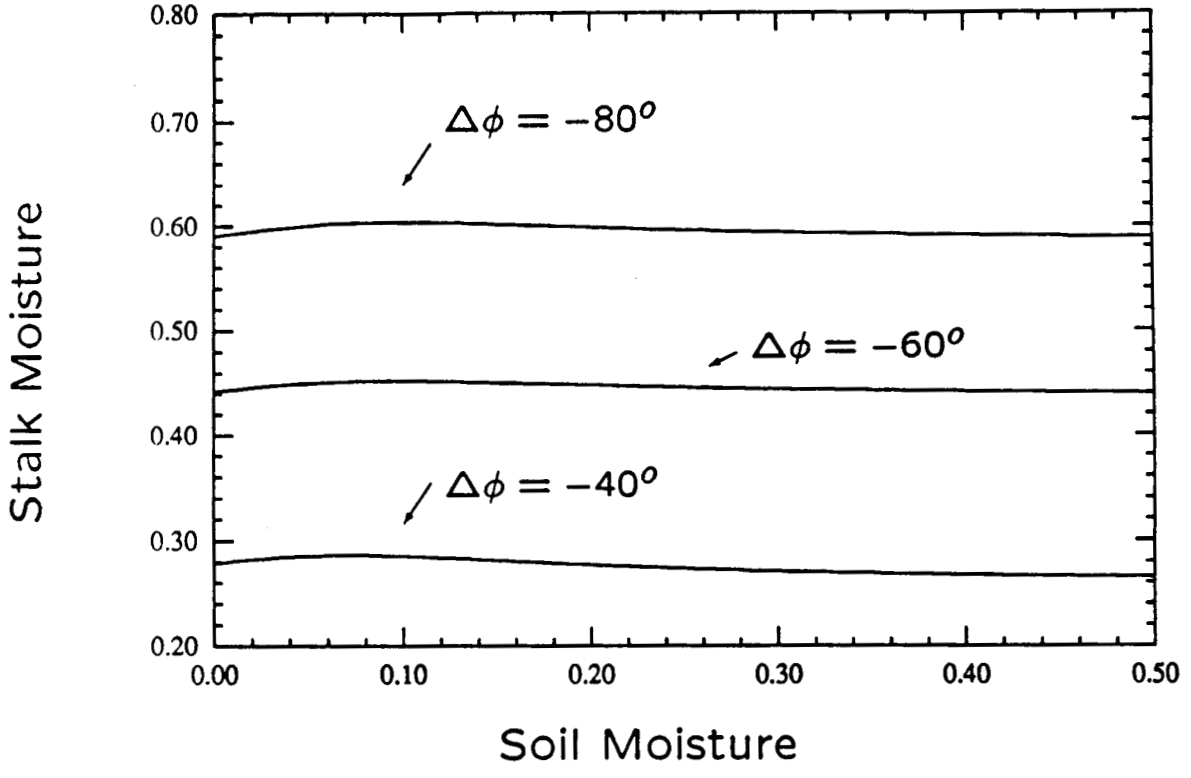


Backscatter Contours, $\theta = 30$ Degrees





Phase Difference Contours, $\theta = 30$ Degrees



Conclusions

- Technique applies to canopies with large enough trunk/stalk biomass.
- Steep incidence angles are most effective.
- Polarization phase difference determines the trunk/stalk moisture.
- Polarization magnitudes determine soil moisture.
- VV polarization magnitude is more effective than HH.