Passive Sensing of Soil Moisture over Forested Terrain

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Talk Outline

- Data collection, modeling and measurements will discussed for the following three campaigns:
  1. Howland Hemlock Forest in Maine
  2. Loblolly Pines, Southern Virginia
  3. Paulownia trees, Maryland Tobacco Farm and Virginia Pines NASA/GSFC

L-Band Active and Passive Sensing of Soil Moisture through Forests

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N Chauhan NPOESS/NOAA

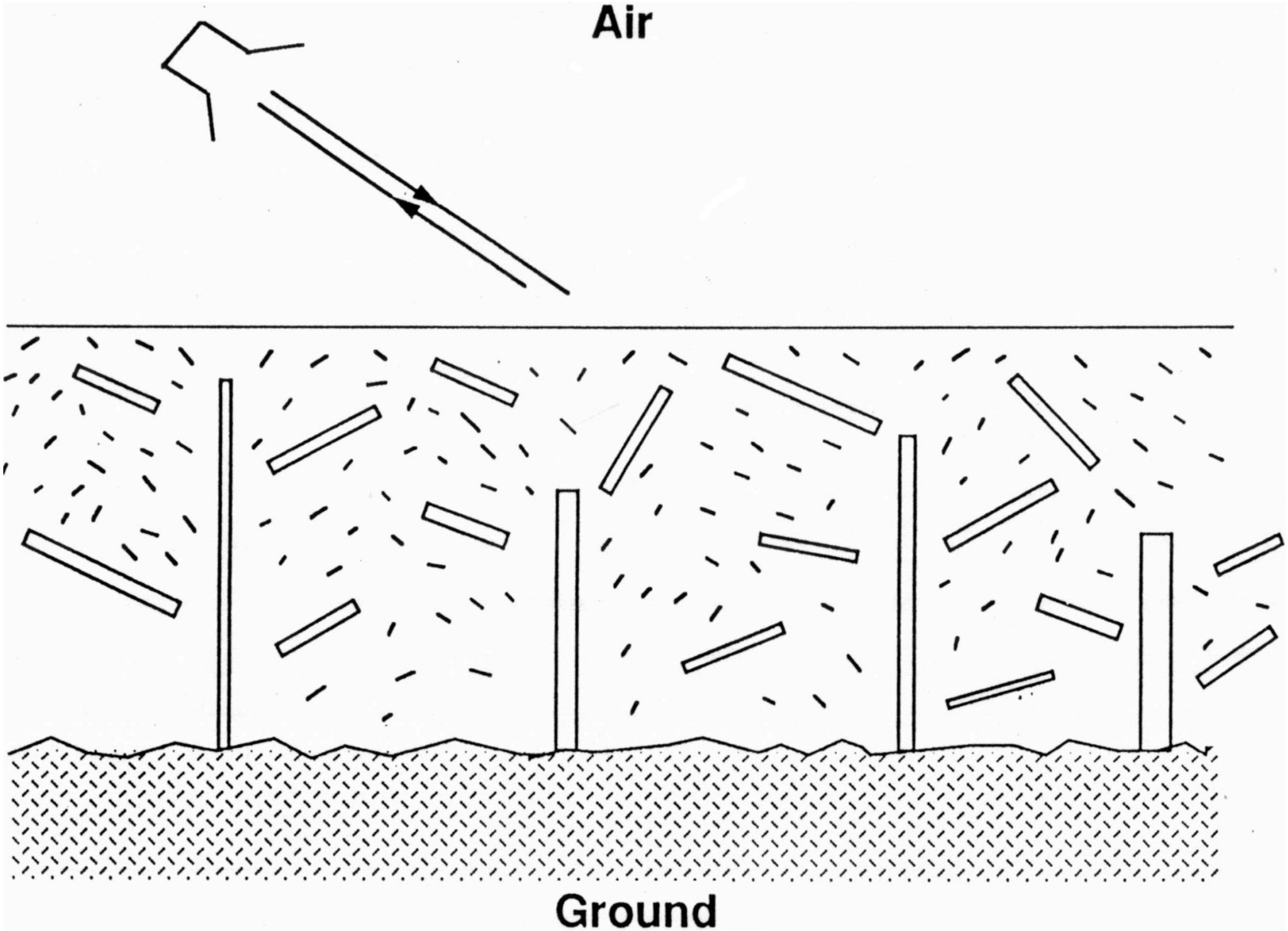
D Le Vine NASA/GSFC

Howland Forest

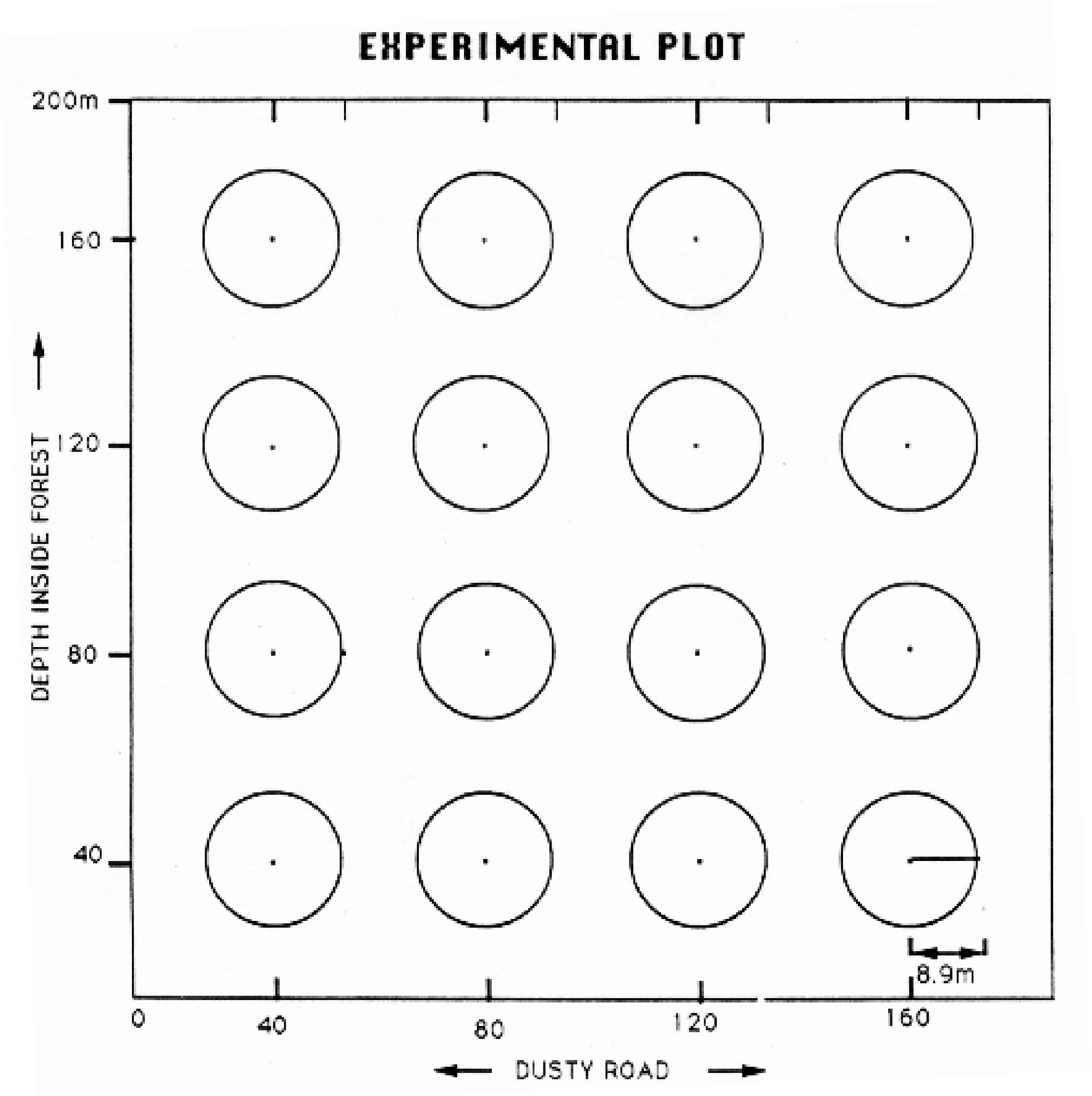
Experiment Site Description

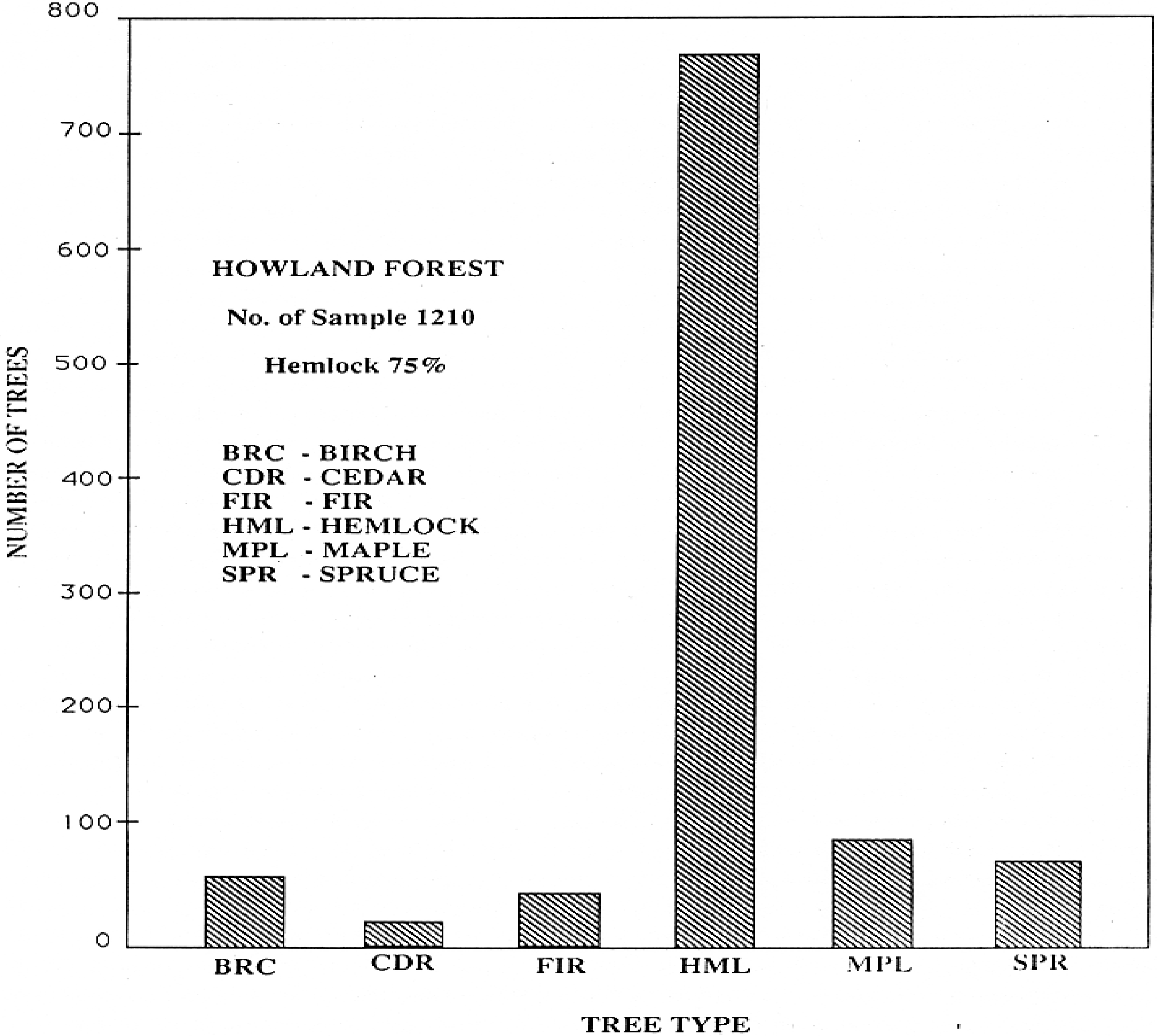
- Location: Howland Maine, USA
- 200x200m^2 of mature hemlock trees
- Forest Height: 15 meters
- Forest Biomass: 28.8 kg/m^2
- NASA JPL AIRSAR flights: July 1989-90
- NASA GSFC PBMR flight: July 1990
- Ground measurements made in July, 1989 and July, 1990 by GW and NASA/GSFC investigators

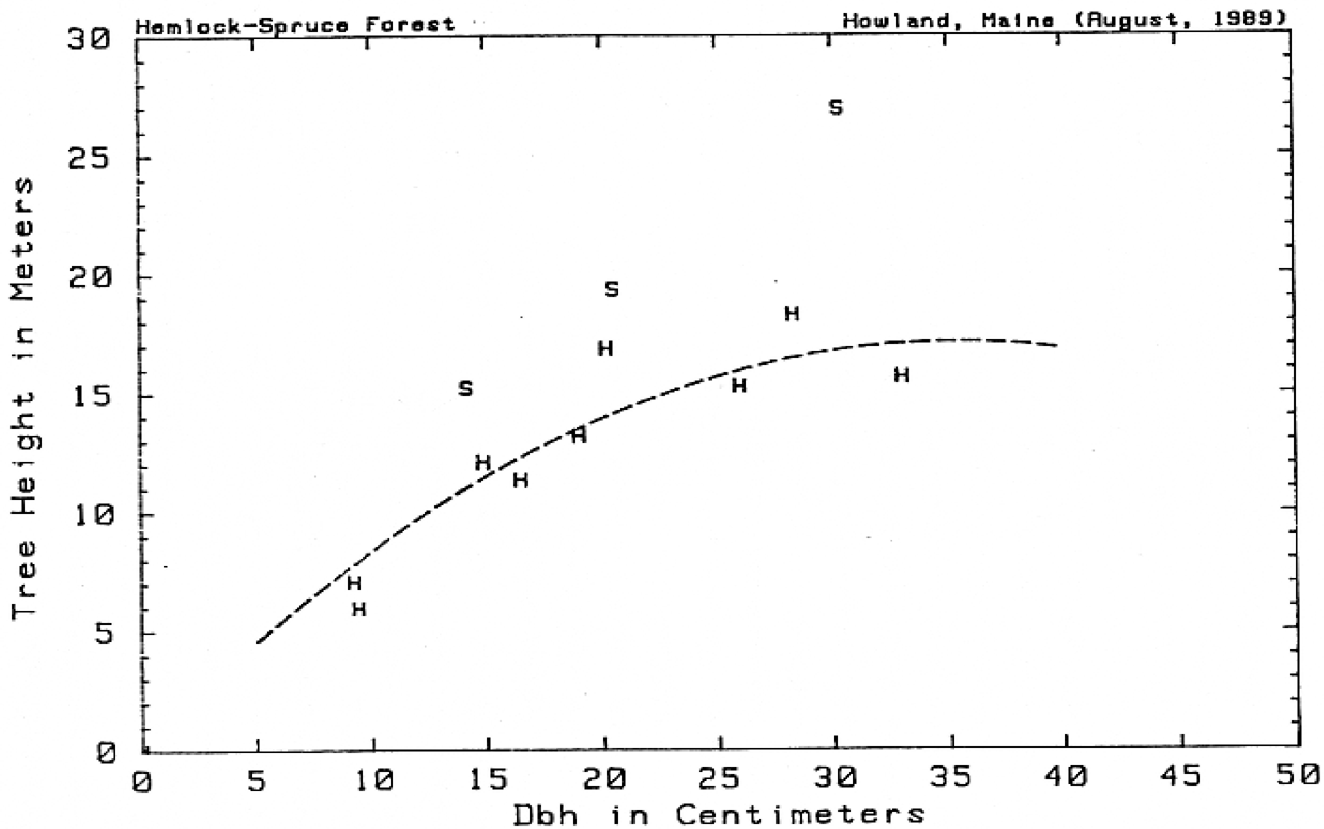
Hemlock Forest Model



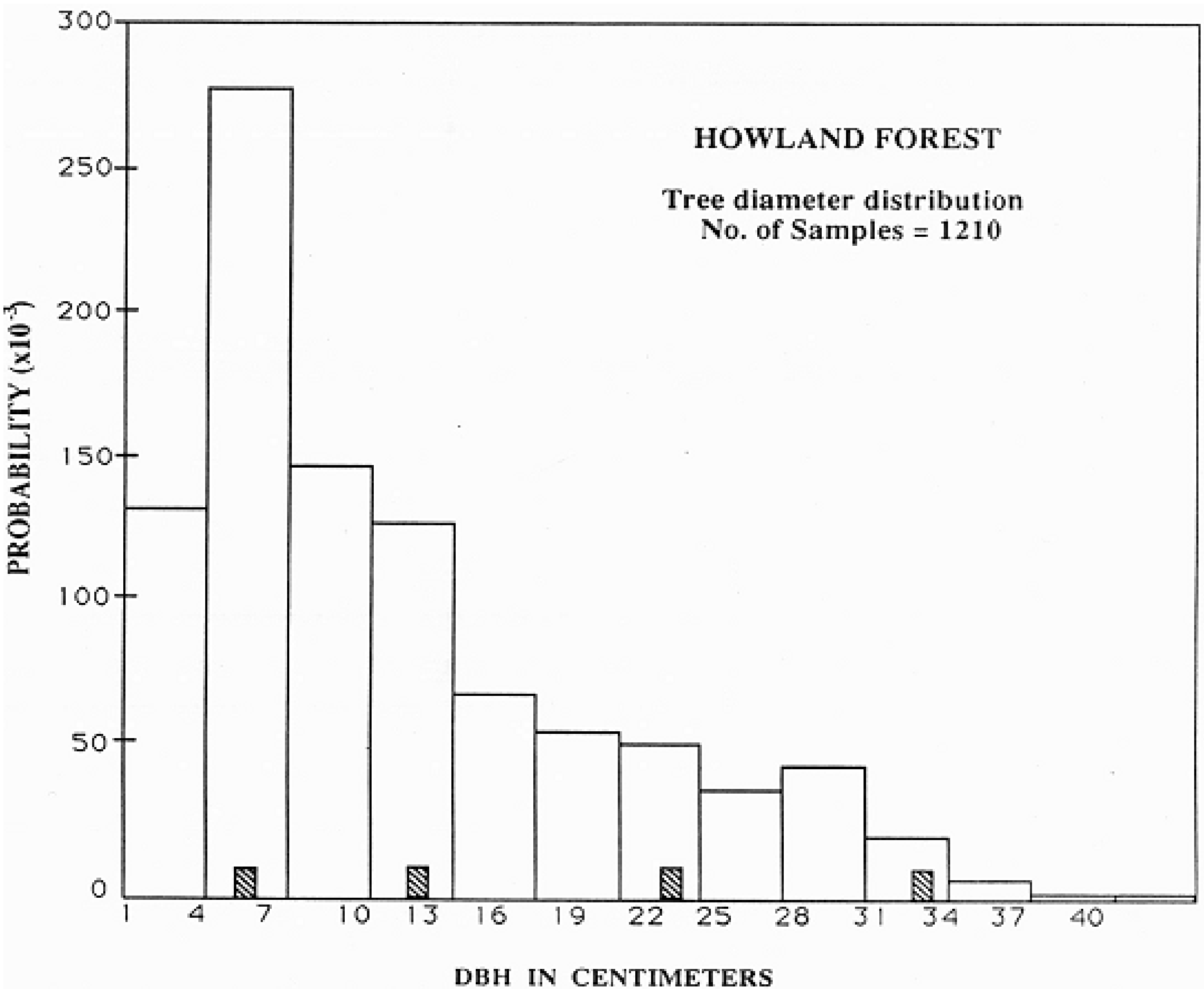
Sampling Strategy
(200m by 200m plot)



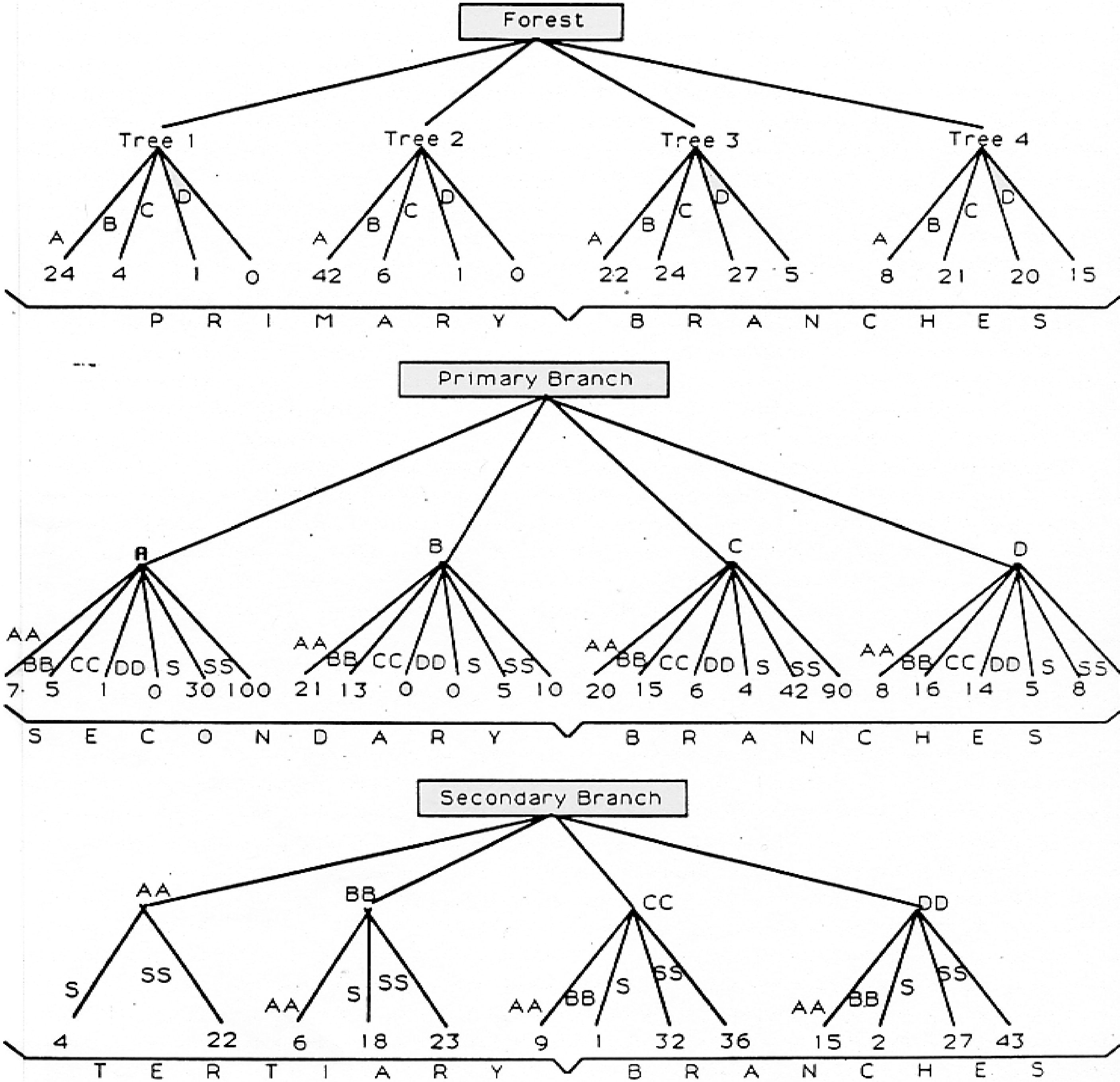

HOWLAND FOREST
No. of Sample 1210
Hemlock 75%
BRC - BIRCH
CDR - CEDAR
FIR - FIR
HML - HEMLOCK
MPL - MAPLE
SPR - SPRUCE
NUMBER OF TREES
800
700
600
500
400
300
200
100
0
BRC
CDR
FIR
HML
MPL
SPR
TREE TYPE


Hemlock-Spruce Forest
Howland, Maine (August, 1989)
Tree Height in Meters
Dbh in Centimeters
0
5
10
15
20
25
30
35
40
45
50
S
H

DBH Distribution of Trunks



BRANCH DISTRIBUTION COMPUTATION



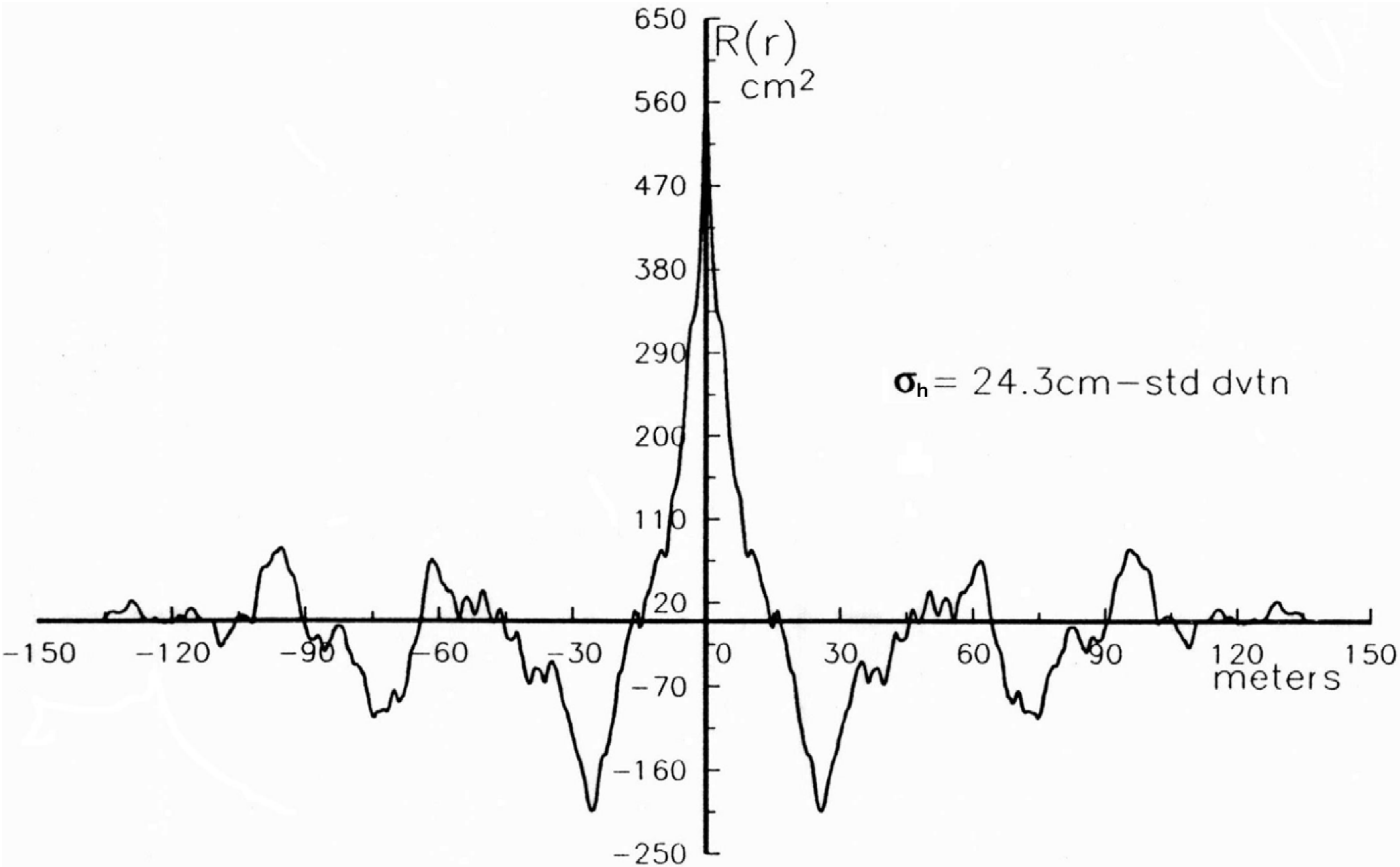
Model Trunk and Branch Sizes

BRANCH AND TREE PARAMETERS

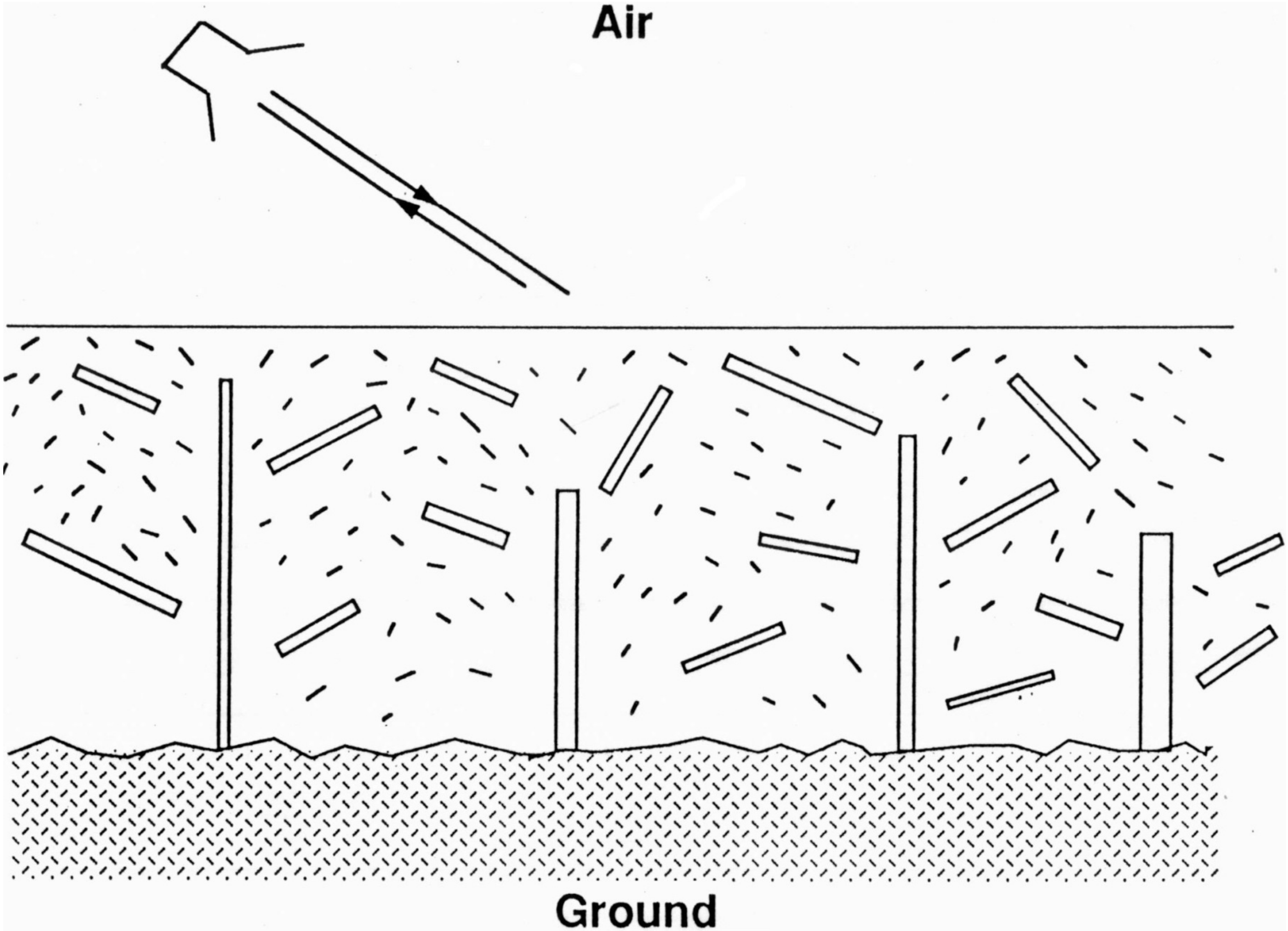
Branch Type	Dia. (cm)	Length (cm)	Probability
AA	0.2	15	0.86684
BB	0.4	30	0.10312
CC	0.6	40	0.01605
DD	0.8	75	0.00619
A	1.1	90	0.00481
B	2.4	165	0.00154
C	3.0	260	0.00119
D	3.5	350	0.00025

Trunk Type	Dia. (cm)	Length (cm)	Probability
T1	5.4	430	0.529
T2	10.9	915	0.255
T3	19.4	1390	0.148
T4	27.7	1460	0.068

Surface Correlation Function



Hemlock Forest Model



Bistatic Scattering Coefficients
Distorted Born Approx.

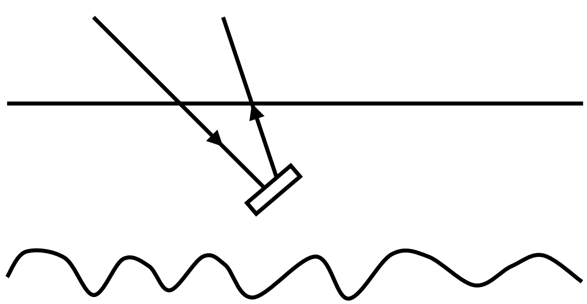
$$\sigma^{o} = \sigma^{o}_{d} + \sigma^{o}_{dr} + \sigma^{o}_{drf} + \sigma^{o}_{s}$$

where

$$\sigma^{o}_{d} = \left(\sum_{i} \rho_{i} d\sigma^{(i)}_{d} \right) \left[\frac{1 - e^{-2\tau}}{2\tau} \right] \quad \text{direct or volume scatter}$$

and

$$\tau = \sum_{i} \rho_{i} d\sigma^{(i)}_{d} \sec\theta_{i}$$



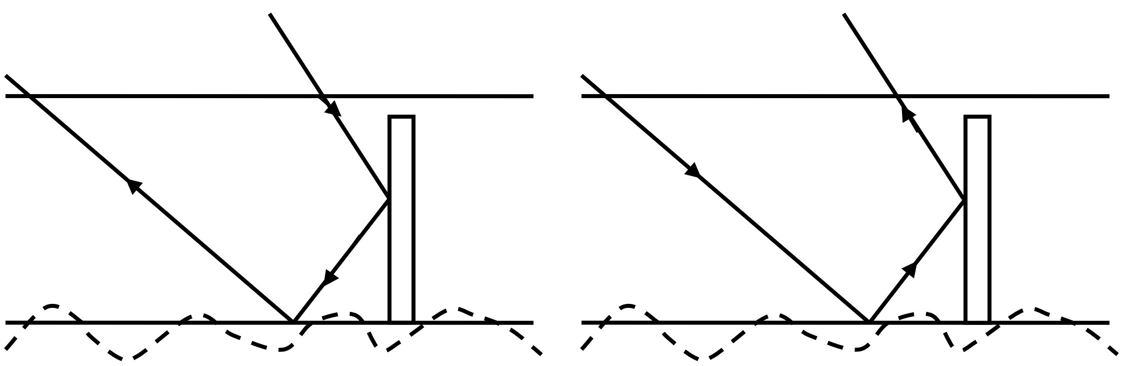
Direct-Reflected (Average Surface)

interference or double bounce

$$\sigma^{\mathrm{o}}_{\mathrm{dr}} = \sum_i \rho_i \mathrm{d}\sigma^{(i)}_{\mathrm{dr}} \mathrm{R_g} e^{-2\tau} \left[2 + 2 * U(bs + sp)\right]$$

$\sigma^{(i)}_{\mathrm{dr}}$ - bistatic scattering X section

$\mathrm{R_g}$ - average reflectivity of the surface



$$\mathrm{R_g} = \left|\Gamma_g\right|^2 e^{-(2k\sigma_h \cos\theta_o)^2}$$

Γ_g - Fresnel reflection coefficient of the ground

Directed-Reflected (Surface Fluctuations)

$$\sigma^{o}_{\text{drf}} = \sigma^{++} + \sigma^{+-} + (\sigma^{-+} + \sigma^{--})U\{bs + sp\}$$

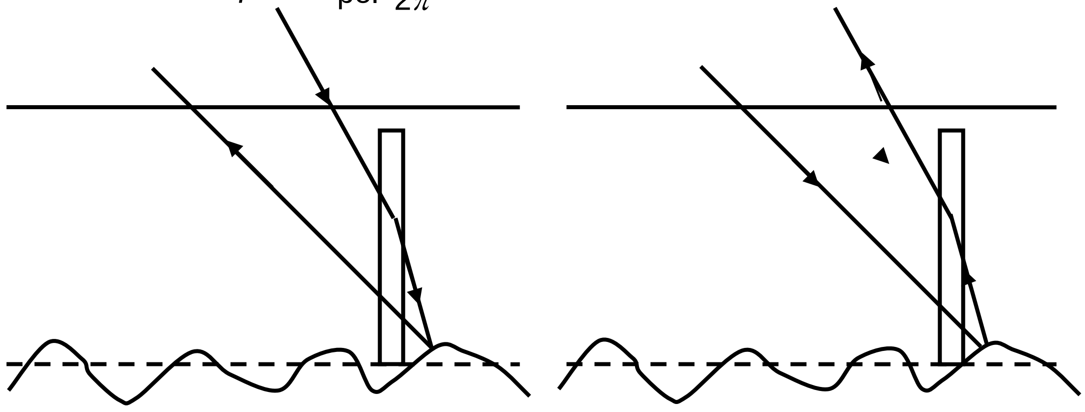
$$\left\langle \left(\text{v}^{+} + \text{v}^{-}\right)\left(\text{v}^{+*} + \text{v}^{-*}\right)\right\rangle$$

σ^{++}, σ^{--} - incoherent(transport) terms

σ^{+-}, σ^{-+} - coherent terms

Typical term

$$\sigma^{++} = \sum_i \rho_i \sum_{\text{pol}} \int_{2\pi} \text{d}\Omega\, \sigma_{\text{scat}} \sigma^{o}_{\text{surf}} e^{i\psi}$$

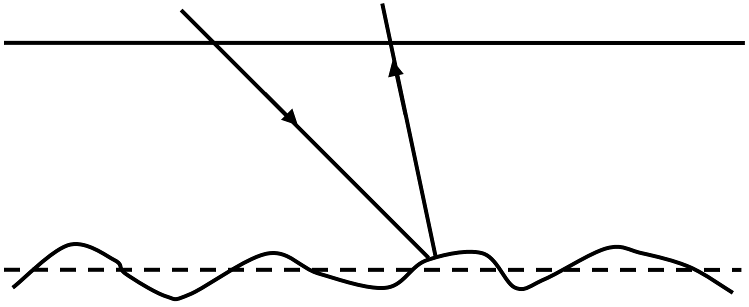


Non-specular scatter from surface

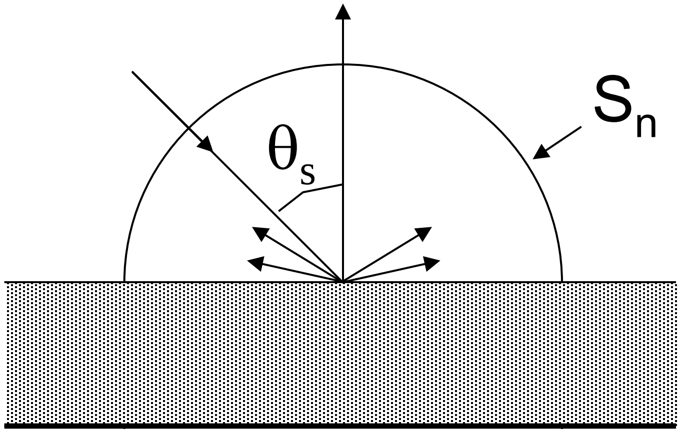
Surface Scatter

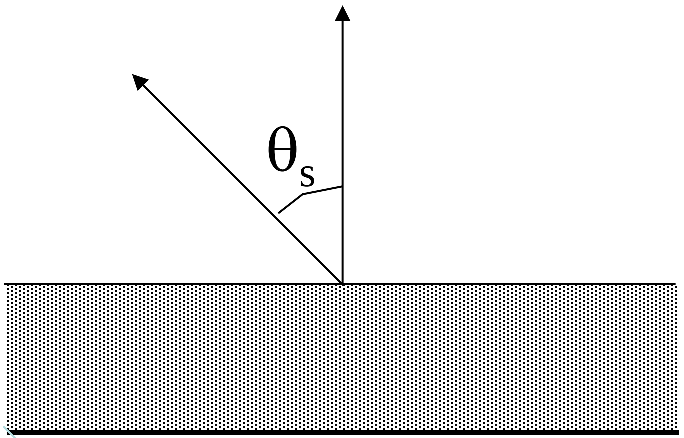
$$\sigma_s^o = \sigma_s^{(Kir)} e^{-2\tau}$$

$\sigma_s^{(Kir)}$ - **Kirchhoff rough surface scattering coefficient**



Peake's Principle





$$W_q^{diff} = \int_{S_n} (\sigma_{qh} + \sigma_{qv}) d\Omega$$

: surface albedo

$$\alpha_q = 1 - W_q^{diff} - W_q^{spec}$$

:absorbtion coefficient

$$e_q = \alpha_q$$

$$T_q = e_q T$$

Howland Forest Model Parameters

- **Layer Thickness = 15 m**
- **Moisture of Scatterers**

  MG(Needles & Sec-Brch) = 50%

  MG(Pri-Brch) = 25%

  MG(Trunks) = 50%
- **Surface Parameters**

  S.D. = 0.24 m

  Correlation Length = 1.0 m

  MV = 30%

Howland Helmlock Attenuation

	P-Band		L-Band		C-Band	
	H	V	H	V	H	V
Needles	3.2	4.5	5.6	7.9	19.8	27.4
Secondary Branches	0.5	0.8	1.2	1.6	7.1	9.7
Primary Branches	5.9	4.9	10.7	9.1	9.8	9.3
Trunks	3.7	8.8	4.2	6.2	4.2	4.6
Total	13.3	19.0	21.7	24.8	40.9	51.0

NASA/JPL AIRSAR

Frequencies 440MHz (P band), 1.25GHz (L band), 5.00 GHz (C band)

Polarizations HH, VV, HV and phase

Ground Resolution – 30 meters (1989-90)

NASA P3 Aircraft

Push Broom Microwave Radiometer (PBMR)

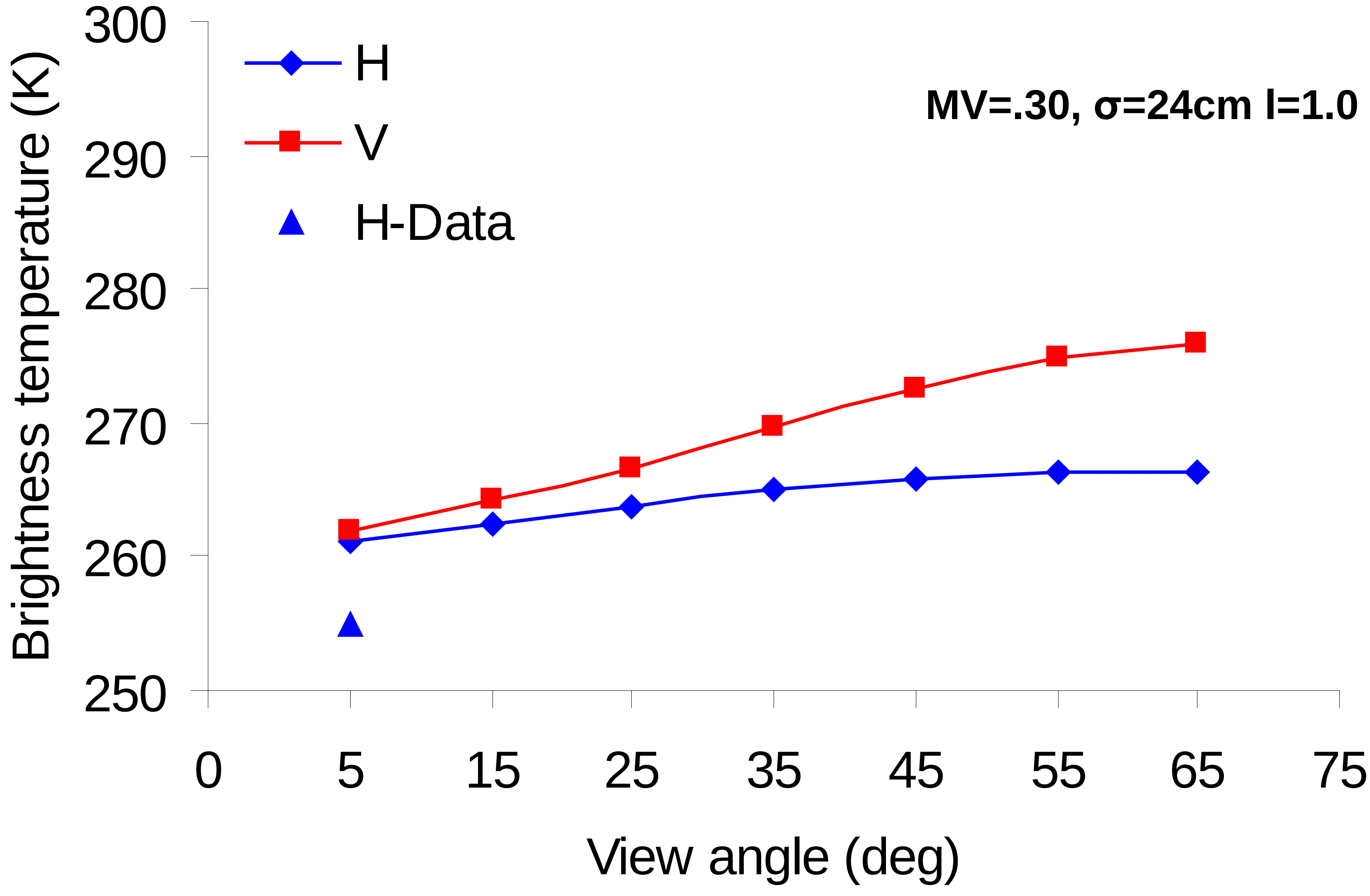
H-POL 1.43 GHz

Model and Experiment Comparison

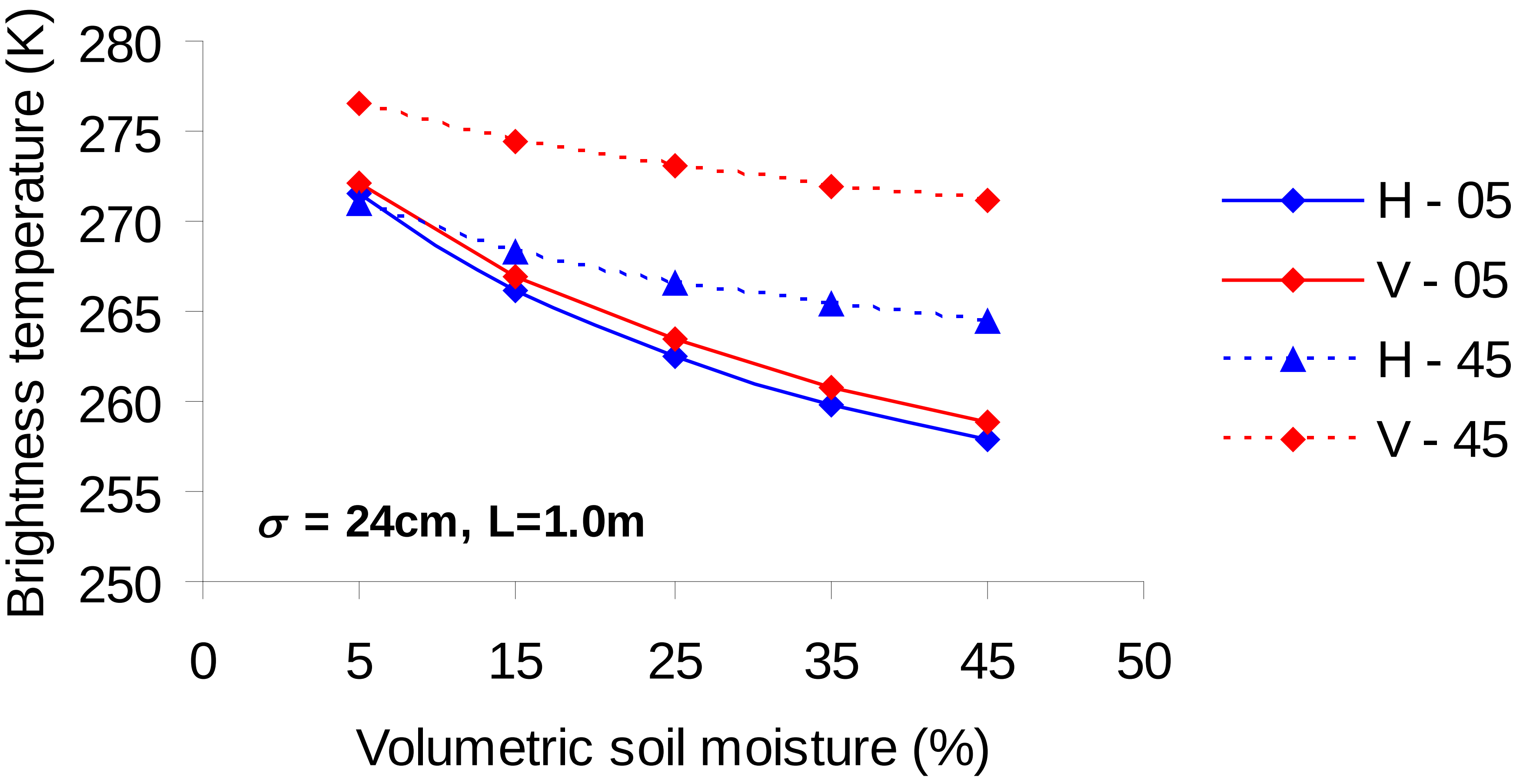
L-Band Radar (1.25 GHz)	HH	VV	HV
Experiment (dB)	-8.4	-9.0	-13.4
Theory (dB)	-8.3	-8.7	-15.4

L-Band Radiometer (1.43 GHz)	H	V
Experiment (K)	255	***
Theory (K)	261	262

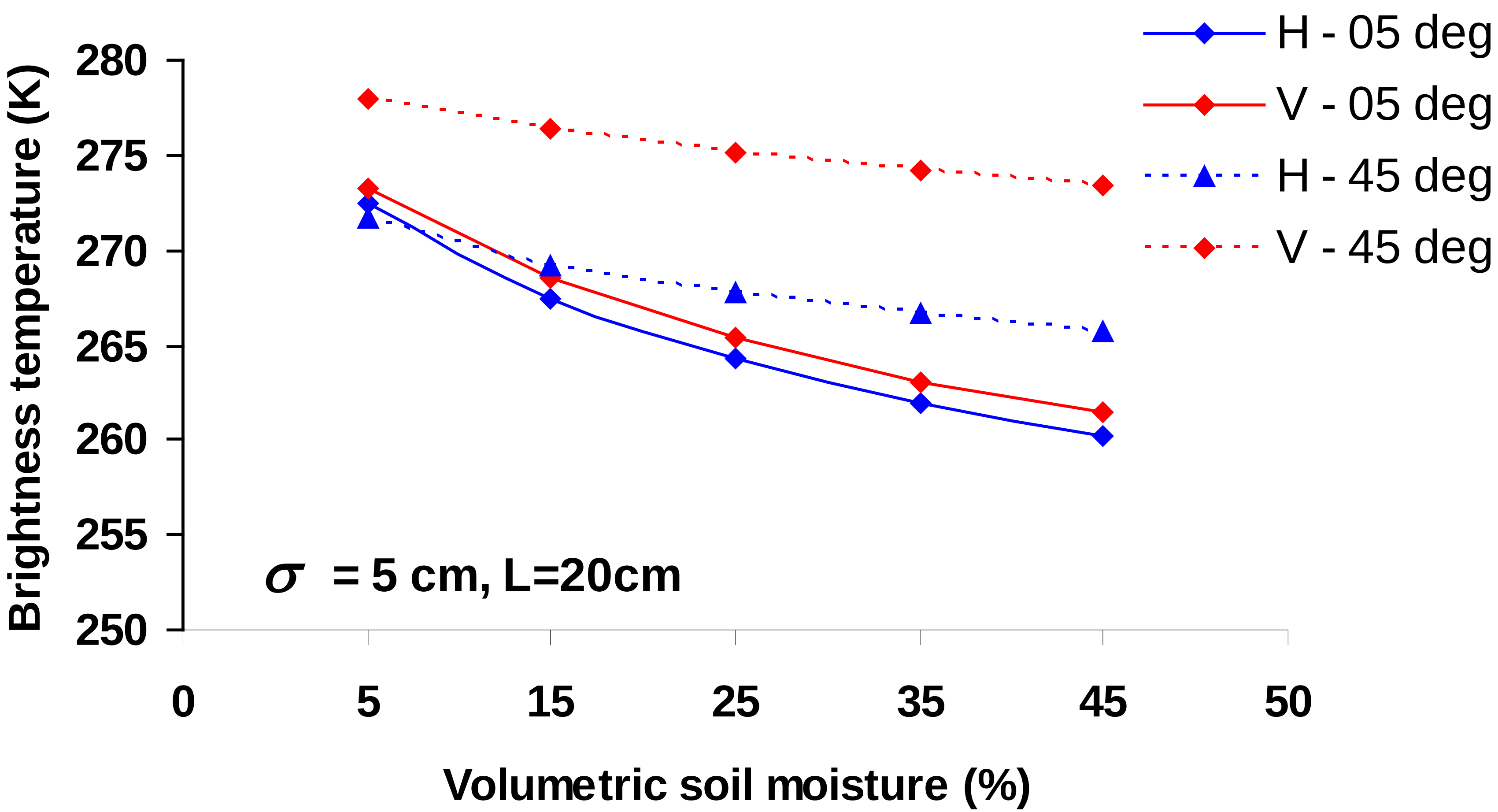
Brightness Temperature vs View Angle



Brightness Temperature vs Soil Moisture



Brightness Temperature vs Soil Moisture



ESTAR and Model Brightness Temperatures over Forests: Effects of Soil Moisture

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NOAA, NPOESS Integrated Program Office

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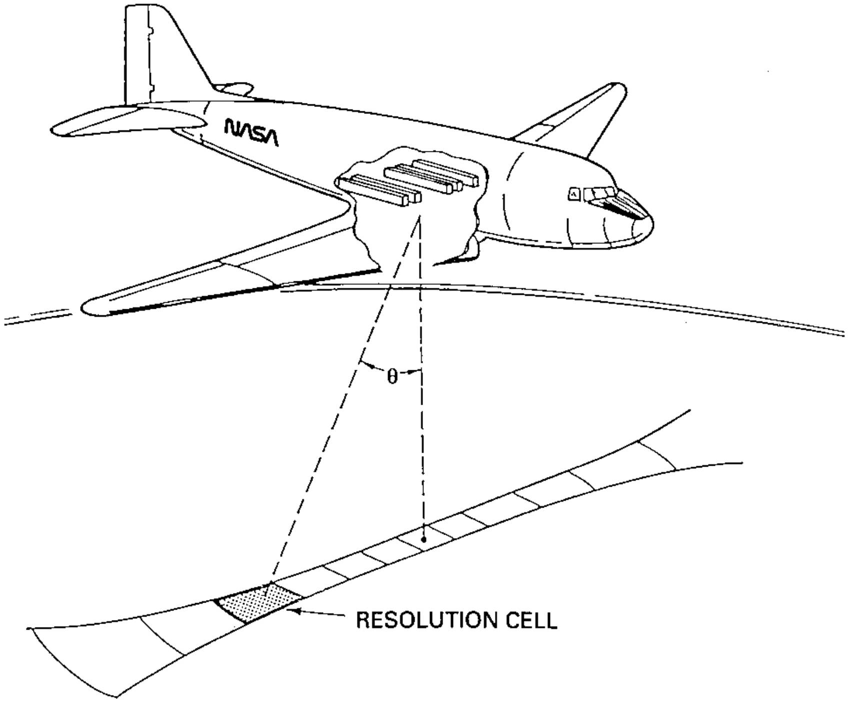
Outline

- Site Description and Instrumentation
- Ground Truth Data
- Model Description
- Inversion Results

ESTAR

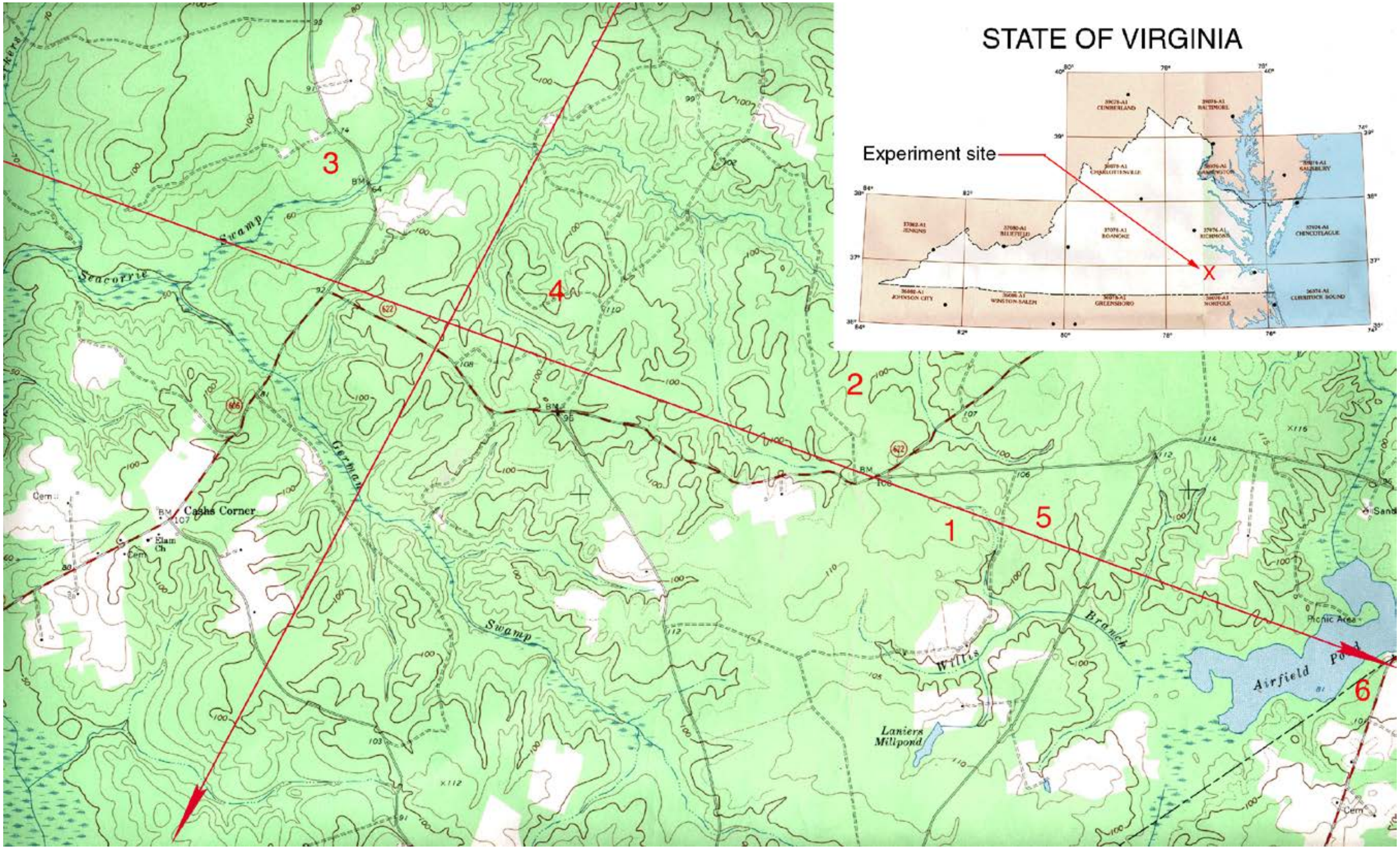


Frequency : L-band (1.4 GHz)
Polarization : Horizontal
Imaging
  Along Track : Real Aperature
  Cross Track : Synthetic Aperature
Sensitivity : 0.5 K
Resolution : ± 4 degrees (nadir)

Site Description

- Location : South Eastern Virginia
- Forest Region : Loblolly Pine, owned by International Paper
- Stands : Uniform on mostly flat ground, 1-2 km on one side
- Stand Age : Varies from 2-40 years with some older sites

Topographic Map of Waverly Site



Sites of various ages in Waverly

Two year old trees at site # 1

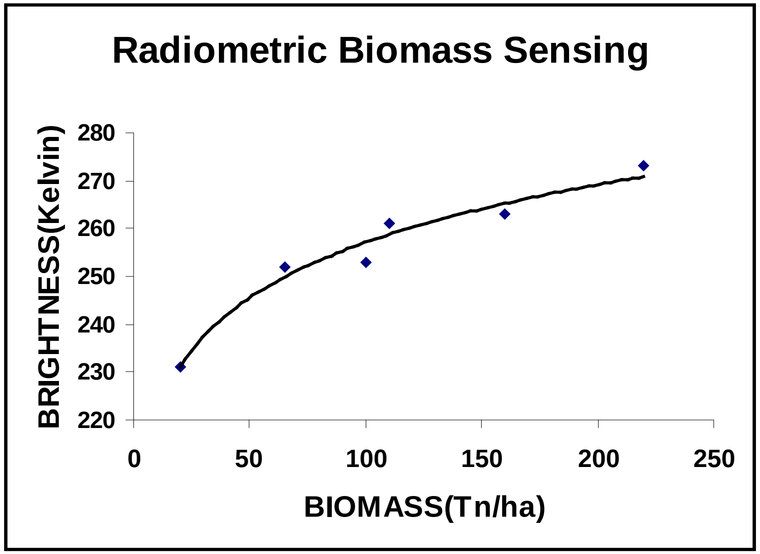
Seven year old trees at site # 2

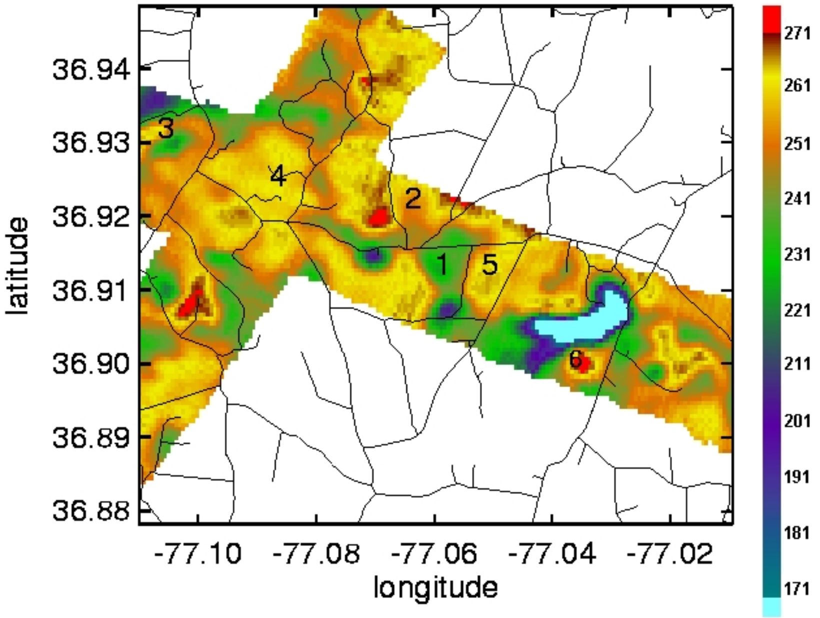
Eighteen year old trees at site # 5

Huge old trees at site # 6

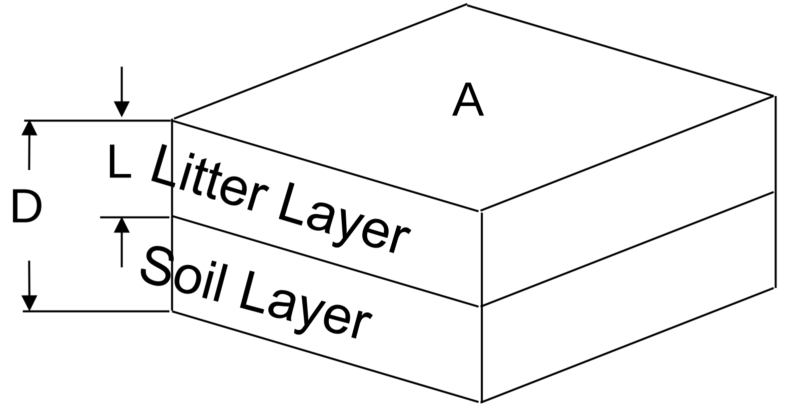
Waverly Virginia Forest Stand Statistics and Brightness Temperatures

SITE	AGE (Years)	AREA (Acres)	TERRAIN	SOIL TYPE	BIOMASS (Tons/ha)	T_B (^{o} K)	σ_T (^{o} K)
1	2	167	Flat	B	20.0	231	5
2	7	120	Flat	B	66.1	252	2.6
3	11	133	Flat	A	103.3	253	2
4	12	404	Hilly	C	113.3	261	1
5	18	141	Flat	B	161.2	263	1.3
6	70+	50	Flat	B	220+	273	4
A-Poorly drained sandy loam, B-Moderately well drained sandy loam, C-Well drained loamy sand							





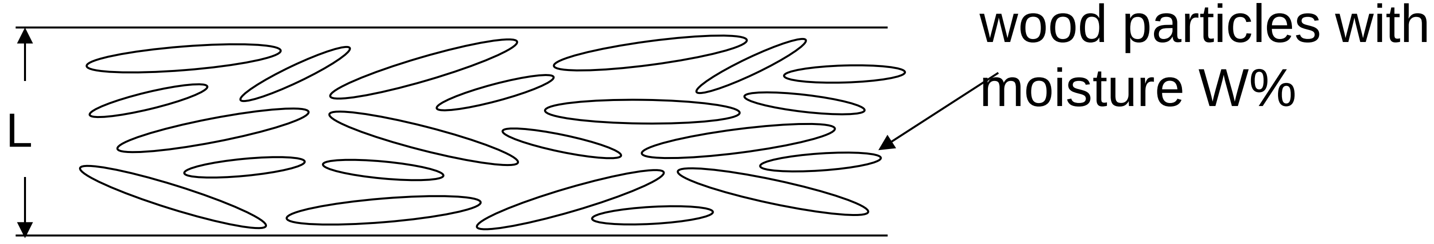
Soil Moisture Measurements



- Forest floor consisted of an organic litter layer over sandy loam.
- At each site, the wet and dry weights of the litter and soil layers were measured. 'A' is the sample area.
- Volume of litter and soil samples were measured. All samples had D = 5 cm.
- 10 sites were measured for each overflight.

Modeling the Litter Layer

- Litter is an organic layer composed mostly of needles (some bark and decomposed branches).
- Litter layer is modeled by a dense distribution of randomly oriented needle shaped wood particles with moisture.



Particle and Macroscopic Dielectric Constants of Litter

Dielectric Constant of Moist Wood Particles vs. dry wood density ρ_w (T = 20° C, F = 1.4 GHz)

$W(\%)$ \ ρ_w	20	60	100	140
0.3	**2.44 + i0.23**	**4.37 + i0.59**	**8.18 + i1.02**	**12.06 + i0.98**
0.4	**2.92 + i0.36**	**5.71 + i1.03**	**10.80 + i1.81**	**15.85 + i1.71**
0.5	**3.40 + i0.53**	**6.97 + i1.57**	**13.38 + i2.80**	**19.75 + i2.66**

Macroscopic Dielectric Constant of Litter vs. fractional volume v_f ($\rho_w = 0.4$ g/cm^3)

$W(\%)$ \ V_f	20	60	100	140
0.3	**1.45 + i0.07**	**1.95 + i0.18**	**2.78 + i0.29**	**3.58 + i0.27**
0.4	**1.62 + i0.10**	**2.37 + i0.26**	**3.62 + i0.44**	**4.83 + i0.41**
0.5	**1.81 + i0.14**	**2.83 + i0.36**	**4.58 + i0.61**	**6.29 + i0.57**

Dielectric Constant of Soil

- Calculated using the Dobson formula, IEEE GRS-23, p. 35-46, 1985
- Soil consists of dry rock particles, air, bound H_2O and free H_2O

$$\varepsilon_s = \varepsilon_s(T, f, m_g\%, \rho_{bs})$$

$m_g(\%)$: gravimetric soil moisture
ρ_{bs} : soil bulk density
T = temperature
f = frequency

Dielectric Constant of Soil (T = 20° C, F = 1.4 GHz, ρ_{bs} **= 1.1 g/cm³**)

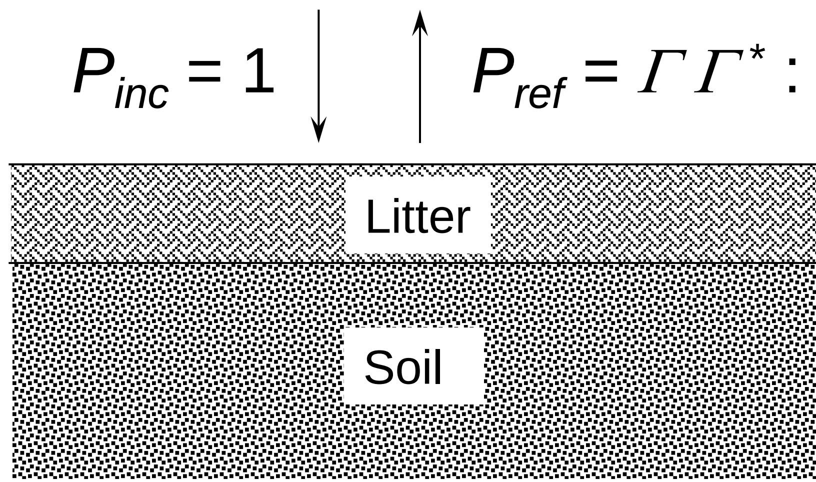
$m_g(\%)$	10	20	30	40
ε_s	**5.54 + i0.80**	**10.50 + i1.34**	**16.94 + i1.99**	**24.77 + i2.73**

Reflectivity from Forest Surface

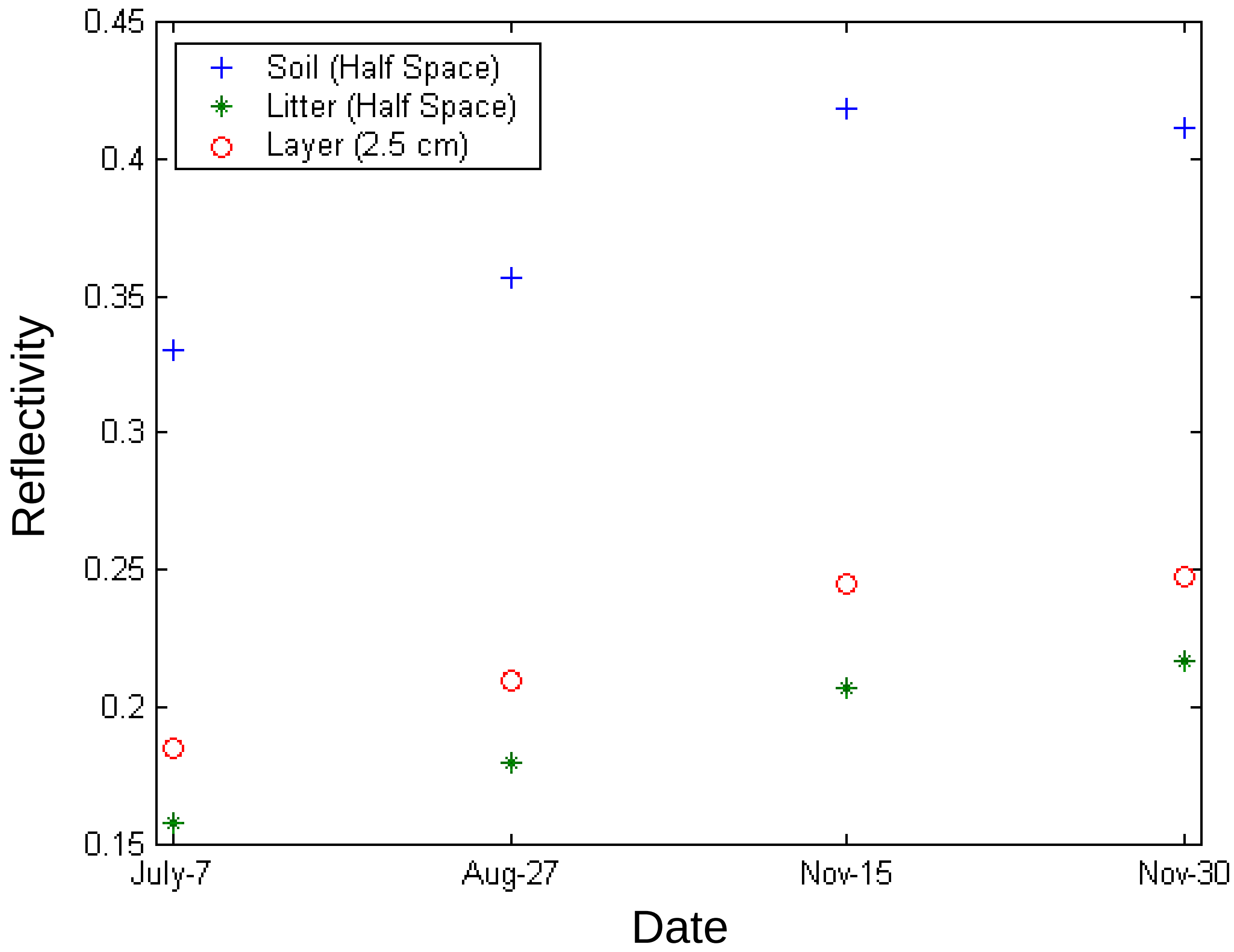
Table: Layer Moistures and Permittivities (v_f = 0.54, ρ_{bs} = 1.1 g/cm^3)

		July – 7	Aug. – 27	Nov. – 15	Nov. – 30
Litter	***W*** **(%)**	53	107	126	133
	ε_{LT}	5.25 + i0.92	6.0 + i0.93	7.05 + i0.92	7.44 + i0.89
Soil	m_g**(%)**	25	28	36	35
	ε_s	13.54 + i1.65	15.54 + i1.85	21.48 + i2.42	20.69 + i2.35

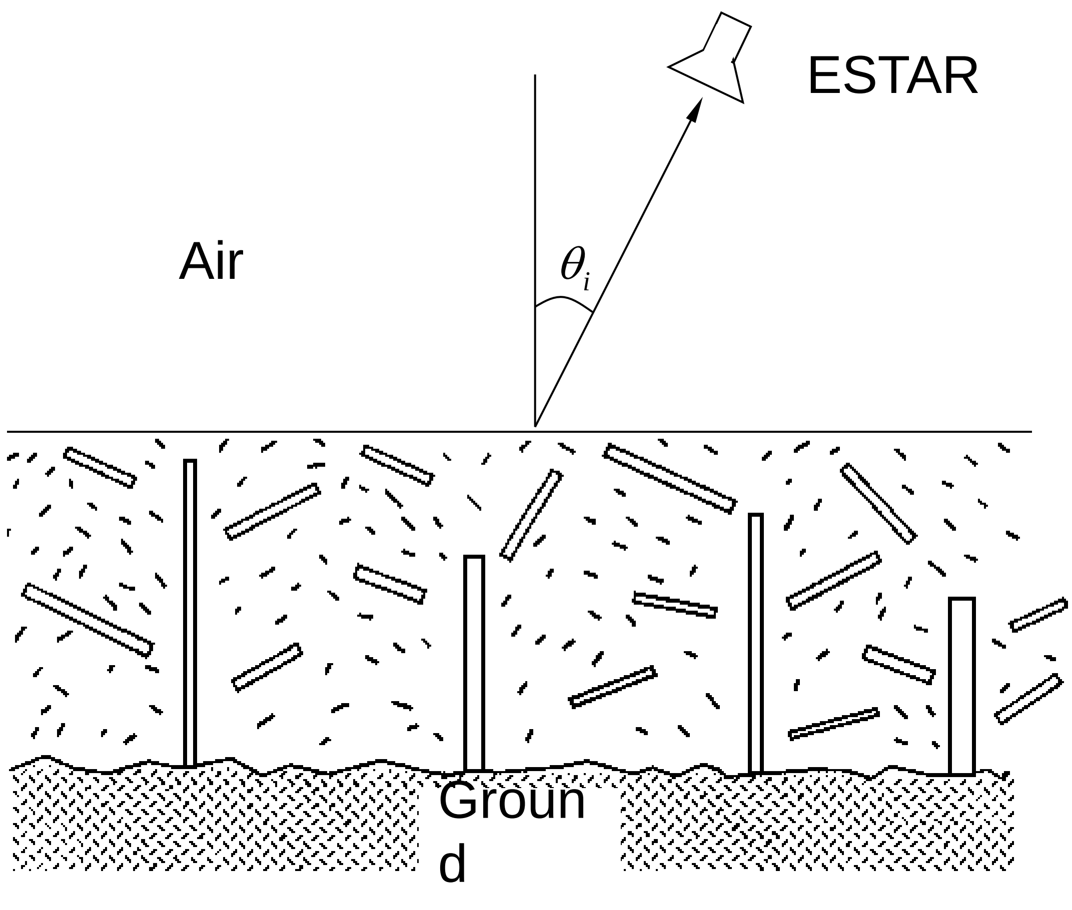
$P_{inc} = 1$ $\quad$ $P_{ref} = \Gamma\,\Gamma^*$: *reflectivity*



Reflectivity of Forest Surface (continued)

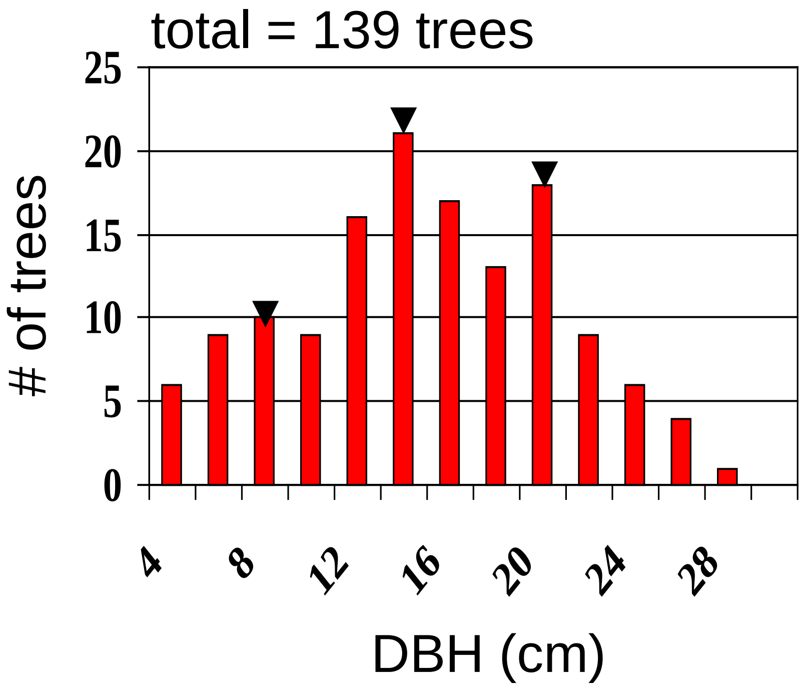


Forest Model

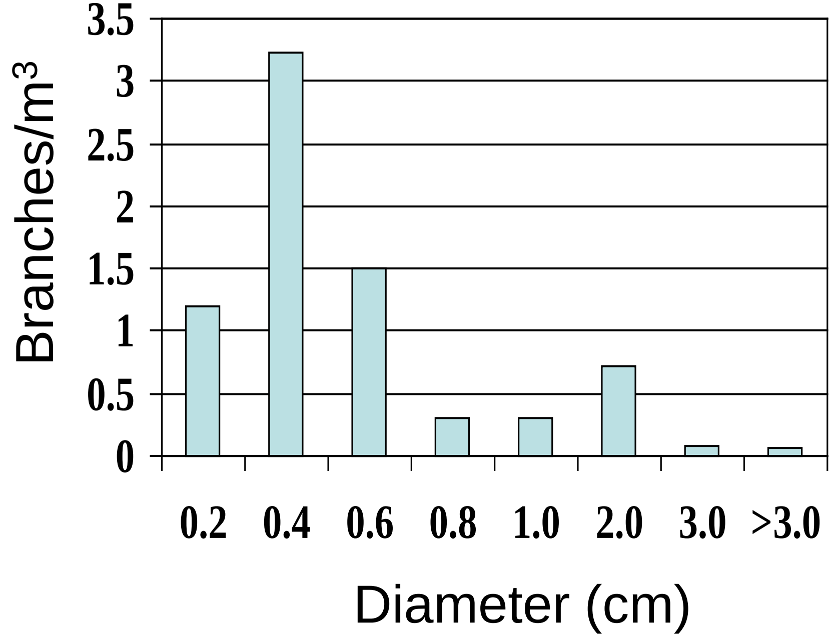


Tree Architecture

DBH Distribution



Branch Distribution



Average stem density = 0.186 stems/m^2

Model Parameters

- Dielectric Constants

    Trunks and Branches : ε_r = 10.5 + i3.0

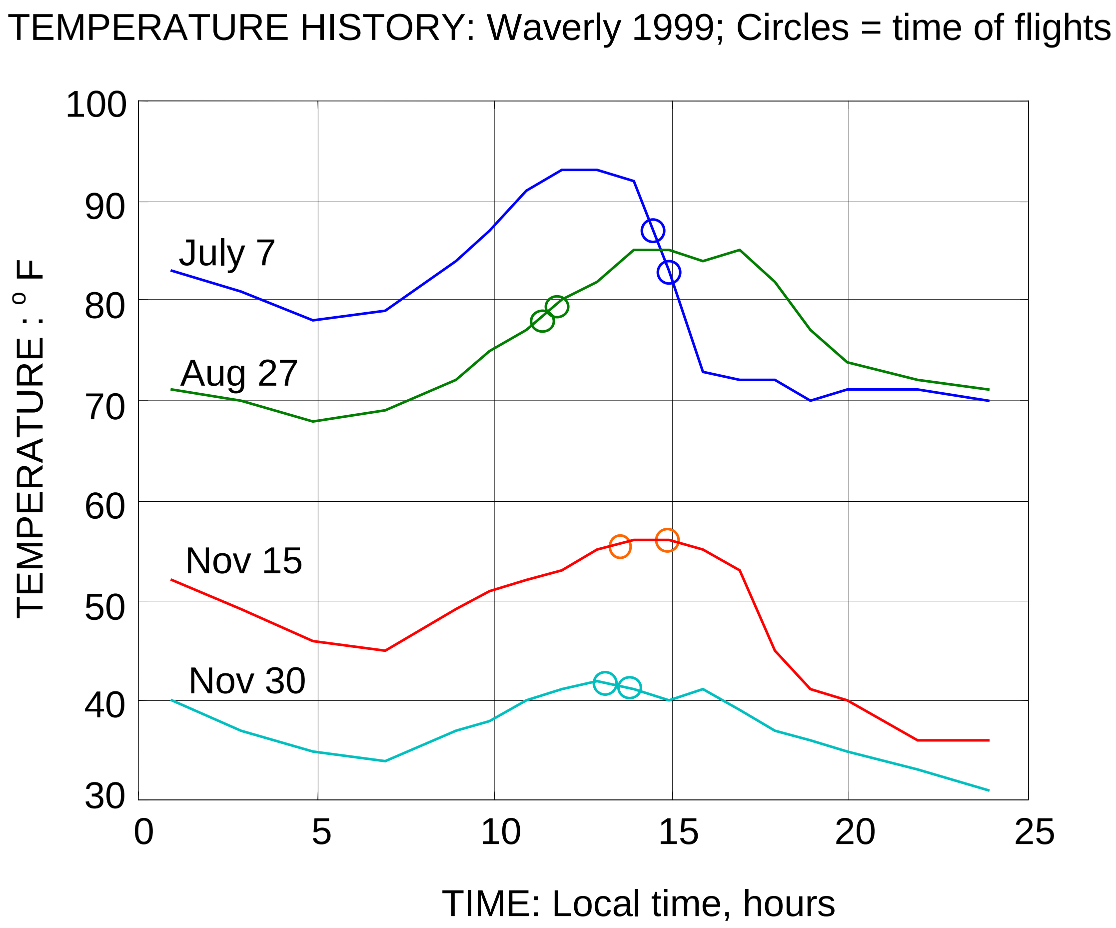
    Needles : ε_r = 20.7 + i7.0

- Surface Properties

    RMS height : σ = 3.0 cm

    Correlation Length : ℓ = 100.0 cm

Wakefield Temperature History on the Dates of Flights in 1999



Measured Brightness Temperatures for APR and APM sites

	July 7	Aug. 27	Nov. 15	Nov. 30
APR (2-year old stands)	265.5	252.0	233.0	235.0
APM (18-year old stands)	281.2	272.0	263.0	262.0
Wakefield Temperatures	302.4	299.1	286.3	276.3
Ground Truth Temperatures	N/A	N/A	N/A	284.5

Brightness Temperature depends on stand age.

Maximum change in brightness temperature between July and November is higher for APR.

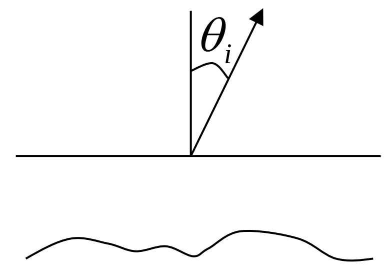
This indicates the higher visibility of soil moisture through smaller trees.

The Relation between Brightness Temperature, Physical Temperature and Soil Moisture

$$T_B = (1 - w)T$$

where

$$w = w^{diff} + w^{spec}$$



with

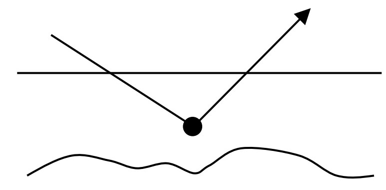
$$w^{spec} = \left|R_g\right|^2 e^{-2\tau} e^{-4k_o^2 s^2 \cos^2\theta_i}$$

$$w^{diff} = \frac{1}{4\pi\cos\theta_i}\int_{4\pi}\left[\sigma_{hh}^{o}(\underline{o},\underline{i}) + \sigma_{vh}^{o}(\underline{o},\underline{i})\right]d\Omega_s$$

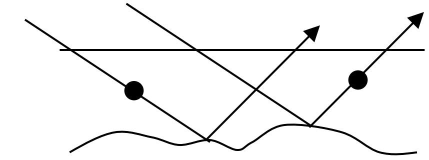
Bistatic Scattering Coefficients

$$\sigma_{pq} = \sigma_{pqd} + \sigma_{pqdr} + \sigma_{pqs}$$

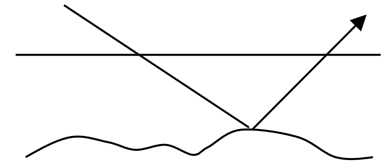
d : direct or volume scatter



dr : direct reflected or double bounce

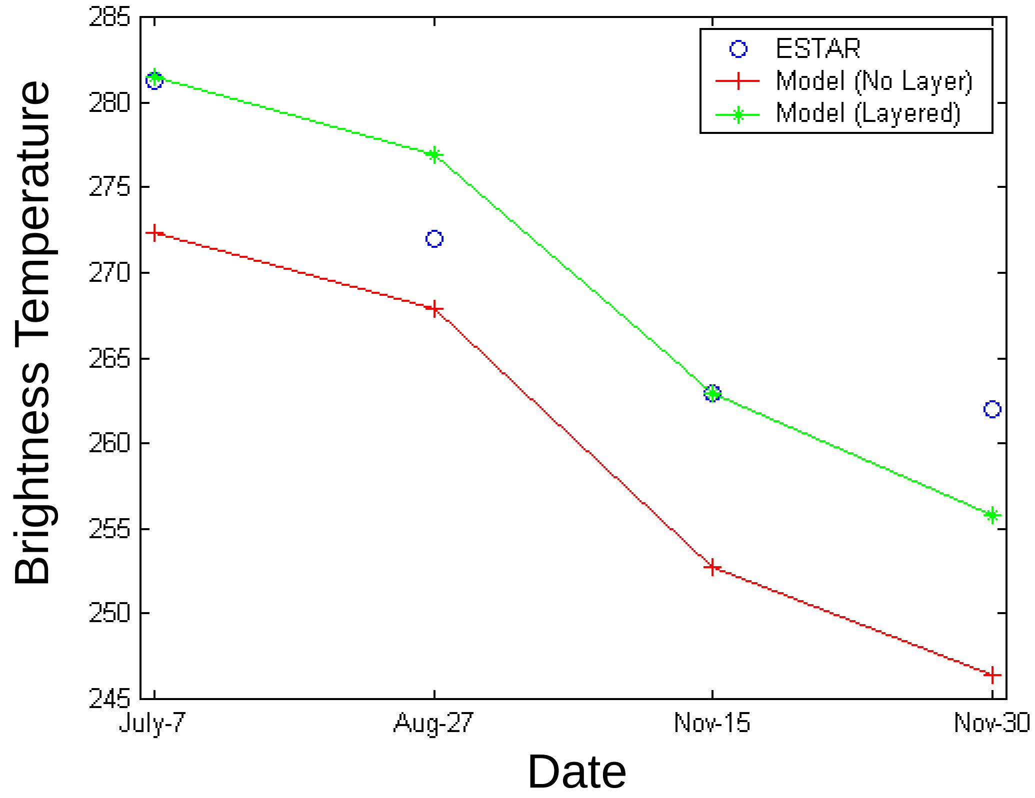


s : surface scatter



□: two way attenuation coefficient

Comparison of Model Results with ESTAR Data



Note : Brightness temperatures averaged over litter layers of 0.5 cm to 5 cm in 0.5 cm increments.

Microwave Soil Moisture Retrieval Under Trees

Peggy O'Neill, Alicia Joseph
NASA / GSFC

Roger Lang, Mehmet Kurum
George Washington University

Michael Cosh, Thomas Jackson
USDA / ARS

ComRAD – Combined radar / radiometer instrument system

Frequency: 1.403-1.424 GHz L radiometers;
1.25, 4.75, and 10 GHz radars

Polarization: dual pol radiometers (LH and LV)
quad pol L, C radars, and XH radar

Antenna: 1.22 m parabolic dish w/broadband feed

Incidence Angle Range: 0° - 175°

Azimuth Angle Range: 0° - 120° autonomous
0° - 360° manual

Platform: 19-m hydraulic boom truck

Power: standard AC line power or self-contained generator

Collaborators: Roger Lang, George Washington U.
Tom Jackson, USDA-ARS
Mark Spicknall, UMD CMREC

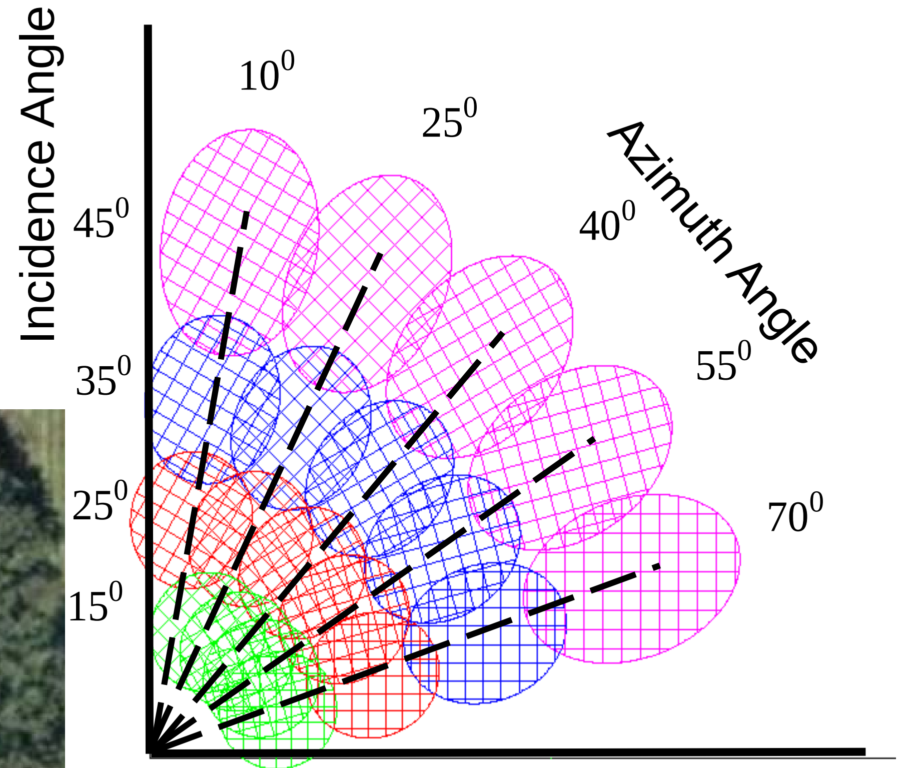
Research use: primarily used in soil moisture algorithm development; can serve as Aquarius, SMAP (active/passive) and SMOS (multi-angle) ground-based simulators

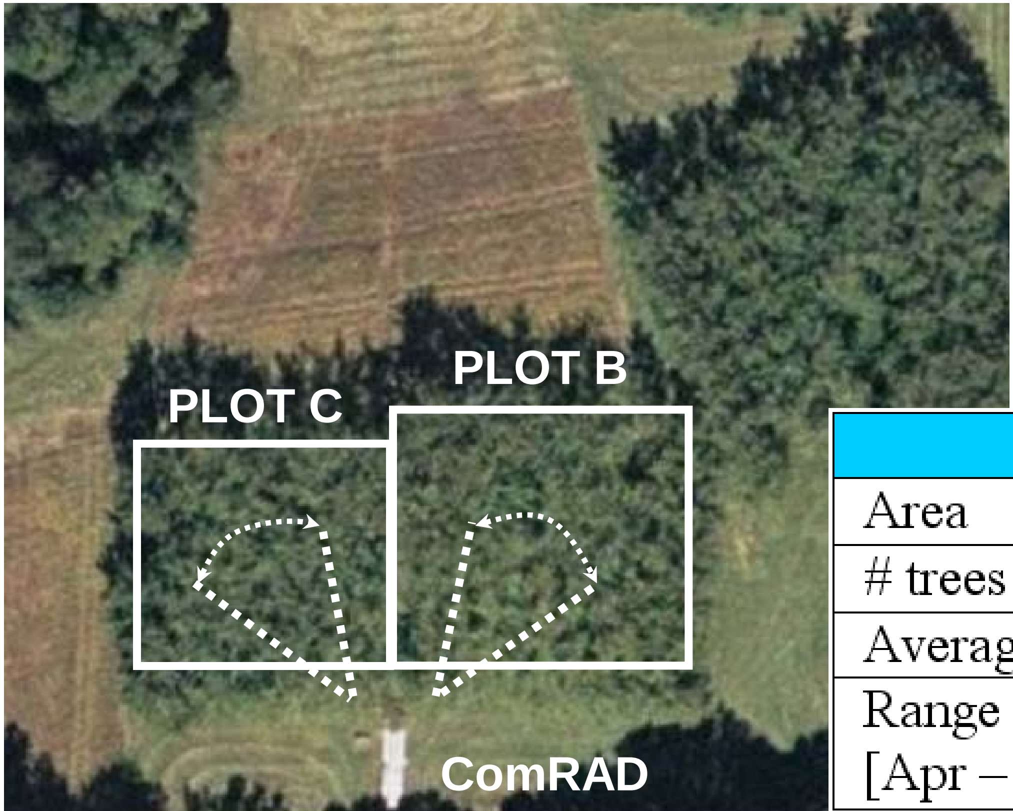
Instruments: dual-pol total power radiometer
vector network analyzer-based quad-pol radars
CropScan visible/infrared radiometer


ComRAD Tree Experiment – APEX '07:
Deciduous Trees

Radiometer Measurement Setup

The truck boom is rotated in a conical scan arrangement with a 15 degree increment to get an average response over trees.





	Plot B	Plot C
Area	33 x 33 m	28 x 28 m
# trees in plot	92	92
Average DBH (cm)	19.4	18.2
Range in VSM (%) [Apr – Nov, 2007]	30 – 45	33 – 44

Tree Destructive Sampling

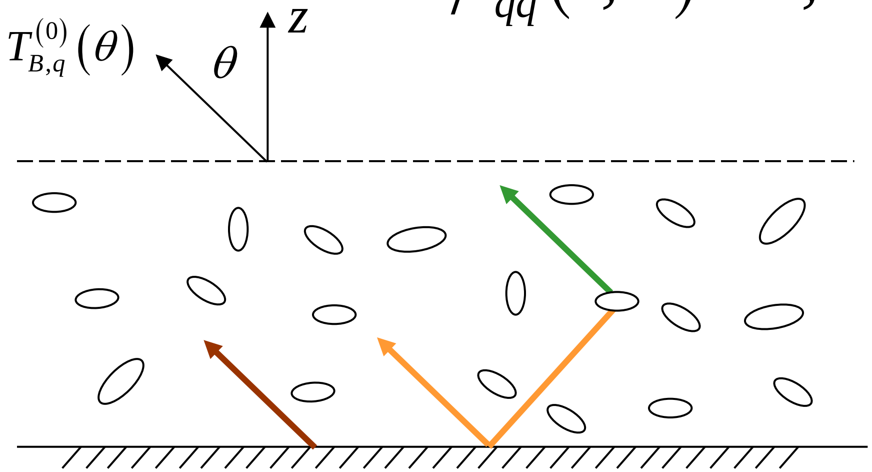


Type	Count	Avg Radius cm	Avg Length cm	dry biomass density	Avg Inclination Angle (up = 0)
Trunk	1	8.73	617.00	0.3938	vertical
Primary-1	1	4.80	171.00	0.7032	Uniform 05-15
Primary-2	1	3.84	12.00	1.2750	Uniform 10-30
Primary-3	1	4.22	245.00	1.0917	Uniform 00-10
Secondary -1	248	0.32	17.95	0.4675	Uniform 20-50
Secondary -2	67	0.41	52.93	0.5079	Uniform 20-50
Secondary -3	9	0.46	94.33	0.4065	Uniform 10-40
Secondary -4	26	0.60	27.31	0.3935	Uniform 35-55
Secondary -5	67	0.64	59.25	0.4248	Uniform 30-50
Secondary -6	53	0.71	114.81	0.5813	Uniform 35-55
Secondary -7	3	1.28	14.33	0.3302	Uniform 35-55
Secondary -8	10	1.30	66.20	0.3665	Uniform 20-40
Secondary -9	34	1.58	153.79	0.5070	Uniform 30-50
Type	Count	leaf area cm2	Leaf Thickness cm	dry biomass density	Avg Inclination Angle (up = 0)
Leaf	2014	324.90	0.28	0.2561	Uniform 0-360

Detailed measurements of size/angle distributions of the tree constituents (trunk, branches, and leaves), water content and dry biomass.

Emission from a Layer of Non-Spherical Particles **in the Absence of Scattering**

$$\psi_{qq}(\hat{s},\hat{s}')=0, \quad and \quad \psi_{pq}(\hat{s},\hat{s}')=0$$



q	: Polarization (h or v)
$\gamma_q(\theta)$	: Transmissivity
$R_{G,q}(\theta)$	: Reflectivity of the Ground
$\omega_{s,q}$	: Single Scattering Albedo
$T_{G,phys}$	: Ground Ambient Temperature
$T_{P,phys}$	: Particle Ambient Temperature

Zeroth Order Solution (*tau-omega model*)

$$T_{B,q}^{(0)}(\theta)=\gamma_q(\theta)\left[1-R_{G,q}(\theta)\right]T_{G,phys}$$

Ground Emission

$$+\left[1-\gamma_q(\theta)\right]\left[1-\omega_{s,q}\right]T_{P,phys}$$

Up-welling Emission From Layer

$$+\gamma_q(\theta)R_{G,q}(\theta)\left[1-\gamma_q(\theta)\right]\left[1-\omega_{s,q}\right]T_{P,phys}$$

Down-welling Emission From Layer Reflected by Ground

VEGETATION EMISSION MODELS

1 Zeroth Order Solution
(*tau-omega model*)

$$e_q^{(0)} = \left[1 - R_{G,q}(\theta)\gamma_q^2(\theta)\right] - \underbrace{\omega_{s,q}\left[1 - \gamma_q(\theta)\right]\left[1 + R_{G,q}(\theta)\gamma_q^2(\theta)\right]}_{\text{Reduction Due to Albedo}}$$

Reduction Due to Albedo

2 *Simplified Zeroth Order Solution*

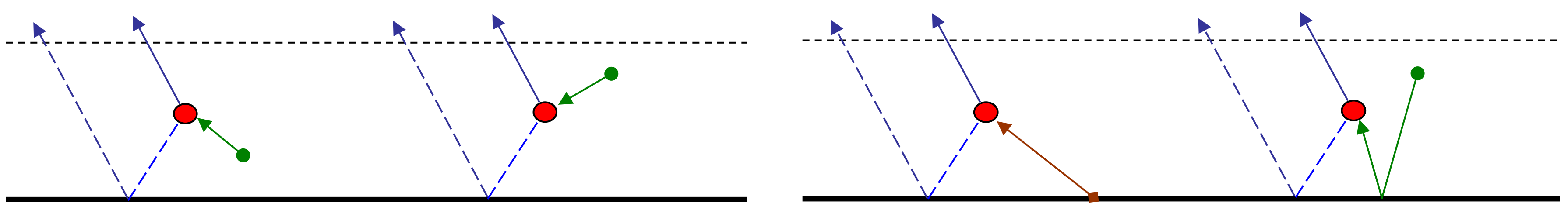
$$e_q^{(S0)} \sim \left[1 - R_{G,q}(\theta)\gamma_q^2\right]$$

3 First Order Solution (*Successivie order of scattering*)

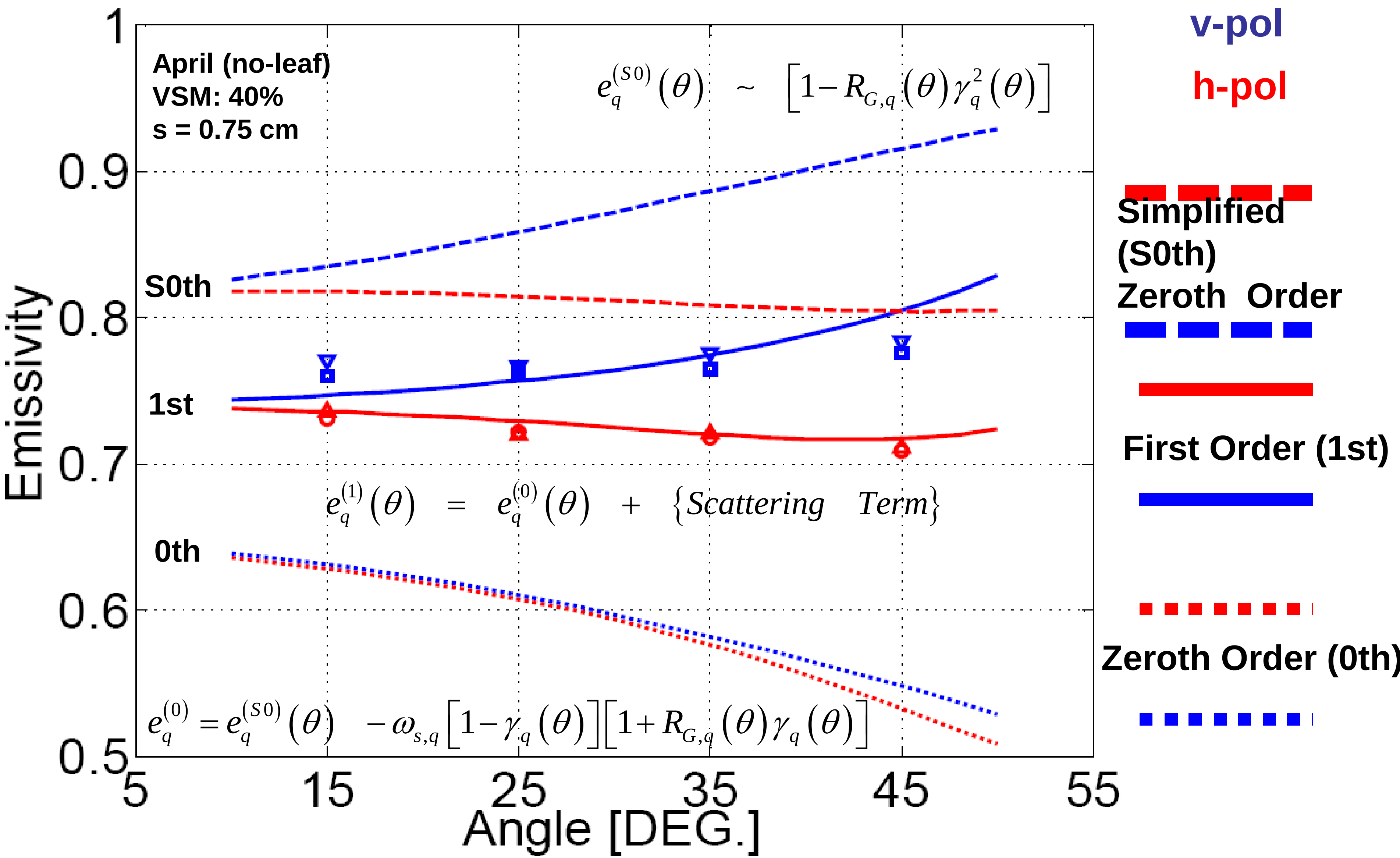
An iterative solution of the RT equation up to the first order [kurum et al., 2009].

$$e_q^{(1)}(\theta) = e_q^{(0)}(\theta) + \{\text{Scattering Term}\}$$

Due to the **single interaction** between particle and emission from the **ground** and the **layer**



Radiometer Angular Response from a Forest Canopy (Models vs Data)



Effective Albedo

$$e_q^{(1)}(\theta) = e_q^{(0)}(\theta) + \underbrace{\{Scattering \quad Term\}}_{\Omega_q}$$

Expanding

$$e_q^{(0)} = e_q^{(S0)}(\theta) - \omega_{s,q}\left[1-\gamma_q(\theta)\right]\left[1+R_{G,q}(\theta)\gamma_q(\theta)\right] + \Omega_q$$

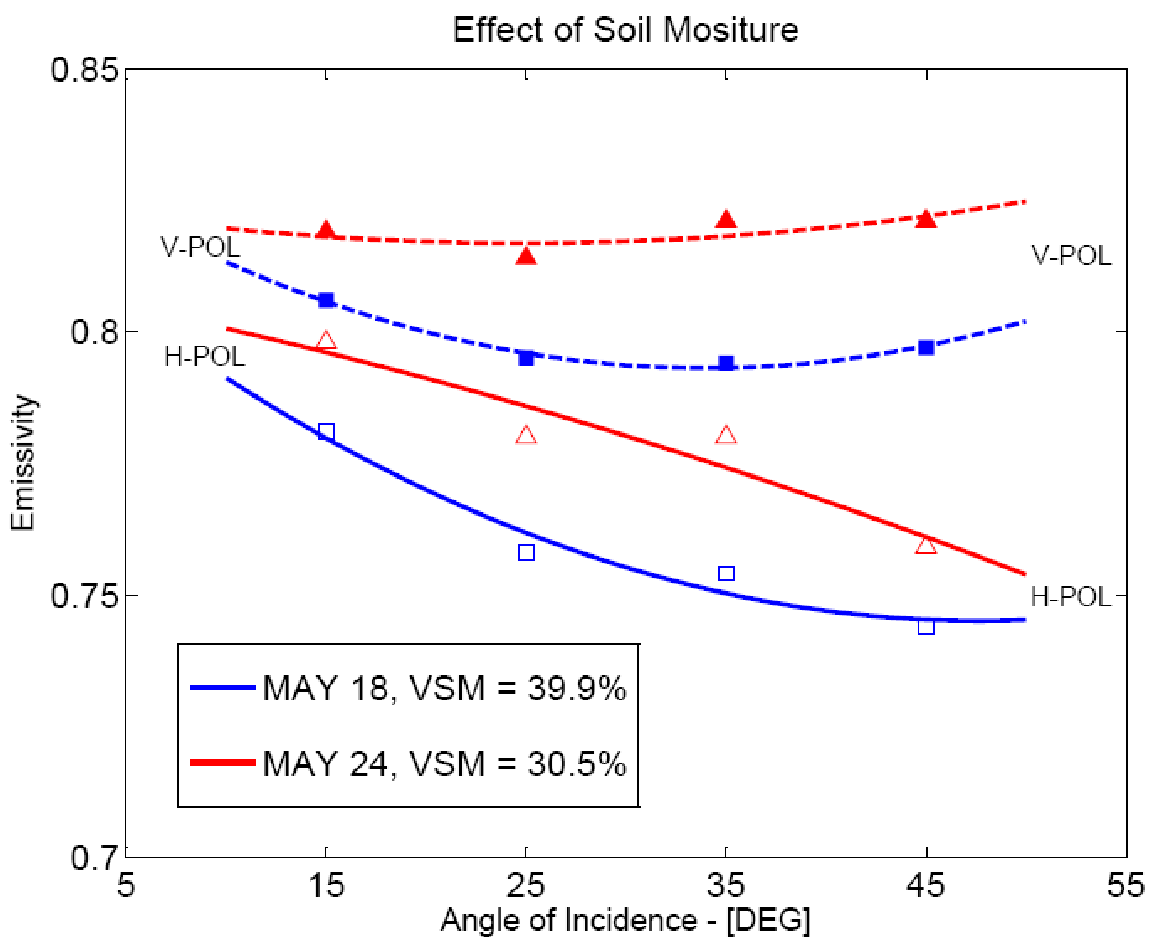
$$e_q^{(0)} = e_q^{(S0)}(\theta) - \underbrace{\left[\omega_{s,q} - \frac{\Omega_q}{\left[1-\gamma_q(\theta)\right]\left[1+R_{G,q}(\theta)\gamma_q(\theta)\right]}\right]}_{\omega_{eff}^{(q)}}\left[1-\gamma_q(\theta)\right]\left[1+R_{G,q}(\theta)\gamma_q(\theta)\right]$$

$\omega_{eff}^{(q)} \leftarrow$ Effective Albedo

$$e_q^{(0)} = e_q^{(S0)}(\theta) - \omega_{eff}^{(q)}\left[1-\gamma_q(\theta)\right]\left[1+R_{G,q}(\theta)\gamma_q(\theta)\right]$$

Effect of Soil Moisture

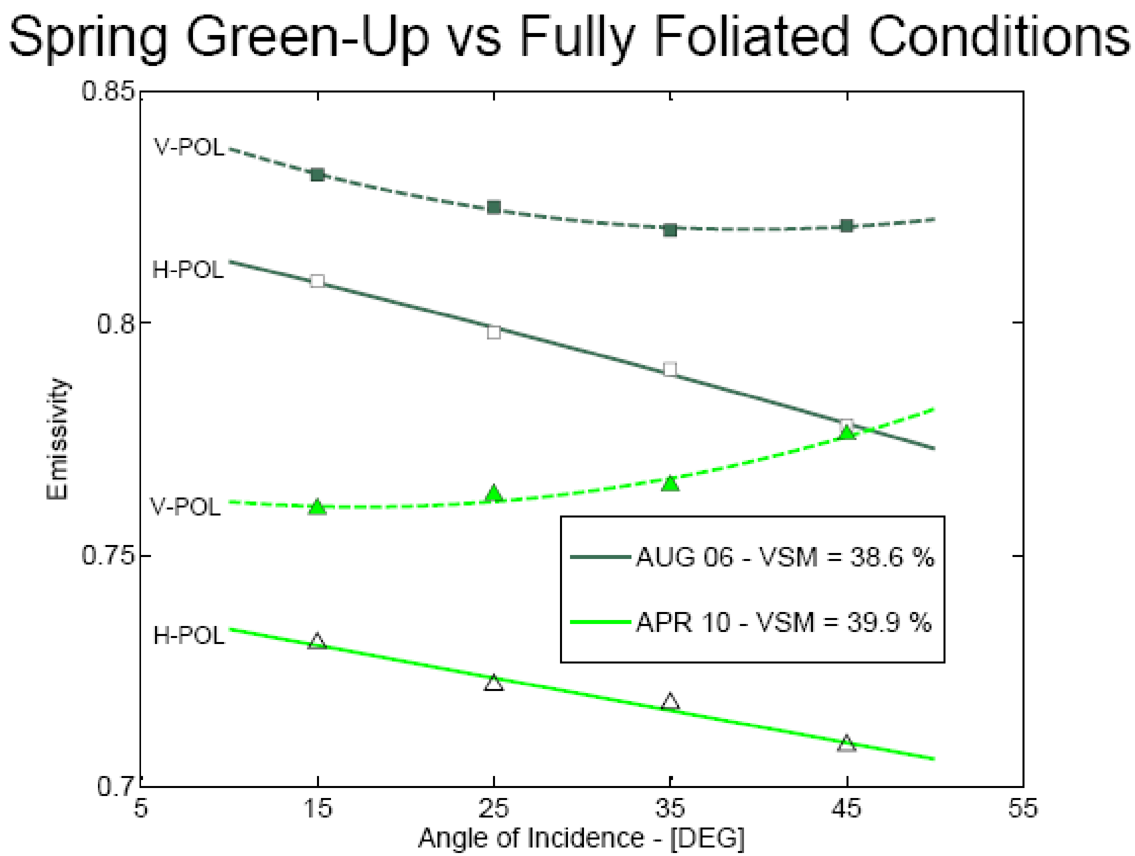
- The two days in proximity to each other (May 18 and May 24) are chosen
  - the tree state does not change
  - soil moisture conditions change.
- For both H and V pol
  - emissivity curves are shifting up as soil moisture decreases.
- For a fixed physical temperature of T = 300 K,
  - the change in brightness temperature for 10 % change in VSM is ~ 11 K.



Solid (H-pol) and dashed (V-pol) lines are the curve fit results and individual triangles (May 24) and squares (May 18) are the measured values.

Effect of Season on the Radiometer Response

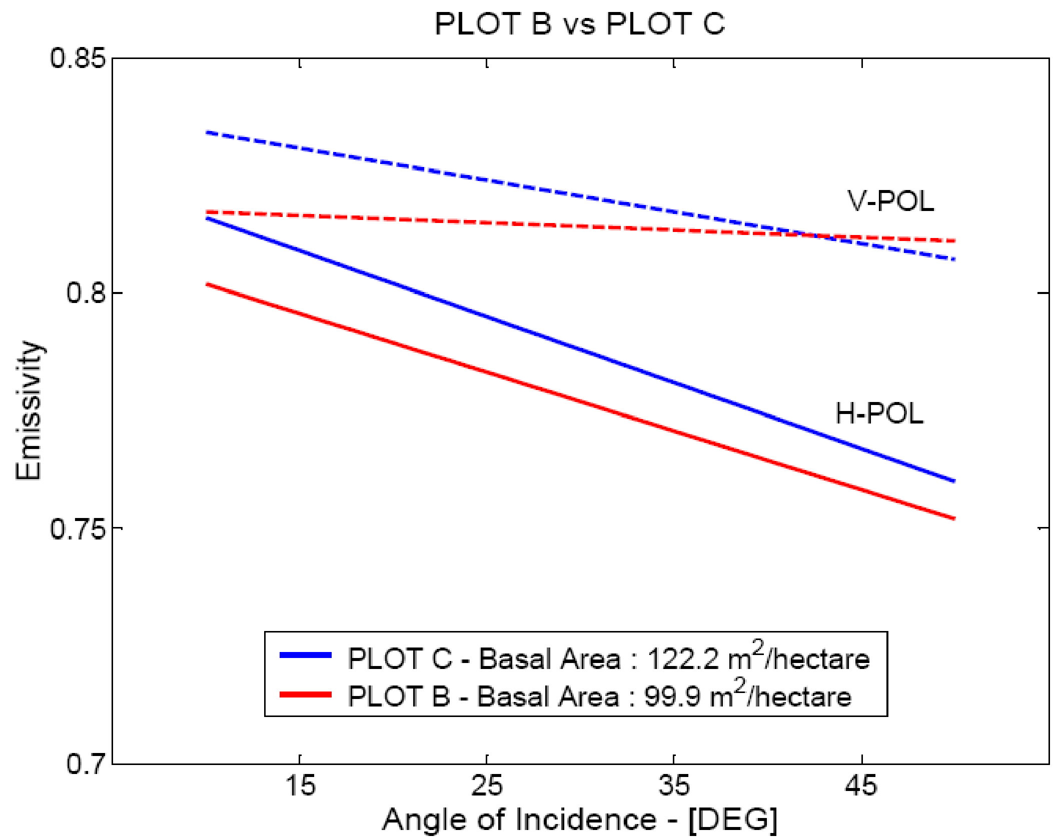
- The radiometer is able to resolve the change in tree state under the condition that the soil moisture does not change.

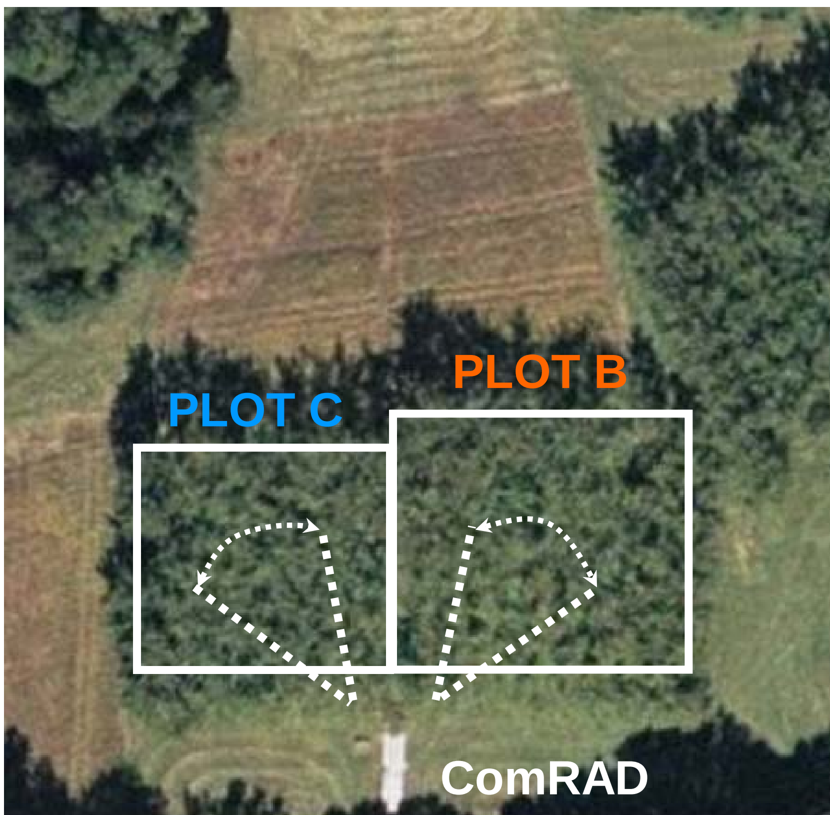


Solid (H-pol) and dashed (V-pol) lines are the <u>curve fit</u> results and triangles (Apr. 10) and squares (Aug. 06) are the measured values.

Effect of Biomass on the Radiometer Response

- Density of Plot C is higher than that of Plot B
- The average emissivity of Plot C is higher than that of Plot B.





	PLOT B	PLOT C
Area	33 x 33 m	28 x 28 m
# trees in plot	92	92
Average DBH (cm)	19.4	18.2
Range in VSM (%) [Apr – Nov, 2007]	30 – 45	33 – 44

COMRAD TREE EXPERIMENT – APEX '08 AND '09

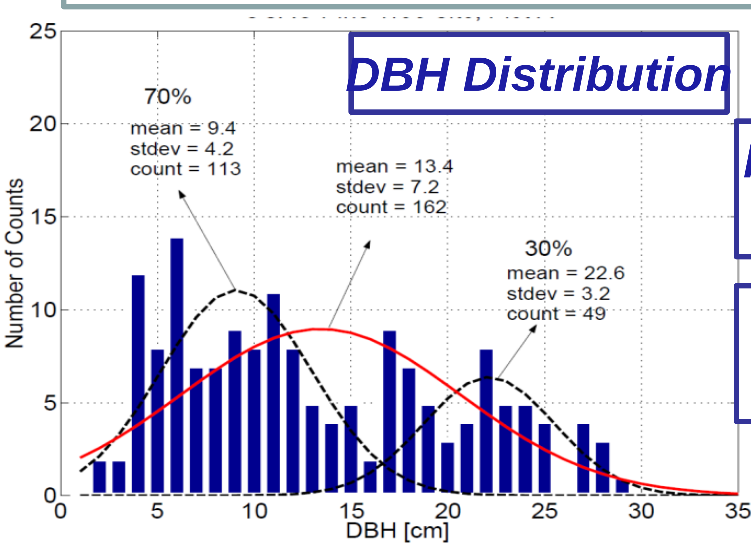
CONIFER TREES

Combined Radar/Radiometer Instrument System

- **Frequency:** *1.403 - 1.424* **GHz Radiometers;**
  1.25 GHz **radar**
- **Antenna:** *1.22* **m parabolic dish w/broadband feed**
- **Incidence Angle Range:** *0^0 – 175^0*
- **Azimuth Angle Range:** *0^0 – 120^0* **autonomous** *0^0 – 360^0* **manual**

om truck

DBH Distribution



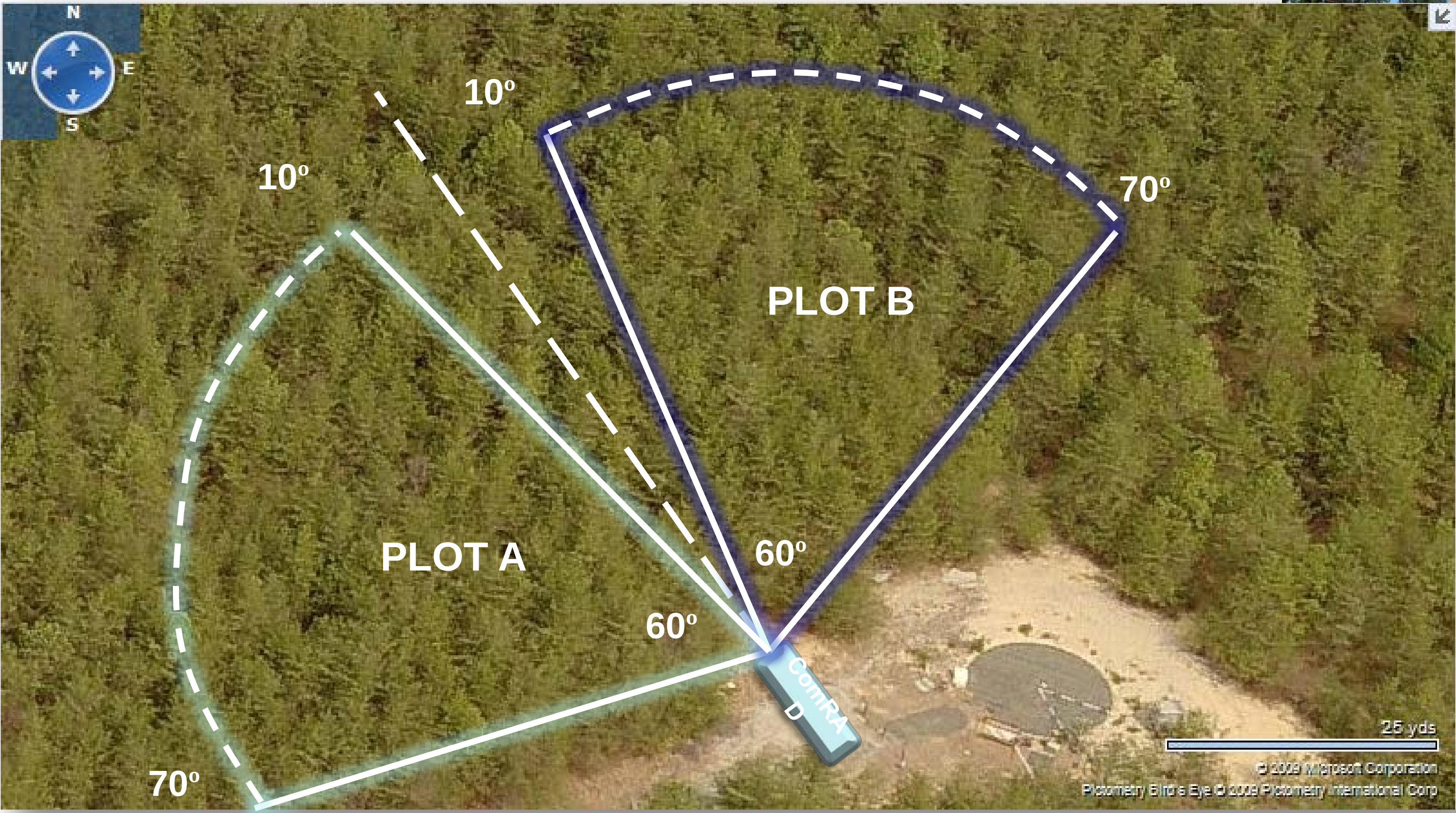
Mean DBH 13.4 cm

Basal Area ~ 34 m^2/ha

Location: Greenbelt, Maryland

ComRAD deployed at natural stand of Virginia pine trees (~ 12 m tall)

NATURAL VIRGINIA PINE TREE SITE AT GODDARD GEOPHYSICAL AND ASTRONOMICAL OBSERVATORY (GGAO)



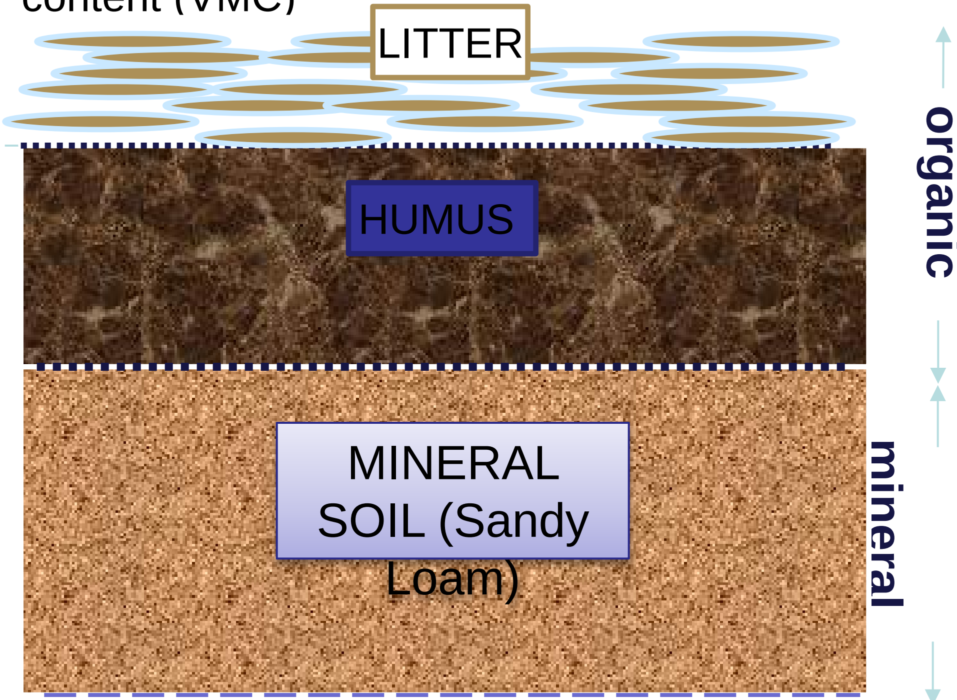
GPS LOCATION : +39° 1' 21.37", -76° 49' 28.87"

FOREST FLOOR CHARACTERISTICS

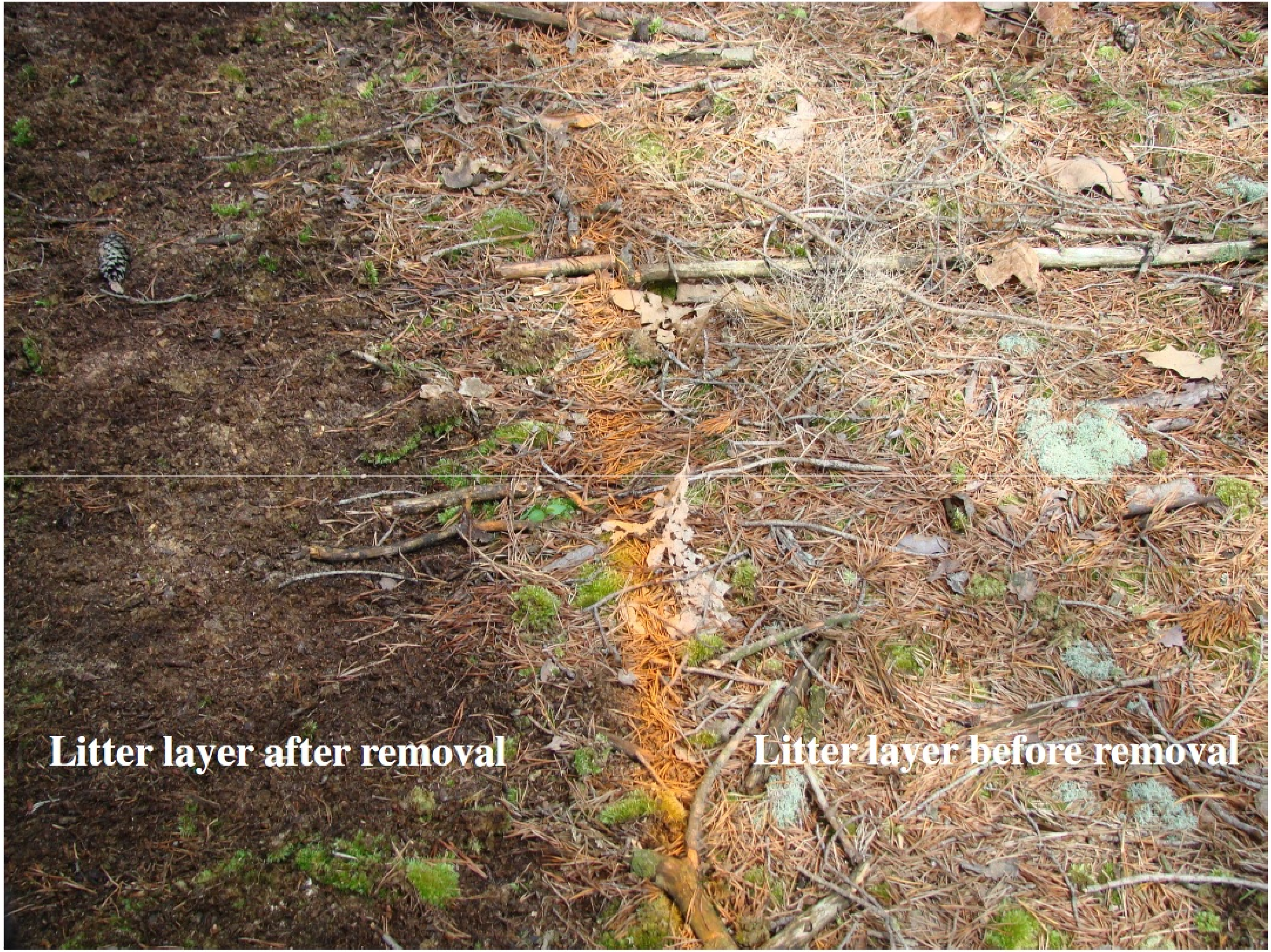
	Litter	Humus	L+H
Thickness	[cm]	[cm]	[cm]
Mean	**0.8**	**2.2**	**3.0**
Stdev	**0.3**	**0.9**	**1.1**

Soil Bulk Density : 1.11 g/cm^3
Organic Layer Bulk Density : 0.15 g/cm^3
Sandy Loam Soil : 57% sand, 13.6% clay
Surface Roughness : σ = 0.5 cm
Moisture Range : 5% - 30% volumetric moisture content (VMC)

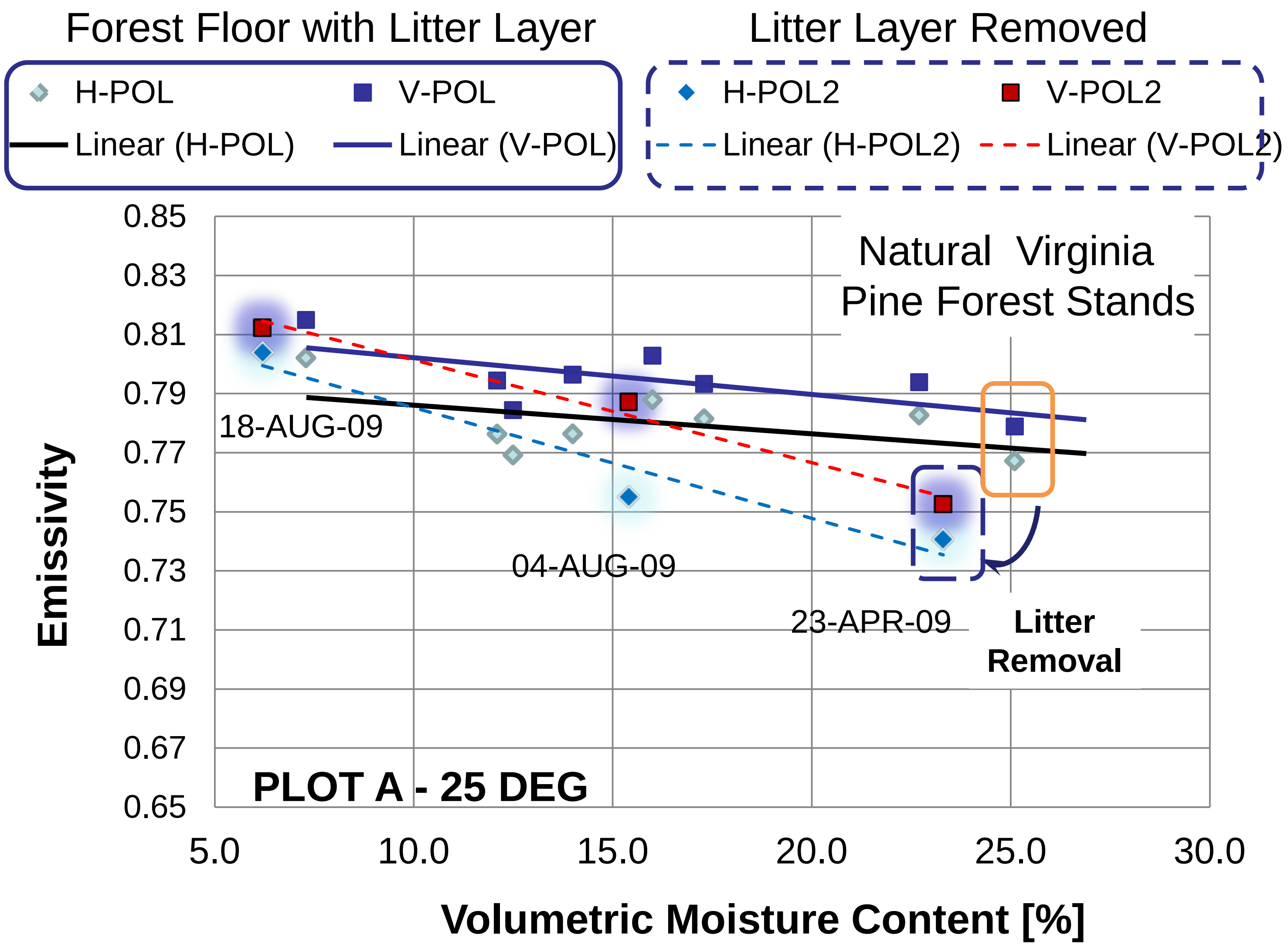
A picture from the Pine Forest Floor



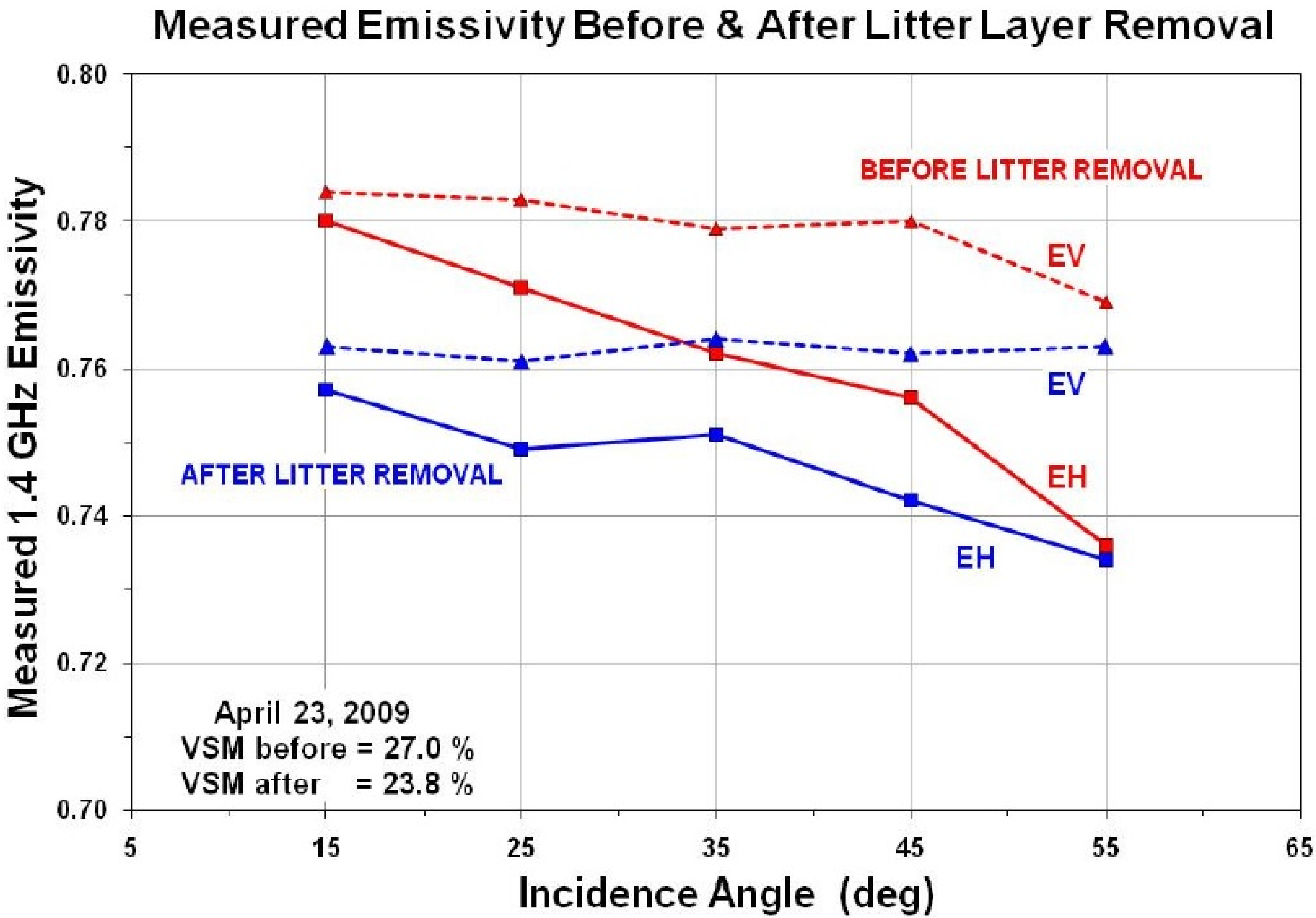
An illustration of the Pine Forest Floor


Litter layer after removal
Litter layer before removal

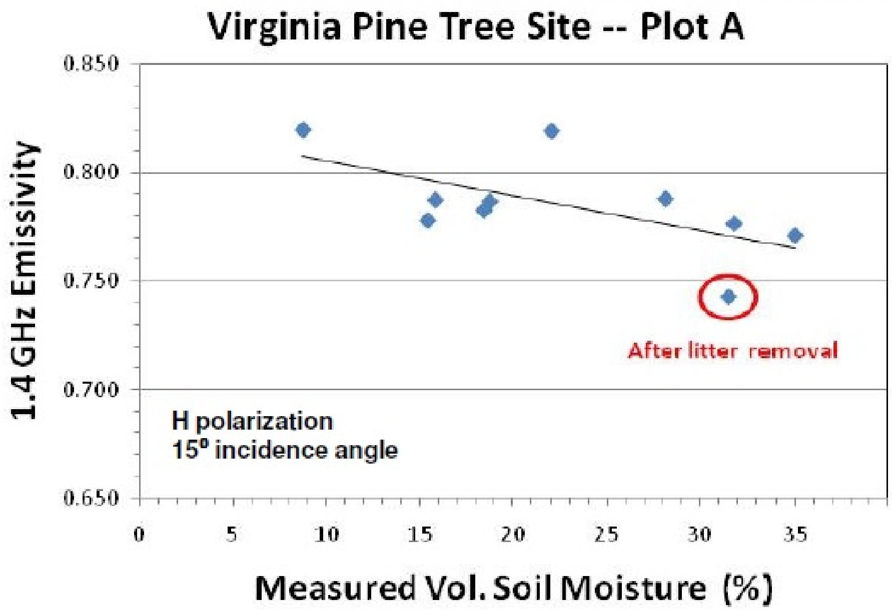
IMPACT OF LITTER LAYER ON THE OBSERVED EMISSIVITY - PLOT A, Θ = 25º



Effect of Litter Layer on Observed Emissivity

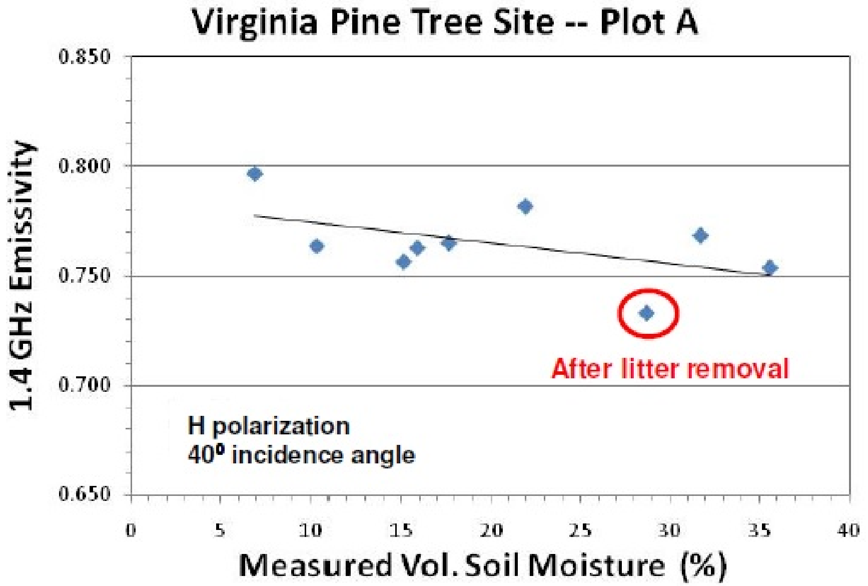


Change in TB with Change in Soil Moisture



- limited sensitivity to the underlying soil moisture is observed through the tree canopy

- unlike the deciduous paulownia tree site, a good dynamic range of soil moisture has been observed so far under the pine trees



Conclusions & Recommendations

- Same tau-omega equation can be used for remote sensing of forests with an appropriate tau and omega.
- Dependence of tau and omega on forest type and age should be studied.
- One should study how you treat heterogeneous pixels when scattering is important.
- Litter can mask the underlying soil moisture particularly for conifer stands.
- Models of litter should be checked with measurements.