# TABLE OF CONTNETS


1. Introduction .......... 1

2. Activities in Support of Experiment .......... 1

3. Methodology .......... 2
   - 3.1 Trihedral Corner Reflectors .......... 2
   - 3.2 Tree Population Surveys .......... 3
   - 3.3 Tree Properties .......... 4
   - 3.4 .......... 5

4. Point Target Emplacements .......... 5
   - 4.1 Mature Red and White Pine - Stand G .......... 5
   - 4.2 Norther Hardwoods - Stand Q .......... 6

5. In-Situ Forest Measurements .......... 6
   - 5.1 Tree Population Summaries .......... 6
   - 5.2 Tree Properties .......... 7
     - 5.2.1 Trunk Dielectric Properties .......... 7
     - 5.2.2 Needle Dielectric Measurements .......... 8
     - 5.2.3 Branch Moisture Measurements .......... 8
   - 5.3 Snowpack Properties .......... 8
   - 5.4 Soil Properties .......... 8

Acknowledgments .......... 9

References .......... 9

# ULTRA-WIDEBAND SAR FOREST EXPERIMENT NEAR RACO, MICHIGAN: APRIL 4 - 12, 1992

M. Craig Dobson

# 1 INTRODUCTION

The University of Michigan performed a number of supporting tasks for an airborne SAR experiment conducted in the vicinity of Raco, Michigan using the SRI, International QueenAir. These activities are briefly listed and the resulting measurements are presented in the following sections for (1) the locations and orientations of trihedral corner reflectors used in forest stands and adjacent forest clearings, (2) biometric surveys of forest stands used by the airborne SAR and (3) time specific properties of the forests during the times of the SAR overflights including the moisture and dielectric properties of the trees, snowcover and soil properties.

# 2 ACTIVITIES IN SUPPORT OF EXPERIMENT

Prior to the airborne experiment, Craig Dobson (U of M) met with Jim Hodges (SRI) in Sault Ste. Marie on March 23 -24, 1992. During this trip, Jim Hodges was introduced to personnel at the US Forest Service office in Sault Ste. Marie, the Chippewa County Airport in Kinross and at Smithers Testing in Raco. The proposed test site for the airborne SAR experiment was surveyed by car. The approximate location of the Hiawatha National Forest is shown in Figure 1.

An attempt was made to visit all potential test sites and forest stands for use in the experiment as shown in Figure 2. However, many roads were snowcovered and impassable as many of the Forest Service roads are not plowed during the winter. Tentative stand selections for the experiment were discussed and agreed upon. The primary locations were determined on the basis of tree height and density, percent of crown closure, accessibility for ground crews and for positioning of point targets (both trihedral corner reflectors and vehicles) and also to provide samples of both coniferous, needleleaf and deciduous, broadleaf species. The selected forest stands were Stand G - a stand of mature red and white pine, Stand Q - a stand of maple trees and with Stand T as a back-up stand of overmature bigtooth aspens and red maple. In addition, potential sources of vehicles to be used by the study were identified for consideration by SRI.

The period of field experimentation lasted from April 4 - 12, 1992. The following generalized schedule was followed during this period:

April 4 - U of M personnel (3) travel to Sault Ste. Marie and meet with SRI personnel.

April 5 - Take SRI personnel to review specific test sites as needed and assist in assembly of trihedral corner reflectors at the Chippewa County Airport.

April 6 - Complete fabrication of the corner reflectors at the Chippewa County Airport. Craig Dobson and John Vesecky arrive at Sault Ste. Marie and participate in a project status and planning meeting. Assist in defining flight headings for Stand G.

April 7 - Survey positions for trihedral corner reflectors in Stand G and a nearby clearing; then deploy, position and orient the reflectors to the expected boresight direction of the SAR. Participate actively in experiment planning meeting.

April 8 - Make *in situ* observations of forest properties in conjunction with the SAR overflights (temperatures, snowpack and tree properties). Record the orientation angles of the trihedral corner reflectors at the time of the SAR overflights. Reorient the trihedral reflectors 180° for a second set of overflights and record those positioning angles. Help to remove the reflectors from Stand G and its associated clearing after the final SAR overflights and move them to Stand Q. Survey in positions for the corner reflectors in Stand Q, place them in the forest and orient them to the expected boresight of the SAR. Identify and locate a suitable clearing in the vicinity of Stand Q for the deployment of additional trihedral corner reflectors. Assist in definition of flight headings and offsets for next day's flights and help coordinate ground crew activities with the flight crew at the project status briefing.

April 9 - Verify and record the pointing angles for the corner reflectors deployed in Stand Q. Survey the clearing near Stand Q and deploy and position trihedral corner reflectors to the expected boresight angle of the SAR. Reorient all trihedrals 180° after the first set of SAR overflights and record the new positions. Obtain *in situ* data for Stand Q. Help remove all point targets from the forest at the conclusion of the SAR overflights.

April 10 - Complete all *in situ* observations at Stands G, Q and T and their associated clearings. Collect samples for laboratory determinations of foliage dielectric properties.

April 11- Conduct laboratory measurements of foliage dielectric properties. Return to Ann Arbor.

# 3 METHODOLOGY

## 3.1 Trihedral Corner Reflectors

The locations of the trihedral corner reflectors at any given forest stand or associated forest clearing were determined in consultation with Jim Hodges and Walter Chesnut. At a given stand or clearing, a transect was first surveyed using a Brunton compass and tape measures to run at an azimuth orthogonal (90°) from the magnetic heading of the expected flight line. At prespecified distances, wire surveyors flags were inserted into the snow to mark the locations for the trihedral reflectors. As needed, lateral offsets from this transect were surveyed (also using the Brunton compass and measuring tapes) to define additional reflector locations and the positions marked with wire flags. The flags were labeled to show location and target number.

The targets were moved from a truck using sleds and set in place such that the near-vertical leg of the trihedral reflector was at the location of the wire flag. The targets were oriented using the Brunton compass to align the front edge of the base of the trihedral to be parallel to the expected heading of the SAR. This angle is given as the azimuth angle and is accurate to +/- 1°. The tilt angle of the reflector is defined as the angle (off vertical) of the rear leg of the trihedral. This positioning was accomplished by excavation of a small pit into the snow under the apex of the trihedral. The trihedrals were inclined at 10° +/- 2°. The angles were measured on the near-vertical rear leg using a digital inclinometer accurate to 0.1°. Finally, the level of the front edge of a trihedral corner reflector was adjusted using wooden shims inserted under the sides of the reflector. The level angle was measured using the digital inclinometer. Positive values of level indicate that the right side is high when facing into the reflector. The reflectors were generally leveled to within +/- 2°. Since many of the targets were positioned up to 18 hours prior to the SAR overflights, there was some concern that the positioning may change as the targets settled in the wet snow. As a consequence, all target positions were checked and recorded prior to each series of constant heading SAR overflights. After a given series of SAR overflights, the targets were rotated as needed and remeasured using the Brunton compass and digital inclinometer.

## 3.2 Tree Population Surveys

Biometric surveys of various forest stands were conducted to statistically describe the specie composition and size distribution of the forest. A forest stand is defined as a homogeneous forested area with respect to specie mix, stocking density (number of stems per unit area), tree height and diameter. Homogeneous forest stands of at least 4 ha in size (200 m X 200 m) were selected on the basis of (1) US Forest Service airphotos and forest compartment maps for the Hiawatha National Forest, (2) P-, L- and C-band SAR imagery acquired on April 1, 1990 and June 6, 1991 by the JPL AIRSAR and (3) ground surveys by forest ecologists and foresters. The locations of some of these stands is shown in Figure 2. Within each homogeneous stand, a baseline of 200 m length was surveyed; orthogonal to this were surveyed a series of 5 randomly located transects each 200 m in length. Eight sample locations were randomly located along each of the 5 transects, resulting in a total of 40 sample locations per stand.

Surveys of each stand were made by forest ecologists and foresters to ascertain the following: (1) tree density by specie, (2) tree diameter, (3) tree height and (4) biomass. At each of the 40 locations, a circular sampling plot of 100 $m^2$ is used to inventory every upper stratum tree (height > 5 m); this results in a 10% sampling of all upper stratum trees. Each tree is identified by specie and measured for "diameter at breast height" (height = 1.3 m). A subset of all trees is measured for height. Two heights are measured: (1) the total tree height and (2) the bole height which is the height to the lowest live branch of a given tree. Regression is used to establish a relationship between diameter and total height for each specie. These relationships are used to estimate the height of all measured trees. A similar procedure is applied for middle stratum trees; but the measured sample represents 3% of the total population. The middle stratum is defined as stems with 1 m < height < 5 m. The cross-sectional area of the stems is calculated from the measured diameters; when summed over all trees of a given specie within the stand, this is expressed as basal area ($m^2$/ha).

Dry biomass is calculated on a per tree basis using allometric relationships available in the literature for a given specie. These relationships are empirically derived from destructive sampling of many different trees over a range of age, height and diameter conditions. The calculated values are typically within +/- 10% of observed. Since deciduous species shed their leaves during the winter (and had no leaves during the April overflights), estimated foliar biomass of deciduous species is ignored for estimates of total dry biomass during the winter.

## 3.3 Tree Properties

During the period from April 8 - 11, 1992 specific trees within stands G, Q and T were selected for *in situ* observations of microwave dielectric properties of the tree trunks. In addition, needle samples were collected from the coniferous species for measurement of microwave dielectric properties using a laboratory technique. Because of their small size and also the general inaccessibility of branches for making direct dielectric measurements, samples were obtained for determination of specific density and volumetric moisture content of branches for the common species. The moisture values can be used to calculate dielectric properties of the branches and stems as functions of temperature and frequency using a dual-dispersion Debye model [1].

The dielectric measurements were made using a field-portable vector network analyzer to measure the reflection coefficient of a coaxial line terminated in the test medium [2,3]. Separate probes were used at P-band (400 MHz) and L-band (1.2 GHz). For selected tree trunks of each of the dominant species at Stands G and Q, measurements were made of the profile of the relative dielectric constant as a function of depth into the trunk. Measurements were made at the surface of the bark layer and then in increments of several millimeters to a maximum depth of 12 cm below the surface. A low-speed drill was used to bore a hole of slightly larger diameter than the coaxial probe tip (0.25" dia.). In order to provide good contact of the probe tip with the medium of interest, the bottom of the bore hole was smoothed with a flat-faced drill bit prior to dielectric measurement. At each depth, the reflection coefficient was measured three times and recorded. The recorded data was post-processed to filter individual values where good surface contact with the trunk was not maintained. The resultant values were used to calculate the relative dielectric constant of the trunk and then averaged as a function of depth for each specie. Although these measurements are made *in situ*, they are time consumptive. The measurements were made after the SAR overflights and until midafternoon of the flight days.

Moisture properties of the branches and dielectric properties of the needles were obtained from cuttings from selected trees of each specie on April 10, 1992. The needles were collected by specie, removed from the stems, chopped into 1 cm lengths and used to pack cylindrical sample holders which could be fitted onto the ends of the coaxial probe tips. Reflection measurements were made of (1) the empty air-filled sample holder, (2) the sample holder packed with a known volume of randomly oriented needles mixed in a host medium of air, (3) the same sample of needles in a known volume of a second host medium (isopropyl alcohol) and (4) the sample holder containing only the second host medium (isopropyl alcohol). A dielectric mixing model is inverted to calculate the dielectric constant of the needle inclusions [4].

The branch sections were cut into small cylindrical pieces and labeled by specie. The wet mass of each piece was recorded along with its length and diameter. The samples were later dried to equilibrium mass at 70°C. The fresh volume, wet and dry masses were used to calculate the specific density of the branch sections as well as the gravimetric and volumetric moistures.

## 3.4 Properties of the Surface Layer

The surface layer underneath the forest canopies and the clearings containing the trihedral corner reflectors was characterized in terms of the physical properties of the snowpack and the underlying soil. Snowpack observations included depth, density, snow water-equivalent and temperature. The soil observations included temperature, thickness of decayed material in the humic layer and the organic soil horizon, soil textural category of the mineral soil, and the dry densities and moisture contents of both the organic and the mineral soil horizons.

For each stand or clearing, snow depth was obtained using a meter stick inserted to the soil surface at semi-random intervals along transects adjacent to the trihedral reflector locations. Care was taken not to measure the snow depth where the surface had been visibly compacted by foot traffic. Snow depth measurements were made during the morning hours and shortly after the termination of the SAR flights. Snow water-equivalent is the mass of water per unit surface area; it is determined by obtaining core samples of the snowpack. The samples were acquired along transects using PVC snow tubes of known diameter. Extracted cores of measured thickness were sealed in plastic bags and weighed to 0.1 g. Since the volume of each sample is known, the average density of the snow column can also be calculated. Snow wetness, the liquid water content of the snow, was not measured; but should be negligible since both air and snow temperatures were found to be below freezing during the early morning SAR overflights.

Soil properties were determined at each stand and clearing at the floor of a snow pit. A trench was excavated to the base of the snowpack. Temperature readings were obtained for (1) air, (2) the snowpack and (3) the upper 5 cm horizon of the mineral soil. The presence or absence of ice crystals in the mineral soil layer was noted. Layer thicknesses of the organic zone was measured using a depth gauge. Steel coring tools were used to volumetrically exhume samples of the organic layer and the upper 5 cm layer of the mineral soil. The samples were placed in sample tins, labeled and weighed. Dry weights were recorded after drying the samples to equilibrium at 105°C. The wet and dry weights of the samples and their associated volumes were used to calculate soil bulk density, gravimetric moisture (water mass / mass of dry soil) and the volumetric moisture (product of bulk density and gravimetric moisture). The moisture and temperature data can be used to estimate the dielectric properties of the soil using either empirical [5] or theoretical [6] models. The empirical approach is only valid for frequencies above 1 GHz however.

# 4 POINT TARGET EMPLACEMENTS

Point targets consisting of 8' trihedral corner reflectors designed by SRI were deployed within two general areas for use on the two flight days. For flights over Stand G on April 8, 1992, a total of 16 reflectors were deployed: 10 within Stand G and 6 in a nearby clearing. For flights over Stands Q and T on April 9, 1992, a total of 14 trihedral reflectors were deployed: 10 within Stand Q and 4 in a nearby clearing.

## 4.1 Mature Red and White Pine - Stand G

The array of trihedral reflectors was installed at the clearing near Stand G between 10:00 and 13:00 hours on April 7, 1992. Ten additional targets were installed within forest Stand G between 15:00 and 18:30 hours on April 7, 1992. The locations of these target arrays are mapped in Figures 3 and 4. The recorded positioning angles for the reflectors are given in Tables 1 and 2 for Stand G and the associated clearing, respectively. Note that all azimuths are given in degrees magnetic. The magnetic declination is 5.2° W. The first (primary) set of orientation angles were measured and recorded just after the SAR flights and immediately prior to spinning the reflectors 180° to secondary orientations appropriate for the second series of overflights. The targets were removed on the afternoon of April 8 after the SAR overflights and after photography had been acquired of each target by Dr. Walter Chesnut.

### 4.2 Northern Hardwoods - Stand Q

An array of 10 trihedral corner reflectors was installed within forest Stand Q between 16:45 and 18:00 hours on April 8, 1992. Airphotos and JPL-AIRSAR data indicated that a clearing of suitable size was situated southeast of Stand Q. The area was surveyed by snowshoe to determine the suitability of this clearing on the evening of April 8. It was found to be small but close and roughly at a heading of 135° from Stand Q. This clearing was surveyed and 4 reflectors were deployed and oriented on the morning of April 9, 1992 between 07:45 and 08:15 hours. Maps of the target locations for Stand Q and the clearing southeast of Stand Q are given in Figures 5 and 6, respectively. The primary and secondary orientation angles for the reflectors are specified in Tables 3 and 4 for Stand Q and the clearing, respectively. The reflectors were removed from the forest and the clearing by sled and snowshoes at the end of the SAR overflights and shipped by truck for storage at the Chippewa County Airport in Kinross.

## 5 IN-SITU FOREST MEASUREMENTS

### 5.1 Tree Population Summaries

The biometric survey results for Stands G, Q and T are given in Tables 5 to 7, respectively. The reported data are subdivided into the upper and middle stratum. The measured quantities of diameter and height are summarized by means and standard deviations. Basal area ($m^2$/ha) and density (stems/ha) are stand averages. Biomass calculations for individual trees are summed over the stand and expressed in tonnes/ha. Note that for the April SAR observations no foliar biomass should be included for the deciduous species; winter and summer biomass estimates are separately tabulated. Summertime biomass is higher.

Stand G is dominantly large red and white pine trees with a large number of red maples in the understory. The mean heights of the pines range from 20.7 m to 23.3 m for white and red pine, respectively. Together the two pine species account for 45% of the stems, 87% of the basal area and 89% of the total dry biomass in the upper stratum. The shorter red maples only account for about 7% of the upper stratum dry biomass because, while plentiful (36% of the stems), they are of small diameter and height. Hence, the red maples only represent 4% of the total basal area of the upper stratum.

Stand Q is primarily maple (red and sugar maple). These two species combined represent 95% of the stem density, 94% of the basal area and 95% of the total dry biomass in the upper stratum. These trees are not large; the red maple and sugar maple have mean heights of 18.5 m and 15.2 m, respectively. The understory is found to be dominated by young sugar maples.

Stand T is an overmature bigtooth aspen stand in transition to red maple. About 25% of the aspen trees are dead; the dry biomass of the live aspens is only 7% of the total for the upper stratum of the stand. The remaining live aspens are large - having average diameters on the order of 25 cm with heights of 20 m - and constitute 43% of the basal area of the upper stratum. In the upper stratum, the two maple species (red and sugar maple) contribute 84% of the stem density, 52% of the basal area and 84% of the dry biomass. The understory is also dominated by young maple trees.

## 5.2 Tree Properties

The microwave dielectric and moisture properties of selected trees of each of the dominant species were measured during the experimental period. Since the dielectric properties of the trunks may be time variant over a 24 hour period [7,8], these measurements were made as quickly as possible during and immediately after the SAR overflights. Needle dielectric properties were made from samples obtained one day after the last SAR overflights as were samples acquired for determination of branch moisture and density conditions.

### 5.2.1 Trunk Dielectric Properties

Microwave scattering by the tree trunks can lead to the dominant source of backscatter from forests at long wavelengths [7 to 10]. Scattering by the trunks is dependent upon geometry (the height and diameter distributions of the trunks), the surface roughness of the bark, and the effective relative dielectric constant of the trunk. A tree trunk is a highly layered dielectric as shown in Figures 7 to 9 for white pine, red pine and maples, respectively. The dry bark layer generally is characterized by a low dielectric constant, about 3, and is of variable thickness for pines and maples. The thickness of the bark layer of aspens does not vary much with the diameter, height and age of the tree. In addition, the bark can have a rough surface for some species such as red pine and the maples while it is relatively smooth (in terms of roughness) for white pine and for aspens. Inside the bark layer is a region of very moist tissue, the cambium region, which typically has a very high dielectric constant for non-frozen trees. The magnitude of the dielectric constant in the cambium zone is specie dependent. The cambium region may be only a few millimeters thick, but the high magnitude of the dielectric constant (as much as 60) means that this region is often critical in controlling trunk scattering mechanisms. Beneath the cambium zone, the dielectric constant typically decreases to a level of 10 to 30 within the moist sapwood region.

Measured dielectric profiles of trees are often highly variable from tree to tree within a given specie, in large part due to the difficulty of establishing a common depth reference because of variable bark thickness. This is shown in the measured data from 6 to 13 trees per stand given in Tables 8 to 10 for Stands G, Q and T, respectively. As a consequence, an attempt is made to normalize the observation depths for various trees within a specie on the basis of the location of the bark / cambium interface. Assuming this interface to be a reference (depth = 0), then the dielectric measurements of different trees within a specie can be combined to provide a composite picture of the dielectric profile with depth into the trunk. Figures 10 to 13 show composite profiles for white pine, red pine, sugar maple and bigtooth aspens, respectively. Also given are empirically fitted equations for estimating the dielectric constant as a function of distance from the bark / cambium interface for the pine species and sugar maple.

Note that the sap had begun to flow in all of the maples, sometimes heavily, hence the high dielectric constants within the thawed trunks are not surprising. Also, the high relative dielectric constant of the bigtooth aspen shown in Figure 13 at depths greater than 80 mm indicates that this tree was probably rotten inside. This is very common for the old bigtooth aspens found in both Stands Q and T.

### 5.2.2 Needle Dielectric Measurements

The P-band dielectric measurements of the coniferous needles are summarized in Table 11. The relative dielectric constants of red and white pines are found to be statistically larger than those of spruces and jack pines (Stand I). Loss tangents for the red and white pine needles are about 0.2.

### 5.2.3 Branch Moisture Measurements

A small number of branch segments for each specie were cut and measured to determine specific density and moisture contents. These results are summarized in Table 12. The volumetric moistures of the branches are found to be maximum (about 0.55 g/cm^3) for low density softwood species such as aspens and white pines and minimum for northern hardwood species with high specific densities such as beech and maple. These values of moisture and density will be used together with the temperature data to estimate relative dielectric constants [1] for use in MIMICS calculations of radar backscatter.

## 5.3 Snowpack Properties

The snow measurements were taken on the days of the SAR overflights. This was important as it was feared that late afternoon air temperatures would climb above freezing and cause melting of the snowpack. Snow depth measurements were generally obtained in the morning during and just after the SAR flights. In general, snow depth was found to be nearly identical for the two clearings near Stands G and Q (32 cm). Since these clearings were sampled on separate days, it may be assumed that significant snow melt did not occur over the two day period. The snow observations are summarized in Table 13. The more shaded forest floor of the coniferous Stand G is found to have a snow depth about 50% deeper than that in the maple forest of Stand Q. Histograms of snow depth for these two forests stands are shown in Figure14.

Because of the sub-freezing snow temperatures in the mornings, it was not possible to obtain snow water-equivalent samples at that time. The snow tubes could not penetrate the thick and hard surface crust of the snow. Consequently, measurements using the snow tubes were delayed until early afternoon when the surface crust had softened. Five to ten samples were taken along transects at each stand or clearing. Snow density is found to vary from 0.32 g/cm^3 to 0.38 g/cm^3. Snow water-equivalent is found to be proportional to average snow depth as measured earlier in the day.

## 5.4 Soil Properties

All of the soil observations were made after the SAR overflights on April 10, 1992. This was not deemed to be a problem since (1) the air temperatures did not rise above freezing for long enough for near surface melt of the snow to penetrate to the bottom of the snowpack and hence modify soil moisture and (2) the mineral soil layer was known to already be completely thawed. The measured moisture and density values for the soils beneath the forest stands and associated clearings are given in Table 13. All of the forest stands and clearings are underlain by sandy soils. At the times of the SAR overflights these soils are found to be completely thawed underneath the insulating snow cover and to be nearly saturated with water. Volumetric moistures are found to vary over the limited range from 0.47 g/cm^3 to 0.5 g/cm^3.

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Table 1

# Retroreflector Positioning

**Site: Raco, MI - Mature red and white pines in Stand G**

**Date Positioned: April 7, 1992**

**Date/Time Rotated 180° from Primary to Secondary Orientations:**
**April 8, 1992 09:15 to 09:47**

| | Primary Orientation | | | Secondary Orientation | | |
|---|---|---|---|---|---|---|
| **Target No.** | **Azimuth** | **Level** | **Tilt** | **Azimuth** | **Level** | **Tilt** |
| RG1a | 151° | 0.6° | 9.6° | 330° | 0.8° | 11.1° |
| RG1b | 146° | -0.7° | 9.9° | 329° | -1.2° | 10.6° |
| RG2a | 147° | -0.5° | 9.7° | 327° | 0° | 10.4° |
| RG2b | 148° | 2.6° | 10.2° | 328° | -0.7° | 10.5° |
| RG3a | 149° | 0.7° | 10.6° | 331° | 1.3° | 9.2° |
| RG3b | 152° | 2.7° | 10.0° | 328° | 0° | 10.8° |
| RG4a | 152° | 0.0° | 10.0° | 328° | 0.2° | 11.1° |
| RG4b | 148° | -0.8° | 10.0° | 332° | -0.1° | 10.7° |
| RG5a | 151° | 0.5° | 10.3° | 331° | -0.4° | 10.7° |
| RG5b | 149° | -0.5° | 10.3° | 331° | 0.5° | 10.7° |

**Azimuths are given in degrees magnetic.**

**Magnetic declination is 5.2° W.**

Table 2

# Retroreflector Positioning

**Site: Raco, MI - Clearing North of Stand G**

**Date Positioned: April 7, 1992**

**Date/Time Rotated 180° from Primary to Secondary Orientations:
April 8, 1992 09:15 to 09:45**

| | Primary Orientation | | | Secondary Orientation | | |
|---|---|---|---|---|---|---|
| **Target No.** | **Azimuth** | **Level** | **Tilt** | **Azimuth** | **Level** | **Tilt** |
| GC1 | 147° | -0.6° | 8.0° | 330° | -1.0° | 9.5° |
| GC2 | 149° | 0.5° | 7.9° | 332° | 0.0° | 10.0° |
| GC3 | 140° | -1.0° | 8.0° | 331° | 0.0° | 10.0° |
| GC4 | 146° | 0.0° | 10.0° | 329° | 1.0° | 10.5° |
| GC5 | 144° | 1.0° | 8.5° | 331° | +0.5° | 10.0° |
| GC6 | 154° | +2.5° | 10.0° | 331° | -0.5° | 10.0° |

**Azimuths are given in degrees magnetic.**

**Magnetic declination is 5.2° W.**

Table 3

# Retroreflector Positioning

**Site: Raco, MI - Northern hardwoods in Stand Q**

**Date Positioned: April 8, 1992 @ 1645 to 1800 hours**

**Date/Time Rotated 180° from Primary to Secondary Orientations:**

| | Primary Orientation | | | Secondary Orientation | | |
|---|---|---|---|---|---|---|
| **Target No.** | **Azimuth** | **Level** | **Tilt** | **Azimuth** | **Level** | **Tilt** |
| RQ1a | 95° | 0.5° | 10.2° | 275° | -0.2° | 10.7° |
| RQ1b | 95° | 0.0° | 9.5° | 275° | -0.1° | 10.3° |
| RQ2a | 96° | 0.1° | 9.7° | 273° | -1.6° | 9.7° |
| RQ2b | 96° | 0.0° | 10.2° | 274° | 0.4° | 10.8° |
| RQ3a | 96° | -0.3° | 10.2° | 275° | 1.0° | 9.9° |
| RQ3b | 94° | 0.0° | 9.5° | 274° | 0.3° | 8.9° |
| RQ4a | 95° | -0.3° | 9.7° | 271° | -1.2° | 10.0° |
| RQ4b | 95° | -0.3° | 9.5° | 273° | -0.5° | 9.3° |
| RQ5a | 95° | 0.1° | 10.5° | 274° | 0.0° | 8.9° |
| RQ5b | 95° | 0.9° | | 273° | -0.3° | 9.0° |

**Azimuths are given in degrees magnetic.**

**Magnetic declination is 5.2° W.**

Table 4

# Retroreflector Positioning

**Site: Raco, MI - Clearing ESE of Stand Q**

**Date Positioned: April 9, 1992 @ 0745 hours**

**Date/Time Rotated 180° from Primary to Secondary Orientations:**

| | Primary Orientation | | | Secondary Orientation | | |
|---|---|---|---|---|---|---|
| **Target No.** | **Azimuth** | **Level** | **Tilt** | **Azimuth** | **Level** | **Tilt** |
| QC1 | 99° | 0.6° | 11.4° | 185° | 0.0° | 10.0° |
| QC2 | 98° | 0.7° | 10.2° | 185° | 0.5° | 10.0° |
| QC3 | 97° | 0.2° | 10.7° | 185° | 0.5° | 9.0° |
| QC4 | 96° | 0.6° | 11.9° | 185° | 0.5° | 9.0° |

**Azimuths are given in degrees magnetic.**

**Magnetic declination is 5.2° W.**

Table 5. Stand G Biometric Survey.

**Site Name:** **Raco**
**Stand Name:** **Stand G**
**Forest Type:** **Mature Pines - Red and White**

**Stand Biometric Survey Data**

| Stratum | Tree Type | | | Diameter (cm) | | | Total Height (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acronym | Scientific Name | Common Name | Mean | Stand. Dev. | No. of Obs. | Mean | Stand. Dev. | No. of Obs. |
| UPPER | ABIBAL | Abies balsamea | Balsam fir | 11.22 | 5.84 | 12 | 11.2 | 5.8 | 11 |
| | ACERUB | Acer rubrum | Red maple | 6.35 | 4.53 | 145 | 13.0 | 6.2 | 13 |
| | BETPAP | Betula papyrifera | Paper birch | 16.73 | 6.89 | 11 | 16.3 | 5.2 | 9 |
| | PICGLA | Picea glauca | White spruce | 8.62 | 4.92 | 25 | 9.3 | 5.7 | 12 |
| | PICMAR | Picea mariana | Black spruce | 18.20 | 8.06 | 2 | 18.0 | 4.2 | 2 |
| | PINBANX | Pinus banksiana (dead) | Jack pine (dead) | 21.40 | 0.00 | 1 | 13.0 | 0.0 | 1 |
| | PINRES | Pinus resinosa | Red pine | 14.69 | 10.52 | 77 | 23.3 | 5.5 | 24 |
| | PINRESX | Pinus resinosa (dead) | Red pine (dead) | 17.10 | 10.40 | 6 | 10.8 | 5.9 | 6 |
| | PINSTR | Pinus strobus | Eastern white pine | 24.64 | 9.92 | 106 | 20.7 | 6.6 | 32 |
| | PINSTRX | Pinus strobus (dead) | Eastern white pine (dead) | 16.50 | 5.79 | 21 | 13.6 | 3.5 | 21 |
| | POPGRA | Populus grandidentata | Bigtooth aspen | 27.10 | 0.00 | 1 | 23.5 | 0.0 | 1 |
| MIDDLE | ABIBAL | Abies balsamea | Balsam fir | 2.63 | 1.14 | 20 | 1.9 | 1.8 | 20 |
| | ACERUB | Acer rubrum | Red maple | 1.24 | 0.78 | 337 | 2.1 | 1.0 | 337 |
| | ACERUBX | Acer rubrum (dead) | Red maple (dead) | 1.10 | 0.00 | 1 | 1.9 | 0.0 | 1 |
| | AMESPP | Amelanchier | Serviceberry | 0.63 | 0.26 | 4 | 1.4 | 0.3 | 4 |
| | BETPAP | Betula papyrifera | Paper birch | 0.92 | 0.55 | 15 | 1.3 | 0.7 | 15 |
| | PICGLA | Picea glauca | White spruce | 2.14 | 1.03 | 15 | 1.5 | 0.6 | 15 |
| | PICMAR | Picea mariana | Black spruce | 2.70 | 0.00 | 1 | 1.7 | 0.0 | 1 |
| | PINSTR | Pinus strobus | Eastern white pine | 1.30 | 0.51 | 6 | 1.7 | 0.4 | 6 |
| | PINSTRX | Pinus strobus (dead) | Eastern white pine (dead) | 13.30 | 8.77 | 2 | 1.3 | 0.7 | 2 |
| | PRUPEN | Prunus pensylvanica | Pin cherry | 1.30 | 0.00 | 1 | 1.8 | 0.0 | 1 |
| | SALSPP | Salix | Willow | 0.70 | 0.00 | 1 | 1.2 | 0.0 | 1 |
| | VIBCAS | Viburnum cassinoides L. | Withe-rod | 0.82 | 0.37 | 9 | 1.3 | 0.2 | 9 |

# Table 5. (continued)

**Stand Name:** Stand G
**Forest Type:** Mature Pines - Red and White

| | Bole Height (m) | | | Basal Area | Density | Dry Biomass (tonnes/ha) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Common Name | Mean | Stand. Dev. | No. of Obs. | (m^2/ha) | (stems/ha) | Total(summer) | Total(winter) | Stem | Crown | Branch | Foliage |
| Balsam fir | 2.5 | 1.1 | 11 | 0.37 | 30 | 1.40 | 1.40 | 1.07 | 0.34 | 0.17 | 0.17 |
| Red maple | 5.2 | 2.7 | 13 | 1.73 | 363 | 13.24 | 12.60 | 10.66 | 2.58 | 1.95 | 0.63 |
| Paper birch | 7.3 | 3.4 | 9 | 0.7 | 27 | 4.18 | 3.99 | 3.48 | 0.69 | 0.51 | 0.19 |
| White spruce | 3.7 | 4.1 | 12 | 0.48 | 62 | 1.60 | 1.60 | 1.28 | 0.31 | 0.17 | 0.14 |
| Black spruce | 7.5 | 4.9 | 2 | 0.14 | 5 | 0.58 | 0.58 | 0.47 | 0.11 | 0.09 | 0.02 |
| Jack pine (dead) | | | | 0.09 | 3 | | | | | | |
| Red pine | 14.8 | 3.9 | 24 | 19.84 | 193 | 104.96 | 104.96 | 84.48 | 20.47 | 15.04 | 5.44 |
| Red pine (dead) | | | | 0.45 | 15 | | | | | | |
| Eastern white pine | 12.5 | 4.3 | 32 | 14.67 | 265 | 60.70 | 60.70 | 53.76 | 6.93 | 4.92 | 2.02 |
| Eastern white pine (dead) | | | | 1.25 | 53 | | | | | | |
| Bigtooth aspen | 14.0 | 0.0 | 1 | 0.14 | 2 | 0.80 | 0.79 | 0.69 | 0.11 | 0.10 | 0.01 |
| | | Stratum | Total | 39.86 | 1018 | 187.45 | 186.62 | 155.89 | 31.55 | 22.94 | 8.61 |
| Balsam fir | | | | 0.03 | 156 | | | | | | |
| Red maple | | | | 0.14 | 2633 | | | | | | |
| Red maple (dead) | | | | 0.00 | 8 | | | | | | |
| Serviceberry | | | | 0.00 | 31 | | | | | | |
| Paper birch | | | | 0.03 | 117 | | | | | | |
| White spruce | | | | 0.02 | 117 | | | | | | |
| Black spruce | | | | 0.00 | 8 | | | | | | |
| Eastern white pine | | | | 0.00 | 47 | | | | | | |
| Eastern white pine (dead) | | | | 0.18 | 16 | | | | | | |
| Pin cherry | | | | 0.00 | 8 | | | | | | |
| Willow | | | | 0.00 | 8 | | | | | | |
| Withe-rod | | | | 0.00 | 70 | | | | | | |
| | | Stratum | Total | 0.40 | 3219 | | | | | | |
| | | STAND | TOTAL | 40 | 4237 | | | | | | |

# Table 6. Stand Q Biometric Survey.

**Site Name:** Raco
**Stand Name:** Stand Q
**Forest Type:** Northern Hardwoods - Maple

**Stand Biometric Survey Data**

| Stratum | Tree Type | | | Diameter (cm) | | | Total Height (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acronym | Scientific Name | Common Name | Mean | Stand. Dev. | No. of Obs. | Mean | Stand. Dev. | No. of Obs. |
| Upper | ACERUB | Acer rubrum | Red maple | 14.96 | 0.40 | 245 | 18.5 | 0.8 | 19 |
| | ACERUBX | Acer rubrum (dead) | Red maple (dead) | 6.84 | 0.30 | 54 | 9.4 | 0.4 | 53 |
| | ACESAC | Acer saccharum | Sugar maple | 10.12 | 0.29 | 455 | 15.2 | 1.1 | 21 |
| | ACESACX | Acer saccharum (dead) | Sugar maple (dead) | 5.69 | 0.29 | 71 | 7.8 | 0.3 | 70 |
| | AMESPP | Amelanchier | Serviceberry | 11.45 | 1.95 | 2 | 17.0 | 1.0 | 2 |
| | FAGGRA | Fagus grandifolia | American beech | 6.69 | 0.44 | 23 | 9.1 | 1.3 | 8 |
| | POPTRE | Populus tremuloides | Quaking aspen | 23.96 | 3.04 | 11 | 18.4 | 1.2 | 11 |
| | POPTREX | Populus tremuloides (dead) | Quaking aspen (dead) | 22.24 | 4.52 | 5 | 11.1 | 3.1 | 5 |
| Middle | ABIBAL | Abies balsamea | Balsam fir | 2.48 | 0.25 | 4 | 1.3 | 0.2 | 4 |
| | ACERUB | Acer rubrum | Red maple | 1.46 | 0.25 | 15 | 1.4 | 0.1 | 15 |
| | ACERUBX | Acer rubrum (dead) | Red maple (dead) | 4.48 | 0.36 | 5 | 3.1 | 0.6 | 5 |
| | ACESAC | Acer saccharum | Sugar maple | 2.03 | 0.13 | 80 | 2.4 | 0.1 | 80 |
| | ACESACX | Acer saccharum (dead) | Sugar maple (dead) | 3.00 | 0.28 | 23 | 2.7 | 0.2 | 23 |
| | AMESPP | Amelanchier | Serviceberry | 1.22 | 0.11 | 28 | 1.6 | 0.1 | 28 |
| | AMESPPX | Amelanchier (dead) | Serviceberry (dead) | 1.25 | 0.25 | 4 | 1.9 | 0.5 | 4 |
| | FAGGRA | Fagus grandifolia | American beech | 1.90 | 0.77 | 2 | 1.5 | 0.4 | 2 |
| | FAGGRA | Fagus grandifolia (dead) | American beech (dead) | 3.90 | | 1 | 4.4 | | 1 |
| | POPTRE | Populus tremuloides | Quaking aspen | 1.10 | 0.44 | 4 | 1.8 | 0.5 | 4 |
| | POPTREX | Populus tremuloides (dead) | Quaking aspen (dead) | 0.77 | 0.07 | 3 | 1.3 | 0.1 | 3 |
| Stand | | | | | | | | | |

Table 6. (continued)

**Site Name:** Raco
**Stand Name:** Stand Q
**Forest Type:** Northern Hardwoods - Maple

| | Bole Height (m) | | | Basal Area | Density | Dry Biomass (tonnes/ha) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Common Name | Mean | Stand. Dev. | No. of Obs. | (m^2/ha) | (stems/ha) | Total(summer) | Total(winter) | Stem | Crown | Branch | Foliage |
| Red maple | 9.8 | 0.8 | 19 | 12.68 | 613 | 112.46 | 108.78 | 88.99 | 23.46 | 19.79 | 3.67 |
| Red maple (dead) | | | | 0.55 | 135 | | | | | | |
| Sugar maple | 7.1 | 0.9 | 21 | 12.59 | 1138 | 67.10 | 66.01 | 57.81 | 9.29 | 8.21 | 1.09 |
| Sugar maple (dead) | | | | 0.53 | 178 | | | | | | |
| Serviceberry | 14.0 | 0.0 | 2 | 0.05 | 5 | 0.65 | 0.62 | 0.53 | 0.12 | 0.09 | 0.03 |
| American beech | 2.0 | 0.7 | 8 | 0.22 | 58 | 0.89 | 0.86 | 0.69 | 0.20 | 0.16 | 0.03 |
| Quaking aspen | 11.8 | 1.5 | 11 | 1.44 | 28 | 8.42 | 8.30 | 7.21 | 1.21 | 1.09 | 0.12 |
| Quaking aspen (dead) | | | | 0.57 | 13 | | | | | | |
| | | **Stratum** | **Total** | **26.98** | **1842** | **189.52** | **184.57** | **155.23** | **34.28** | **29.34** | **4.94** |
| Balsam fir | | | | 0.02 | 31 | | | | | | |
| Red maple | | | | 0.03 | 117 | | | | | | |
| Red maple (dead) | | | | 0.06 | 39 | | | | | | |
| Sugar maple | | | | 0.26 | 625 | | | | | | |
| Sugar maple (dead) | | | | 0.15 | 180 | | | | | | |
| Serviceberry | | | | 0.03 | 219 | | | | | | |
| Serviceberry (dead) | | | | 0.00 | 16 | | | | | | |
| American beech | | | | 0.01 | 31 | | | | | | |
| American beech (dead) | | | | 0.01 | 8 | | | | | | |
| Quaking aspen | | | | 0.00 | 31 | | | | | | |
| Quaking aspen (dead) | | | | 0.00 | 23 | | | | | | |
| | | **Stratum** | **Total** | **0.35** | **1054** | | | | | | |
| | | **STAND** | **TOTAL** | **27.33** | **2896** | **189.52** | | **155.23** | **34.28** | **29.34** | **4.94** |

# Table 7. Stand T Biometric Survey

**Site Name:** Raco
**Stand Name:** Stand T
**Forest Type:** Mature Aspen/Maple

**Stand Biometric Survey Data**

| Stratum | Tree Type | | | Diameter (cm) | | | Total Height (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acronym | Scientific Name | Common Name | Mean | Stand. Dev. | No. of Obs. | Mean | Stand. Dev. | No. of Obs. |
| Upper | ABIBAL | Abies balsamea | Balsam fir | 13.85 | 1.35 | 2 | 12.8 | 2.3 | 2 |
| | ACERUB | Acer rubrum | Red maple | 9.82 | 0.33 | 388 | 12.8 | 1.6 | 30 |
| | ACERUBX | Acer rubrum (dead) | Red maple (dead) | 5.00 | 0.39 | 25 | 7.3 | 0.5 | 25 |
| | ACESAC | Acer saccharum | Sugar maple | 6.84 | 0.34 | 202 | 11.8 | 1.3 | 18 |
| | ACESACX | Acer saccharum (dead) | Sugar maple (dead) | 5.87 | 0.98 | 3 | 7.7 | 1.2 | 3 |
| | AMESPP | Amelanchier | Serviceberry | 3.90 | 0.33 | 14 | 7.5 | 0.8 | 5 |
| | FAGGRA | Fagus grandifolia | American beech | 8.95 | 1.13 | 16 | 10.8 | 1.4 | 10 |
| | PICGLA | Picea glauca | White spruce | 12.45 | 2.85 | 2 | 8.5 | 0.0 | 2 |
| | POPGRA | Populus grandidentata | Bigtooth aspen | 25.62 | 0.82 | 79 | 19.5 | 1.0 | 22 |
| | POPGRAX | Populus grandidentata (dead) | Bigtooth aspen (dead) | 19.47 | 1.34 | 33 | 12.1 | 0.8 | 33 |
| | POPTRE | Populus tremuloides | Quaking aspen | 23.32 | 2.02 | 6 | 21.4 | 2.1 | 6 |
| | POPTREX | Populus tremuloides (dead) | Quaking aspen (dead) | 21.25 | 9.25 | 2 | 14.0 | 2.0 | 2 |
| | PRUPEN | | | 3.63 | | 1 | 5.0 | | 1 |
| | PRUSER | | | 4.47 | 1.01 | 3 | 6.7 | 0.9 | 3 |
| Middle | ABIBAL | Abies balsamea | Balsam fir | 5.40 | 2.70 | 2 | 4.5 | 0.4 | 2 |
| | ACERUB | Acer rubrum | Red maple | 1.29 | 0.05 | 191 | 2.0 | 0.1 | 191 |
| | ACERUBX | Acer rubrum (dead) | Red maple (dead) | 2.91 | 0.48 | 30 | 2.5 | 0.2 | 30 |
| | ACESAC | Acer saccharum | Sugar maple | 1.20 | 0.10 | 193 | 1.8 | 0.1 | 193 |
| | ACESACX | Acer saccharum (dead) | Sugar maple (dead) | 2.20 | | 1 | 3.2 | | 1 |
| | AMESPP | Amelanchier | Serviceberry | 1.21 | 0.10 | 61 | 1.9 | 0.1 | 61 |
| | AMESPPX | Amelanchier (dead) | Serviceberry (dead) | 2.30 | | 1 | 2.2 | | 1 |
| | FAGGRA | Fagus grandifolia | American beech | 1.80 | 0.21 | 45 | 2.2 | 0.2 | 45 |
| | FAGGRAX | Fagus grandifolia (dead) | American beech (dead) | 3.97 | 1.21 | 3 | 3.7 | 0.9 | 3 |
| | GAYBAC | | | 0.90 | | 1 | 1.5 | | 1 |
| | PICGLA | Picea glauca | White spruce | 2.60 | 0.61 | 2 | 1.6 | 0.5 | 3 |
| | POPGRA | Populus grandidentata | Bigtooth aspen | 26.40 | 9.10 | 3 | 1.5 | 0.4 | 2 |
| | POPGRAX | Populus grandidentata (dead) | Bigtooth aspen (dead) | 14.97 | 2.79 | 6 | 1.6 | 0.2 | 6 |
| | POPTRE | Populus tremuloides | Quaking aspen | 0.50 | 0.00 | 2 | 1.2 | 0.2 | 2 |
| | PRUSER | | | 0.90 | | 1 | 1.8 | | 1 |
| | PRUSERX | | | 0.90 | | 1 | 1.2 | | 1 |
| | SORAME | | | | | | | | |
| | STAND | | TOTAL (live) | | | | | | |

# Table 7. (continued)

**Site Name:** Raco
**Stand Name:** Stand T
**Forest Type:** Mature Aspen/Maple

| | Bole Height (m) | | | Basal Area | Density | Dry Biomass (tonnes/ha) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Common Name | Mean | Stand. Dev. | No. of Obs. | (m^2/ha) | (stems/ha) | Total(summer) | Total(winter) | Stem | Crown | Branch | Foliage |
| Balsam fir | 1.5 | 0.5 | 2 | 0.08 | 5 | 0.013 | 0.013 | 0.010 | 0.003 | 0.002 | 0.002 |
| Red maple | 6.4 | 0.5 | 21 | 10.5 | 970 | 113.644 | 110.198 | 88.414 | 25.230 | 21.784 | 3.446 |
| Red maple (dead) | | | | 0.14 | 63 | | | | | | |
| Sugar maple | 4.8 | 0.4 | 15 | 2.78 | 505 | 45.335 | 44.662 | 38.939 | 6.396 | 5.723 | 0.673 |
| Sugar maple (dead) | | | | 0.02 | 8 | | | | | | |
| Serviceberry | 3.9 | 0.7 | 5 | 0.05 | 13 | | | | | | |
| American beech | 2.7 | 0.7 | 10 | 0.31 | 40 | 12.101 | 11.891 | 9.477 | 2.624 | 2.414 | 0.210 |
| White spruce | 1.3 | 0.8 | 2 | 0.06 | 5 | | | | | | |
| Bigtooth aspen | 11.6 | 0.6 | 21 | 10.99 | 198 | 12.501 | 12.296 | 10.802 | 1.699 | 1.494 | 0.205 |
| Bigtooth aspen (dead) | | | | 2.83 | 83 | | | | | | |
| Quaking aspen | 12.5 | 1.1 | 6 | 0.66 | 15 | 0.938 | 0.921 | 0.818 | 0.120 | 0.103 | 0.017 |
| Quaking aspen (dead) | | | | 0.21 | 5 | | | | | | |
| | 1.5 | | 1 | 0 | 3 | | | | | | |
| | 3.5 | 0.3 | 3 | 0.01 | 8 | 4.919 | 4.686 | 4.023 | 0.896 | 0.663 | 0.233 |
| | | **Stratum** | **Mean** | **25.44** | **1762** | **189.451** | **184.667** | **152.483** | **36.968** | **32.183** | **4.786** |
| Balsam fir | | | | 0.04 | 16 | | | | | | |
| Red maple | | | | 0.26 | 1492 | | | | | | |
| Red maple (dead) | | | | 0.28 | 234 | | | | | | |
| Sugar maple | | | | 0.38 | 1507 | | | | | | |
| Sugar maple (dead) | | | | 0 | 8 | | | | | | |
| Serviceberry | | | | 0.08 | 477 | | | | | | |
| Serviceberry (dead) | | | | 0 | 8 | | | | | | |
| American beech | | | | 0.14 | 351 | | | | | | |
| American beech (dead) | | | | 0.03 | 23 | | | | | | |
| | | | | 0 | 8 | | | | | | |
| White spruce | | | | 0.01 | 23 | | | | | | |
| Bigtooth aspen | | | | 0.96 | 16 | | | | | | |
| Bigtooth aspen (dead) | | | | 0.97 | 47 | | | | | | |
| Quaking aspen | | | | 0 | 16 | | | | | | |
| | | | | 0 | 31 | | | | | | |
| | | | | 0 | 8 | | | | | | |
| | | | | 0 | 8 | | | | | | |
| | | **Stratum** | **Mean** | **1.87** | **3945** | | | | | | |
| **TOTAL (live)** | | | | **27.31** | **5707** | | | | | | |

Table 8. Dielectric measurements of trees in Stand G.

Stand: Raco G
Date: 08-April-1992
Start Time: 8:30
Stop Time: 14:35
Device Id: P148, L102

| Specie | dbh (in cm) | Tree # | Depth (in mm) | P Band Real E | P Band Real E SD | P Band Imag E | P Band Imag E SD | L Band Real E | L Band Real E SD | L Band Imag E | L Band Imag E SD | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Redpine | 25 | 1 | 0 | 3.11 | .61 | .4 | 0 | 2.68 | .34 | .74 | 0 | bark |
| Redpine | 25 | 1 | 6.5 | 2.46 | 0 | .6 | 0 | 2.92 | .34 | .82 | .12 | bark |
| Redpine | 25 | 1 | 22 | 33.29 | 2.97 | 8.25 | .68 | 7.01 | .34 | .5 | 0 | bark |
| Redpine | 25 | 1 | 23 | 20.02 | 0 | 4.37 | 0 | 22.03 | 1.59 | 8.42 | .56 | cambium |
| Redpine | 25 | 1 | 28 | 14.16 | 0 | 2.47 | 0 | 9.18 | .68 | 2.87 | .26 | |
| Redpine | 25 | 1 | 41 | 18.88 | 1.28 | 3.52 | .3 | 27.51 | 1 | 8.95 | 1.48 | |
| Redpine | 25 | 1 | 54 | 17.09 | 0 | 3.73 | 0 | 20.01 | .65 | 6.61 | .06 | |
| Redpine | 25 | 1 | 73 | 22.48 | .69 | 3.14 | 0 | 28.87 | .43 | 10.77 | .33 | |
| Redpine | 25 | 1 | 81 | 22.47 | 1.39 | 4.4 | 0 | 32.29 | 1.23 | 12.1 | .07 | |
| Redpine | 25 | 1 | 91 | 34.48 | 3.74 | 4.88 | .64 | 27.79 | .92 | 8.3 | .77 | |
| Redpine | 25 | 1 | 113 | 22.96 | 1.2 | 4.19 | .3 | 27.55 | .94 | 7.84 | .19 | |
| Whitepine | 32.5 | 2 | 0 | 2.95 | .69 | 0 | 0 | | | | | |
| Whitepine | 32.5 | 2 | 4.5 | 15.62 | 0 | 2.51 | 0 | 9.26 | 1.6 | 2.46 | .59 | bark |
| Whitepine | 32.5 | 2 | 5.7 | 45.41 | 2.46 | 10.22 | .9 | 38.8 | .54 | 13.76 | .04 | cambium |
| Whitepine | 32.5 | 2 | 7.2 | 38.51 | .75 | 8.14 | .35 | 33.89 | 4.83 | 8.67 | 1.35 | xylem |
| Whitepine | 32.5 | 2 | 8.9 | 21.74 | .74 | 3.79 | .01 | 24.61 | .18 | 14.99 | 1.09 | depth>100mm tree hollow |
| Whitepine | 32.5 | 2 | 11 | 21.82 | 1.29 | 4.01 | .31 | 8.21 | 1.02 | | | |
| Whitepine | 32.5 | 2 | 12 | 16.6 | 1.38 | 2.93 | .3 | 14.74 | 2.1 | 1.34 | 4.75 | |
| Whitepine | 32.5 | 2 | 21 | 18.56 | 0 | 2.81 | .27 | 15.83 | 1.82 | 5.19 | .62 | |
| Whitepine | 32.5 | 2 | 29 | 12.04 | 1.96 | 2.1 | .6 | 8.69 | .9 | 2.79 | .41 | |
| Whitepine | 32.5 | 2 | 47 | 18.07 | .69 | 3.16 | 0 | 9.42 | .68 | 3.17 | .14 | |
| Whitepine | 32.5 | 2 | 62 | | | | | 15.66 | .5 | .5 | .14 | |
| Whitepine | 32.5 | 2 | 68 | 26.08 | 1.01 | 4.48 | 0 | 26.37 | .93 | 8.88 | .3 | |
| Whitepine | 32.5 | 2 | 82 | 13.67 | .69 | 2.53 | 0 | 8.93 | .9 | 3.09 | .63 | |
| Redpine | 34 | 3 | 0 | 3.43 | .69 | 0 | 0 | 1.72 | 0 | | | bark |
| Redpine | 34 | 3 | 22 | 19.21 | 2.66 | .86 | .31 | 22.57 | 2.98 | 7.35 | .32 | cambium |
| Redpine | 49.1 | 4 | 0 | 2.46 | 0 | | | 2.12 | .3 | .56 | 0 | bark |
| Redpine | 49.1 | 4 | 22 | 43.25 | 3.09 | 8.95 | .29 | 39.3 | 9.87 | 13.34 | 1.89 | cambium |
| Redpine | 34.5 | 5 | 0 | 3.43 | .69 | 1.27 | .9 | 2.84 | .3 | .7 | .12 | bark |
| Redpine | 34.5 | 5 | 13 | 27.88 | 1.39 | 5.15 | .28 | 37.41 | 3.16 | 12.41 | 1.76 | cambium |
| Redpine | 51 | 6 | 0 | 2.46 | 0 | 0 | 0 | 2.84 | .3 | .76 | 0 | bark |
| Redpine | 51 | 6 | 23 | 52.15 | 1.57 | 9.7 | .25 | 49.89 | 1.12 | 17.39 | .28 | cambium |
| Whitepine | 38.7 | 7 | 0 | 2.61 | 0 | 0 | 0 | 1.72 | 0 | .19 | .13 | bark |
| Whitepine | 38.7 | 7 | 10 | 39.77 | .71 | 6.88 | .32 | 39.06 | 1.46 | 14.9 | .48 | cambium |
| Whitepine | 35.3 | 8 | 0 | 1 | 0 | 0 | 0 | 2.2 | .34 | .28 | 0 | bark |
| Whitepine | 35.3 | 8 | 6.2 | 11.23 | 0 | 1.79 | .11 | 12.24 | 1.84 | 3.46 | .28 | cambium |
| Redpine | 31.9 | 9 | 0 | 1.5 | 0 | .63 | 0 | 2.92 | .34 | .45 | .13 | bark |
| Redpine | 31.9 | 9 | 13 | 55.18 | 3.52 | 6.99 | .72 | 53.49 | 2.94 | 16.32 | 1.07 | cambium |
| Whitepine | 16.9 | 10 | 0 | 1 | 0 | 0 | 0 | 2.44 | 0 | .55 | 0 | bark |
| Whitepine | 16.9 | 10 | 5 | 39.77 | 2.54 | 6.62 | .58 | 40.49 | 8.67 | 12.51 | 2.88 | cambium |
| Whitespruce | 7.1 | 11 | 0 | 5.38 | 0 | .21 | .3 | 4.2 | .3 | 1.22 | .13 | bark |
| Whitespruce | 7.1 | 11 | 3 | 28.88 | 0 | 2.28 | 2.28 | 38.67 | 2.91 | 13.28 | .85 | cambium |
| Whitepine | 33.5 | 12 | 0 | 1 | 0 | 0 | 0 | 2.68 | .34 | .56 | 0 | bark |
| Whitepine | 33.5 | 12 | 8 | 41.77 | 1.87 | 7.05 | .3 | 43.64 | 5.48 | 15.82 | .69 | cambium |

le 9. Dielectric measurements of trees in Stand Q.

```
d: Raco Q
:  09-April-1992
t Time: 9:40
 Time:  15:43
ce Id:  P148
```

| ie | dbh (in cm) | Tree # | Depth (in mm) | P Band Real E | P Band Real E SD | P Band Imag E | P Band Imag E SD | Comments |
|---|---|---|---|---|---|---|---|---|
| h | 12.6 | 1 | 0 | 10.54 | 1.65 | | | bark |
| h | 12.6 | 1 | 4.5 | 15.57 | 3.15 | 2.37 | 1.11 | cambium |
| rMaple | 29 | 2 | 0 | 5.2 | .23 | | | bark |
| rmaple | 29 | 2 | 6.5 | 25.82 | 0 | 0 | 0 | cambium |
| rmaple | 29 | 2 | 8.6 | 58.82 | 2.18 | 3.67 | .35 | sap flow |
| rmaple | 16 | 3 | 0 | 2.94 | .69 | | | bark |
| rmaple | 16 | 3 | 5.3 | 20.44 | 2.49 | 1.32 | .54 | cambium |
| rmaple | 16 | 3 | 7.2 | 40.97 | 1.31 | 3.34 | .01 | sap flow |
| rmaple | 13.5 | 4 | 0 | 2.45 | 0 | | | bark |
| rmaple | 13.5 | 4 | 4.5 | 36.16 | 2.43 | 4.85 | .31 | heavy sap flow |
| rmaple | 13.5 | 4 | 8 | 25.82 | 0 | 3.06 | .31 | got worse(sap flow) |
| aple | 8.6 | 5 | 0 | 11.19 | 0 | 1.28 | 0 | bark |
| aple | 8.6 | 5 | .4 | 13.13 | .69 | 2.14 | .31 | bark |
| aple | 8.6 | 5 | 2.5 | 52.69 | 2.49 | 4.74 | .02 | sap flow |
| rmaple | 30 | 6 | 0 | 1 | 0 | 0 | 0 | bark |
| rmaple | 30 | 6 | 9.2 | 3.91 | 0 | | | cambium |
| rmaple | 30 | 6 | 44 | 12.65 | 0 | .96 | .32 | |
| rmaple | 13.8 | 7 | 0 | 6.84 | 0 | 1.47 | .3 | bark |
| rmaple | 13.8 | 7 | 1.2 | 14.11 | 1.46 | 2.25 | .33 | bark |
| rmaple | 13.8 | 7 | 4.6 | 37.88 | .74 | 6.33 | .35 | cambium |
| aple | 19.4 | 8 | 0 | 8.47 | .23 | 1.25 | 0 | bark |
| aple | 19.4 | 8 | 3.2 | 28.86 | 0 | 5.47 | .28 | cambium |
| aple | 19.4 | 8 | 5.1 | 38.04 | .75 | 4.56 | .01 | sap |
| rmaple | 25.6 | 9 | 0 | 3.92 | 0 | .61 | 0 | bark |
| rmaple | 25.6 | 9 | 3.5 | 19.04 | .69 | 3.98 | .3 | bark |
| rmaple | 25.6 | 9 | 4.5 | 58.52 | .73 | 5.69 | .28 | cambium |
| rmaple | 25.8 | 10 | 0 | 2.46 | 0 | 0 | 0 | bark |
| rmaple | 25.8 | 10 | 6 | 15.13 | 2.76 | 3.75 | .9 | cambium |
| rmaple | 25.8 | 10 | 8 | 44.29 | .71 | 5.16 | .01 | sap flow |
| aple | 16.4 | 11 | 0 | 11.19 | 0 | 2.56 | 0 | bark |
| aple | 16.4 | 11 | 1 | 17.02 | 0 | 4.52 | 0 | bark |
| aple | 16.4 | 11 | 2 | 13.38 | .73 | 2.88 | .33 | bark |
| aple | 16.4 | 11 | 4 | 17.03 | 0 | 3.21 | 0 | cambium |
| aple | 16.4 | 11 | 4.3 | 56.75 | 2.61 | 6.13 | .03 | sap flow |
| aple | 16.4 | 11 | 6 | 48.89 | .76 | 4.7 | .01 | |
| aple | 16.4 | 11 | 12 | 50.17 | 4.35 | 4.72 | .03 | |
| aple | 16.4 | 11 | 17 | 46.14 | 1.88 | 3.14 | .33 | |
| aple | 16.4 | 11 | 44 | 43.63 | 0 | 1.4 | .11 | |
| aple | 16.4 | 11 | 61 | 47.63 | .71 | 5.55 | .32 | |
| maple | 23.6 | 12 | 0 | 2.46 | 0 | .63 | 0 | bark |
| maple | 23.6 | 12 | 6 | 15.57 | .79 | 3.18 | .53 | bark |
| maple | 23.6 | 12 | 9 | 50.65 | 1.43 | 5.94 | .01 | steady sap flow |
| maple | 23.6 | 12 | 16 | 33.43 | 1.23 | 5.14 | .01 | |
| maple | 23.6 | 12 | 39 | 49.14 | 1.88 | 5.66 | .3 | |
| maple | 23.6 | 12 | 76 | 34.67 | 0 | 4.54 | 0 | |
| maple | 23.6 | 12 | 112 | 29.25 | .49 | 3.86 | 0 | |
| ı | 10 | 13 | 0 | 8.28 | 1.19 | 1.05 | .3 | bark |
| ı | 10 | 13 | 1 | 17.03 | 1.19 | 3.59 | .3 | cambium |
| ı | 10 | 13 | 3 | 11.68 | .49 | 1.25 | .63 | through cambium |
| ı | 10 | 13 | 5 | 21.9 | .69 | 3.17 | .01 | |

le 10. Dielectric measurements of trees in Stand T.

id: Raco T
:: 10-April-1992
t Time: 11:00
Time: 13:20
ce Id: P148

| ie | dbh (in cm) | Tree # | Depth (in mm) | P Band Real E | P Band Real E SD | P Band Imag E | P Band Imag E SD | Comments |
|---|---|---|---|---|---|---|---|---|
| ooth Aspen | 21.6 | 1 | 0 | 2.46 | 0 | 1.02 | .29 | bark |
| ooth Aspen | 21.6 | 1 | 1.3 | 2.46 | 0 | .61 | 0 | bark |
| ooth Aspen | 21.6 | 1 | 1.5 | 2.79 | .46 | 0 | 0 | bark |
| ooth Aspen | 21.6 | 1 | 2 | 1.49 | 0 | 0 | 0 | bark |
| ooth Aspen | 21.6 | 1 | 2.7 | 1.49 | 0 | 0 | 0 | bark |
| ooth Aspen | 21.6 | 1 | 3.1 | 2.46 | 0 | .2 | .16 | bark |
| ooth Aspen | 21.6 | 1 | 5 | 2.3 | .23 | 0 | 0 | bark |
| ooth Aspen | 21.6 | 1 | 6.1 | 10.74 | .69 | .61 | 0 | cambium |
| ooth Aspen | 21.6 | 1 | 6.4 | 8.96 | 1.15 | 1.21 | 0 | |
| ooth Aspen | 21.6 | 1 | 7.2 | 5.87 | .69 | .6 | 0 | |
| ooth Aspen | 21.6 | 1 | 7.5 | 5.87 | .49 | .6 | .01 | |
| ooth Aspen | 21.6 | 1 | 10 | 16.11 | 2.39 | 1.36 | .35 | |
| ooth Aspen | 21.6 | 1 | 12 | 12.69 | 1.46 | 1.52 | .31 | |
| ooth Aspen | 21.6 | 1 | 19 | 3.92 | 0 | 0 | 0 | |
| ooth Aspen | 21.6 | 1 | 44 | 6.84 | .01 | .3 | .3 | |
| ooth Aspen | 21.6 | 1 | 72 | 26.66 | 3.69 | 4.06 | .96 | |
| ooth Aspen | 21.6 | 1 | 85 | 25.59 | 2.67 | 4.79 | .31 | |
| ooth Aspen | 21.5 | 2 | 0 | 3.92 | 0 | 1.21 | 0 | bark |
| ooth Aspen | 21.5 | 2 | 21 | 4.65 | .73 | 0 | 0 | bark |
| ooth Aspen | 21.5 | 2 | 81 | 9.77 | 0 | 1.82 | 0 | cambium |
| ooth Aspen | 27.5 | 3 | 0 | 11.72 | .98 | 2.44 | .62 | bark |
| ooth Aspen | 27.5 | 3 | 2 | 5.38 | 0 | .6 | 0 | |
| ooth Aspen | 27.5 | 3 | 5 | 5.06 | .46 | 1.01 | .29 | |
| oth Aspen | 30 | 4 | 0 | 2.46 | 0 | 0 | 0 | bark |
| oth Aspen | 30 | 4 | 5.8 | 7.57 | .73 | 1.82 | 0 | older_tree |
| oth Aspen | 30 | 4 | 11 | 20.02 | 2.94 | 4.97 | .63 | cambium |
| oth Aspen | 19.4 | 5 | 0 | 17.09 | 0 | 3.69 | 0 | bark |
| oth Aspen | 19.4 | 5 | 2 | 2.95 | .69 | .2 | 0 | bark |
| oth Aspen | 19.4 | 5 | 6 | 14.65 | .69 | 2.46 | .88 | cambium |
| oth Aspen | 17.1 | 6 | 0 | 2.46 | 0 | .6 | 0 | bark |
| oth Aspen | 17.1 | 6 | 3 | 4.65 | .73 | .61 | .01 | cambium |
| oth Aspen | 17.1 | 6 | 12 | 4.25 | .83 | | | |
| oth Aspen | 17.1 | 6 | 19 | 2.46 | .69 | 0 | 0 | |

Table 11. Relative Dielectric constants of needles at P-band.

Raco Needle Measurements
April 10, 1992
P-Band
P148, Tip #3, Rubbing Alcohol

| | ε' | | ε' | | |
|---|---|---|---|---|---|
| Specie | Mean | Std Deviation | Mean | Std. Deviation | # of Samples |
| Jackpine | 12.208 | 2.554 | 1.752 | 0.494 | 5 |
| Redpine | 17.097 | 3.645 | 3.186 | 0.783 | 10 |
| Whitepine | 16.235 | 2.874 | 3.351 | 0.694 | 10 |
| Blackspruce | 13.583 | 2.395 | 3.066 | 0.666 | 3 |
| Whitespruce | 11.534 | 4.873 | 2.450 | 1.510 | 5 |

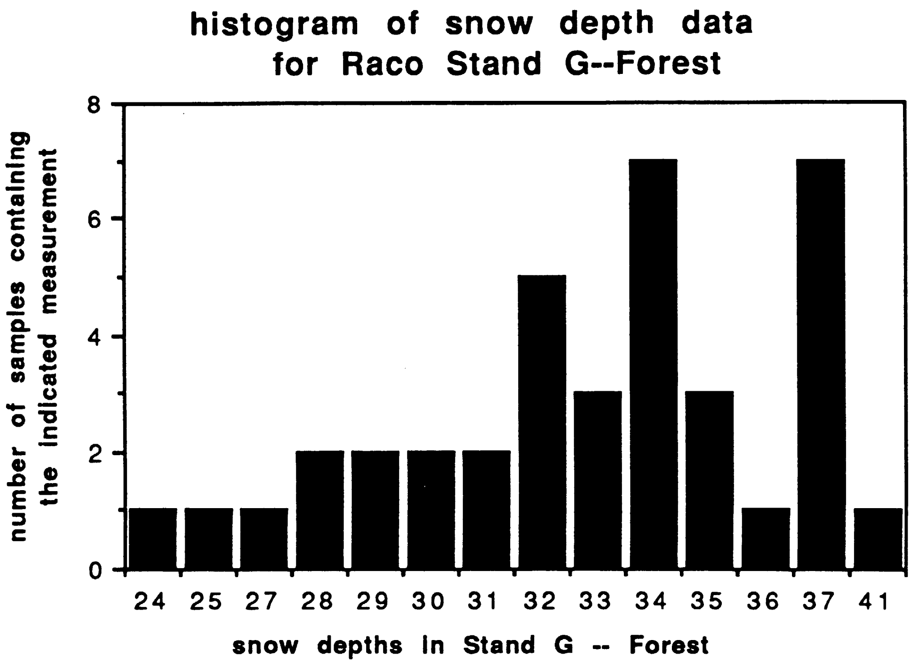
Table 12. Branch Moisture Measurements.

Raco Tree Branch Measurements
April, 1992

| | Volumetric Moisture ($g/cm^3$) | | Specific Denisty ($g/cm^3$) | | |
|---|---|---|---|---|---|
| Specie | Mean | Std Deviation | Mean | Std. Deviation | # of Samples |
| Aspen | .5443 | .0193 | .3922 | .0319 | 8 |
| Beech | .4077 | .0046 | .6290 | .0147 | 5 |
| Maple | .4550 | .0803 | .0622 | .0983 | 6 |
| Jack Pine | .5341 | .0834 | .4638 | .0626 | 8 |
| Red Pine | .4870 | .0419 | .4582 | .0456 | 8 |
| White Pine | .5495 | .0508 | .3504 | .0131 | 8 |

Table 13. Soil and Snow Observations

| | RACO - Stand G | | RACO - Stand Q | |
|---|---|---|---|---|
| | Forest | Clearing | Forest | Clearing |
| **Snow Observations** | | | | |
| Date | 4/8/92 | 4/8/92 | 4/9/92 | 4/9/92 |
| Snow Depth | | | | |
| Start Time | 8:15 AM | 10:40 AM | 10:55 AM | 2:20 PM |
| Stop Time | 9:00 AM | 11:50 AM | 11:15 AM | 3:20 PM |
| Mean (cm) | 35.886 | 32.684 | 25.400 | 31.350 |
| Standard Deviation (cm) | 6.338 | 3.569 | 6.077 | 3.373 |
| No. of Observations | 22 | 38 | 15 | 40 |
| Snow Water Equivalent | | | | |
| Start Time | 1:50 PM | 2:50 PM | 11:15 AM | 3:40 PM |
| Stop Time | 2:35 PM | 4:00 PM | 11:55 AM | 4:50 PM |
| Mean (g/cm^2) | 13.581 | 10.961 | 8.069 | 11.702 |
| Standard Deviation (g/cm^2) | 4.385 | 1.742 | 2.063 | 0.931 |
| No. of Observations | 5 | 10 | 5 | 9 |
| Mean Snow Density (g/cm^3) | 0.378 | 0.335 | 0.318 | 0.373 |
| **Soil Observations** | | | | |
| Date | 4/10/92 | 4/10/92 | 4/10/92 | |
| Time | 12:15 PM | 1:15 PM | 11:00 AM | |
| Temperatures | | | | |
| Air (°C) | 0.5 | 2.0 | 0.0 | |
| Snow (°C) | 0.0 | 0.0 | -0.4 | |
| Soil (°C) | 1.4 | 1.0 | 1.0 | |
| Snow Depth (cm) | 21.0 | 24.0 | NA | |
| Soil State | Thawed | Thawed | Thawed | |
| Thickness of Needle and Humus Layer (cm) | | 2 | | |
| Thickness of Organic Layer (cm) | 5 | 2 | 5 | |
| Mineral Soil Texture | Sand | Sand | Sand | |
| Bulk Density (g/cm^3) | | | | |
| Organic Layer | 0.411 | | 0.584 | |
| Mineral Soil | 1.122 | 1.441 | 1.370 | |
| Gravimetric Moisture (g/g) | | | | |
| Organic Layer | 1.575 | | 1.198 | |
| Mineral Soil | 0.421 | 0.346 | 0.341 | |
| Volumetric Moisture (g/cm^3) | | | | |
| Organic Layer | 0.647 | | 0.700 | |
| Mineral Soil | 0.472 | 0.496 | 0.467 | |



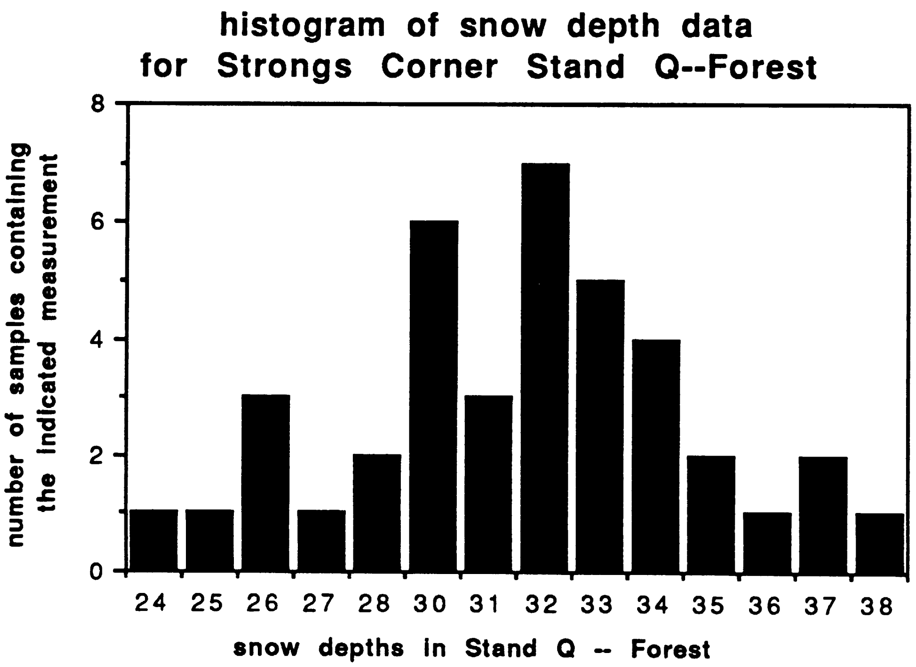
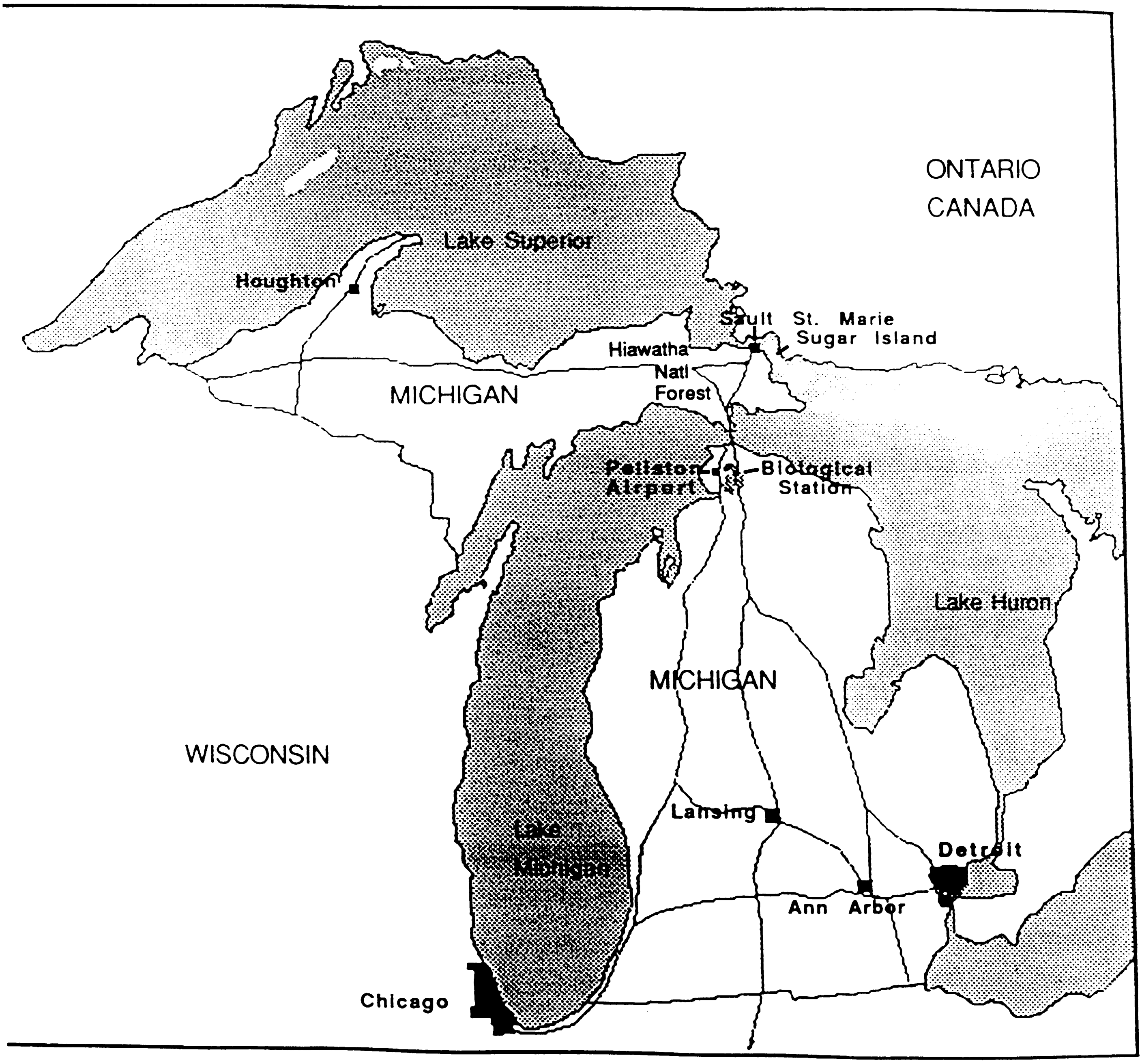




Figure 14. Histograms of snow depth in Stands G and Q.




The University of Michigan
Microwave Image Processing Laboratory

Figure 1. Experimental Test Site is west of Sault Ste. Marie in the Hiawatha National Forest.

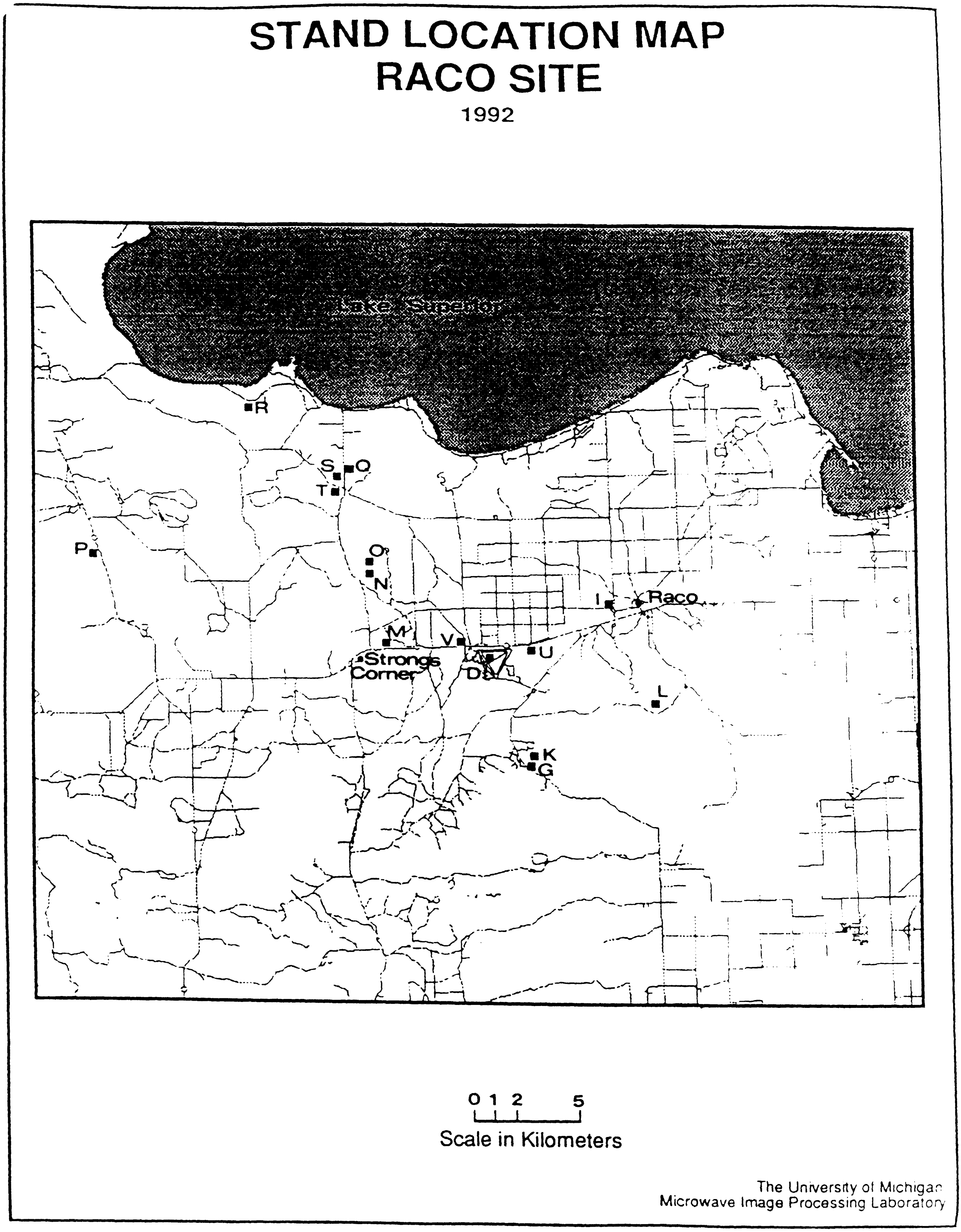



Figure 2. Locations of forest stands in the vicinity of Raco, Michigan.

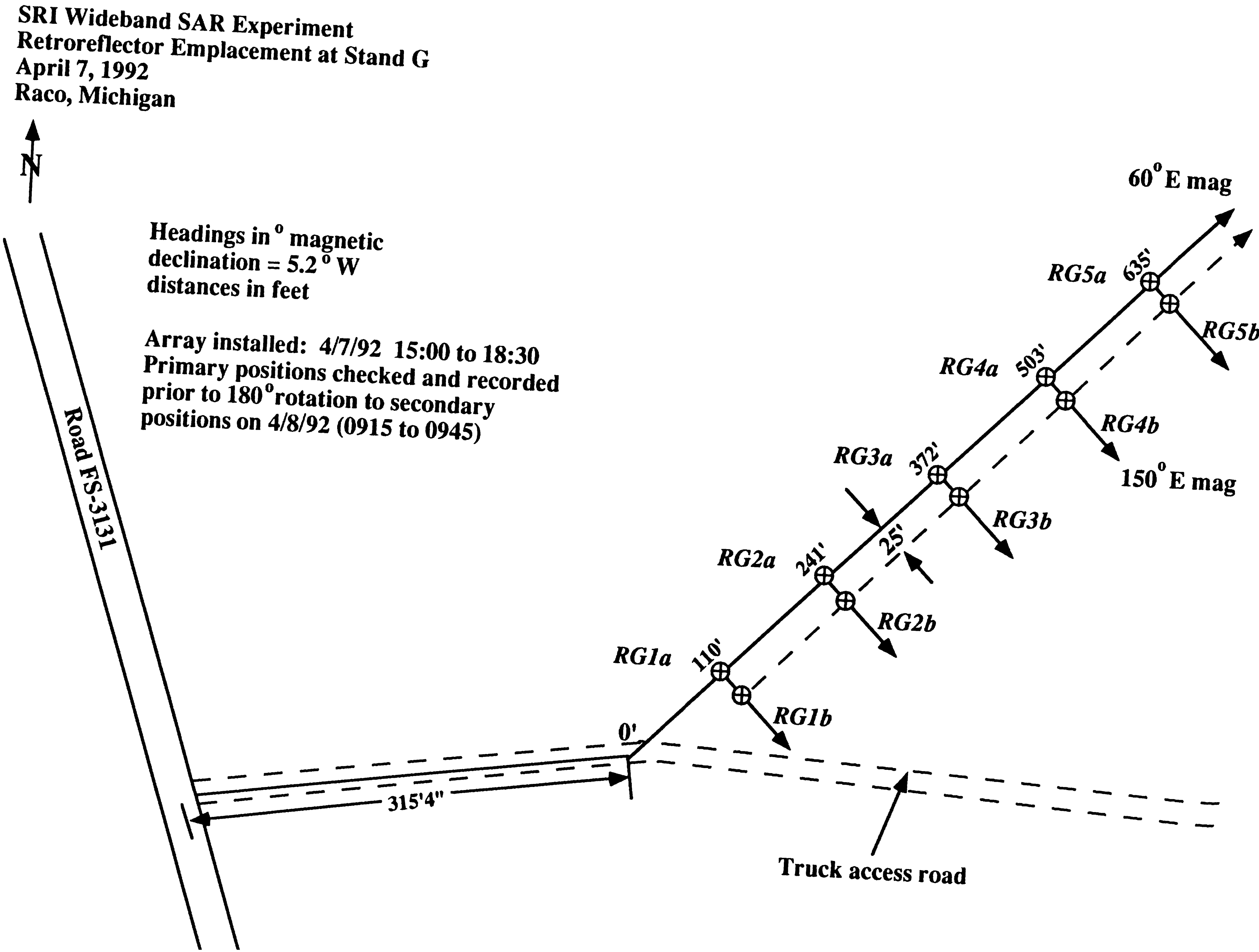

SRI Wideband SAR Experiment
Retroreflector Emplacement at Stand G
April 7, 1992
Raco, Michigan
N
Headings in ° magnetic
declination = 5.2 ° W
distances in feet
Array installed: 4/7/92 15:00 to 18:30
Primary positions checked and recorded
prior to 180°rotation to secondary
positions on 4/8/92 (0915 to 0945)
Road FS-3131
315'4"
0'
RG1a
110'
RG1b
RG2a
241'
RG2b
RG3a
372'
RG3b
25'
RG4a
503'
RG4b
RG5a
635'
RG5b
60° E mag
150° E mag
Truck access road

Figure 3

**SRI - Wideband SAR Experiment**
**Retroreflector Emplacement**
**Clearcut North of Stand G**
**Raco, Michigan**
**April 7, 1992**

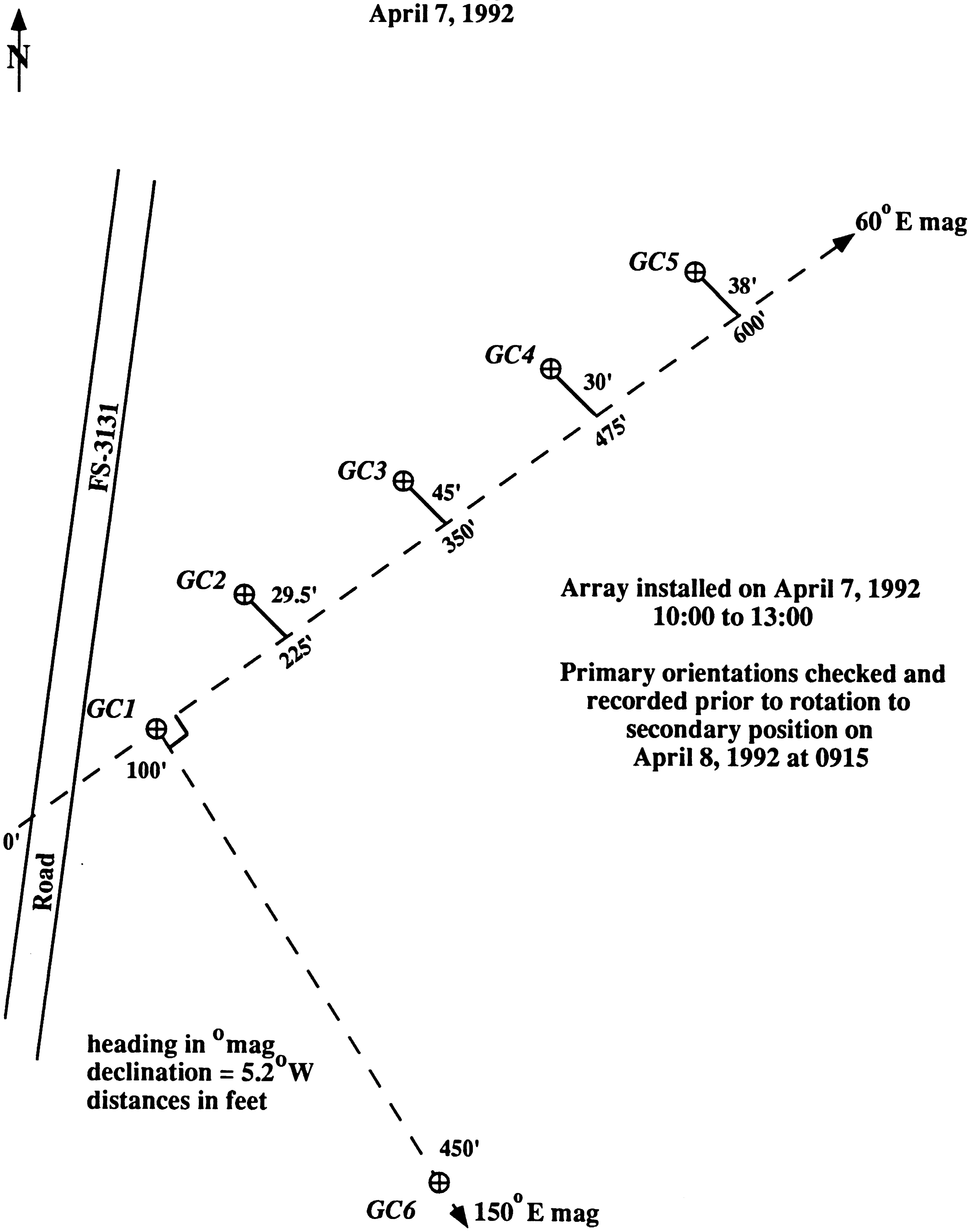
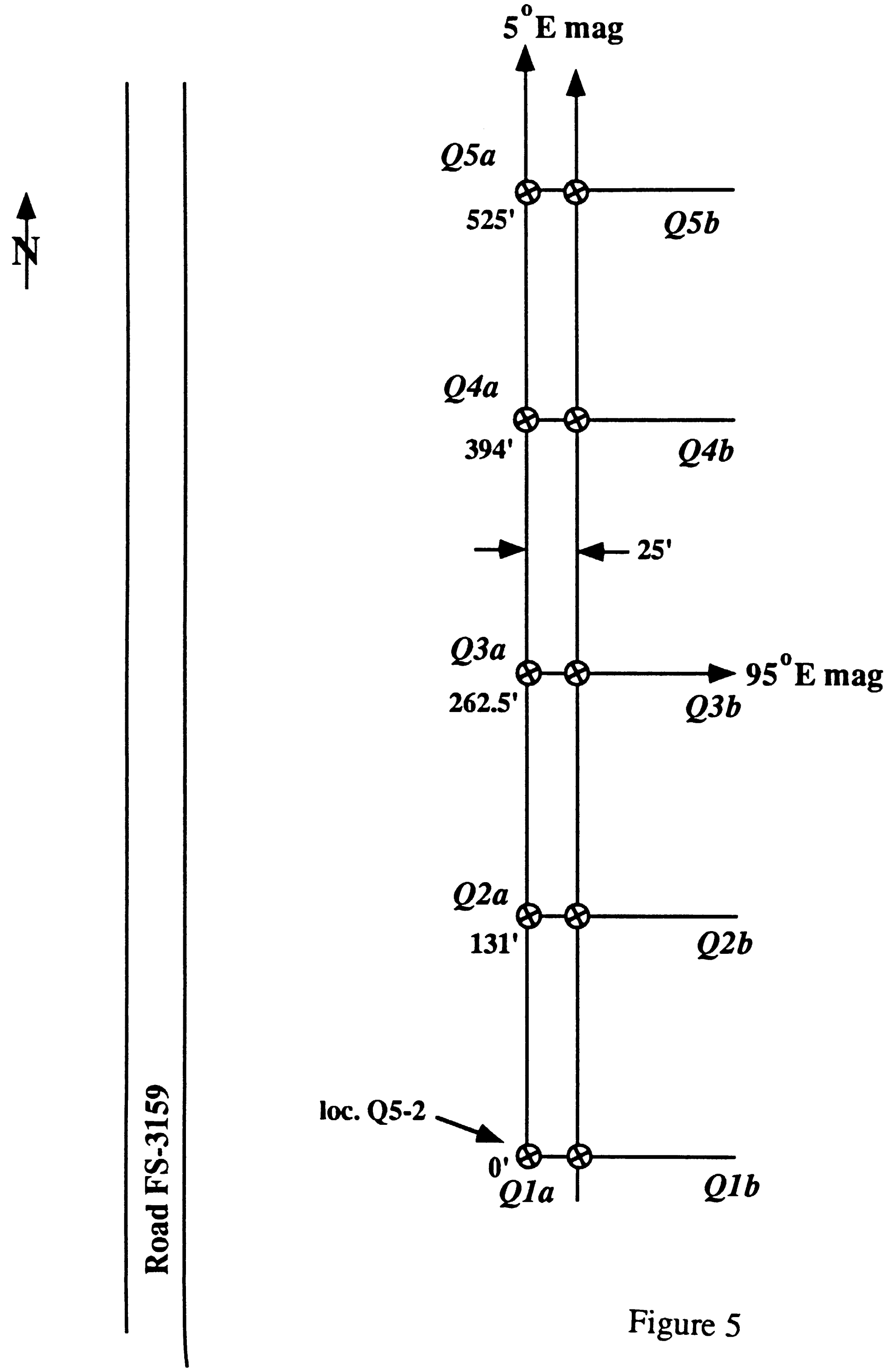



Figure 4

**SRI Wideband SAR Experiment**
**Retroreflector Emplacement in Stand Q**
**April 8, 1992**
**Raco, Michigan**




**headings in °magnetic**
**declination = 5.2° W**
**distances in feet**

**Array installed 4/8/92**
**16:45 to 18:00**

**Primary orientation**
**recorded at deployment**

**Secondary orientations**
**recorded after rotation on**
**April 9, 1992**

Figure 5

**SRI Wideband SAR Experiment**
**Retroreflector Emplacement at Clearing ESE of Stand Q**
**April 9, 1992**
**Raco, Michigan**

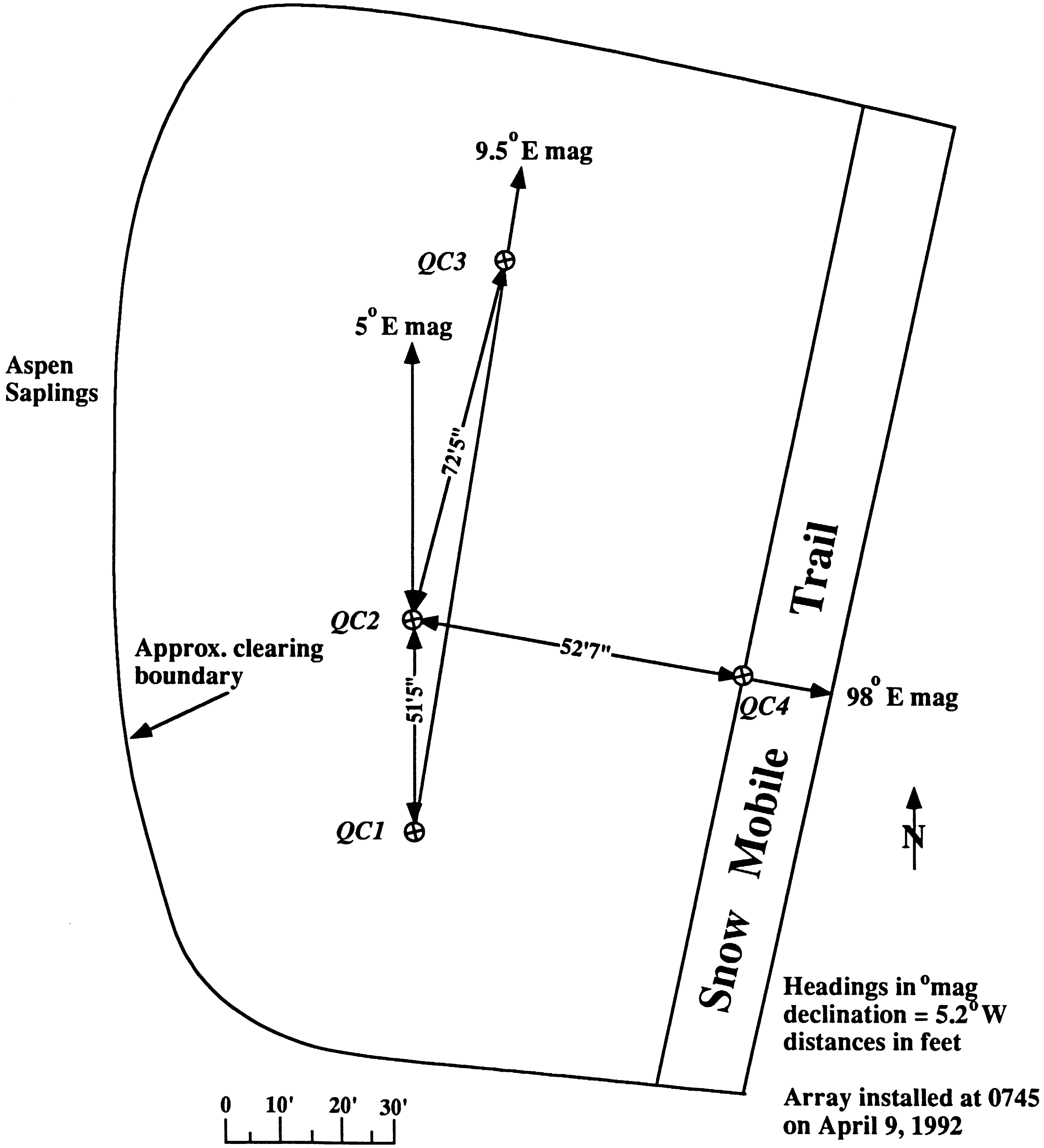



Figure 6

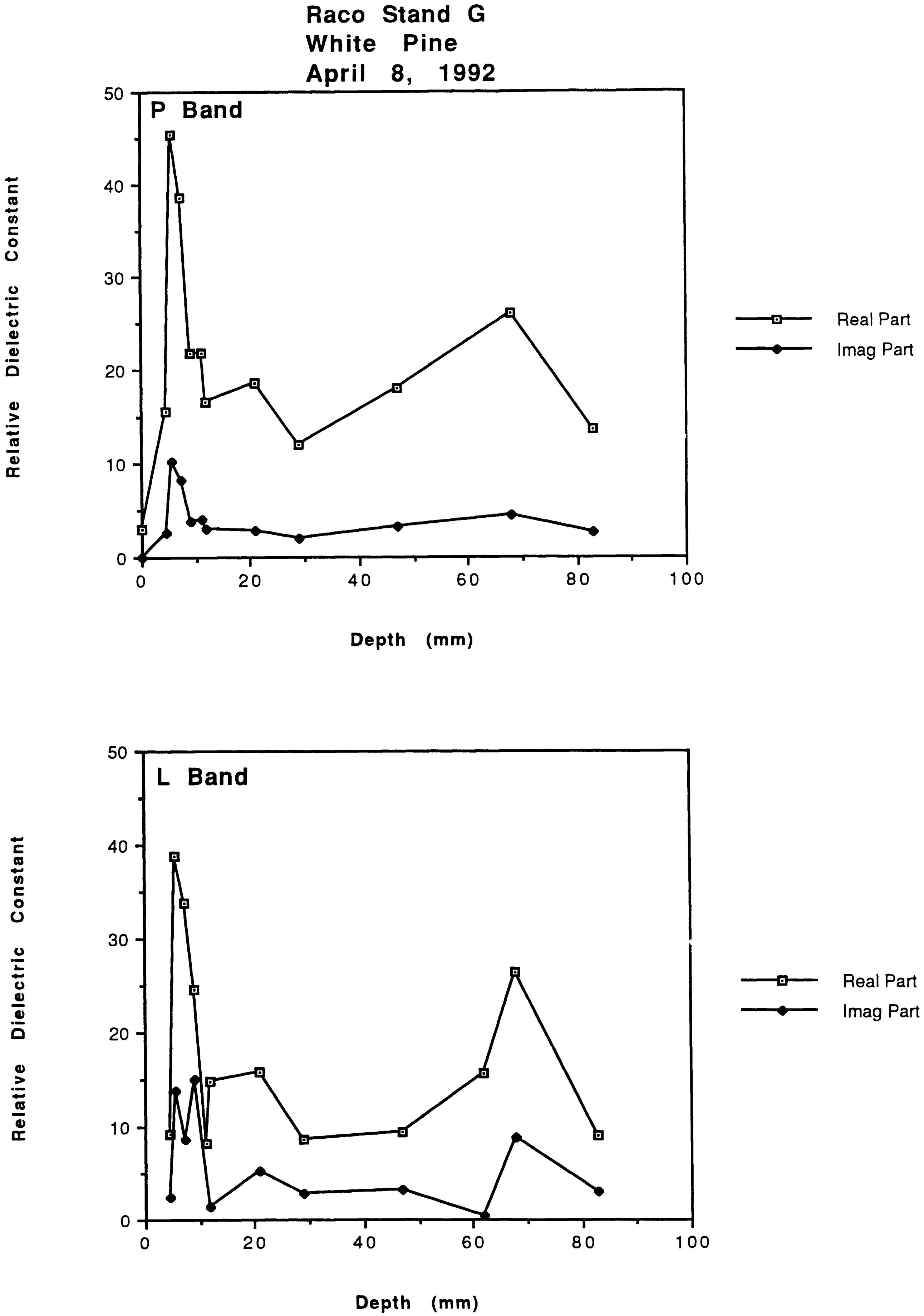



Figure 7. Dielectric constant as a function of depth into the trunk of a white pine tree in Stand G, at (a) P-band and (b) L-band.

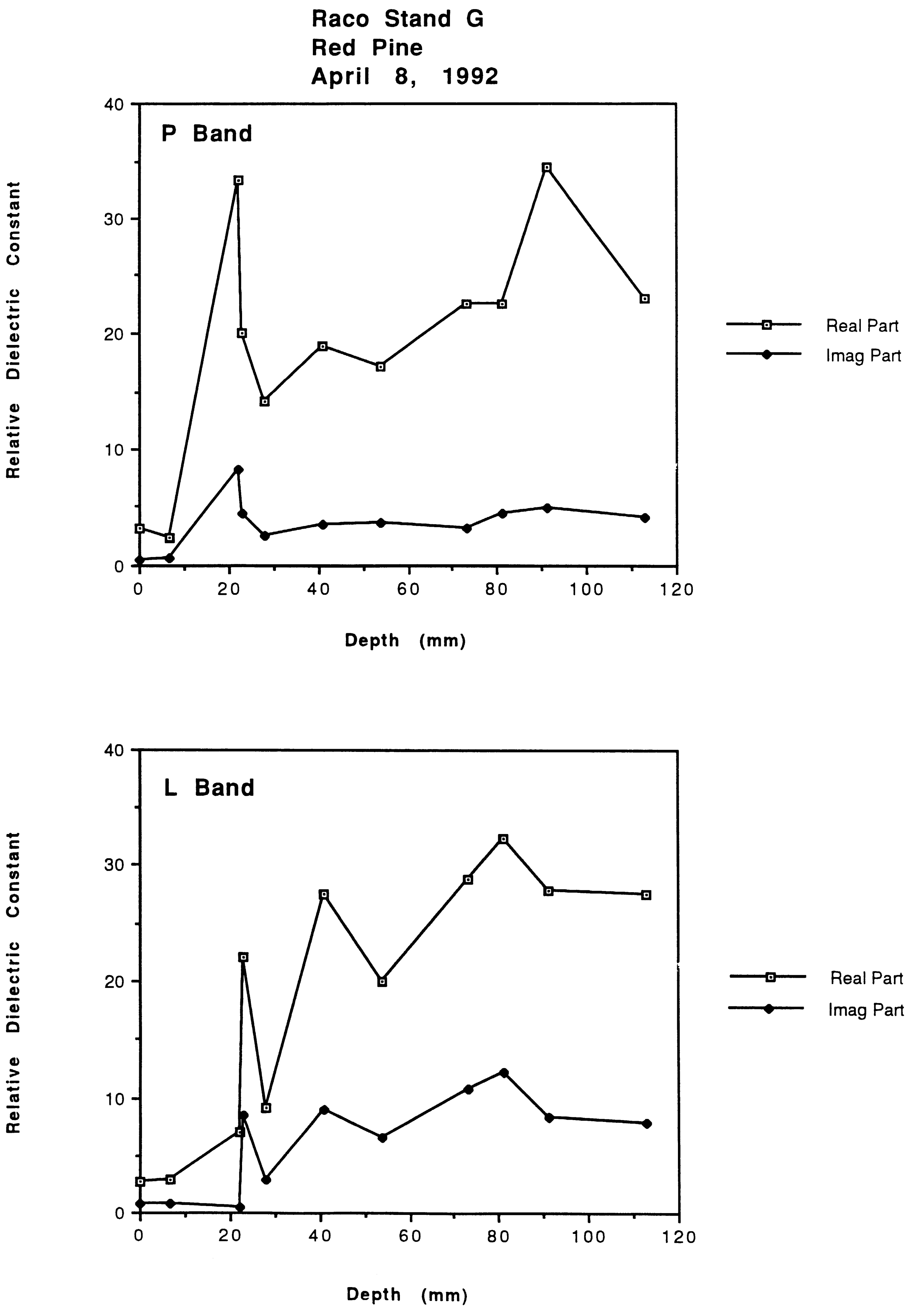
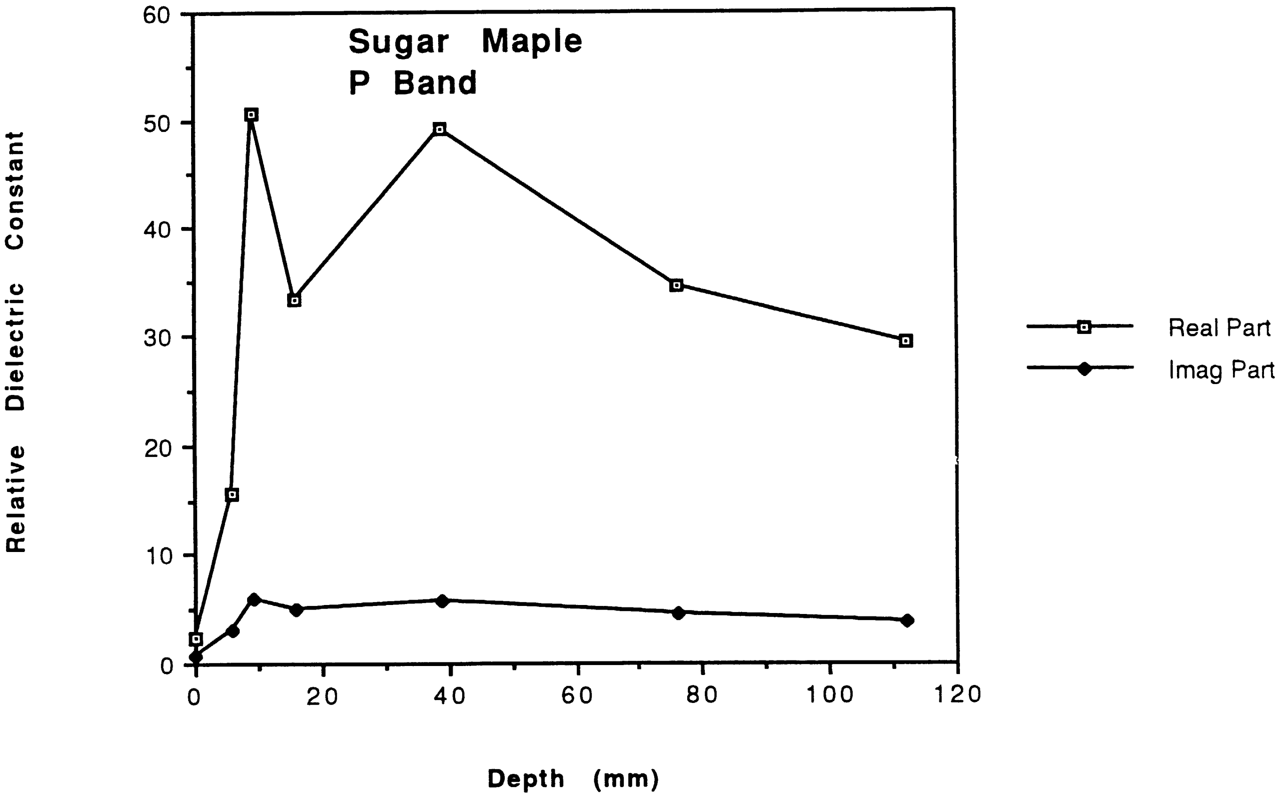



Figure 8. Dielectric constant at a function of depth into the trunk of a red pine tree in Stand G at (a) P-band and (b) L-band.

Raco Stand Q
April 9, 1992



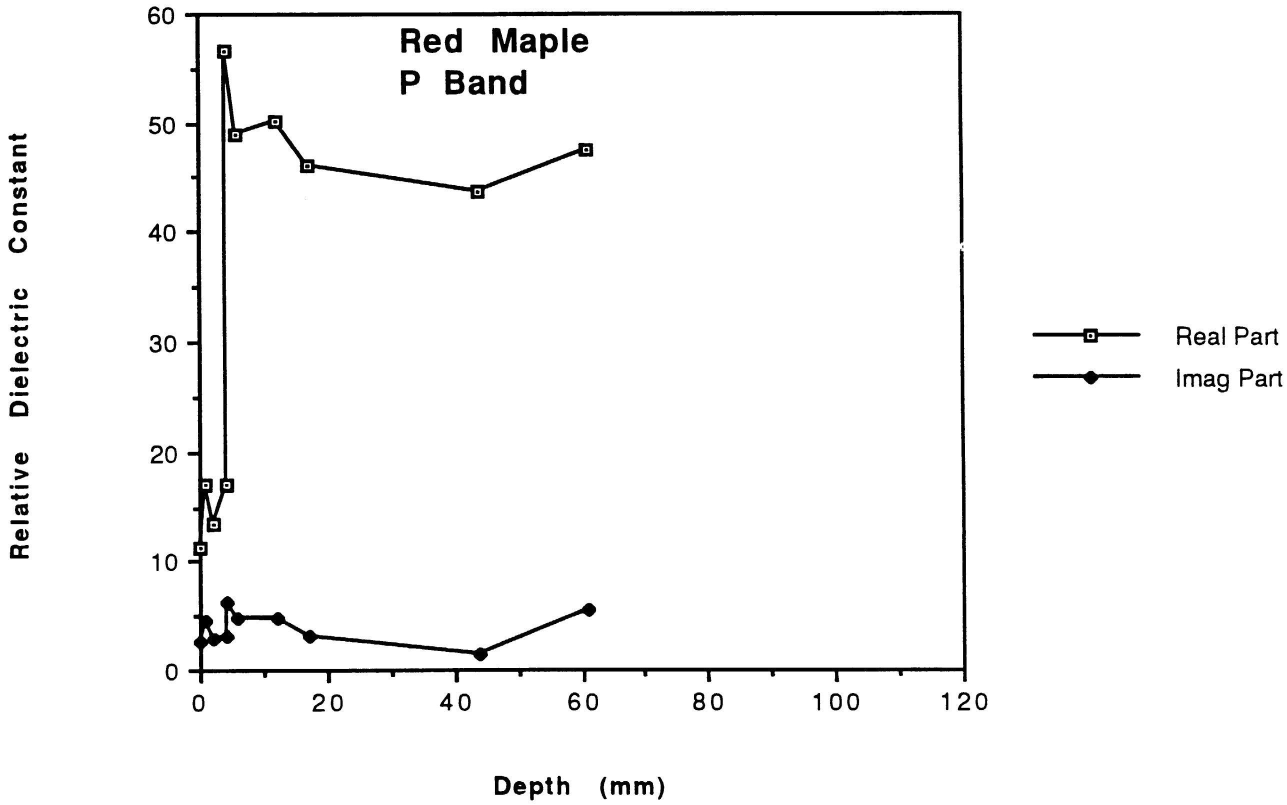
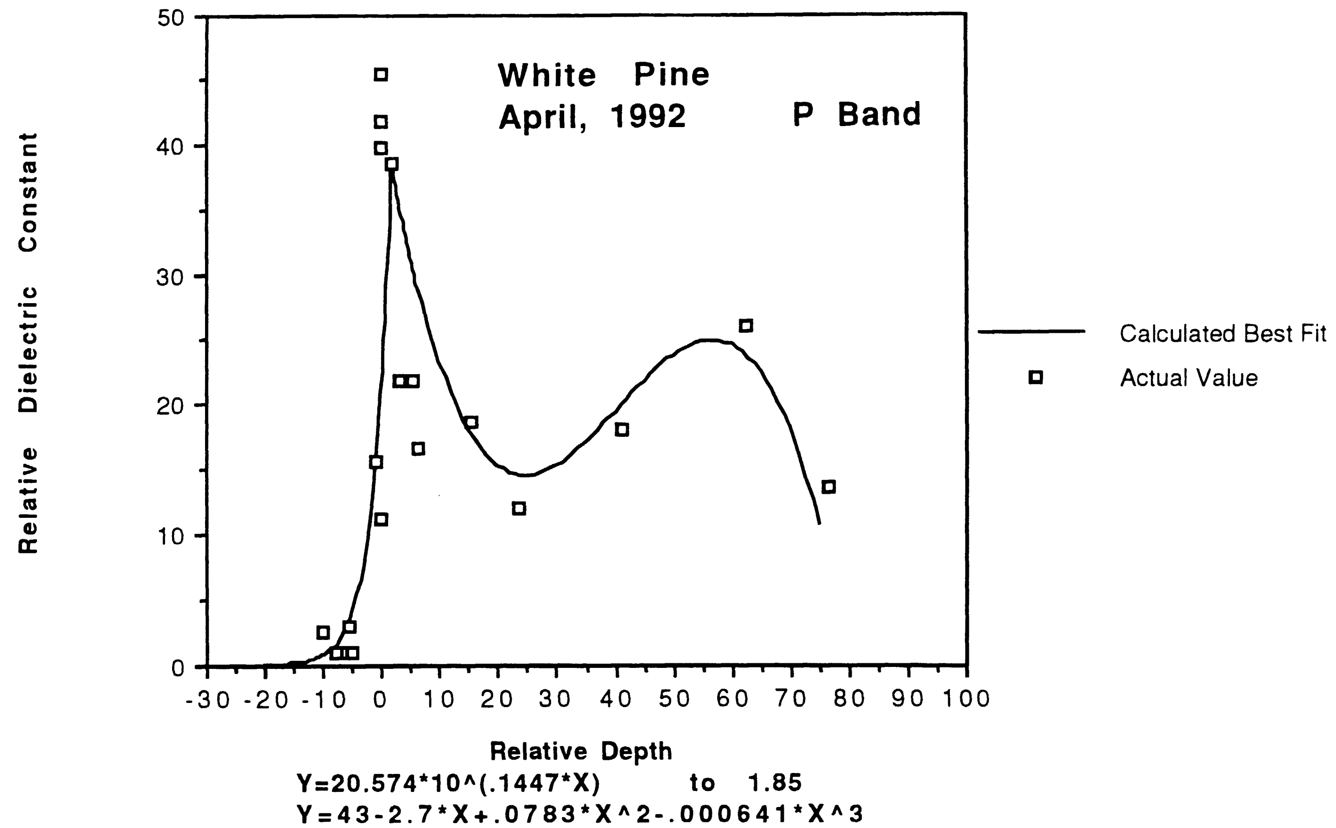




Figure 9. P-band dielectric constant as a function of depth into the trunks of (a) a sugar maple and (b) a red maple.



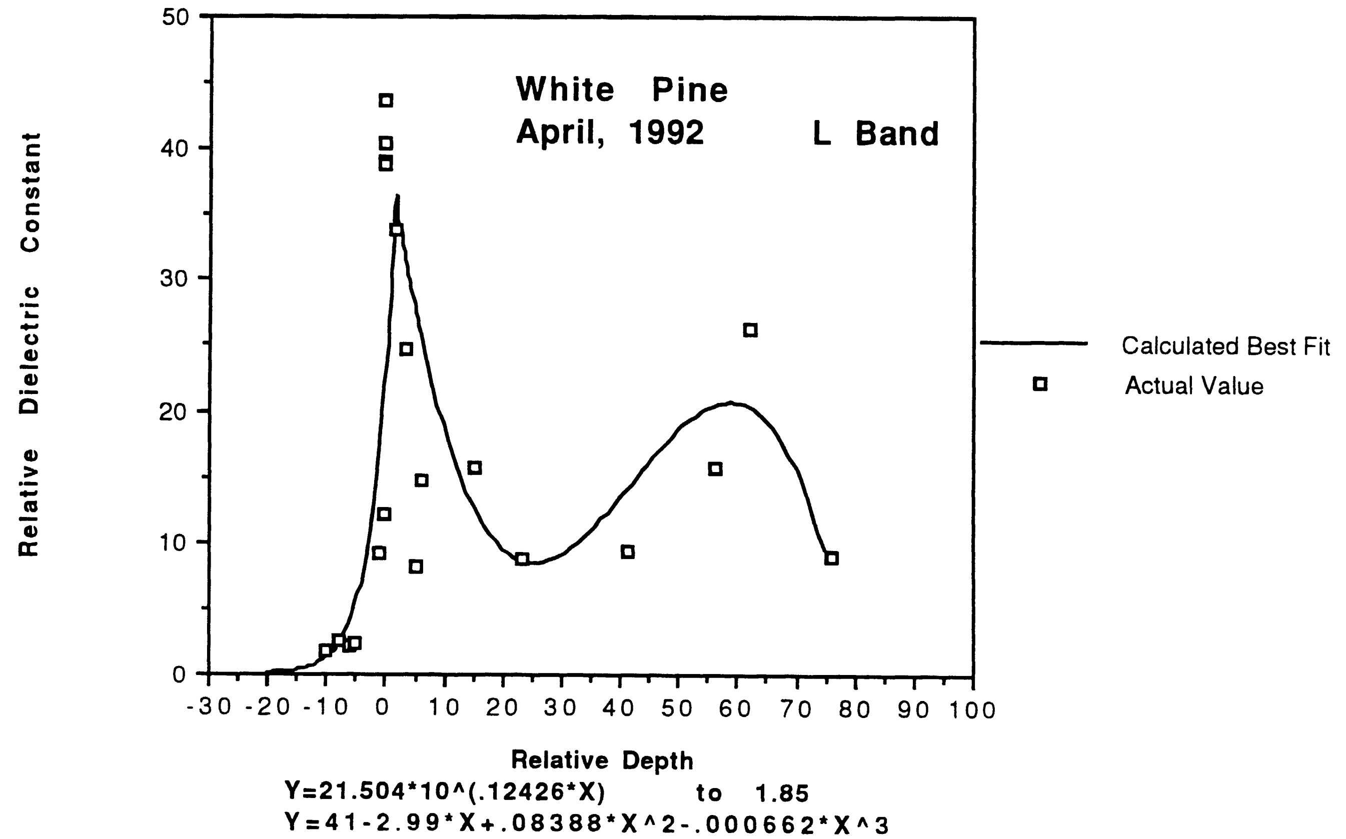
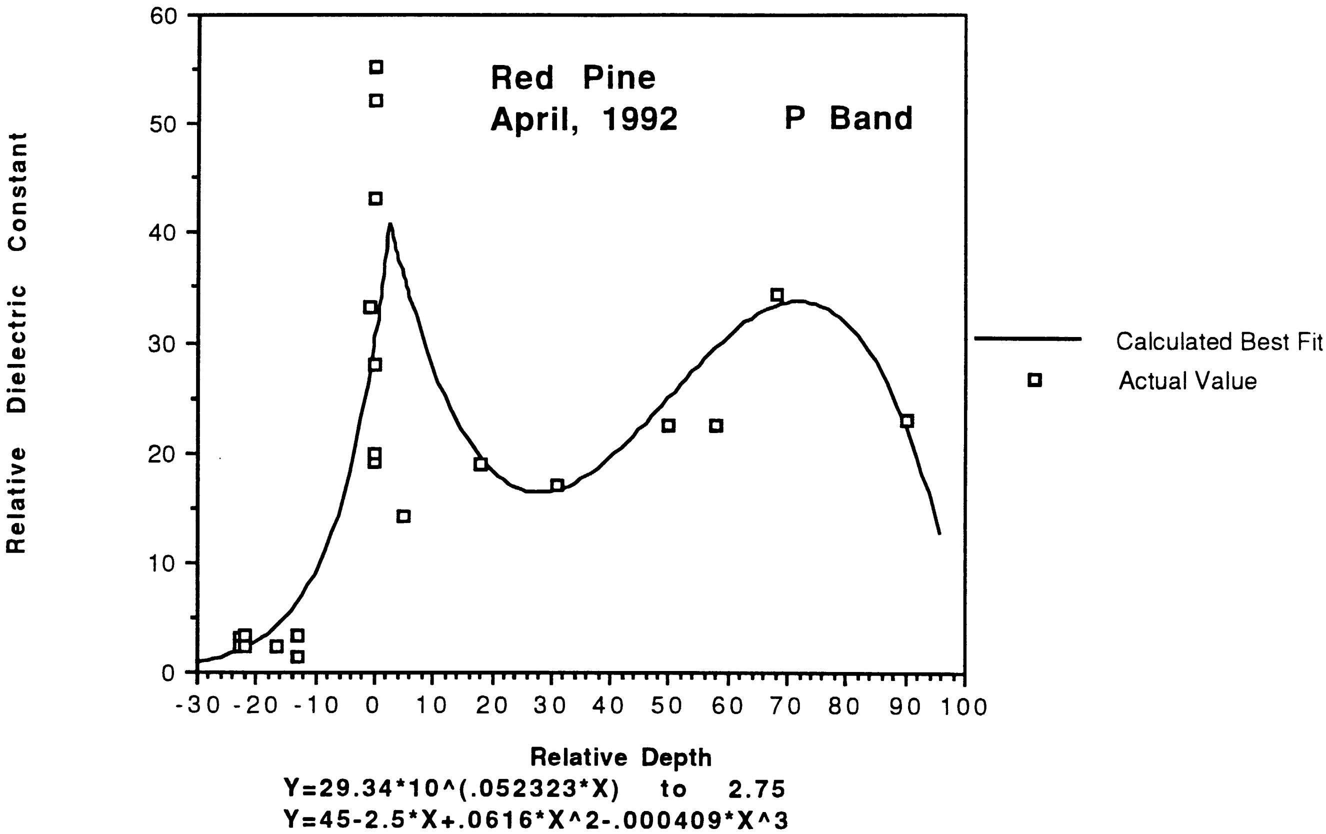




Figure 10. Composite dielectric profile of white pine (a) P-band and (b) L-band. Depth is relative to the bark/cambium interface.



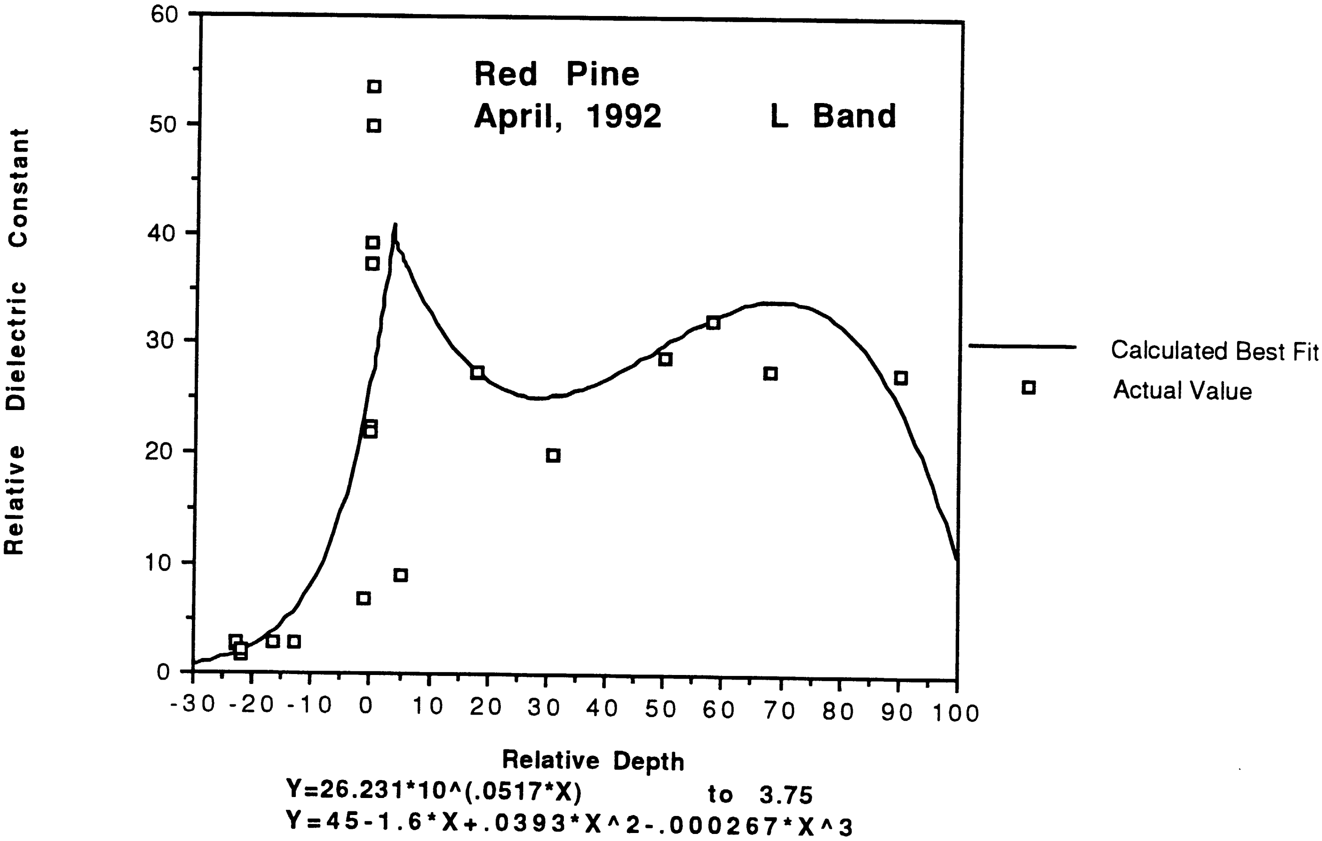




Figure 11. Composite dielectric profile of red pine at (a) P-band and (b) L-band. Depth is relative to the bark/cambium interface.

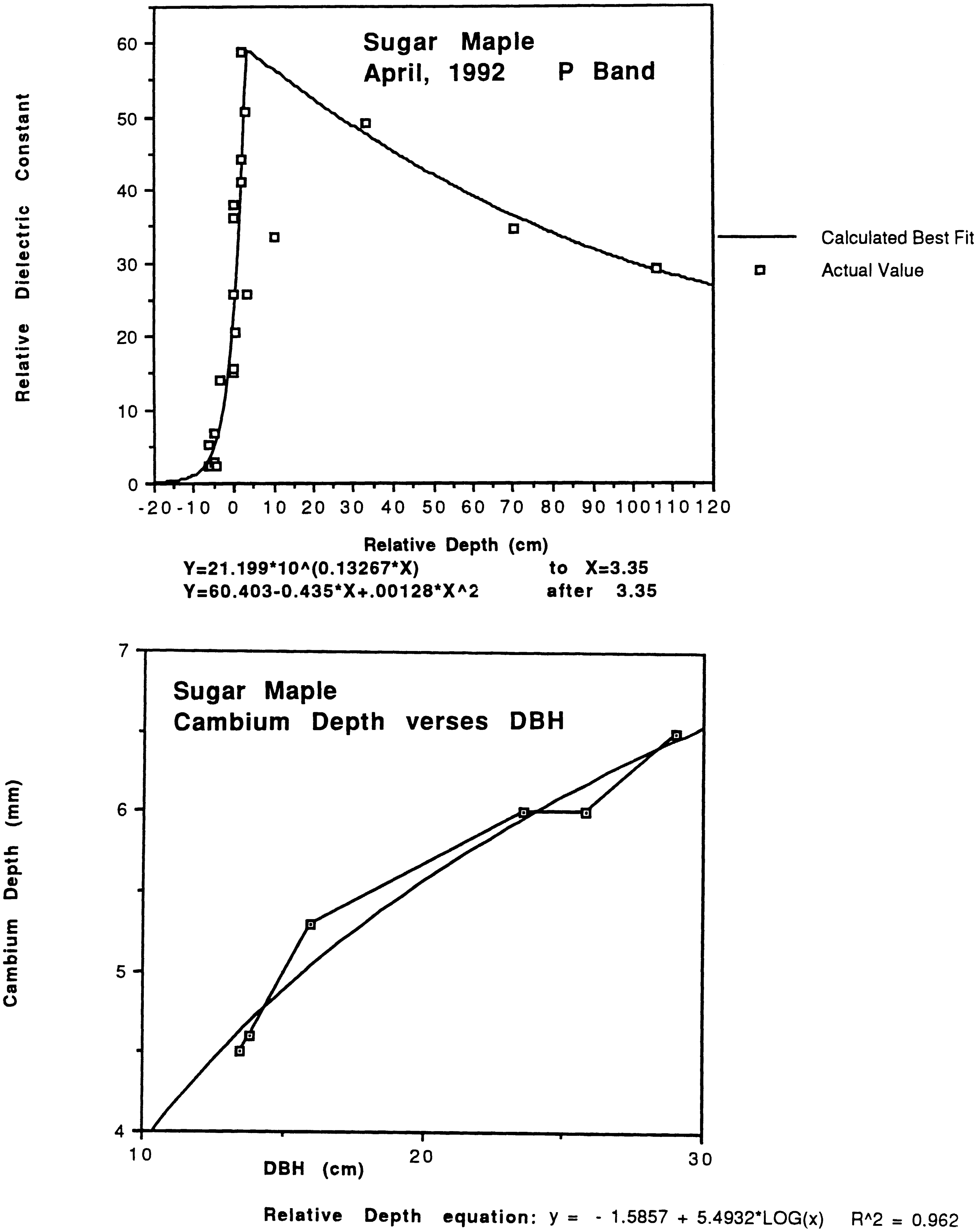



Figure 12. Composite dielectric profile of sugar maple at P-band as a function of relative depth (a) where x = 0 is defined by the bark cambium interface. Since bark thickness increases with tree diameter, cambium depth is related to diameter (b).

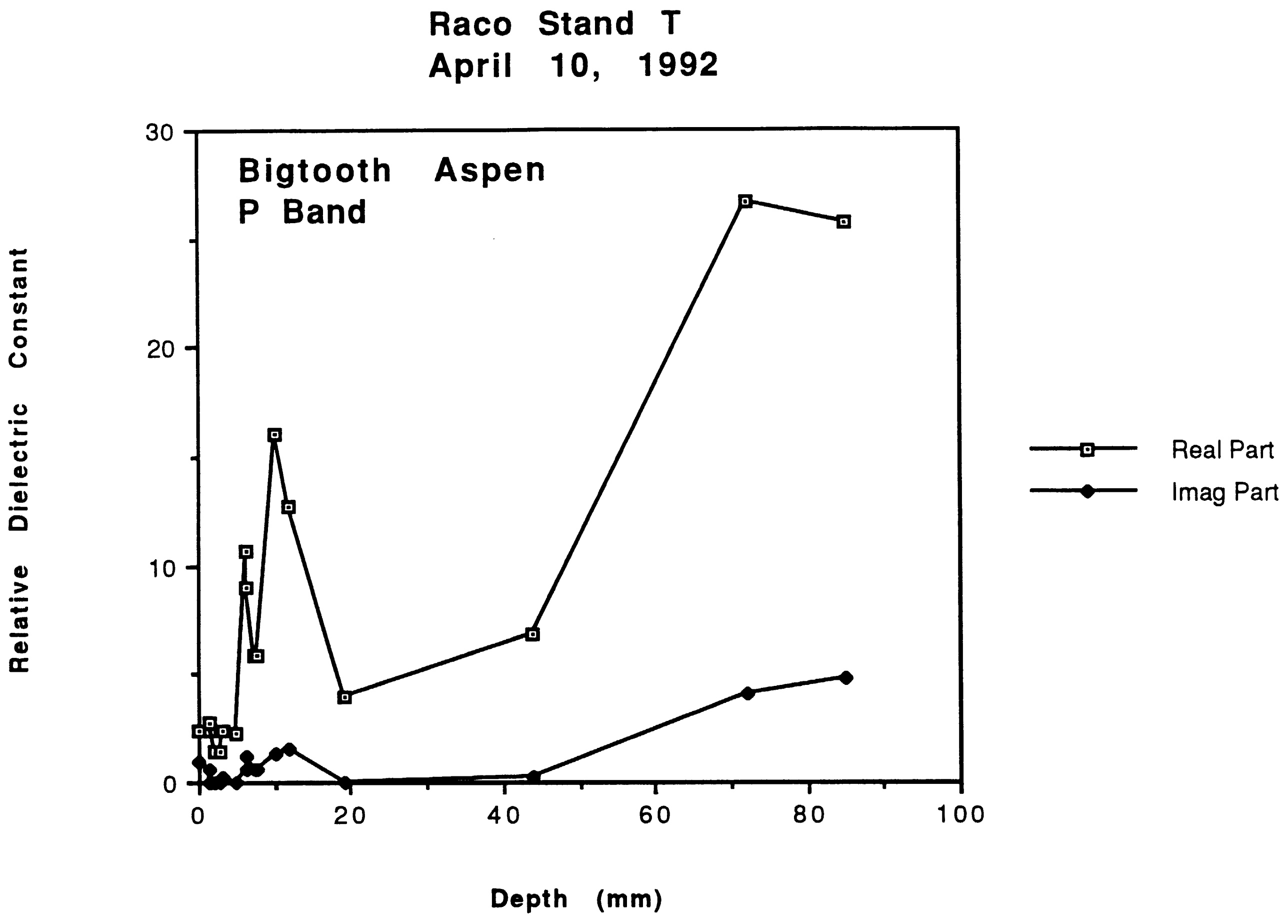



Figure 13. Composite dielectric profile of 6 bigtooth aspen trees. Bark thickness is approximately constant for all trees so depth is relative to the surface of the bark.