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Abstract

Radar images from the Seasat Synthetic Aperture Radar (SAR) produced unusually high returns from corn and sorghum fields, which seem to indicate a correlation between nodal separation in the stalk and the wavelength of the radar. These images also show no difference in return from standing or harvested corn. Further investigation using images from the Shuttle Imaging Radar (SIR-A) substantiated these observations and showed a degradation of the high return with time after harvest. From portions of corn and sweet sorghum stalks that were sampled to measure stalk water content, it was determined that near and after maturity the water becomes more concentrated in the stalk nodes. The stalk then becomes a linear sequence of alternating dielectrics as opposed to a long slender cylinder with uniform dielectric properties.

Introduction

Microwave sensors show increasing acceptance as a source of new information for earth resources applications under day/night and in some instances, all weather conditions. Characteristic frequencies and wavelengths of some of these sensors are shown in Table 1. With the launch and operation of SEASAT in 1978, publicly available radar imagery from a space platform became a reality. The availability of these data over widely varying types of terrain resulted in observations of phenomena that could not readily be detected in the limited supply of L-band aircraft radar imagery. The Synthetic Aperture Radar (SAR) flown on SEASAT also provided images showing some potential confusion factors that are of importance when the radar data are used for studies or applications in hydrology. One example is the increased return from vegetation when the vegetated areas have had recent rainfall, thus increasing the efficiency of scattering of the radar energy.

Other observations of vegetated areas were made during the validation experiments for the SAR where the plants were not wet on the surface, yet some plants produced an abnormally high return. Vegetation appeared to fall into two classes that produce two distinct scattering effects in radar imagery. One class contains all plants having relatively continuous material even though the plant material is distributed through the vegetation volume in widely varying dimensions such as a forest canopy with trunks, limbs, branches and twigs. The other class contains all plants characterized by a more or less distinct nodal structure. It is this latter class of vegetation that is of interest in this report.

Background

Early studies of the effects of vegetation on radar images were conducted in Kansas (Simonett, et al., 1967) using X- and K-band imaging radar systems. Since most radar images were collected for either military or geologic interpretation, only relatively short wavelengths were used prior to the development of an L-band imager by the Environmental Research Institute of Michigan. This longer wavelength provided an opportunity to observe more wavelength dependent phenomena when the L-band imagery was compared with the X- or K-band images.

Table 1: Radar band designations.

Band	Frequency	Wavelength
L (SEASAT, SIR-A)	1.25 GHz	23 cm
C	4-8 GHz	3.8-7.5 cm
X	8-12.5 GHz	2.4-3.8 cm
K	18-26.5 GHz	1.1-1.7 cm

Sibley (1973) made an attempt to understand the effects of vegetation on backscatter of microwave energy by considering the dimensions and permitivity of the vegetation layer as a volume. Most modelers have followed this approach in general (Bashirinov, 1975, Kirdiashev, 1979, Attema, 1978, Allen, 1982, and Jackson, 1982) but with different measurements to characterize the vegetation.

It is generally recognized that the scattering of energy and thus the radar return is dependent on both the geometric and dielectric properties of the vegetation. The dielectric properties have been estimated in some instances by use of a mixing formula or inferred by measurement of the water content of the vegetation. Geometric properties of vegetation have received much less attention except in special cases related to geologic interpretation of the imagery. Finding a satisfactory measure to characterize the geometry of the vegetation volume has been more difficult. Crop height and density, leaf area index, stalk diameters, stalk densities and branching orders have been used. Others have attempted to model plants as cylinders and plates oriented in systematic or random fashion (Lang, 1982).

Modeling of the radar backscatter can provide better understanding of the interaction of microwave energy with objects or volumes under certain circumstances. First, the objects must be simple enough that they can be represented either as a volume or a simple geometric form. Secondly, one must have in hand the dielectric properties of the material being modeled and the distribution of these properties within the volume being modeled. Considering these requirements, it is not likely that modeling the elements of plants will be very successful until more is known about the fundamental characteristics of various portions of the plants.

Recent and ongoing measurement programs where dielectric measurements of vegetation are being made (Ulaby, et al., 1983) have used the conventional approach that corn plants can be represented as parts that can be modeled as surfaces and cylinders. They have divided the plant into four parts: tassels, leaves, ears and stalks. These elements are chopped up and packed into a wave guide to measure the dielectric properties of each portion. This measurement program has resulted in the discovery that at least some plant water in corn is saline. Salinity has a known effect on the imaginary part of the dielectric constant of water.

The possibility that stalk node spacings might be a major influence on the magnitude of the radar return first became apparent on SEASAT SAR imagery (Blanchard and Chang, 1983). Figure 1 shows an enlarged view of an agricultural area near Sublette, Kansas on (a) color infrared photography and (b) SEASAT SAR imagery, respectively. The letters indicate fields with the following cover conditions:

A = dry bare soil with a circular tillage pattern

B = dry bare soil

C = freshly irrigated milo

D = freshly irrigated bare soil

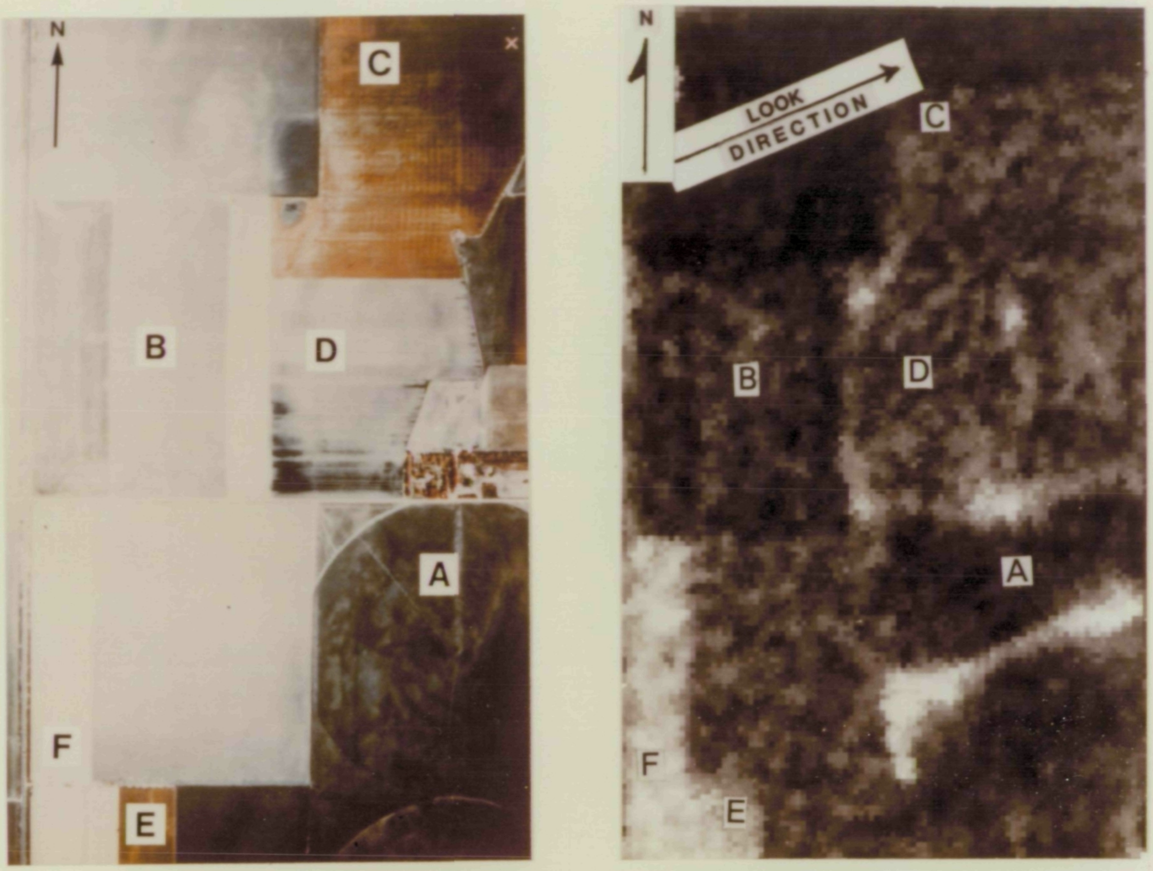
E = standing corn (this field was being harvested at the time the images were taken)

F = cut corn that has been combine harvested with stalks lying randomly scattered on the ground

An examination of Figure 1 clearly demonstrates that: 1) the SEASAT SAR distinguished between wet and dry bare soil (field D vs. field B), 2) SAR data were relatively unaffected by certain types of vegetation (fields C and D have the same radar return), and 3) the SAR responded strongly to surface roughness in the form of row structure when viewed perpendicular to the radar look direction (field A). However, fields of mature corn produced extremely high radar returns despite a reduction in water content due to ripening combined with low soil moisture conditions (fields E and F). In fact, no significant difference was detected in backscatter response between standing corn stalks and cut stalks that were randomly scattered across the field after combine harvesting. Since these corn stalks have nodes or joints spaced approximately one radar wavelength apart, it seems probable that the dielectric properties of the stalks as a volume are influenced by their geometrical structure and by the distribution of plant material (with possibly different dielectric properties) within the stalk.

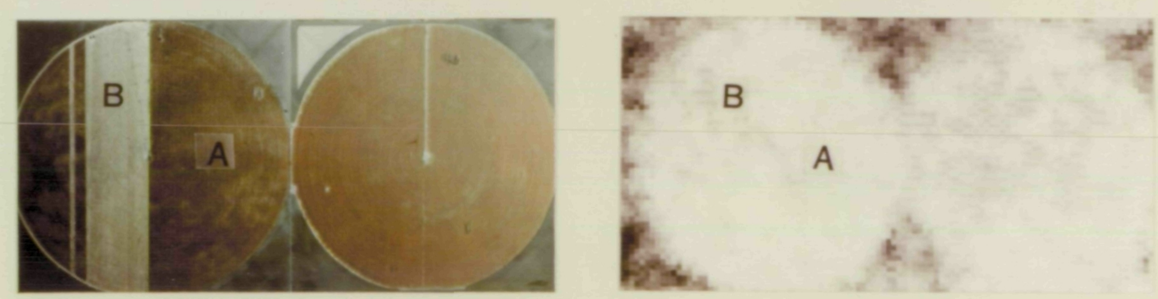
A review of additional fields where both aerial photos and SAR data were available reveals numerous instances where portions of corn fields had been harvested at the time the imagery was collected. A second example is shown in Figure 2 to confirm the observation that freshly harvested stalks produce the same return as standing stalks.

In addition to these observations at the L-band wavelengths, cursory examination of X-band and a limited supply of C-band imagery indicates that this phenomena may occur at any frequency when plants with nodal separations approximately equal the wavelength are imaged with a radar. We propose that this similarity in return implies that some aspect of the plant retains its scattering strength even



(a) (b)

Figure 1. Images of color infrared (a) and Seasat SAR, L-band radar (b) showing standing corn, E, and harvested corn stalks, F, indicating the high return from corn and no difference due to the orientation of the stalks. Both images were collected October 7, 1978 near Sublette, Kansas.



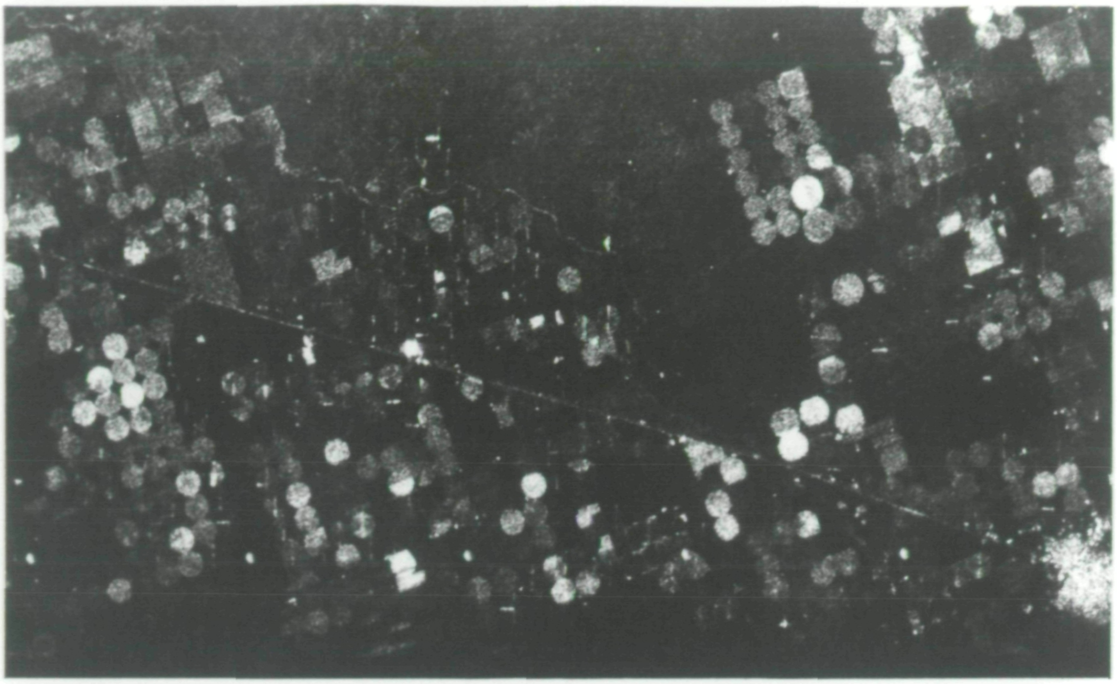
(a) (b)

Figure 2. Images of color infrared (a) and Seasat SAR L-band radar (b) showing standing corn, A, and harvested corn, B, at a secondary site on October 7, 1978 near Sublette, Kansas.

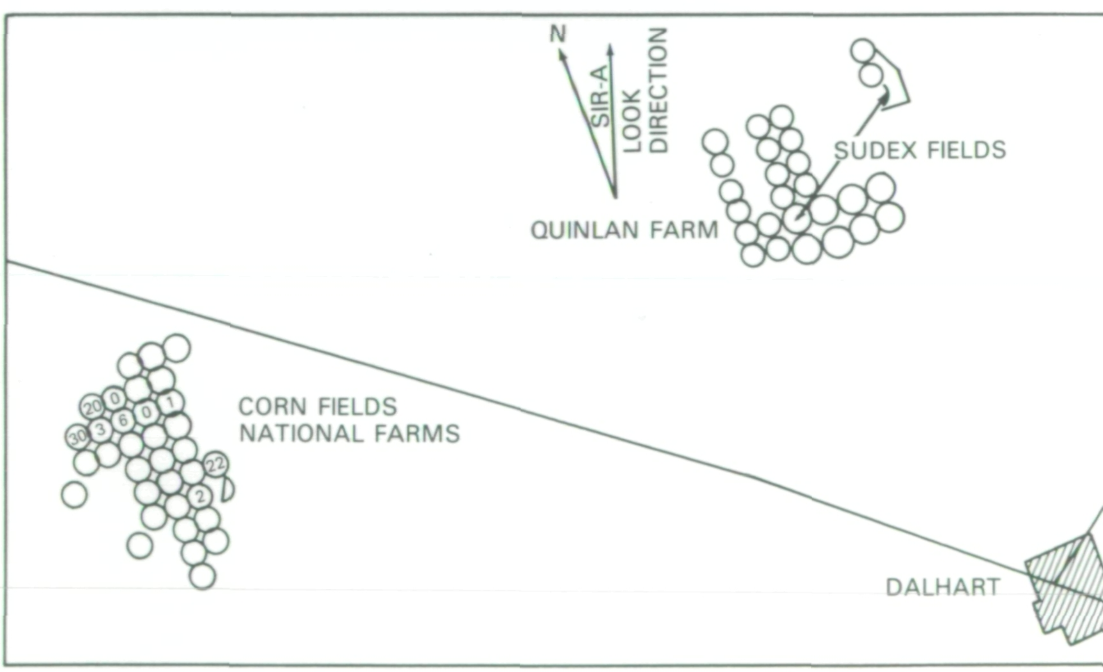
after harvesting. We suspect the stalks and the distribution of stalk nodes within the vegetation volume is responsible for the similarity. If we attribute the high return to the relatively constant nodal separation within each stalk, we might expect the nodal separations between stalks to be random, both when standing and after harvest. As yet, measurement of the distribution of nodes has not been made under field conditions.

These observations were reinforced after examination of SIR-A radar imagery obtained with the same wavelength as the SEASAT SAR but at an angle of ≈ 45° off nadir. Figure 3 depicts a portion of a SIR-A image taken November 13, 1981 over an agricultural area near Dalhart, Texas characterized by center pivot irrigation systems. A portion of this area had been intensively studied in August, 1980 when a field experiment was conducted to evaluate the utility of combinations of sensors for estimation of soil moisture and for classification of vegetation. A field trip was made to this area after the SIR-A overpass. With the cooperation of the county extension agent and several farmers, the crops, field conditions, stage of harvest and tillage conditions for the 13th of November were documented for several fields. In several instances, stalks were available from corn and sorghum fields; thus, mean node spacings could be measured. Records were also available to document the date of harvest on a number of fields.

The bright returns from fields in Figure 3 can all be attributed to the presence of either corn or sorghum. In the right-hand portion of this image, there were fields of mature "Sudex", a hybrid sorghum



(a)



(b)

Figure 3. Radar (L-band) imagery of the Dalhart, Texas area collected November 13, 1981. "Data take" 24B of the SIR-A mission (a) and a map of the area (b) indicating the location of some corn and sudan fields. Numerals indicate days since harvest of corn fields.

approximately 3 meters in height with a mean stalk node spacing of 23 cm. This produced the highest return on the first generation radar image. The next highest return came from two corn fields in the left portion of the image, marked "0" to indicate that the fields were harvested on November 13, the day of the overpass. The mean stalk node spacing of the corn was 17.8 cm. Fields identified as grain sorghum showed less return. Although no stalk measurements were available for grain sorghum at Dalhart, other node separation measurements from central Texas range from 5 cm to 15 cm depending on the variety of grain sorghum and the seasonal growing conditions.

As in the SEASAT data, both freshly cut corn and standing corn produce approximately the same return in the SIR-A images. Since these images were collected later in the season than the SEASAT images, there were corn fields that had been harvested for some time prior to imaging. The magnitude of the backscattered response decreased in the fields as the time after harvesting increased. The numbers within circles shown in Figure 3 indicate the number of days since harvest. One can readily see that the high return from the stalks diminishes after approximately one month to a level similar to adjacent fields of wheat and pasture.

The SEASAT SAR and SIR-A data substantiate the initial observation that in reality vegetation falls into two categories with each category producing significantly different scattering effects. It is apparent in this imagery that stalks with nodal spacing near the wavelength of the radar produce excessive scattering effects at or near harvest time. The radar return increases as the nodal spacing approaches the wavelength. Since spacings greater than the radar wavelength have not been observed, there is no way to determine if the return would decrease with greater spacing.

The inability to detect differences in returns from standing and harvested stalks seems at first to defy our expectations concerning polarization effects. If we assumed no differences in dielectric properties along the stalks, they would appear to the radar as long slender rods perpendicular to the horizontally polarized electric field of the radar when standing and randomly oriented when harvested. It may be possible at the observed angles (≈ 20 on SEASAT and ≈ 45 on SIR-A) that node separations in standing corn appear as a random distribution of distances from stalk to stalk. If this is true, the radar wave would be in phase with nodal spacing within each individual stalk but out of phase between stalks. The in-phase distribution within the stalk would remain intact when the stalks were on the ground after harvest and the random distribution between stalks would remain random.

In addition, this condition of the stalk producing a high return persists to some degree for a period after harvest. Whether the diminishing of return over an approximately 30 day period is associated with decay of the stalk structure or loss of moisture from the stalk (or both) could not be determined from the data collected at the Sublett and Dalhart sites.

Preliminary Stalk Studies

Corn, sweet sorghum and grain sorghum stalks have been examined to determine the general structure of the plant. Samples of these plants were collected from the farms of the Beltsville Agricultural Research Center at Beltsville, Maryland in August 1982 and September 1983. A cursory examination of the stalk structure showed marked differences between the internal structure of the grain sorghum and the sweet sorghum plants. An overall comparison between corn, sweet sorghum and grain sorghum stalks can be seen in Figure 4a. The general appearance of corn stalks after harvesting with a combine is shown in Figure 4b. The corn stalk structure was very similar to the sweet sorghum stalk structure. Grain sorghum stalks have closely spaced nodes with very minor apparent difference between nodal material and the plant material in the intervening stalk. In contrast, the sweet sorghum and corn stalks exhibit major differences between the internal structure of the nodes and the intervening stalk.

Figure 5 and 6 illustrate the changes in the internal structure of corn stalks with time after harvest.

Samples of corn and sweet sorghum stalks selected from mature corn were separated into parts such that the gravimetric moisture content of discrete portions of the stalk could be determined. Moisture content of node sections and the intervening stalk was measured by drying in a convection type electric oven. There was no significant difference in the percent moisture on a gravimetric basis between the two portions of the plants. The stalk surface or bark

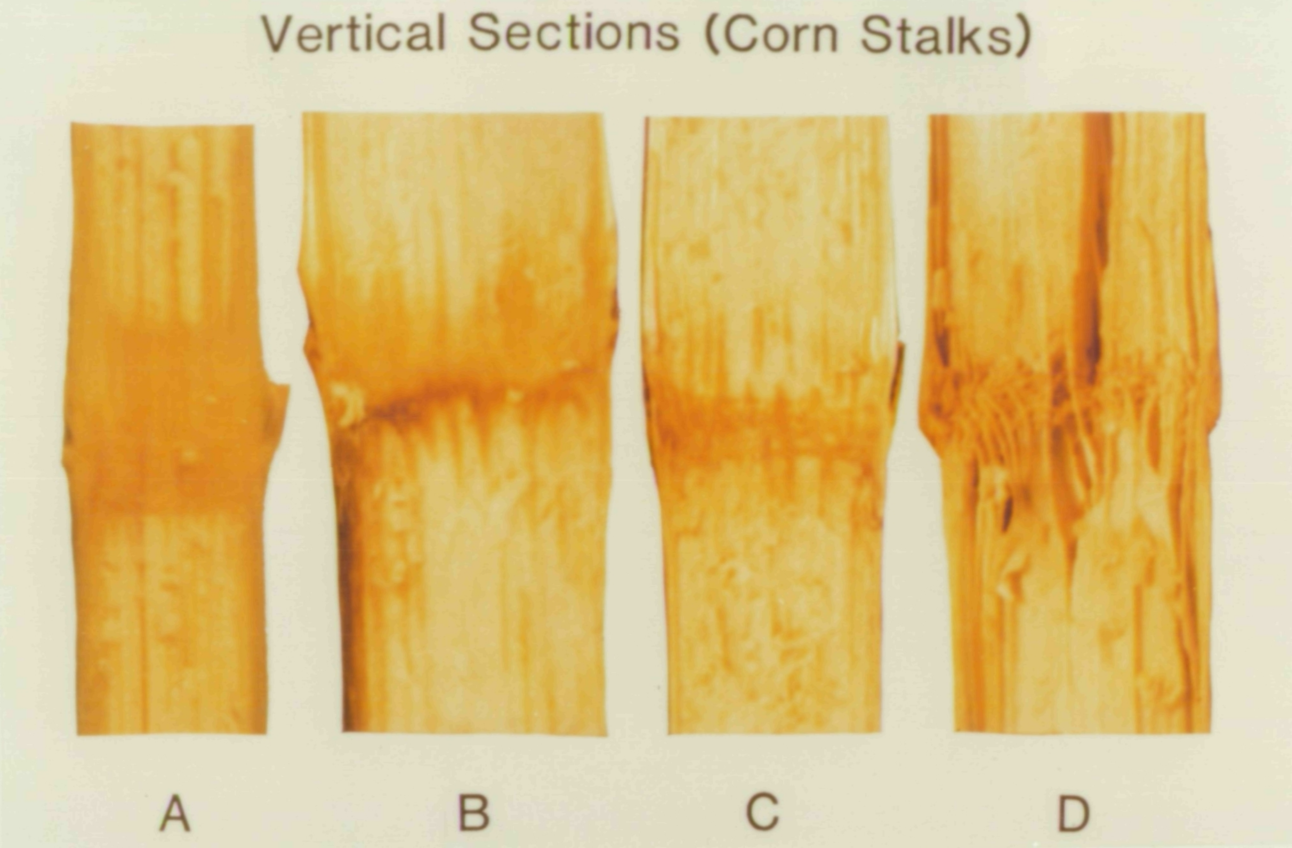


Figure 5. Vertical cross section of corn stalks, A at Harvest, B after 10 days drying (in open air), C after 20 days drying and D after 30 days drying.

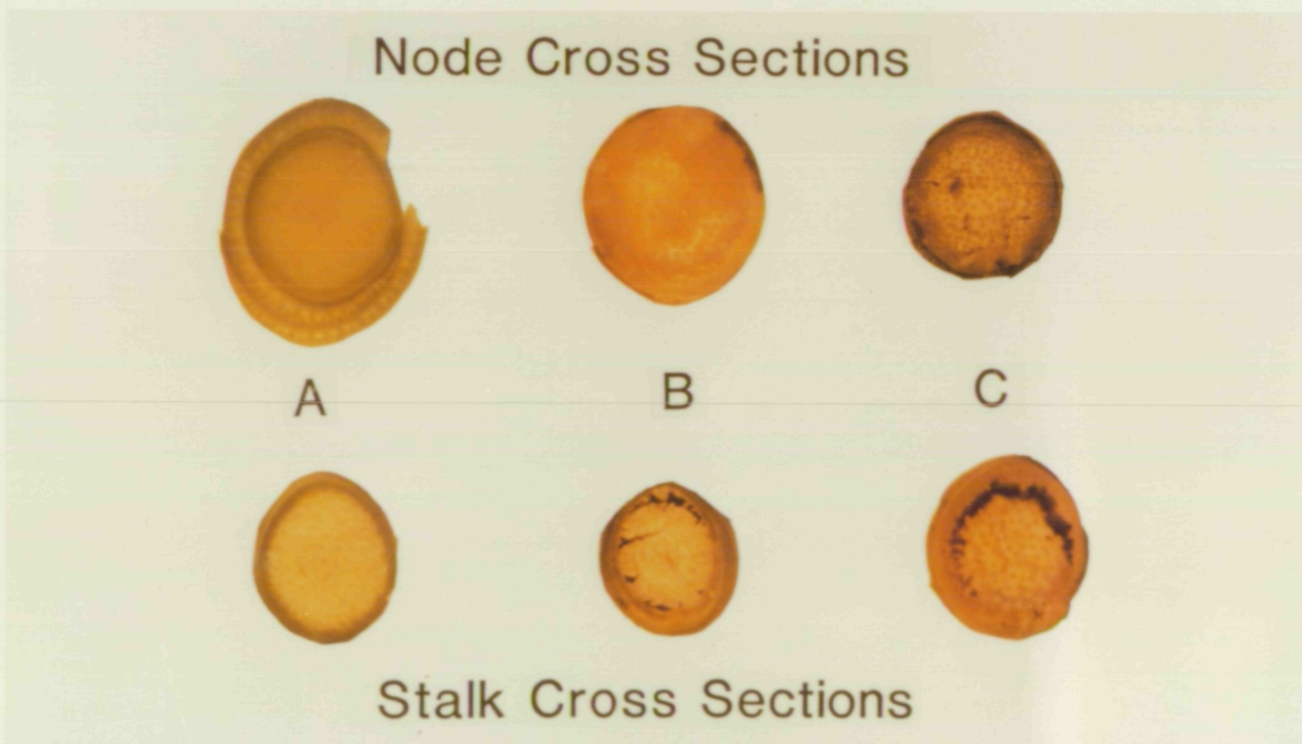


Figure 6. Cross sections of nodes and the intervening stalks from corn, (A) at maturity, (B) 12 days after harvest and (C) 30 days after harvest.

(a)

(b)

Figure 4. Photographs of (a) stalk cross sections from corn (left of scale), hybrid sweet sorghum (right of scale) and grain sorghum (far right) showing difference in node spacing and (b) stalks randomly scattered after harvest.

was included in these samples and no density measurements were made on the samples.

Additional samples of the internal portion of nodes and intermediate stalks were selected from both corn and sweet sorghum. Volumes of these internal cores were measured prior to drying, thus the density and volumetric water content could be determined. The average volumetric water contents are shown in Table 2. Although these data are meager, they show that the volumetric or free water content in corn at harvest is twice as high in the node cores as it is in the core of the intervening stalk. After twelve days of drying, the water content of the node cores was three times the water content in the intervening stalk. The sweet sorghum was cut at an earlier stage of growth where the nodal structure had not fully developed. After twelve days of drying, the water content of the nodal cores was only fifty percent larger than the intermediate stalk cores. The concentration of water in the nodes apparently occurs with maturity and progresses at a more rapid pace after maturity as the total water content of the stalk is reducing, i.e. water evaporates from the intervening stalk faster than from the nodes during and after plant maturity.

The progressive imbalance in water content along the stalk changes the stalk from a long slender cylinder with relatively constant dielectric properties to one with alternating high and low dielectric properties. Conventional modeling techniques have treated plant stalks as cylindical objects with uniform dielectric properties. Currently available dielectric properties of vegetation were

Table 2: Water content of corn and sorghum cores.

Date	Crop	Portion of Plant	Average Water Content (g/cc)	Ratio (Node Water)/(Stalk Water)
9/16/83	Corn	Node Core	.713	
	Corn	Stalk Core	.333	2.14
9/28/83	Corn	Node Core	.561	
	Corn	Stalk Core	.185	3.03
9/28/83	Sorghum (green)	Node Core	.719	
	Sorghum (green)	Stalk Core	.491	1.46

determined from material that has been chopped or crushed where the differences within the stalks are obliterated. Therefore, to fully understand the fundamental reaction that takes place and to develop a model describing the radar response, the dielectric properties of the material in the separate portions and of the stalk with alternating dielectrics must be measured. A program is currently being initiated to acquire such measurements and develop a model to describe the observed phenomena.

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