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Wave Behavior in Plant Tissue

Abstract

Non-electromagnetic standing waves have been found in plants. Some characteristics of these waves such as velocity, antinode spacings, and frequencies have been determined. Proof for their existence consists of measured electrical patterns, recorded oscillations, and excitation behavior. These standing waves are here termed W-waves for their discovery in wood.

Introduction

During the winter of 1987-1988 while studying xylem anisotropy (Wagner 1981 and Wagner 1988a,b,c,d) a surprising observation was made. Sections of trunk of varying lengths were cut from near the bases of live small trees and from shrubs of several different species. Immediately after cutting, the trunk section was completely debarked and two probes were inserted. A fixed probe was placed about 3 mm from the cut at the bottom (base) of the dowel-like section as a reference and the second probe was used to measure voltages incrementally up the sample (Figure 1). Probing revealed two outstanding electrical features. First the probes showed that negative voltage peaks occurred at regular intervals of 7.6 cm. Second, the samples were usually highly negative between the ends (base and top of the trunk sections). The 7.6 cm spacing of voltage peaks slowly emerged within a few minutes following insertion of the probes. The upper probe sometimes recorded what seemed to be a pulse reflected back and forth in the fresh sample of tree or shrub. Here was surprising evidence of a standing wave building up which reminded one of a resonating organ pipe. The shorter trunk sections tested seemed to show the greatest contrast between voltage lows and highs with the peak voltages higher. This occurred in all species tested: mountain lilac (*Ceanothus integerrimio*), willow (*Salix* sp.), California black oak (*Quercus kellogii*), Douglas-fir (*Pseudotsuga menziesii*), hazelnut (*Corylus* sp.), madrone (*Arbutus menziesii*), and ponderosa pine (*Pinus ponderosa*). Slowly the periodically distributed charge disappeared beginning at the bottom of the tree or shrub section. The top of the sample often became highly charged (approx. 250 mv) and then finally the charge disappeared. After these tantalizing first results from freshly cut tree sections, the present study was undertaken to characterize in more detail the wave patterns observed in trees and other plants *in situ.*

Standing Waves

Standing waves arise from the superposition of wave trains traveling in opposite directions. Two wave trains traveling in opposite directions interact at some points to produce constructive (antinodes) and at other points to produce destructive (nodes) interferences. The results are the stationary peaks and valleys of a standing wave pattern. Standing waves can be produced in a string or rope tied to rigid supports, in an open or closed pipe, in a radio antenna or transmission line, in crystals, and so on. Reflection of a traveling wave from boundaries is generally what produces the waves traveling in opposite directions. For example, reflection of sound from a boundary such as the end of an organ pipe produces a wave traveling in the opposite direction in the pipe. When the waves reflect back and forth inside the pipe they interact to produce the familiar standing wave pattern. See, for example, Halliday and Resnick (1970: 313-316) or other introductory physics text for further discussion.

Materials and Methods

Compared to surface probes, penetrating electrodes proved more reliable. Most of the penetrating probes were made of #16 nickel plated steel pins, etched in dilute nitric acid. The etching removed the nickel and reduced the probe resistance to near 100k ohms (calculated by using loaded and unloaded voltages) which can be as high as 500k ohms with smooth steel. Probing, on debarked surfaces, was done quickly on cold (near 2°C) high humidity mornings to prevent drying.

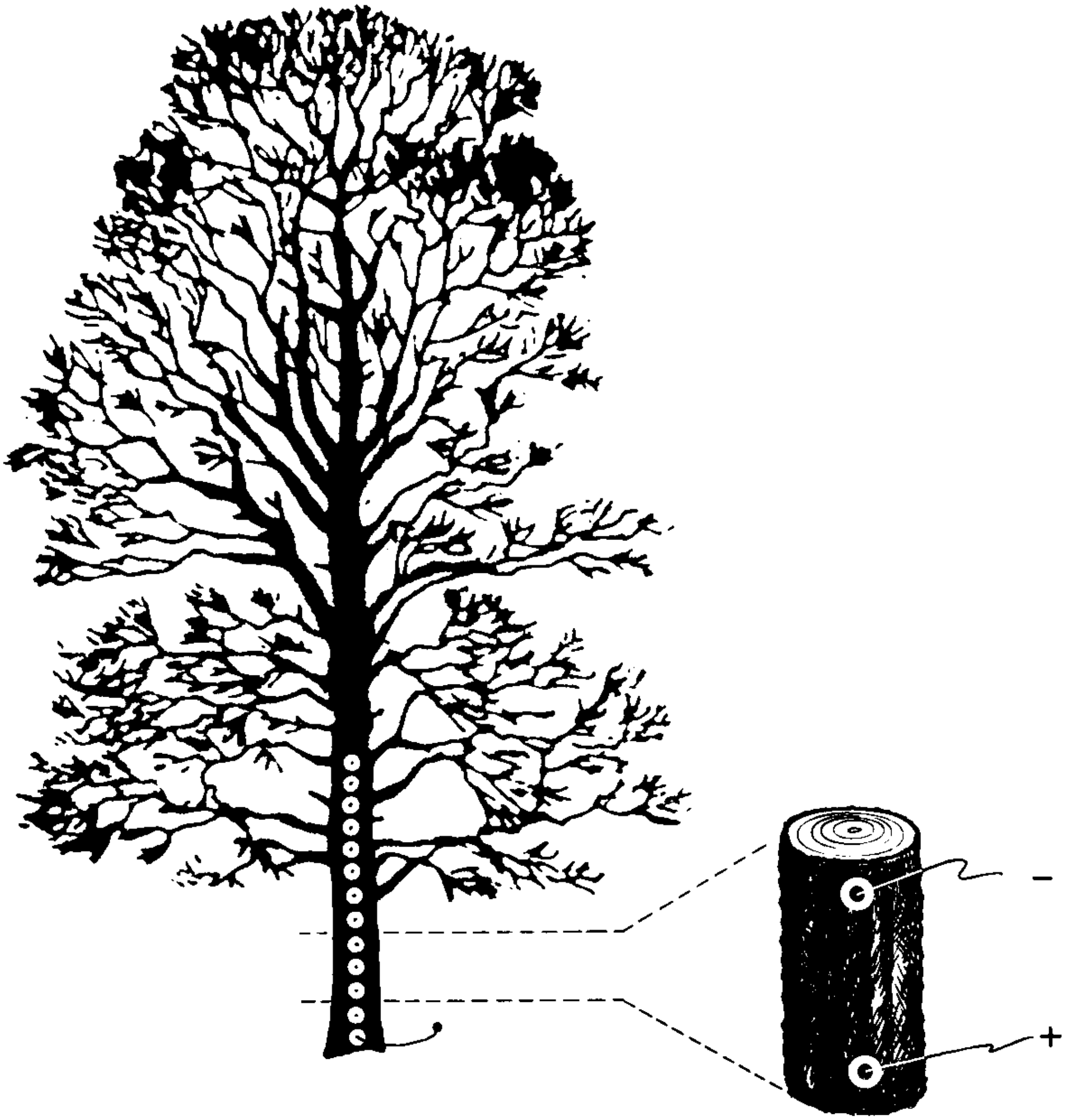

Figure 1. This is a schematic of a tree with contacts in place and of a cut section. The reference probes are at the bottom of the tree and the section diagram. The polarity placed on the section is representative of the polarity obtained when standing waves were first observed on cut sections.

Two methods of placing probes were used. One method, the two probe method, involved inserting one electrode near the base of the tree, the reference probe, and the other further up. The multielectrode method involved inserting several electrodes along the tree above the reference probe (Figure 1). Spacings between electrodes were 2.5 cm. (1.0 in.). The bark was cleared by hand from a 0.64 cm diameter area using a wood drill bit from which the centering screw was removed. Care was taken not to damage the underlying xylem. The electrode was pushed about 4 mm into the exposed xylem. The basic patterns were still observed in trees not debarked but these patterns were not so well defined. A 1.3 cm (0.5 in.) electrode spacing was considered but to prevent excessive tree damage a 2.5 cm (1.0 in.) spacing was used instead. (Measuring along tree trunks was done with a measuring tape calibrated in inches.) When inserting electrodes attempts were made to avoid branches. The sequential probes in series were kept in line as much as possible as they went up the tree. This may not have been necessary since early data revealed, especially in the small diameter cases, that maximum voltage areas circled cut sections and tree trunks. Differences in composition and placement of probes possibly produced some scatter in the data but not enough to obscure the wave pattern.

A Keithley Instrument millivoltmeter (169) was used to take readings from probes on trees and other samples. Its input impedance was 11 megohms so if the probe resistance happened to be as high as 500k ohms the maximum voltage error would have been less than 5 percent. Separate battery operated (DC) supplies were used to power the strip chart recorder and the offset adjustable amplifiers. Coaxial cable, common mode cancellation with differential amplifiers, and grounding were used where possible to minimize unwanted signals. Checks were continuously made to find and eliminate stray electrical signals.

Pattern measurements were taken daily between 900 hours to 1800 hours during the first month. Later the data were taken about twice a week. In the beginning, hundreds of sequential probes were placed on a madrone, a ponderosa pine, and other trees and readings taken. From initial tests it was found that a one meter row of probes (electrodes) was usually sufficient to detect standing waves. Pine and fir tend to coat electrodes with pitch so probe resistance needs periodic checking. If the probe resistance became too high the electrodes were moved.

Since much of the data deal with multiples of a specific length, units that emphasize this length are utilized as needed (i.e. $p = 7.6$ cm. (3.0 in.).

A zero crossing is a point where a wave pattern crosses the zero polarity (determined by the reference electrode) axis. Since the zero crossing location depends on where along in the total wave pattern the reference electrode is placed one cannot always easily determine ahead of time what the end-to-end polarity of a cut section will be.

Pulse velocity

To determine the velocity of the wave trains producing the stationary standing wave patterns, "damage" pusles were utilized. For measuring "damage pulse" velocities, one electrode was pushed into the tree at 0.3 m and a second at 1.8 m above the ground. Then either chopping at the base of the tree with an ax or driving in a nail was usually sufficient to produce a traveling disturbance (pulse) in the wave pattern that apparently moved up the tree, was reflected from the tree top, and then traveled down to the bottom (Figure 3). A Houston Instrument high impedance input 2 channel strip chart recorder was used to record damage pulses. Since the DC output from the probes on a tree can be more than 400 mv two offset adjustable high input impedance amplifiers with an approximate gain of one were built so that the chart recorder could be centered on the 20 mv scale. Frequencies from the strip chart recorder data were determined by counting the number of cycles per unit time. The base diameters of trees examined ranged from 9 cm to 54 cm. The trees tested were so large and the instruments and displacement used to produce a damage pulse could be so small that it is unlikely that a sonic effect produced the damage curve.

To relate the damage pulses to the wave patterns a nail was driven in successively up a tree and recordings made from two probes in place. (Douglas-fir 8.8 m with 10 cm base dia.; 11 March 1988 for figure 4). Starting at the base of the tree, a #8d nail was driven in (approx. 0.6 cm.), pulled and then driven in again, successively up the tree at p/3 intervals. This was done 42 times. At each nail location a damage curve was recorded on the strip chart recorder from the two electrodes in place on the tree. The maximum voltage displacement of each curve was plotted versus distance up the tree (Figure 4).

Results

Standing Waves

Initially the two probe method at p/6 intervals failed to show periodicity clearly although there was a low level pattern. This method showed large patterns, however, with zero crossings several meters apart (or with only one crossing at the base of the tree) on the debarked trunks of red alder (*Alnus rubra*) and willow (late February 1988). Not until multiple probes were placed at p/6 and p/3 intervals did shorter wavelength repeating patterns show clearly with high stability (Figure 2).

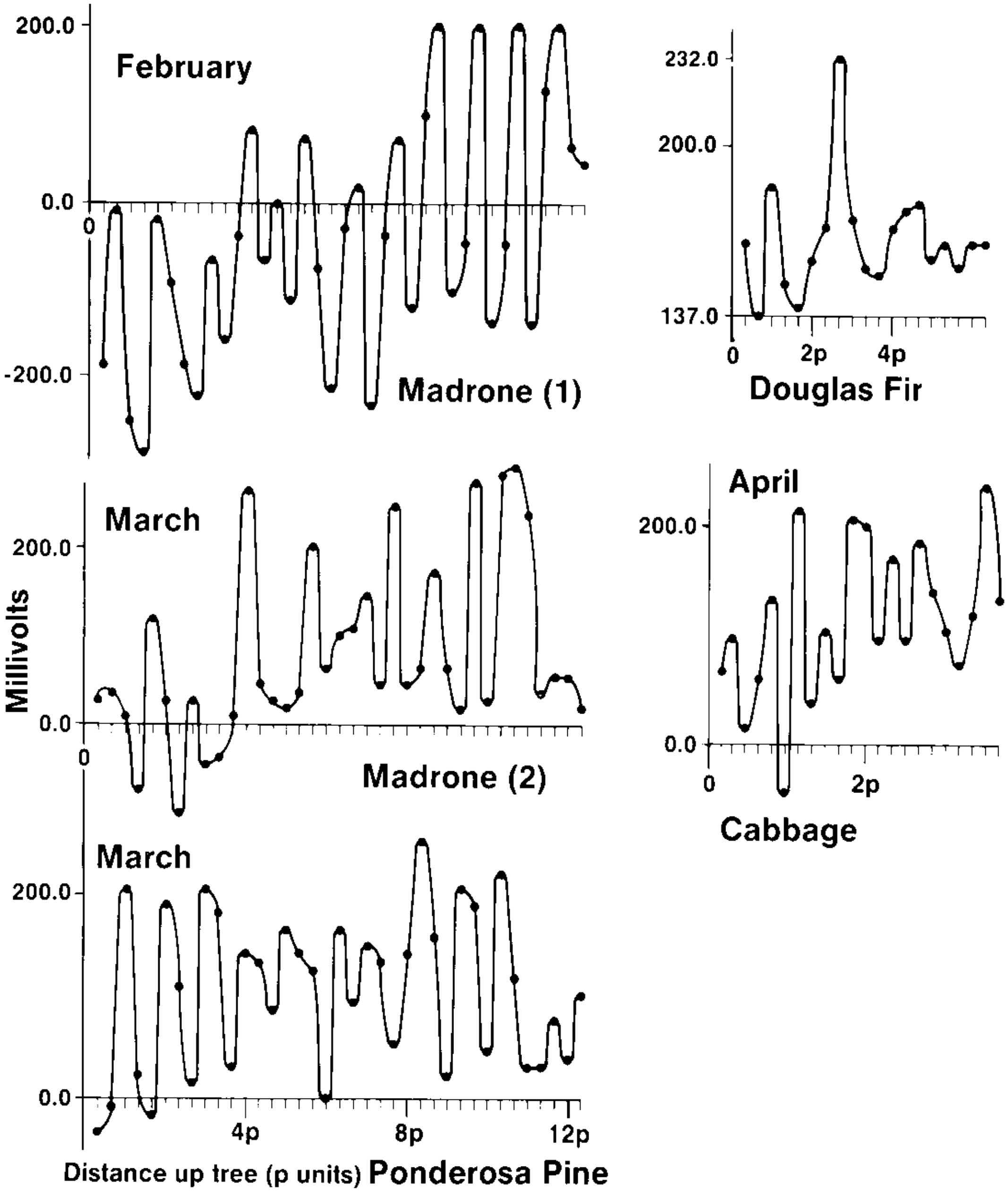

Figure 2. Wave patterns from four different plants (trees except for cabbage). These patterns were obtained from plotting voltages, taken from equally spaced probes, versus distance up the named species. Note that all the maximum voltages lie in the 200-300 mv. range. The probe spacing was p/3 except for cabbage where it was p/6 where p = 7.6 cm. The lowest probe (indicated by 0) was used for the voltage reference. The madrone 1 and madrone 2 plots are from the same tree and the same probes with a month between readings. See the text.

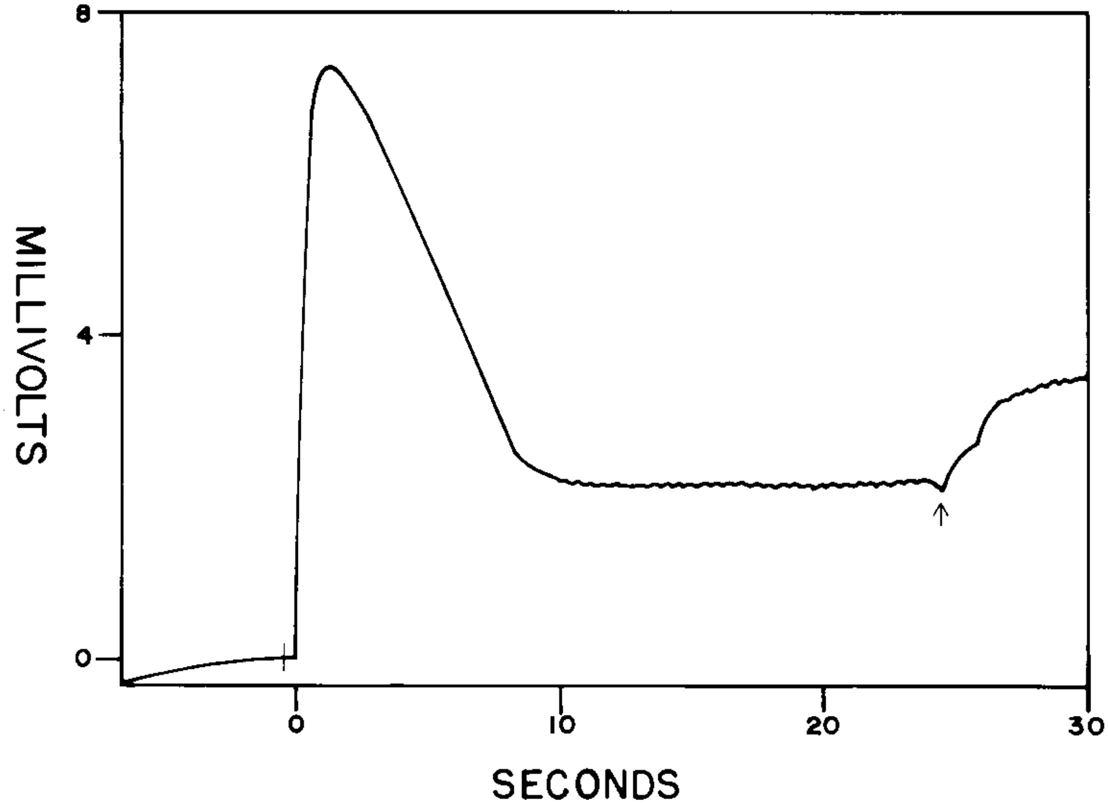

Figure 3. After centering the strip chart recorder this is the output from two Douglas-fir probes before and after a chop with an ax to the base of the tree. The two probes were placed at 0.3 m and 1.8 m from the ground. The 0 seconds is the time the pulse passed the lower probe on its way up after the chop. The line crossing the curve just to the left of zero represents the approximate time of the chop. The arrow points to the reflection blip.

Included in Figure 2 are short sections of patterns from madrone, Douglas-fir, ponderosa pine, and cabbage (*Brassica* sp.). First, notice how the madrone patterns (i.e. 1 & 2 Figure 2; using the same probes on the same tree) changed from February 28 (1) to March 25 (2). This was a very gradual change from day to day. The February peaks in the March pattern have shifted, and/or have changed amplitude, or merged. The predominant spacing is p in the February pattern while the March pattern shows the spacing between the main peaks to have a tendency to favor a 2p spacing. Referring to the ponderosa pine pattern (March 25 data), the main peaks were still spaced at near p as they were in February (not shown). The pine apparently had not yet broken dormancy but the madrone showed signs of some leaf growth. In cabbage (unpeeled) the probes were spaced at p/6. The graph shows an average spacing of 3.4 cm between peaks (April 9 data). The last probe lay in a fast growing region of the cabbage stalk which may explain the larger spacing between the last two peaks of the graph.

Searching for a zero crossing on a 10.5 m Douglas-fir provided the short pattern from probes centered 8.5 m high. The reference probe was at the base of the tree. Since there was no structure less than 137 mv the reference line was placed at +137 mv instead of zero as a convenience in plotting. The predominant spacing here was close to 2p. The modes involving p and 2p are easier to see but the patterns indicate that other modes are present because their structure is more complex than pure sine.

Pulse Velocity

For pulse velocity measurements we chopped into the base of the tree. The curve of Figure 3

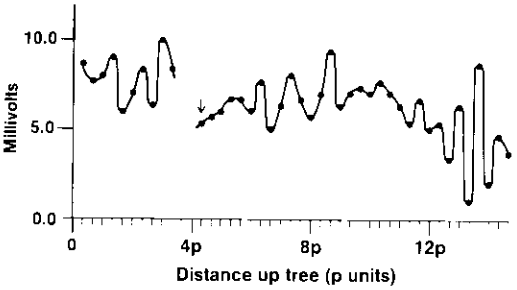

Figure 4. The wave type pattern (coming from 2 probes) resulting from driving in a nail successively up a tree. The nail was driven in at p/3 spaced intervals going up the tree where p = 7.6 cm. The nail that was driven in was lined up with the two electrodes in the tree. This necessitated skipping the electrode at location #12. Recall that there are electrodes at 0.3 m (location #12) and at 1.8 m. Also #11 was skipped due to proximity to #12. Hitting the nail at location #13 apparently caused the curve displacement downward due to the mechanical interaction with the probe at #12 but the approximate periodicity still continued. The arrow indicates location #13. Locations #11 and #12 are in the break.

represents the output due to a chop on an 8.8 m Douglas-fir. This curve is designated a damage curve. The first tall peak is a direct response to the chop. Notice the small downward inflection in the curve at approximately 25 seconds indicated by the arrow. This is a reflection blip. Usually there is some positive drift all along the damage curve but the relatively large positive drift after the reflection blip here (Figure 3) is somewhat unusual. So far only shorter trees (6.0-11.0 m) have clearly produced reflection blips. Larger trees have produced delayed oscillations but no definite reflection blips so far.

Driving a nail in a tree 42 times successively up the tree produced another standing wave type pattern with near p periodicity (Figure 4). This oscillatory response to excitation seems to indicate the presence of standing waves in the tree.

Discussion

In initial tests, the trunk samples were taken near the base of trees or shrubs because this area was relatively free of branches. These samples usually had a negative polarity. If they had been taken from other portions of the tree the polarity would likely have been positive. This perhaps is due to long wavelength patterns in trees which make regions alternate in polarity as one probes up a tree. Patterns like this were found in later winter tests on alder and willow as mentioned earlier. Perhaps when a short tree section is cut out, a long wavelength pattern furnishes the energy for the build up of the small pattern (7.6 cm) mentioned in the introduction.

The tree patterns (Figure 2) apparently are the result of the action of standing waves that distribute charges to the probed locations. A good analogy might be a Kundt's tube (Halliday and Resnick, 1970: 340) where acoustical standing waves in a pipe produce a pattern in cork dust or filings along the standing wave. Strictly speaking the pattern is evidence of the standing wave, but not the standing wave itself. (Most standing waves are detectable only from their effects.) The tree patterns observed from the probes apparently are analogous. They are produced by and provide evidence for the underlying standing waves.

Apparently electromagnetic waves do not produce the patterns because the apparent wave velocity is very small and a tree does not provide a very suitable medium because it is electrically conductive. However, this makes it difficult to monitor the various frequencies directly. As yet we have not developed a good transducer. The waves, however, pile up charge and thus voltages can be measured. The magnitude of fast changing voltages is small. It apparently takes time to build up charge sufficient to indicate a voltage as large as in the case of the a tree pattern where voltages are often hundreds of millivolts. Frequently small amplitude oscillations, usually less than one millivolt, were observed on the strip chart recorder when data were taken at 2.5 cm/hr and 25 cm/min (Table 1). (The lowest frequency oscillations listed in the table, however, had amplitudes of tens of millivolts apparently because there was time to build up charge). The observation of oscillations, especially with frequencies like 3.0 and 5.7 Hz, which are near calculated pattern frequencies, tends to confirm the presence of standing waves in plants.

Reflection calculations

Initially it was found that the delay between a chop and a "reflection blip" was approximately proportional to the tree height. This suggested reflection. Using the delay time and twice the tree height several tentative velocities were calculated. One also needed to take into account the probe

TABLE 1. Oscillation frequencies that have been measured coming from probes on trees. Only frequencies less than or equal to 5.7 Hz have been found so far. Two observed frequencies (3.0 and 5.7 Hz) were found to agree very closely with frequencies calculated from antinode spacings and a measured velocity. See further details in the text.

Frequency Observed	Associated Phenomenon	Date Temp	Comments
3.0 Hz.	Damage pulse	3/11/88 14.4°C	Ponderosa Pine 2p pattern
0.013 Hz.	Recent probes	2/17/88 6°C	2 hr. sampling madrone
0.01 Hz.	Recent probes	8/4/87 16°C	1 hr. sampling Douglas fir
0.005 Hz.	Recent probes	7/2/81 27°C	0.8 hr. sampling oak
Many low pulses	Recent disturbance	Anytime	Growing and dormant
0.53 Hz.	Ringing after damage	3/17/88 23°C	Ponderosa pine
0.0025 & 0.0027 Hz.	Possibly stomata behavior	7/87 approx. 30°C	Hot PM; oak; higher frequency superimposed on low
5.7 Hz.	Recent probes	3/31/88 21.1°C	Ponderosa Pine p pattern

locations. Further experimentation with the calculations, to produce the best agreement between velocities from trees of different heights, showed that one needed to consider the following three cases:

Case 1) A positive going blip. This was the most common response to an ax chop. This was hypothesized to be an indication of a reflected signal on its way down after reflection from the top of the tree. It was detected by the top of the two probes in the tree. Apparently there is no phase reversal when a pulse is reflected at or near the tree top.

Case 2) A negative going blip. It was hypothesized to be due to a pulse which missed the upper and the lower probes on the way down. The pulse was then apparently reflected from the base of the tree with a phase reversal and the upper probe detected the pulse as it passed. (In no case so far has it been reasoned that the lower probe detected a reflected pulse. Perhaps this is due to the wave pattern arrangement in the vicinity of the lower electrode and the base of the tree.)

Case 3) First a positive going blip and then a negative going blip. This seems to represent a combination of 1) and 2). This permits a second calculation of velocity with one chop, because one velocity can be obtained using case 1 and a second velocity calculated by using the time delay between the two blips and twice the height of the top contact. This helped confirm that a velocity was being measured since the two velocities were approximately the same. The two velocities obtained, however, usually differed from one another by several percent. The difference may be due to the ambiguity in the exact location of the bottom and top of a tree for reflection purposes. This type of response seemed to occur with a relatively high amplitude damage pulse.

If the curve in figure 3 is assumed to be a case 2 curve then a careful measurement from 0 seconds (the time the pulse passed the lower probe on its way up) to the point where the curve starts to bend downward (the time the reflected wave returns) gives an elapsed time of 23.9 seconds. The tree height was 8.8 m. Double the height and add 1.5 m for the distance from the tree base to the upper probe less the height of the lower probe; divide this sum by 23.9 seconds and the calculated velocity is 79.9 cm/second, the distance traveled divided by the elapsed time.

Measurement of several tree heights combined with the corresponding damage curve revealed initially that the pulse velocity was 90 ± 6 cm/sec. (5 Douglas-fir and madrone of various heights). Combining this velocity with the p spacing gives a calculated frequency of 5.9 Hz (the wavelength is twice the antinode spacing and frequency equals velocity divided by wavelength). Data taken a month later (19 April 1988) revealed a lower average velocity of 81 cm/sec (Douglas-fir) perhaps due to the effect of breaking dormancy.

Conclusions and Observations

Possibly the wave behavior described here is common to all plants. However the wave behavior is not restricted to live plants. Similar phenomena have been observed in sections of trees filled with salt solution (unpublished data). Salt solution-filled wood and live trees provide channels for movement of these waves but channels may not be necessary.

It is assumed that the wave phenomena discussed here are related to phenomena observed in *Mimosa pudica* and in carnivorous plants (Jacobson 1965, and Stuhlman *et al.* 1950). The wave velocities obtained, for example, seem to be similar to the velocities obtained for stimuli traveling in these plants.

The many futile attempts by other workers (e.g. Raber 1933) to obtain repeatable electrical data using electrodes in plants can perhaps be explained in terms of changing and shifting seasonal wave patterns (e.g. madrone in figure 1). A suggested name for the waves described herein is "W-waves" since they were first observed in wood samples.

Acknowledgments

The author wishes to thank Dr. Joe Zaerr of the Oregon State University College of Forestry for his comments and suggestions on this paper. I am grateful to my wife Claudia for her assistance in taking data. I also wish to thank Dr. Terry Johnson of Rogue Community College for his help in doing some of the experiments.

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Received 17 June 1988
Accepted for publication 11 October 1988