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W-Waves and Plant Spacings

Abstract

W-waves have characteristic frequencies in plants. To see if branch patterns might correlate with these frequencies branch, twig, stem, and leaf spacings were analyzed in a number of plants. The distributions of frequencies (Hz) associated with spacings were found to correlate closely with a spectrum analysis of actual frequencies emitted by plants. The distributions appear to be frequency spectra of plant utilized W-waves.

Introduction

Earlier I reported the discovery of W-waves in plants (Wagner 1988a,b; 1989). Evidence for the existence of W-waves consisted of measured electrical patterns, recorded oscillations, excitation behavior, and reflection phenomena. Measured electrical patterns appeared to indicate that standing waves are always present in plants and may play a part in their physiology. Recorded oscillations are another feature that demonstrated the presence of waves. Evidence indicated that the observed waves were not electromagnetic (Wagner 1988b; 1989) but as they interacted weakly with charge it was possible to observe some of their effects with ordinary electrical measurement equipment. I disturbed the apparent standing wave pattern in a tree at different locations and detected oscillatory behavior coming from two probes in the tree; a typical response upon disturbing any standing wave pattern. The velocity of the waves in the tree was found to be 90 ± 6 cm/sec using pulse reflection (Wagner 1988b). All the evidence pointed to the existence of waves in plants.

The presence of standing waves in plants led to the idea that nodes (or antinodes) may be likely places for the growth of branches or other plant structures. To test this hypothesis several thousand branch and other spacings on plants were measured to see if the frequency distributions of plant growth spacings would demonstrate discrete groups.

Observation of such discrete spacings would suggest that the growth spacings are related to the standing waves already observed in plants. As such discrete groupings of spacings were found I attempted to correlate the frequencies from a low frequency spectrum analyzer connected to probes in plants with the frequencies (Hz) calculated from observed plant growth spacings.

Methods and Materials

Measurement of Spacings

Details of the methodology of electrical signal measurements on trees and other plants were described earlier (Wagner 1988a,b; 1989). The plants used in this study grew at an altitude near 460 m. Measurements of plant growth spacings (i.e. distances between branches, twigs, stems, or leaves) were taken with a rule calibrated in millimeters and estimated to the nearest 0.1 mm. It is difficult to measure the spacings between branches, twigs, and leaves on branches accurately without good reference points. A few plants, such as big leaf maple (*Acer macrophylla*) with its bands at branch locations, syringa (*Philadelphus* sp.) or sweet corn (*Zea mays saccarata*), have distinct features which do provide good reference points. For consistency, appropriate reference points were chosen in every case. Spacings between needles on conifers were omitted from these measurements because the spacings are so small. While an attempt was made to take a representative random sample of spacings so that a distribution would be typical of the spacings from a particular species of plant, the spacings of branches on tree trunks were ignored because there were relatively few branches per tree.

The data recorded were spacings between: (1) twigs and small branches on one young (approx. 5 m) white fir (*Abies concolor*); (2) lower branches of three (approx. 30 m) white fir trees; (3) leaves and stems on several prickly lettuce (*Lactuca serriola*) plants; (4) twigs, mostly from lower branches, on two young Douglas-fir trees (*Pseudotsuga menziesii*) (9 m) growing in the open (emphasizing new but completed growth); (5) twigs on another young Douglas-fir (8 m) growing in semishade; (6) lower branches of 5 approximately 15 m ponderosa pines (*Pinus ponderosa*) growing in a clump with other trees; (7) leaves and branches on one bigleaf maple, cut down for easy access; (8) leaves and branches on one small (approx. 4 m) Oregon ash (*Fraxinus latifolia*); (9) leaves and branches on one syringa shrub; (10) joints on many stalks of sweet corn; (11) leaves and branches on some lower branches of two delicious apple trees (*Pyrus Malus* sp.); and (12) leaves and branches from four different Concord grape (*Vitus labrusca*) vines. No attempt was made to obtain all the spacings from any particular tree or other plant except in the case of prickly lettuce.

The plant growth spacings were analyzed to see if they clustered into discrete groupings by taking the frequency distributions of the measured spacings using 1 mm intervals. Spacing mostly appeared to be discrete (Figure 1). Each spacing in the twelve sets of data above was then converted to a frequency in Hz by dividing a W-wave speed of 96 cm/sec by twice the spacing (see data analysis), (96 cm/sec was within the previously measured wave speed of 90 ± 6 cm/sec (Wagner 1988a,b)). The number of spacings in each 0.1 Hz interval (bin) was plotted against frequency in Hz for each set of data to make the 12 graphs of Figures 2-5. By converting spacings to frequency (Hz) and taking the distribution I could compare frequencies derived from growth spacings directly with frequencies found from spectrum analysis. Any correlation between these frequencies would tend to indicate the W-waves with their wave patterns were involved in setting plant growth spacings. I did not attempt to verify if an existing branch spacing pattern correlated with the *in situ* standing wave pattern in a particular plant as I assumed that the standing wave pattern slowly changes as the plant grows (see Wagner 1988b).

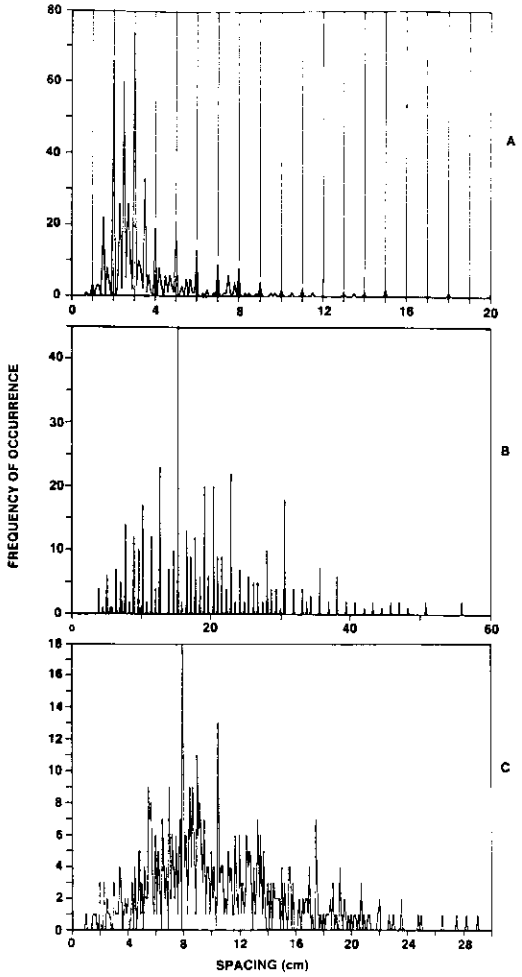

Figure 1. Spacing distributions of (A) 536 branch and leaf spacings from the lower branches of two delicious apple trees, (B) 429 spacings from the lower branches of five ponderosa pine trees (approx. 15 m high), and (C) 502 leaf and branch spacings from Concord grape vines. The interval used in taking the distributions was 0.1 cm.

Measurement of W-wave Frequencies

Direct measurements of the frequency spectrum of electrical signals (Figures 6 and 7) were recorded on a frequency spectrum analyzer (Schlumberger 1201) by placing probes in the plants (Wagner 1988a,b; 1989). Concern for possible 60 Hz interference led to testing the analyzer far away from 60 Hz sources but the same apparent W-wave peaks (harmonics) usually appeared when a 48.8 Hz supply was used. Care was taken to assure that any peak considered as a W-wave peak from the spectrum analyzer was found only in association with plants. Peaks such as 60 Hz harmonics from ac power are common (60 Hz also appears to be a common W-wave frequency) and numerous electronic devices radiate other spurious signals so spectra were taken approximately 1500 times to validate the various

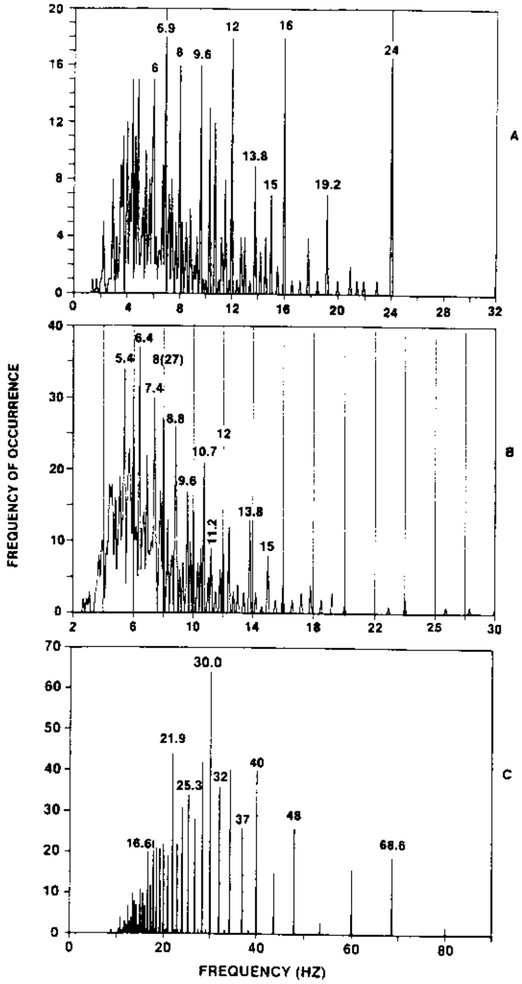

Figure 2. Frequency of occurrence of spacings (converted to frequency in Hz by using f = 48/s where f is the frequency and s is the spacing. See the text) versus frequency (Hz) of branch, twig, stem, and leaf spacings for (A) 489 spacings on a young white fir (5 m), (B) 863 spacings on the lower branches of three 30 m white fir*, and (C) 720 spacings on prickly lettuce. The bin (intervals used in obtaining the distributions) in these frequency distributions is 0.1 Hz. The frequencies above peaks in Figures 2-5 were taken from the Lotus 1,2,3 worksheets used for data analysis.

*Number in parenthesis after a frequency refers to the number of spacings for that peak.

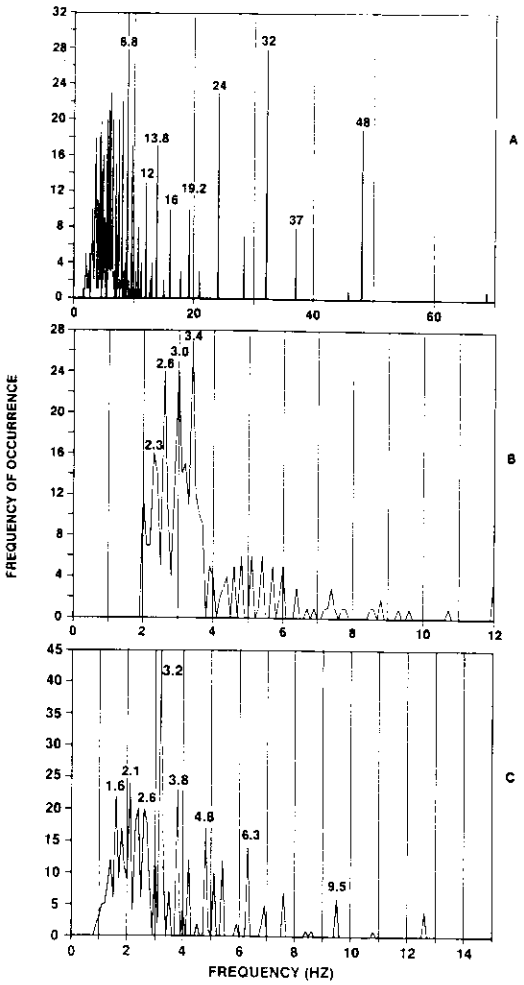

Figure 3. Frequency of occurrence of spacings versus frequency (Hz) for (A) 633 spacings from two Douglas-fir (9 m) growing in the open, (B) 314 spacings from a young (8 m) Douglas fir growing in semishade, and (C) 429 spacings from the lower branches of five approximately 15 m ponderosa pine growing in a clump with several other trees.

apparent W-wave frequencies. Common mode cancellation and coaxial cable with appropriate grounding was used to minimize undesirable signals. No attempt was made to compare amplitudes of the same frequency peak in different plants on the spectrum analyzer. The spectrum analyzer data were taken from 1 July to 8 October 1988.

The spectra were also confirmed, checked, and analyzed in the following ways:

(1) A battery operated instrumentation amplifier in a metal box (a 90 cm aluminum cube) was connected to a potted plant in the same metal box with appropriate probes. A pair of coaxial cables took the signal to the differentially

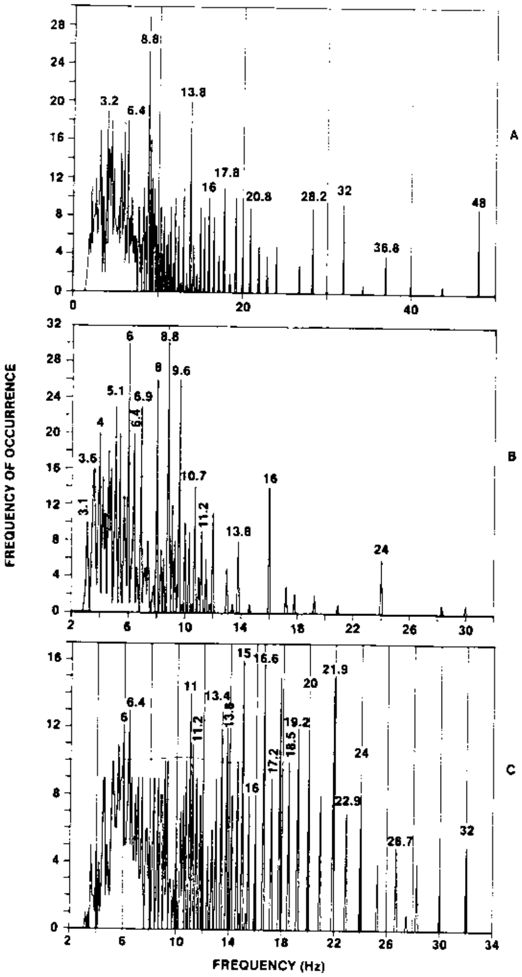

Figure 4. Frequency of occurrence versus frequency (Hz) for (A) 865 branch and leaf spacings from a big leaf maple (approx. 10 m), (B) 622 branch and leaf spacings from a small (4 m) Oregon ash, and (C) 642 branch and leaf spacings from a syringa (shrub).

connected spectrum analyzer outside the metal box (Figure 8). The amplifier increased the signal amplitude feeding into the spectrum analyzer to the millivolt range with the typical peaks (usually harmonics of 0.16 Hz with certain harmonics that usually are of higher amplitude) I have associated with plants still appearing, but at much higher amplitudes. This confirmed that the observed frequencies were coming from the plant and not the spectrum analyzer. All appropriate measures were taken for common mode cancellation of unwanted signals.

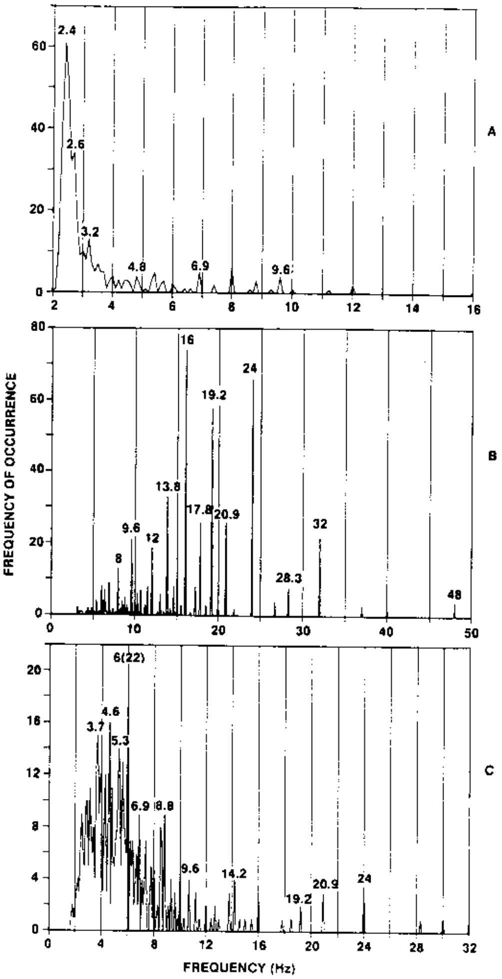

Figure 5. Frequency of occurrence versus frequency (Hz) for (A) 392 joint spacings on sweet corn, (B) 536 branch and leaf spacings from the lower branches of two delicious apple trees, and (C) 502 leaf and branch spacings from Concord grape vines.

(2) The apparent plant frequencies were also confirmed on a Schlumberger 1220 low frequency spectrum analyzer; a considerably different analyzer which is more sensitive and better designed to reduce spurious responses than the 1201.

(3) Probes in a control dead dry log did not give plant spectra, but they were observed, however, from salt solution filled logs.

(4) Almost all observed peaks appeared to represent harmonics or subharmonics and this fact was used to check peak validity. If the

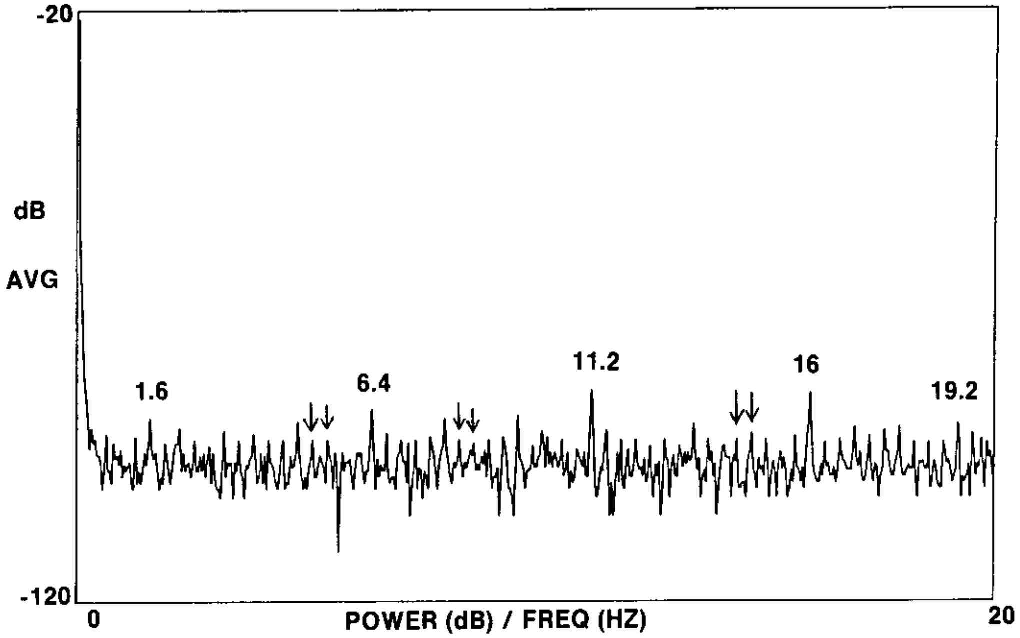

Figure 6. Spectrum (0-20 Hz) from contacts spaced about 3 cm on a willow (*Salix* sp). Notice the peaks spaced at 0.32 Hz and the 1.6 Hz harmonic peaks which often have greater amplitude than the ordinary 0.32 Hz spaced peaks. This spectrum was chosen as rather typical of spectra from plants. Several of the 1.6 Hz harmonic peaks have been marked to indicate the frequency of the peak. This is essentially the same as the spectrum of Figure 7 except that only a detailed portion of the spectrum (baseband 20 Hz) is shown allowing the structure between the 1.6 Hz spaced peaks to be seen. The arrows indicate 0.32 Hz spaced peaks. The scales are linear.

spectrum baseband was set at 30000 Hz peaks were usually observed spaced at 800 Hz (not shown) with the last one at 29600 Hz due to the resolution characteristics of the spectrum analyzer and the nature of the spectrum. If the baseband was set at 2000 Hz the observed peaks were usually spaced at 80 Hz with the 10th peak representing the first 800 Hz peak observed on the analyzer with a 30000 Hz baseband. If the baseband was set at 500 Hz the observed peaks were often spaced at 16 Hz intervals with the fifth peak at 80 Hz or, if the baseband was 100 Hz, the observed apparent plant frequencies were on 1.6 Hz intervals (Figure 7). If the baseband was set at 20 Hz the commonly observed interval was 0.32 Hz, with larger peaks at 1.6 Hz intervals (Figure 6). For basebands of 1 Hz peaks were found at 0.16, 0.08, 0.04, and 0.02 Hz. Characteristically certain harmonics often appear to be larger than others, for example, the 7th and 10th harmonics of 1.6 Hz (11.2 and 16 Hz) using a 20 Hz baseband (note also the larger peaks of Figure 7). There appears to be a regular repeating characteristic pattern in the relative amplitude of harmonics but it has not yet been completely determined. The above harmonics seem to appear only when probes in plants or salt solution filled wood samples are used or from certain other types of sensors in the vicinity of plants (Wagner 1989).

(5) Another technique which appears to confirm the presence of W-wave frequencies involves running a small ac electric current through a plant using one probe near the top and the other near the bottom of the plant. Connecting the spectrum analyzer to two probes in the plant set between the current supply probes indicates that the small ac current frequency beats with W-wave frequencies (Wagner 1989). When the spectrum analyzer reveals a peak at an ac source frequency S, other peaks are also often seen symmetrically placed about this peak. These other peaks

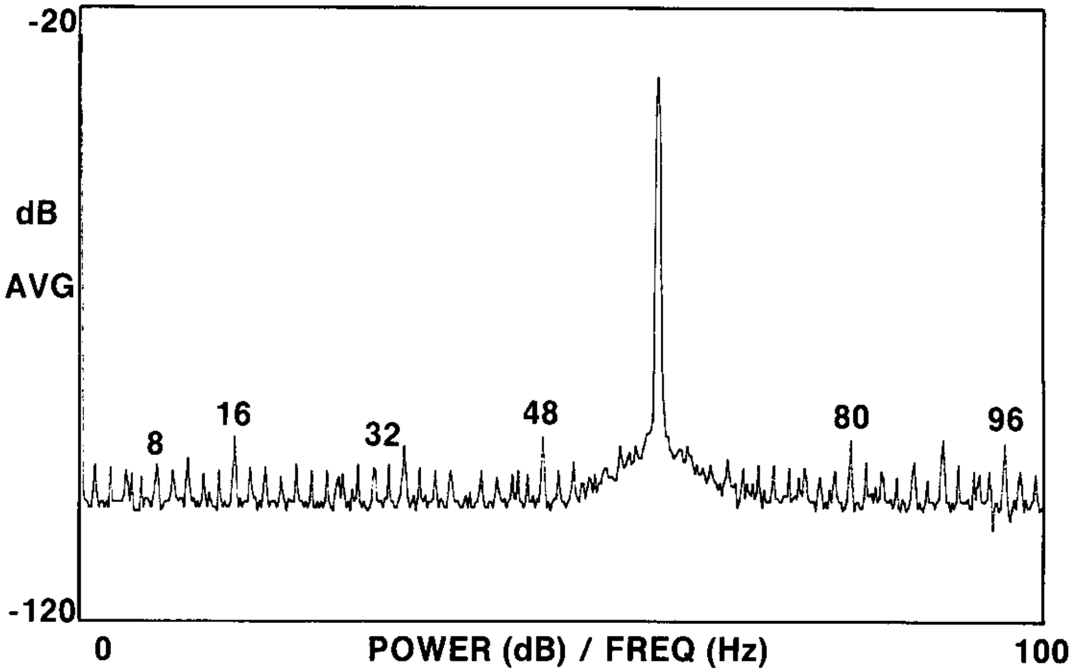

Figure 7. Spectrum (0-100 Hz) from probes on madrone (*Arbutus menziesii*). The 1.6 Hz spaced peaks show clearly. The large peak is the 60 Hz power peak which is difficult to eliminate near 60 Hz power lines. This spectrum was taken at 0543 hrs 2 August 1988 at a temperature of 10.6° C. Again this was a typical spectrum from probes in a plant. The scales are linear.

appear at frequencies $S+g_n$ or $S\text{-}g_n$ where the g_n appear to be common W-wave frequencies. Many apparent W-wave frequencies have been observed which match those commonly observed on the spectrum analyzer using the first method (two probes without a special ac source to produce beats). This beat (or heterodyne) four probe technique appears to provide an additional check on the validity of the observed W-wave frequencies. Amplitudes are often orders of magnitude larger than those observed by the simple two probe method first used. The beat method is more tedious than the direct approach since only a few frequencies usually appear with a given applied frequency but it appears to show peaks of important W-wave frequencies outside the 1.6 Hz harmonic series of the two probe method (e.g. 4, 10, and 12 Hz).

(6) The given spectra (e.g. Figures 6 and 7) result from at least eight averages on the 1201 spectrum analyzer to minimize noise. Exponential averaging was used (usually with a Hanning window) with a time constant of several seconds to several minutes (depending on the baseband used). The slow rise and fall of some of the peaks could be seen as the spectrum analyzer averaged.

(7) In initial phase tests two begonia plants (*Begonia* sp.) were displaced vertically from one another by approximately one meter. Pairs of probes were placed in each plant and the probe outputs run through high input impedance bandpass filters with center frequencies of 80 Hz (usually a large amplitude W-wave frequency). A phasemeter indicated that the 80 Hz signals obtained were related by a constant phase angle. This apparently indicated that the two 80 Hz W-wave signals were not only real but that they were causally linked (e.g. perhaps the 80 Hz signals came from a spacial (and vertical) standing W-wave pattern common to both plants).

Data Analysis and Results

If standing waves are responsible for the spacings between plant structures then both a wavelength and a frequency can apparently be

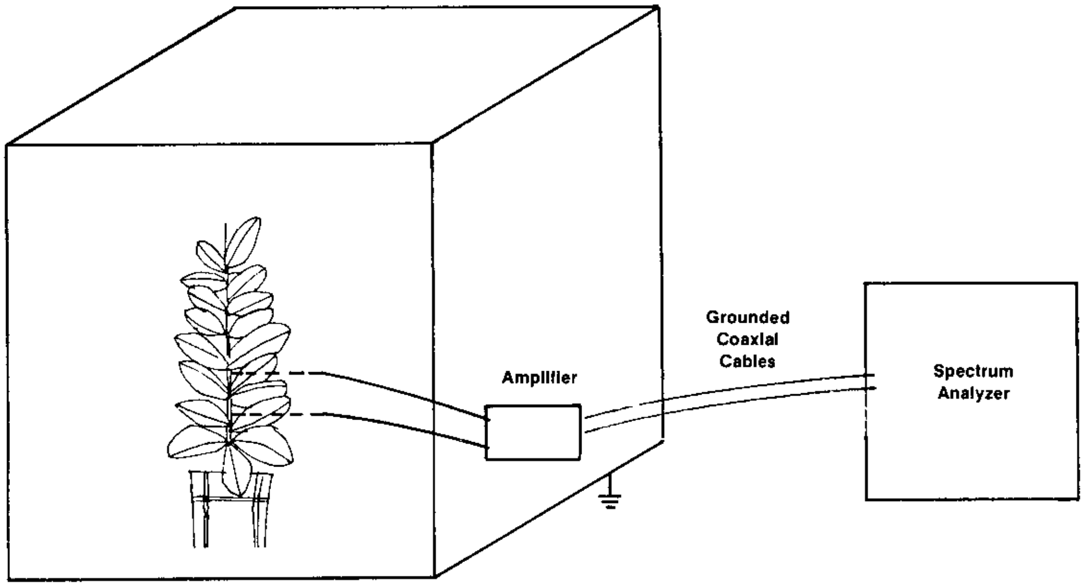

Figure 8. A diagram of one experimental setup used to show that W-waves appear in metal shields. The amplifier used was battery powered so that everything having to do with the amplifier was in the shield (aluminum box) except for the two grounded coaxial cables, going through small holes in one side of the box, taking the amplified signal to the spectrum analyzer. (See the text.)

associated with a particular spacing. As is well known for waves in general, the frequency is given as the quotient of the wave velocity and the wavelength. The *in situ* wave velocity was taken as 96 cm/sec. This velocity was chosen because a preliminary study suggested that more plant frequencies found on the spectrum analyzer matched frequencies (Hz) determined from branch spacings when this velocity was used. 96 cm/sec compares favorably with the velocity of 90 ± 6 cm/sec previously obtained from direct impulse and response measurements (Wagner 1988a,b). The frequency (f_n) of a particular spacing (using 96 cm/sec) is defined here by the following formula:

$$f_n = 96/2s_n = 48/s_n$$

where s_n is a particular spacing. The 2 in the denominator is chosen because the spacing might correlate to antinode or node spacing which is 1/2 the wavelength. The above formula was used to convert all the spacings to frequencies (Hz). Figures 2-5 are distributions of the spacings converted to frequencies in Hz. I measured the power spectrum of electrical signals from the same plants but all plants tested seemed to give the same basic spectrum.

A complete set of the spectral peaks does not always appear on the spectrum analyzer. Some peaks appear while the spectrum analyzer is averaging, then disappear and again reappear (e.g. 2.4 Hz usually seemed to show on hot afternoons). However, just by placing probes in a branch of any plant one can often obtain an almost complete set of apparent plant frequencies for the particular baseband used (e.g. Figures 6 and 7). All of the peaks shown are harmonics (integral multiples) of 0.16 Hz (or 0.02 or 0.04 or 0.08 Hz). Notice in Figure 6 that most of the peaks are spaced at 0.32 Hz, which is typical for a 20 Hz baseband. Larger amplitude peaks appear at multiples of 1.6 Hz. Even if the smaller peaks (e.g. Figure 6) fail to show in a spectrum, at least some of the 1.6 Hz series are almost always present.

After much experimentation it was decided that the most important criteria for real plant peaks on the spectrum analyzer was that they should be harmonics of 0.02, 0.04, 0.08, or 0.16 Hz, since harmonics of these particular frequencies almost always seemed to be associated with plants in my latest studies. These harmonics include the 1.6 Hz series of harmonics, which often have higher amplitudes and appear more often than other harmonics (again see Figures 6 and 7).

In Figure 7 the peaks are spaced mostly at 1.6 Hz (baseband 100 Hz). There are enough frequencies available, however, as indicated by the spectrum analyzer (e.g. Figures 6 and 7 and spectra not shown), that the distribution of branch spacings could be nearly a continuum but some of the harmonics appear to be more dominant than others. The 1.6 Hz series with their large amplitudes seem to show up in a large number of corresponding plant spacings. There probably are selection rules that determine which frequencies are dominant in setting plant spacings (it is recognized that there are many other factors involved in setting branch spacings such as environment and genetics).

Although I believe that plant spacings are set not by W-wave noise but by definite, numerous, harmonically related W-wave frequencies, it is useful to consider a criterion for peak validity when noise is present in case our assumptions are incorrect. The statistical error associated with a counting process is of the order of $\sqrt{N}$, where N is the number of counts in a particular spacing bin (interval). So in determining the validity of a plant peak, a peak which is 20 counts high would have an uncertainty of the order of $\sqrt{20}/20$ x 100 percent. If a peak is still far above the peaks in adjacent bins after $\sqrt{N}$ is subtracted from the number of spacings in that peak it can be called a real peak. This criterion not only appears to demonstrate the validity of many W-wave frequencies when frequency (Hz) is plotted versus frequency of occurrence, but if spacings are plotted versus frequency of occurrence, it becomes clear that many more of the peaks in all the distributions appear to be real by this criterion (e.g. Figure 1). I estimated that the maximum error in the frequency (Hz) in the frequency of occurrence versus frequency (Hz) plots is ±0.1 Hz. The results, however, seem to indicate that the error is generally less than ±0.1 Hz and probably within the possible bin error of ±0.05 Hz since so many peaks seem to fit the 1.6 Hz series (Figures 2-5).

As an introduction to plant spacing distributions Figure 1 shows three distributions where the spacings are not converted to frequency (Hz). First notice Figure 1A where the spacing distribution is plotted for data from two apple trees. Calculations reveal that most of the larger peaks fit common W-wave frequencies when using frequency equals 96 cm/sec divided by two times the spacing (e.g. for a sample calculation take the 2 cm spacing from Figure 1A and use it as s_n in the formula $f_n = 48/s_n$ given above. This gives 24 Hz, a common W-wave frequency as revealed on the spectrum analyzer). Similarly, in Figure 1B I have a plot of spacings versus frequency of occurrence for data from five ponderosa pines. The largest peak is very apparent with a spacing of 15 cm, or 3.2 Hz using the frequency formula. In Figure 1C where the number of spacings is plotted versus spacing for concord grape, more real peaks by the above $\sqrt{N}/N$ criterion are shown than later when frequency of occurrence is plotted versus frequency (Hz) in Figure 5C.

Where growth spacings are converted to frequency it can be seen that many of the peaks repeat from plant to plant. Figure 2A, for example, shows real peaks (using the noise criterion above) at frequencies at 2.2, 6, 6.9, 8, 9.6, 12, 13.8, 15, 16, 19.2, and 24 Hz and others. Consider the validity of the 6 Hz peak. There are 15 spacings in this peak. The square root of 15 is near 4. Subtracting 4 still leaves the peak considerably higher than the adjacent peaks. The validity of the 6, 6.9, 8, 9.6, 12, 13.8, 15, 16, 19.2, and 24 Hz peaks is obvious by my criterion. Some of these peaks fit into the 1.6 series of harmonics observed on the spectrum analyzer (Figures 6 and 7) and the remainder into the 0.04, 0.08, or 0.16 series of harmonics. It appears that possible bin (±.05 Hz) and measurement errors can take care of most variations from exact fit on the spectrum analyzer peaks. In Figure 2B, some of the peaks match those of figure 2A. In Figure 2C the main peaks are: 21.9, 30, 32, 37, 40, 48, 60, and 68.6 Hz. The graphs reveal that many peaks are in the real category, as determined by our noise criteria, especially at the higher frequencies. Characteristically, it appears that, for most of the distributions shown in Figures 2-5, those peaks at lower frequencies suggest a possible continuum of larger spacings, but if a spacing rather than a frequency (Hz) distribution is analyzed this may not be the case (Figure 1). A careful study of individual peaks suggests that no spacing is random, especially at the higher frequencies, since every peak even with only one spacing in it seems to match a 0.02, 0.04, 0.08, or a 0.16 Hz harmonic or one of the apparently more dominant harmonics of 1.6 Hz. For example, notice in figure 2C the two spacings at 80 Hz which is usually a very dominant peak on the spectrum analyzer and notice the peaks at 48 Hz in Figures 4A and 5B.

The prominence of particular peaks apparently varies not only from species to species but within the same species. Comparing spacings from plants of the same species growing in the shade and the sun it appears that shade grown plants would have larger spacings as growth is longer in the shade. This seems to be borne out by the two sets of Douglas-fir data (Figure 3A and B). Some of the main peaks of the shaded fir are at longer wavelengths (or lower frequencies: 2.3, 2.6, 3.0, and 3.4 Hz compared to 8.7, 24, 32, and 48 Hz for example) than the trees grown in the sun.

The main peaks seen in the ponderosa pine data (Figure 3C) at 1.6, 2.1, 2.4, 2.6, 3.2, 3.8, 4.8, 6.3 and 9.5 Hz (6.3 and 9.5 Hz are within 0.1 Hz of 6.4 and 9.6 Hz) show an almost perfect fit with the 1.6 Hz series from the spectrum analyzer and to other peaks that most commonly appear on the spectrum analyzer. The 2p (3.2 Hz) spacing discussed in the early data (Wagner 1988a,b) provides by far the most prominent peak here.

In Figure 4A the big leaf maple provides the largest peak at 8.8 Hz. Maple branches provide visible clues to a possible correlation between structure and wave behavior with groups of closely spaced bands often appearing just above branch whorls. These bands appear to be analogous to the standing waves that appear in small water pools connected to larger pools where a large wave has been generated. The branch whorl apparently produces a disturbance in the larger wave pattern and the results appear on the upper side of the whorl. In Figure 4B the dominant peaks are 6 and 8.8 Hz with a less dominant peak at 9.6 Hz. In Figure 4C some large peaks are at 6.4, 11, 15, 16.6, 17.2, 17.8, 19.2, 21.9, 24, 32 Hz and so on. These either fit the 1.6 series or fit the other series to probably within the possible bin error. The "signature" of syringa seems to be more complex than the signatures from other plants studied.

In sweet corn (Figure 5A) the major peaks are at 2.4 Hz and a minor peak at about 2.6 Hz which may not be real. The closest 0.32 Hz series frequency (multiple of 0.32 Hz) is 2.56 Hz and 2.4 Hz fits a 0.16 Hz series peak. Minor peaks which may not be significant are also at 3.2, 8, and 9.6 Hz which are multiples of 1.6 Hz. Figure 5B yields peaks at 9.6, 12, 13.8, 16, 19.2, 24, and 32 Hz. These peaks fit with the 1.6 series and other available frequencies. In Figure 5C the major peak is at 6 Hz (with 22 spacings) and some of the other peaks do not appear to be real. Complicated growth patterns may make it appear that spacings are less discrete. Possible variations in the *in situ* W-wave velocity during the growing season could also be a possible cause for scatter (Wagner 1988b).

When I take into account that plant frequencies can be quite small (0.04 Hz and less), and that plant frequencies can appear to be harmonics of any of the low frequencies observed on the spectrum analyzer, then all of the plant peaks from spacings fit W-wave frequencies within experimental error. A statistical correlation would appear to be meaningless for this reason. I have noticed that certain frequencies seem to be dominant, particularly those which are multiples of 1.6 Hz. Considering, for example, the number of spacing frequencies in the peaks that are labelled in Figures 2-5 (usually the peaks with the largest amplitudes) 42 percent of these spacing frequencies represent harmonics (integral multiples) of 1.6 Hz; 9.5 percent represent harmonics of 0.16 Hz (but not of 1.6 Hz); 11.7 percent represent harmonics of 0.08 Hz (but not of 1.6 Hz and 0.16 Hz); 21.1 percent represent harmonics of 0.04 Hz, and 16 percent represent harmonics of 0.02 Hz (Note: (1) There are 2300 spacings converted to frequency in the labelled peaks with about 7000 spacings represented in all the graph data; (2) Harmonics of 0.02 and 0.04 Hz are not distinguishable because the bin (interval) width used accommodates ±0.05 Hz from the center frequency.) The large percentage of 1.6 Hz harmonics reinforces the idea that these harmonics are dominant, as suggested by the spectrum analyzer data (Figures 6 and 7).

Discussion

There are so many frequencies available in the apparent W-wave spectrum that almost any plant spacing could be allowable but it seems that certain frequencies, such as the multiples of 1.6 Hz, appear more often than others in plant spacings. Other common frequencies that appear are 4, 6, 10, 12, 60, and many others that are not integral multiples of 1.6 Hz but appear to be multiples of lower frequency subharmonics observed on the spectrum analyzer (e.g. 0.16, 0.08, 0.04, and 0.02 Hz). Since it is not clear what determines an important W-wave frequency, more study is required.

The most important observation in this study is that branch spacings often seem to be in discrete spacing groups (noise would not be expected to produce definite repeating spacings) rather than in smooth distributions and this discrete spacing would be expected from standing wave determined spacing distributions. Many of the peaks in the plant distributions repeat from plant to plant which possibly indicates the close interrelationships of plants and a common source for W-waves. Usually the major plant peaks match the major spectrum analyzer peaks shown in Figures 6 and 7, or they are harmonically related as observed earlier.

It is possible that some of the data do not fit exactly on peaks which represent W-wave frequencies because of the following hypotheses:

1) End effects. Standing wave patterns tend to set the branch spacings but with variations stemming from growing conditions. There is some evidence that wavelengths tend to be longer near ends (from unpublished data taken on salt solution filled samples) and plants grow from their ends. It is not yet clear how end effects fit into the picture but end effects are common in wave phenomena (e.g. Strutt 1945:487).

2) Errors in measurement. The spacings for the prickly lettuce data, for example, were hard to obtain because the leaves alternated from side to side along the stalk. There may be some unconscious rounding in measurement especially where there is no good reference point as in white fir. I tested this hypothesis on a white fir by covering all numbers and delineating lines except for mm marks on the measuring rule before measuring a spacing. The spacing was then marked on the rule and then the rule numbers were uncovered to see and record the spacing. This procedure was repeated until sufficient data were obtained for a comparison with data taken by the usual method. The data were then analyzed and compared to data taken without the covering precautions. This experiment indicated that there was some rounding error, but not enough to warrant retaking the data.

3) Frequency distribution slot (bin) and measurement error. Using the calculus one can derive an approximate expression that relates small changes in spacing to small changes in frequency. The relation follows:

$$\Delta s_n = -s_n^2 \, \Delta f_n/48$$

Δs_n and Δf_n represent small changes (or errors) in spacing and frequency respectively. For example, if an interval (bin) is centered on 6 Hz (8 cm spacing) then the approximate allowable spacing error to stay within a bin of width 0.1 Hz is ±0.7 mm. If the interval is centered on 60 Hz (8 mm spacing), however, one would have to measure within approximately ±0.007 mm to stay within the bin. This suggests that different bins should be used for different frequency ranges. A millimeter measurement error at 60 Hz would mean an approximate frequency error of ±7.5 Hz while a millimeter error at 6 Hz would mean an approximate frequency error of ±0.075 Hz. The possible error introduced by the computer in taking the distributions was considered negligible.

Conclusions and Observations

These data, as reported earlier (Wagner 1988a and 1989), indicate the W-waves are apparently associated with some plant growth behavior patterns. The discrete spacing data by itself hints at the likelihood of some type of standing wave function with frequencies repeating on individual plants and from plant to plant. A comparison of spectrum analyzer data, where actual frequencies are measured, with spacing frequencies calculated with a wave speed of 96 cm/sec, reinforces the idea that W-waves explain the discrete plant spacings. This invites further investigation into the source(s) and function of W-waves.

The number 1.6, which appears here, is close to the *golden ratio* (Dixon 1989). Perhaps W-waves are related to the Fibonacci numbers as they are manifested in plants. W-waves might also be involved in other natural phenomena, such as in the formation of quasicrystals, where the *golden ratio* appears.

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