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Practical Considerations for Using A TDR Cable Tester to Measure Soil Water Content

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SUMMARY

Time domain reflectometry (TDR) technology can be used to measure soil water content, but due to an incomplete understanding of this technology, some scientists are reluctant to invest their resources it. The objectives of this paper are to discuss the basic principles of TDR to measure soil water content, to present the equations to convert TDR screen readings to soil water content values, and to describe a custom built TDR system. Commercial cable testers operate under the assumption the dielectric constant of the medium is known. For soils applications the dielectric constant varies with soil water content and is unknown, but the equations developed allow the user to overcome this situation. The custom built TDR system described here uses a commercially available cable tester; a balun transformer; shielded, two wire transmission cable; and wave guides constructed from stainless steel welding rod. Several of these systems have been used intensively for six years.

1. INTRODUCTION

Accurate and precise measurement of soil water content is often essential to interpret properly the experimental results from field, laboratory and greenhouse experiments. This is especially true for field studies on water and solute transport related to management practices such as irrigation scheduling, drainage, and the use of ground covers to conserve water and minimize surface water runoff.

Devices commonly used to monitor temporal and spatial changes in soil water status of field soils are the neutron moderation meter (van Bavel et al., 1956, 29), electrical resistance blocks (Bouyoucos 1953, 447), and tensiometers (Richards, 1928, 719). Less commonly used devices include vapor pressure psychrometers (Richards and Ogata, 1958, 1089), heat dissipation sensors (Phene et al., 1971, 27), and dual gamma radiation attenuation units (Gardner and Calissendorff, 1967, 101). All of these devices are calibrated by using gravimetric determination of soil water content (Gardner, 1986, 493). One advantage of the time domain reflectometer (TDR) is its capability to rapidly measure water content in the surface 10 to 15 cm of soil, a zone where current methodology has severe limitations.

Time domain reflectometry technology is not new. It has been used by the communications industry to test transmission lines or cables for continuity and to locate weak or broken spots in these cables. Commercial TDR cable testers are available for this purpose. The adoption of the principles of time domain reflectometry to measure soil water content was pioneered by Davis and Chudobiak (1975, 75) and implemented by Topp and associates in the early 1980's (Topp et al., 1980, 574; Topp and Davis, 1981, 13; Topp et al., 1984, 313).

A TDR instrument has several components: (1) a signal generator that initiates a step voltage pulse which propagates along the transmission line from the instrument; (2) a voltage sampler which samples or measures the voltage on the transmission line at the instrument at selected time intervals; (3) a timer which controls when the sampler measures voltages and when the generator sends pulses; (4) a computer to assemble the voltage as a function of time and to calculate the distances to reflections which cause voltage changes; and (5) a display to show the pattern of the voltage-time relationship.

During the past 5 years, interest in the TDR to measure water content in field soils has increased (Grantz et al., 1990, 144; van Wesenbeeck and Kachanoski, 1988, 363). Even though the use of the TDR for research in soil water management studies is gradually increasing, there has been considerable reluctance by many soil scientists to invest their time and resources in this methodology. Until recently, one reason for this reluctance was the unavailability of a reliable commercial TDR instrument dedicated to the measurement of soil water content. Several commercial units are now available for this purpose. A second reason for this reluctance is that potential users have not had a good understanding of how to adapt this technology for their particular application. Many researchers wish to assemble a TDR system that does not have the limitations of the present commercial units. There is much confusion however, concerning the kinds and sources of commercially available electronic components to use when making radio frequency measurements, how to assemble the components properly, and how to calculate correctly the soil water content once the system is assembled and field data are collected.

The purpose of this paper is: (1) to present a simple explanation of the relationships among wave propagation by a TDR, wave guide length, and soil water content, and (2) to describe the approach we used to construct a reliable TDR system for measuring soil water content. This presentation is not intended to be a comprehensive literature review of TDR, nor will it include a discussion of the use of TDR to measure soil salinity (Dalton et al., 1984, 989; Dasberg and Dalton, 1985, 293) or solute transport parameters (Kachanoski et al., 1992). References are cited for some related topics to allow the reader to obtain additional information.

2. MATERIALS AND METHODS

2.1 BASIC TDR OPERATION AND SOIL WATER CALCULATIONS

Shown in Fig. 1 is a schematic of a TDR system using a parallel pair wave guide (transmission line) to measure soil water content. Components of the system are a cable tester (TDR unit), a balun (balanced-unbalanced) transformer, a shielded balanced pair transmission line (or cable), and two parallel rods serving as a wave guide inserted into the soil. The upper right part of Fig. 1 shows an ideal representation of what appears in the cable tester display. The lower right diagram shows, in an schematic form, the pattern of reflections that are received and measured by the voltage sampler and appears in the display. In this reflection diagram the returning reflections are shown at 30° to the vertical and can be related to time and voltage display as diagrammed. Any time the voltage signal (propagate wave) passes an interface of changing impedance, a portion of the signal is transmitted through the interface and the remaining portion is reflected. This gives rise to a complicated pattern of reflections.

The path of the voltage signal in Fig. 1 is from point A at the TDR unit to the balun at point B where a ripple is reflected and the remainder travels along the shielded balanced pair transmission line until it encounters the soil at C where a measurable portion of the signal is reflected back to the source and measured as a drop in voltage at C (upper right, Fig. 1). The remaining portion of the signal (wave) enters the soil and travels in the soil, guided by the parallel rods as a wave guide. When this wave arrives at the end of the wave guide pair (D), essentially all of the wave is reflected back along the wave guide pair. A portion of this returning wave will then be reflected downward when the wave reaches the top of the soil and the balun on the return trip. Eventually, a portion of the wave reflected from D arrives at the TDR instrument to be recorded as an increase in voltage at D in the upper part of

Fig. 1.

The proportion of the original wave that returns or is reflected upward depends on factors such as soil water content, soil electrolyte concentration, and clay content (Topp et al., 1980, 574). For example, other factors being equal, a greater loss in voltage occurs for a soil with a higher electrolyte concentration compared to one with a lower concentration (Dalton and Van Genuchten, 1986, 237). The greater electrical conductivity of a relatively higher electrolyte concentration allows a greater proportion of the electrical signal to be "lost" into the surrounding soil thus reducing the power of the signal conducted along the wave guides. Except in extreme cases, this "loss of signal" creates no problem in using TDR to measure soil water content although the amount of loss increases as wave guide length increases and limits soil probe length. The loss of signal due to electrical conductivity and multiple reflections of signal at the impedance mismatches contribute to more complex slopes and patterns to actual displays as in

Fig. 2.

The TDR unit or cable tester must have the capability to measure accurately the amount of time elapsed from the time the propagated wave enters the soil (time at point C) along the wave guide until it arrives at the end of the wave guide and the reflected signal returns (time at point D, upper right, Fig. 1, Fig. 2). Topp et al. (1982, 672) discussed in detail the extrapolation procedure required to determine accurately the time at which the reflection occurs. The intersection of two tangents to the voltage trace at D in Fig. 2 identifies the correct reflection time. Hence the time required for the propagated wave to travel from point C to the intersection of the two broken lines at D in Fig. 2 is the time of interest. This time is equal to the distance between the two broken, vertical lines intersecting the time axis in Fig. 2. The success of using TDR to measure soil water content hinges upon the precision and accuracy of measuring this time interval.

2.2 CALCULATION OF SOIL WATER CONTENT

The propagation velocity (m/s) of a plane wave (V'_p) generated by the TDR is given by

$$V'_p = \frac{L}{t} \qquad [1]$$

where L = linear distance (m) the wave travels along the transmission line wave guide.
and t = time required for wave to travel the distance L (s)

The propagation velocity of a plane wave can also be written as (Kronig, 1959, 384)

$$V'_p = \frac{c}{\sqrt{K}} \qquad [2]$$

where c = speed of light (3×10^8 m/s)
and K = dielectric constant of the medium (unitless)

Using equations [1] and [2] we can define

From Fig. 1, we note that the wave travels to the end of the wave guide of length ℓ and back, for a total distance of 2ℓ.

$$K = \left(\frac{ct}{L}\right)^2 \quad [3]$$

Substituting 2 ℓ for L in equation [3] we have

$$K = \left(\frac{ct}{2\ell}\right)^2 \quad [4]$$

A TDR cable tester, such as Tektronix models 1502B or 1502C, measures propagation velocity, but convert the result to equivalent cable distance by comparing the measured velocity to that for vacuum. In a vacuum K = 1 and V_p = c. Thus the relative propagation velocity of a wave in any medium to that in a vacuum (V_{pm}) is given from equation [2] as

For water,

$$V_{pw} = \frac{1}{\sqrt{K_w}} = \frac{1}{\sqrt{80}} = 0.11 \quad [6]$$

For polyethylene, a common cable dielectric,

$$V_{pp} = \frac{1}{\sqrt{2.26}} = 0.67 \quad [7]$$

For measurement in soil, however, the dielectric constant is unknown as is the relative velocity in the soil. From the apparent length (ℓ_a) of the wave guide in the soil as given by the cable tester, it is possible to calculate the dielectric constant of the soil as determined by the following equations. From equations [4] and [5], the velocity of propagation in soil relative to that in air V_{ps} is

$$V_{ps} = \frac{1}{\sqrt{K_s}} = \frac{2\ell}{ct} \quad [8]$$

Solving equation [8] for ℓ (the actual length of the wave guides) gives

$$\ell = \tfrac{1}{2} ctV_{ps} \quad [9]$$

The similar equation for ℓ_a is

$$\ell_a = \tfrac{1}{2} ctV_a \quad [10]$$

where V_a is the setting of the velocity knobs on the cable tester and ℓ_a is the measured apparent length of the wave guide in soil.

From equations [9] and [10] we obtain

$$\frac{\ell_a}{\ell} = \frac{V_a}{V_{ps}} \qquad [11]$$

The numerical value of ℓ_a is read directly from the cable tester screen. For determining soil water content, a setting for V_a of 0.99 is both convenient and useful. Recall from equation [8] that V_{ps} is inversely related to K_s, therefore

$$\frac{\ell_a}{\ell} = \frac{0.99}{V_{ps}} = 0.99\sqrt{K_s} \qquad [12]$$

From the above equation we obtain

$$K_s = 1.01\left(\frac{\ell_a}{\ell}\right)^2 \qquad [13]$$

Once K_s has been computed soil water content, Θ (m^3/m^3), is calculated using the following empirical equation

$$\Theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}K_s - 5.5 \times 10^{-4}K_s^2 + 4.3 \times 10^{-6}K_s^3 \qquad [14]$$

This relationship was developed using a wide range of porous materials at different water contents (Topp et al., 1980, 574). Because the dielectric constant ranges from 3 to 7 for many mineral soil components (Weast, 1989, E-54), this empirical relationship is assumed to hold for most mineral soils. We recommend, however, that the relationship given by [14] be verified by constructing a calibration curve for the particular soil being studied.

2.3 CONSTRUCTION OF A TDR SYSTEM

There are many ways to assemble a TDR system using commercially available components and the system that we describe is but one option; it is the option that we chose to construct and use for our particular applications. Our applications range from determing day to day water extraction patterns as a function of depth by row crops in the field, monitoring the root zone to schedule irrigation, and measuring infiltration and solute transport in soil columns in the laboratory. A system using coaxial cable and a three-prong wave guide would have served the same purposes. A variety of connection/wave guide sizes, switches, and other components can also be used to construct a reliable TDR system depending on the interests, requirements, and constraints of the user.

The schematic diagram in Fig. 3 shows how the various system components of our units are connected. We use either a 1502B or 1502C Tektronix cable tester (Tektronix, Inc., PO BOX 1197, Redmond, OR 97756). It is important to evaluate carefully the 'horizontal accuracy' specification when selecting a cable tester because this specification defines the ability of the device to measure accurately ℓ_a, the apparent length of the wave guide (see equation [10]). The distance between the two vertical broken lines intersecting the time axis in Fig. 2 is directly related to ℓ_a. A TP103 impedance matching balun transformer (Anzac, Electronic Division, Burlington, MA) mounted in a small metal box (#34F955, type 2417) (Newark Electronics, Newark, NJ) is connected to the cable tester with a BNC connector. The 1-m-long (arbitrary length) extension cable was constructed from #C5720 shielded, 186 ohm, 22 gauge 2/c TV lead-in wire (Anixter, Morrisville, NC) and is equivalent to Belden #9090 wire. This extension cable has insulated solderless male leads at both ends. This extension cable connects to the female receptacle of the balun transformer box (connection A) and to the wave guide cable (connection B) in Fig. 3. This cable/balun stays with the cable tester as the user moves the TDR from site to site and is used to "plug into" the wave guide cable which remains attached to the wave guide (connection C, Fig. 3).

The wave guide cable (Fig. 3) is constructed from the same shielded cable used for the extension cable, but has #39F1561 insulated standard 3/32" tip jack female connectors (Newark Electronics) at both ends. The length of wave guide cable, i.e. the cable connecting wave guides to the cable tester, is not critical and can extend many meters without affecting performance of the TDR system. We construct the length of the wave guide cable based upon the particular application. For example, in tillage plots, we base the wave guide cable length on the most desirable distance between the wave guide location (in the plot) and the location where the cable tester extension cable will be "plugged into" the extension cable attached to the cable tester (outside the plot boundary). This arrangement minimizes disturbance around the area where the water content measurements are being taken. The user will save time when taking a series of readings in the field if the wave guide cables are approximately the same length. This is because the user can offset on the TDR screen the distance the propagated wave travels from the cable tester to the upper end of the wave guide (C in Fig. 1 and Fig. 2). This eliminates the need to scroll the wave form across the screen while hunting for the "soil" portion of the wave form. To instill rigidity and minimize breakage, all connector-to-cable connections are covered with vinyl heat shrink tubing.

Wave guides can be constructed from a variety of metal rods, but stainless steel welding rod minimizes corrosion and is inexpensive. The diameter of the welding rod is not critical, but we have had good success using 3/32 inch (2.38 mm) diameter rod, type ER316L, which comes in 91-cm lengths, and can be obtained from any welding supply company. A larger diameter welding rod, for example 3/16 inch (4.76 mm) diameter, grade 316, (Carpenter Speciality Steels, 5355 Morse Dr., Decatur, GA), is used to construct heavier wave guides for use in soils with high soil strength, or when the wave guides are installed to depths greater than 30 cm. When larger diameter rods are used, a lathe is used to reduce the diameter of the upper end to 2.38 mm to accept the female connector of the wave guide cable. Other methods of connection are possible including direct soldering, but the connectors allow a range of lengths of wave guides to be easily attached. This wave guide/cable arrangement facilitates the use of a variety of wave guides for different experiments requiring different depths of measurement.

Wave guides are inserted into the soil in a parallel configuration using the assistance of a jig (Fig. 4). Hole spacing from center to center is 5 cm, but this spacing is arbitrary. The wider the spacing, the more power loss per unit depth occurs. Wave guides are positioned in the jig and are pushed or tapped with a rubber mallet into the soil. After inserting the rods about half way into the soil, the jig is removed and the rods are pushed into the soil until the right angle bend is flush with the soil surface. When a pair of wave guides will be left in place for a series of measurements, a wave guide cable is attached to the pair of guides (connection C, Fig. 3) and this cable remains attached for the duration of the study. When a reading is desired, the extension cable, which is attached to the cable tester through the balun transformer, is attached to the wave guide cable (connection B in Fig. 3). After the reading is taken, connection B is disconnected. More readings can be taken by connecting the extension cable to the wave guide cable attached to another pair of wave guides. If a series of wave guides are in close proximity, the time required to take readings can be minimized by terminating the female connectors of the wave guide cable in a connector panel (Fig. 5) installed at a convenient location, for example, at the edge of an experimental plot.

Some TDR applications may not justify the permanent installation of wave guides. For example, if the user wishes to measure soil water content one time only, it is impractical to install wave guides in the manner discussed above. In this case, a portable hand held device with permanently attached parallel wave guides of the desired length can be used (Fig. 6). The parallel wave guides are inserted all the way into the soil, the wave guide cable connected to the extension cable, and the reading taken. With all cable connections remaining intact, the portable wave guides are removed from the soil, the TDR unit carried to the next site, the portable wave guides reinserted into the soil, and the meter read. Many measurements can be taken in a short time period.

3. RESULTS AND DISCUSSION

Several TDR systems have been assembled according to the plans described above and have been functioning for periods ranging from 1 to 6 years. Again, we emphasize that the system described is only one of many possible ways to assemble the component parts, but this particular system was designed to meet the specific requirements and flexibility to measure soil water content in our research applications. Wave guides 75 cm long have been successfully used in both sandy and clayey soils, while 2-m-long wave guides have been used in gravelly soils. Many system parameters are arbitrary: spacing of wave guides, the kind of conductor used for the wave guides, and the choice of shielded TV cable rather than coaxial cable. However, selection of the appropriate balun transformer is critical unless a 3 prong wave guide is used.

One advantage of the TDR system compared to other soil water content measurement methods is that the average water content of the surface layer (e.g. 0 to 15 cm deep) of soil can be determined accurately and easily. Changes in soil water content fluctuate widely at this depth. The capability of this TDR system to track soil water content in the surface layer is illustrated by the work of van Wesenbeeck and Kachanoski (1988, 363) who measured the spatial and temporal distribution of soil water in the 20-cm-deep tilled layer under a corn crop on silty clay loam soil. One hundred pairs of wave guides were used; they were segregated into four groups of twenty-five pairs of wave guides. The wave guide cables for each group of wave guides terminated at a common panel (Fig. 5). This arrangement allowed a field technician to collect data for all 100 pairs of wave guides in less than 30 minutes. While it is possible to multiplex and automatically record TDR data (Heimovaara and Bouten, 1990), the ease in measuring as many as 100 wave guide pairs in half an hour may not warrant multiplexing, especially if daily data is needed and access to plots is convenient.

To measure soil water content at depths shallower than the 0 to 10 cm depth, a wave guide pair can be inserted horizontally in the wall of a small pit dug adjacent to the targeted area of interest. The inserted wave guides are connected to the wave guide cable and the hold backfilled to make a permanent installation. This approach is also used to measure water content at specific depths in a soil profile. Still another approach to measuring water content in the 0 to 10 cm depth is to install the wave guide pair at an angle other than 90° with the soil surface. Installing a 20 cm long wave guide pair at an angle of 30° with surface, for example, allows the user to double the volume of soil sampled in the 0 to 10 cm depth.

Greater detail pertaining to the components, construction, and suppliers of components may be obtained from the senior author.

4. CONCLUSIONS

The series of equations developed shows step by step the relationship between the numerical value for distance or length read on the TDR screen and soil water content. Details concerning the construction of the authors' TDR system are presented to serve as one example of many different combination of cable tests, transmission cables, and wave guides that can be assembled to meet the specific requirements of the researcher.

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LIST OF FIGURES

Figure 1. Schematic diagram of TDR system using a parallel pair wave guide to measure soil water content. Physical arrangement is given on the left, the idealized output display in the upper right and the schematic pattern of reflections in the lower right.

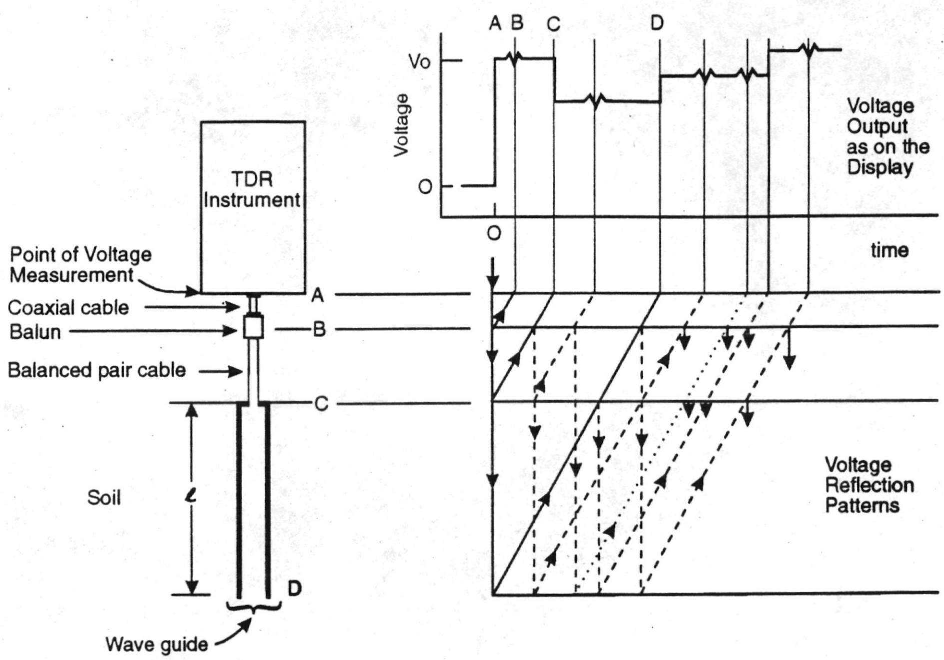
Figure 2. TDR output trace showing voltage as a function of time.

Figure 3. Schematic showing how a pair of parallel wave guides is connected to the cable tester.

Figure 4. Wave guides are installed in a parallel, vertical orientation with the assistance of a jig. The top part of the wave guide fits into a notch cut into a bolt. This prevents bending the wave guide during installation.

Figure 5. The female connectors on cables permanently attached to wave guides are terminated in a connector panel.

Figure 6. Portable parallel wave guide unit.



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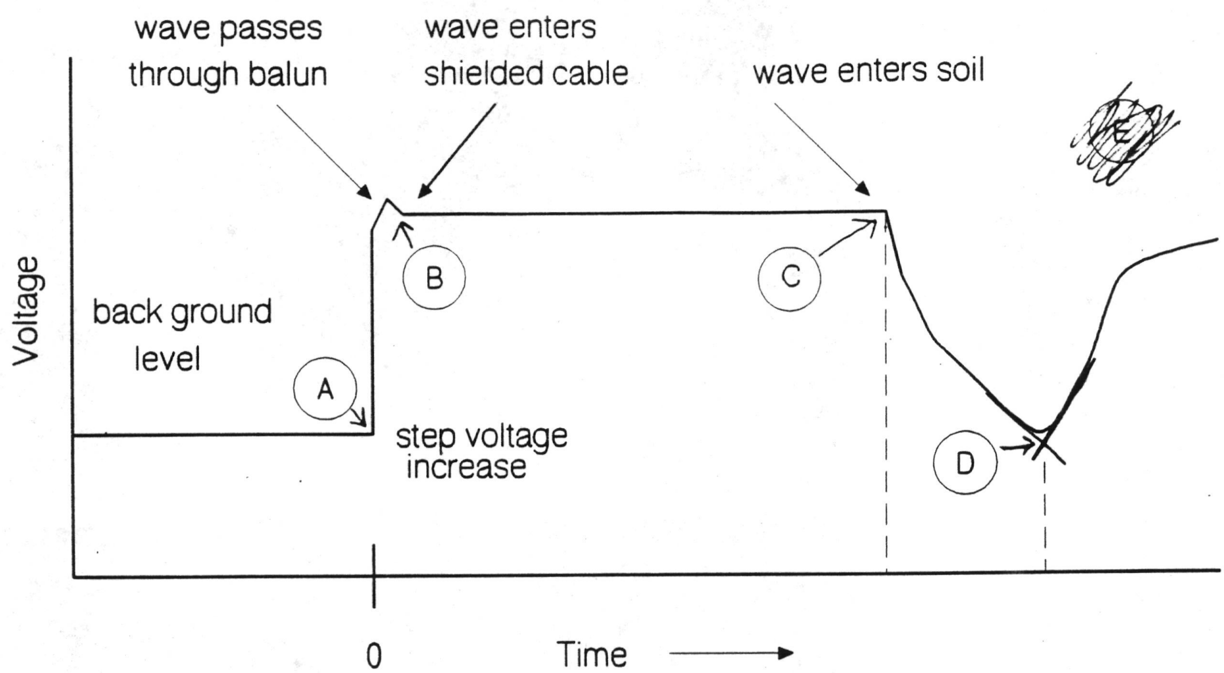

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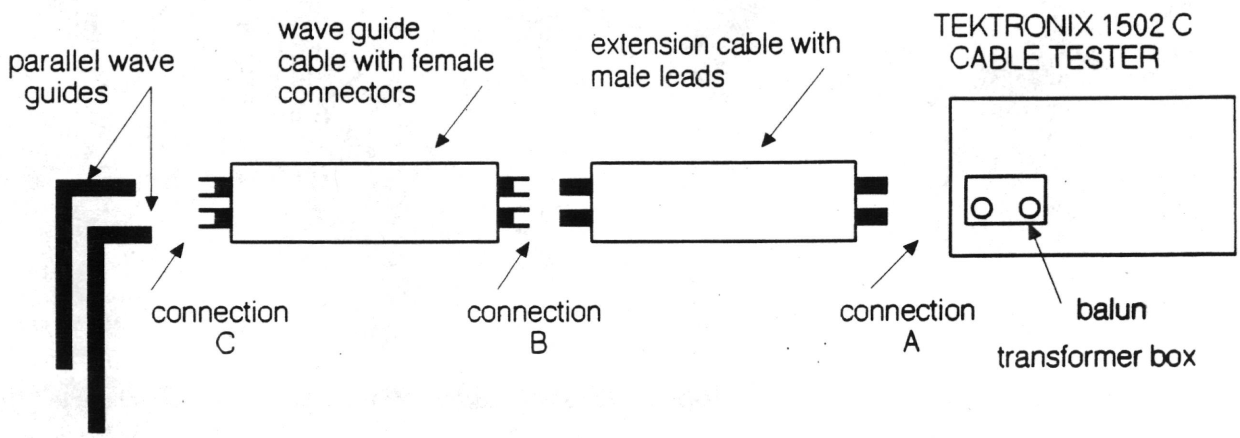

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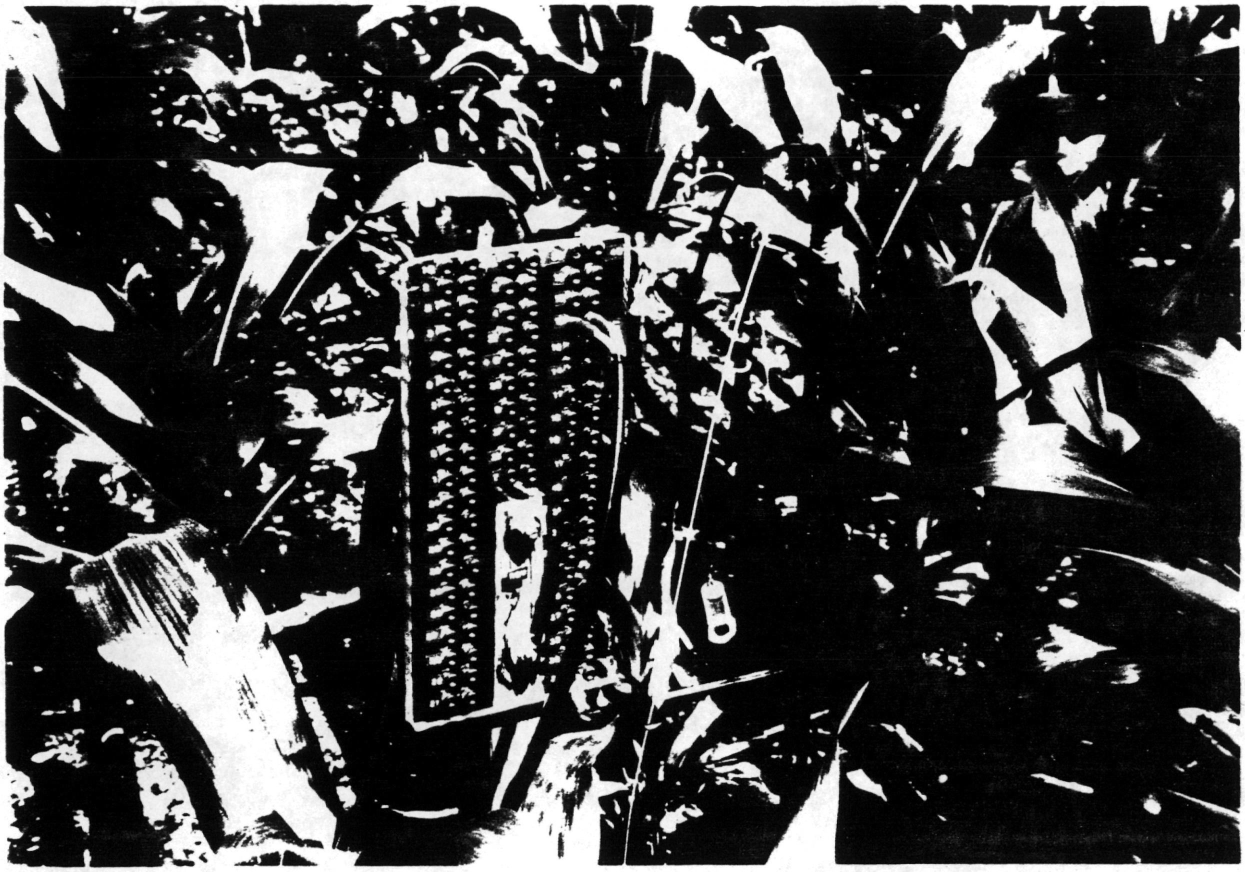

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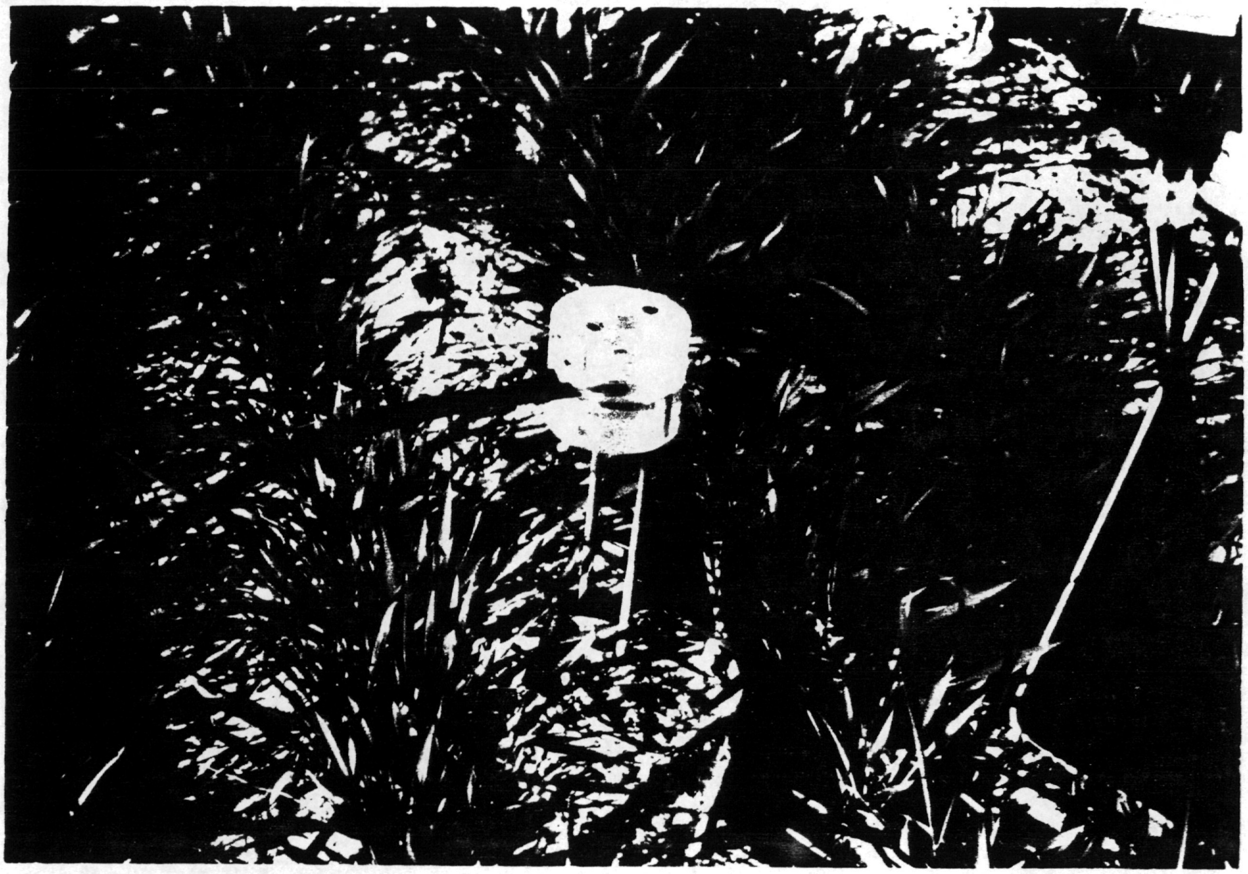

Figure 6. Portable parallel wave guide unit.