Journal of Hydrology, 93 (1987) 67–78
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

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SOIL MOISTURE MEASUREMENT BY AN IMPROVED CAPACITANCE TECHNIQUE, PART I. SENSOR DESIGN AND PERFORMANCE

T.J. DEAN, J.P. BELL and A.J.B. BATY

Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon. OX10 8BB (U.K.)

(Received October 21, 1986; revised and accepted February 6, 1987)

ABSTRACT

Dean, T.J., Bell, J.P. and Baty, A.J.B., 1987. Soil moisture measurement by an improved technique, Part I. Sensor design and performance. J. Hydrol., 93: 67–78.

It has long been recognised that dielectric constant is a sensitive measure of the moisture content of soil. One method of measuring the dielectric constant of soil in the field is to incorporate the soil as part of the dielectric of a capacitor. A new capacitance sensor operating at 150 MHz is described; it makes use of advances in electronic component technology to give a stable and sensitive probe for in-situ field measurements. The sensor has been developed as part of an integrated system of soil moisture measurement comprising in addition a technique for access tube installation and appropriate calibration. Details of instrumental performance are given here and results of the field calibrations reported in Part II.

INTRODUCTION

Since the dielectric constant ε of free water at frequencies less than 1000 MHz is 80 (e.g. Hasted, 1973) and values for typical dry soil are about 4, measurement of the dielectric constant offers a potentially very sensitive determination of soil moisture content.

A substantial volume of literature exists on the dielectric properties of soil and on instruments using this property to measure soil moisture. Early work (Smith-Rose, 1933) was carried out at low frequencies, in the KHz range, and gave unreliable results with anomalously high values of ε but in the 1960s the importance of interfacial polarization effects in heterogeneous materials such as moist soil was recognised (Hoekstra and Delaney, 1974). The relaxation frequency of the relatively macroscopic electric dipoles associated with interfacial polarization is about 27 MHz and subsequent measurements have been made at frequencies above 30 MHz so that such dipoles cannot respond to the applied field and hence do not contribute to the measured dielectric constant.

Dielectric constant may be measured by capacitance and one of the first workers with this technique to appreciate the need for using a high frequency was Thomas (1966) who used a bridge method at 30 MHz which required manual

0022-1694/87/$03.50

balance and which used a probe inserted directly into the surface layers of the soil. For hydrological studies knowledge of changes in the upper metre or so of soil is required and it is generally desirable to make measurements at different depths in a vertical access tube. This method is used in more recent reports (Kuraz and Matousek, 1977; Malicki, 1983; Galfy, 1984).

In evaluating the performance of the capacitance probe, comparison must be made with existing alternative methods and a survey of these has been made by Schmugge et al. (1980). It is generally accepted that the standard for calibration of all other techniques is the gravimetric method with oven-drying of a known volume to 105°C. The fact that the capacitance probe responds to a small volume of soil necessitates very accurate sampling techniques in the gravimetric method to make valid comparisons.

An instrument designed for field use must meet certain criteria. Sites for measurement are often remote and overall weight and configuration of measuring equipment are important. Direct reading, as distinct from null balance, is considered essential and in any case is desirable if automatic recording is also intended. Since the calibration function is to some extent dependent on soil type, preference is for raw, rather than processed, data even though this may have less immediate significance for the user. The response time should be short, preferably not more than one second, so that the whole measurement sequence can be as straightforward and rapid as possible. The instrument should be moisture proof but the cost penalty for protection against complete immersion is not usually justified.

The probe described here (Fig. 1) has two units, a hand-held reader linked by cable to the sensor which is inserted down the access tube. The modular design of the sensor allows for various electrode configurations so that it is not restricted to use in access tube systems but may be permanently buried for long-term recording either for data collection or as a basis for irrigation control or flood warning systems. During development and evaluation of the probe it became clear that the design and calibration were intimately bound with the access tube design and technique of installation. To obtain the calibration data presented in Part II considerable care and discipline are required in the field work.

The dielectric constant of a material arises from its polarization or electric dipole moment per unit volume. The free water molecule has a particularly high permanent electric dipole moment which determines the high value of dielectric constant. To contribute to the dielectric constant the electric dipoles, of whatever origin, must respond to the frequency of the electric field. The freedom to respond is determined by the local molecular binding forces so that the overall response is a function of the molecular inertia, the binding forces and the frequency of the electric field. Of the total soil moisture present some dipoles will be less free to respond than others. Soil is a complex matrix of soil particles, air, water and solutes and molecular binding forces may be physical or chemical. In turn, the soil particles consist of silica, clay minerals and humus. When comparing different methods for measuring soil moisture in

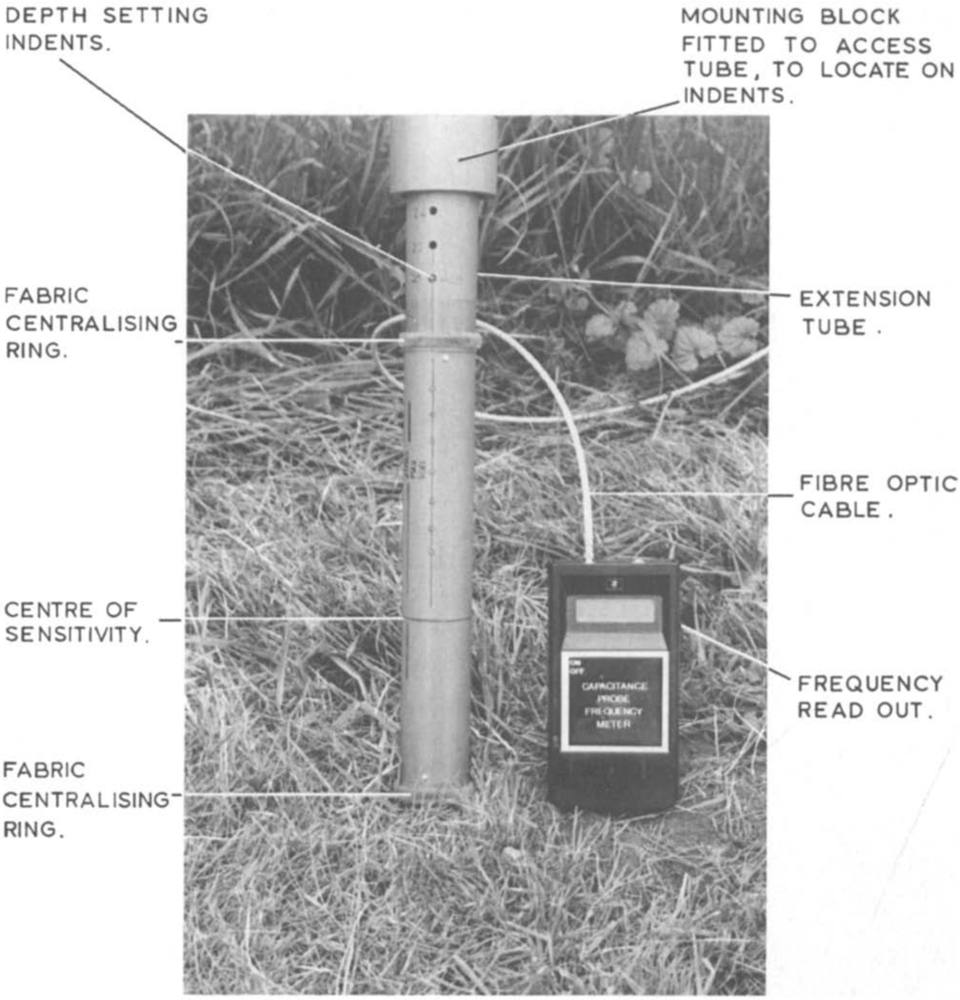

Fig. 1. The sensor and hand-held frequency reader.

different soils, consideration must be given to what is actually measured and to what constitutes "soil moisture". This aspect is considered in more detail in Part II.

PRINCIPLES OF OPERATION

The design described here, with the sensor inserted in the access tube, measures the capacitance of the electrode system with dielectric comprising the in-situ moist soil surrounding the access tube. The capacitor forms part of the feedback loop of a modified Clapp high-frequency transistor oscillator operating at about 150 MHz. This type of oscillator is particularly stable and suitable for high-frequency operation with relatively little drift with temperature, about 0.33% per °C or 0.5 MHz per °C. Circuit analysis, see Fig. 2, gives the frequency of oscillation F as an inverse square root function of the capacitance to be measured, C:

$$F = \frac{1}{2\pi\sqrt{L}}\left(\frac{1}{C} + \frac{1}{C_b} + \frac{1}{C_c}\right)^{1/2} \qquad (1)$$

C_b is the total base capacitance including the emitter-base interelectrode capacitance of the oscillator transistor and, similarly C_c is the total collector capacitance. The volume contributing to the capacitance C includes the probe outer case, air volumes inside the probe and between the probe and the access tube, the access tube wall and the surrounding moist soil. The only varying contribution is from the moist soil.

The relation between the measuring capacitance and the dielectric constant is:

$$C = g\varepsilon \qquad (2)$$

where g is a geometrical constant that is difficult to calculate for other than simple electrode geometries. There is no simple relation (Hasted, 1973) between the dielectric constant and the volumetric moisture content of soil θ so the overall relation:

$$F = f(\theta) \qquad (3)$$

must be determined empirically by calibration against a standard technique.

The probe readout is connected to the sensor by cable to allow operation in access tubes to a depth of, say, two metres. However for circuits operating at frequencies of 150 MHz, any distributed conducting system can introduce radiative feedback which is influenced by capacitative effects of nearby bodies, such as the observer, so that a variable shift in frequency may result. Such factors can give an error equivalent to about 2 moisture vol. %. The problem has been completely eliminated in the design described here, by fitting battery power supplies in the sensor and using a fibre optic cable to link the sensor to the readout. With this design there are no conductors between the sensor and readout and the probe is unaffected by the environment of the fibre optic cable and the readout. As the frequency response of currently available fibre optic

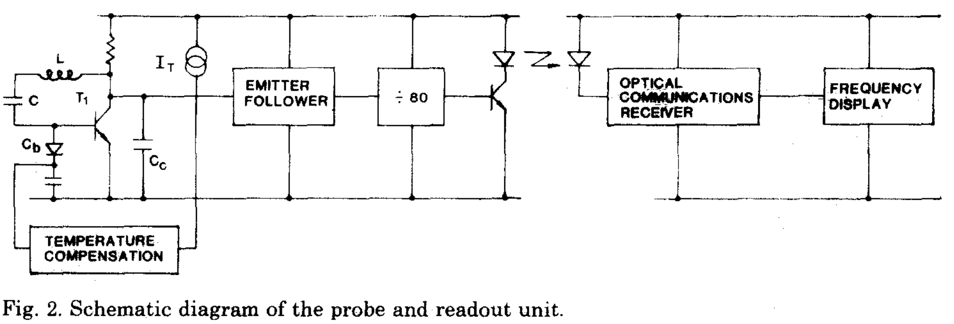

Fig. 2. Schematic diagram of the probe and readout unit.

transmitters and receivers does not extend to 150 MHz, the transistor oscillator is matched to a CMOS divide-by-80 integrated circuit to give a signal frequency below 2 MHz which can be handled by the phototransmitter.

DESIGN DETAILS

The sensor unit of the probe is machined from polyacetal and comprises a top cap assembly, a tubular outer case and a bottom end cap. The top cap assembly houses the lithium batteries and the fibre optic transmitter and supports the printed circuit board which plugs into the electrode assembly mounted in the tubular outer case. The outer case diameter is 44 mm and the complete sensor unit, of length 290 mm, is centred in the access tube, i.d. 47 mm, by flexible nylon fabric rings housed in the top and bottom caps.

In order to position the probe at selected depths in the access tube, it is fitted with PVC extension tubes of the same diameter as the sensor case and of length 400 mm. In use, a mounting block fitted to the top of the access tube holds a spring-loaded key that provides precise and reproducible depth positioning by locating in a series of indents spaced every 20 mm along the extension tubes. The method also defines the rotational orientation of the sensor with respect to the access tube. Five extension tubes enable use to a depth of 2 m with precise depth positioning at 20 mm intervals.

The sensor on–off switch is mounted on the printed circuit board and activated remotely via a nylon Bowden cable. This cable and the fibre optic cable are routed to the sensor through the extension tubes for added protection.

PERFORMANCE OF THE PROBE

The probe readout displays five digits and in air at 15°C reads 1918.0 KHz which represents an operating frequency of 153.44 MHz divided by a factor of 80. The air value is of no interest for soil moisture measurement but is used as a day-to-day monitor of probe stability. Here, and in part II, five digits, e.g. 19180 ignoring the decimal point, will be used as the sensor response and will be referred to as the frequency. Circuit stability is such that there is at most ± 1 variation in the least significant digit of the display.

Typical values for the operating range in soil are 16600 for dry soil, effectively zero moisture content, and 14100 at 0.5 moisture volume fraction (MVF), both figures depending to some extent on the type of soil. So a frequency span of 2500 represents a span of 0.5 MVF in soil moisture. On average the resolution of the probe is equivalent to a soil moisture content of ± 0.0002 MVF (± 0.02 moisture vol. %) but since the response is nonlinear the sensitivity is greater at low moisture content.

Temperature dependence

Dimensional changes in the electrode geometry due to temperature will add to the temperature dependence but the predominant contribution is from the temperature coefficient of the interelectrode capacitance of the oscillator transistor, T1. Although the circuit is designed (Fig. 2) to minimise this effect by using component capacitors in parallel with the unknowns, in practice the circuit stability is such that the residual is observable.

To improve the performance, a temperature dependent current generator I_T is mounted adjacent to the oscillator transistor T1 and drives a voltage controlled capacitor that forms part of C_b. From eqn. (1) the effectiveness of the temperature compensation depends upon the value of the sensor capacitance C. The performance has been optimized for the operating range in soil and so, as shown in Fig. 3, is less effective at the air frequency. The reading varies between 16482 at 0°C and 16462 at 30°C corresponding to better than 0.004 MVF (0.4 moisture vol. %) total error over 30°C.

Stability

Thermal and temporal stability are potential problems with any electronic device used in the field. With instruments inserted for short periods into the soil these effects may be exaggerated by transient thermal gradients. If, for example, an instrument from a carrying case exposed to the sun (say at 20°C) is lowered into an access tube with a temperature of 12°C, short term transient effects, as components change temperature, may be superimposed on equilibrium performance. To assess this the probe was positioned in an in-situ access tube to a depth of 110 cm. The initial probe temperature was approximately 21°C and in the access tube at 110 cm the temperature was 14°C. The probe was left on continuously and readings were taken every 15 to 30 min, as indicated in Table 1. The total drift, a change of 4 in the least significant digit, is equivalent to about 0.001 MVF (0.1 vol. % moisture). Overall reproducibility of both the measuring circuit and the depth-setting mechanism, determined by repeating a profile with 30 depths after an interval of three hours, was 6 in the least significant digit, equivalent to ± 0.001 MVF (± 0.1 vol. % moisture).

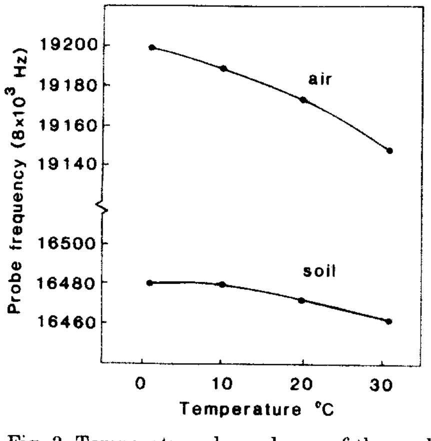

Fig. 3. Temperature dependence of the probe in soil and in air.

TABLE 1

Values of frequency versus time

Time	Frequency	Time	Frequency
14.45	14833	16.15	14829
15.00	14833	16.45	14829
15.15	14832	17.15	14830
15.30	14830	17.15	14830
15.45	14830		

Sensitivity variation with distance from the probe

The soil region monitored by the probe is by analogy with work on the neutron probe (Bell, 1976), referred to as the "sphere of influence". For the capacitance probe the region is not spherical; neither is it sharply delineated. As with the neutron probe the sensitivity tails to zero over several centimetres. This variation in sensitivity is discussed under the headings axial, radial and volumetric sensitivity and somewhat different approaches have been taken for the three cases. One of the difficulties in making these measurements is that the electric vector field lines are refracted at boundaries between regions of different dielectric constant and hence the introduction of a sample will, to some degree, influence the region being measured.

Although clearly the probe integrates over the whole region of sensitivity the axial sensitivity determines the depth resolution and the radial sensitivity determines the susceptibility to lateral inhomogeneities.

Axial sensitivity

Figure 4 shows the response to a thin, 18 mm, PVC annular disc traversed along the length of the probe. The probe was suspended horizontally within a standard PVC access tube away from interference.

The measured frequency is with respect to the air frequency, 18900 in an access tube, rather than a soil frequency. The sensitivity ($\partial F/\partial C$) at 19000 is some 10× to 40× larger than ($\partial F/\partial C$) at soil frequencies. However, the field shape should be independent of frequency over this range and the relatively thin parallel-sided PVC disc should not introduce significant field distortion.

The axial centre of sensitivity of the probe, which is the datum for the access tube depth readings, has been taken as the peak of this response. From Fig. 4, 90% of the response is from a region 8.5 cm above and 8.5 cm below the centre of sensitivity, that is a vertical extent of 17 cm. The probe is sensitive over a total vertical extent of about 34 cm. To assess the performance in a situation more appropriate to use of the probe in the field, the vertical extent of the sensitive volume has also been measured at a typical soil frequency. The probe was fixed within an access tube mounted in an empty soil drum. To raise the level progressively, soil was then added and the frequency noted as a function of the soil height above the centre of sensitivity. Figure 5 shows how the

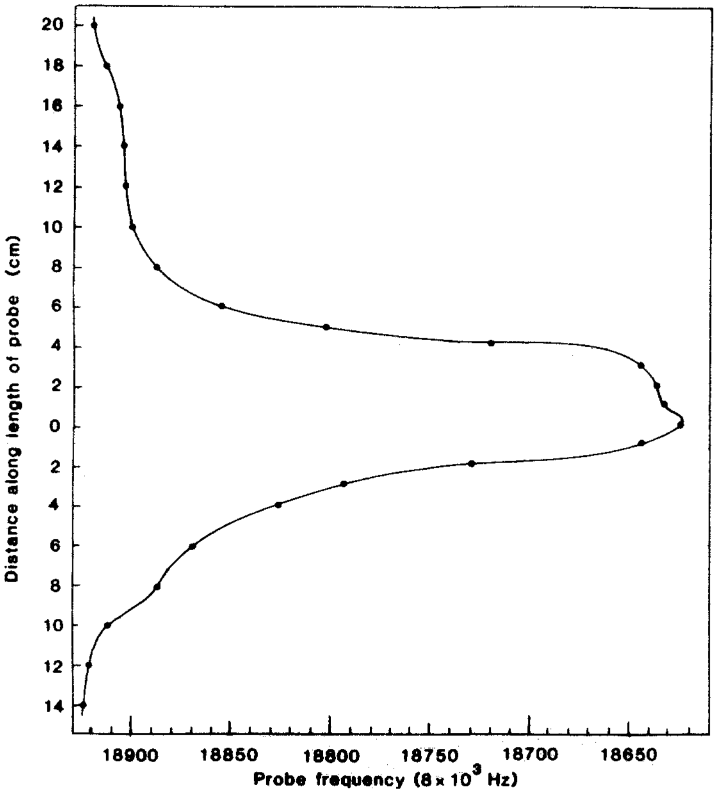

Fig. 4. Frequency response for a plastic annular disc 18 mm wide, 100 mm diameter, passed along the length of the probe with reference to the peak of the response.

frequency approaches a plateau and further soil addition has no effect. The depth of soil at the onset of the plateau represents the extent of the sensitive region and this depth is about 22 cm for material above the centre of sensitivity. The whole experiment was repeated with the probe inverted and the plateau then occurred at 13 cm below the centre of sensitivity giving an overall region of 35 cm.

The agreement between the result in soil and the figure from the PVC disc in air suggests that the vertical extent of the sensitive volume is effectively independent of the medium and its dielectric constant.

Radial sensitivity

A method analogous to that used for the axial sensitivity measurement was adopted. The response to a series of PVC open-ended tubes of equal height but differing radii was determined. The probe was installed vertically in a standard access tube and placed within each of the PVC tubes, in succession. The wall thickness of each tube is 2 mm. Figure 6 shows the frequency reading for each tube plotted against the mean diameter of the tube. Ninety percent of the response arises from material within a diameter of 13 cm.

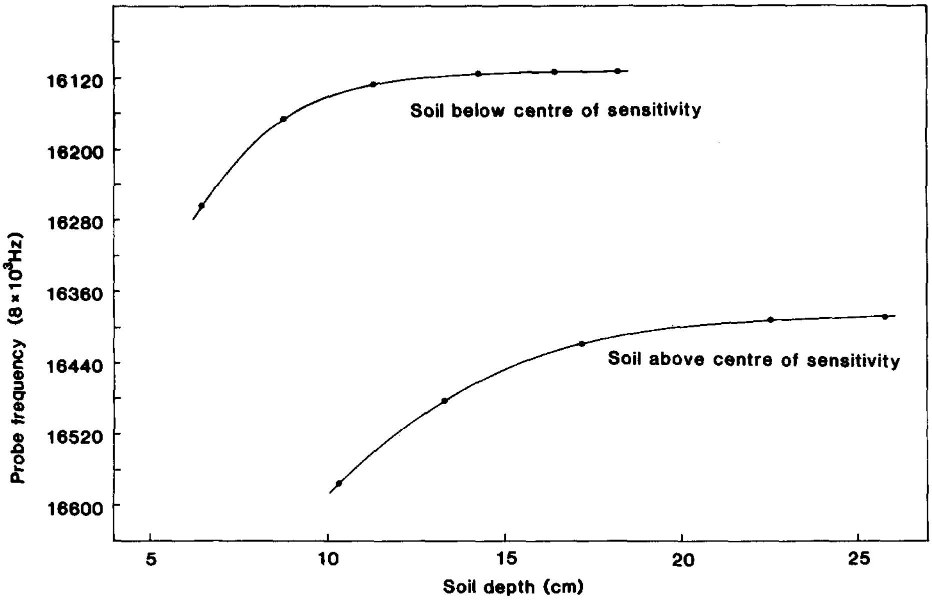

Fig. 5. Frequency response for a progressive increase in material above and below the centre of sensitivity.

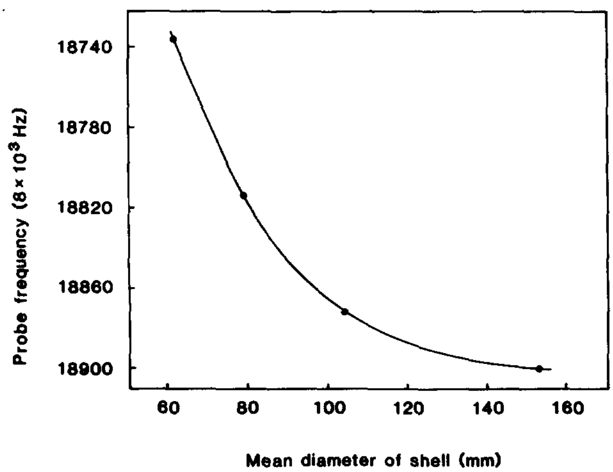

Fig. 6. Radial frequency response.

Volumetric sensitivity

To supplement the axial and radial results and to obtain at least a qualitative description of the three-dimensional sensitivity a technique analogous to the search coil method was used. The probe was mounted horizontally on a smooth uniform surface, without an access tube, and profiles of constant frequency difference ΔF were plotted using a small "pill box" filled with water. The height of the pill box was 48 mm, approximately the same as the diameter of the probe.

The pill box should be large enough to give an adequate response, yet small enough to have an unambiguous position. This criterion is difficult to meet and hence the results obtained, using a 30 mm diameter pill box, are tentative.

With the pill box remote from the probe a frequency of 18673 was obtained. The locus of positions of the pill box giving a response of 18668, that is a difference of 5 in the last digit, is shown in Fig. 7 as the 5-digit contour. This signal, a frequency change of 5 digits is, despite the good stability of the probe, smaller than desirable. The 15-digit contour, i.e. 18673 to 18658, is closer to the probe and the pill box dimensions are not negligible compared with the distance from the probe. The 2-digit and 10-digit contours are also shown. The contours confirm the generally ellipsoidal shape of the sensitive volume, with the major axis along the axis of the probe.

Significance of an annular air gap between the access tube and the soil

It is important to install the access tube with the minimum of compression or disturbance of the surrounding soil. The technique developed, described in detail in Part II, is based on the method for installing aluminium neutron probe access tubes although plastic tubes are used; it is however modified to minimise soil disturbance and the possibility of an air gap round the access tube.

For the capacitance probe the possibility of an air gap is particularly significant due to the high sensitivity, and hence undue weighting, given to the soil close to the probe. To evaluate the importance of the effect, a drum with in-situ access tube, was packed with moist soil of consistency such that any deforma-

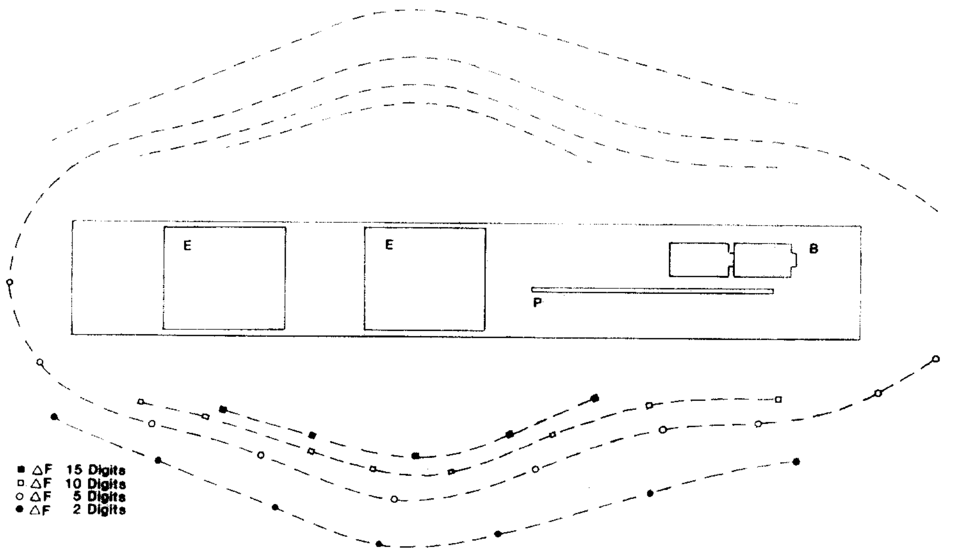

Fig. 7. Contours of constant ΔF determined with a 30 mm diameter water filled "pill box". The probe electrodes are shown at E. B and P refer to the batteries and the printed circuit board.

tion tended to be retained. This configuration was assumed to have zero air gap and probe measurements were taken every 2 cm down the access tube.

A steel rod, machined to be a close radial fit within the access tube, was then used to "rock" the tube so as to set up an annular air gap tapering from 5.5 mm at the soil surface down to zero at the bottom of the access tube. The profile measurements were then repeated and Fig. 8 shows the difference in reading, arising from the annular air gap, as a function of the calculated gap width assuming a linear relation between gap width and depth. The departure from linearity near the origin is to be expected from the finite spatial resolution of the probe. In practice moist soil possesses a certain degree of elasticity and this is consistent with the observed 0.5 mm intercept which suggests that the technique can tolerate such gaps during access tube installation without prejudice to the accuracy of the measurement. The presence of large gaps can be expected to cause significant errors and the techniques described in Part II are designed to minimise such effects.

CONCLUSIONS

The capacitance probe is precise, sensitive, lightweight, economical in construction, simple and quick in use.

Resolution in measuring a vertical soil moisture profile is good and should be better than the neutron probe but the limited radial penetration necessitates great care to avoid air gaps when installing access tubes.

The results presented here are weighted towards the features of interest, and critical to the use of the probe and the capacitance method. There is scope for further optimisation of the electrode geometry to improve the shape of the soil

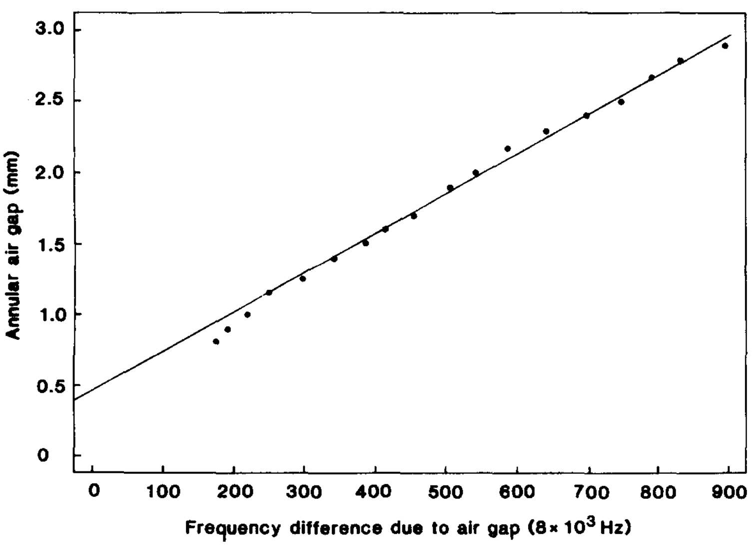

Fig. 8. Effect of annular air gap (calculated) on frequency.

region measured by the probe. Ideally this should be disc shaped for maximum lateral averaging and good vertical resolution.

Due to the complexity of moist soil, calibration of the probe in individual soils is required and Part II presents results from field and laboratory measurements.

REFERENCES

Bell, J.P., 1976. Neutron probe practice. Inst. Hydrol., Rep. 19: 1–63.

Galfy, J., 1984. High-frequency moisture probe. Commercial brochure, Vituki Res. Cent., Budapest, 2 pp.

Hasted, J.B., 1973. Aqueous Dielectrics. Chapman and Hall, London, 302 pp.

Hoekstra, P. and Delaney, A., 1974. Dielectric properties of soils at U.H.F. and microwave frequencies. J. Geophys. Res., 79: 1699–1708.

Kuraz, V. and Matousek, J., 1977. A new dielectric soil moisture meter for field measurement of soil moisture. Int. Comm. Irrig. Drain., 26: 76–79.

Malicki, M., 1983. A capacity meter for the investigation of soil moisture dynamics. Zesz. Probl. Postepow Nauk Roln., 201–213.

Schmugge, T.J., Jackson, T.J. and McKim, H.L., 1980. Survey of methods for soil moisture determination. Water Resour. Res., 16: 961–979.

Smith-Rose, R.L., 1933. The electrical properties of soils for alternating currents at radio frequencies. Proc. R. Soc. London, 140: 359 pp.

Thomas, A.M., 1966. In situ measurement of moisture in soil and similar substances by fringe capacitance. J. Sci. Instrum., 43: 21–27.