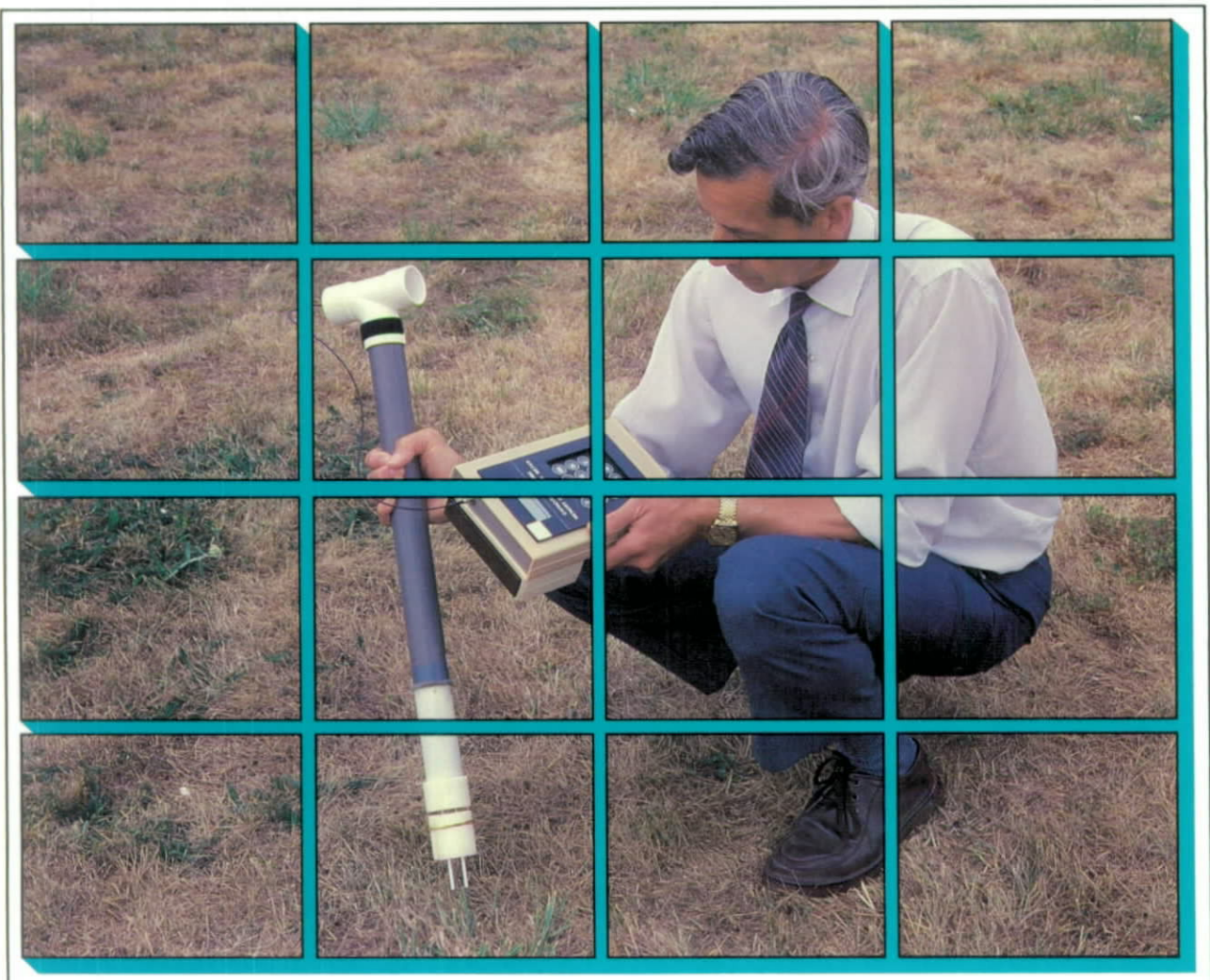# Report No. 125

The IH capacitance probe for measurement of soil water content

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August 1994

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Abstract

Dielectric constant is a sensitive measure of the volumetric water content of soil. At the Institute of Hydrology an instrument has been developed, the Capacitance Probe, which measures electrical capacitance, and hence dielectric constant, for field measurement of soil water content. A number of designs are described which enable the probe to be used in surface, borehole and non invasive applications and also in automatic logging mode.

Discussion of the theory of the dielectric constant of a composite material such as moist soil is followed by description of the versions of the instrument. Using liquids of known dielectric constant for calibration a model is developed that accurately describes the instrumental response. Values for the linearity, stability and sensitivity, together with the method of their determination are given. For this work individual probes were not interchangeable and their intercalibration is described.

Application of the probe requires calibration and a number of techniques are presented together with results for some overseas sites. Soil density, type and structure are important in the calibration and severe salinity will interfere with the result. Finally future possibilities are explored.

Contents

1 The historical background

In the 1970s and early 80s the established and accepted means for *in situ* measurement of soil water content in the field was the neutron probe (Bell, 1976). It was recognised, however, that the instrument did not give a correct result in the surface 20 to 30 centimetres without some significant additional means such as, for example, an artificial soil pod. In the early 1980s this drawback was addressed and a programme was started to develop a capacitance probe for surface zone measurement.

An instrument for use in the field needs to be robust and reliable. Ideally it should be lightweight, easy to use and rapid in response with direct reading as distinct from null balance or the need to reset such as adjustment to 100 per cent. For measurements that are straightforward in interpretation, for example temperature, display in engineering units is essential but for more subtle variables, such as soil moisture, this may not be so necessary.

Many measurements, particularly of environmental variables, are indirect in the sense that the instrument actually determines some related property. This is certainly the case in respect of 'soil water content' which, in addition, is an ambiguous term having a meaning in hydrological studies somewhat different from, for example, that in agriculture (Bell *et al.*, 1987). The attraction of the determination of soil water content by the capacitance method is that it is based on the measurement of soil dielectric constant. This method is inherently sensitive since the dielectric constant of water is 80 whereas that of soil solid material is commonly 3 to 5 and air has a value of 1. The value for the composite wet soil is therefore very sensitive to the proportion of water present. In addition electromagnetic, as distinct say from nuclear, methods are generally easy to use.

In the early stages of the development programme, when our understanding was far from complete, it was decided to build a version for use in an access tube as an initial step rather than proceed straight to an instrument for surface measurement. This decision was influenced by worries about the significance of direct soil contact with the capacitor plates and other similar uncertainties.

After a study phase with several lash-up models a number of prototypes were built with progressive improvements in design and performance and a prolonged and extensive calibration programme was carried out in conjunction with a number of IH users. Subsequently the design was patented (Dean *et al.*, 1985) and moves to licence the probe for commercial manufacture, by the Didcot Instrument Company of Abingdon, were initiated. An integral part of the instrument system is an engineered means for professional installation into the soil of the vertical plastic access tube that enables the probe to determine the water content depth profile.

In parallel with commercialisation of the access tube probe a development programme was started on a version for measurement of water content in the top 5 and 10 cm surface zones of the soil (sometimes called the SCIP, Surface Capacitance Insertion Probe). Stimulation for this work arose from the need for surface measurements to calibrate and confirm air and satellite remote sensing research programmes. A number of prototypes were built keeping as much of the design as possible common to the access tube version. The probe capacitor is simply two 10 cm rods projecting from the base of the probe which in use is pushed directly into the soil thereby providing a rapid and simple measurement (Robinson & Dean, 1992). For time series studies the rods were made detachable and inserted by jig into the soil with exposed tops so that repeated measurements, without spatial variability, could be made by plugging the probe body onto the buried rods.

The surface probe design was modified with o-ring seals to make a waterproof version that could be permanently buried in the soil and coupled to a logger to give an automatic measurement system. The sensor is switched on remotely by the logger for a few seconds, to conserve battery life, and a measurement is made every two hours or at whatever interval is required. Recently this system has been made the basis of an automatic soil water station which includes sensors for rainfall, soil temperature and soil tension, both pressure transducer and gypsum block.

For specific applications other variants have been made. A horticultural study on the influence of irrigation on seed germination required the soil water content in the soil band from 10 mm to 20 mm below the surface. This would be impractical except that seed bed soil

is very finely divided and the probe could be deployed so as to retain maximum sensitivity: nevertheless it is at the boundary of the probe's performance. The circuit has also been applied to dynamically sense soil water content from a moving tractor (Whalley et al., 1992).

Most recently the basic probe geometry has been modified for non-invasive measurement, specifically on masonry. A study of the suitability and performance characteristics of the probe for this application was carried out for the Building Research Establishment. The capacitor rods were attached parallel to the base of the probe, rather than projecting from it, so that the probe could be held against the masonry surface. This sacrifices substantial sensitivity but in practice adequate sensitivity is available for accurate measurements to be made. Performance was determined as a function of water content for limestone and sandstone blocks and the influence of salt content was assessed (Dean & Cooper, 1993).

Note on nomenclature. The probe reader displays 5 figures such as 1456.7 which represents an oscillator frequency of 80 x 1456.7 kHz or 116.54 MHz. In the text this will generally be referred to as 14567 counts so that 14567 differs from 14566 by one count. However when fitting analytical expressions to data the probe reading is expressed as 1.4567 so that the constants determined for the equation are not unwieldy. The terms *probe frequency, probe reading* and *probe count* are used interchangeably in the text. Water content is expressed as per cent by volume. A change from 10 per cent to 11 per cent is referred to as a change of 1 per cent and this should not be interpreted as a fraction of some full scale value. This latter form will never be used in the context of water content.

2 Physics of the measurement

2.1 Capacitance and dielectric constant

Wet soil is a composite material made up essentially of solids, air and water. The dielectric constant of water is 80 and of air is 1 whereas that of commonly occurring soil solids is of the order 3 to 5. Not surprisingly the dielectric constant of the composite solid is very sensitive to the proportion of water present and hence its measurement forms an attractive method for the determination of soil water content.

Dielectric constant is an electromagnetic property of materials somewhat analogous, in a loose way, to resistivity and is defined as the electric dipole moment per unit volume. (An electric dipole is analogous to a magnet and its moment is the product of the electric charges and the spacing between them). If an electric field is applied the dipoles attempt to rotate in order to align with the field and, if the field is alternating, they attempt to follow the alternations. However the dipoles are also subject to intermolecular forces, which may limit their freedom, and the extent to which they do follow the field reversals determines their contribution to the dielectric constant. The frequency of the field reversals is an important concept, fundamental to an understanding of the physical processes of the measurement. Response of dipoles to an exciting frequency introduces the idea of phase lag between the dipole and the field and such topics are usually treated by complex notation.

In this case:

$$\varepsilon = \kappa - j\varepsilon_1 \qquad [2.1]$$

and now using more precise terminology we have a complex permittivity with a real part, κ, the dielectric constant, and an imaginary part, ε_1.

The dielectric constant of a material can be measured by using it as the dielectric instead of air in a capacitor and recording the change in capacitance. Capacitance is a pure geometric property of the conductors forming the capacitance so that

$$C = g\kappa \qquad [2.2]$$

and for a simple parallel plate capacitor

$$g = \frac{A}{d} \qquad [2.3]$$

where A is the plate area and d the spacing.

In general, permittivity and relative permittivity are used interchangeably as it is usually obvious which term is appropriate. Relative permittivity is the ratio of permittivity to that of vacuum which for practical purposes is the same as air. Relative permittivities, or dielectric constants, are the values normally tabulated. For SI units:

$$\kappa = \kappa_r \kappa_o \qquad [2.4]$$

where $\kappa_o = 8.85$ pF m^{-1} and κ has the same units so that the relative dielectric constant is dimensionless. Hence in the case of numerical substitution equation 2.3 becomes

$$g\kappa_o = \frac{8.85A}{d} \quad pF \qquad [2.5]$$

In the case of two infinitely long parallel rods, g can be determined by simple analysis but this is not possible for the two cylinders of the access tube probe. Even for the rods the presence of other circuit conductors has an effect on g and in any case the infinite model will be an aproximation.

There are a number of techniques for measuring capacitance and a particularly simple and direct method is to include the capacitor in the tuned circuit of an oscillator and note the frequency of oscillation (this is then the field reversal frequency referred to above). The dependence of frequency on capacitance is non-linear and given by:

$$F = \frac{1}{2\pi\sqrt{LC}} \qquad [2.6]$$

where L is the oscillator inductance and C is the total capacitance comprising the unknown and various fixed printed circuit board components.

As explained in section 2.2 the electromagnetic field frequency, that is the oscillator frequency, must be high, typically 100 MHz. At such frequencies localised circuit component concepts begin to fail and circuit fields extend beyond the confines of the circuit. These effects must be included in C in the above equation and also allowed for in the instrument design and the way it is used. In particular the operator's hands and body must be kept more than 10 cm. or so away from the oscillator circuitry.

2.2 Theory of dielectric constant in composite materials

In a composite material there are several contributions to the total electric dipole moment per unit volume, that is the dielectric constant. The particular contributions will be very dependent upon the electromagnetic field frequency. This follows from the simple dipole model since, at relatively low frequencies, for a given dipole inertia the dipole will readily reverse as the field reverses. As the frequency increases a value is reached at which the dipole can no longer respond quickly enough to follow the field and it ceases to contribute to the dielectric constant. This frequency will be a function of the inertia of the dipole and the strength of the forces that bind it to nearby molecules.

The water molecule has a permanent electric dipole moment due to the centre of gravity of the negative electric charge, the hydrogen ions, being displaced from that of the positive charge, the oxygen ion. For water in soil the dipoles begin to lag the field at frequencies of a few Gigahertz and the dielectric constant progressively falls from the value of 80.

At much lower frequencies, less than 30 Mhz, electric charges on the surfaces of voids in the material act as gross dipoles and can give dielectric constant values of several thousand, (see Figure 2.1 for the general form of the variation of dielectric constant with frequency). These contributions drop out at about 30 Mhz and were the source of anomalous results and poor reproducibility in early attempts to measure soil water content via dielectric constant. These are the so called interfacial polarisation effects (Hoekstra & Delaney, 1974) and, once elucidated, established a window for reliable measurement of between 30 Mhz and 1 or 2 Ghz, the frequency at which sensitivity falls. For circuit rather than travelling wave techniques the practical upper limit is probably a few hundred Mhz and the IH probe operates at about 100 to 150 Mhz.
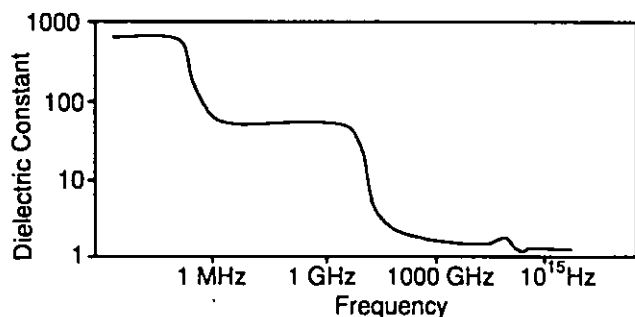
Given the significance of frequency, the dielectric constant of a composite material is not the straightforward addition of the individual components. There is no simple theory (Ansoult et al., 1985) but approximate models have been proposed that are valid over limited ranges. They are dielectric mixing models based on volume (Roth et al., 1990) with the geometrical arrangement of the components as a parameter. The general expression for three components, air, soil and water is:

$$\kappa^{\alpha} = v_a \kappa_a^{\alpha} + v_s \kappa_s^{\alpha} + \theta \kappa_w^{\alpha} \qquad [2.7]$$

where κ is the dielectric constant, θ is the volumetric water content, v is volumetric fraction and subscripts a and s refer to air and soil. If the components are arranged as parallel layers α is 1 whereas if they are in series α is -1. Clearly these are highly idealised situations and in practice α has an intermediate value that is essentially determined empirically. There is some evidence that $\alpha = 0.5$ describes experimental data reasonably well and has the merit of coinciding with a straightforward refractive index mixing model.

So, certainly for small perturbations, it is justifiable to use this mixing model to examine theoretically the influence of density, porosity and composition variations, as carried out in section 7.3. However it makes no attempt to include the subtle property of soils covered by the term "structure".

2.3 Dependence of soil dielectric constant on water content

A full description of the dielectric constant of moist soils represents a formidable bank of data comprising variation with soil composition, density and water content over the full frequency

Figure 2.1 Dependence of dielectric constant on frequency
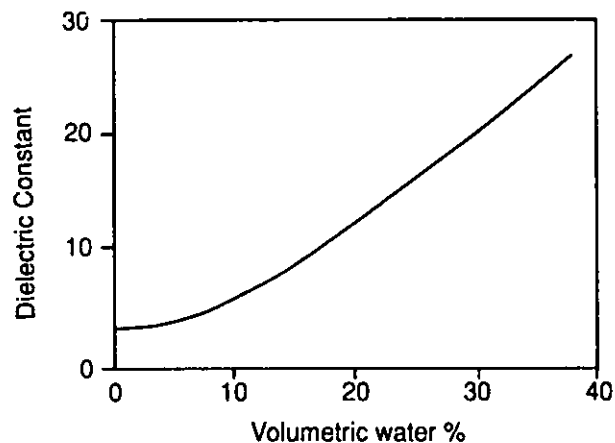
Figure 2.2 Dependence of soil dielectric constant on water content

range and possibly also taking temperature into consideration. In addition the influence of soil structure is uncertain so that it is not clear how laboratory and field samples compare. However the general form is shown in Figure 2.2 for frequencies in the U.H.F and microwave regions.

The results can be represented by a quadratic dependence of κ on θ and a field calibration at Grendon using the surface probe is described by:

$$\kappa = 2.5 - 0.06\theta + 0.02\theta^2 \qquad [2.8]$$

R^2 for this curve fit is 0.979. The negative coefficient for θ is not physically sound, however the slope of κ is positive at $\theta = 1.5$ % so it is not a serious deficiency.

This expression was determined from the results of the Grendon field calibration, that is F versus θ (see 7.3), and the dielectric constant calibration which gives F versus κ (see 5.1) but is entirely in agreement with the literature (Hoekstra et al., 1974; Topp et al., 1980; Malicki et al., 1989; Malicki & Skierucha, 1989; Brisco et al., 1992; Campbell, 1990; Roth et al., 1992).

3 IH capacitance probes

3.1 Access tube version

This probe is designed for use within a vertical access tube, installed to a suitable depth in the soil, and provides the user with a soil water profile against depth. The instrument has two units, the sensor and the frequency reader, linked together by fibre optic cable. A series of extension handles are fitted to the sensor which enables it to be set accurately at 2 cm intervals down the access tube to a total depth of a nominal 2 metres.

In its carrying case the probe weighs 5 kg and is easily transported. In use its response is effectively instantaneous and, as depth location is simple and precise, a complete depth profile may be determined in a few minutes. The calibration expression relating frequency to volumetric soil water content is non-linear having increased sensitivity at low water contents. This can be an advantage in some circumstances and obviously is no problem with computer handled data but it does reduce the visual significance of the read-out. The diameter of the soil volume over which the probe is sensitive is limited to about 13 cm (Dean et al., 1987) and for accurate measurements it is essential to install the access tube with the greatest care (Bell et al., 1987).

The sensor and depth setting handle

The sensor body is of polyacetal and comprises a top cap assembly, a cylindrical outer case and a bottom end cap as shown in Figure 3.1. Sensor diameter is 44 mm, length is 290 mm and its axis is centred in the access tube, internal diameter 47 mm, by flexible nylon fabric rings housed in the top and bottom caps. Access to the battery compartment is by unscrewing the 19 mm plug in the top cap assembly which also houses the on-off switch and the signal-out cable socket. The axial centre of sensitivity is 114 mm from the bottom end of the probe. See 7.2 for description of the capacitor plate geometry.

To position the probe at specific depths in the access tube, it is fitted with PVC extension tubes 400 mm long and of the same diameter as the sensor case. 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 the series of holes spaced every 20 mm along the extension handles. This also defines the rotational orientation of the sensor with respect to the access

tube. Three extension handles enable use to a depth of 1.8 metres with precise depth positioning at 20 mm intervals. For convenience an access tube extension piece may be fitted to enable measurements to be taken through the air/soil-surface interface and to raise the mounting block well above ground level.
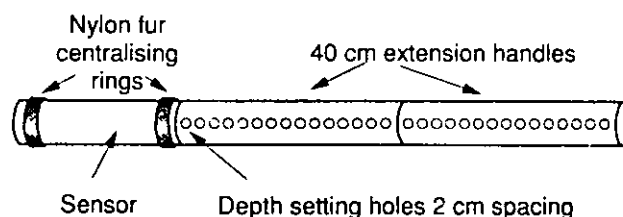
Figure 3.1 *Access tube sensor and depth setting handles*

Frequency reader

The reader displays the sensor frequency, divided by 80, in kHz with a resolution of five digits. Connection to the sensor is via a 4 metre fibre optic cable into a socket, adjacent to the battery charging jack socket, on the end face of the reader. The on-off switch is a slide switch on the side of the reader.

Use of the probe

The sensor batteries are lithium manganese dioxide and are not rechargeable but have an operating life of 8 to 10 hours and a shelf life of about five years. The probe reading with the sensor freely held in air is slightly dependent on temperature (about 3 or 4 counts per degree C) so will change slowly through the seasons, however a distinct change of about 40 counts will occur when the sensor batteries need replacing. Perhaps a more reliable test is that the probe reading should be steady to one count with at most a change of one count per minute as shown in Table 1. To renew the batteries unscrew the 19 mm plug in the top cap assembly and fit two new cells (Duracell PX28L 6 volts) with the positive terminal uppermost.

AAA sealed nickel cadmium rechargeable batteries are used in the frequency reader. Five are in series and provide about 5 hours of operation with a display of "LW" to indicate the

Table 1 *Typical probe stability from switch on*

Time from switch on, minutes	Air Count
0	19078
1/4	19079
1/2	19080
3/4	19080
1	19080
1 1/4	19081
1 1/2	19081
1 3/4	19081
2	19082
2 1/4	19082
2 1/2	19082
2 3/4	19082
3	19082
3 1/4	19083
3 1/2	19083
3 3/4	19083
4	19083
4 1/4	19083
4 1/2	19083
4 3/4	19083
5	19083
5 1/4	19083
5 1/2	19083

need for recharge. The charger provided is connected via the 3.5 mm miniature jack socket on the front of the reader and may be left connected indefinitely as it only provides 9 milli amps. Conversely the unit will not provide a rapid charge and about 24 hours is required.

When using the probe in the field users are strongly advised to establish a strict routine and not deviate from the preferred method. A ten point schedule is recommended:

1. Screw the fibre optic cable securely into the sensor. Avoid bending the cable to a radius tighter than 2 cm and take care not to strain the cable-coupling joint.
2 . Thread the cable through the first extension handle and screw the handle to the sensor. Repeat for additional handles.
3. Fit the access tube extension over the cable and on to the probe from the handle end.
4. Screw the fibre optic cable securely into the frequency reader socket.
5. Dry each access tube internally in sequence to avoid collecting water in the nylon fur.
6. Switch on the frequency reader, it should read 0.1 kHz but is very sensitive and some spurious counts are of no concern.
7. Switch on the sensor and take an air reading with the extension tube slid up the handle and at least 15 - 20 cm clear of the sensor. The sensor should be 30 cm clear of any other bodies.
8. Fit the extension tube to the top of the access tube, with the orientation pin in the access tube slot.

9. Set the depth locating pin at 986 (equivalent to 14 cm above the access tube rim) and take readings progressively at 2 cm intervals down the tube. N.B. at 0 the centre of sensitivity will be in the plane of the access tube rim.
10. At the end of the depth profile remove the probe and take a second air reading which should be within 10 counts of the first.

3.2 Surface probe

For a development programme aimed at improved understanding of the instrument characteristics and performance, nine surface probes have been built with as many parts as possible common to the access tube probe. These models have been used to build up experience in field use, soil water content calibration techniques, dielectric constant calibration techniques and user evaluation. Also for determination of instrumental characteristics such as time stability, probe interchangeability, spatial sensitivity and linearity along the probe rods. Many of these results will apply equally to the access tube probe but the surface probe has a more convenient and compact geometry.

For the surface probe the capacitor plates are two stainless steel rods firmly held in a Delrin block which is the bottom cap of a shortened body holding the printed circuit board and battery housing, as shown in Figure 3.2.
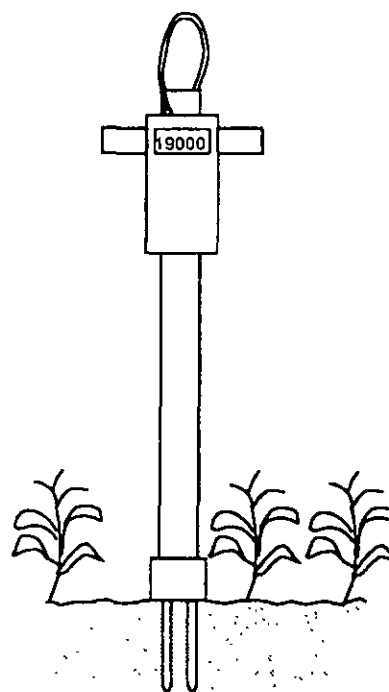

Figure 3.2 *Surface probe*

The reader is supported by an extension tube and cross handle screwed to the probe body so that the two units are separated by about 200mm. They are linked by fibre optic cable and the geometry ensures that use of the handle does not influence the probe reading.

The probe rods are 6 mm diameter and 100 mm long with the bottom 10 mm pointed to facilitate direct insertion into the soil surface and thereby give the soil water content for the top 10 cm surface zone of the soil. To give the added flexibility of a 5 cm surface measurement a 50 mm Delrin block of the same diameter as the probe is slid over the rods. For specialist studies on seed germination, 80 and 90 mm spacers have been used providing insertion depths of 2 cm and 1 cm.

Subsequently an engineered version of this probe has been designed and built and designated as a commercial prototype. The changes made have been largely mechanical and towards reduction in the number of friction contacts in the electronics so as to reduce costs and improve robustness and reliability, see 8.1.

Masonry probe

In situations where the soil surface is baked hard, a non-invasive probe geometry is advantageous. The performance characteristics of such a design have been evaluated on limestone and sandstone masonry blocks. Such blocks have the advantage of providing a stable matrix that can be wetted and dried without unknown density and structure changes.

A straightforward modification was made to the surface probe, see Figure 3.3, whereby the 100 mm rods were fixed perpendicular to the probe axis rather than axially. Electrical circuit connection was made to the mid point of the rods.

3.3 Installed probe for automatic recording

Manually operated instruments have an essential role to play but, for many environmental studies, automatic recording systems are essential. The installed probe consists of a buried surface probe, an interface and an Instrument Section logging system. Modifications to the buried
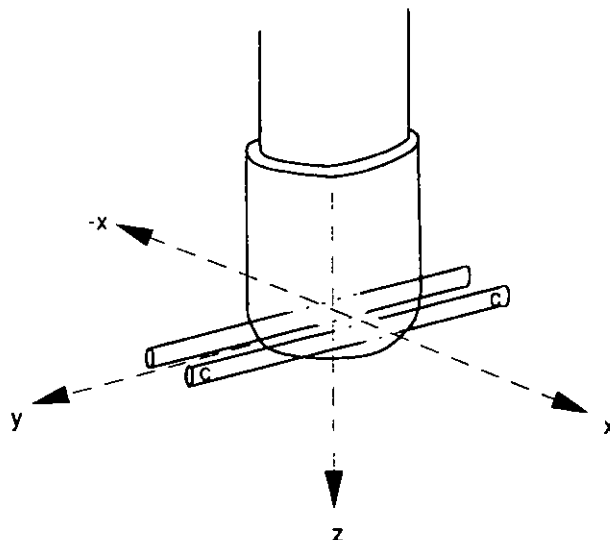

Figure 3.3 Rod orientation for the masonry probe

probe include O-rings on the rod housings and an O-ring sealed end cap to cover the top cap assembly. Fibre optic cables are taken through the end cap by commercial gland seals.

For this version the printed circuit board is extended so that the circuit can be switched on by an optical signal generated by the logger and interface. Hence the buried probe has two fibre optic connecting cables to provide both signal output and remote excitation. Since hourly sampling is adequate and the probe is on for little more than one second the probe batteries allow for about one year of operation.

In initial trials the probes have been buried horizontally at depths of 5, 10 and 15 cm. with the rods inserted into undisturbed soil and soil repacked around the probe body so that ultimately a uniform surface is recovered. One consequence of this is that the soil dielectric constant packed round the body depresses the probe frequency and reduces the sensitivity. This is offset to some extent by the elimination of spatial variability, however overall the detailed performance is yet to be determined. An alternative method of installation has been used for probe depths of 40 and 50 cm using a plastic access tube inserted at 45°. This should reduce the significance of the packed soil since it provides an air gap round the body, but this remains to be demonstrated.

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4 Circuit analysis

Figures 4.1 and 4.2 show the electronic circuits of the probe and reader. The oscillator circuit used in the probe is the Clapp, (Amos, 1965) which is a development of the Colpitts, and is particularly stable to changes in temperature.

4.1 The probe high frequency transistor oscillator

Primarily the aim of the analysis is to determine the dependence of the oscillator frequency on the circuit component values, including the probe rods that form the measuring capacitor. In addition, circuit stability, oscillator gain and oscillator start up condition are also of interest.

The analysis is based on the current transfer function, $T(\omega)$, defined by:

$$i_x = T(\omega) \, (-\beta i_b) \qquad [4.1]$$

where β is the transistor gain and ω is the angular frequency, $2\pi F$. The currents are shown in Figure 4.3 which is the equivalent circuit of the oscillator. Z_1, Z_2 and Z_3 represent the circuit and the other components are the model of the transistor.

Kirchoff's laws give:

$$(i_c - \beta i_b) \, r_d + i_2 Z_2 = 0$$

$$i_1 Z_1 + i_3 Z_3 - i_2 Z_2 = 0$$

$$i_1 Z_1 + i_x r^1{}_{11} = 0$$

$$i_c = i_2 + i_3$$

$$i_1 = i_3 + i_x \qquad [4.2]$$

with the symbols shown in Figure 4.3 and with:

$$Z_1 = -\frac{j}{\omega C_1} \qquad Z_2 = -\frac{j}{\omega C_2} \qquad Z_3 = j\omega L - \frac{j}{\omega C_r} \qquad [4.3]$$

where C_r represents the capacitance of the probe rods.

Solving 4.1 and 4.2 for $T(\omega)$. $T(\omega) =$

$$\frac{r_d Z_1 Z_2}{r^1{}_{11} r_d (Z_1 + Z_2 + Z_3) + Z_1 Z_2 Z_3 + Z_2 r^1{}_{11}(Z_1 + Z_3) + Z_1 r_d (Z_2 + Z_3)} \qquad [4.4]$$

The oscillator frequency is determined by the condition that the imaginary part of the transfer function, $T(\omega)$ is zero. Hence

$$r^1{}_{11} r_d (Z_1 + Z_2 + Z_3) + Z_1 Z_2 Z_3 = 0 \qquad [4.5]$$

From 4.3 and 4.5 the definitive equation for the oscillator frequency, ω is obtained.

$$(\omega L - \frac{1}{\omega C_T}) - \frac{1}{r^1{}_{11} r_d \omega C_1 \omega C_2} (\omega L - \frac{1}{\omega C_r}) = 0 \qquad [4.6]$$
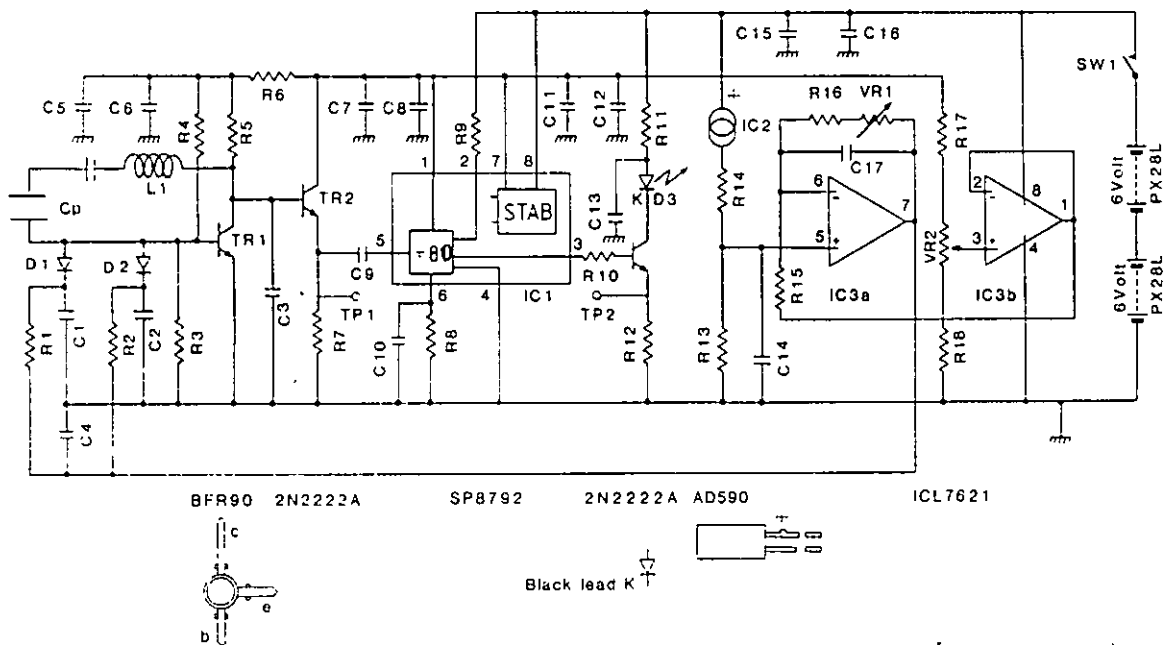
Figure 4.1 Circuit diagram of the probe sensor
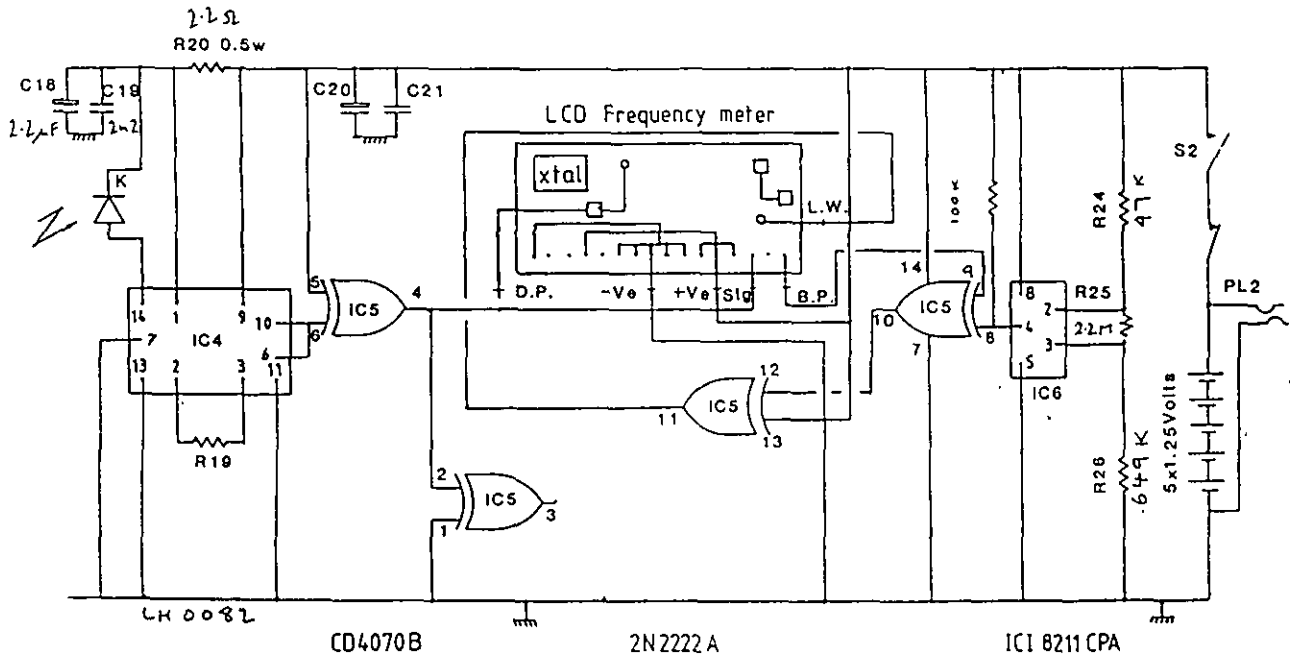
Figure 4.2 Circuit diagram of the reader
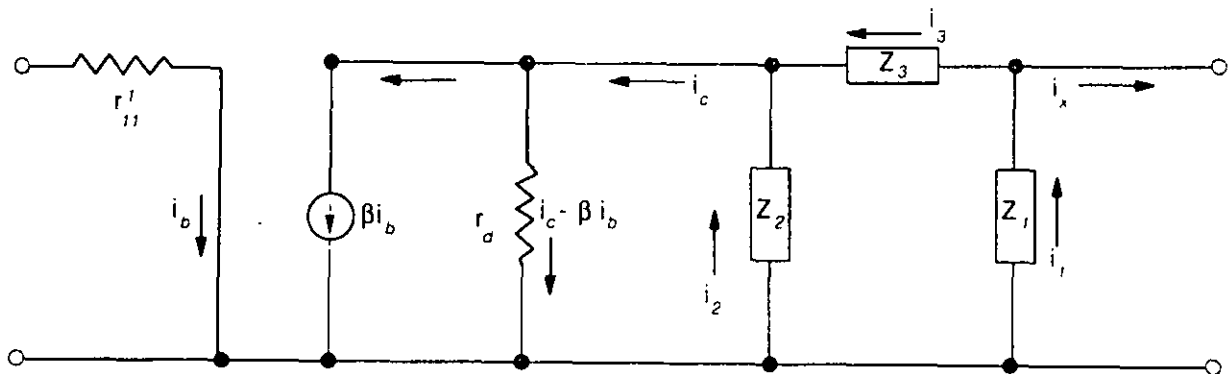
Figure 4.3 Equivalent circuit of the transistor oscillator

where

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_r} \qquad [4.7]$$

This can be solved to a close approximation by assuming $\omega_o + \delta$ is a solution, where $\omega_o = (LC_T)^{-1/2}$, which gives:

$$\omega = \frac{1}{\sqrt{LC_T}} + \frac{C_T\sqrt{LC_T}}{r^1{}_{11}r_dC_1C_2}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) \qquad [4.8]$$

For most purposes ω_o is a sufficiently accurate solution as the additional term is about 1000 times smaller. Hence for use in section 5.2 we have for the resonant frequency:

$$2\pi F = \frac{1}{\sqrt{L}}\sqrt{\frac{1}{C_r} + \frac{1}{C_1} + \frac{1}{C_2}} \qquad [4.9]$$

The full response function of the probe displays the frequency, F, divided by 80 and this forms the basis of equation 5.5.

At resonance the gain is given by $1/T(\omega_o)$, which of course is real. Actually this is the attenuation of the feedback network which must be equalled by the transistor gain if the circuit is to oscillate.

$$Gain = \frac{Z_2 r^1{}_{11}(Z_1+Z_3) + Z_1 r_d(Z_2+Z_3)}{r_d Z_1 Z_2} \qquad [4.10]$$

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Using the resonance condition this resolves to:

$$Gain = -\left(\frac{r^1_{11}C_1}{r_dC_2} + \frac{C_2}{C_1}\right)$$ [4.11]

The negative sign results from the sign convention used in equation 4.1.

4.2 Temperature compensation

Whilst the Clapp oscillator is substantially insensitive to temperature there is a residual dependence and other factors,such as thermal expansion of the rods and their spacing, contribute to a resultant temperature coefficient which the inherent oscillator stability, of 1 in 10^4, makes clearly visible. To reduce its significance a temperature compensating circuit is included comprising a temperature sensor, the AD590, an amplifier and two variable capacitance diodes, BB809s. The resultant stability is 1 in 10^4 per degree C. For the middle of the range this is about equivalent to .02 per cent water content per degree C.

4.3 Frequency reader

Signal level at the photo-receiver is low and a high gain amplifier, LH0082, is used before input to the LCD frequency meter module. Consequently care is needed when monitoring the circuit. The meter module includes a microprocessor and the circuit layout must minimise interaction between it and the photo-receiver input.

5 Theoretical analysis of the surface probe

Use of the capacitance probe requires a calibration to relate the displayed frequency reading to soil water content. The instrument responds to the dielectric constant of the soil which is a strong function of the soil water content, but not uniquely determined by it (see section 2.3). There is a strong case for separating the probe response function into two parts:

$$f = \text{function}(\kappa) \qquad [5.1]$$

$$\kappa = \text{function}(\theta) \qquad [5.2]$$

The first function is fixed by the instrumental constants of the design, electronic and mechanical, and can be determined in the laboratory with acceptable precision using liquids of known dielectric constant. The second function is discussed in the literature and is usually expressed as a quadratic in the soil water content but is to some extent influenced by the soil constituents, density and structure (see section 2.3).

There are two advantages to this approach; the liquid samples can be treated as standards and used to confirm probe stability and, using the second function, results can be compared with the literature and with measurements made by time domain reflectometry, TDR.

5.1 Calibration against liquids of known dielectric constant

With the surface capacitance probe this is particularly straightforward. A 2 litre plastic beaker is filled to the rim with the liquid and the

Table 2 Liquid dielectric constant values

Liquid or reference	Dielectric constant at 15 C	Temperature coefficient
Air	1	0
Chloroform	4.90	-368 *
Acetone	21.7	-472 *
Ethanediol	39.6	-0.224 **
Water	82.2	-0.38 per C

* 10^5 dκ/κdT
** d(log$_{10}\kappa$)/dT

probe rods immersed either 5 or 10 cm exactly as they are inserted in the soil. The beaker diameter of 155 mm and height of 157 mm ensures that the sensitive volume of the instrument is completely enclosed. Table 2 lists the liquids used together with the temperature coefficients of their dielectric constants (Kaye & Laby, 1985; *Chemical Rubber Company Handbook*, 1965).

5.2 Description of the model for determination of equation 5.1

The model is described by four constants and a parameter, "p". The constants are:
L   the circuit inductance;
C_b the sum of the printed circuit board capacitors in series including the temperature compensation components;
C_3 the effective capacitance due to stray electric field outside the confines of the printed circuit board;
g   the geometric factor associated with the rod capacitance, C_r and defined by the equation:

$$C_r = g \, \kappa_0 \, \kappa_r \qquad [5.3]$$

Here κ_0 is the permittivity of free space, see equation 2.4.

The parameter "p" describes the fractional length of probe rod in the soil so that p=1 for 10 cm rods and p=0.5 for 5 cm rods. With this scheme a Delrin spacer of 10 cm covering the complete rod length corresponds to p=0.

The dielectric media are in parallel and their contributions can be assumed proportional to the length of rod, so that:

$$C_r = pg\kappa_0\kappa_S + (1-p)g\kappa_0\kappa_D \qquad [5.4]$$

where κ_S and κ_D are respectively the dielectric constants of the soil and the Delrin spacer.

Applying this expression to the circuit analysis in section 4 leads to the following response function:

$$F^2 = \frac{1}{(160\pi)^2 L} \left(\frac{1}{pg\kappa_0\kappa_S + (1-p)g\kappa_0\kappa_D + C_3} + \frac{1}{C_b} \right)$$

$$[5.5]$$

Constants L and C_b are given by the circuit analysis in section 4 and, with some assumptions, g can be calculated from electromagnetic theory.

5.3 Calculation of g

Following Krauss (1984) the capacitance of two infinite parallel conductors is amenable to calculation. If κ_r is the dielectric constant of the medium surrounding the conductors and C/l is the capacitance per unit length then:

$$\frac{C}{l} = 12.1 \frac{\kappa_r}{\log[\frac{h}{r}+\sqrt{(\frac{h}{r})^2-1}]} \quad (pF\ m^{-1}) \quad [5.6]$$

where r is the conductor radius, the probe rod radius in our case, and 2h is the centre to centre spacing of the conductors. For the capacitance probe geometry, r=3, h=10 and l=0.1, and we find:

$$C = 1.49\ \kappa_r \quad [5.7]$$

so that $g\ \kappa_o = 1.49$. $\quad [5.8]$

As stated earlier g is a purely geometrical factor determined by the shape and layout of the conductors although this only holds if the dielectric constant of the surrounding medium is uniform. This value of g will hold, then, to the extent that the length to spacing ratio is large and approximates to infinity. There are of course other conductors on the printed circuit board and in the model they have been included in C_3 rather than as an effect on g.

5.4 Development of the response function of the model

Frequencies were determined with the 10 cm probe and 5 cm, using the Delrin spacer, for the liquids listed in Table 2. The results are listed in Table 3.

Table 3 *Probe frequency against dielectric constant for experimental probe 355 (A), 5cm and 10cm.*

Dielectric constant	Rod length parameter	Probe frequency
1.0	0.5	1.7564
1.0	1.0	1.9169
4.9	0.5	1.5328
4.9	1.0	1.4650
21.7	0.5	1.2088
21.7	1.0	1.1229
39.6	0.5	1.0890
39.6	1.0	1.0425
82.0	0.5	1.0118
82.0	1.0	0.9908

This data enables the constants of the model to be calculated using a statistical four parameter non-linear curve fitting programme. The resulting expression is:

$$F^2 = \frac{9.126}{p\kappa_s+(1-p)2.756+2.215}+0.8482 \quad [5.9]$$

$R^2 = .9986$

and the standard errors of the constants are:

9.1262	.614
2.7560	.242
2.2150	.130
0.8482	.0238

Now there are a number of predictions of the model that can be checked independently. Comparison of equations 5.5 and 5.9 gives:

a) $(160\ \pi)^2\ g\ \kappa_o\ L = 1/9.126$

b) $\kappa_D = 2.756$

c) $(160\ \pi)^2\ C_b\ L = 1/0.8482$

d) $C_3 = 2.215\ g\ \kappa_o$ $\quad [5.10]$

The dielectric constant, expression b, of Delrin is 3.7 at 10 kHz (Brydson, 1982) and will have a lower value at the probe frequency of about 100 MHz. In addition, for ease of instrument use, the Delrin spacer has the same diameter, 50 mm, as the probe body and does not fill the full diameter of the field so that the probe measures a composite spacer of delrin and air. The model prediction, therefore, of 2.8 is eminently plausible.

If section 5.3 is followed so that $g\kappa_o = 1.49$ then, from expression a:

L = 0.291 microhenries

which agrees very well with the value, 0.24 microhenries, of the component inductor in the circuit. Also printed circuit board tracks will tend to increase the total board inductance.

Using this value of L in expression c gives:

C_b = 16.03 pF

In practice the board capacitance is made up of:
three 18 pF components;
two variable capacitance diodes that are part of the temperature compensation circuit;
interelectrode capacitance of the oscillator transistor, probably about 1 pF;

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emitter-base capacitance of the emitter follower transistor, about 25 pF, which combine to give about 15 pF which is certainly acceptable agreement with the model.

Finally expression d gives:

$$C_3 = 3.30 \text{ pF}$$

This is the most difficult factor to evaluate as it is purely speculative but clearly a small value, representing a small field loss, is most credible and 3.3 pF meets this criterion.

Overall, then, this model provides an accurate representation of the capacitance probe response and is soundly based on the physics of the instrument. Together with an expression such as equation 2.8 it gives the response to soil water content or, alternatively, if the probe is calibrated directly against soil water content, it gives the dependence of soil dielectric constant on water content which may in turn be compared with the literature.

6 Instrumental characteristics of the surface probe

6.1 Linearity of response along the rod length

Usually there will be a gradient of water content in the top 5 and 10 cm of the soil and the probe will return an average measurement that will only approximate to an arithmetic average of water content. The degree of approximation will depend on the extent to which the square law dependence of dielectric constant on soil water content is approximately linear over the water content range encountered in the particular sample, and also the extent to which the probe sensitivity varies with distance along the length of the rods. This latter characteristic has been measured experimentally.

A small PVC disk 46 mm diameter by 3mm thick was used as a "search coil" and the dependence of probe reading on the position of the disk was determined. It can be assumed that the disk, which is thin compared with the rod length, will have negligible effect on the field pattern. The reading, or signal, from the disk is the difference between the air count and the disk reading. The results, shown in Figure 6.1, are plotted as per cent of the reading with the disc at the mid point (50 mm) of the rods. Linearity is within 6% of the mid point reading over 90% of the rod length, discounting the rod points. Hence the probe sensitivity is effectively constant along the rod length and it can reasonably be assumed that any non-linear averaging is only due to the non-linear dependence of dielectric constant on volumetric water content.
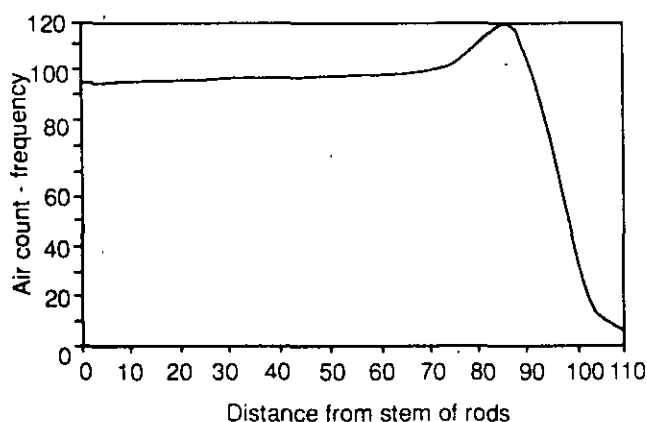
6.2 Spatial sensitivity

The probe has three axes of sensitivity, illustrated in Figure 6.2 and, as the rods are not symmetrically connected in the electronic circuit, there are four responses, namely +X, -X, Y and Z. These have been assessed by noting, for each axis in turn, the probe reading as a function of the distance from the water surface in a full two litre beaker. For the Z axis the probe rods were also taken into the water.
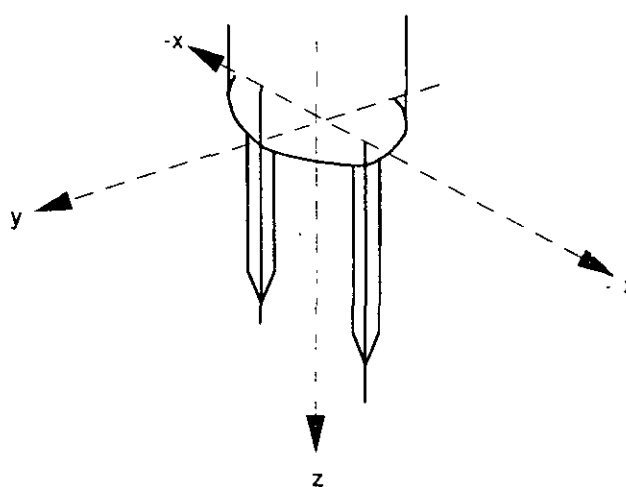
Figure 6.2 *Rectangular axes for description of spatial sensitivity*

Results are listed in Table 4. The cut off at the point tips is quite sharp and is in line with the small signal results in section 6.1.

In addition contours of constant response have been plotted in the X-Y plane at the mid length of the rods. A 3 mm sheet of perspex with two 6 mm holes matching the probe rod spacing was held horizontally. The probe was inserted vertically with the rods uppermost and projecting through the two holes. A 5 cm long 6.4 mm diameter perspex tube sealed at the bottom and filled with water was effectively measured by the probe analogous to a "search coil" technique. The rods projected 7.5 cm through the perspex sheet so that the centre of the water-filled perspex tube was in the X-Y plane at the mid length of the rods. It is assumed that the cylinder dimensions are small enough not to distort the electric field of the probe.

Figure 6.1 *Small signal linearity along the probe rods*

Table 4 Spatial sensitivity measurements

Z Axis mm	Frequency	X+Axis mm	Frequency	Y Axis mm	Frequency
-100	10017	1	17389	2	17542
-90	10027	2	17775	3	17884
-80	10048	3	18019	4	18085
-70	10082	5	18278	5	18259
-60	10139	9	18556	7	18474
-50	10228	24	18930	10	18695
-40	10378	54	19090	13	18807
-30	10617	104	19137	18	18922
-20	11128	X-AXIS		23	18992
-10	12364	1	18958	33	19062
0.5	18794	2	19002	43	19096
10	19084	3	19041	53	19114
20	19105	5	19079	63	19126
30	19117	10	19113	93	19141
40	19124	17	19130	103	19143
57	19133	32	19140		
120	19143	52	19143		

Sensitivity contours were determined by plotting the positions of the cylinder that produced given levels of signal. Results are shown in Figure 6.3 and give a more readily visualised appreciation of the region to which the probe is sensitive. As expected the major response arises from the regions close to the rods and between the rods. A theoretical treatment for the parallel rod geometry has been given by Knight (1992). He is interested in TDR but the analysis is equally valid for the capacitance probe.

6.3 Spatial variability

In order to make a measurement the probe rods are inserted into the soil which may well disturb the soil water distribution particularly in the soil close to the rods and, as section 6.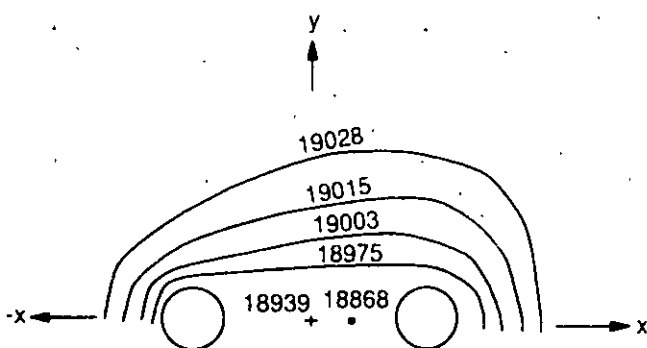2 shows, this is the most sensitive region of the probe. One way to estimate the significance of this is to make repeated measurements spatially very close to one another and see how well they reproduce. However in the field, and even in the laboratory, this is open to doubt due to the uncertainty of spatial variability. Nevertheless this approach was adopted albeit with an intensive series of readings in order to improve the statistical significance of the result.

As illustrated in Figure 6.4 a field area of short grass 6m by 2m was marked by tape into 12 one metre squares. Each square was measured at 9 points, nominally at the (25cm,25cm), (25cm,50cm), (25cm,75cm), (50cm,25cm) etc positions. Experimental probe A and the commercial prototype probe were used at both 5cm and 10cm depths so that in all 4 x 108 = 432 measurements were made. Four readings were taken at each position but not at the same point and not in a rigorous pattern so spatial variability is to be expected between each of the four series of measurements. The sequence was 5cm probe A, 5cm commercial prototype, 10cm probe A and 10cm commercial prototype and the total duration over which the results were obtained was three hours. The measurements were made on 31.08.92.

The results are presented in Figure 6.5 and show 108 readings for each probe. These comprise 6 transects of 18 readings parallel to the X axis across the 6 metre plot, for each probe. The transects are then plotted sequentially across the paper so that in fact points 19 to 36 are the second and 37 to 54 the third transect etc. An intercalibration expression, see 6.5, from the 5 and 10cm air and water

Figure 6.3 Contours of constant sensitivity in the X-Y plane at Z=50mm.

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1 2 3 4 5 6 7 8 9	1 2 3 4 5 6 7 8 9				

```
- - →    X Axis
↓
Y Axis
```

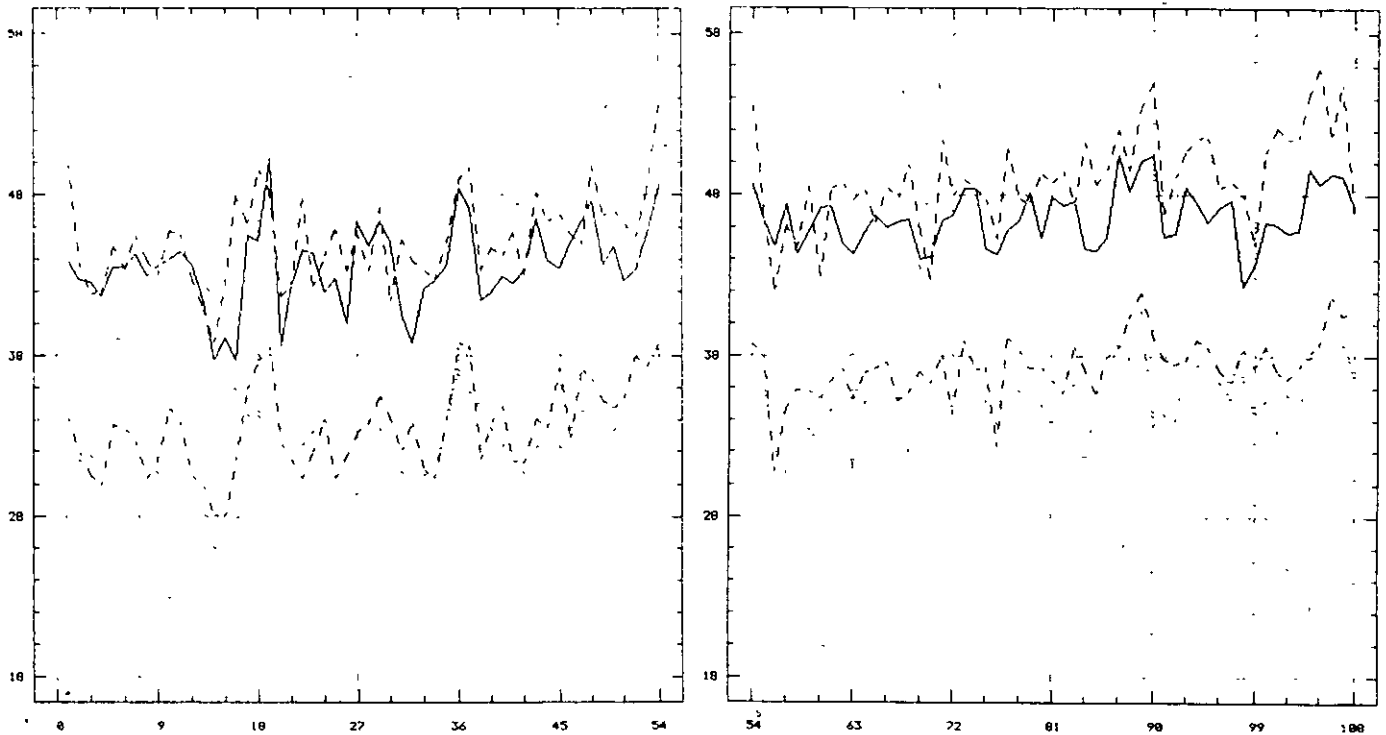***Figure 6.4*** *Grid of one metre squares for spatial variability study*

Figure 6.5 *The six transects across the 6m by 2m plot. Water content is shown for the 5 cm, — and - - ; and 10 cm, ... and - . - measurements.*

counts, has been used to convert the commercial prototype readings to equivalent probe A readings and all frequency readings have then been converted to water content from the probe A Wallingford topsoil calibration, section 7.3. For the 5cm data the two probes agree to +/- 2% apart for 15 points and ignoring points 16, 95 and 98 where there is a clear effect of spatial variation. Taking the 10cm data, the probes agree to +/- 2% apart from the four points 63, 84, 90 and 108. This is to be expected since the surface 5cm will clearly experience greater spatial variability and in addition the relatively larger volume of the 10cm sample will provide better averaging. On the assumption then that typical spatial variability is within +/- 2% it is clear that the dip from 36% to 26% in the span from points 11 to 15 and 18 is a real feature.

Results of a more formal analysis are given in Figure 6.6 which shows the correlation matrix for the four sets of data. The correlation coefficient between the two 5cm runs is 0.7147 whereas for the 10cm runs it is 0.8342 substantiating the subjective deductions in the paragraph above. Interestingly the next best coefficient, 0.7635, is between the two runs of the commercial prototype.

Probe A 5cm	1.0000	0.7147	0.7403	0.7520
Comprot 5cm	0.7147	1.0000	0.6756	0.7635
Probe A 10cm	0.7403	0.6756	1.0000	0.8342
Comprot 10cm	0.7520	0.7635	0.8342	1.0000

Figure 6.6 *Correlation matrix for the four sets of data*

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6.4 Time stability

It is important that a user is aware of the inherent probe stability so that a significant change, arising from a fault situation, is not overlooked. Table 5 shows measurements with the masonry probe obtained by standing the probe in a marked position on a PVC block. The data cover a period of 27 days and show an overall span of about 10 counts in 17000.

Table 5 Stability of reading over a period of 27 days

Day number	PVC frequency
1	17983
4	17988
5	17983
6	17982
7	17989
11	17980
12	17988
13	17987
14	17992
15	17986
20	17988
21	17983
27	17988

Table 6 Long-term stability for a number of probes over 2.5 years

DATE	Probe number				
	355	356	357	352	353
MAY 91	19166	19208			
JUN 91				18950	19149
JUL 91	19172	19248			19158
AUG 91	19153		19261		
SEP 91	19186	19278		18930	19139
OCT 91	19186				
NOV 91	19164	19256		18941	19166
JAN 92		19245			
FEB 92			19310		
MAR 92	19167		19245		19181
APR 92			19306		
MAY 92	19186		19297	18955	
JUN 92			19282		
JUL 92	19151		19202	18921	
AUG 92	19166				
NOV 92			19248	19012	19155
DEC 92	19162				
JAN 93					19153
FEB 93	19169		19211	18990	
MAR 93			19194	18960	
APR 93				18970	
DEC 93	19188				19133

Very long-term stability is complicated somewhat by the residual temperature dependence after temperature compensation, see section 4. The air count of access tube probe no. 250 was 17976 on 8.7.88 and 17977 on 18.11.93 demonstrating the inherent dimensional and electronic stability. For probe 250 the air count varies between 18000 at low temperature and 17920 at high. Table 6 gives results for 5 probes over a period of about 30 months.The reading of 19012 for probe 352 in November 1992 was subsequently traced to a dry joint on the printed circuit board.

6.5 Probe intercalibrations

Due to component and dimensional tolerances the prototype probes, both access tube and surface versions, are not interchangeable. In consequence calibration data, obtained either in the field or in the laboratory, is specific to a particular probe. Probe intercalibrations are then used to extend the calibration data to additional probes.

Intercalibrations, particularly for the surface probe with its relatively small sensitive volume, can be obtained from the range of liquids used for the dielectric constant calibration, see section 5.1. Measuring each of the four liquid samples, together with the air value, with two probes easily enables a transform function interelating the two probes to be deduced. Despite the non-linear dependence of probe frequency on dielectric constant the transform function is very closely linear, with a correlation coefficient usually of 1.00, presumably because the probes only deviate one from another by 1 or 2 parts per 100.

Again for the surface probe an alternative method is to use the laboratory sample holder which has two thin walled PVC tubes, round which the wet soil sample is packed, all within a 2 litre plastic beaker. This enables probes repeatedly to be inserted into the sample without disturbing the contents. A satisfactory range of values is obtained with water, a wet soil sample, a dry soil sample, a solid PVC block with two drilled holes for the probe rods and the air count.

In fact any measurement that can be made repeatedly without disturbance can be used to determine the transform function. For the access tube version two given probes are simply each run down an access tube. This will probably give a limited range of values and the air count will also need to be used. In addition a sealed access tube can be fitted into a drum, say 25 litres, of water to enable a water count to be taken.

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In section 6.3 the Commercial Prototype measurements are compared with Probe A, one of the experimental probes. Four equivalent readings were used to determine the intercalibration expression in this case, namely 10cm air count, 5cm air count, 5cm water count and 10cm water count. The intercalibration expression is:

$$F_A = 0.882332\, F_{CP} + 0.205300 \qquad [6.1]$$

with a value of 1.00 for R^2. The deviation of the slope from unity is not surprising as the detailed geometry of the Commercial Prototype is different from that of Probe A.

For the access tube probe a one metre access tube together with the air count gives the following expression for probes 250 and 354:

$$F_{354} = 1.04029\, F_{250} - 0.06955 \qquad [6.2]$$

and R^2 of 0.9996.

6.6 Use of the probe for a field measurement

Essentially the probe measures the dielectric constant of the medium between and close to the capacitor plates which are the stainless steel rods. However such is the sensitivity of the instrument that the presence of material in the fringes of the electric field associated with the rods is readily detectable. It is therefore essential that the user's hands are kept clear of the sensor body, that is no closer than the handles of the instrument. Similarly the user should not stand close up against the instrument.

To monitor the stability of the probe, principally the battery state, it is advisable to regularly note the air reading. This is obtained by holding the instrument by the handles in the air and ensuring the rods are no closer than half a metre to any other material. Less frequently, say once a month, a water reading should be taken by simply immersing the full length of the rods in water. Ordinary tap water is acceptable. Apart from the battery condition the air count is most sensitive to the state of the rods and their electrical contacts whereas the water count primarily monitors the circuit components. Each measurement however will have a residual temperature dependence of the order 50 counts, that is 50 in 17000 or 10000.

To make a measurement the probe should obviously be inserted as directly as posssible into the soil, without rocking. However in practice it is remarkably resilient to sloppy insertion. Typically a reading will change from say 11000 to 11025 with noticeable rocking in the soil. This is in contrast to Gaudu (1993), possibly due to the lower operating frequency of their probe. Equally the probe should be fully inserted into the soil but not sunk below the level of the rods.

In some situations insertion of the sensor rods may cause migration of soil water due to compression effects which in turn will cause the reading to drift. In these circumstances, as what is actually happening is uncertain, the simplest and most reproducible procedure is to take an immediate measurement.

7 Calibration against soil gravimetric water content

In principle either field or laboratory calibration can be carried out and in practice both approaches are desirable in initial fundamental studies on instrument performance. Essentially calibration requires a progressive increase in water content, uniformly distributed, with unchanged dry bulk density and soil structure. With laboratory calibration uniform distribution of water content is difficult to achieve without removing material, adding water and mixing, and then replacing the wetter material which destroys the structure and usually changes the density. Field calibration has uncertain uniformity of water content and suffers from spatial variability since samples are destroyed by gravimetric determination of water content. In addition, as the volume of a field sample is difficult to measure accurately, there is increased error in the gravimetric determination.

With the access tube probe, laboratory samples are so large that no satisfactory results have been obtained and calibration rests on field measurements. However an additional approach, not so far taken but following on work with the surface probe, is to use the results of the dielectric constant calibration and various derived expressions, from the literature and our own work, for dependence of soil dielectric constant on volumetric water content.

7.1 Access tube probe: access tube installation

In the case of the access tube probe the process of access tube installation offers the opportunity of making a simultaneous gravimetric calibration. The only weakness is that the soil structure, composition and density will change to some degree with depth down the profile and this may obscure the genuine changes in water content. From the theoretical point of view a calibration curve is desired for a particular soil type and condition, however in practice if the soil changes with depth then that is the situation under measurement.

The following equipment is required for access tube installation (see Figure 7.1):
- ground plate with holding augers and 64 cm guide tube;
- standard auger with split pin;
- shallow pitch auger for dry soil removal;
- dry soil extractor for very dry soil removal;
- stone removing auger with large pitch;
- steel inner guide tube;
- access tube driving hammer;
- various spanners;
- pvc access tube with cutting shoe and sealing bungs (the tube should be marked at 4 cm intervals starting from the bottom, cutting shoe, end);
- plastic bags and marker for soil samples for subsequent gravimetric analysis.

The top surface of the ground plate is the datum for all soil removal by auger and it is the plane in which the rim of the access tube will automatically be positioned on completion of the installation. This ensures correlation of all soil removal and subsequent capacitance probe measurements.

The auger handle has two location holes, 4 cm apart, and a split pin. With the split pin in the lower location the tip of the auger is level with the bottom of the access tube and will clear soil to that level. With the pin in the upper location the tip of the auger projects 4 cm clear of the access tube and will clear ahead of the tube to allow it to be hammered in.

The ground plate should be anchored firmly to the soil with as much contact as possible to give added stability. Preferably the plate should be horizontal so that there is minimal tendency for
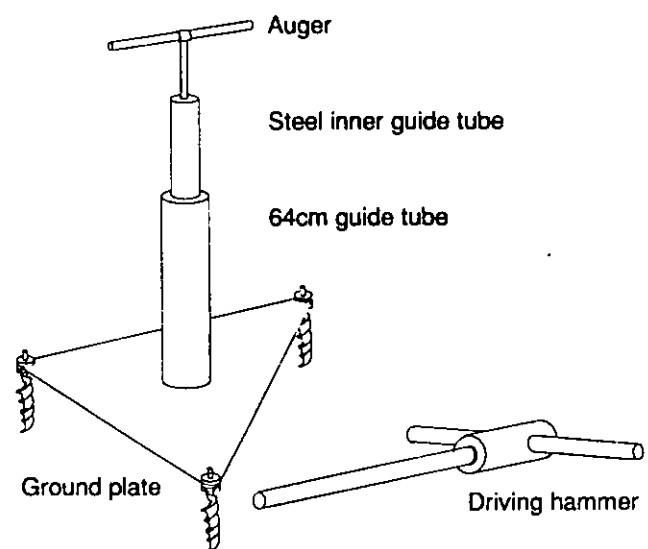

Figure 7.1 Installation equipment

unwitting side loading on the access tube during augering and hammering. The 64 cm guide tube should be screwed into the ground plate and the inner guide tube screwed into the access tube. Insertion of the access tube assembly into the guide tube will then indicate the approximate depth of the soil surface below the datum.

Installation of the access tube is carried out by the sequence:
1. split pin in upper location, auger 4 cm ahead;
2. put the soil collected in a marked plastic bag;
3. hammer the tube down 4 cm, guided by the markings;
4. split pin in lower location, auger to clear soil;
5. put this second soil sample in the plastic bag;
6. seal the plastic bag.

Repeat the sequence until the access tube rim is in the datum plane and flush with the surface of the ground plate. In the process it will be necessary to progressively remove the guide tube which is in three parts. Remove the ground plate and augers and unscrew the inner guide tube. Seal the bottom of the access tube with the size 39 rubber bung.

Complete the field activity by measuring the depth profile with the capacitance probe. The soil samples represent a cylindrical sample 4 cm long by 5 cm diameter, that is 78.5 ml volume. Standard practice in the laboratory, for gravimetric analysis, is:
● weigh the sample wet - WW
● oven dry at 105 degree C for 24 hours
● cool in a dessicator
● weigh the dry sample - WD

Calculate per cent volumetric water content:

$$\theta = \frac{WW - WD}{78.5} * 100 \qquad [7.1]$$

This procedure provides a one to one correspondence between capacitance probe frequency readings and gravimetric water contents which thereby forms the calibration.It is unlikely to be complete since the range of water contents achieved is fortuitous and, as stated above, the different water contents will come from different soil layers which may have different properties. A subsequent tube installation with different soil conditions will extend the range and improve the calibration. This, together with the theoretical expression for the calibration curve, forms the preferred solution to calibration.

For fundamental studies of instrument

performance it is desirable to have a calibration for a given soil even if such a uniform soil is not frequently found in practice. This is best achieved by taking the dielectric constant calibration and inserting literature expressions for dependence of dielectric constant on volumetric water content for the particular soil.

7.2 Access tube probe calibration equation

Table 7 Dielectric constant data for access tube probe 250

Dielectric constant	Probe frequency
1.0	1.7742
4.96	1.4999
22.0	1.3594
40.2	1.3276
80	1.3106

The capacitor plate geometry of the access tube probe consists of two axial cylinders separated by 30mm and is not so amenable to calculation as the two rods of the surface probe. Consequently, for the access tube probe, modelling the response cannot include the independent calculation of the geometrical constant g that relates capacitance and dielectric constant.

With this model the constants are:
L   the circuit inductance;
C_b the sum of the printed circuit board capacitors, including the temperature compensation components;
C_3 the effective capacitance due to stray electric field outside the confines of the printed circuit board;
g   the geometric factor associated with the electric field penetrating the measured soil.

The response function developed from section 4 is:

$$F^2 = \frac{1}{(160\pi)^2 L} \left(\frac{1}{g\kappa_o\kappa_s + C_3} + \frac{1}{C_b} \right) \qquad [7.2]$$

As in section 5.4 liquids of known dielectric constant have been used to determine the constants. For experimental access tube probe no. 250 a three parameter non-linear curve fit then gives, from the data in Table 7:

$$F^2 = \frac{3.76432}{\kappa_s + 1.55790} + 1.67624 \qquad [7.3]$$

$R^2 = .99982$

Standard errors are:

3.76432 .158
1.55790 .104
1.67624 .00785

Comparison of equations 7.2 and 7.3 gives, using the component value of L= 0.24 micro henries and with some reduction:

$$C = 4.38 \, \kappa_s$$

which is larger than the corresponding surface probe factor which is to be expected from the larger surface area of the cylinder plates.

$$C_3 = 6.83 \, pF$$

which is in line with the increased field loss within the body of the probe, compared with the surface probe.

$$C_b = 9.8 \, pF$$

and this is smaller than for the surface probe due to a higher setting of the temperature compensation voltage which reduces the compensating capacitances.

From this response function there are three possible approaches. If calibration data relating probe frequency and gravimetric water content by volume are available then a second order polynomial can be assumed for the dependence of κ_s on θ and the constants, A B and C can be determined by fitting the equation:

$$F = [\frac{3.76432}{A+B\theta+C\theta^2+1.55790} + 1.67624]^{\frac{1}{2}} \quad [7.4]$$

The constant "A" represents the dielectric constant of the dry soil with $\theta = 0$ and provides an internal consistency check on the validity of the calibration since for most soils it should lie between 2 and 3.

If the reading is not physically acceptable then

$$\kappa_s = 2.5 + B\theta + C\theta^2 \quad [7.5]$$

should be tried.

In the event that an acceptable fit is not obtained then an empirical, but physically plausible, expression of the form:

$$F = A(B + 1/\theta) \quad [7.6]$$

may be used as a local calibration, pending further clarification.

Finally if the dependence of κ_s on volumetric water content is known from some other programme then this can be substituted directly into equation 7.3 to provide a calibration.

In any case, since the model is not exact, it may be that a somewhat empirical expression, such as equation 7.6, fits the experimental data better than the more sophisticated model.

7.3 Surface probe

Calibration equation

The surface probe, compared with the access tube probe, is relatively easy to calibrate against volumetric soil water content determined gravimetrically. Gravimetric soil samplers have been designed with 5cm diameter, approximately equivalent to the soil measured by the probe, and with length of 5cm or 10cm, to match the penetration depth of the two versions of the probe.

To obtain a calibration point a measurement is made in the normal way with the probe and then, immediately, the soil sample for gravimetric determination is taken from precisely the position measured by the probe. This one to one correspondence between the probe and gravimetric measurements avoids the problem of spatial variability and is to be preferred to the technique of making several nearby measurements and averaging the data.

Table 8 Extraction from Zimbabwe field calibration data

5 cm probe frequency	% water content	10 cm probe frequency	% water content
1.6242	3.52	1.5550	3.60
1.1602	36.45	1.1272	38.35
1.1645	34.32	1.1443	31.75
1.2953	23.30	1.2265	21.00
1.2810	25.17	1.1870	24.20
1.3765	14.42	1.2629	15.21
1.2785	26.69	1.2097	22.66
1.3612	13.70	1.2491	14.40
1.2541	23.85	1.1905	23.22
1.4067	10.40	1.2833	13.61
1.2501	23.16	1.1970	22.46
1.4478	9.92	1.2804	13.04
1.2908	22.23	1.2074	20.27
1.5147	6.46	1.2845	11.13
1.3270	19.96	1.2345	19.30

A calibration was obtained for experimental probe 356 (B), in the course of irrigation studies in Zimbabwe. The measurements refer to bare

soil and in total 75 were made for both the 5 and 10cm probes. Five readings were taken for each nominal level of soil wetness and the *median* of each group of five is given in Table 8, (so that actual data is used rather than averages).

The results can be fitted with a physically plausible, but mathematically concise, curve such as equation 7.6. If the fit is not satisfactory over the whole range of water contents then a suitable mathematical expression can be used. Alternatively the fit can be based on the probe response determined from the dielectric constant calibration thereby obtaining both the probe calibration and the dependence of dielectric constant on water content for the particular soil type involved, but at the expense of a more cumbersome expression.

In the case of the Zimbabwe data the water content range is quite large, 3 to 40%, and equation 7.6 does not give satisfactory agreement. The best mathematical functions are:
for the 5cm probe:

$$F = \frac{0.336400}{\sqrt{\theta}} - 0.077325\sqrt{\theta} + 1.58137 \qquad [7.7]$$

with R^2 = .973

and in the case of the 10cm probe:

$$F = \frac{1.81007}{\theta^{0.132287}} \qquad [7.8]$$

with R^2 = .964

Probe 356 (B) is closely interchangeable with probe 355 (A) so that equation 5.9 from section 5.4 can be used as the dielectric constant response function. Following section 7.2 a quadratic expression in θ for κ_s is used:

$$\kappa_s = A + B\theta + C\theta^2 \qquad [7.9]$$

and the constants are determined from fitting the 5 and 10cm data as one set to equation 5.9. This tacitly assumes that the soil type does not change in the top 10cm and gives:

$$F = \left[\frac{9.126}{p(1.37754 + .6145300 - .00073790\theta^2) + (1-p)2.756 + 2.215} + .8482\right]^{\frac{1}{2}} \qquad [7.10]$$

with p = .5 for the 5cm probe
and p = 1 for 10cm
and R^2 = .955

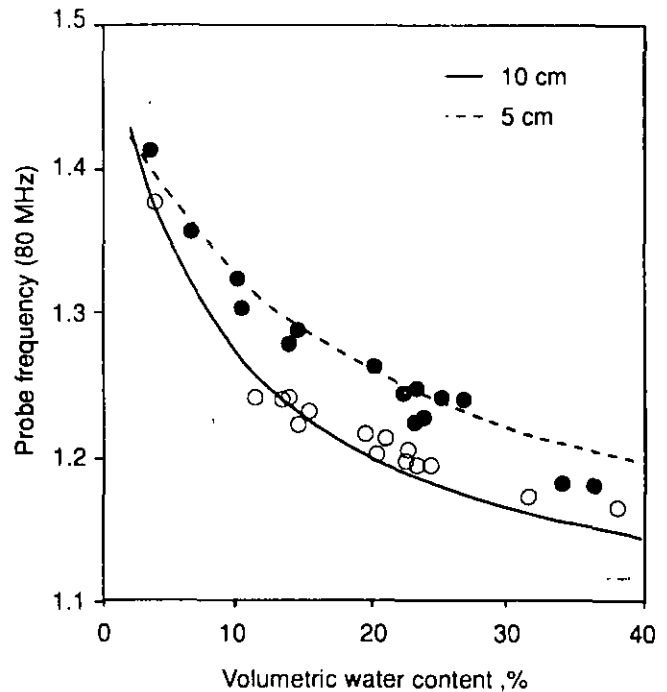This is the most satisfying approach and the value of R^2 is only 1% less than for the 10cm

Figure 7.2 *Zimbabwe results, experimental points and theoretical curves*

mathematical fit but agreement between the model and data at high water content as plotted in Figure 7.2 is not satisfactory. Of course the model is not exact and empirical equations are likely to provide a better fit. However the 5 and 10cm frequencies are surprisingly similar at water contents of 30 to 40% with a difference that is more typical of the figures in pure water. In this case the soil had been cultivated and was well mixed down to more than 15cm so uniform soil type and structure must be assumed, as required by the model. The results at high water content remain, therefore, something of an enigma. Further work is desirable but probe 356(B) is currently still in Zimbabwe.

More soil data using the surface probe
Apart from the U.K. and Zimbabwe the surface probe has been used at a number of sites overseas.

Machakos, Kenya. Experimental probe 501 (J) is in use for measurement of soil water content in the surface zone as part of a water balance study of agroforestry systems on hill slopes at Machakos, which started in November 1992. Probe 501 (J) has not been calibrated against dielectric constant but has been intercalibrated against probe 355(A) to give:

$$F_J = 0.993945\,F_A \qquad [7.11]$$

Using this expression with equation 5.9 gives a

dielectric constant calibration for probe 501 (J).

$$F_J = [\frac{9.016}{p\kappa_s+(1-p)2.756+2.215} + .838]^{\frac{1}{2}} \quad [7.12]$$

As the soil surface is somewhat rough, the 10 cm probe results are expected to be more reliable and, over several months, 58 gravimetric calibration samples have been taken. Using this data in equation 7.12, with p = 1, gives:

$$\kappa_s = 2.4132 + .3824\theta + .003259\theta^2 \quad [7.13]$$

with $R^2 = 0.971$

standard errors are respectively, 0.18, 0.034 and 0.0012.

The dry soil value of 2.41, with $\theta = 0$, is very satisfactory. By substituting p = .5 in equation 7.12 a predicted 5cm calibration curve is obtained:

$$F_J = [\frac{9.016}{0.5(2.4132+ .3824\theta+ .003259\theta^2)+ 3.593} + .838]^{\frac{1}{2}} \quad [7.14]$$

Available experimental data at 5cm is shown in Figure 7.3 together with the predicted 5cm calibration curve. There is significant scatter on
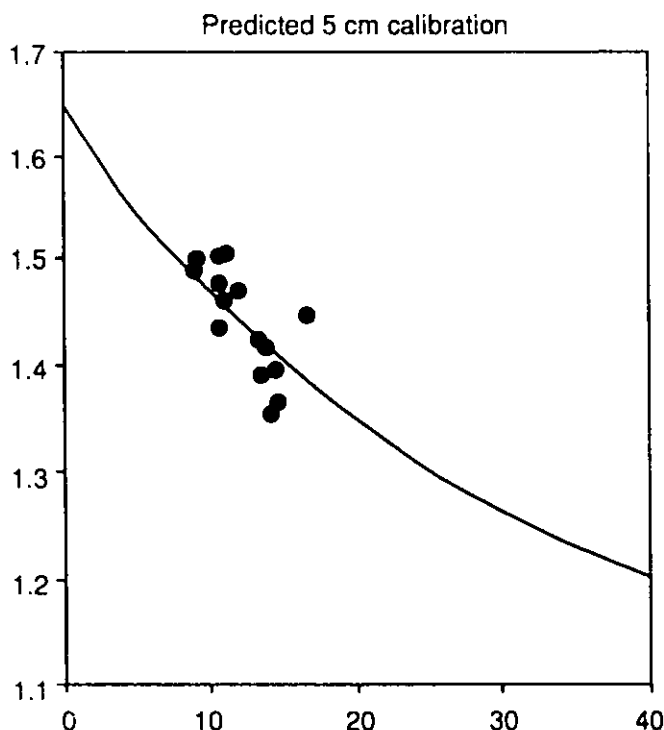

Predicted 5 cm calibration

Figure 7.3 *Experimental data points for 5cm depth and theoretical calibration*

the field data but it is entirely consistent with the theoretical curve.

Combining the 5 and 10cm data in equation 7.12 gives a very similar expression to 7.13 for the soil dielectric constant, thereby confirming no gradient of soil type in the top 10cm.

$$\kappa_s = 2.431 + .373\theta + .003533\theta^2 \quad [7.15]$$

with $R^2 = .966$ and effectively no change in the standard errors.

Sahelian Centre, Niger. In the summer of 1992 experimental probes 353(H), 357(C) and 501 (J) were used at two sites near the Sahelian Centre, Niger. Measurements were made at depths of 1, 2, 5 and 10cm. The soil is a crusted sand overlying Laterite and can form a very hard cement-like composition. Acceptable gravimetric samples can be difficult to obtain and indeed the probe, particularly 10cm is not always easy to insert. The results reported here are for 5 and 10cm depths and, as most of the results were obtained with probe 353(H), the data from the other probes have been converted to equivalent 353(H) figures. Using equation 7.16,

$$F_H = 1.00395 \, F_A \quad [7.16]$$

with equation 5.9 gives the dielectric response function for probe 353(H), equation 7.17.

$$F_H = [\frac{9.198}{p\kappa_s+(1-p)2.756+2.215} + .8549]^{\frac{1}{2}} \quad [7.17]$$

Fitting the 5 and 10cm data to equation 7.17 gives the calibrations for both depths and the dielectric constant, κ_s as a function of water content.

$$\kappa_s = 3.03 + .3134\theta + .00348\theta^2 \quad [7.18]$$

with $R^2 = 0.965$ and standard errors .053, .026 and .0022.

The dry soil value of 3.03 is marginally high probably due to the high dry bulk density of about 1.65 g cm^{-3}, see page 31.

Summary of data from Zimbabwe, Kenya and Niger. Figure 7.4 shows the dependence on water content of the derived soil dielectric constants for the three sites. Also plotted is the mixing model for sand, see equation 7.21, assuming particle (SiO$_2$) density of 2.65 g cm^{-3} and 4.4 for dielectric constant. 1.6 is assumed for the dry bulk density. The mixing model
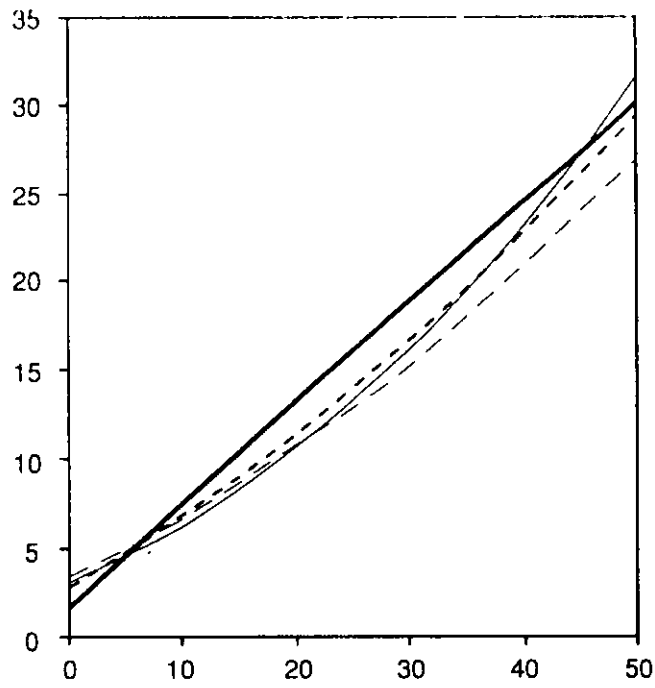
Figure 7.4 *Dependence of soil dielectric constant on water content:* ―― *Zimbabwe,* ― ― ― *Kenya,* ― ―*Niger and* ―― *the mixing model*
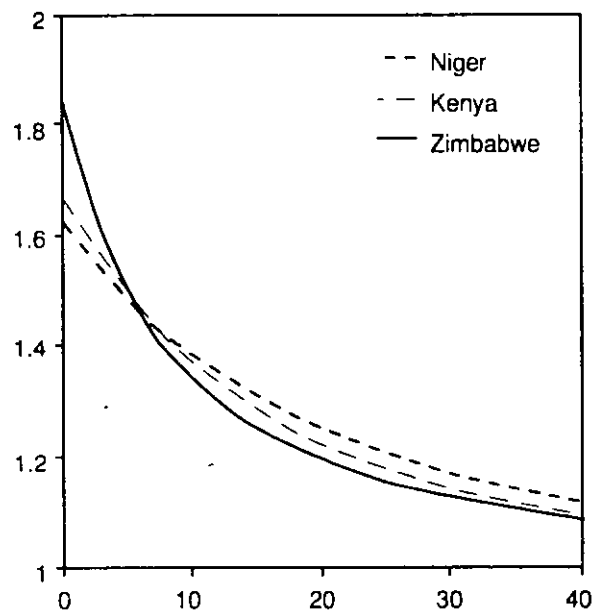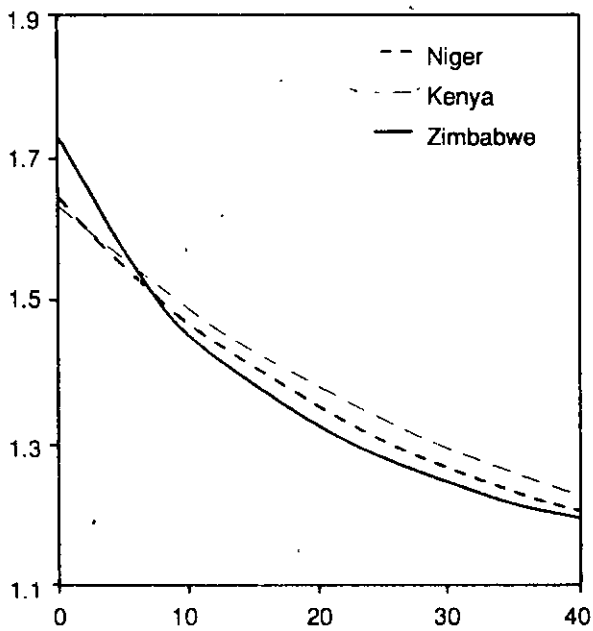

Figure 7.5A and 7.5B *5 and 10 cm calibration curves*

30

agrees very well with the general numerical values obtained with the capacitance probe but the shape shows more curvature. In fact the Zimbabwe result in particular is surprisingly linear and, also including UK data, is unique.

5 cm calibration curves for the three sites and the different probes are shown in Figure 7.5A and 10 cm in Figure 7.5B.

Influence of density, soil type, soil structure and bound water

Soil is a composite material which, for the purpose of this section, can be assumed to comprise particulate solid material which may be porous, air and water. If the water content increases it is assumed that it does so by displacing air. This leaves the dry bulk density constant but in practice this is not the case for real soils. As indicated in section 2.2 the dielectric constant of the composite material is not the simple sum of the individual components but depends on the structure of the dielectric pathways (Hasted, 1973). If the volumetric fractions of the particles, air and water are respectively f_{part}, f_{air} and f_{water} then it can be said that the composite dielectric constant lies between:

$$\kappa_{soil} = f_{part}\kappa_{part} + f_{air}\kappa_{air} + f_{water}\kappa_{water}$$

and

$$\kappa_{soil}^{-1} = f_{part}\kappa_{part}^{-1} + f_{air}\kappa_{air}^{-1} + f_{water}\kappa_{water}^{-1} \quad [7.19]$$

where, in terms of capacitance, the first expression refers to parallel pathways and the second to serial, that is the index for κ lies between +1 and -1. The sum of the volumetric fractions is unity and for soil studies they are better expressed in terms of porosity, ϕ, and volumetric water content, θ.

$$f_{water} = \theta \quad \text{and} \quad f_{air} + \theta = \phi \quad \text{and} \quad f_{part} = 1 - \phi$$

In addition $\kappa_{air}=1$ and κ_{water} is about 80, depending on temperature.

There is some evidence (Ansoult et al., 1985) that a value of +1/2 for κ is often supported by experimental results. For non-lossy dielectrics this is equivalent to a simple refractive index mixing model. Making these substitutions gives:

$$\sqrt{\kappa} = (1-\phi)\sqrt{\kappa_{part}} + (\phi-\theta) + \theta\sqrt{\kappa_{water}} \quad [7.20]$$

At IH, dry bulk density, ρ is routinely determined from gravimetric sampling and, with the particle density, ρ_{part} can replace porosity. By definition:

ρ = mass of soil particles/ total volume

ρ_{part} = mass of soil particles/ volume of soil particles

ϕ = volume of air in the dry state/ total volume

which gives: $1 - \phi = \rho / \rho_{part}$
and taking $\kappa_{water}^{1/2} = 9$ and replacing fractional water content by per cent content, we find:

$$\sqrt{\kappa}_{soil} = \frac{\rho}{\rho_{part}} (\sqrt{\kappa}_{part} - 1) + 1 + 0.08\theta \quad [7.21]$$

which gives a quadratic expression for κ_{soil} which is usually adequate although some workers have used a cubic. Too much should not be expected of this model but it should be an adequate description of small changes in density or indeed the scale of the effect of density and soil particle dielectric constant. It must be remembered that, particularly for swelling soils, density will not be independent of water content. Soil structure is reflected in the porosity but strictly in the pore size distribution rather than the absolute value. However the ratio of density to particle density can be expected to depend on the soil history.

Partial differentiation of equation 7.21 gives the relative significance of changes in water content, density and soil (particle) dielectric constant.

$$\frac{1}{2\sqrt{\kappa}} d\kappa = (\frac{\sqrt{\kappa}_p - 1}{\rho_p}) d\rho + \frac{\rho}{2\rho_p\sqrt{\kappa}_p} d\kappa_p + 0.08 d\theta \quad [7.22]$$

where subscript "p" now refers to particle properties.

To get some feel for this, take typical values of $\rho_p=2$, $\kappa_p=4$, $\rho=1$ and $\theta=30$. For this situation a water content change of 30 to 31% is equivalent to a density change of 1 to 1.16 (that is 16%) and a soil dielectric constant change of 4 to 4.64 (also 16%). If $\kappa_p=6$ then changes are, in density 1 to 1.11 and in soil dielectric constant 6 to 6.78. This readily explains why field calibration results have not shown a discernable effect due to density.

The statistical approach of Ansoult (1985) is closer to treating the problem from first principles but nevertheless retains a parameter that is essentially arbitrary and can be used to improve agreement with experiment.

Some authors (Dirksen & Dasberg, 1993; Roth et al., 1990) include a 4th volumetric fraction term in equation 7.19 representing bound water. This,

as the term suggests, refers to water molecules that are coupled to some degree to soil molecules and hence are not completely free to align with the applied alternating electric field. Consequently their dielectric constant is less than 80 and their behaviour is more akin to that of ice molecules with a dielectric constant of 3.5. The strength of the binding force for a given molecule will determine how closely the dielectric constant approaches the free water value and presumably there can be a range of values in a complex material. However it is not clear how the proportion of bound water or the strength of binding can be determined

independently and hence apparently the result is simply to add another degree of freedom to the model.

The effect on the capacitance probe of bound water, with a reduced dielectric constant, is to increase the frequency. In the course of the work at IH anomalous results have occurred but almost invariably a reduction in frequency has been involved, hence no evidence of bound water has been found. It seems over-complicated to postulate that the routine situation involves the presence of bound water so that its absence produces a reduction in frequency.

8 Current and future developments

8.1 New designs

Engineered version of the surface probe

To establish the concept and feasibility of the surface probe experimental models were built using, wherever possible, hardware from the access tube probe. Subsequently the interest from users was such that nine of these "lash up" models were built. This ensured a very exhaustive and comprehensive programme of field testing but rather delayed the design and development of the engineered, commercial prototype, version. Use of the experimental models identified a number of failings to be addressed by the design of the commercial prototype. Some of these were recognised from the start and none were concerned with the principle of the measurement technique. Apart from mechanical robustness the main improvements incorporated were:
non-latching on/off switch to extend battery life;
built-in reader to give an integrated instrument;
removal of surplus parts associated with the access tube version;
water proofing, (not tested for immersion).

Due to the axial symmetry of the instrument there was little cost penalty incurred by retaining fabrication, rather than moulding, techniques of manufacture.

Future possibilities for the manual surface probe

The commercial prototype, Model I above, is the simplest, and lowest cost, version of a potential family of three instruments. Model II would include a microcomputor chip to convert frequency to volumetric soil water content and display both readings. This begs a number of questions such as is one, or more than one, calibration expression used and if so which one? If more than one, how is it identified and how selected?

Model III would have the additional facility of storing data together perhaps with time and site information. It would probably require a key pad which indeed may be desirable for Model II.

Buried probe

One attraction of the surface probe is the ease and speed of use which enables numbers of measurements and surveys over considerable areas to be made very rapidly. However automatic data collection is also very desirable

and the probe geometry and design is readily interfaced to, and controlled by, a data logger.

Initially the experimental version was fitted with a modified printed circuit board which enabled power to be switched on remotely by an optical signal generated by the logger. O-rings and a sealing cap with cable glands for the fibre optic cables made the sensor waterproof and suitable for semi-permanent buried installation at a desired soil depth.

Early field trials were carried out with individual sensors buried horizontally at a depth of 5 cms and coupled to a CR10 logger with an IH developed interface. This was necessary to convert the high frequency optical input to an electrical input that could be measured by the CR10. Installation involved insertion of the probe rods into undisturbed soil and careful backfill of the soil round the probe body to minimise overall soil disturbance. Trials at both Wallingford and Rosemaund were used to assess sampling intervals and confirm battery life. These trials showed immediately an interesting diurnal fluctuation that had been unobservable under previous measurement methods.

The automatic soil water station

Results with the buried probe opened up the possibility of a comprehensive range of soil sensors that together would constitute an automatic soil water station (ASWS) analogous to the automatic weather stations that have been central to much of the IH research programme.

Experimental installations have been set up at Wallingford and subsequently at two sites in the river Ock catchment for flood warning studies with the NRA. These stations measure rainfall and, at three depths, soil water content, soil water tension and temperature. The sensors feed, via an IH interface, to a CR10 data logger with solar back-up for battery power and, if desired, telemetry to IH via the cellnet telephone network. Extension to five depths has been built into the design and successfully field tested.

8.2 Influence of salinity and exotic materials

Preliminary study has been made of the effect of salinity in soil, and in limestone and sandstone

masonry (Dean & Cooper, 1993). Both were laboratory investigations and comprised measuring the effect on probe frequency of the addition, to standard soil or masonry samples, of a NaCl solution with a range of molar strengths. The presence of NaCl ions will increase the soil conductivity which requires that, in the oscillator analysis, the rod capacitance must be represented by a resistor and capacitor in parallel. The impedance of this equivalent circuit is:

$$Z = \frac{\frac{1}{jwC}r}{r + \frac{1}{jwC}}$$ [8.1]

where C is the rod capacitance with wet soil prior to the addition of saline ions and r is the resistance arising from the conductivity. Rationalising equation 8.1 gives:

$$Z = \frac{r}{1 + \omega^2 C^2 r^2} - \frac{j}{\omega C(1 + \frac{1}{\omega^2 C^2 r^2})}$$ [8.2]

In equation 8.2 the imaginary term is the effective capacitance that determines the probe frequency.

As soil conductivity increases the resistance decreases and progressively increases the effective capacitance. But the influence on C is very small until the resistance is close to being equal to $1/\omega C$ when the effective capacitance is doubled. Further decrease in resistance dramatically increases the effective capacitance. The increase in the effective capacitance depresses the probe frequency. In the sense that the equivalent circuit of a transmission line is a network of capacitors, resistors and inductors, it is worth noting that the above applies equally to measurement of dielectric constant by time domain reflectometry.

Both dielectric hysterisis and conduction contribute to the resistance term. The conductivity is the value appropriate to the high frequency, of the order 100 MHz, although the literature uses σ_{DC} (Topp et al., 1980; Topp et al., 1988) but Krauss (1984) uses σ at the high frequency. Rather elaborate models (Mualem & Friedman, 1991) have been proposed, for the mechanism of the conduction term, that distinguish between water film on soil particles and interstitial water. It does seem clear that the conductivity will be reduced if the water content is so low that there are no continuous regions for the current generation.

No attempt will be made here to make too much of this approach. The straightforward calculation

below indicates the qualitative characteristics of the model.

$$F^2 = 9.126 g K_o \left(\frac{1}{C + 2.215} + \frac{1}{16.03} \right)$$ [8.3]

With reference to Figure 8.1, at F=1.1880 the rod capacitance, from equation 8.3, is 21.93 pF for the standard Wallingford top soil calibration. For the sample with 0.3 M NaCl the equivalent frequency is F=1.1200 and the corresponding effective capacitance is 31.27 pF. Solving equation 8.2 for r gives:

$$r = \frac{1}{\omega \sqrt{C_{eff} C - C^2}}$$ [8.4]

and with $\omega = 2\pi \times 1.12 \times 80 \times 10^6$ we find r = 124 ohms. The geometrical factor, g, is the same as for capacitance, namely equation 5.8 with κ_o=8.85 pFm^{-1}, and gives for the conductivity:

$$\sigma = \frac{1}{gr} = \frac{1}{0.168r} = 48 \ mSm^{-1}$$ [8.5]
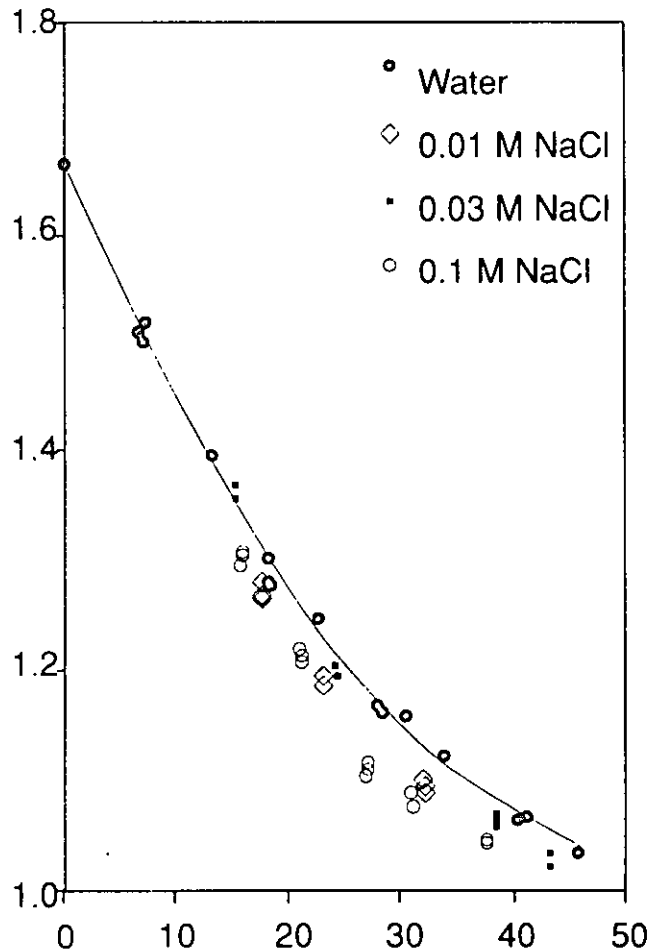
This value is somewhat low but not implausible.

Figure 8.1 Effect of salinity on the Wallingford top soil laboratory calibration

Other than salinity, and acidity, a possible source of interference is the dielectric constant of the soil particles, or some of them. Of commonly occurring materials, water is certainly unique in the high value of its dielectric constant. However ferroelectric materials, such as barium titanate, $BaTiO_3$ have values of several thousand but, fortunately for the capacitance probe, are relatively rare in natural occurrence. Rutile, TiO_2 can be found in some soils and has a value between 89 and 173 depending on crystalline structure and orientation. Due to the relatively low proportions present the effects will tend to be second order and since there is bound to be some spatial uniformity their contribution can substantially be calibrated out in many situations.

Acknowledgements

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