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Measurement of Soil Water Content Using a Simplified Impedance Measuring Technique

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A probe has been designed which uses a simplified impedance measuring system to determine soil water content. Apart from cost and simplicity, a major advantage is its d.c. voltage output which allows continuous unattended recording by most field data loggers. The calculated soil water volumetric fraction (θ_v) determined by this new method compares well with results from the standard neutron probe.

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1. Introduction

The measurement of soil water content and soil water fluxes is critical to a wide range of environmental studies including acidification, pollution and nutrient uptake. There is a major current concern in the effective conservation and protection of water, and this interest is likely to increase with attention being focused on the effects of climate change. As a consequence, soil water content is an important component in many modelling studies, e.g. in calculation of evapotranspiration, and in estimation of losses to groundwater.

Many experimental field installations include the measurement of both hydrochemical fluxes, involving sampling systems, e.g. lysimeters, along with quantification of soil water fluxes to identify infiltration, the movement of wetting fronts, and solute transport within soil profiles. Frequently, sites are sloped, have complex soil profiles which may include horizons of very much less permeable material, and require the measurement of both lateral and horizontal soil water fluxes. These have been quantified in some cases using arrays of tensiometers (Mullins *et al.*,[1] Wheater *et al.*[2]), but there are restrictions in their usage depending on climatic conditions, e.g. freezing, along with practical problems in continuous measurement. In sites with complex soil physical and chemical properties that can result in severe short range variability, any field instrumentation requires to be robust, as well as inexpensive to allow multiple installations for replication and reproducibility, and preferably to have an output suitable for continuous monitoring to allow the critical measurement of soil water fluxes.

The neutron probe, which detects water thermalized neutrons from an americium–beryllium fast neutron source, is currently the accepted standard method for the measurement of soil water content (Bell[3]). However, it is necessary to instal permanent metal access tubes into the soil to permit the probe head to be lowered to the depths where measurements are to be taken. The automated application of this technique is precluded at unattended sites since not only is a radioactive source used but operator intervention is necessary.

Soil moisture blocks, which are based on the measurement of the electrical resistance between inert metal electrodes cast into blocks of gypsum, are very easy to use with data loggers but are generally unsuitable for longer-term monitoring of soil water content due to the interferences and eventual dissolution caused by the acidic nature of many soils (Wellings *et al.*[4]).

Techniques based on the measurement of the dielectric constant of the soil, either capacitance probes or time-domain reflectometry (TDR), are becoming increasingly popular. Such techniques depend on the fact that the dielectric constant of water (~80) is significantly greater than that of most soil matrix materials (~4) and of air (~1).

The capacitance probe, like the neutron probe, requires the installation of permanent access tubes, and operator intervention is necessary to position the sensing head within these tubes. The sensing head incorporates an oscillator circuit, the operating frequency of which is determined by an annular electrode, fringe-effect capacitor, the value of which

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depends on the dielectric constant of the soil surrounding the probe. By measuring the frequency and referring to calibration data, the operator can assess the volumetric water content. (Dean *et al.,*[5] Wobschall[6]).

TDR instruments are easier to instal and facilitate the accumulation of data (Topp *et al.,*[7] Malicki & Skierucha,[8] Topp & Davis[9]), but there are still some problems in both the interpretation of data and field calibration (Whalley,[10] Zegelin *et al.,*[11] Roth *et al.*[12]). These instruments produce a trace of time against reflection amplitude of a fast rise-time electromagnetic pulse which is applied to a transmission line probe of known length inserted into the soil. The velocity of propagation of such pulses along the probe is a function of the soil's dielectric constant, which in turn is dependent on the water content of the soil. Since the probe is designed to give identifiable reflections from its beginning and end on the trace, the velocity of propagation can be determined and hence the water content may be calculated. Some instruments have the facility of processing and storing this information automatically to give soil water content values, but some uncertainty may exist as inhomogenieties around the probe wires such as voids and stones can produce features on the trace which obscure the probe start and end points (Whalley,[10] Dalton *et al.,*[13] Yanuka *et al.*[14]). Interpretation of TDR traces may also be confused by conductivity effects.

Chouikhi and Wilde[15] describe a technique for measuring the water content of foodstuffs by using a laboratory impedance analyser to quantify impedance mismatch reflections from an open-ended transmission-line probe. Our proposed instrument also uses impedance mismatch reflections, but the analysis is carried out using a very much simpler voltage standing wave method.

The device is relatively cheap (it is anticipated that 20 will be available for the cost of a TDR instrument), capable of installation in large numbers, including permanent burial within the soil profile, and since the output is a d.c. voltage it can be used with commercial multichannel loggers to monitor changes in soil water content and therefore fluxes.

2. Principle of the device

The device is shown diagrammatically in *Fig. 1,* and comprises a 100 MHz sinusoidal oscillator, a fixed impedance section of coaxial transmission line, and a stainless steel wire sensing probe which behaves as an additional section of transmission line with an impedance dependent on the dielectric constant of the soil surrounding the probe wires.

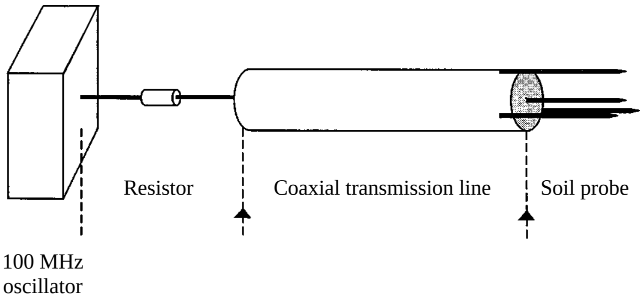

Fig. 1. Diagrammatic representation of the MLURI soil moisture probe

The behaviour of an electrical insulator changes with the frequency of the voltage applied across it, but it is generally accepted that the following expression for the dielectric constant (K) is valid for wet soils at excitation frequencies below about 1 GHz (Krauss,[16] Whalley[10])

$$K = K' - i(K'' + \sigma_{dc}/2\pi f \varepsilon_0) \qquad (1)$$

where K' and K'' are the real and imaginary parts of the dielectric constant respectively, ε_0 is the permittivity of free space, σ_{dc} is the d.c. conductivity and f is the frequency of the excitation voltage. The real part of this expression is an index of the electric flux density existing in the insulator for a given voltage applied across it, while the imaginary part describes losses and leakage due to conductivity. For most soils the value of K' is much greater than that of K'' (Topp *et al.*[7]), but since there are always soluble salts present, the electrical conductivity can be significant. In order to minimize the contribution of the imaginary term, measurements are made at high frequencies, usually between 30 MHz (Wobschall[6]) and 1 GHz, or using a fast rise-time pulse having a significant part of its frequency spectrum in this range.

The impedance (Z) of a coaxial transmission line is dependent on its physical dimensions and the dielectric constant of the insulating material. The reader is referred to standard texts on transmission line theory (Krauss,[16] Lorrain & Carson[17]) for the derivation

$$Z = \frac{60}{\sqrt{K}} \ln\left(\frac{r_2}{r_1}\right) \qquad (2)$$

where r_1 is the radius of the inner conductor, r_2 is the radius of the shield conductor, and K is the dielectric constant.

The oscillator signal is propagated along the transmission line into the soil probe, and if the probe's impedance differs from that of the transmission line, a proportion of the incident signal ρ, is reflected back along the line towards the signal source. ρ is called the reflection coefficient and can be expressed in terms of the probe and transmission line impedances:

$$\rho = \frac{Z_p - Z_l}{Z_p + Z_l} \tag{3}$$

where Z_p is the probe impedance, and Z_l that of the transmission line.

The reflected component interferes with the incident signal causing a voltage standing wave to be set up on the transmission line, i.e. a variation of voltage amplitude along the length of the line. Since the incident and reflected components have a sinusoidal waveform, the standing wave is also sinusoidal.

In practice, multiple signal reflections also take place at the soil probe ends which affect the standing wave. Modelling these probe reflections is complex since the attenuation of probe signals is also a function of the dielectric constant of the soil, but the effect described dominates, and for simplicity of description a single reflection at the transmission line/probe junction is considered.

If the oscillator provides a signal (V_o) at the beginning of the transmission line

$$V_o = a \sin 2\pi ft \tag{4}$$

where a is the amplitude, f is the frequency of oscillation and t is the time since some arbitrary instant, then the reflected component at the same point will be

$$V_o = a \sin 2\pi ft + a\rho \sin 2\pi f\left(t - \frac{2l}{v_p}\right) \tag{5}$$

where l is the length of the transmission line and v_p is the velocity of propagation of signals along the line. If the transmission line is made $v_p/4f$ in length, then this reduces to

$$\begin{aligned} V_o &= a \sin 2\pi ft - a\rho \sin 2\pi ft \\ &= a(1-\rho) \sin 2\pi ft \end{aligned} \tag{6}$$

The peak value of this expression is

$$\hat{V}_o = a(1-\rho) \tag{7}$$

This value is reached at each cycle of the oscillator. Similarly it will be found that the peak voltage at the transmission line-probe junction is

$$\hat{V}_j = a(1+\rho) \tag{8}$$

and the difference in amplitude between these two points is

$$\hat{V}_j - \hat{V}_o = 2a\rho = 2a\left(\frac{Z_p - Z_l}{Z_p + Z_l}\right) \tag{9}$$

Hence by measuring this amplitude difference the soil probe's relative impedance can be assessed. Because of the difficulties alluded to in modelling the response, an empirical approach was taken to calibrate the device.

The probe's impedance is at its lowest value when the probe wires are immersed in water and an attempt was made to use the reflection at the probe tip to reduce the probe's apparent impedance under these conditions by making the probe length to be

$$\frac{c}{4f\sqrt{K_w}} = 83 \text{ mm} \tag{10}$$

where K_w is the dielectric constant of water and c is the velocity of light in vacuum. This causes the signal reflected at the probe tip to interfere destructively with the incident one at the transmission line/probe junction, thus simulating a low impedance at this point. In practice, probe wires of this length were felt to be too fragile for use in stony soils, and a compromise length of 60 mm was chosen.

3. Prototype construction

The prototype device used to obtain the data given below had a stainless steel enclosure approximately $50 \times 35 \times 20$ mm containing the oscillator and electronic circuitry, to which was attached a 430 mm length of 22 mm diameter stainless steel tube. The tube was provided with a 3·2 mm diameter steel centre wire and resin insulation to form a $v_p/4f$ length of coaxial transmission line. This terminated in the sensing head which consisted of a central stainless steel wire (a continuation of the transmission line centre wire), which formed a coaxial inner conductor, surrounded by three stainless steel wires each 2·4 mm in diameter equispaced on a 26 mm pitch circle diameter. These acted as coaxial shield conductors, being soldered to the stainless steel tube transmission line. All the sensing wires were 60 mm in length.

4. Results and discussion

Water in unsaturated soils is held within a range of pore spaces by the interactions between gravity, surface tension and evapotranspiration. Because the relationships between the components forming the soil matrix are constantly changing, this influences the soil water content, so that water can be present as a combination of hygroscopic water (on the surface), capillary matrix water and gravitational water (Curtis & Trudgill[18]).

The soil water content is determined in a standard way by drying at 105°C to give gravimetric data, and using soil bulk density to determine volumetric water content. Particle size will to some extent determine bulk density so that soils with different particle size classes and packing will have different volumetric water contents with the same volume of water in the same mass of soil. Although the above features confuse comparisons between different techniques, it is necessary to compare this new technique with standard methodologies as well as to examine some of the external factors which could influence its behaviour.

The probe response was compared with an accepted technique, in this case the neutron probe, under simulated field conditions. The effective sensing volume of the probe head was also determined so that its range could be measured. Tests were also made to study the effects on the device of bulk density of the soil, conductivity, operating voltage and temperature.

The instrument's response was compared with that of a neutron probe by inserting a permanent neutron probe access tube down the axis of a 500 mm diameter drum which was filled to a depth of 500 mm with dry soil. The proposed device was buried adjacent to the access tube at a depth of 250 mm from the soil surface, and its output continuously recorded. The soil was wetted, then permitted to dry over a period of weeks and neutron probe readings were taken periodically with the neutron source positioned 250 mm from the surface. Further readings were taken with the neutron source at depths of 150 mm and 350 mm to confirm the uniformity of the water content. Results in *Fig. 2* show a strong relationship between voltage output and neutron probe count.

If these data are converted to volumetric soil water content using the relationship derived for the proposed probe and a neutron probe equation then the results in *Fig. 3* are obtained. This illustrates the very strong correlation between these two techniques and confirms the performance of the proposed probe. The divergence from a 1:1 ratio has also been observed when comparisons have been made between various TDR instruments and neutron probe techniques (E. Fisher, personal communication), perhaps as a function of the choice of equation used in neutron probe calibration.

In order to assess the effective sampling volume of the instrument, a number of cylindrical containers of identical length but differing diameters (30–500 mm) were packed with a range of evenly moistened homogeneous soils. The instrument was inserted along the axis of each in turn and the output voltage recorded. The results suggested that there was no change in output once a radius of 50 mm had been reached, and it was concluded that the dielectric constant of all the soil within this radius of the probe centre wire contributed to the measurement. As for a three-wire TDR probe, it was speculated that the sensitivity of this design is also heavily biased towards the central wire conductor, but experiments are continuing to determine the exact nature of its field.

4.1. *Bulk density*

Initially, tests on instrument response were carried out in the laboratory by inserting the instrument into a vertical plastic cylinder of around 150 mm diameter having a layer (150 mm) of dried packed homogeneous soil, below and above which were layers (200 mm) of polyethylene beads. Water was applied to the top of the cylinder at a constant rate and the output voltage continuously monitored. Four different

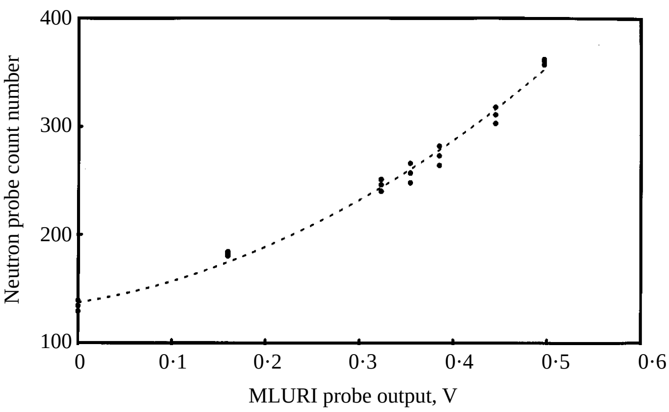

Fig. 2. Neutron probe count numbers against MLURI probe output (V). $y = 593x^2 + 138x + 137$; $r^2 = 0{\cdot}994$

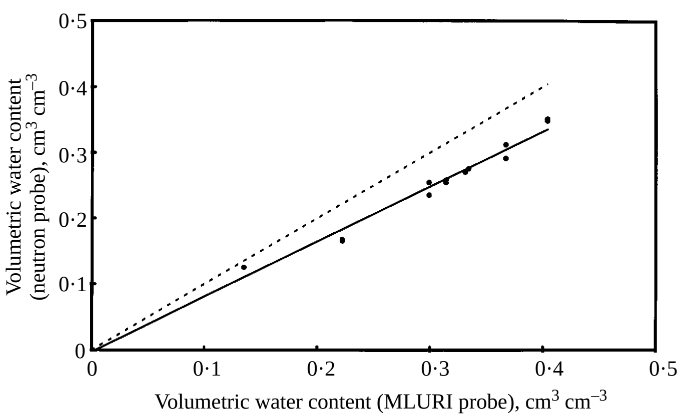

Fig. 3. Comparative volumetric water content (θ_v) $cm^3\ cm^{-3}$ measured by neutron probe against MLURI probe. - - - - 1:1 ideal relation; $y = 0{\cdot}837x - 0{\cdot}003$; $r^2 = 0{\cdot}973$

mineral soils were used and gave differing wetting responses, both temporally and in magnitude and these were ascribed to variation of the soils' bulk densities which ranged from 0·9 to 1·2 g cm^{-3} (*Fig. 4*).

Calibration of soil moisture content using a soil of known bulk density suggested that there was a strong cubic relationship between volumetric moisture fraction (i.e. bulk density × moisture content) and the instrument output.

A wide range of soil bulk densities (from around 0·5 g cm^{-3} for an organic horizon to around 1·6 g cm^{-3} for a C-horizon sample) were therefore used under controlled volumetric conditions to give a range of soil water contents determined by drying at 105°C yielding the calibration curve shown in *Fig. 5*. This is similar to that obtained using TDR which, again, is dependent on soil bulk density (Topp *et al.*[19]). Much of the variation in the data set is probably owing to practical laboratory difficulties in maintaining volumetric conditions, but repeated tests have shown that the calculated cubic relationship can be used for a wide range of physical soil types.

The equation derived from these tests was used in the comparison between this proposed technique and neutron probe measurements.

4.2. *Conductivity*

The imaginary part of the dielectric constant of soil is dependent on the electrical conductivity of the soil solution owing to salinity, [Eqn (1)]. The degree to which this could influence the output was investigated by testing the instrument with a range of conductivities which might be expected in "normal" UK soil conditions, i.e. from around 20 μS cm^{-1}, corresponding to rainfall input, to more than 1500 μS cm^{-1}. The probe head was immersed in beakers of 500 cm^3 containing increasingly concentrated solutions of potassium chloride up to 1500 μS cm^{-1}. Results showed that the signal was reduced by around 80 mV across a range of 1100 mV for this increase in conductivity in pure solutions. However, this reduction in probe output was much less marked when adding known conductivity solutions to soils under the above conditions. Here the effect was reduced to around 15–20 mV, but this may also reflect the exchange properties of the soils under test. Other dielectric constant water sensing techniques are similarly insensitive to changes in conductivity, for example, Topp *et al.*[7] and Zegelin *et al.*[11] conclude that the velocity of propagation of electromagnetic pulses along a TDR soil probe is nearly independent of the soil's conductivity although the resulting trace shape may be altered; this however means that the design of any automatic trace interpretation algorithm is correspondingly more difficult.

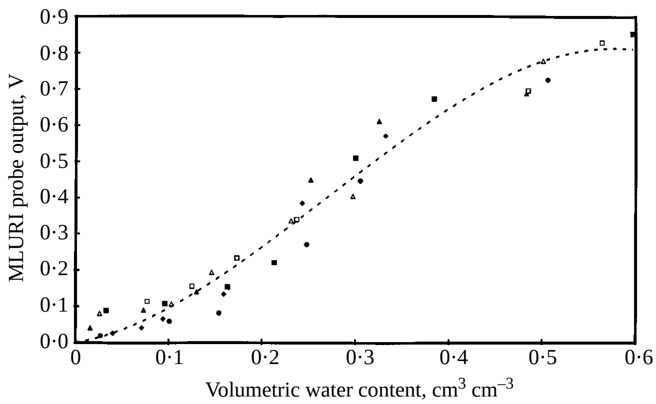

Fig. 5. Calibration curve for MLURI probe output V against determined volumetric water content cm^3 cm^{-3}. Soil bulk density □, 0·50 g cm^{-3}; △, 0·95 g cm^{-3}; ●, 0·89 g cm^{-3}; ■, 1·13 g cm^{-3}; ▲, 0·91 g cm^{-3}; ◆, 1·60 g cm^{-3}. $y = -7{\cdot}044x^3 + 5{\cdot}711x^2 + 0{\cdot}460x - 0{\cdot}001$, percentage variation 95·3

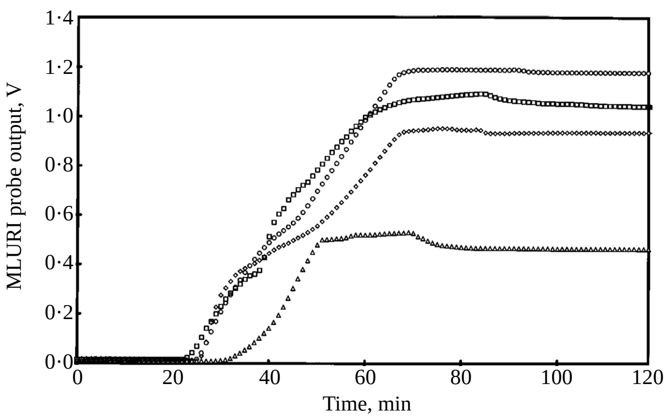

Fig. 4. MLURI probe responses to artificial wetting of a range of mineral soils. Logger offset +1 V. △, sand; ◇, soil a; □, soil b; ○, soil c

4.3. *Operating voltage*

The instrument's output is a function of the oscillator amplitude which, in the original uncompensated design used for the prototype, depended on the supply voltage set at 12 V d.c. Tests were carried out at various voltages between 11 and 13 V and the response determined in a range of wet and air-dried soils. The data obtained are illustrated in *Fig. 6a,* and if the lines through points obtained with the same soil water content are extrapolated then they converge at a point corresponding to around 4 V, which is the value at which the oscillator starts to operate (*Fig. 6b*).

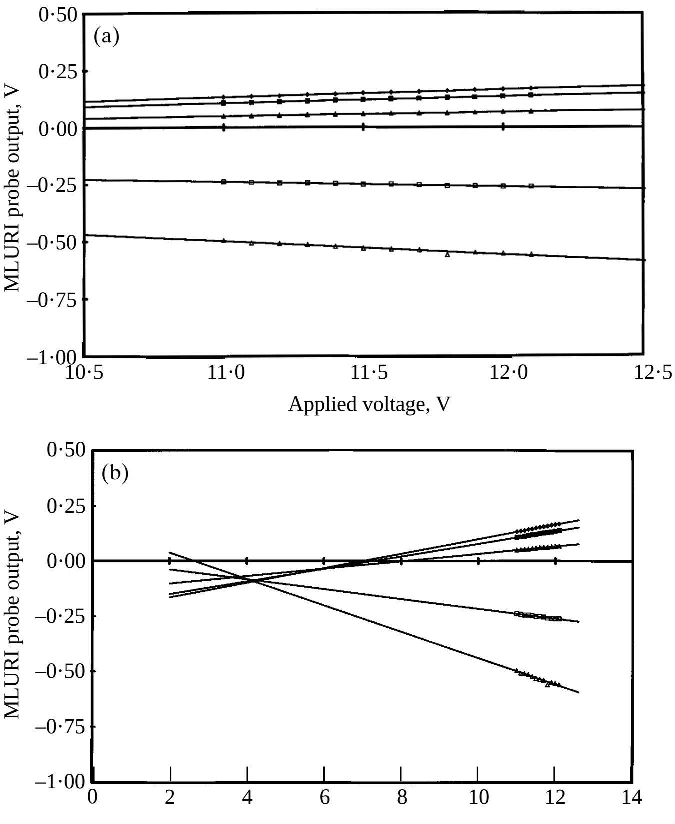

Fig. 6. (a) Effects of supply voltage on MLURI probe response in a range of soils and in air; (b) extrapolated MLURI probe response to supply voltage. ◆, air; □, wet soil; ■, dry soil; △, slurry; ▲, moist soil

Because changes in soil water content may produce only small shifts in output signals it would therefore be necessary to record the supply voltage at the time of data collection. While this could easily be accommodated using current logging techniques, a new design will accept a range of supply voltage from 8–15 V with minimal effect on oscillator amplitude.

4.4. *Temperature*

The influence of temperature on instrument output was also studied using soils with a range of water contents. There was a slight change in probe output across a range of 25°C which varied between 15 and 20 mv for the soils tested, i.e. 1–2% of the total range. This variation was probably primarily due to the temperature dependent forward voltage of the rectifier diodes used in the amplitude sensing circuit but this has been greatly reduced in the current design by a compensating technique.

4.5. *Calibration*

The prototype probes were calibrated using five different solutions of known dielectric constants. The probe reproducibility was found to be within 1% and the calibration curve is plotted in *Fig. 7* of square root of dielectric constant against output voltage. A linear relationship between square root of dielectric constant and volumetric water content (θ_v) is discussed by Whalley[10]

$$\theta_v = \frac{\sqrt{K} - q}{p} \tag{11}$$

where p and q are constants for a specific soil type having typical values of 8·1 and 1·6 respectively, and this can be used in conjunction with the calibration curve to convert output voltages to volumetric water content.

5. Conclusions

The instrument described has been shown to be suitable for determining changes in soil water contents under simulated field conditions. The component costs are relatively low, it is easy to construct and is robust enough to withstand normal field conditions. Tests indicate that it can be applied to a wide range of soils without recalibration with an accuracy of $\pm 0{\cdot}02\ \mathrm{cm^3\,cm^{-3}}$. A major advantage over other techniques described here, is the ease with which its output can be continuously or periodically monitored and this should facilitate the determination of the critical changes in soil water fluxes over a wide range of environmental studies.

A new design of probe is now being tested which

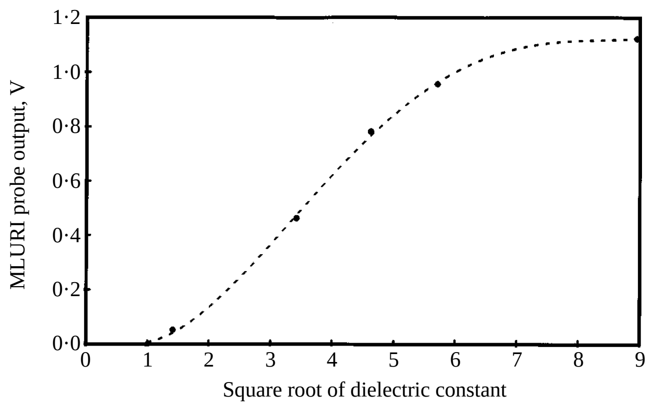

Fig. 7. Probe output voltage responses to pure liquids of known dielectric constants. Liquids used were cyclohexane, acetone, methanol and water. $y = -0{\cdot}023x^3 + 0{\cdot}165x^2 - 0{\cdot}220x + 0{\cdot}084$; $r^2 = 0{\cdot}999$

will accept a wide range of supply voltage, is much less sensitive to temperature changes and is very much more compact as it employs a small internal transmission line.

Acknowledgements

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The design is subject of a provisional patent application by MLURI. Further developments towards commercialisation have been carried out in collaboration with Delta-T Devices, Cambridge. Currently, a robust, reliable production version manufactured by Delta-T is undergoing independent scientific appraisal.

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