

Microwave dielectric properties of horticultural peat products

G. Ayalew, N.M. Holden and S.M. Ward

Peat Technology Centre, Department of Biosystems Engineering, University College Dublin, Ireland

SUMMARY

The microwave dielectric properties of horticultural peat and compost peat were measured with a HP85107C network analyser in conjunction with a HP85070B open-ended coaxial dielectric probe for the frequency range 0.5–20 GHz. Loose samples had volumetric water contents ranging from 0.11 to 0.24 Mg m⁻³. For analysis, samples were compressed to 1.0× (no compression), 1.2×, 1.5× and 2.0× original bulk density, giving volumetric water contents ranging from 0.11 to 0.48 Mg m⁻³. The raw relative permittivity data exhibited a high degree of variability, but rank-based removal of outlier measurements helped to improve their coherence with volumetric water content. The difference between horticultural peat and compost peat was insignificant in terms of both the dielectric constant and the loss factor. The results suggest that relative permittivity data after the removal of outliers can be of sufficiently high quality for sensing applications in the horticultural peat industry such as dedicated water content monitoring, nutrient management, and foreign body detection systems for health and safety purposes, given the low-precision requirements that are appropriate for horticultural and compost peat as high-volume, low-value and non-critical commodities.

KEY WORDS: compost, growing medium, permittivity, relative complex permittivity, soil additive.

INTRODUCTION

Horticultural peat is a granular material produced by scarifying the surface of peat bog. Depending on its origin and formation history, peat has air-dry poured (not compressed) bulk density ranging from 0.16 to 0.59 Mg m⁻³, ratio of mass of >2 mm particles to mass of <2 mm particles between 0.71 and 4.48, and porosity 46–84% (Holden & Ward 1997). It is used in horticulture as a growing medium and as a soil additive (Ayalew & Ward 2000). Generally speaking, horticultural peat is a poorly decomposed peat product (Holden & Ward 1997); whilst compost peat is basically peat with added mineral fertiliser, although the exact chemical composition and dosage of the fertiliser are trade secrets. Where distinction is necessary in this paper, horticultural peat will be referred to as 'peat' and compost peat as 'compost'.

Knowledge of the wide-band frequency dielectric properties of peat and compost is relevant to the design and development of production and processing equipment because heating, attenuation, reflection and transmission during interaction with electromagnetic radiation all depend on the relative complex permittivity (Nelson 1999, Ayalew &

Ward 2000). Recent developments in the peat industry call for knowledge of microwave properties for the detection of glass contaminants in horticultural peat (Ayalew & Ward 2000, Ayalew *et al.* 2004). Relative permittivity data for horticultural peat are lacking from the public domain[‡]; therefore this paper may provide the first published information.

Such information could also improve the implementation of time-domain reflectometry (TDR) for the determination of water content (Holden 1997) and hydraulic conductivity (Holden 2001) by allowing more accurate instrument calibration; and it could serve as a basis for future refinement for application in the interpretation of remotely sensed data.

Electromagnetic interactions with peat and compost depend upon the real and imaginary parts of the relative complex permittivity, given as:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad [1]$$

where ε is the relative complex permittivity, ε' is the

[‡] M. Hallikainen, Space Technology Laboratory, Helsinki University of Technology, Finland (pers. comm.).

real part (dielectric constant) which denotes the electric energy storage capacity, and ϵ'' is the imaginary part - sometimes referred to as the loss factor - which accounts for the dissipation of electrical energy as heat (Ramo *et al.* 1984, Pozar 1998, Nelson 1999). The high relative permittivity value of water compared to the very low relative permittivity of the organic matter (Nelson 1973) present in horticultural peat means that the predominant factor in the variation of its relative permittivity is attributable to variation in water content. Permittivity (at constant temperature) generally increases with water content as for other organic substances (Nelson 1973) and soils (Hallikainen *et al.* 1985). The relative proportions and total content of intercellular and inter-particle water depend, among other things, on the degree of humification; higher humification being associated with lower porosity and, in consequence, lower water content (Bell 1992).

The study described in this paper aimed to determine the influence of volumetric water content on the dielectric properties of peat and compost in the 0.5–20 GHz region of the electromagnetic spectrum.

MATERIALS AND METHODS

Fifty-four samples were taken from two Irish peat and compost production factories over a period of four weeks. Twenty-eight of these samples were peat and the rest were compost. Their volumetric water contents (measured at poured density) were determined by oven drying at 105°C for 12 hours (Holden & Ward 1997), and ranged between 0.11 and 0.24 Mg m⁻³ (56.2–73.4% wet-basis water content). The poured bulk densities of the samples ranged from 0.18 to 0.33 Mg m⁻³.

The real and imaginary parts of the relative complex permittivity were measured using a Hewlett-Packard HP85070B dielectric probe in conjunction with a HP85107C network analyser (Figure 1). The HP85070B is an open-ended coaxial probe with a nominal frequency range 0.2–20 GHz. The precision of the probe is highest when measuring high dielectric constant values; and for a substance of $\epsilon' = 5$ ranges from about $\pm 20\%$ at frequencies <1 GHz to $\approx \pm 4.5\%$ at frequencies of about 20 GHz (within the temperature range -40–200°C). However, the fact that the probe senses a small volume of material causes difficulty in attaining good performance for heterogeneous samples (Figure 2). The probe method was chosen because it permits a large number of samples and replicates to be analysed over a wide range of

frequencies, but at the cost of the higher level accuracy that could have been achieved using an alternative method such as the resonant cavity method.

The recommended calibration procedure (Hewlett-Packard 1993) was followed (samples were at 25°C), and the probe was fixed on a rigid support to minimise cable movements that could have introduced errors not accounted for by calibration (Blackham & Pollard 1997).

For each of the 54 samples, measurements of relative permittivity were made while each sample was at its uncompressed maximum (poured) volume, and at three compressed volumes corresponding to packing densities 1.2 \times , 1.5 \times and 2.0 \times those of the uncompressed samples, giving a total (n) of $54 \times 4 = 216$ measurements. The resulting range of bulk densities was 0.18 to 0.66 Mg m⁻³. The rationale behind compression was to simulate both industrial packing of peat at 'higher-than-poured' densities and the variable bulk density of peat in its undisturbed state (Grigal *et al.* 1989).

The sample container was a graduated glass cylinder of internal diameter 25.6 mm, cut to hold a maximum volume of 30 ml. For measurement of each sample, the container was initially filled to the brim with sample material without pressure (compression = 1.0), and measured by scanning at frequency values selected on a logarithmic scale across the range 0.5–20 GHz. The sample was then compressed with a flat-bottom plunger of diameter slightly less than that of the cylinder until its volume was 25 ml and re-measured; and this procedure was repeated sequentially with compression to volumes of 20 ml and 15 ml.

The first step of data analysis involved elimination of outlier measurements using a rank-based criterion, whereby the rank according to water content was compared with that according to permittivity and a measurement having a deviation in rank above an absolute threshold of 8% was considered an outlier. Linear and second-order polynomial regressions were then made of dielectric constant and loss factor on volumetric water content, using the data both before and after the removal of outliers.

The corrected data were then used to make plots of dielectric constant and loss factor against frequency at different levels of water content. This was done separately for the peat and compost samples. A subset of the corrected data was used to make plots for poured density samples, i.e. those samples whose density had not been changed by compression. All trend lines on plots were computed using a cubic-splines routine, after Press *et al.* (1992).

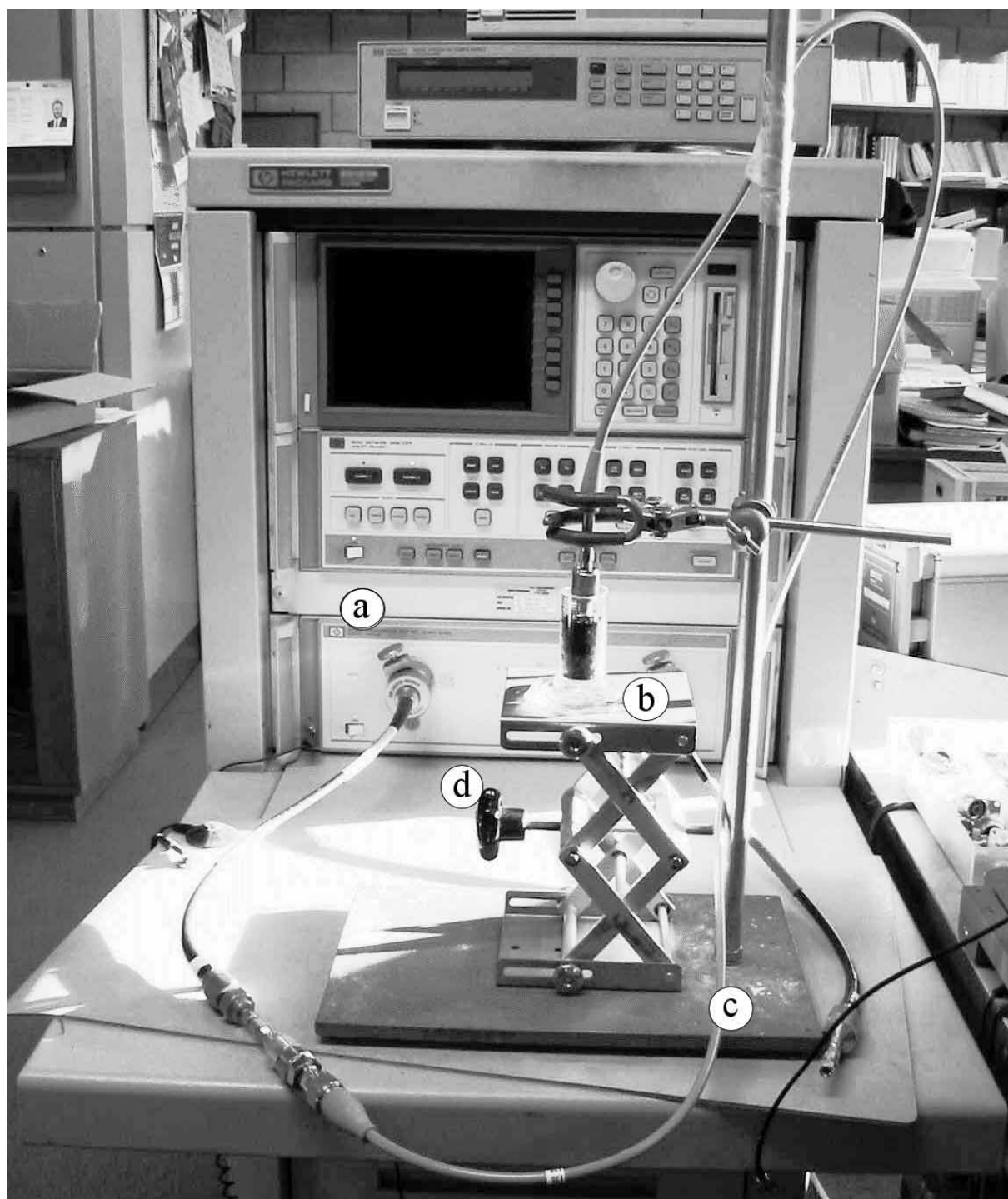


Figure 1. Experimental setup for permittivity measurements. Key: (a) the HP85107C network analyser; (b) sample holder and HP85070B probe end; (c) retort stand, base, and clamp; (d) laboratory jack providing height adjustment for the sample.

RESULTS

The removal of outliers

Table 1 compares the R^2 values of linear and quadratic regressions of dielectric constant and loss factor on volumetric water content before and after the removal of outlier measurements, for both peat

and compost samples. Better fits were obtained using the quadratic than the linear polynomial model. A clear improvement in R^2 values was achieved by removing outliers, and comparison of R^2 values for peat and compost shows that this operation improved the statistical fit more for the compost samples than for the peat samples.

Table 1. Comparison of R^2 values for linear (*Lin*) and quadratic (*Quad*) polynomial regressions of permittivity against volumetric water content for peat and compost samples, before and after removal of outlier samples using the rank-based criterion.

Frequency (GHz)	BEFORE		AFTER	
	R^2, Lin	$R^2, Quad$	R^2, Lin	$R^2, Quad$
Dielectric constant, peat samples, $n = 112$				
0.50	0.480	0.617	0.807	0.849
1.05	0.483	0.621	0.807	0.846
2.00	0.486	0.622	0.813	0.852
5.29	0.500	0.627	0.826	0.862
10.03	0.521	0.639	0.839	0.868
20.00	0.560	0.672	0.869	0.886
Loss factor, peat samples, $n = 112$				
0.50	0.368	0.525	0.817	0.857
1.05	0.402	0.559	0.824	0.900
2.00	0.392	0.563	0.815	0.911
5.29	0.385	0.554	0.799	0.889
10.03	0.383	0.523	0.769	0.844
20.00	0.451	0.544	0.798	0.849
Dielectric constant, compost samples, $n = 104$				
0.50	0.390	0.390	0.914	0.950
1.05	0.395	0.396	0.920	0.954
2.00	0.403	0.403	0.921	0.958
5.29	0.408	0.409	0.927	0.961
10.03	0.411	0.411	0.937	0.964
20.00	0.441	0.441	0.954	0.968
Loss factor, compost samples, $n = 104$				
0.50	0.237	0.238	0.927	0.942
1.05	0.276	0.278	0.920	0.938
2.00	0.266	0.266	0.851	0.877
5.29	0.282	0.283	0.782	0.844
10.03	0.252	0.252	0.796	0.867
20.00	0.255	0.256	0.821	0.842

Dielectric constants and loss factors of samples

Figures 3 and 4 show plots of dielectric constants and loss factors as functions of frequency, constructed using the corrected data, for peat and compost samples respectively. The graphs are drawn for average volumetric water content (**m**) with bin-widths of 0.03 Mg m^{-3} and centred at the indicated values. The mean bulk densities (**b**) and the number of samples in each group (**n**) are also indicated. Figures 5 and 6 show similar plots for peat and compost samples at poured density.

The mean dielectric constants declined steadily with increasing frequency up to about 20 GHz, where the rate of decline became steeper. The mean loss factors in both peat and compost samples exhibited a decline down to a broad minimum around 2–5 GHz and then rose to the end of the frequency range.



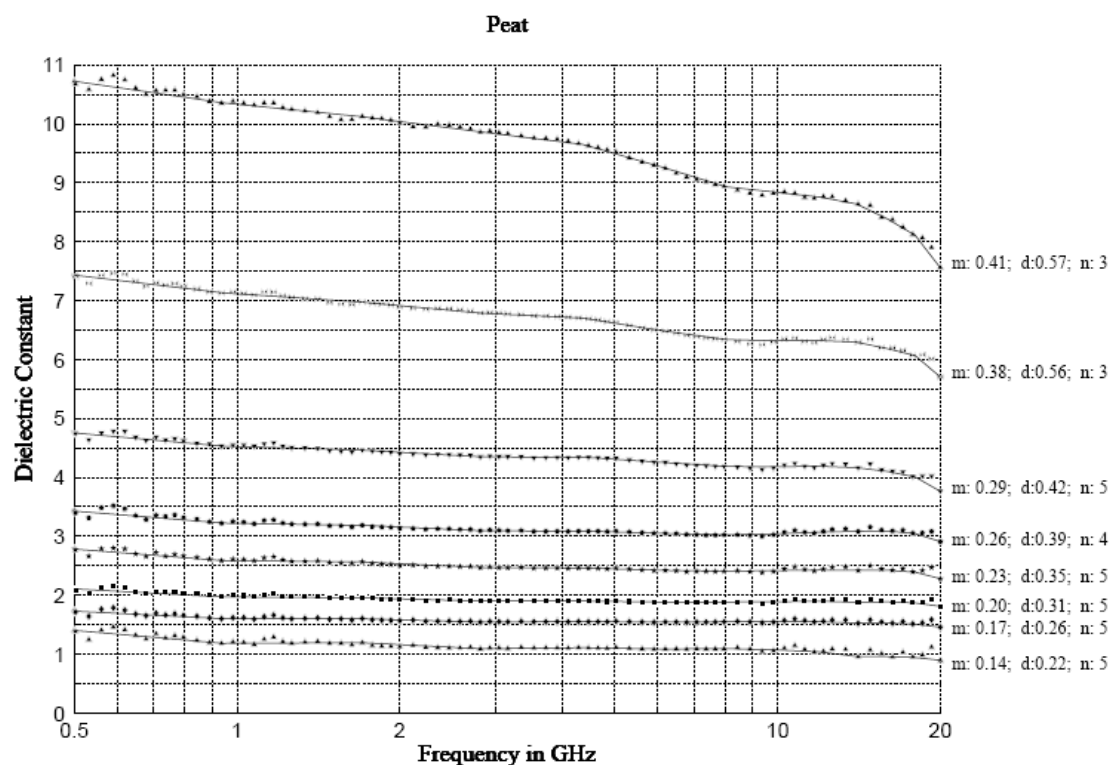
Figure 2. A newly-filled sample holder prior to a typical permittivity measurement.

DISCUSSION

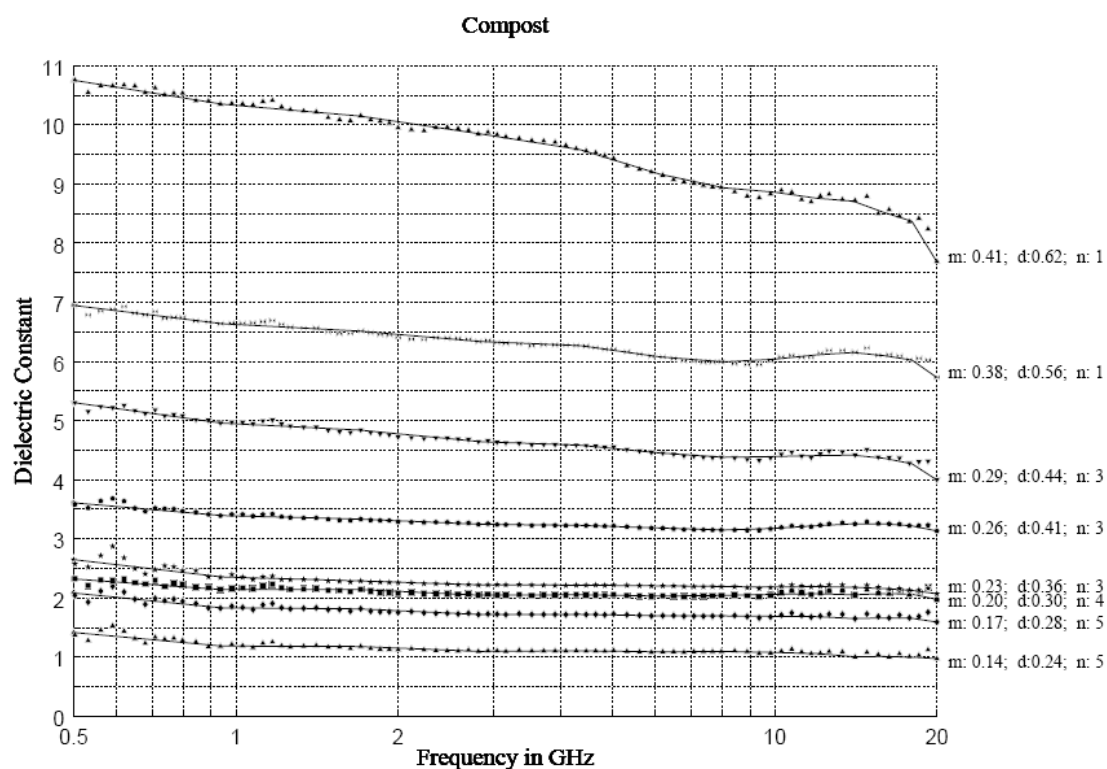
Although the outlier removal method described above does not have a mechanism to ensure the total elimination of outlying measurements in terms of permittivity values (even higher R^2 values), it helped avoid exaggerated deviations, which resulted in great improvements in correlation. The second-order polynomial dependence of the dielectric constant and the loss factor on water content also became more apparent after the removal of outliers.

The second-order polynomial dependence of the regression of dielectric constant on volumetric water content may be explained in terms of the progressively increasing free (unbound) water layer and its contribution to relative permittivity as volumetric water content is increased. The general decline of the dielectric constant close 20 GHz, and the increase in its extent with increasing water content, may be explained in terms of the dielectric relaxation that occurs around 19.240 GHz at 25°C in the Debye model of permittivity for water (Burdette *et al.* 1980, Grant *et al.* 1989).

The fact that loss factors in both peat and compost samples exhibited a broad minimum around 2–5 GHz may be explained in terms of the physical basis of the loss factor. The first portion of the curve (the declining phase) may be attributed to

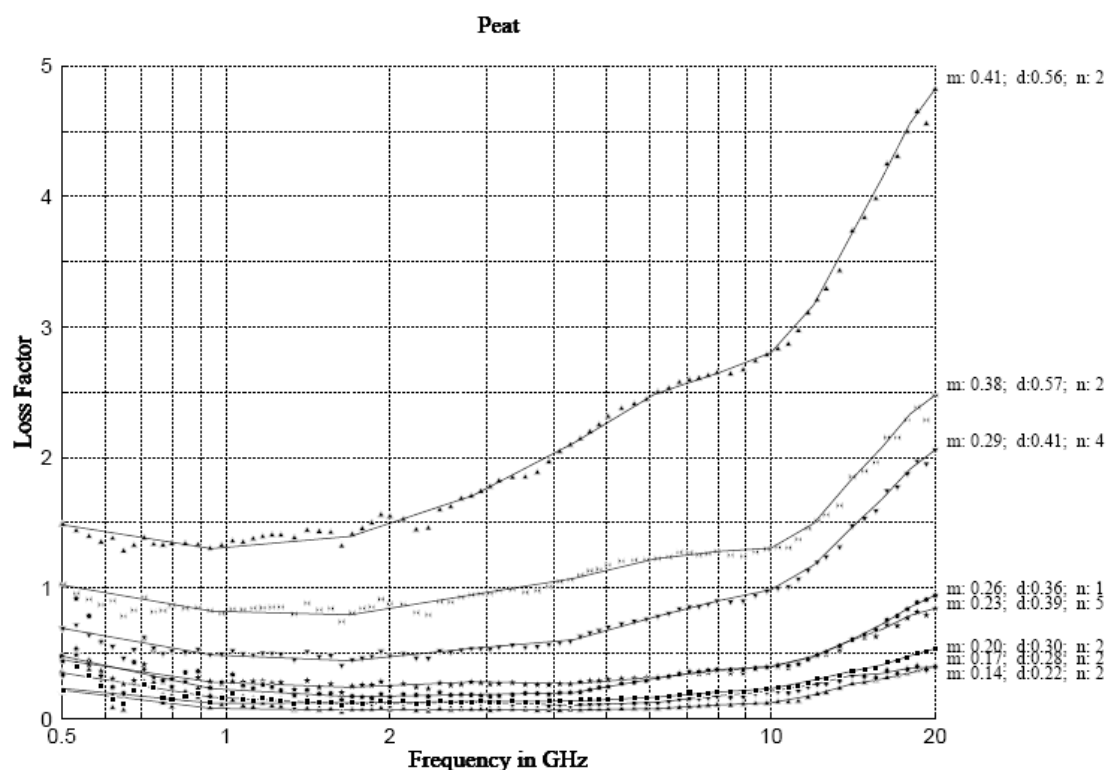


(a)

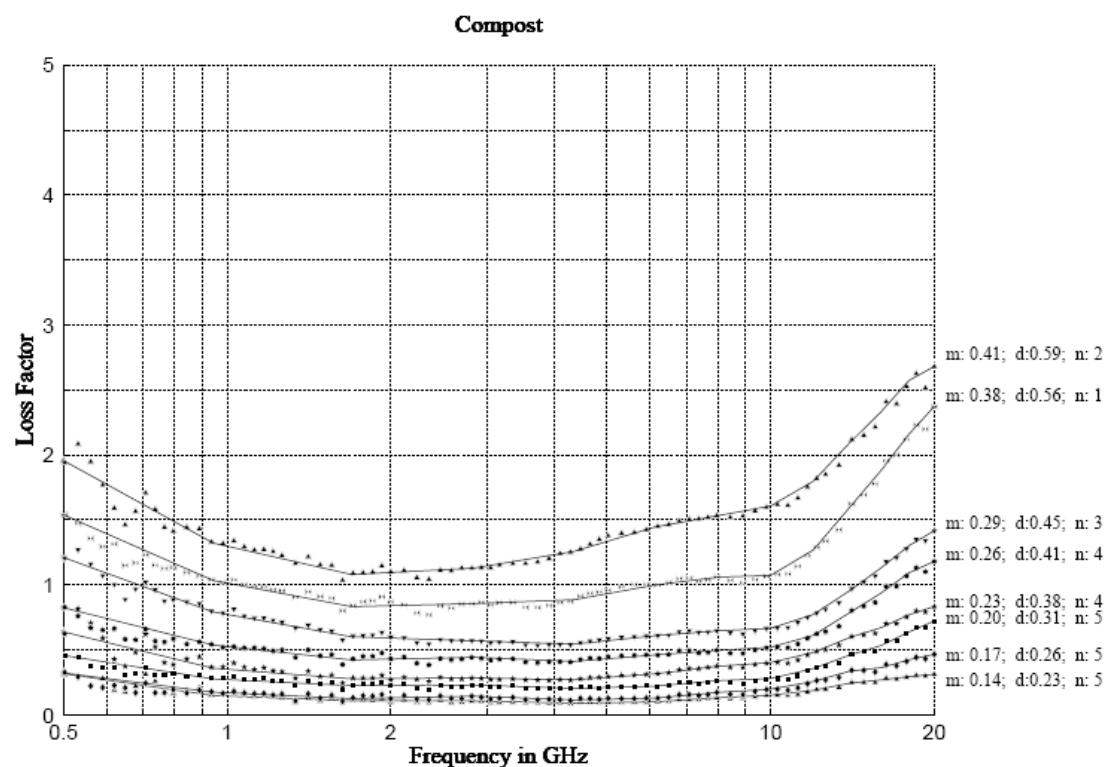


(b)

Figure 3. Plots of mean dielectric constants for (a) peat and (b) compost samples (**m**: volumetric water content in Mg m^{-3} ; **d**: average wet bulk density in Mg m^{-3} ; **n**: number of samples).

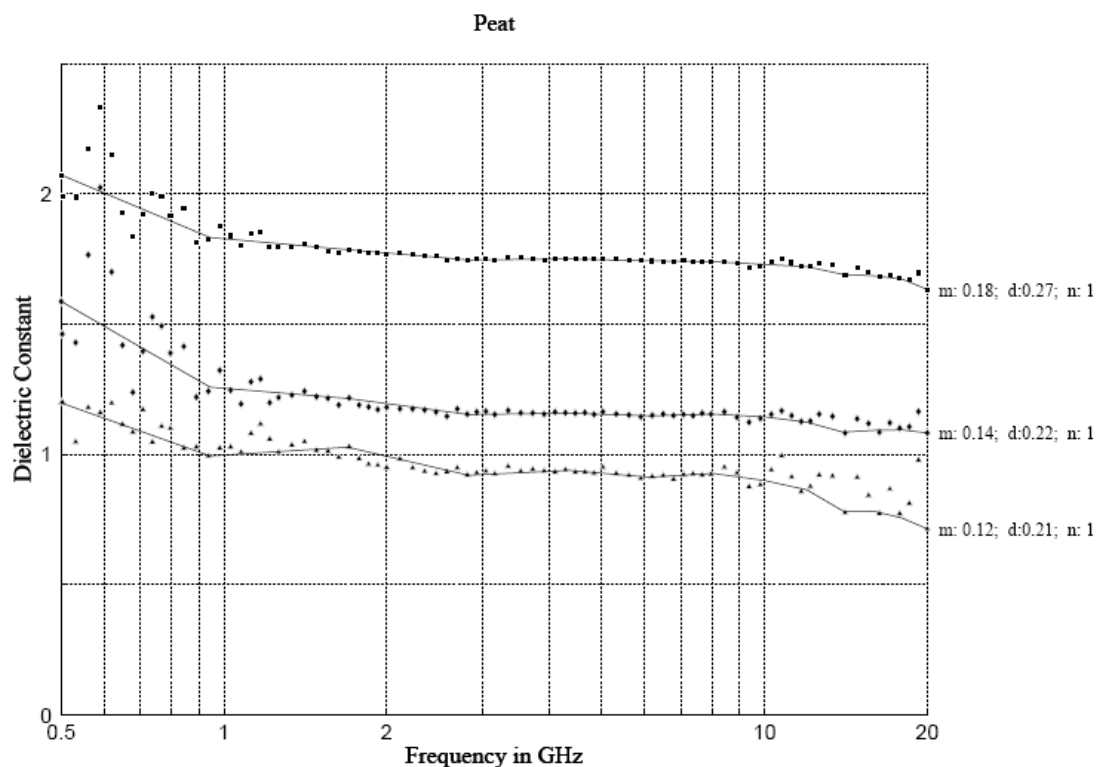


(a)

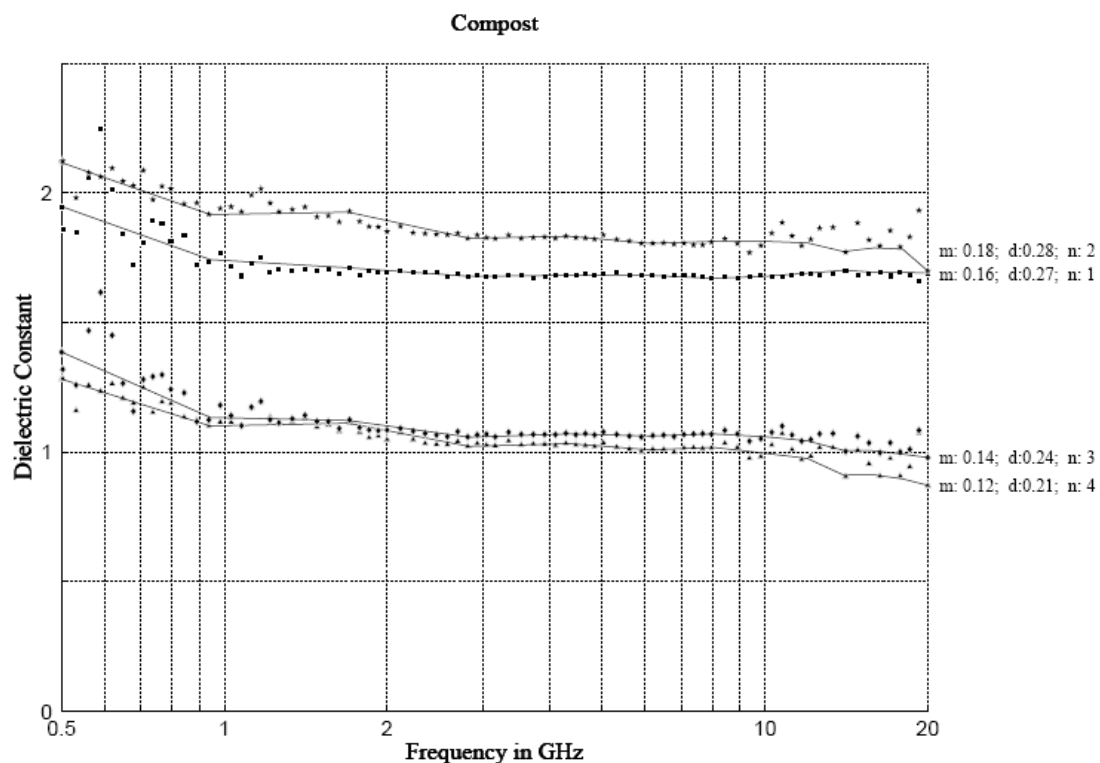


(b)

Figure 4. Plots of mean loss factors for (a) peat and (b) compost samples (**m**: volumetric water content in Mg m^{-3} ; **d**: average wet bulk density in Mg m^{-3} ; and **n**: number of samples).



(a)



(b)

Figure 5. Plots of mean dielectric constants for (a) peat and (b) compost samples at poured density (**m**: average volumetric water content in $\text{Mg}\cdot\text{m}^{-3}$; **d**: average wet bulk density in $\text{Mg}\cdot\text{m}^{-3}$; and **n**: number of samples).

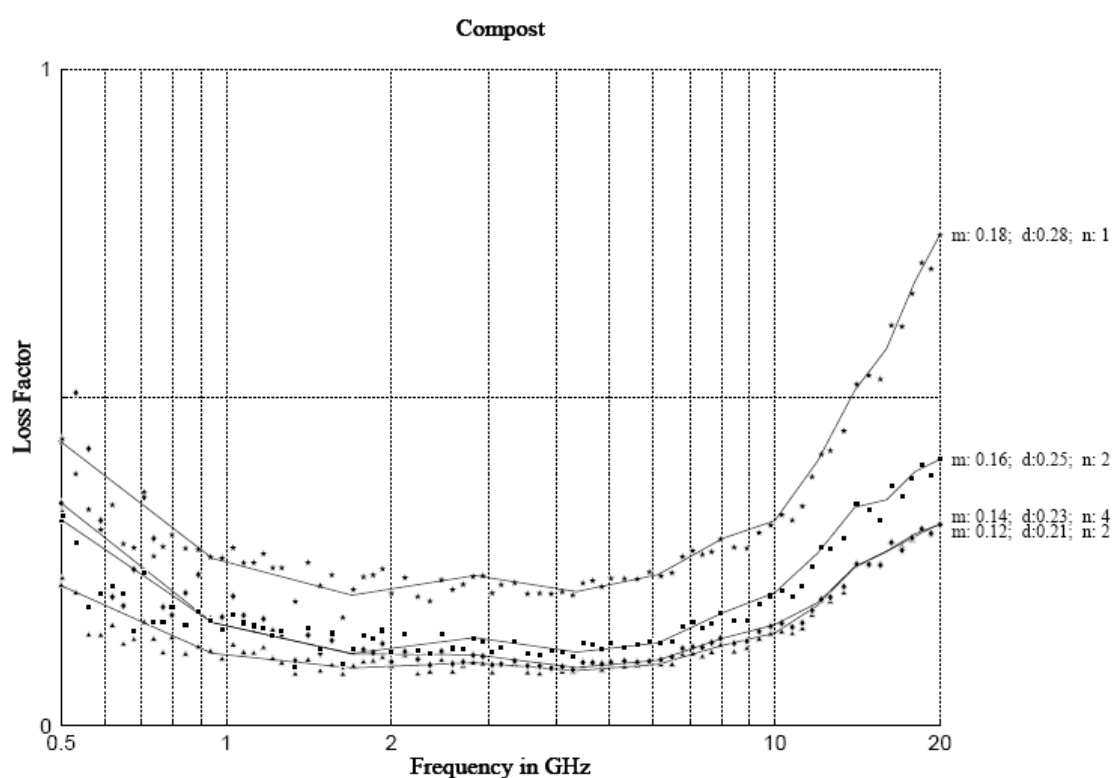
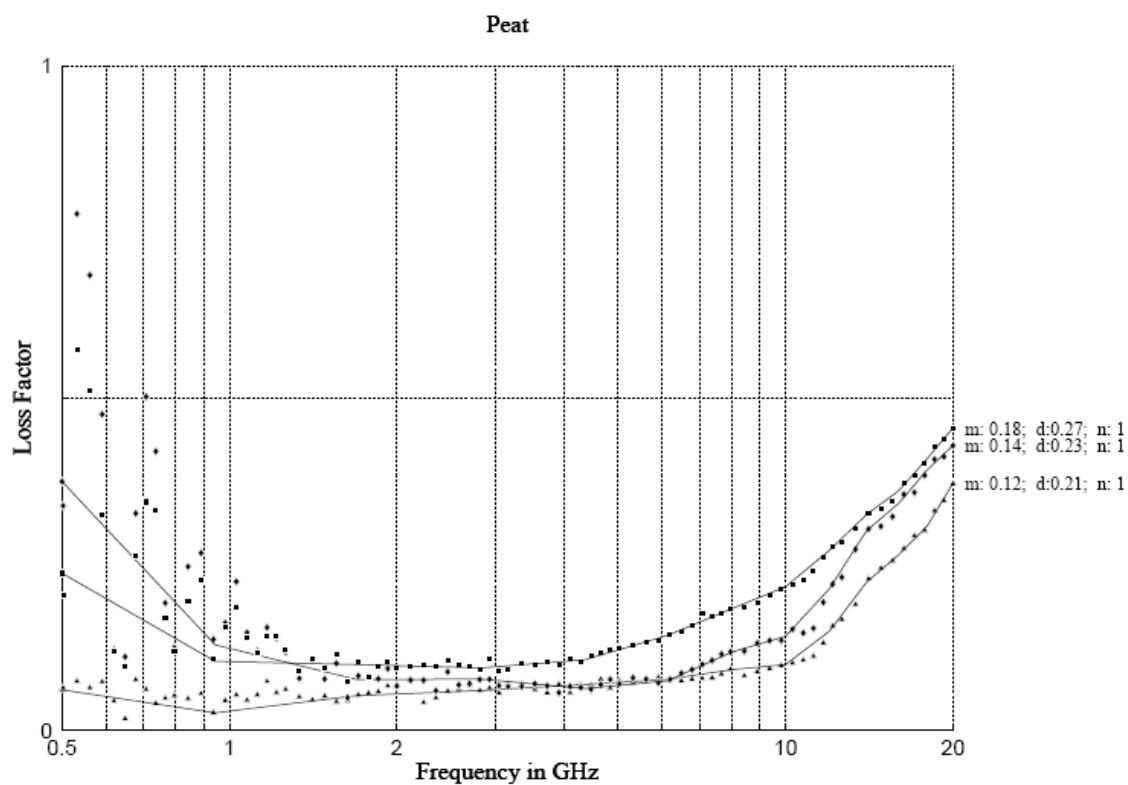


Figure 6. Plots of mean loss factors for (a) peat and (b) compost samples at poured density (**m**: average volumetric water content in $\text{Mg}\cdot\text{m}^{-3}$; **d**: average wet bulk density in $\text{Mg}\cdot\text{m}^{-3}$; and **n**: number of samples).

the progressively decreasing contribution from ionic conduction (Hewlett-Packard 1993, Nelson *et al.* 1994) and bound water relaxation (Nelson *et al.* 1994); and the second portion (the rising phase) to the increasing contribution from polar losses (Burdette *et al.* 1980, Grant *et al.* 1989, Hewlett-Packard 1993) due to free water relaxation (Nelson *et al.* 1994). The respectively decreasing and increasing trends of the dielectric constant and the loss factor with increasing frequency are similar to those determined for water (Burdette *et al.* 1980, Grant *et al.* 1989), and for vegetables by Nelson *et al.* (1994). The differences between the ranges of peat and compost dielectric constant and loss factor values are insignificant as depicted in Figures 3–6.

Another observation to be made here is that the relative permittivity values of moist peat and compost samples (especially at low water content levels) are disproportionately low given the volumetric content of water, which is a high relative permittivity substance (*ca.* 80 at 25°C). This suggests that not all of the water in peat is free water, which seems contrary to the statement by Bell (1992) that most of the water in partially decomposed substances exists in the form of free water, but may reflect the presence in peat of strongly bound adsorbed water as described, for example, by Hobbs (1986).

The overall scatter of data can be explained in terms of at least three types of possible sources of variation, namely the instrumental/measurement system, the peat itself, and personnel factors. The contribution of the instrumental/measurement system and process uncertainty is likely to be high because the sensing region at the tip of the open-ended co-axial probe is very small (3 mm diameter) in relation to the particle size distributions of peat and compost. The second source of variation is that introduced by the origin and processing of the peat. Peat may originate through various processes of formation from different substrates which often vary in their degree of decomposition. Furthermore, it forms aggregates (whose nature is partly influenced also by the production process) incorporating relatively dense and less dense material. This produces small-scale variations in relative permittivity. Therefore, the scatter of data can be associated with the random aggregation as well as the formation history of the peat, which make it heterogeneous with widely varying bulk density.

Although the results show substantial scatter in the relative permittivity data, the peat industry requires modest levels of precision, since the product itself is non-critical in human safety terms. This low-precision requirement may be explained using the example of moisture measurement, for

which the peat industry requires precision levels of around $\pm 3\%$ (Ayalew & Ward 2000) for wet basis water content measurement. This corresponds approximately to the range $\pm 0.0048 \text{ Mg m}^{-3}$ to $\pm 0.0177 \text{ Mg m}^{-3}$ volumetric, depending on bulk density, so that low R^2 values are quite acceptable.

Potential improvement is possible through control of particle size distribution, and through the use of an alternative permittivity measurement technique such as the microwave cavity technique, in which the sample is enclosed in a resonant cavity and permittivity is calculated from the frequency shift required to achieve resonance with the substance in the cavity (Ramo *et al.* 1984, Nelson 1999). Although sampling is more representative, the drawbacks of this technique compared with use of the dielectric probe are comparatively restricted frequency range and more difficult measurement procedure.

The relatively small magnitudes of the relative permittivity values of peat products and their relative independence of frequency suggests that the choice of frequency for applications can be decided on the basis of considerations other than water content. Advantages such as higher antenna gain and smaller effective reflection area (radar cross-section) of targets in reflection applications with increasing frequency (decreasing wavelength) makes higher-frequency microwaves attractive (Pozar 1998).

Application of the above results to remote sensing may be possible with appropriate consideration of the fact that the density of peat is a function of depth (Grigal *et al.* 1989) as well as composition.

CONCLUSIONS

1. Variability in relative complex permittivity (dielectric constant and loss factor) data for peat and compost samples can be removed, at least partially, by removal of outlier measurements using a rank based method. This means that the technique is suitable for applications in the handling and processing of horticultural peat products.
2. The methods and results presented in this paper provide a basis for understanding the design and implementation challenges for potential applications of permittivity data in horticultural peat production, which range from the optimisation of water and nutrient use to health and safety systems such as glass fragment detection sensors (Ayalew *et al.* 2004).

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Editor: Olivia Bragg

Author for correspondence:

Gashaw Ayalew, Department of Biosystems Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland.

Tel: +353-1-7165597 or +353-8-74118873; Fax: +353-1-4752119; E-mail: gashaw.ayalew@ucd.ie