Airborne Measurements of Forest and Agricultural Land Surface Emissivity at Millimetre Wavelengths

Tim J. Hewison
UK Met. Office (Remote Sensing)
Y70, DERA Farnborough, Hampshire, GU14 0LX, UK.
Tel:+44-1252-395781 Fax:+44-1252-515523 Email:tjhewison@meto.gov.uk

Abstract—
Passive microwave radiometers have been operated on an aircraft over the same (NOPEX) area of Sweden, near Uppsala in September 1995 and March 1997. Their measurements have allowed the calculation of the emissivity of boreal forest and agricultural land surfaces at 24, 50, 89 and 157 GHz over a range of incidence angles and polarisations. These results show consistent differences between dense forestry, where the emissivity is close to 1 and open land, where it is approximately 0.96. These differences are examined and a model is presented to parameterise these surfaces by use of a Debye-like effective permittivity and Fresnel's reflection coefficients.

I. Introduction

The launch of the next generation of satellite microwave instruments provides the opportunity to retrieve atmospheric temperature and humidity profiles over land as well as sea. This requires realistic representation of the surface's microwave emissivity over the 20-200 GHz and 0-50° incidence angle range by a fast parametric model. Airborne measurements provide an important link to span the gap between small-scale, ground-based studies and large-scale, satellite images.

This paper reports the results of airborne measurements made by the UK Meteorological Office over the NOPEX (NOrthern Processes EXperiment) area, near Uppsala in Sweden. This region contains extensive areas of dense boreal forest dominated by spruce and pine with about 15% deciduous, broadleaf trees, as well as lakes, wetland and open agricultural land, some of which was vegetated in September 1995.

One flight was made on 6 September 1995 on a warm day, after heavy rain. Two further flights took place on 14 and 18 March 1997 in much colder conditions.

II. Emissivity Model

This paper considers the surface/canopy system as a whole. In this way, the surface can be represented in terms of a specular reflector, based on a Debye-like form of effective relative permittivity, ε at frequency ν, which is parameterised in terms of ε_s, the effective static permittivity, ε_∞, its high frequency limit, and ν_r, the effective relaxation frequency. The ionic conductivity term has been neglected, as its contribution is insignificant above 20GHz.

$$\varepsilon(\nu) = \frac{\varepsilon_s - \varepsilon_\infty}{1 - i.\nu/\nu_r} + \varepsilon_\infty \qquad (1)$$

The fresnel formulae, define the power reflectivity in vertical and horizontal polarisations, Γ_v and Γ_h of a specular surface in terms of its complex relative permittivity, ε, and the angle of incidence, θ. The emissivity (ϵ) is the complement of this $[\epsilon(\nu,\theta) = 1 - \Gamma(\nu,\theta)]$.

Such a scheme can represent dielectric surfaces, such as open water, by setting $\varepsilon_s > \varepsilon_\infty$, and volume scattering, such as sea ice by $\varepsilon_s < \varepsilon_\infty$. However, surfaces exhibiting non-monotonic emissivity spectra, such as dry snow [1], cannot be accurately presented without the addition of a scattering term. It is proposed that the effects of variable surface roughness and vegetation cover are absorbed into these three parameters, which may be tuned to represent changes of these variables.

An additional parameter for polarisation mixing, Q, was added by Wang and Choudhury [2] and is included in the proposed model to explain the observed angular variation of emissivity:

$$\begin{aligned} \Gamma'_h &= (1-Q)\Gamma_h + Q\Gamma_v \\ \text{OR} & \\ \Gamma'_v &= (1-Q)\Gamma_v + Q\Gamma_h \end{aligned} \qquad (2)$$

Most vegetation (except when very sparse, short or dry) appears optically thick at millimetre wavelengths, due to absorption and volume scattering within the canopy. In this extreme the effective emissivity is determined by the vegetation's single scattering albedo, the ratio of its volume scattering to extinction coefficients [3], which are frequency dependent. This process is also absorbed into the effective permittivities and setting the polarisation mixing parameter, $Q = 0.5$, in the proposed model. The effective surface temperature is that of the vegetation, as measured by thermal infrared radiometry.

III. Instrumentation

This paper presents measurements made by the UK Meteorological Office (UKMO) on the C-130 Hercules. The main instruments used in this study are the microwave radiometers, known as Deimos and MARSS (Microwave Airborne Radiometer Scanning System). These are total power radiometers both with a 3 second scan, which includes various views downward (and upward for MARSS) and of two onboard black body calibration targets. These instruments are described in full in [4], [5].

IV. Emissivity Calculation

Measured brightness temperatures must be converted to surface emissivity to extend them to general application.

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The following formula is used to calculate the emissivity using only aircraft data:

$$\epsilon(\nu,\theta)=\frac{T_n(\nu,\theta)-T_z(\nu,\theta)}{T_S-T_z(\nu,\theta)} \quad (3)$$

where ϵ is the emissivity at frequency ν and incidence angle θ, T_n and T_z are the up- and down-welling brightness temperatures, respectively, and T_S is the surface temperature. The calculation of each of these terms is discussed below.

There are several stages involved in the emissivity calculation, which are described in full in [1]. Downwelling brightness temperatures at Deimos' frequencies are predicted from MARSS' observations. Corrections are applied for absorption by the atmosphere below the aircraft. The emissivity calculation assumes cloud-free conditions (filters are applied to ensure this criterion is met).

The surface temperature, T_S, is measured by the aircraft's Heimann radiometer in the thermal infrared. This is assumed to represent the effective radiative temperature of the surface, as penetrated depths are very small ($\leq$ 10mm) at millimetre wavelengths. This is typical of the surface temperature available to retrieval schemes for satellite data.

V. Emissivity Spectra

Footage from the aircraft's downward facing video camera was studied to identify periods during which homogeneous surface types were overflown. A category was assigned to each sample according to the vegetation type and density, and surface temperature. "Open" refers to canopy cover between 30-70%; "Close" refers to canopy cover greater than 70%. From the three flights, 142 samples were identified in this way, with periods ranging from 10–50 seconds, corresponding to track lengths of 1–5km.

Both of Deimos' channels measure two polarisations in each of its five downward views, which rotate with scan angle, so as to align vertical and horizontal in the forward view (+35°).

MARSS's channels measure only one polarisation in each of its nine downward views. This polarisation rotates with scan angle. The 157 GHz channel is aligned so the polarisation rotates from horizontal in the +20° view to vertical at −40°. The polarisation of the 89 GHz channel also rotates, but only approaches horizontal in the nadir view and is intermediate at the scan extremes.

Emissivity curves were calculated for each of the samples identified from video, grouped into radiometrically resolvable categories. Fig. 1 shows the mean and standard error of the emissivity measured in each view, together with lines fitted to the effective permittivity coefficients given in Table II, shown as solid lines for vertical and horizontal polarisations. The dashed lines on these graphs indicate the average of these polarisations, calculated by setting the polarisation mixing parameter, $Q = 0.50$.

The calm *Lake Water* behaves as a specular surface, closely following the double-Debye model proposed by Lamkaouchi *et al.* [6], shown by the continuous curves.

TABLE I
Coefficients of Effective Permittivity

Category	Permittivity Coeffs			Pol.
	ε_s	ε_∞	ν_r/GHz	Q
Lake Water	From [6]			0.00
Lake Ice	40.8	3.03	0.44	0.00
Bare Soil	2.28	1.86	21.8	0.50
Frozen Soil	117.8	1.97	0.19	0.35
Grass/Crops	2.21	1.33	138	0.42
Close Conifer	1.66	1.01	163	0.50
Other Forest	1.57	1.22	87.3	0.50

Some grease ice was present in March 1997, so these results should not be taken as significant validation of the permittivity models. Note the bias evident in these curves at low incidence angles (< 10°), due to reflection of the aircraft in the surface.

Lake Ice also exhibits specular behaviour, though the bias at low incidence angles is insignificant. The apparent decrease in the ice's emissivity at 24 GHz may be attributable to the fact that it was not sufficiently thick to be treated as an infinite dielectric slab.

Although *Bare Soil* has a high emissivity, very little polarisation contrast was observed. Such behaviour cannot be explained by a simple Bragg scattering model, which implies the emissivity tends to unity as the roughness increases. A geometric optics model could reproduce these results, but is too computationally expensive for use in operational satellite retrievals. The dashed curves on these plots represent an average of vertical and horizontal polarisations, as would be obtained with a polarisation mixing parameter, $Q = 0.5$. This provides a reasonable fit to the observations, except at 157 GHz.

Frozen Soil surprisingly shows lower average emissivities than samples where the surface temperature was measured to be > 0°C. However, the variance was even greater in this category and the polarisation at 24GHz is characteristic of the specular behaviour of ice on the surface, though this was not evident on the video footage.

Crops/Grass have been combined here, as their nadir emissivity spectra could not be differentiated. This group shows very similar emissivity curves to bare soil, and actually appears to have more polarisation contrast.

Close Conifer Forest was observed in March 1997 and shows very high emissivity at all frequencies, with no polarisation, due to the large optical depth of the canopy and its low single scattering albedo.

Other Forest combined all remaining forest categories observed in summer and winter. The average canopy density of this group was somewhat lower, exposing some bare soil and rocky outcrops, resulting in a decrease in emissivity, especially at the lower frequencies.

VI. Conclusions

This paper has presented the measurements of boreal forest and agricultural land in Sweden by airborne microwave

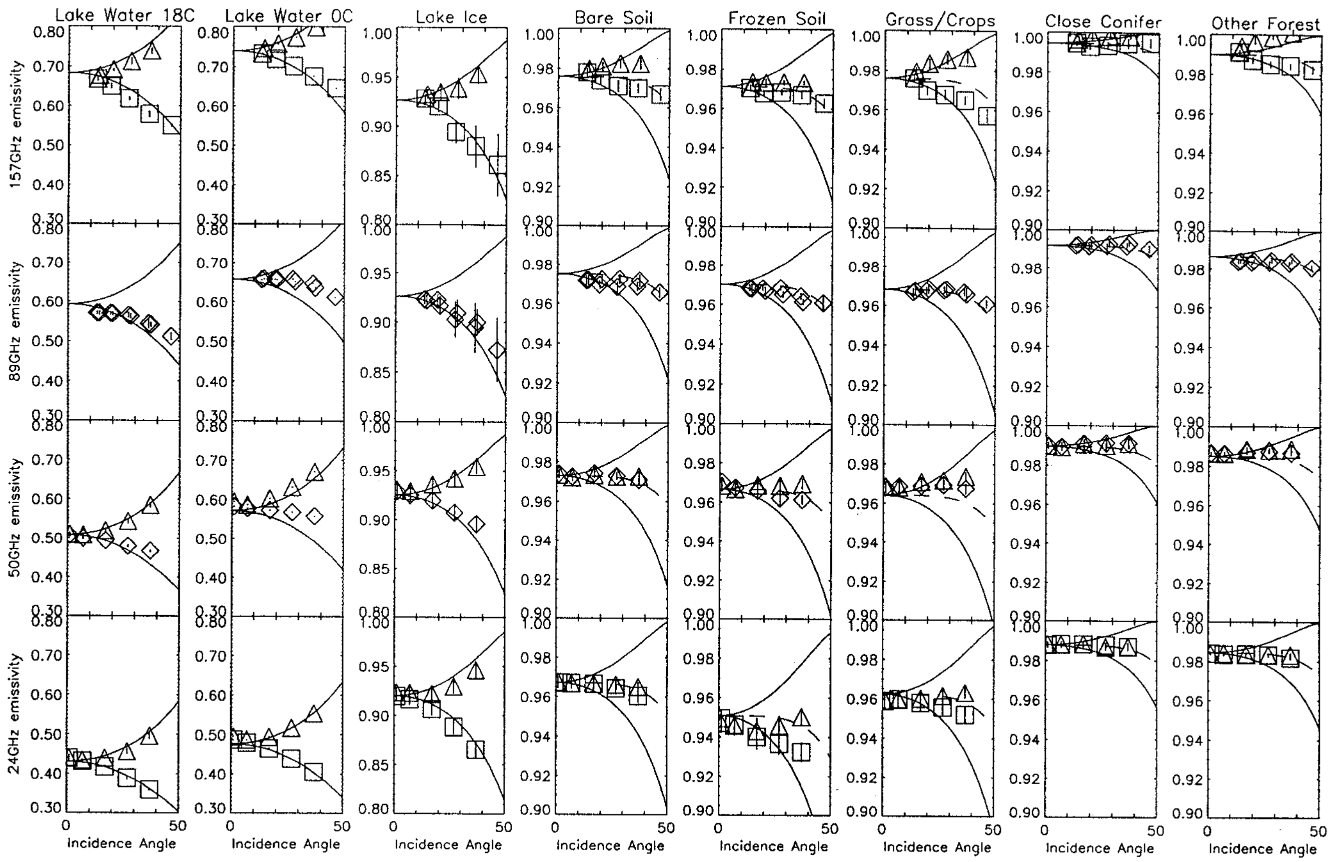

Fig. 1. Angular Variation of Emissivity. △: Vertical, □: Horizontal, ◇: Mixed Polarisation

radiometers. They have allowed the development of a fast, parametric model capable of representing the emissivity of these surfaces over the range of frequencies and view angles needed for the next generation of satellite sounding instruments.

The model presented is based on a 3 parameter Debye formulation of effective permittivity, and Fresnel's equations can predict the variation of emissivity with frequency from 20-200 GHz. With a more extensive dataset, complemented by high density ground truth data, it may be possible to relate these parameters to physical variables, such as biomass or soil moisture.

An additional polarisation mixing parameter is necessary to represent the observed decrease in polarisation contrast over land surfaces. It is likely that this parameter is frequency dependent, though this cannot be confirmed because of the limitations of the instruments used in this experiment.

VII. Acknowledgments

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References

[1] T.J.Hewison, S.J.English, "Analysis of a Microwave Airborne Campaign over Snow and Ice (MACSI)", Proceedings of EMAC94/95 Final Results workshop WPP-136, ESTEC, 1997.

[2] J.R.Wang and B.J.Choudhury, "Remote Sensing of Soil Moisture Content over Bare Field at 1.4GHz Frequency," *J. Geophys. Res.*, **86**, 1981, pp.5277-5282.

[3] A.A.van de Griend and M.Owe, "Microwave Vegetation Optical Depth and Inverse Modelling of Soil Emissivity Using Nimbus/SMMR Satellite Observations," *Meteorol.Atmos.Phys.*, Vol.54, 1994, pp.225-239.

[4] T.Hewison, "The Design of Deimos: A Microwave Radiometer with Channels at 23.8GHz and 50.3GHz for the UK Met. Research Flight C-130 Aircraft," *Proc IGARSS*, 1995, pp.2261-3.

[5] S.J.English, C.Guillou, C.Prigent and D.C.Jones, "Aircraft measurements of water vapour continuum absorption," *Quarterly Journal of the Royal Meteorological Society*, vol.120, 1994, pp.603-625.

[6] K.Lamkaouchi, A.Balana and W.J.Ellison, "New permittivity data for Sea Water (30-100GHz)," *Report on extension to ESTEC/ESA Contract No 11197/94/NL/CN*, 1996

[7] W.J.Ellison, A.Balana, G.Delbos, K.Lamkaouchi, L.Eymard, C.Guillou, C.Prigent, "Study and measurement of the dielectric properties of sea water," *ESTEC/ESA Report on Contract No 11197/94/NL/CN*, 1996