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A fast generic microwave emissivity model

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Abstract

In recent years an increasing diverse range of passive microwave satellite data has become available for applications in numerical weather forecasting, climate studies and environmental monitoring. Many of these data types are measuring top of atmosphere radiance which has originated from both the surface and the atmosphere. When retrieving atmospheric quantities such as temperature, humidity or cloud liquid water content near the surface it is necessary to correctly account for the contribution to the measured radiance from the surface. This depends on the surface emissivity, which varies widely with surface type, roughness and temperature. For real time applications such as numerical weather forecasting, it is necessary to be able to model the surface emissivity very quickly. There is therefore a need for a fast surface emissivity model for any surface type, instrument geometry and observation wavelength. A fast generic emissivity model has therefore been developed. This is a semi-empirical model. Some aspects are physically based, for example many surfaces can be assumed to be dielectric media. Other aspects such as geometric roughness have been parameterised for speed. For some complex or poorly understood aspects of the electromagnetic interaction empirical adjustments are made to fit observed values. The model has been compared with emissivities derived from aircraft radiometer measurements at 24, 50, 89 and 157 GHz. It is also intended to compare with data from the SSM/I and AMSU instruments. For the ocean surface the fast model fits observed data to within 1-2%, and it fits the unparameterised model to within 0.1-0.3%.

Key-words: microwave, emissivity, AMSU, SSM/I, radiometer, radiance, fast-model, ocean, land

1. Introduction

Radiances measured at the top of the atmosphere now form a key part of the global meteorological observation network for numerical weather prediction (NWP) (Eyre 1993, Gadd *et al.* 1995, Derber 1997). Over the sea passive microwave data has been used for ocean and atmosphere applications, whereas over land and ice surfaces the most extensive studies have been for surface applications. A few studies have attempted to retrieve cloud liquid water over land surfaces (Jones and Vonder Haar 1990, Jones and Vonder Haar 1997, Greenwald *et al.* 1997, Combs *et al.* 1998) and Prigent and Rossow (1998) have investigated retrieval of skin temperature, water vapour and liquid water using a climatology of emissivity derived in Prigent *et al.* (1997). English (1998) showed that humidity retrievals from the Advanced Microwave Sounding Unit are particularly sensitive to emissivity and emissivity model error, whereas temperature retrievals are more sensitive to the quality of prior knowledge of skin temperature. These studies have shown that there is potential for retrieving information on cloud liquid water path, water vapour profiles and skin temperature over land using microwave radiances, but that the information is very sensitive to a range of parameters, including emissivity. With an increasing number of different microwave sensors, and the desire to expand the use of radiance observations over land and ice surfaces, a need has arisen for a generic all-surface emissivity model.

Isaacs *et al.* (1989), van de Griend and Owe (1994), Felde and Pickle (1995), Prigent *et al.* (1997) and Sherjal *et al.* (1998) have attempted to estimate land surface emissivity at high frequency in the context of extending atmospheric parameter retrievals to land and ice surface and recent measurements by Matzler (1994), Hewison and English (1998) and Hewison (1998) have improved estimation of land and ice emissivity at frequencies higher than those traditionally used for land and ice surface applications. Theoretical models have primarily been applied using low frequency approximations (e.g. dense medium or strong fluctuation theory) which make them unsuitable for higher frequency applications (e.g. Surdyk and Fily 1995).

This paper presents a generic emissivity model which adopts a semi-empirical approach. At the heart of the model are equations which represent real physical processes, such as specular reflection by a surface, Bragg scattering and layering. However the coefficients used in these models are not physically derived, but are based on a mixture of laboratory measurements and aircraft radiance observations. Although the equations relate to physics which is inappropriate for some surfaces, it still provides a suitable mathematical framework for a purely empirical model.

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2. The surface emissivity model

Surfaces can be divided into those which behave like a dielectric medium and those which do not. The former are characterised by homogeneity on a scale large compared to the wavelength of observation. In this case emissivity can be easily calculated if the dielectric properties of the medium are known. If however there are irregularities the theory may have to be modified. It may be possible to treat the medium as an effective dielectric medium, using for example Maxwell-Garnett theory to predict effective dielectric properties for the heterogeneous mixture. As the complexity of the electromagnetic interaction with the surface increases, more terms need to be added to the estimation of surface emissivity. Where we have no *a priori* information to use in these models, their increased complexity may be of little value for sounding applications. Here the requirement is for a simple model which constrains the retrieval of emissivity in a physical way. One such model was proposed by Grody (1993), but this did not predict polarisation or view angle dependence. We extend the Grody approach by bringing it closer to the physical processes which determine the emissivity. There are five components to the model.

2.1 Specular reflection

The Fresnel reflectivities $R_h(\nu, \theta)$ and $R_v(\nu, \theta)$ where ν is frequency of the observed radiance and θ is the incidence angle can be calculated if the permittivity of the surface is known. For water the permittivity is calculated from laboratory measurements (Lamkaouchi *et al.* 1997) of the Debye parameters. For non-ocean surfaces, an estimation of the Debye parameters is made which gives the best fit to the observed spectral radiance variation, which is measured using airborne radiometers at 24-157 GHz. For surfaces which are not homogeneous (i.e. they do not have a single permittivity) the permittivity is better defined as an effective (rather than average) permittivity i.e. the permittivity which when used in the Fresnel reflection equation gives the observed reflectivities. The Fresnel reflectivities can be written,

$$R_v(\nu, \theta) = \left| \frac{-\epsilon(\nu)\cos(\theta) + \sqrt{\epsilon(\nu) - \sin^2(\theta)}}{\epsilon(\nu)\cos(\theta) + \sqrt{\epsilon(\nu) - \sin^2(\theta)}} \right|^2$$

$$R_h(\nu, \theta) = \left| \frac{-\cos(\theta) + \sqrt{\epsilon(\nu) - \sin^2(\theta)}}{\cos(\theta) + \sqrt{\epsilon(\nu) - \sin^2(\theta)}} \right|^2$$

This effective permittivity, $\epsilon(\nu)$, can be calculated from a form of the Debye equation simplified to,

$$\epsilon(\nu) = \frac{\epsilon_s - \epsilon_\infty}{1 - \frac{i\nu}{\nu_r}} + \epsilon_\infty$$

For some surfaces the Debye parameters ($\epsilon_s, \epsilon_\infty, \nu_r$) are well defined measurable quantities (e.g. Lamkaouchi (1997) for saline water). For other surfaces they have no physical meaning but are useful to give some form to the parameterisation. English (1998) derived a model for the ocean surface in this form, and Hewison and English (1998) and Hewison (1998) have applied it to land and ice surfaces, deriving the coefficients empirically from measured brightness temperatures over field sites.

2.2 Bragg scattering

It has been shown that Bragg scattering is an important process in determining the surface reflectivity (Wu and Fung 1972, Choudbury 1979). The Fresnel reflectivities are multiplied by a factor $B(\nu, \theta, h)$, where h is a function of small-scale roughness, and is again empirically derived from aircraft measurements (Hewison 1998, Hewison and English 1998). $B(\nu, \theta, h)$ can be written as,

$$B(\nu, \theta, h) = e^{-h\cos^2(\theta)}$$

where $h=(4\pi v\sigma/c)^2$, σ is small scale surface roughness, c is the speed of light and π is pi. For the ocean it is difficult to separate the small-scale and large scale roughness, to determine σ^2 , and various wave-spectra models exist. It is accepted that slope variance has a power-law behaviour of the form k^{-4} , where k is wavenumber (see Apel 1994) across a wide range of wavenumbers. The dependence on windspeed is expected to be close to linear. So it is assumed that σ^2 has the form U^b/v^4 , where U is windspeed and b a constant. Therefore for ocean h is assumed to have the form aU^b/v^2 , where a and b are constants, and the term $(4\pi/c)^2$ has been absorbed into a . In section 3 it will be shown that setting both a and b equal to unity gives good agreement with measurements of rough ocean brightness temperature.

Bragg scattering can also be an important process for other surfaces, but here we do not usually have a parameter equivalent to windspeed for the ocean to use in a parameterisation. Hewison (1998) and Hewison and English (1998) therefore found the value of σ^2 which gave good agreement with aircraft brightness temperature measurements in the mean sense.

2.3 Multiple-layering

Surfaces often have a fractional coverage by another optically thick medium (e.g. foam on ocean). We therefore multiply the modified reflectivities by $(1-F)$, where F is the fractional coverage of the upper medium, (see Wilheit 1979). This very simple treatment only works when the upper layer is optically thick, and is included primarily to solve the foam problem.

2.4 Geometric roughness

Roughness which has a large scale compared to the wavelength of observations gives geometric specular reflection. Large scale roughness effects are not modelled except for the ocean surface. To calculate emissivity it is necessary to have a model of wave slopes as a function of windspeed (e.g. Cox and Munk 1955). A geometric calculation is required to calculate the contribution from each slope measured by a radiometer. Furthermore it is necessary to know the previous path of the reflected ray from each slope, which have often undergone previous reflections on other slopes. Therefore it is a slope part of the code, whose accuracy depends strongly on how representative the ocean slope model is. As large scale roughness often corresponds to ocean swell, which may have no relation to instantaneous windspeed, this is a large source of error. In this model the specular reflectivities have a factor $\Delta R_v(v,\theta,U)$ and $\Delta R_h(v,\theta,U)$ added to vertical and horizontal polarisations respectively, where U is windspeed. This follows the approach of Petty and Katsaros (1994), except that all the differences between a specular reflection and an integration across all the slopes, are included in $\Delta R_v(v,\theta,U)$ and $\Delta R_h(v,\theta,U)$. ΔR_v and ΔR_h are parameterised in terms of windspeed, frequency and the secant of view angle. This scheme builds on that proposed by Petty and Katsaros (1994) except that more predictors are used to calculate ΔR_h and ΔR_v , and no predictor using skin temperature is employed (it was found to be unnecessary). At a surface skin temperature of 273K and assuming the variance of roughness to be proportional to windspeed the Petty and Katsaros formula reduces to,

$$\Delta R \propto W(a+b.\theta)$$

where a and b are coefficients which depend on frequency and polarisation. In this model the secant of the view angle is found to be a better predictor than angle and the polynomial is extended to achieve higher accuracy (of 0.1%) such that,

$$\Delta R \propto W(a+b.\sec\{\theta\})+c.\sec\{\theta\}+d.\sec^2\{\theta\}+e.W^2$$

and a , b , c , d and e are coefficients which are a function of frequency and polarisation. Furthermore in this model it is found that a , b , c , d and e are all monotonic functions of frequency, ν , such that $a=a_0+a_1 \cdot \nu$ and similarly for b , c , d and e . In this model ΔR is defined to include reflected rays from non-specular angles, so no additional non-specular term is needed. Mathematically ΔR is defined as,

$$\Delta R=(T_s-T^\uparrow)/(T_s-T^\downarrow)-R$$

where T^\uparrow is calculated without a specular assumption, i.e. all geometric roughness effects are absorbed into ΔR using an approach based on Wilheit (1979), where the Cox and Munk (1955) slope roughness has been used. At high frequency the total Cox and Munk geometric slope roughness is used, and for frequencies below 35 GHz the slope variance is linearly reduced towards the Cox and Munk slick value at 0 GHz. This parameterisation of roughness gives a similar spectral slope to that presented by Wentz (1982). Fig. 1 compares the fast model to the full geometric optics solution for 24 GHz, and Fig. 2

shows the same result at 157 GHz. At low frequency the fast model is near perfect, the standard deviation being less than 0.1% with no bias. At higher frequency the fit is slightly less good, with a standard deviation just over 0.3%. This is because the geometric slope variance is higher and the correction due to roughness is correspondingly larger. The loss of accuracy in the fast model is still small compared to the uncertainty in the slow model, which is around 1.0%, and is also larger at higher frequency.

2.5 Depolarisation

The four processes modelled above do not and can not allow for all mechanisms which depolarise the emitted radiance. Importantly biomass depolarises, and other surfaces such as sea-ice show less polarisation than would be expected from a specular reflectivity calculation. If good agreement with the specular calculation is found for nadir observations the depolarisation can not be caused by geometric roughness, which would decrease the nadir reflectivity. Therefore to allow the model to fit aircraft observations a fifth term, simply called a depolarisation factor, $Q(v)$, is added (see Hewison 1998).

2.6 The complete model

Dropping the arguments, the emissivity forward model can be written,

$$E_v = (1 - \{(1-F)(R_v.B + \Delta R_v)\})Q + (1 - \{(1-F)(R_h.B + \Delta R_h)\})(1-Q)$$

$$E_h = (1 - \{(1-F)(R_h.B + \Delta R_h)\})Q + (1 - \{(1-F)(R_v.B + \Delta R_v)\})(1-Q)$$

The parameter F is neglected for surfaces other than foam-covered water, and ΔR_v and ΔR_h are also only calculated for the ocean. The coefficients $\epsilon_s, \epsilon_\infty, v_r, h$ and Q are listed in Table 1 for a range of surfaces. Note for some surfaces small scale roughness has been absorbed in to $\epsilon_s, \epsilon_\infty$ and v_r , and h is set to zero.

Surface type	Permittivity coefficients			Roughness	Depolarisation
	ϵ_s	ϵ_∞	v_r	σ	Q
OPEN WATER					
Ocean	From Lamkaouchi (1997)			0.1W	0.0
SEA ICE					
Grease ice	23.7	7.7	17.3	0.0	0.15
Baltic Nilas	1.6	3.3	2.2	0.0	0.0
Arctic Nilas	12.6	5.1	21.2	0.0	0.0
New ice (no snow)	2.9	3.4	27.0	0.0	0.0
New ice (snow)	2.2	3.7	122.0	0.0	0.15
Brash ice	3.0	5.5	183.0	0.0	0.0
Compact pack ice	2.0	1.7e6	4.9e7	0.0	0.0
Fast ice	1.5	77.8	703	0.1	0.35
Lake ice + snow	1.8	67.1	534	0.1	0.15
Multi-year ice	1.5	8.5e4	4.7e6	0.0	0.0
WINTER LAND SURFACES					
Forest and snow	2.9	3.4	27.0	0.0	0.0
Deep dry snow	3.0	24.0	60.0	0.1	0.15
Frozen soil	117.8	2.0	0.19	0.2	0.35
SUMMER LAND SURFACES					
Forest	1.7	1.0	163.0	0.0	0.5
Open grass	2.2	1.3	138.0	0.0	0.42
Bare soil	2.3	1.9	21.8	0.0	0.5

Table 1: Emissivity model coefficients from Hewison (1998), Hewison and English (1998) and English (1998). Note for ocean $\sigma=0.1W$ where $W=10m$ windspeed.

3. Validation

Fig. 3 shows the calculated emissivity plotted against values estimated from measurements of ocean brightness temperatures made by the radiometers described in the introduction. The "observed" emissivity has an accuracy of about 0.5% at 24 GHz and 1.0% at 157 GHz. Four plots are shown, which indicate the validation of a flat specular model, a model with Bragg

scattering removed, a model with no representation of geometric roughness, and finally the "complete" model, which represents both processes (sometimes referred to as a two-scale model). At 24 GHz the standard deviation falls from 1.54% when roughness is not modelled to 1.05% when roughness is modelled. The most significant part of this improvement arises from modelling geometric roughness, but the Bragg component is also important. Bias is similarly reduced from 1.92% to 0.35%, indicating that a large part of both the geometric and Bragg effects is one-sided (i.e. bias). Results are slightly different at 157 GHz and are shown in Fig. 4. Again modelling roughness improves the fit from a standard deviation of 2.04% to 1.30%, but almost all of this arises from geometric roughness, the Bragg component being unimportant at high frequency. Fig. 5 shows validation versus view angle and for vertical and horizontal polarisations for both a calm ocean surface (windspeed 0 ms^{-1}) and a rough ocean surface (windspeed 12 ms^{-1}) at 24 GHz. Without the modelling of roughness a significant higher bias occurs at high windspeed, whereas the complete model gives a residual bias of +1% near nadir and +1.5% (horizontal polarisation) and -1.5% (vertical polarisation) at 40° for the calm and rough ocean cases. Fig. 6 shows a plot of emissivity differences (calculated minus observed), again at 24 GHz, against windspeed at the nadir view angle. When roughness is not modelled a linearly increasing bias with windspeed is observed, which is removed by the modelling of roughness (note both flat and rough models accounted for the effect of whitecapping).

For other surfaces validation is more difficult. It is not straightforward to separate emissivity model errors from the errors due to inadequate background information. For example dense forest has a highly predictable emissivity which varies little with snow cover and wetness. However more open forest has a variable emissivity, because of variations in emissivity arising from the forest floor. Therefore the emissivity model really needs to know the fractional coverage of forest in the field of view. Typically this will not be known. However it is important to be distinct that this is a background error not an emissivity model error. Emissivity model errors arise when the physics in the model is incorrect, or empirically tuned coefficients are not globally representative. Assumptions such as specular reflection, Bragg term coefficients, effective permittivities, depolarisation all have errors which contribute to the forward model error. Because we have simplified the model to be consistent with the level of background information available, the forward model error for non-sea surfaces will be high. Much larger gross errors can occur if the wrong surface is assumed, but these should be identified by adequate quality control. If two surfaces are radiometrically very similar, the emissivity model coefficients will be adequate as a first guess for either surface in an atmospheric profile retrieval package. A number of existing studies have derived emissivities for a wide range of surface types at frequencies above 20 GHz (Comiso *et al.* 1989, Isaacs *et al.* 1989, Mätzler 1994, Felde and Pickle 1995, Prigent *et al.* 1998). Comparison of the current model with these studies shows broad agreement, as illustrated by Fig. 7 (land surfaces) and Fig. 8 (sea ice). Difficulties do arise where surface type classifications are poorly defined ("dense" forest, "dry" snow, "young" ice etc.).

For land surfaces the emissivity depends strongly on vegetation cover. The model of Isaacs *et al.* and the study by Prigent *et al.* all showed emissivity to rise with increasing vegetation biomass, especially for horizontal polarisation. However precise values range considerably, some of which is due to varying definitions of land surface classes. For example bare soil 85-90 GHz mean emissivity (the average of vertical and horizontal) ranges from as low as 0.89 and 0.92 in the studies by Prigent *et al.* and Mätzler to 0.96 in this paper and 0.98 in Felde and Pickle. Those studies which separated frozen soil from unfrozen soil showed emissivity to increase by around 0.02 on freezing. Short grass very slightly increases the emissivity (increases range from 0.00 to 0.02), but forest or dense vegetation increases the emissivity close to unity (with the exception of Felde and Pickle, which showed a lower emissivity for dense forest than soil).

Snow cover also significantly changes the emissivity. The study by Mätzler is the most comprehensive for frequencies above 20 GHz. This study showed the emissivity of dry snow to be low (0.6-0.8) and most variable at highest frequency, in agreement with Hewison's results. The low emissivity is due to volume scattering in the snow crust, which increases with decreasing wavelength. The precise depression of the brightness temperature depends on the thickness of the crust, which is variable and gives the observed high variability. This short scale noise will be spatially averaged over a satellite instrument field of view. The radiative transfer is almost linear so the effective emissivity will have a mean close to the mean which would be expected from the mean crust thickness in the field of view, and have low noise due to the spatial averaging. The model coefficients in Table 1 do not agree with the permittivity model in Mätzler (1994), nor should they be expected to. The fast model coefficients should not be interpreted as Debye parameters, and do not correspond to permittivity of real snow, because the effect of scattering has been absorbed into the effective permittivity. For a scattering surface the parameters used in this model have no physical meaning, but the analogy with a Debye form is a convenient mathematical framework.

The results for sea ice have been compared with Comiso *et al.* (1989). Comparing at 90 GHz, the emissivities for open water are in good agreement. The emissivity of nilas is slightly lower in Comiso's study (0.89-0.90, compared with 0.92), probably due to higher salinity in the Weddell sea ice compared to the Baltic. Good agreement is achieved for grease ice. Comiso's young ice category is assumed to be equivalent to Hewison's bare new ice, in which case Comiso again found a lower emissivity (0.86 against 0.91). Compact pack ice in Hewison's paper gives a very similar emissivity to Comiso's smooth and

rough first year sea ice, both around 0.85. Therefore the two studies give reasonable agreement for very thin ice and older, snow covered ice, but Hewison's paper, on which the model presented in this paper is based, may be biased towards low salinity ice for young, snow-free ice types. Hewison's paper confirmed that signatures usually associated with first-year or multi-year sea ice can be observed in much younger snow covered compact pack ice, fast ice and lake ice.

4. Conclusions

A fast emissivity model capable of predicting emissivity has been generated from a mixture of theoretical and empirical information, and building on existing studies where possible. It has been demonstrated to give good agreement with aircraft observations of emissivity, and to give similar emissivities to previous studies. A new parameterisation of both geometric roughness and Bragg scattering have been introduced, which lends itself to fast computation and simple calculation of model adjoint and tangent-linear, whilst retaining a fully generic capability. For the ocean surface the model is accurate to 0.5%. For other surfaces the accuracy is variable, ranging from 5-10% for snow surfaces, 2-5% for ice and open land and 1-2% for forest. Comparison with existing measurements and model predictions has been attempted for a range of surfaces, but is hampered by varying or imprecise definitions of surface categories, and lack of information on heterogeneity. Nonetheless for most surface categories fair agreement can be achieved.

The model is designed for atmospheric sounding applications. It does not have the sophistication to retrieve surface parameters except for the ocean, but is intended to solve the boundary condition problem in retrieving water vapour, temperature, cloud liquid water and precipitation rate from passive microwave radiometers.

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6. Figures

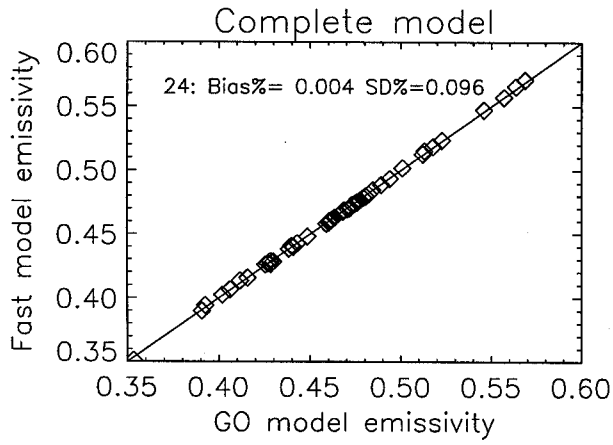


Figure 1: The fit of the fast model to the full geometric model at 24 GHz.

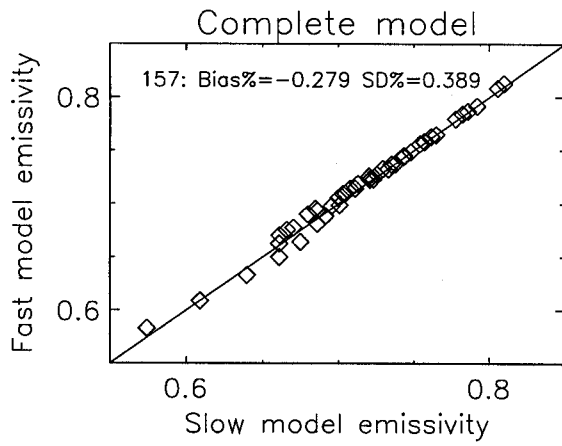


Figure 2: The fit of the fast model to the full geometric model at 157 GHz.

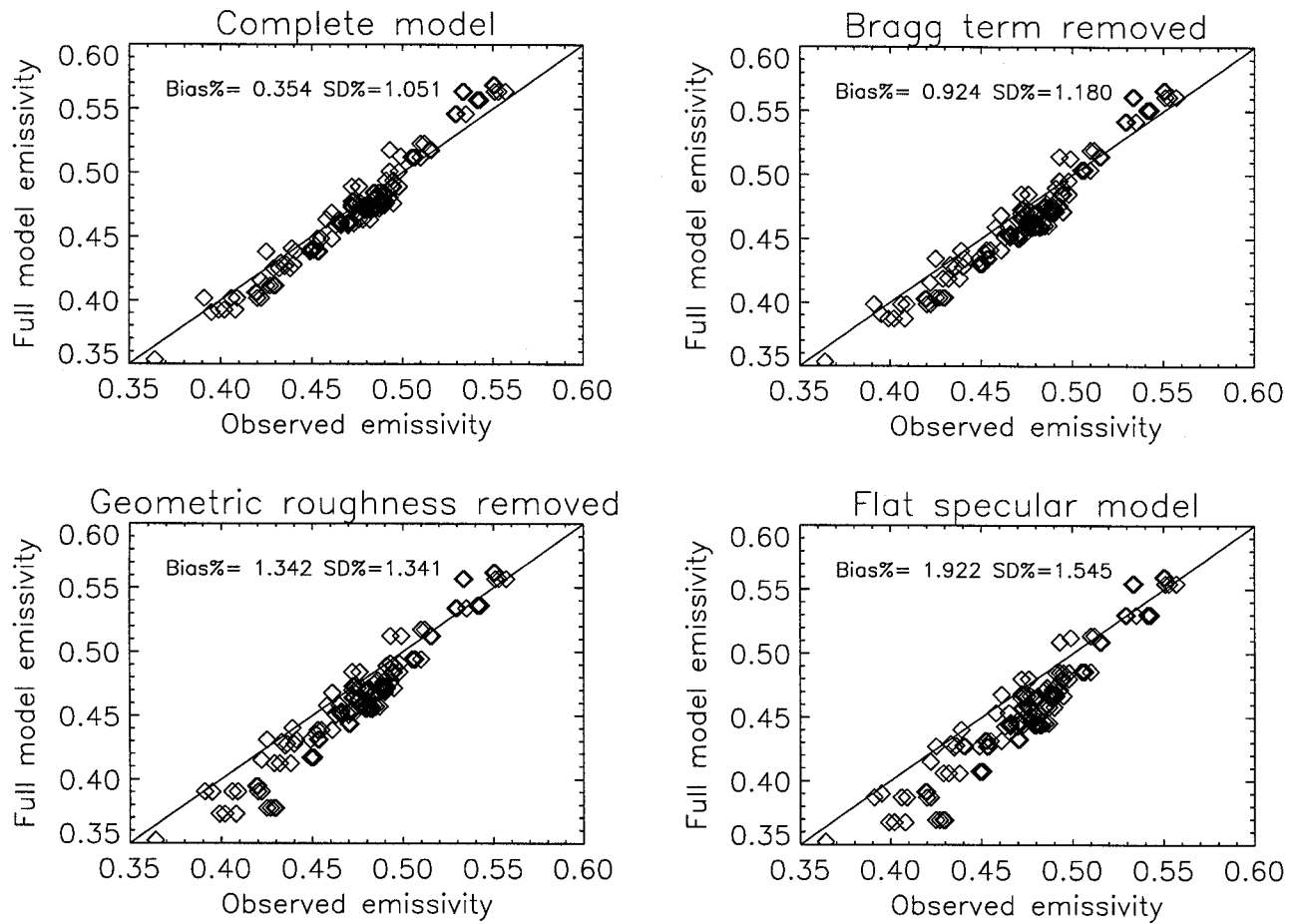


Figure 3: Calculated emissivity from full model versus emissivities estimated from airborne radiance measurements at 24 GHz. The comparison is shown using a specular flat model (with foam), a model with no Bragg term, a model with no geometric optics integration and finally the full model. The roughness modelling is realistic in the sense that it improves the fit to the observation both in terms of bias and standard deviation.

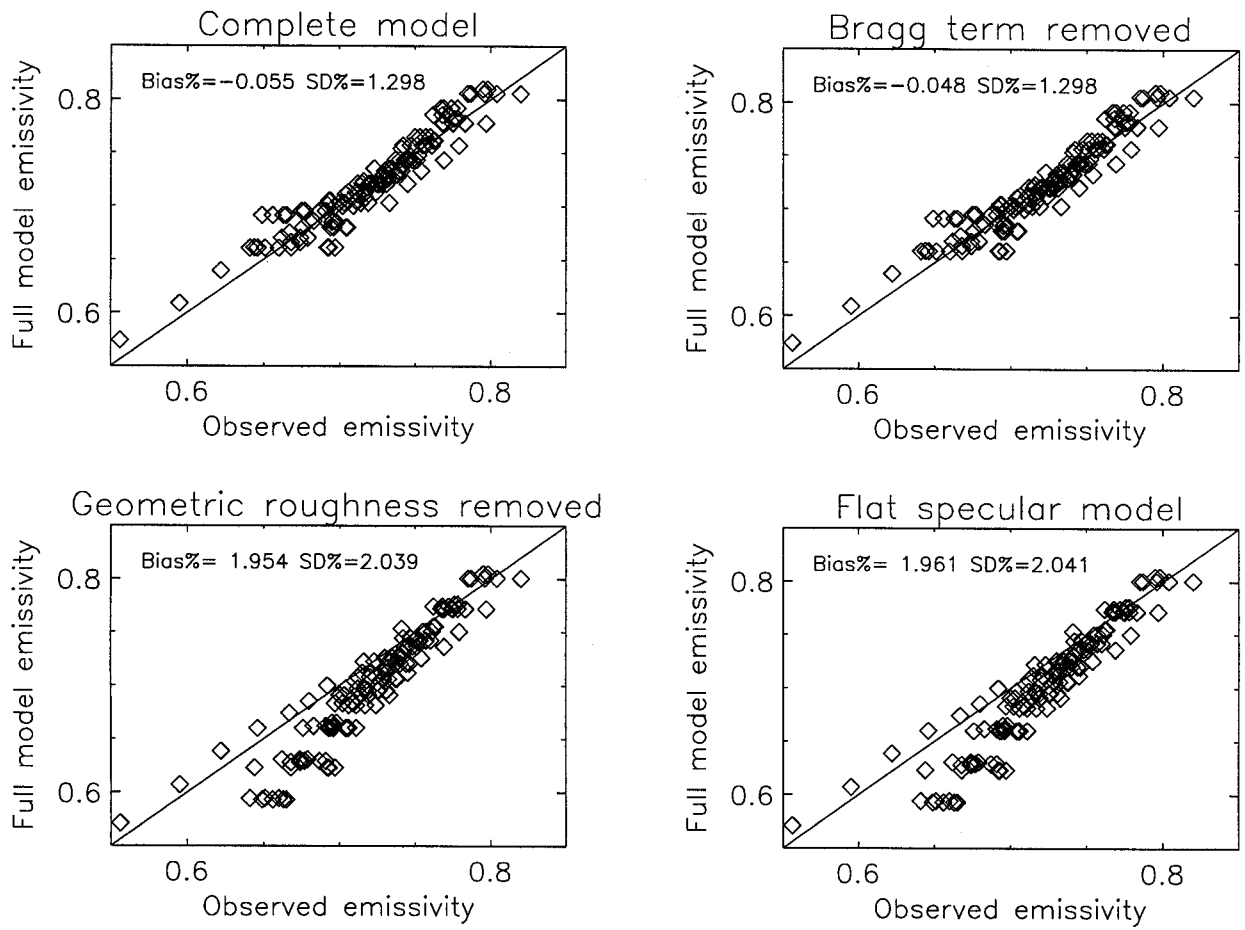


Figure 4: As Fig. 3 for 157 GHz.

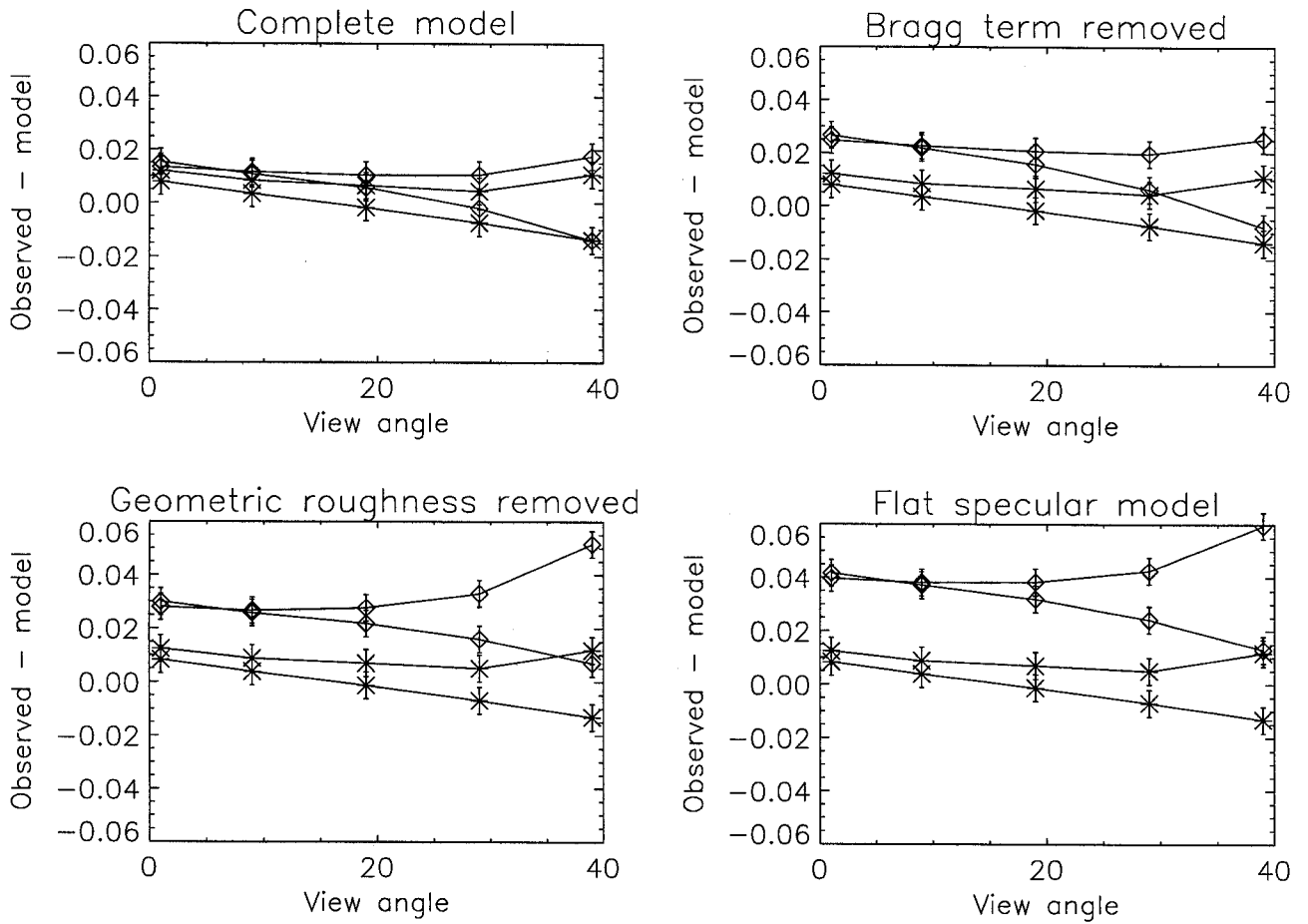


Figure 5: Difference between calculated emissivity and "observed" emissivity at 24 GHz versus incidence angle for vertical and horizontal polarisations. In each figure there are two pairs of curves. The upper pair is for the rough ocean (windspeed 12 m/s) and the lower pair for a calm ocean. In each pair the upper curve is horizontal polarisation (i.e. at large view angle the model tends to underestimate horizontal polarisation and overestimate vertical polarisation so more depolarisation is occurring than would be expected). This could be corrected by setting $Q \approx 0.03$ for the ocean surface.

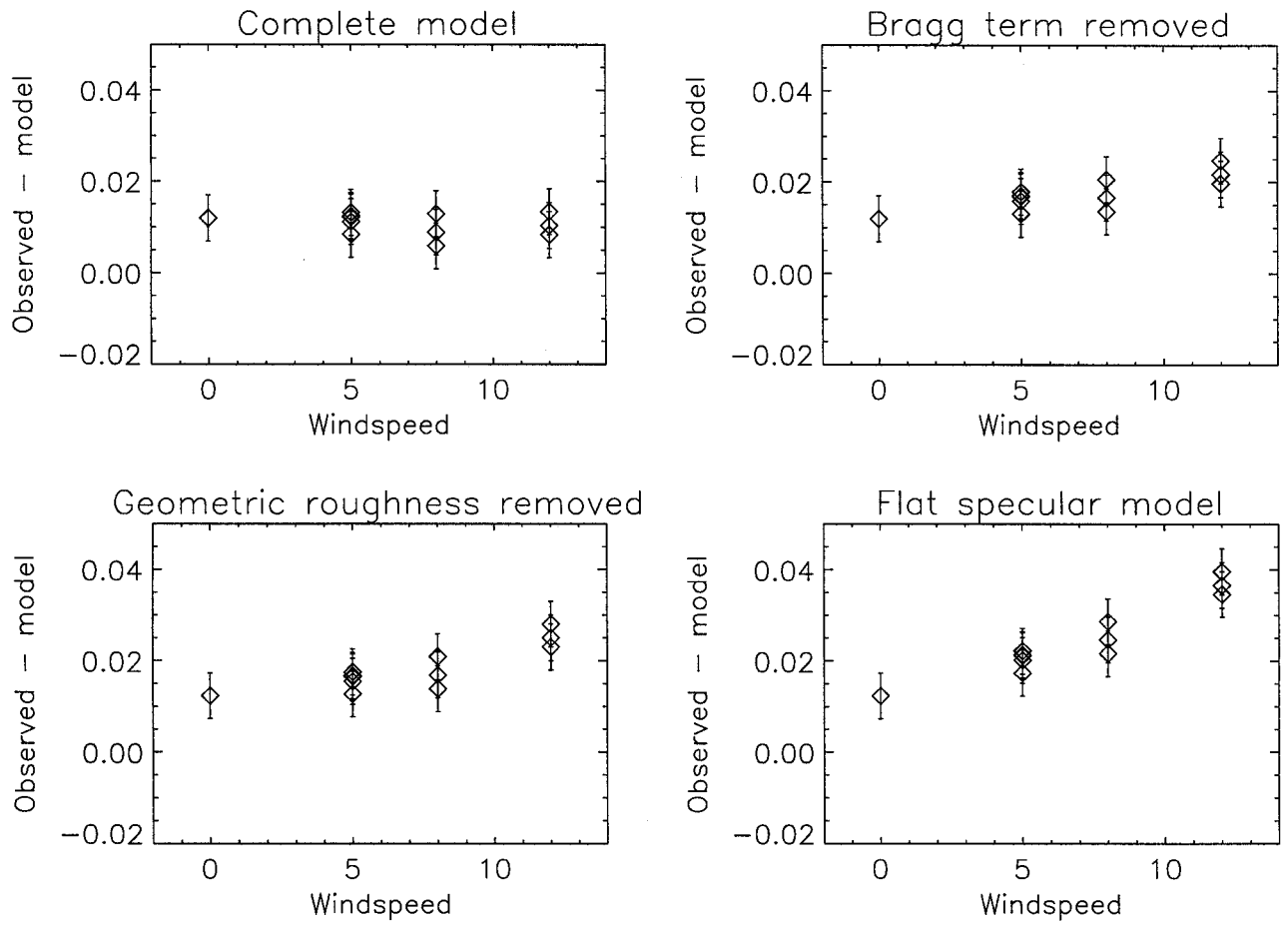


Figure 6. Difference between calculated emissivity and "observed" emissivity at 24 GHz versus windspeed. The linear trend of difference with windspeed for a specular surface is replaced by a constant bias when roughness is modelled.

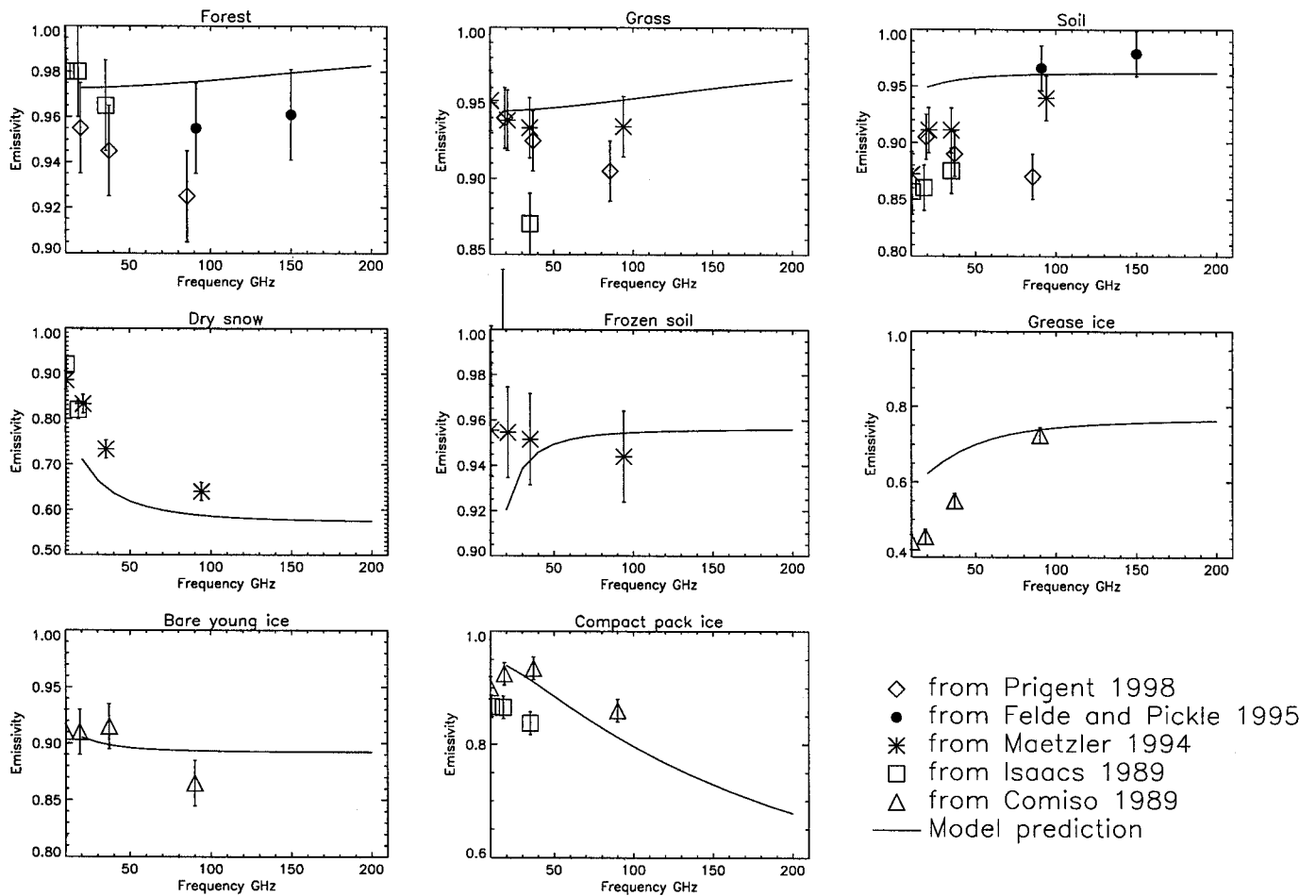


Figure 7. Mean emissivity (vertical plus horizontal polarisation) plotted against frequency from the fast model and from a range of literature sources for land surface types (soil/desert, frozen soil, grass, forest, dry snow) and sea ice (grease ice, bare young ice/new ice, compact pack ice/first year ice). These are for a range of angles 0-54°.

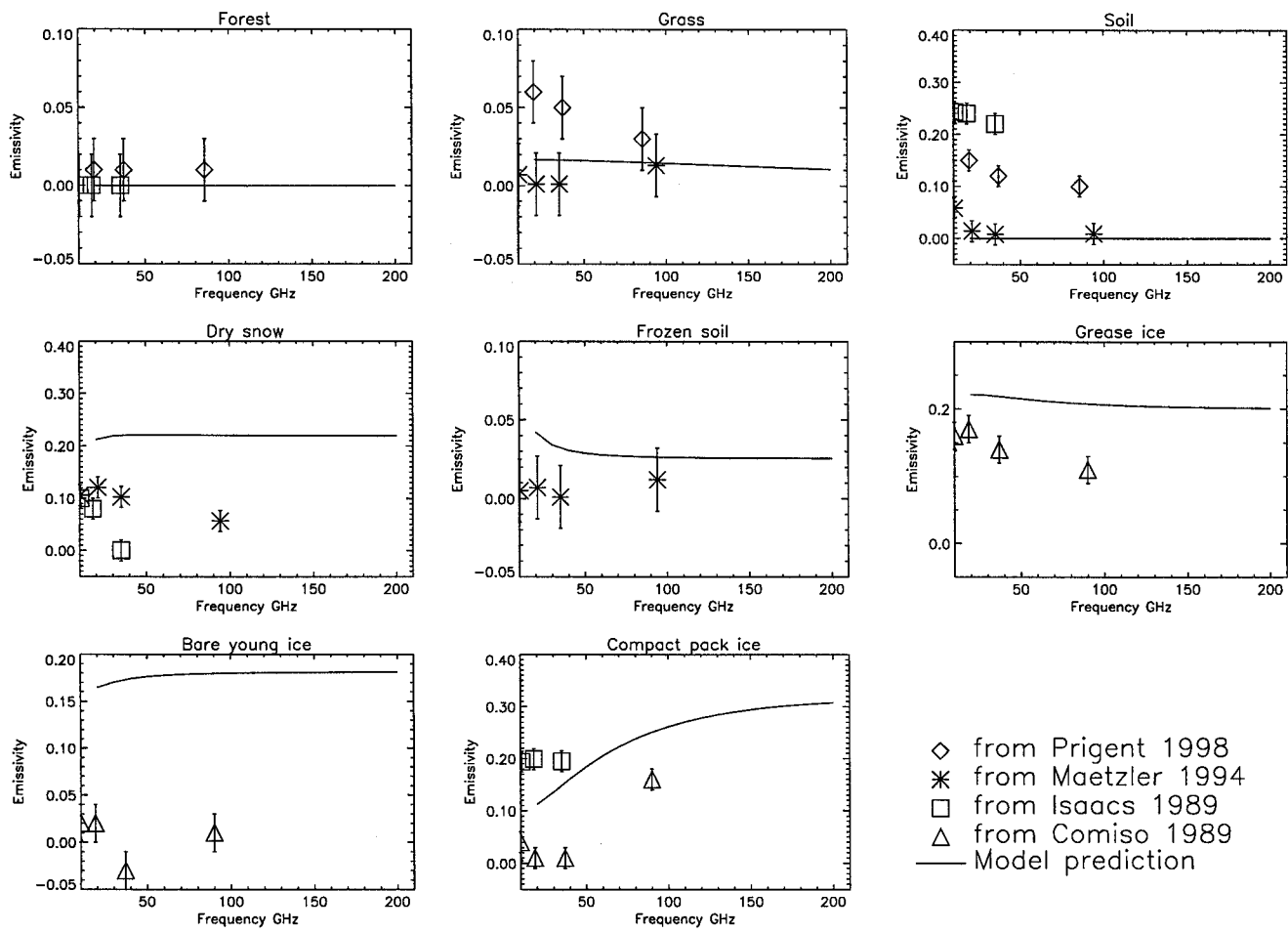


Figure 8. As Fig. 7 but for polarisation difference (vertical minus horizontal) at an incidence angle of 50-53°.