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Capability of *Bhaskara* SAMIR to distinguish atmospheric water vapour and liquid water contents

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Abstract. An environmental model to compute microwave brightness temperatures for downward looking radiometers on board satellite is described. The effects of water vapour, oxygen and clouds on the brightness temperature have been studied for frequencies from 5 to 50 GHz for a standard tropical atmosphere. The effect of look angle on brightness temperature has also been investigated. Based on the model it has been shown that while the radiometers on board *Bhaskara* at 19·35 and 22·235 GHz are capable of giving the atmospheric water vapour and liquid water contents, the ability to distinguish these quantities is more for the combination of the frequencies 22·235 and 31 GHz.

Keywords. Water vapour; liquid water; brightness temperature; *Bhaskara* SAMIR; microwave radiometer.

1. Introduction

Atmospheric water vapour and liquid water contents are important meteorological parameters. Monitoring these quantities over ocean by conventional techniques is difficult. Remote sensing from satellites with passive microwave radiometers offers a good possibility for getting this information.

The Indian Satellite *Bhaskara* has on board passive microwave radiometers operating in the frequencies 19·35 and 22·235 GHz. Preliminary attempts have been made (Pandey *et al* 1979) to derive water vapour and liquid water contents in the atmosphere with *Bhaskara* data for selected passes over Bay of Bengal and Arabian Sea.

The present paper deals with a detailed analysis of the factors involved in the distinction of water vapour and liquid water contents in the atmosphere by microwave radiometry in the frequency range 5 to 50 GHz. A suitable environmental model for carrying out the studies has been described. The results are discussed with special reference to the *Bhaskara* frequencies.

2. Radiation received by a satellite microwave radiometer

The microwave radiation reaching a satellite radiometer can be expressed in terms of the following :

(i) The radiation emitted by the sea.
(ii) The upwelling radiation emitted by the atmosphere.
(iii) The down-welling radiation emitted by the atmosphere and extra terrestrial sources and reflected upward from sea surfaces.
(iv) The attenuation of the radiation emitted and reflected from the sea surface by the intervening atmosphere.

For convenience of computations, the atmosphere has been divided into layers each 1 km thick and is characterised by pressure, temperature and humidity. A standard tropical atmosphere with exponential variation of pressure and humidity has been used in the computation. The model is sensitive to the altitude distribution of atmospheric water vapour and this is automatically taken into account while defining the dimensionless quantity ' ability factor ' for relative comparison of a pair of frequencies. The top of the atmosphere has been set at 30 km above which the water vapour is assumed to be negligible.

3. The environmental model

The emissivity of the sea water plays a key role in determining the radiation emitted by the surface. The emissivity has been calculated by assuming a smooth air-water interface using Fresnel relations to calculate reflectivity from dielectric properties of the surface as a function of viewing angle and polarisation. The emissivity is then given by

$$\epsilon = 1 - | R(\theta, \phi) |^2. \tag{1}$$

The polynomial fits by Holinger (1973) for static dielectric constant, relaxation time and ionic conductivity in terms of salinity and temperature have been used in the computation. These polynomials are based on the data of Saxton and Lane (1952). Since no laboratory measurements of dielectric properties of sea water were available, the measurement on aqueous sodium chloride was approximated to be sea water as far as its electrical properties are concerned.

The above regression equations were used to predict ϵ' and ϵ'' for any given temperature, salinity and frequency. These quantities were then used to compute emissivity using Fresnel's formula (Pandey and Sharma 1980). The dielectric properties of pure water were obtained from the above general expressions by setting salinity to zero.

The upwelling and downwelling radiation is obtained from the solution of radiative transfer equation. The intensity of radiation is described in terms of brightness temperature under Rayleigh-Jeans approximation.

The model used for computing absorption coefficients due to water vapour is the one given by Staelin (1966) based on the interpretation of Barret and Chung's (1962) formula.

The model for computing absorption coefficients due to oxygen molecule is the one given by Rosenkranz (1975). The details of the computation and results for a standard tropical atmosphere are described by Pandey *et al* (1979).

The model for calculating absorption coefficients due to cloud is the one suggested by Paris (1971) and extended by Pandey *et al* (1979) using the polynomial fits of Hollinger and co-workers (Hollinger 1973; Hollinger *et al* 1975) in terms of real and imaginary parts of relative dielectric constants and liquid water contents.

4. Computational procedure

For a non-scattering atmosphere in local thermodynamic equilibrium, the zenith brightness temperature is given by the solution of radiative transfer equation (Chandrasekhar 1960) as

$$T_B = \int_0^\infty [T(z)\,\alpha(z) \exp - \int_0^z \alpha(z')\, dZ']\, dZ \tag{2}$$

where $T(z)$ is the atmospheric temperature at height z and $\alpha(z)$ is the total absorption at height z.

The apparent temperature ideally measured by a radiometer at an altitude h above the surface of the ocean is given by

$$\begin{aligned} T_B = {} & \mathrm{r}\,[T_c \exp[-\sec\theta \int_0^\infty \alpha(z)\, dz] + \int_0^\infty T(z)\,\alpha(z)\sec\theta \\ & \times \exp[-\sec\theta \int_0^Z \alpha(z)\, dZ] \exp[-\sec\theta \int_0^h \alpha(z)\, dz] \\ & + \epsilon T_S \exp[-\sec\theta \int_0^h \alpha(z)\, dz] + \int_0^h T(z)\,\alpha(z)\sec\theta \\ & \times \exp[-\int_Z^h \alpha(z')\, dz']\, dZ. \end{aligned} \tag{3}$$

The first term of equation (3) is the cosmic background radiation whose contribution is small and has not been included in the computation. The second term is called sky brightness temperature and for computer implementation, it can be written as

$$T_{sky} = \sum_{i=1}^{n-1} [(1 - t_i)\, \bar{T}_i \prod_{j=0}^{i-1} t_j] \tag{4}$$

$$t = \text{transmittance} = \exp[-\sec\theta \int \alpha(z)\, dz].$$

This is the downwelling radiation received at the surface. The term with emissivity in equation (3) is the surface contribution to the brightness temperature.

The last term of equation (3) is upward propagating emission from the intervening atmosphere between ocean surface and satellite height. For computational purposes,

$$T_{\text{atm}} = \sum_{i=1}^{n-1} [(1 - t_i)\, \bar{T}_i \prod_{j=i+1}^{n} t_j] \tag{5}$$

Thus equation (3) is written as

$$T_B = [T_{\text{sky}}(1 - \epsilon_S) + T_S \epsilon_S]\, t + T_{\text{atm}}. \tag{6}$$

Equations (4), (5) and (6) are the main equations from which computational results are presented.

5. Results and discussions

The variation of brightness temperatures generated from the model described in § 3 for frequencies from 5 to 50 GHz is shown in figure 1 for a standard tropical atmosphere. The first curve is for a clear atmosphere with molecular oxygen and water vapour as the only absorbers. The increased brightness temperature at water vapour resonance is evident from the figure. The curve shows a minima around 30 GHz after which it increases continuously suggesting the influence of

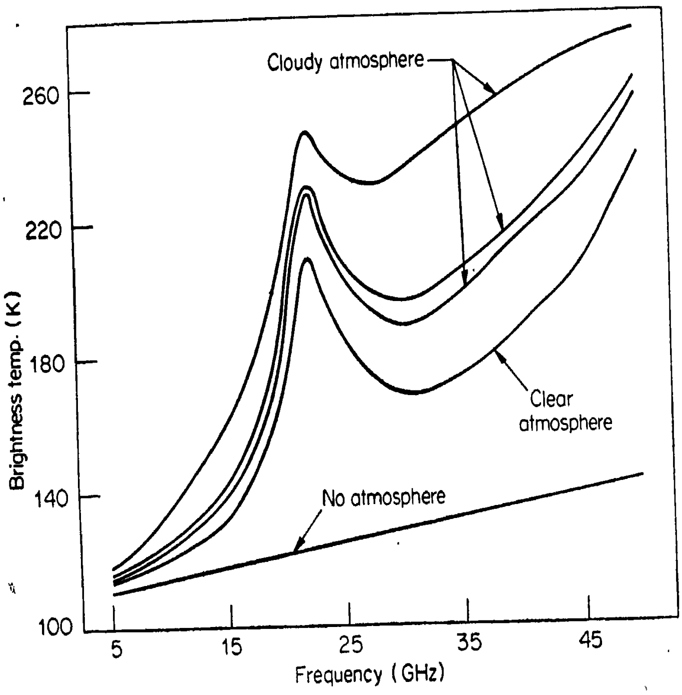

Figure 1. The effect of clouds on brightness temperature.

5 mm oxygen band. Curves II, III and IV are obtained after introducing clouds with different amounts of liquid water contents (table 1). It is found from curve I and II that a cloud with a liquid water content of 0·04 g/cm^2 produces a change of only about 8° K in brightness temperature near 19 GHz whereas at frequencies near 31 GHz, a change of about 21° K is observed.

The line in figure 1 with no atmosphere represents the surface contribution to the total brightness temperature which is equal to the product of emissivity and sea surface temperature. While calculating the emissivity the sea surface salinity is taken to be 35 ppt and sea surface temperature to be 30° C. The increase in brightness temperature is due to frequency dependence of the emissivity. The contribution of the atmosphere to the total brightness temperature is about 80° K at 22·235 GHz and about 34° K and 48° K for 19 GHz and 31 GHz frequencies.

It is also seen from figure 1 that the effect of atmosphere becomes significant only for frequencies greater than about 10 GHz. For frequencies below about 30 GHz, the major contribution to the total brightness temperature comes from water vapour. The role of oxygen becomes significant for higher frequencies i.e. near 60 GHz oxygen complex.

Figure 2 shows the variation of brightness temperature with different look angles from 0 to 70°. For frequencies below 15 GHz, the brightness temperature corresponding to the horizontal polarisation (T_{BH}) decreases with look angle whereas the brightness temperature corresponding to the vertical polarisation (T_{BV}) increases monotonically with look angles. For frequencies above around 30 GHz, the T_{BH} initially remains constant upto around 20° look angle and then slowly decreases with minimum around 50° look angle and then increases further. It can also be seen that for a particular look angle near 50°, change in T_{BH} from 20 to 25 GHz is more (21°) than T_{BV} which is about 11° K. For a particular frequency (say 20 GHz) T_{BV} is more sensitive (27° K) than T_{BH} (8° K) for a change of 10° look angle from 40° to 50°. The contribution of atmosphere to the total brightness temperature at different look angles shows the pronounced effect for angles greater than about 30°.

Table 1. Model of the clouds used in computation.

Height (km)	Liquid water density in g/m^3 for			
	I	II	III	IV
0·0	No cloud	0	0	0
1·0		0	0	0
2·0		0·0051	0·05	0·21
3·0		0·15	0·10	0·63
4·0		0·2409	0·40	1·05
5·0		0·0039	0·05	0·40
6·0		0	0	0

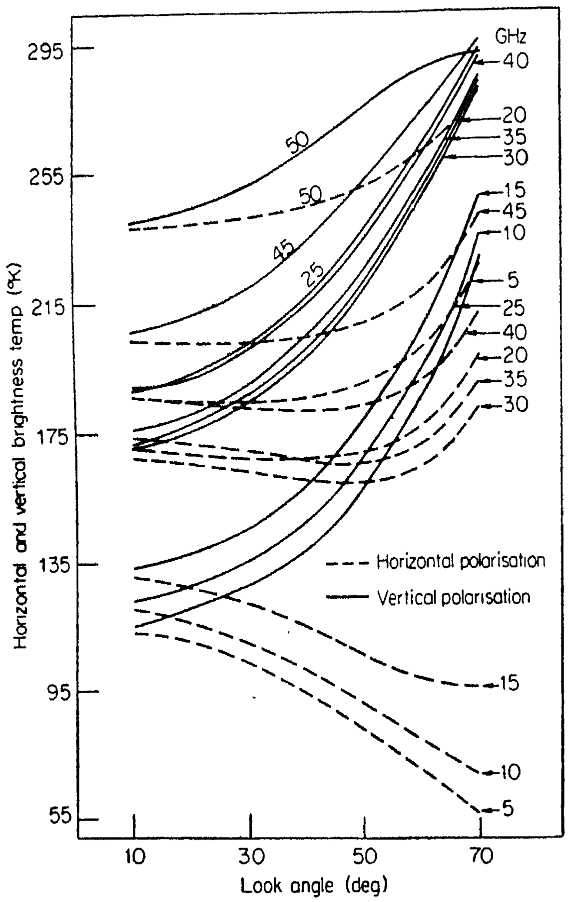

Figure 2. Variation of microwave brightness temperature with look angle at different frequencies.

6. Distinction of water vapour and liquid water content

Water vapour has a weak resonance line at 22·235 GHz and therefore can be detected at that frequency. But the detection may be confused due to the presence of liquid water in the clouds. Therefore a second radiometer at some other frequency is required which may resolve this ambiguity.

In order to decide the choice of the second observing frequency, the environmental model was used to generate an ability factor from 5 GHz to 50 GHz frequencies that are generally used for satellite microwave radiometry. The ability factor provides a measure of the ability of a two frequency measurement to separate the effects of liquid water and water vapour.

The ability factor as defined by Hollinger (1979) is illustrated in figure 3. For different water vapours and liquid water contents in the atmosphere, the brightness temperatures for different frequencies (5 to 50 GHz) are plotted as ordinates versus the brightness temperature at 22·235 GHz as abscissa. From this graph

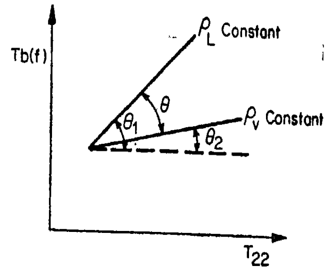

Figure 3. Definition of ability factor.

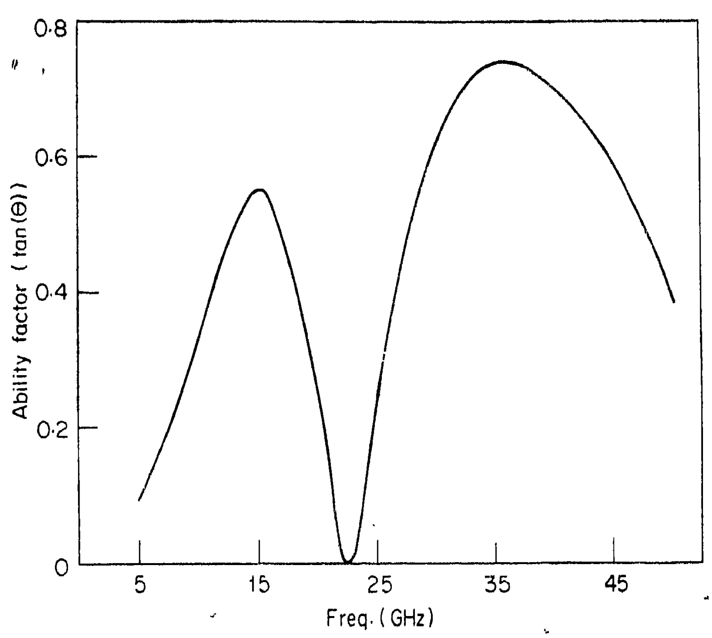

Figure 4. Ability factor versus frequencies for a dual frequency radiometer, one at 22·235 GHz and the other between 5 and 50 GHz.

$$\tan \theta_1 = \left[\frac{\partial T_B(f)}{\partial \rho_v} \Big/ \frac{\partial T_B(22)}{\partial \rho_v}\right] \rho_L = \text{constt},$$

and $$\tan \theta_2 = \left[\frac{\partial T_B(f)}{\partial \rho_L} \Big/ \frac{\partial T_B(22)}{\partial \rho_L}\right] \rho_v = \text{constt}. \tag{7}$$

where ρ_L = density of liquid water; ρ_v = density of water vapour; $T_B(f)$ = brightness temperature at frequency (5–50 GHz in the present study) and $T_B(22)$ = brightness temperature at water vapour resonance, 22·235 GHz.

From this, the ability factor is defined as

$$\text{Tan}(\theta) = \tan(\theta_1 - \theta_2) = \frac{\tan \theta_1 - \tan \theta_2}{1 + \tan \theta_1 \tan \theta_2}. \tag{8}$$

Figure 4 shows the variation of ability factor with frequencies from 5 to 50 GHz. It can be seen that the ability factor is maximum around 15 GHz and 37 GHz.

Although maximum ability is around the above two frequencies, the frequencies 19 and 31 GHz are generally used probably due to hardware reasons. The ability of 22 and 31 GHz radiometer is about 67% as compared to the ability of 32% for 19 and 22 GHz in distinguishing water vapours and liquid water contents in the atmosphere. The error analysis was also performed to estimate the total atmospheric water vapour and liquid water content using 19-22 GHz frequencies and 22–31 GHz frequencies. The same set of atmospheric conditions were used to obtain regression equations in terms of brightness temperatures. Taking a measurement error of 1° K in brightness temperature at three frequencies, it was found that the uncertainty in W and Q with 19–22 GHz frequencies are 0·1730 and 0·1280 respectively whereas for frequencies 22–31 GHz, it becomes 0·1251 and 0·0530. These results are in agreement with results obtained by Grody (1976).

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