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Evaluation of frequencies for sea surface temperature and salinity measurements using passive microwave radiometers

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ABSTRACT. Theoretical investigations have been carried out for a proper choice of frequencies for measuring sea surface temperature and salinity, with passive Microwave Radiometers. The brightness, temperature and emissivity has been calculated using an improved model for the dielectric constant of sea water. This was developed by Klein *et al.* (1977) for frequencies below the X-band. A simple model of air-water interface, neglecting the atmospheric contribution has been used in this study. It was found that multifrequency microwave radiometer operating between 1 to 3 or 4GHz is suitable for simultaneous measurement of sea surface temperature and salinity. For measurement of only sea surface temperature, frequencies between 4 to 7GHz, with an optimum frequency around 4.5GHz should be considered. Additional experimental investigation is needed to justify the use of frequencies below 10GHz for sea surface temperature measurement, because of the atmospheric contribution to the brightness temperature.

The need for accurate experimental measurement of dielectric constants has been pointed out, keeping in view the accuracy of present day microwave radiometers.

1. Introduction

It is recognised that the measurement of sea surface temperature is an important requirement for investigations in meteorology and oceanography. Values of salinity, in addition to sea surface temperature, are useful for the study of circulation over estuaries, tracing river outflow and for studying ocean freezing processes.

Infrared Radiometers have been used from Nimbus Satellites to measure sea surface temperature with some success (Smith *et al.* 1970). But, they suffer degradation from rain cloud, sun glitter, water vapour and aerosols. It has now become possible to avoid these difficulties to a greater extent by using passive microwave radiometers. The resolution of the satellite borne radiometers are poor, but much improved when used on aircraft.

To measure sea surface temperature and salinity with a passive microwave radiometer, the emissivity of the sea surface must be known accurately. This, in turn, depends upon the dielectric properties of the sea water. The implementation of passive microwave sensing of sea surface temperature, and other ocean surface properties, places stringent requirements on the accuracy with which the dielectric properties of sea water must be known at the operating frequency. The study by Hidy *et al.* (1972) shows that in the absence of rough sea surface conditions, measurements could be made which were accurate to 0.1°K brightness temperature, and 0.3° K in meloecular temperature.

Measurements of dielectric constants have been made by Ho *et al.* (1973-74) at S and L band frequencies, keeping in view the accuracy required for interpreting microwave radiometric data. But, the earlier measurements of dielectric constants have been used by Stogryn (1971) to derive statistical fits to the dielectric parameters. Their quoted accuracies seem inadequate to match the capability of modern microwave radiometers. Keeping this in view, Klein *et al.* (1977) have reexamined Stogryn's results and some of the recent measurements. They drived new regression fits for dielectric parameters, which will provide the brightness temperature to within 0.3°K at frequencies below X-band.

In this paper the following calculations and discussions are presented :

(*i*) The dielectric properties of water as a function of salinity and temperature, observing frequency, polarisation and look angle,

(*ii*) The brightness temperature of a calm sea based on these dielectric properties, as a function of salinity and temperature frequency, polarisation and look angle,

(*iii*) Accuracy requirements for dielectric constant measurements,

(*iv*) Comments on present experimental methods.

The above results have been used in a simple model of air-water interface (neglecting atmospheric effects, to investigate the range of frequencies suitable for temperature and salinity measurements with passive microwave radiometers.

For accurate retrieval of sea surface temperature and salinity, the effect of atmospheric emission/absorption, cosmic background, sky emission and antenna pattern correction, should be considered. The effect of surface wind, producing roughness and foam (whitecaps at high yield speed > 7m/sec), on brightness temperature is complicated by the fact that it depends on air-sea temperature difference, the duration and fetch of the wind as well as on the history of the wave spectrum of the sea. A satisfactory analytical expression is not available, and empirical relations (Hollinger 1975) are used to estimate the increase in brightness temperature due to ocean roughness. This is added to the brightness temperature calculated for idealised calm sea condition. Hollinger (1973) studies microwave properties of a calm sea based on dielectric parameters taken from Saxton and Lane (1962).

2. Method of computation of dielectric properties

The complex dielectric constant of sea water at microwave frequencies is adequately described by the Debye (1920) expression:

$$\epsilon = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} - j\frac{\sigma}{\omega\epsilon_0} \tag{1}$$

where, $\omega = 2\pi f$ (f in Hertz)

ϵ_∞ = 4.9, dielectric constant at infinite frequency,

ϵ_s = static dielectric constant,

σ = ionic conductivity in mhos/metre,

τ = relaxation time in seconds,

ϵ_0 = permittivity of free space, $= 8.854 \times 10^{-12}$

The above Eqn. (1) can be rewritten in the following form;

$$\epsilon = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \times \frac{1 - j\omega\tau}{1 - j\omega\tau} - j\frac{\sigma}{\omega\epsilon_0}$$

$$= \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} - j\left[\frac{\omega\tau(\epsilon_s - \epsilon_\infty)}{1 + \omega^2\tau^2} + \frac{\sigma}{\omega\epsilon_0}\right] = \epsilon' - j\epsilon'' \tag{1.1}$$

where ϵ' and ϵ'' are real and imaginary parts of the dielectric constant and is given by

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} \tag{1.2}$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty)\,\omega\tau}{1 + \omega^2\tau^2} + \frac{\sigma}{\omega\epsilon_0} \tag{1.3}$$

The static dielectric constant, relaxation time and conductivity are functions of salinity and temperature. To calculate the dielectric properties of water for any combination of salinity and temperature, the following regression equation given by Klein *et al.* (1977) were used.

The regression equation for ionic conductivity of sea water is :

$$\sigma(T, S) = \sigma(25, S)\exp(-\Delta\beta) \tag{2}$$

$$\Delta = 25 - T \tag{2.1}$$

$$\beta = 2.033 \times 10^{-12} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 - S(1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta^2) \tag{2.2}$$

and $\sigma(25, S) = S(0.182521 - 1.46192 \times 10^{-3} S + 2.09324 \times 10^{-5} S^2 - 1.28205 \times 10^{-7} S^3)$ (2.3)

where T is the temperature in degrees centigrade and S is salinity in parts per thousand.

The specific form of the polynomial fit for static dielectric constant is given by

$$\epsilon(T,S) = \epsilon_s(T)\,a(S,T) \tag{3}$$

where $\epsilon_s(T) = 87.134 - 1.949 \times 10^{-1} T - 1.276 \times 10^{-2} T^2 + 2.491 \times 10^{-4} T^3$ (3.1)

and $a(S,T) = 1.000 + 1.613 \times 10^{-5} ST - 3.656 \times 10^{-3} S + 3.210 \times 10^{-5} S^2 - 4.232 \times 10^{-7} S^3$ (3.2)

for modelling relaxation time, Klein *et al.* have used Stogryn's expression, after converting normality into salinity by :

$$\tau(S,T) = \tau(T,0)\,b(S,T) \tag{4}$$

where $\tau(T, 0)$ is the pure water value of the relaxation time, whose regression equation is :

$$\tau(T, 0) = 1.768\times10^{-11} - 6.086\times10^{-13}T + 1.104\times10^{-14}T^2 - 8.111\times10^{-17}T^3 \quad (4.1)$$

and
$$b(S, T) = 1.000 + 2.282\times10^{-5}ST - 7.638\times10^{-4}S - 7.760\times10^{-6}S^2 + 1.105\times10^{-8}S^3 \quad (4.2)$$

3. Method of computation of emissivity and brightness temperature

For frequencies below 10 GHz, the contribution from surface to the brightness temperature T is maximum and is given (neglecting atmospheric effects), by

$$T_B(\lambda) = e_\lambda(T, S)T_s = (1 - R^2)T_s \quad (5)$$

where the dependence of emissivity on surface roughness has been omitted. T_B and T are in degree's Kelvin, R is the Fresnel's reflection coefficient for air water interface and e is the emissivity, which for smooth, calm sea water is given by (Hollinger 1973, Hidy *et al.* 1972)

$$e_h = 1 - |R_h|^2 \quad (5.1)$$

$$e_v = 1 - |R_v|^2 \quad (5.2)$$

where,
$$|R_h|^2 = \frac{[(p - \mu)^2 + q^2]}{[(p + \mu)^2 + q^2]} \quad (5.3)$$

and
$$|R_v|^2 = \frac{[(\mu\epsilon' - p)^2 + (\mu\epsilon'' - q)^2]}{[(\mu\epsilon' + p)^2 + (\mu\epsilon'' + q)^2]} \quad (5.4)$$

$$\mu = \cos\theta$$

The subscripts h and v refer to the horizontal and vertical linearly polarised component of the radiation, when the electric field vector is perpendicular or parallel to the plane of incidence, θ is the look angle and the variables p and q are :

$$p = \frac{1}{\sqrt{2}}\left[\left\{(\mu^2 + \epsilon' - 1)^2 + \epsilon''^2\right\}^{\frac{1}{2}} + (\epsilon' + \mu^2 - 1)\right]^{\frac{1}{2}} \quad (5.5)$$

$$q = \frac{1}{\sqrt{2}}\left[\left\{(\mu^2 + \epsilon' - 1)^2 + \epsilon''^2\right\}^{\frac{1}{2}} - (\epsilon' + \mu^2 - 1)\right]^{\frac{1}{2}} \quad (5.6)$$

Therefore, for nadir looking case $\mu = 1$ and

$$|R_h|^2 \approx |R_v|^2$$

Hence, the emissivity can be calculated by (Hidy *et al.* 1972, Ho and Hall 1973)

$$e = 1 - \left|\frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}}\right|^2 \quad (6)$$

For $\theta > 0$, R_h and R_v should be computed separately and TB_H and TB_V will be corresponding brightness temperatures. Here ϵ is the complex dielectric constant of sea water at microwave frequencies, whose imaginary part include the contribution from any d.c. conductivity of the medium.

4. Accuracy of dielectric constant measurements

The practical resolution and accuracy that a passive microwave radiometer has achieved, have put a stringment requirement on the accuracy with which dielectric constants should be measured for measuring sea surface temperature and salinity variations.

The emissivity for normal incidence is given by :

$$e = 1 - \left|\frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}}\right|^2$$

where the second term is the fresnel reflection coefficient and ϵ is the complex dielectric constant. Taking logarithms of both sides, and differentiating

$$\frac{\delta e}{1 - e} = -2\left(\frac{1 + \sqrt{\epsilon}}{1 - \sqrt{\epsilon}}\right) \frac{-\frac{1}{2}\epsilon^{-1/2}(1 + \sqrt{\epsilon}) - \frac{1}{2}\epsilon^{-1/2}(1 - \sqrt{\epsilon})}{(1 + \sqrt{\epsilon})^2} \quad (7)$$

$$\delta_e = 2(1 - e)\,\text{Real}\,\frac{\delta\epsilon}{\sqrt{\epsilon}(1 - \epsilon)} \quad (7{\cdot}1)$$

since $\epsilon >> 1$

$$\delta e \simeq 2(1 - e)\,\text{Real}\,\frac{\delta\epsilon}{\epsilon^{3/2}}$$

since $\epsilon^{3/2} \approx 10^3$ [typical value of ϵ at 10°C of sea water ≈ 80]

$$\delta_e \approx 1{\cdot}30\times10^{-3}(\delta\epsilon' + \delta\epsilon'') \quad (7{\cdot}2)$$

and for $T = 300°\text{K}$

$$\triangle T_B \approx 0{\cdot}4\,(\delta\epsilon' + \delta\epsilon'')°\,\text{K} \quad (7{\cdot}3)$$

For $\triangle T_B$ to be less than 0.4°K, $(\delta\epsilon' + \delta\epsilon'')$ must be less than 1. For present day radiometers $\triangle T_B < 0.1°\text{K}$ is within the state of the art and ϵ' and ϵ'' should be measured with an accuracy of better than 0.1–0.2 per cent.

5. Comments on the experimental methods of dielectric constant measurements

There are different methods (Von Hippel 1961, Montgomery 1947) for the measurement of dielectric constant of solutions, but the cavity perturbation technique is currently used by the

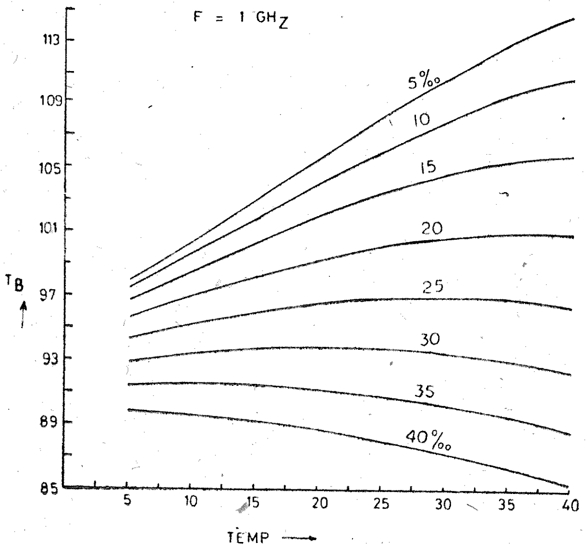

Fig. 1. Brightness temperature (°K) *versus* calm sea surface temperature (°C) at normal incidence for various salinities at frequency of 1 to 4 GHz

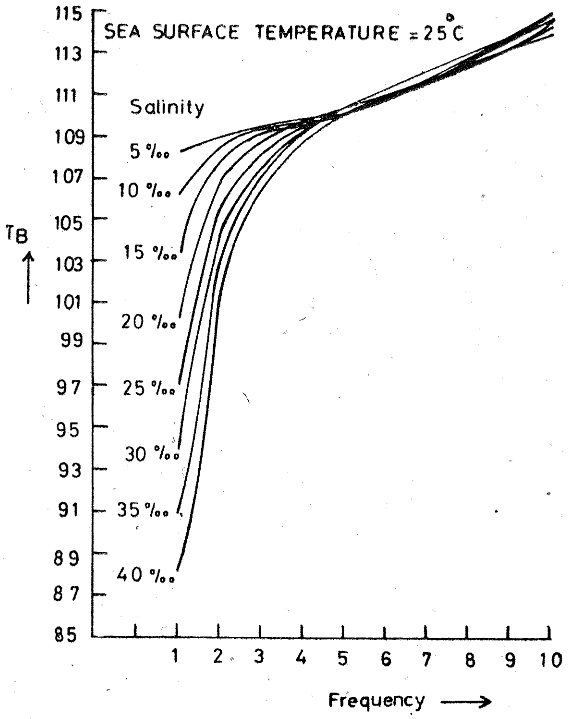

Fig. 2. Calculated brightness temperature (°K) for a sea surface temperature of 25°C at various salinities for frequencies from 1 to 10 GHz

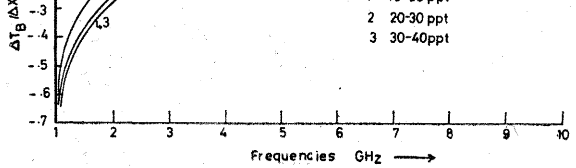

Fig. 3. Effect of salitity change (various ranges) on brightness temperature at frequency 1 GHz

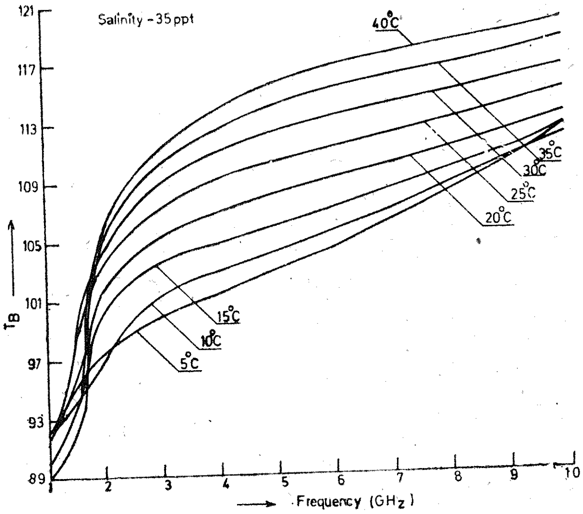

Fig. 4. Calculated brightness temperature (°K) for a sea surface salinity of 35 ppt at various temperatures for frequencies from 1 to 10 GHz.

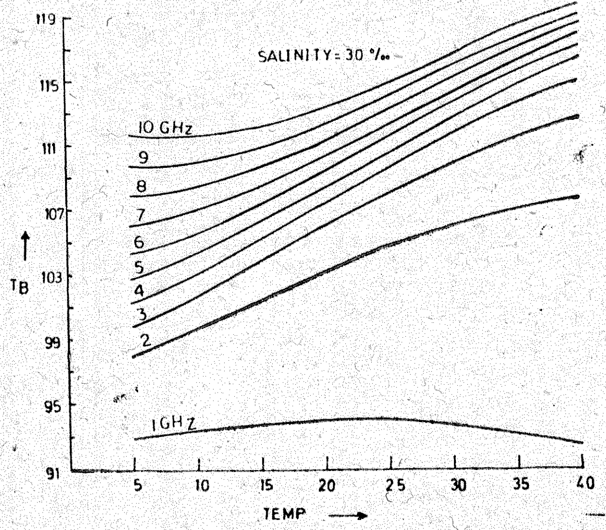

Fig. 5. Variation of calculated brightness temperature (°K) *versus* calm sea surface temperature (°C) at 30 ppt salinity for different frequencies from 1 to 10 GHz.

National Bureau of Standards. This provides results which meet the accuracy requirements of most microwave radiometers. In this technique a sample tube of small, but known volume, is inserted along the axis of a cylindrical cavity excited in the TM 010 mode. Form measurements of the shift of resonant frequency, and change in quality factor *Q* of the cavity, the value of the dielectric constant can be determined. The quoted accuracy with this method is 0.1-0.2 per cent.

In view of the growing interest and capability of passive microwave radiometers to sense ocean surface phenomenon, laboratory investigations should be initiated to measure dielectric constants of actual sea water from the Bay of Bengal, Arbian Sea and Indian Ocean during different seasons of the year. It may be worthwhile to point out that laboratory simulation of sea water with different normalacy Nacl solution in water will not give the same value of the dielectric constant, because of the presence of additional ions in sea water.

6. Results and Discussions

Fig. 1 shows the variation of brightness temperature with molecular sea surface temperature for different values of sea surface salinity. The temperature range is from 5° to 40°C in steps of 5°C, with salinity variations from 5 to 40 ppt in steps of 5 ppt. The brightness temperature has been calculated for a nadir view for frequencies from 1 to 10 GHz. It is observed that the brightness temperature is more sensitive to salinity for lower frequencies below 3 to 4 GHz and shows no variation for frequencies higher than 4 GHz.

Fig. 2 shows the variation of brightness temperature with frequency from 1 to 10 GHz for different values of salinity from 5 to 40 ppt for a particular sea surface temperature. As seen from the graph the change in brightness temperature is more prominent for frequencies between 1 to 2 GHz than between 2 to 3 GHz.

Fig. 3 shows the change in brightness temperature due to change in salinity at 25°C from frequencies from 1 to 10 GHz. The three curves have been drawn far salinity range 10-20 ppt, 20-30 ppt and 30-40 ppt. Depending upon the achievable resolution of microwave radiometer and other design consideration any frequency between 1 to 4 GHz preferably between 1 to 3 GHz can be selected for salinity measurements keeping the accuracy requirement in consideration.

Fig. 4 shows the variation of brightness temperature with frequencies for different temperature from 5° to 40°C for 35 ppt salinity. We observe that frequencies below 3 to 4 GHz are also sensitive to temperature. Consequently for salinity determination the temperature variation needs to be taken into account, and it cannot be measured independently. Thus, a two frequency radiometer between 1 to 3 or 4 GHz may be used for both sea surface temperature and salinity measurements.

Fig. 5 shows the variation of brightness temperature with sea surface temperature for different frequencies and 30 ppt salinity. At 1 GHz, the output is less sensitive to temperature variations and the sensitivity increases with frequencies greater than 2 GHz. Fig. 6 shows the change in

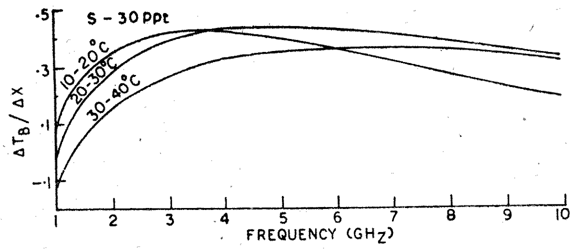

Fig. 6. Effect of temperature change (various ranges) on brightness temperature for frequencies from 1 to 10 GHz.

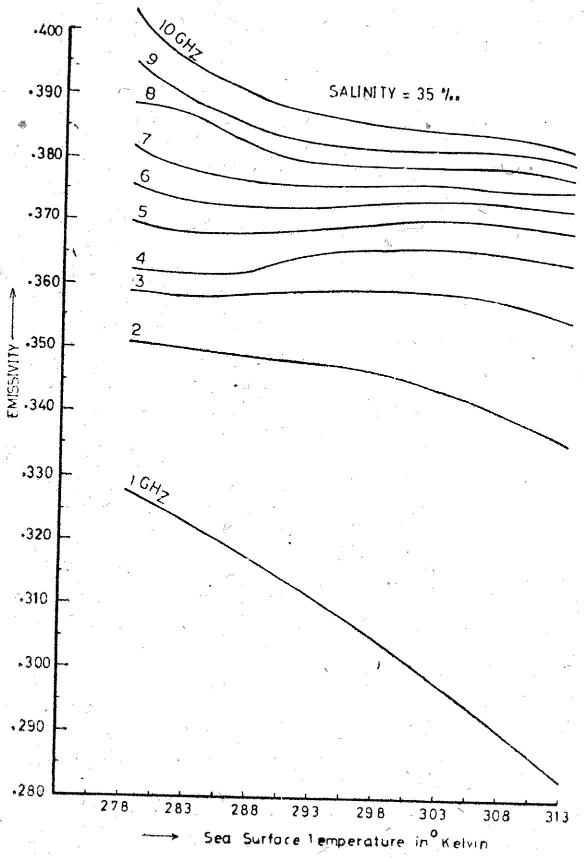

Fig. 7 Calm sea surface emissivity *versus* sea surface temperature (°K) at 35 ppt salinity for different frequencies from 1 to 10 GHz'

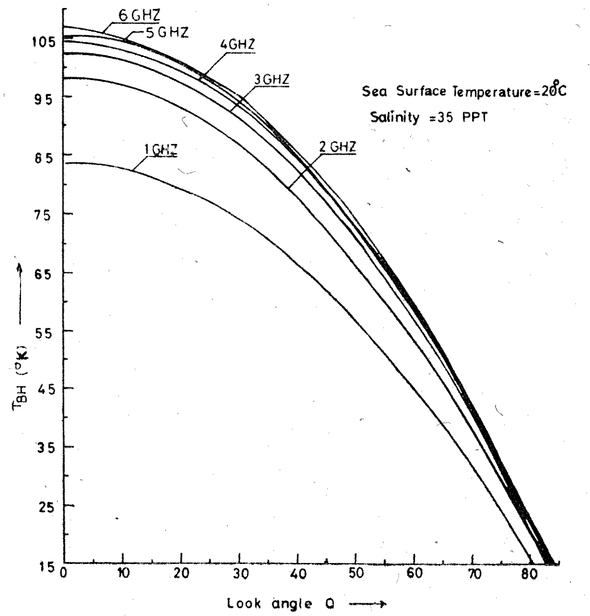

Fig. 8. Calculated horizontal polarisation brightness temperature (°K) *versus* look angle at a sea surface temperature of 20°C, salinity 35 ppt or frequencies from 1 to 6 GHz

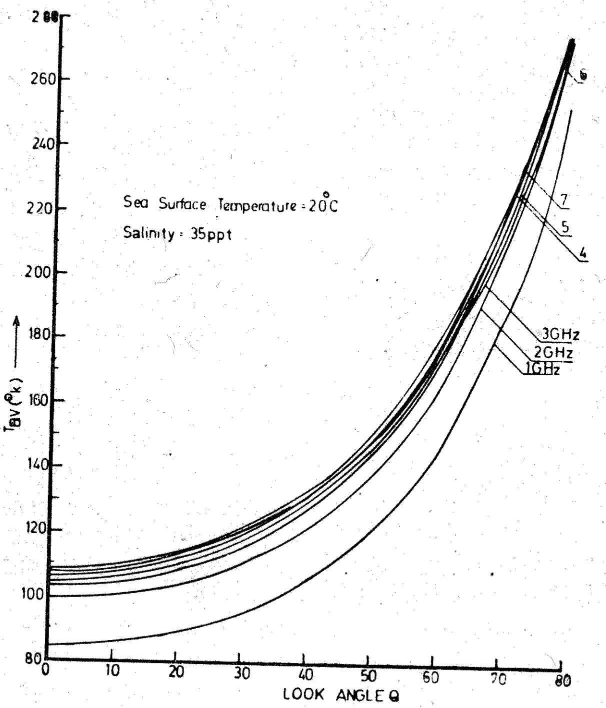

Fig. 9. Calculated vertical-polarisation-brightness temperature (°K) *versus* look angle at a sea surface temperature of 20 °C, salinity 35 ppt for frequencies from 1 to 7 GHz.

brightness temperature with temperature change for different frequencies and for temperature ranges of 10-20, 20-30 and 30-40°C, where a constant salinity of 30 ppt has been assumed.

An examination of Figs. 4, 5, 6 indicates that for temperature measurements alone, frequencies between 4 to 7 GHz can be selected, with an optimum frequency around 4 GHz for temperature ranges upto 40°C. However, if atmospheric corrections can be properly taken care of, other frequencies up to 10 GHz could as well be used for their determination, the choice will then depend upon the accuracy requirement and the range of temperature variation expected.

Fig. 7 is the variation of emissivity with temperature at different frequencies for 35 ppt salinity. We see that specular emissivity for frequency between 4 and 9 GHz and temperature range 290°—313° K is almost temperature indeindependent. Such a characteristic may be employed for designing a radiometer as a good sea water temperature sensor, once the surface roughness effect and atmospheric attenuation are compensated.

Figs. 8 and 9 show variation of brightness temperature for horizontal and vertical polarisation with look angle for different frequencies from 1 to 10 GHz. Figs. 8 and 9 indicate that for horizontal polarisation T_{BH} decreases with look angle and becomes evident only after an angle greater than 20°C. The maximum change occurs around 70°. Fig. 9 shows that T_{Bv} increases exponentially with look angle, with a maximum around 70 ° . Thus for vertical polarisation, the change in T_{BV} is more than that for horizontal polarisation, for the same look angle range. This result could be utilized in the design of microwave radiometers.

7. Conclusions

(1) A model to calculate dielectric parameters developed by Klein *et al.* (1977) has been used. The need for accurate measurement of dielectric constant has been brought out.

(2) Brightness temperature and emissivity have been calculated with the new model and their dependence on salinity, temperature, frequency, look angle has been studied. A simple model of brightness temperature, neglecting atmospheric effects has been used in the study.

(3) We find that a multi-frequency microwave radiometer could be used with frequency between 1 and 3 or 4 GHz for simultaneous measurement of sea surface temperature and salinity.

(4) For measurement of sea surface temperature alone, a frequency between 4 and 7 GHz could be used with an optimum frequency around 4 GHz. It has yet to be established that how far frequencies higher than 7 GHz are suitable for remote measurement of sea surface temperature and with what accuracy, by proper comparison of sea truth with aircraft flights.

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