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Passive microwave atmospheric measurements - Part I : Absorption of microwaves by atmospheric gases-Oxygen and water vapour

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ABSTRACT. The expression for absorption coefficient for microwave frequencies which is required in the inversion of radiative transfer equation is described in terms of meteorological parameters. Computational scheme has been developed and the results obtained for a standard tropical atmosphere for 19.35 GHz and 22.235 GHz, the frequencies used in satellite microwave radiometer onboard the second Indian satellite *Bhaskara* Relative contribution to the absorption coefficients for frequencies from 10 GHz to 70 GHz is also described for surface meteorological parameters. The algorithm and subroutine package may as well be used for interpreting any microwave radiometric data for meteorological and oceanographic studies.

1. Introduction

The microwave emission of the non-scattering atmosphere is directy related to its absorption properties. In clear atmosphere, water vapour and oxygen are the two main absorbers in the atmosphere because they have resonances in or near this spectral region (22.235 GHz water vapour resonance line and 60 GHz oxygen complex) and they occur in sufficient abundances.

In the present paper, the relationships of absorption coefficients of water vapour and oxygen molecules with meteorological quantities are described. In order to interpret data received from the Satellite Microwave Radiometer (SAMIR) onboard India's second satellite *Bhaskara,* we have presented the results of computation using standard tropical atmosphere for 19.35 GHz and 22.235 GHz which are the two frequencies at which SAMIR senses radiation. In the analysis, oxygen has been assumed to be well mixed upto 90 km while water vapour is highly variable and is confined only upto about 30 km.

2. Background for microwave radiometry

The intensity of thermal radiation from blackbody using Rayleigh-Jeans approximation is given by

$$B_{\nu}(T) = \frac{2k\,\nu^2}{C^2}\,T \qquad (1)$$

The same approximation is applied to the radiation intensity from any other source by writing

$$I(\nu, T) = \frac{2\,k\,\nu^2}{C^2}\,T_B \qquad (2)$$

where T_B is the brightness temperature, *i.e.,* the temperature to which a blackbody must be raised in order that blackbody radiates the same intensity at frequency ν as does the source. It is given by $T_B = \epsilon_\lambda T$ where is ϵ_λ the emissivity of the surface and T is its physical temperature.

Following Stogryn (1975), the total radiation received by a satellite microwave radiometer is given by

$$T_{aj}(\theta) = L(z, \theta) \Big[\epsilon_j(\theta)\, T_g + \{1 - \epsilon_j(\theta)\}\, T_{sky}(\theta) \Big] + T_{atm}(z, \theta) \qquad (3)$$

where,

J = horizontal or vertical polarizations

$T_{aj}(z, \theta)$ = apparent temperature at an altitude z and nadir angle θ

$L(z, \theta)$ = transmittance

$$= \exp\left[-\sec\theta \int_0^z \alpha(u)\, du\right]$$

$\alpha(z)$ = total absorption coefficient of the atmosphere at an altitude z

$\epsilon_j(\theta)$ = surface emissivity

T_g = surface temperature

$$T_{atm}(z, \theta) = \sec\theta \int_0^{z'} T_{air}(z).\, \alpha(z) \times$$

$$\exp\left[-\sec\theta \int_0^{z'} \alpha(u)\, du\right].\, dz$$

$T_{air}(z)$ = thermometric temperature profile of the air

$$T_{sky}(\theta) = \sec\theta \int_0^{\infty} T_{air}(z).\, \alpha(z) \times$$

$$\exp\left[-\sec\theta \int_0^{z} \alpha(u)\, du\right].\, dz$$

For clear sky, the absorption coefficient is given by

$$\alpha = \alpha_{O_2} + \alpha_{H_2O} \tag{4}$$

This paper will describe the absorption due to oxygen and water vapour.

3. Absorption due to oxygen (O_2)

Meeks and Lilley (1963) first proposed the use of strong absorption region near 5 mm for remote sensing of the atmospheric temperature profile. For these and other studies of microwave propagation in the atmosphere, there is a need of accurate expression for the absorption coefficient for oxygen as a function of frequency, temperature and pressure. In view of the need for accurate absorption formula which could be put into computable form, Rosenkranz (1975) reexamined the shape of 5 mm oxygen band in the atmosphere and treated the problem of absorption by first order approximation to the impact theory of overlapping lines. By including the coupling between the adjacent rotation states in molecular collisions, he has devised a simple approximate method for computing the interference between lines from measurements on resolved lines.

In the present paper the calculation of microwave absorption coefficient for oxygen is based on the computational scheme suggested by Rosenkranz (1975) which relies principally on the work of Gordon (1966) and VanVleck (1947). The model takes into account 40 molecular magnetic dipole transitions which relate the total angular momentum states of the molecules to the incident radiation. The angular momentum quantum number N interacts with electron spin to form two more states with total angular momentum number $J=N+1$ and $J=N-1$. Transition between states $J=N$ and $J=N\pm1$ permit resonant absorption at frequencies $\nu_N\pm$ (Table 1). These frequencies are grouped between 50 and 70 GHz with one at 119 GHz. Pressure line broadening and temperature dependence are also accounted for the basic formula relating the absorption, coefficient α in nepers/km to frequency ν in GHz, pressure P in millibars and temperature T in Kelvin is given by

$$\alpha_{o_2} = C\, P^2 \frac{\nu^2}{T^2} \left\{ \sum_N \phi_N \left[\overset{+}{f_N}(\nu) + \right.\right.$$

$$\left. + f_N{}^{+}(-\nu) + f_N{}^{-}(\nu) + \bar{f_N}(-\nu) \right] +$$

$$\left. + \frac{0.70\, W_b}{\nu^2 + (P\, W_b)^2} \right\} \tag{5}$$

where,

$C=0.330$ is a constant for α_{o_2} in nepers per kilometre.

Fractional population of state N, ϕ_N is :

$$\phi_N = \frac{2N+1}{0.725\, T} \exp\left[-2.0685 \frac{N(N+1)}{T}\right] \tag{6}$$

Shape factor for the transition lines $f_N\pm$ is :

$$f_N\pm(\nu) = \frac{W_N (d_N\pm)^2 + (\nu - \nu_N\pm)^2 - Y_N\pm}{(\nu - \nu_N\pm)^2 + (PW_N)^2} \tag{7}$$

and $\nu_N\pm$ are the resonant frequencies as per Table 1. The summation is over odd rotational states from 1 to 39 (Rosenkranz 1975).

Amplitudes of positive and negative transition lines at $\nu_N{}^{+}$ and $\nu_N{}^{-}$ (Table 1) are given by

$$\overset{+}{d_N} = \left[\frac{N(2N+3)}{(N+1)(2N+1)}\right]^{\frac{1}{2}} \tag{8}$$

$$d_N{}^{-} = \left[\frac{(N+1)(2N-1)}{N(2N+1)}\right]^{\frac{1}{2}} \tag{9}$$

The non-resonant linewidth used is given by

$$W_b = 0.48 \times 10^{-3} \left(\frac{300}{T}\right)^{0.89} \text{ GHz} \Big/ \text{mb} \tag{10}$$

TABLE 1

Resonant frequencies of molecular oxygen and calculated amplitude factor used in the absorption subroutine due to oxygen

N	Frequencies		Amplitude	
	$\overset{+}{\nu}_N$ (GHz)	$\overset{-}{\nu}_N$ (GHz)	$\overset{+}{d}_N$	$\overset{-}{d}_N$
1	56.2648	118.7503	0.9129	0.8165
3	58.4466	62.4863	0.9820	0.9759
5	59.5910	60.3061	0.9924	0.9909
7	60.4348	50.1642	0.9958	0.9952
9	61.1506	58.3239	0.9974	0.9971
11	61.8002	57.6125	0.9982	0.9980
13	62.4112	56.9682	0.9987	0.9986
15	62.9980	56.3634	0.9990	0.9989
17	63.5685	55.7838	0.9992	0.9992
19	64.1278	55.2214	0.9994	0.9993
21	64.6789	54.6711	0.9995	0.9994
23	65.2241	54.1300	0.9996	0.9995
25	65.7647	53.5957	0.9996	0.9996
27	66.3020	53.0668	0.9997	0.9997
29	66.8367	52.5422	0.9997	0.9997
31	67.3694	52.0212	0.9998	0.9997
33	67.9007	51.5030	0.9998	0.9998
35	68.9601	50.9873	0.9998	0.9998
37	68.9601	50.4736	0.9998	0.9998
39	69.4887	49.9618	0.9998	0.9998

Interference coefficients for coupling between near states due to molecular collisions is given by

$$Y_N{}^{\pm} = d_N{}^{\pm}\left[\frac{2d^{\pm}_{N+2}\cdot W_{NUP}}{\nu_N{}^{\pm}-\nu^{\pm}_{N-2}} + \frac{2d^{\pm}_{N-2}\cdot W_{NDN}}{\nu_N{}^{\pm}-\nu^{\pm}{}_{N-2}} - \frac{W_b}{\nu_N{}^{\pm}} - \frac{W_b}{\nu_N{}^{\pm}+60}\right] \quad (11)$$

The resonant halfwidths are computed as

$$W_N = 1.16 \times 10^{-3}\left(\frac{300}{T}\right)^{0.85} \quad (12)$$

and the line widths for the collisional coupling are computed in a sequence using the formulas

$$W_{NDN} = W_b - W_N - W_{NUP}$$

and

$$W_{N-2,\,UP} = W_{NDN}\,\frac{\phi_N}{\phi_{N-2}} \quad (13)$$

The calculations for α_{O_2} have been implemented in the form of a software subroutine package to be used either in standalone mode for absorption calculation or as part of a larger atmospheric radiative transfer programme.

The analysis discussed above does not take into account high altitude Zeeman splitting (about 40 km) nor the Doppler broadening above 80 km. However, since comparatively little absorption takes place due to low pressure at high altitudes Zeeman and Doppler effect may be neglected.

4. Absorption due to water vapour

The water vapour molecule absorbs in the microwave region because of its permanent electric dipole. Water vapour has a single, weak, pure rotational resonance line which arises from the transisiton 5_{23}—6_{16}, at 22.235 GHz, about which the spectral region being considered is centred. Fortunately, this line has extensively been studied and its structure is known with an accuracy exceeding our requirement for formulation (Becker and Autler 1946, Townes & Shallow 1955). The absorption coefficient in nepers per kilometre is (Hollinger *et al.* 1975, Liebe 1969):

$$\alpha_{H20} = \nu^2 .\, P .\, 10^5\left[\frac{3.24 \times 10^{-4}}{T^{3.105}}\exp\left(\frac{-644}{T}\right)(P + 0.0147\,\rho\,T)\left(\frac{1}{(\nu-\nu_0)^2+(\Delta\nu)^2} + \frac{1}{(\nu+\nu_0)^2+\Delta\nu^2}\right) + 2.55 \times 10^{-8}\frac{\Delta\nu}{T^{1.5}}\right] \quad (14)$$

where,

ν = frequency of observation in GHz

P = total pressure in mb

TABLE 2

Absorption due to oxygen and water vapour for the standard tropical atmosphere (Selby *et al.* 1975) at 19.350 GHz

Height (km)	Pressure (mb)	Temperature (°K)	Water vapour density (gm/m³)	Oxygen absorption coefficient (neps/km)	Water vapour absorption coef. (neps/km)	Total absorption coefficient (neps/km)	Integrated absorption in nepers from	
							Surface to 25 km	25 km to surface
0.0	1013.0	300.0	0.1900E-02	0.2028E-02	0.4223E-01	0.4426E-01	0.0	0.09903
1.0	904.0	294.0	0.1300E-02	0.1712E-02	0.2880E-01	0.3001E-01	0.08713	0.06190
2.0	805.0	288.0	0.9300E-01	0.1441E-02	0.1967E-01	0.2111E-01	0.06269	0.03634
3.0	715.0	284.0	0.4700E-01	0.1183E-02	0.9462E-02	0.1064E-01	0.07857	0.02045
4.0	633.0	277.0	0.2200E-01	0.9965E-03	0.4215E-02	0.5211E-02	0.08650	0.01253
5.0	559.0	270.0	0.1500E-01	0.8366E-03	0.2720E-02	0.3557E-02	0.09088	0.00815
6.0	492.0	264.0	0.8500E-00	0.6914E-03	0.1440E-02	0.2131E-02	0.09372	0.00531
7.0	432.0	257.0	0.4700E-00	0.5759E-03	0.7395E-03	0.1315E-02	0.09545	0.00358
8.0	378.0	250.0	0.2500E-00	0.4775E-03	0.3621E-03	0.8396E-03	0.09652	0.00252
9.0	329.0	244.0	0.1200E-00	0.3879E-03	0.1579E-03	0.5459E-03	0.09722	0.00181
10.0	286.0	237.0	0.5000E-01	0.3188E-01	0.5959E-04	0.3784E-03	0.09768	0.00135
11.0	247.0	230.0	0.1700E-01	0.2592E-03	0.1815E-04	0.2774E-03	0.09801	0.00102
12.0	213.0	224.0	0.6000E-02	0.2080E-03	0.5693E-05	0.2137E-03	0.09825	0.00078
13.0	182.0	217.0	0.1800E-02	0.1664E-03	0.1503E-05	0.1679E-03	0.09844	0.00059
14.0	156.0	210.0	0.1000E-02	0.1344E-03	0.7340E-06	0.1351E-03	0.09859	0.00043
15.0	132.0	204.0	0.7600E-03	0.1046E-03	0.4819E-06	0.1051E-03	0.09871	0.00031
16.0	111.0	197.0	0.6400E-03	0.8177E-04	0.3482E-06	0.8211E-04	0.09881	0.00022
17.0	93.7	195.0	0.5600E-03	0.6000E-04	0.2592E-06	0.6026E-04	0.09888	0.00015
18.0	78.9	199.0	0.5000E-03	0.4013E-04	0.1938E-06	0.4032E-04	0.09893	0.00010
19.0	66.6	203.0	0.4900E-03	0.2700E-04	0.1593E-06	0.2716E-04	0.09896	0.00007
20.0	56.5	207.0	0.4500E-03	0.1837E-04	0.1231E-06	0.1849E-04	0.09899	0.00004
21.0	48.0	211.0	0.5100E-03	0.1255E-04	0.1175E-06	0.1267E-04	0.09900	0.00003
22.0	40.9	215.0	0.5100E-03	0.8631E-05	0.9922E-07	0.8730E-05	0.09901	0.00002
23.0	35.0	217.0	0.5400E-03	0.6154E-05	0.8949E-07	0.6243E-05	0.09902	0.00001
24.0	30.0	219.0	0.6000E-03	0.4403E-05	0.8481E-07	0.4488E-05	0.09902	0.00000
25.0	25.7	221.0	0.6700E-03	0.3148E-05	0.8072E-07	0.3229E-05	0.09903	0.0

TABLE 3

Absorption due to oxygen and water vapour for the standard tropical atmosphere (Selby 1975) at 22.235 GHz

Height (km)	Pressure (mb)	Temperature (°K)	Water vapour density (gm/m^3)	Oxygen absorption coefficient (neps/km)	Water vapour absorption coeff. (neps/km)	Total absorption coefficient (neps/km)	Integrated absorption in nepers from	
							Surface to 25 km	25 km to surface
0.0	1013.0	300.0	0.1900E-02	0.2348E-02	0.9613E-01	0.9847E-01	0.0	0.27180
1.0	904.0	294.0	0.1300E-02	0.1981E-02	0.7257E-01	0.7455E-01	0.8651	0.18529
2.0	805.0	288.0	0.9300E-01	0.1667E-02	0.5732E-01	0.5899E-01	0.15828	0.11852
3.0	715.0	284.0	0.4700E-01	0.1369E-02	0.3241E-02	0.3378E-01	0.19966	0.07214
4.0	633.0	277.0	0.2200E-01	0.1153E-02	0.1692E-01	0.1807E-01	0.22559	0.04621
5.0	559.0	270.0	0.1500E-01	0.9680E-03	0.1280E-01	0.1377E-01	0.24151	0.03023
6.0	492.0	264.0	0.8500E-00	0.7999E-03	0.8093E-02	0.8893E-02	0.25285	0.01896
7.0	432.0	257.0	0.4700E-00	0.6663E-03	0.4988E-02	0.5655E-02	0.26012	0.01168
8.0	378.0	250.0	0.2500E-00	0.5523E-03	0.2962E-02	0.3515E-02	0.26470	0.00710
9.0	329.0	244.0	0.1200E-00	0.4487E-03	0.1597E-02	0.2046E-02	0.26748	0.00432
10.0	286.0	237.0	0.5000E-01	0.3687E-03	0.7450E-03	0.1114E-02	0.26906	0.00274
11.0	247.0	230.0	0.1700E-01	0.2998E-03	0.2846E-03	0.5845E-03	0.26991	0.00189
12.0	213.0	224.0	0·6000E-02	0.2405E-03	0.1132E-03	0.3537E-03	0.27038	0.00142
13.0	182.0	217.0	0.1800E-02	0.1924E-03	0.3834E-03	0.2308E-03	0.27067	0.00113
14.0	156.0	210.0	0·1000E-02	0.1653E-03	0.2389E-04	0.1792E-03	0.27088	0.00092
15.0	132.0	204.0	0.7600E-03	0.1209E-03	0.2066E-04	0.1416E-03	0.27104	0.00076
16.0	111.0	197.0	0.6400E-03	0.9452E-04	0.1972E-04	0.1142E-03	0.27117	0.00064
17.0	93.7	195.0	0.5600E-03	0.6936E-04	0.2012E-04	0.8947E-04	0.27127	0.00053
18.0	78.9	199.0	0.5000E-03	0.4639E-04	0.2191E-04	0.6830E-04	0.27135	0.00045
19.0	66.6	203.0	0.4900E-03	0.3121E-04	0.2610E-04	0.5731E-04	0.27141	0.00039
20.0	56.5	207.0	0.4500E-03	0.2124E-04	0.2894E-04	0.5018E-04	0.27146	0.00084
21.0	48.0	211.0	0.5100E-03	0.1451E-04	0.3949E-04	0.5600E-04	0.27152	0.00029
22.0	40.9	215.0	0.5100E-03	0.9979E-05	0.4734E-04	0.5732E-04	0.27157	0.00023
23.0	35.0	217.0	0.5400E-03	0.7116E-05	0.5917E-04	0.6629E-04	0.27163	0.00017
24.0	30.0	219.0	0.6000E-03	0.5092E-05	0.7745E-04	0.8255E-04	0.27171	0.00009
25.0	25.7	221.0	0.6700E-03	0.3640E-05	0.1019E-03	0.1056E-03	0.27180	0.0

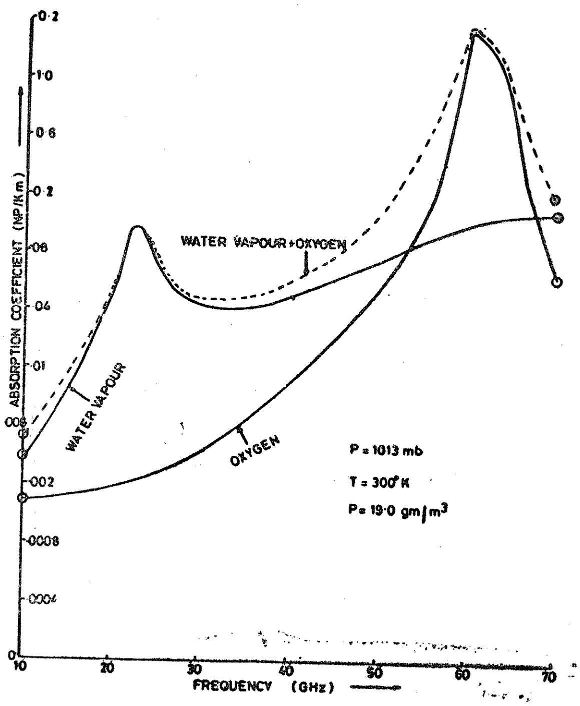

Fig. 1. Calculated absorption coefficient as a function of frequency

T = temperature in degrees Kelvin
ν_0 = 22.235 GHz and
ρ = water vapour density in gm/m^3

$$\Delta\nu = 2.58 \times 10^{-3} \left[P + 0.0147 \rho T \right] \times \left(\frac{T}{318} \right)^{-0.625} \qquad (15)$$

5. Method of computation and results

In order to calculate absorption coefficients and hence transmittances due to oxygen and water vapur from equations 5 and 14. the atmosphere has been divided into layers, each of one kilometer thickness (Stogryn 1967).

The top of the atmosphere has been fixed at 30 km, just above the altitude where the assumed water vapour distribution reaches zero. Pressure, temperature and humidity profile for each layer is taken for a standard tropical atmosphere described by Selby *et al.* (1975) and is given in Table 2 for the sake of ready reference.

Tables 2 and 3 show the results of the computation of the absorption coefficients due to O_2 and H_2O vapour at each kilometre height at 19.35 and 22.235 GHz frequencies. In order to calculate the integrated absorption which is required for computing brightness temperature, trapezoidal rule has been used for linear combination of water vapour and oxygen absorption coefficients. The integrated absorption $f(z) = \int_0^z \alpha(u)\, du$

where, $\alpha(u) = \alpha_{O_2} + \alpha_{H_2O}$ is given in Tables 2 and 3 for 19.35 and 22.235 GHz at each kilometre height in the atmosphere.

Fig. 1 depicts the absorption of water vapour and oxygen as a function of frequency from 10 GHz to 70 GHz. The values of surface parameter of pressure, temperature and density are 1013 mb, 300°K and 19 gm/m^3. The role of water vapour resonance at 22.235 GHz can easily be seen from the graph.

6. Concluding remarks

The importance of absorption due to O_2 and H_2O vapour in the transfer of thermal microwave through the atmosphere has been brought out. A method of deriving absorption coefficient as a function of frequency, and atmospheric meteorological parameters has been developed. The results of the computation for 19.35 and 22.235 GHz microwave frequencies are given. Calculated absorption coefficients for different frequencies demonstrate the relative contribution at each frequency.

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