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Remote sensing of atmospheric water content from Satellite Microwave Radiometer (SAMIR) on *Bhaskara*

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ABSTRACT. The Indian Satellite *Bhaskara* has onboard a microwave radiometer (SAMIR) with two channels; one in 19.35 GHz and the other in 22.235 GHz. Data from the radiometer has been used for the determination of integrated water vapour and liquid water content over oceans. The regularisation method of regression analysis suggested by Grody (1976) which follows directly from radiative transfer theory has been used. The satellite derived water vapour content has been compared with nearest radiosonde observations and APT pictures. The *Bhaskara* passes for orbit Nos. 300, 314 329 dated June 27, 28 and 29 were analysed and the results are discussed.

1. Introduction

Atmospheric water vapour is one of the most important constituent of the air in deciding weather and climate although it is only 2 per cent of the total mass of the atmosphere. The variability in water vapour content of the atmosphere is of great significance for several reasons.

(*i*) The amount of water vapour present in a given volume of air is an indication of the atmosphere's potential capacity for rain.

(*ii*) Water vapour is a regulator of heat loss from the earth because of its power to absorb radiation.

(*iii*) The amount of water vapour present decides the quantity of latent heat energy stored up in the atmosphere for the growth of depressions, storms and tropical cyclones.

(*iv*) The amount of liquid water content of the cloud gives an indication of the rain bearing potential of a cloud.

Passive Microwave Remote sensing offers a unique capability to sense total atmospheric water vapour and liquid water content over oceans in the presence of most types of clouds. These quantities are important for understanding the development of tropical cyclones and have been used for typhoon study by Rosenkranz *et al.* 1978 and Grody (1976). The vertical temperature structure of the atmosphere is already obtained on operational basis from TIROS-N satellite using microwave sounding units (Westwater 1972, Fritz *et al.* 1972).

The earlier successful attempts to derive total atmospheric water content was from Mariner-2 Venus probe (Barath *et al.* 1969), Cosmos 243 and Cosmos 384 (Basharinov *et al.* 1969) data. Nimbus-5 (Nimbus E) satellite microwave radiometer data incorporated channels 22.235 and 31 CZz for evaluation of this capability. Nimbus-G incorporates multifrequency radiometer to get these informations. Out of the various methods that have been used in the literature for estimation of atmospheric water content over oceans, (Fymat *et al.* 1978), the method described by Grody (1976 and Staelin 1973, 1976) and Rosenkranz *et al.* (1972) have been used extensively.

In the present paper, the authors have used the statistical inversion algorithms (also known as regularisation method) suggested by Grody (1976, 1979) for the frequencies of 19.35 and 22.235 GHz, satellite microwave radiometer frequencies onboard India's second satellite *Bhaskara.* These microwave frequencies are for the first time, have been used for atmospheric water vapour and liquid water determination over oceans and provided a novel view of a tropical depression as regards its total water vapour and liquid water is concerned.

2. Description of Satellite Microwave Radiometer (SAMIR) on *Bhaskara*

The *Bhaskara* (earlier named *SEO,* satellite for earth observations) launched on 7 June 1979 is a low orbitting experimental satellite at an altitude of 525 km with an inclination of 51 deg. The satellite carries as one of its payload a Microwave Radiometer system called SAMIR (Satellite Microwave Radiometer) and consists of three Radiometers R1, R2 and R3 of which R1 and R2 are at 19.35 GHz and R3 at 22.235 GHz. The R1 and R2 scans the surface at angle of 5.6, 2.8, —2.8 and —5.6 and cold sky at 180 deg. The R3 radiometer scan the earth's surface at view angles of 11.2, 2.8, —2.8 and —11.2 and cold sky at 180 deg. The two frequency radiometers, 19.35 and 22.235 GHz have temperature sensitivity better than 1 deg. K, beamwidth of 14.02 and 22.86 deg., integration time of 210 and 350 ms and ground resolution of 125 km and 200 km near nadir, respectively. The details of the system onboard *Bhaskara,* their payload and characteristics, type of the data product has been described in detail in a document '*Satellite for Earth Observation* (*SEO*)' 1976.

3. Physical basis for relationship between brightness temperature and atmospheric water content

The relationship between brightness temperature and atmospheric water content can be understood by considering a hypothetical case of an isothermal earth atmosphere system.

The brightness temperature, obtained from radiative transfer equation can be written as :

$$T_{B\,(\nu)} = T_0\,[1 - \tau_\nu^{2\sec\theta}(1 - \epsilon_{s\,(\nu)})] \qquad (1)$$

where,

T_0 = Temperature of the earth atmosphere system.

τ_ν = Total atmospheric transmittance due to H_2O vapour, liquid H_2O and O_2.

As Grody (1976) shows even such a simple model incorporates most of the important radiative transfer effects for frequencies below 40 GHz. The total atmospheric transmittance is a product of water vapour, oxygen and liquid water droplet transmittances.

$$\tau_\nu = [\tau_{\nu(H_2O)}\ \tau_{\nu\,(O_2)}] \cdot \tau_{\nu(\text{liquid})}$$

$$\approx \tau_{\nu(H_2O)} \cdot \tau_{\nu(\text{liquid})} \qquad (2)$$

Assuming oxygen transmittance near unity.

For frequencies below 50 GHz and water droplet smaller than 50 microns corresponding to non-precipitating clouds — The liquid water cloud transmittance is approximated by Rayleigh limit, dependent only on liquid water volume and not on drop size distribution. Thus, the frequency, temperature and liquid water dependence is adequately given by Goldestein (1951) and Staelin (1966).

$$\tau_{\nu(\text{liquid})} = e^{-K\nu^2 Q} \qquad (3)$$

$$K = 1\cdot 11\ e^{[0.0122(291 - T_{cl}) - 4]}$$

where,

T_{cl} = cloud temperature in degrees Kelvin

ν = frequency in GHz

Q = integrated liquid water content in kg/m²

K = a parameter which depends on mean cloud temperature, T_{cl}.

For small values of exponent argument (3) can be written as :

$$\tau_{\nu(\text{liquid})} = e^{-Q/Q_0(\nu)}$$

$$\approx 1 - \frac{Q}{Q_0(\nu)}$$

$$Q_{0(\nu)} = \frac{1}{K\nu^2} \qquad (4)$$

which is valid for $Q << Q_0$ (40) $\sim$ 5 kg/m². The transmittance due to water vapour, neglecting near unity oxygen transmittance can be approximated as :

$$\tau_{\nu(H_2O)} = -e^{\,W/W_0(\nu)}$$

$$\approx 1 - \frac{W}{W_{0(\nu)}} \qquad (5)$$

which is reasonable for $W << W_0(22) \sim 18$ g/cm². It should be noted that absorption due to ice cloud is two order of magnitude less than liquid water cloud of the same water content and therefore has been neglected. Also, whereas the absorption due to rainfall is greater than that of liquid water clouds of the same water content, for the present purpose the effect of precipitation is neglected by assuming that area of precipitation is small compared to the instrument field of view. This approximation is very well valid for SAMIR as its field of view are larger than SCAMS and NEMS instruments where this assumption has been used (Grody 1979).

Combining Eqns. (4) and (5) into Eqn. (1), we obtain a linear approximate form, as :

$$T_B(\nu)=\epsilon_{s(\nu)}T_s+2T_s\left[\frac{W}{W_0(\nu)}+\frac{Q}{Q_0(\nu)}\right](1-\epsilon_{s(\nu)}) \quad (6)$$

Thus brightness temperature measurements at two frequencies enable the determination of Q and W, given a reasonable estimates of the temperature T_s ,surface emissivity ϵ_s and mean cloud temperature (contained in Q_0 and necessary for determination of liquid water only). The solution has thus the general form :

$$W=w_0+w_1T_B\ (\nu_1)+w_2\ T_B\ (\nu_2) \quad (7)$$

$$Q=q_0+q_1\ T_B\ (\nu_1)+q_2\ T_B\ (\nu_2) \quad (8)$$

The form of Eqns. (7) & (8) suggests the use of a statistical linear regression solution technique with brightness temperatures as predictors where the coefficients contain the variation in temperature and emissivity of the dependent data sample.

4. Simulation results and examples of SAMIR derived water content

The coefficients appearing in Eqns. (7) & (8) have been derived from the forward calculation of the following expression for brightness temperature for a non-scattering atmosphere in local thermodynamic equillibrium.

$$T_B(\nu)=\left\{1-\epsilon\nu(\theta,T_s)\right\}\left\{T_c\exp\left[-\int_0^{\infty}\alpha(\theta,z)\,dz\right]+\int_0^{\infty}T(z,\theta)\ \exp\left[-\int_0^{z}\alpha(\theta,z)dz\right]\alpha(\theta,z)dz\right\}$$

$$\exp\left[-\int_0^{H}\alpha(\theta,z)\,dz\right]+\epsilon\nu\ (\theta,T_s)\ T_s\times$$

$$\exp\left[-\int_0^{H}\alpha(\theta,z)\,dz\right]+\int_0^{H}T(z,\theta)\exp\left[-\int_0^{z}\alpha(\theta,z)dz\right]$$

$$\times\alpha\ (\theta,\ z)\ d_z \quad (9)$$

$\epsilon_\nu\ (\theta, T_s)$ = emissivity of sea at molecular temperature T_s for nadir viewing angle θ

H = altitude of spacecraft

T_c= Total extraterrestrial background radiation temperature

$T(z,\theta)$ = temperature of the atmosphere at altitude z and viewing angle θ

$\alpha(\theta,z)$=atmospheric absorption coefficient at z and θ

The first term in Eqn. (9) comprises the temperature of the downward radiation of the extraterrestrial noise, attenuated by the entire atmosphere and the second downward radiation of the atmosphere itself, reflected by the ocean surface and in turn attenuated by the intervening atmosphere between the ocean and radiometer. The third term accounts for the upward emission of the atmosphere between the ocean and radiometer.

Standard tropical atmospheric profiles of temperature water vapour and liquid water (value less than 5 kg/m^2) were used in computing brightness temperatures using Eqn. (9) which were then correlated with different amount of water vapour and liquid water. The method of computing theoretical microwave brightness temperature for a standard tropical atmosphere is described by Pandey *et al.* (1979) for 19 and 22 GHz frequencies using the above equations. The cloud was introduced in the atmosphere artificially and the corresponding relative humidity was adjusted to 100 per cent at that layer for water vapour absorption coefficients. The effect of sea state was taken into account by performing calculations of T_B's with 10 per cent increased surface emissivity in 20 per cent sample (100) (Grody 1979). The emissivity was determined as a function of frequency and temperature from the equations gives by Stogryn (1971); Hollinger (1975); Pandey *et al.* (1979). These Eqns. were based on laboratory measurements by Saxton and Lane (1952), Grant *et al.* (1957) and others. The expressions for absorption coefficients due to water vapour, O_2 and cloud liquid water used in computing brightness temperature at each km height of the horizontal stratified atmosphere is the one described by Pandey *et al.* (1979) (Barret and Chung 1962; Liebe 1969; Goldestein, attenuation by condensed water propagation of short radiowaves, Kerr Ed. 1951, D. H. Staelin, 1966, Hollinger 1975).

The linear regression equations obtained for water vapour and liquid water over ocean surfaces are :

$$W=-6\cdot435+0\cdot0606\ T_{22}-0\cdot0123T_{19}\ \mathrm{g/cm^2} \quad (10)$$

$$Q=-3\cdot143+0\cdot0289T_{19}-0\cdot0032T_{22}\ \mathrm{kg/1m^2} \quad (11)$$

However, it should be emphasised here that water vapour and liquid water determination is possible only over oceans with these two frequencies. This is due to the fact that at microwave frequencies, the terrestrial surface and

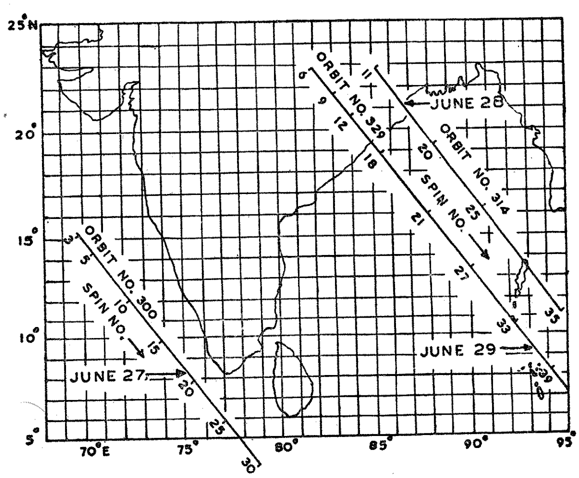

Fig. 1. Subsatellite points for *Bhaskara* pass on 27, 28, 29 June 1979

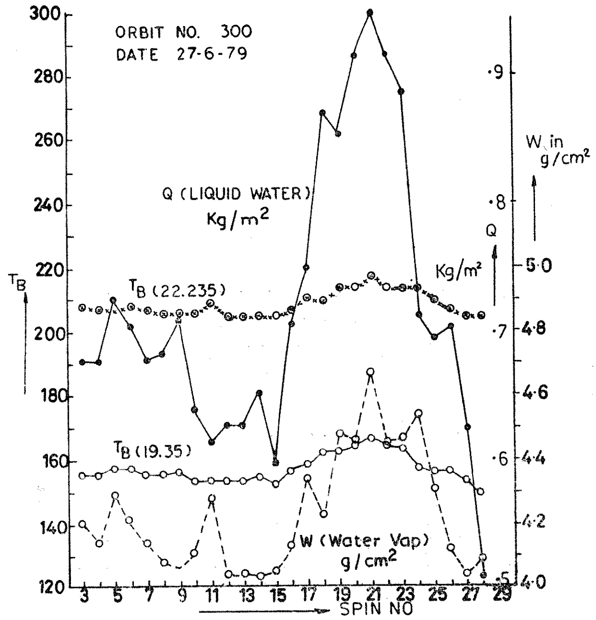

Fig. 2. Water vapour and liquid water as determined from Satellite Microwave Radiometer (SAMIR) onboard *Bhaskara* on 27 June

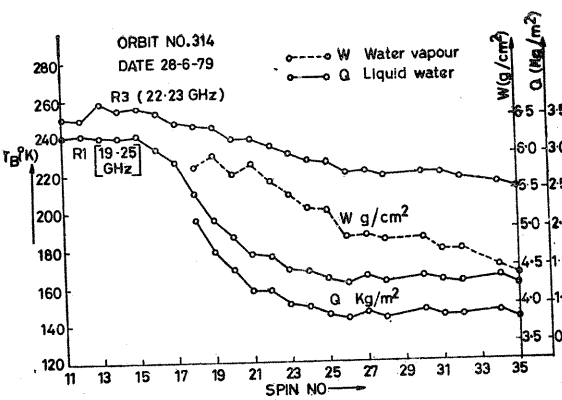

Fig. 3. Water vapour and liquid water as determined from Satellite Microwave Radiometer (SAMIR) onboard *Bhaskara* on 28 June

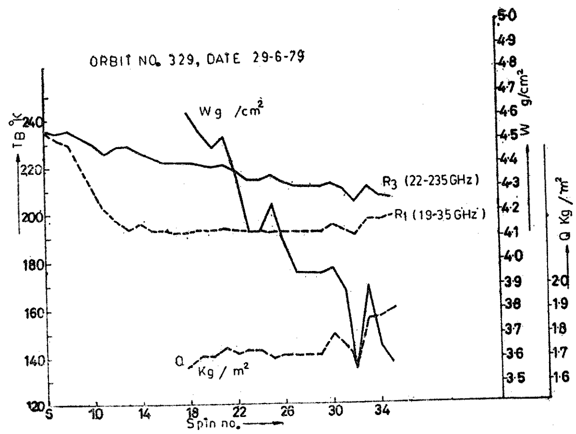

Fig. 4. Water vapour and liquid water content of a tropical depression on 29 June over Bay of Bengal as derived from SAMIR onboard *Bhaskara*

troposphere are in local thermo-dynamic equilibrium and radiate with intensity directly proportional to T_B The microwave emissivity of land surfaces is typically near 0.8-1.0 and thus their brightness temperature range from 0.8-1.0 times their physical temperature. This land brightness temperature is nearly the same as water vapour temperature and thus neither appears in emission nor in absorption. The ocean, on the other hand has surface emissivity of the order of 0.4 and will thus have a brightness temperature of the order of 130 deg. K, much below the temperature of the atmospheric water and therefore, atmospheric water vapour and liquid water appears warm against the cold background of the ocean.

We shall now describe some of the results obtained using regression equations 10 and 11 for *Bhaskara* passes for 27, 28 and 29 June over

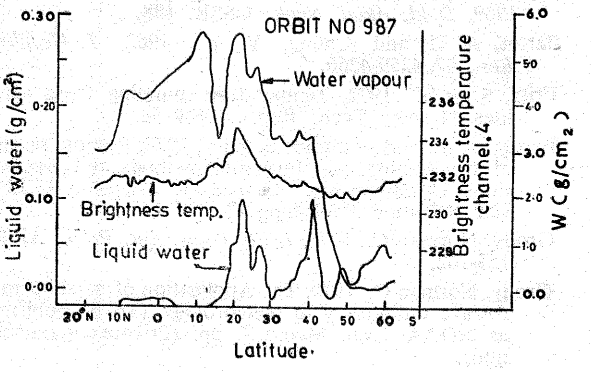

Fig. 5. Water vapour and liquid water in a tropical cyclone on 22 February 1973 south of India near 62° E Long. (*After* D.H. Staelin *et al.*, from NEMS 22 and 31 GHz frequencies, *J. Appl. Met.*, 1976)

Arabian Sea and Bay of Bengal. These three passes alongwith spin no which gives Lat. and Long. of subsatellite points are shown in Fig. 1.

(*i*) The values of water vapour and liquid water content over Arabian Sea for 27 June is plotted in Fig. 2. The average value of water vapour is about 4.0 gm/cm² neglecting the sudden increase in water vapour and liquid water content from spins 15 to 24 which may be due to antenna beam grazing the coastal land and subsequently increasing the brightness temperatures R_1 and R_3. The liquid water content varies from 0.5 to 0.7 kg/m² near spin 5. The APT picture shows scattered cloudiness near spin 5 (Lat. 14.5 deg. N, Long. 10.5 deg. E) and spin 30 (Lat. 3.5 deg. N, Long. 79.0 deg. E) but the increased water vapour/and liquid water content near spin 5 suggests the presence of deep clouds.

(*ii*) The *Bhaskara* pass for 28 June is shown in Fig. 1 The values of water vapour and liquid water content is plotted in Fig. 3. The minimum value of the water vapour and liquid water content is 4.4 gm/cm² and 0.8 kg/m² for spin No. 35 (Lat. 11, Long. 95) and continuously goes on increasing till it reaches a maximum value of 6.0 gm/cm² and 2.1 kg/m². The APT picture shows cloudiness near 15-20 deg. N to 85-90 deg. and less cloudiness in the remaining satellite pass. The *Indian Daily Weather Report* at 0830 hr. IST indicates the presence of low pressure area *a* the north head Bay and adjoining coastal West Bengal and low pressure area is well marked with central pressure 992 mb scattered cloudinees along the east coast has also been reported.

(*iii*) The *Bhaskara* pass for 29 June is near to the satellite pass of 28 June and is shown in Fig. 1. The values for total water vapour and liquid water content are plotted in Fig. 4. It is interesting to note that water vapour content shows the continuous increase as one approaches towards the north Bay. However, there is a tendency of Q to show the similar behaviour as that of W but it is not very marked. This may be due to non-linear effect for high values of liquid water and water vapour content. The *Indian Daily Weather Report* (IDWR) reports well marked low pressure area over north Bay concentrated into depression on 28th night moving northwards and entered Bangladesh at 0830 IST at 23 deg. N, 89.5 deg. E. The entire east coast beyond 15 deg. N is reporting complete overcast sky under the influence of depression. Steep pressure gradient over Bay of Bengal with central pressure about 988 mb has been reported.

The analysis of APT picture also indicates qualitatively the presence of dense clouds near 18.20 deg. N to 85 deg. E. For higher spins, APT picture does not show much cloud.

Since the centre of depression lies over land, water vapour and liquid water content could not be estimated. Nevertheless it is interesting to find the low level convergence near the centre of depression.

(*iv*) The comparison of the total moisture content over Bay of Bengal and Arabian Sea for 27 and 28 June are made in Table 1. The mean monthly precipitable water as obtained from radiosonde observations (Mokashi 1977) for the coastal stations are also shown in Table 2. A fairly good agreement is found. It is also interesting to find higher moisture content over Bay of Bengal than over Arabian Sea. The reason for this is under investigation.

(*v*) The results obtained by Staelin *et al.* (1976) for a tropical cyclone on 22 February 1973, south of India near 62 deg. E Long. is given in Fig. 5 to compare the magnitudes of water vapour and liquid water content derived. Our results conform to the results obtained by Staelin *et al.* (1976).

TABLE 1

Total moisture content

	W gm/cm²		Q kg/m²	
	Max.	Min.	Max.	Min.
Bay of Bengal 27 June 1979	6.0	4.4	1.5	0.8
Arabian Sea 28 June 1979	4.6	4.1	0.7	0.5

TABLE 2

Mean monthly precipitable water for June (1956-1961)

Station	Precipitable water
Calcutta	5.74
Madras	5.1
Vishakhapatnam	5.4
Bombay	5.13
Pune	3.93
Trivandrum	4.63

5. Conclusions and future potential

The satellite microwave radiometer on board India's second satellite *Bhaskara* has demonstrated the ability of 19.35 and 22.235 GHz channel, to determine integrated abundances of water vapour and liquid water over oceans and in tropical depressions. However, the accuracies of these parameters estimated to be about 10 per cent could not be definitely established because of the lack of accurate data for comparison. Nevertheless the comparison with mean monthly average from coastal station in both Arablan Sea and Bay of Bengal is encouraging. These data, when combined with APT pictures or other satellite pictures will definitely provide a unique portrait of the oceanic weather systems.

It is, however, suggested that nonlinear approximations for tropical regions, where brightness temperatures saturate for high value of water vapour content should be attempted which may improve the results.

It is also recommended that in future spacecrafts more frequencies should be added to delineate surface effects, for example, 6 GHz, which could provide sea surface temperature also and 31 GHz for better atmospheric separtability. Further attempts can also be made to derive the regression coefficients experimentally from simultaneous aircraft or satellite and radiosonde observations under variety of meteorological conditions.

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