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INTRODUCTION

Persistent demand for new generation of communication system with higher data rate and channel capacity have kindled research in higher frequencies, extending well into the millimeter wavelength regions of the spectrum. This has become possible through recent advances in mm-wave component and system technology. The mm-wave band is largely exploited because it can provide a wide range of advantages, such as, shorter wave-lengths, wider bandwidths that result in compact system with higher data transfer rate and channel capacity. Besides these, higher frequencies will have better immunity to interference or jamming.

A number of factors, which are not generally considered at lower wavelengths, can influence performance and reliability of the mm-wave communication system. These should be accounted for in the design. Above 10 GHz, radio waves start to interact with various atmospheric gases, particularly oxygen, water vapour and other hydrometeors in the form of precipitation. They introduce additional signal attenuation which must be understood and predicted correctly before designing a mm-wave system. Adequate fade margin would not only ensure a predetermined level of reliability and performance but also reduce cost of the system.

1.1. Atmospheric influence on radio wave propagation :

Troposphere is the lowest region of the atmosphere extending upto 16 km near the equator and decreases in height towards poles with about 11 km in latitude 50 and 9 km near the poles, where precipitation and clouds are confined. Major signal attenuation takes place within troposphere while ionosphere (60-1000 km) becomes transparent at mm-wave band. Radio-wave propagation is affected in troposphere by the following reasons;

- Absorption by tropospheric gases
- Attenuation by hydrometeors
- Refraction effects changing angle-of-arrival, focusing and defocusing
- Multipath fading and ducting
- Tropospheric scatter from turbulent fluctuations in the refractive index
- Scintillation on terrestrial and earth-space paths

Each of these contributions has its own characteristics as a function of frequency, geographic location and elevation angle. At elevation angles above 10^0 only gaseous attenuation, rain attenuation and possibly scintillation will exceed a few tenths decibels, depending on propagation condition. Oxygen and water vapour are the two main constituents of the earth's atmosphere that absorb radio energy; such attenuation is frequency dependent and also varies with radiometeorological parameters. Oxygen molecules possess a small magnetic moment which interacts with the magnetic field of the radio waves giving rise to a broad absorption band near 60 GHz, together with isolated lines near 119 GHz and at frequencies above 350 GHz. Water vapour has a weak absorption line near 22 GHz, with much stronger lines around 183 and 325 GHz and many more in the infra-red region of the spectrum [*Gibbins,* 1986(b)]. The absorption due to oxygen is fairly uniform around the world and can be predicted easily. On the other hand water vapour is a highly variable parameter which changes with location and season. Therefore, studies of water vapour is more important and would be useful to a variety of applications, e.g.,

- Meteorology
- Communication in mm-wave band
- Aircraft flying data
- Agriculture, atmospheric pollution and biology

Most of the mm-wave communication systems operate at frequencies around the atmospheric 'windows' where the absorption is minimum. The maxima of the absorption bands are utilised in remote sensing of atmospheric gases. Atmospheric water vapour can, in general, be measured by,

- Radiosonde
- Infra-red hygrometers
- Radiometers

In India, atmospheric monitoring is done by radiosonde with two launches daily taken by India Meteorological Department. However, radiosonde has poor accuracy in relative humidity measurement at higher altitudes and balloon ascension path can not be controlled along zenith. Thus, radiosonde practically gives slant path parameters of unknown angle. In contrast to this, radiometry is a convenient and powerful remote sensing method which can give accurate, continuous data along vertical and slant paths. Both ground based and satellite based radiometers are proven to be quite useful for remote sensing of water vapour. Moreover, highly sensitive radiometers operating at emission lines of atmospheric minor constituents are capable of sensing these gases and their fluctuations. Of the various emission lines the attenuation at 22.235 GHz line is the least and, therefore, a ground-based radiometer can see through greater heights of the atmosphere, thus providing information on the total atmospheric column within the antenna beam.

A study of the geographical and seasonal distribution of water vapour content over the Indian sub-continent made from radiosonde observation indicates that the water vapour content is nearly maximum particularly during the monsoon months at Calcutta (lat.22°32′N, lon.88°20′E) a tropical station near the Bay of Bengal. We are, therefore, prompted to undertake the radiometric studies of the atmosphere in different climatic conditions at the water vapour line at 22.235 GHz over Calcutta.

The same 22.235 GHz radiometer was taken to Indian Antarctic base station Maitri (lat.70°45′S, lon.11°44′E), the driest continent of the world to study the dynamic variation in atmospheric water vapour during polar summer. Simultaneous measurement of surface meteorological parameters were also recorded continuously to understand water vapour distribution and transport in more detail.

1.2. Millimeterwave imaging from satellite :

High resolution remote sensing image data of earth's surface may be acquired from satellite borne sensitive radars and radiometers operating within a particular band of electromagnetic spectrum. The operational band of wavelength is crucial because each range of frequency has its own merit in terms of information it can extract from the scene under observation. Shorter wavelengths can sense finer surface features in imaging. Because of the wide view possible from a satellite platform and in many applications information obtained through remote sensing has value only if it can be acquired cost effectively and processed rapidly. In such a situation, it is obvious to turn to the computers to achieve economy and fast speed of processing. With introduction of powerful digital computers, sensors, communication and data processing technology, the present earth observing satellites can provide high quality of image and other forms of data about earth's surface [*Koopmans,* 1983]. The merits of mm-wave imaging include the following [*Carver et al.* 1986; *Leberl* 1978; *Ulaby et al.* 1975] :

- Antenna size will be much reduced which will be convenient for satellite or aircraft installation.
- In millimeterwave band, low atmospheric loss at certain frequencies and highly directional antenna beam are attractive parameters for imaging.
- Millimeterwaves are fairly transparent to cloud cover, thus allowing imaging of the regions which remain cloudy. Millimeterwaves also suffer less attenuation to fog, snow and even to rain at low rates.
- Millimeterwaves are more immune to interference and interception.
- Millimeterwaves penetrate more deeply into vegetation than optical waves. Likewise, it is also capable of penetrating ground significantly. For dry soil, penetration depth is high as compared to that in wet soil.

The remote sensing data have great potential for solving many problems; for weather forecasting [*Chadwick* 1983] topographic mapping [*Adams et al.* 1981], soil moisture determination [*Blanchard et al.* 1983; *Bradley et al.* 1981], crop mapping [*Brisco et al.* 1982], flood mapping, land use mapping, monitoring urban developments [*Bryan* 1975, 1983], locating iceberg boundary [*Matzler et al.*1984], monitoring iceberg movement at Antarctica, monitoring ship traffic and fishing fleets and many other application areas. Imaging from satellite can provide an economical means to monitor the polar regions because of darkness and the harsh environment [*Swift et al.* 1991].

Global sea surface temperature is the most important geophysical parameter required for the understanding of climatic changes. Many climatic phenomena are associated with small changes in sea-surface temperature (typically 0.3 K) over large geometric scales. Earth based measurements can not provide sufficient coverage in a short time scale with consistent accuracy. In contrast, a space-borne radiometer can cover most of the earth's surface on a short time-scale with reasonable accuracy.

First microwave observations of the earth surface was carried out by Electrically Scanned Microwave Radiometer(ESMR) launched on NIMBUS 5 in 1972. The operating frequency was 19.3 GHz and used a phased array scan along cross track to produce an image. The spatial resolution was 50 km and for single frequency operation, it was used for geophysical application. The second attempt was scanning multi-channel microwave radiometer (SMMR) at 6.6 GHz and another system called Special Sensor

Microwave/Imager SSM/1 [1987] at 19-85 GHz both launched on Seasat 1, Nimbus 7 [1978]. Apart from multi-frequency operations, these systems had the dual polarization and data obtained, may be used for wider applications.

However, the spatial resolution could not be much improved and was almost the same as ESMR. Since the launch of ESMR there was a constant demand for increasing spatial resolution and exploring the advantages of different frequencies in both microwave and millimeterwaves. That resulted in a system called Electronically Scanned Thinned Array Radiometer (ESTAR). The system utilised real aperture along the direction of aircraft motion and synthetic aperture in the cross-track direction.

The first earth observational synthetic aperture imaging radar was the SEASAT satellite launched in June 1978. Some variations of aperture synthesis was proposed by *Schanda* [1979] for earth viewing from space. Carl Wiley and co-workers at Hughes Aircraft Company demonstrated some variations of aperture synthesis for implementation in space. A two channel microwave radiometer (1.35 cm, 1.9 cm.) was taken aboard Mariner 2. Passive observations of earth were started in 1968 by Cosmos 243, which was equipped with four radiometers at 3.5, 8.8, 22.2, 37 GHz [*Basharinov et al.* 1971]. Since then microwave radiometers are regularly aboard aircraft which include Cosmos 384, Nimbus 5, 6, 7 and Skylab, Tiros, Seasat. Of particular importance among these radiometers are the Electrically Scanning Microwave Radiometers (ESMR) system flown aboard Nimbus 5 (1.55 cm.) and Nimbus 6 (0.81 cm.). They have provided synoptic images of the entire globe. Measurements of the aerial distribution of Antarctic sea ice have been done successfully with passive microwave imagers [*Zwally et al.* 1983]. Nimbus-7 SMMR carried 10 channels microwave radiometers which gave vital information on multilayer ice, thickness, ice temperature, snow cover and surface melting [*Svenden et al.* 1983; *Cavalieri et al.* 1984; *Swift et al.* 1985; *Swift and Cavalieri*, 1985; *Comiso,* 1986]. Multichannel microwave instruments also allowed Nimbus-7 satellite to provide various sea ice parameters. Satellite passive microwave remote sensing of sea ice has been extensively reviewed by *Untersteiner et al.* [1984]; *Cavalieri et al.* [1985].

1.3. Radiometric sensing of atmospheric gases and hydrometeors :

Remote sensing of atmospheric water vapour and other constituents by ground-based and satellite borne radiometric observation and earth imaging at centimeter and millimeterwave regions are reported from :

1. Aerospace Corporation, California, USA
2. Air Force Cambridge Research Laboratories, Mass, USA
3. Environment Research Laboratory, Boulder, Colorado, USA
4. Indian Space Research Organisation (ISRO), Ahmedabad, India
5. International Telecommunication Satellite Organisation (INTELSAT)
6. Jet Propulsion Laboratory, California, USA
7. National Physical Laboratory (NPL), New Delhi, India
8. National Aeronautics and Space Administration (NASA), USA
9. Naval Research Laboratory, Washington D.C., USA
10. NHK Laboratories, Tokyo, Japan
11. Onsala Space Observatory, Sweden

12. Radio Research laboratory, Tokyo
13. Research Laboratory in Electronics, MIT, UK
14. Rutherford Appleton Laboratory (RAL), UK
15. Wave Propagation Laboratory, USA

In 1946, Dicke proposed a modulation technique to solve the gain fluctuation problem of total power radiometer [*Dicke*, 1946]. Thus, a new generation of radiometer called 'Dicke type radiometer' was evolved which revolutionised the field of remote sensing. Subsequently, a flurry of development took place in radiometer technology and they are now being used extensively for ground-based as well as satellite-borne observations.

Barrett and Chung [1962] observed that 22.235 GHz (1.35 cm) water vapour line may be effectively used to detect stratospheric water vapour from ground based observations. Later, *Croom* [1965a] studied thoroughly the radiometric sensing of stratospheric thermal emission and absorption near 22.235 GHz rotational line of water vapour with ground based radiometric observation up to a height of 80 km. He observed that, above 70 km, Doppler broadening is comparable to pressure broadening. He also observed that emission line measurement is ten times better than absorption line measurement using sun as a source. *Croom* [1965b] made another theoretical examination on the use of strong water vapour line at 183.311 GHz (1.64 mm) for measuring vertical distribution of water vapour. He found that 1.64 mm line would not be suitable for ground based measurement of stratospheric water vapour. Rather it would be ideal for water vapour profiling of troposphere from ground based observations.

Stratospheric water vapour measurement at 22.235 GHz was reported by *Bonvini* *et al.* [1966]. Atmospheric effects on propagation at millimeter wavelengths was given by *Altshular* [1968]. Later, 22.2 GHz resonance line of water vapour was successfully used to estimate total water column of the atmosphere from space-borne radiometer as reported by *Grody* [1976], *Staelin* [1981]. The strong water vapour resonance line 183 GHz was found suitable for profiling atmospheric water vapour [*Njoku*, 1982].

Cloud, in particular, profoundly affect the reflection, transmission and absorption of the solar radiation entering the atmosphere, and thus have a controlling influence on the earth-atmosphere energy budget [e.g. *Derr et al.* 1990]. *Staelin* [1966] discussed the determination of profile information from multispectral emission or extinction observation. In addition, he discussed the possibilities of simultaneous vapour and cloud liquid determination. *Toong et al.* [1970] showed that ground based microwave measurements of atmospheric emission at 5 wavelengths near 1 cm have enabled separate determination of the water vapour and liquid water contents of the atmosphere. *Falcone* [1971] made an experimental study of emission and absorption mode of measurement at 13 and 35 GHz when compared with theoretical values derived from radiative transfer equation they showed good agreement. The microwave radiometers operating at 22.235, 53.65, 50.8 GHz were used by *Rosenkranz et al.* [1972] for measurement of water vapour and cloud liquid water. The measured values agreed well with direct hygrometric measurements. Emission measurement was also done by *Fogarty* [1975] which shows no correlation with surface dew point temperature. *Grody* [1976] used satellite radiometric data in finding the correlation of water vapour content and liquid water with brightness temperature at microwave frequencies. *Gibbins* [1984] measured atmospheric emission under clear weather condition in the frequency range of 22-150 GHz. At higher frequencies the experimental attenuation values were higher than theoretical values. This may be due to the emission of other meteorological variables. *Westwater* [1978] observed that a dual frequency ground based microwave radiometer operating at 1 and 1.4 cm wavelength range can provide continuous measurements of integrated water vapour and cloud liquid water. The accuracy of vapour and liquid determination is estimated as a function of cloud amount. *Hogg and Guiraud* [1979] measured atmospheric attenuation at 20.6 and 31.65 GHz and found cloud liquid dependence on the retrieval of water vapour. Because sea surface emissivity is small and remains fairly constant, *Grody* [1980] obtained good measurement accuracy of water vapour by satellite borne microwave spectrometer operating at 22.235, 31.65 GHz over the sea. *Snider et al.* [1980] used ground based radiometers at 20.6 and 31.65 GHz in addition to satellite borne receiver at 28.56 for direct and continuous measurement of cloud liquid. Absorption in non-precipitating clouds ranged from less than 0.1 dB to maximum of about 5.5 dB and integrated liquid reached to a maximum of about 4.8 mm. *Westwater et al.* [1980] further discussed the cloud liquid measurements at 20.6 & 31.65 GHz. They observed that the conventional retrievals of vapour in presence of clouds with high liquid content were not satisfactory. It is true that the attenuation, or opacity, of clouds is linearly proportional to the amount of liquid water in clouds, the same is not necessarily true for brightness temperatures. The non-linearity arises, particularly at the higher levels of cloud attenuation, because emission from the top of the cloud is attenuated by the lower part of the cloud and so can not be combined linearly. To cope with the problem an 'adaptive' retrieval algorithm was developed by *Westwater and Guiraud* [1980] in which the retrieval coefficients are themselves functions of the retrieved parameter. Other examples of non-linear techniques are used when atmospheric attenuations become significant. *Hogg et al.* [1983] used radiometer having channels at 20.6, 31.65, 52.85 and 58.8 GHz with a pulse doppler VHF radar for retrieving temperature and water vapour profiles and wind measurements in troposphere. This technique resulted in getting temperature profiles and water vapour values more close to that obtained by radiosonde. Many examples of such radiometers have been discussed in the literature, mostly with particular reference to the determination of the wet path delay, for example by *Moran and Rosen* [1981], *Pandey and Kakar* [1983], *Elegard* and *Lundqvist* [1984], *Resch* [1984], *Resch et al.* [1984], *Gary et al.* [1985], *Janseen* [1985] and *Robinson* [1988], while the errors involved in deducing path delays have been considered by *Beckman* [1985]. Applications of microwave radiometers to determine the geophysically more fundamental parameters of total precipitable water vapour and cloud liquid content, from which most of the related quantities such as path delay and microwave attenuation can be deduced, include those by *Westwater and Guiraud* [1980], *Hogg et al.* [1983] and *Rocken et al.* [1991].

The calculations of attenuation and brightness temperature used to determine these algorithms were carried out using the model for complex refractivity developed by *Liebe* [1989] for dry air and water vapour, which includes 44 oxygen absorption lines and 30 water vapour lines, together with small corrections for non-resonant refractivity of dry air due to the Debye spectrum of oxygen and pressure induced nitrogen absorption, and an empirical non-resonant water vapour continuum. Cloud attenuation were determined using the Raleigh approximation to Mie scattering theory (since the size of water droplets in clouds is considerably smaller than the wavelength employed by the radiometer) together with a double-Debye model for the dielectric permittivity of water [*Liebe et al.* 1989].

To investigate the frequency dependence of atmospheric attenuation *Shimada et al.* [1985] measured atmospheric attenuation at 11, 18, 35 and 48 GHz using sun tracker in Tokyo, Japan. Observations reveal that for each frequency, seasonal variation of measured atmospheric attenuation was more remarkable than annual variation of measured atmospheric attenuation. They have also inferred that the measured atmospheric attenuation can be divided in two parts, one part is due to water vapour attenuation and the other due to oxygen attenuation. Thus the estimation of water vapour attenuation from theoretical formula of specific attenuation at both sides of 22 GHz water vapour line was found smaller than the measured values.

Elegard et al. [1985] carried out an extensive error analysis using an extremely large radiosonde database which include a wide range of climates from arctic to tropical regions, they found that the optimum frequencies were site dependent. Investigation of 22 GHz water vapour absorption line for different vertical distributions can provide a useful indicator of the optimum frequency as described by *Westwater* [1978] and *Hogg et al.* [1983]. *Hogg* found a frequency zone near 21/25 GHz which is least sensitive to the vertical distribution of water vapour and ideal for remote sensing. It is interesting to note that this value differs considerably from that deduced by *Westwater* [1987] though both of them used the same technique. This may be due to differences between the spectroscopic data and absorption models available in 1978 and the most recent information from *Liebe* [1989]. *Westwater* and *Snider* [1989] of Wave Propagation laboratory (WPL), USA conducted ground based zenith viewing with transportable and steerable three channel radiometer at 20.6, 31.65 and 90.0 GHz during 1987-1988 at San Nicolas Island, California, Denver and Colorado respectively. From their investigation of marine stratocumulus clouds at San Nicolas Island during July 1987, the amount of precipitable water vapour was varying between 0.9 to 3.1 cm and having a mean value of 1.9 cm. Also from their observations of cloud over Denver during Dec.1987, a relatively dry period and during Aug.1988, a typical Denver summer period, they have reported that during Dec.1987, precipitable water vapour contents were low, ranging from 0.1 to 1.0 cm. and having a mean value of 0.5 cm whereas during Aug. 1988, precipitable water vapour ranged between 1.06 to 3.2 cm with a mean value of 2.03 cm.

In India, Sharma [1979] has studied the atmospheric water vapour content over New Delhi using ground based radiometer at 22.235 GHz.

India has launched two remote sensing satellites in June 1979 and in Nov. 1981. Both carried similar payloads, which included a system called Satellite Microwave Radiometer (SAMIR) consisting of three radiometers two at 19.35 GHz and one at 22.235 GHz [*Pandey et al.* 1981]. Using standard tropical atmospheric profiles of temperature, water vapour and liquid water, a simulated set of computed apparent temperature and corresponding values of integrated precipitable water vapour and cloud liquid water were generated. Linear regression equations were then obtained and later used to retrieve integrated water vapour and cloud liquid water from observations made during passes over the Arabian Sea and the Bay of Bengal [*Pandey et al.* 1981, 1984]. *Bhattacharya* [1985] studied the atmospheric water vapour and atmospheric attenuation over New Delhi from ground based radiometric observations at microwave frequencies.

Calcutta, being one of the most humid regions in eastern India, ground based radiometric studies of the atmosphere at water vapour line on 22.234 GHz in the emission mode has been in operation at the Institute of Radiophysics and Electronics for the last 7 years. Observations were made under a wide range of climatic conditions. The same 22.235 GHz radiometer was taken to Antarctica and was put into continuous operation from Dec.1991 to Mar.1992 to study Antarctic water vapour variations. This thesis gives an account of the detail studies on water vapour and related mm-wave communication aspects over a tropical region Calcutta and at Antarctica. A number of new weather features were observed during the study especially at Antarctica which are all included in the thesis.

1.4. ORGANISATION OF THE THESIS :

Chapter 1	:	Introduction and scientific background on which the present problem is undertaken.
Chapter 2	:	The radiometer hardware and calibration technique.
Chapter 3	:	A fresh consideration on the selection of radiometer operating frequency in water vapour remote sensing.
Chapter 4	:	Integrated water vapour measurement with 22.235 GHz radiometer at Calcutta and Antarctica.
Chapter 5	:	Water vapour distribution and transport at Antarctica.
Chapter 6	:	Shift of millimeterwave window frequencies at different Indian locations.
Chapter 7	:	Millimeterwave attenuation models and their comparison with experimental results.
Chapter 8	:	A proposal on millimeterwave communication at Antarctica.
Chapter 9	:	Summary and concluding remarks.