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Review

Wave propagation phenomena in troposphere: Indian experience

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Abstract The work carried out on tropospheric radio wave propagation has been reviewed in this paper Emphasis has been given on the studies related to radio climatology both for clear air and precipitation, propagation characteristics involving fixed (terrestrial line of sight and transhorizon) and mobile as well as marine communication Attenuation of radio wave due to water vapour, rain and cloud also has been outlined

Keywords Troposphere, wave propagation, radio climatology, microwave communication, LOS, rain attenuation

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Plan of the Article

1. **Introduction**
2. **Characterisation of the tropospheric medium**
3. **Fixed, mobile and marine communication**
4. **Rain, water vapour and cloud attenuation**
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1. Introduction

Prediction of radio field strength at VHF (very high frequency), UHF (ultra high frequency) and microwave frequency bands and exploring new remedial measures to overcome propagation problems with good degree accuracy is not possible in spite of intense research work. The radio researchers/engineers have developed empirical relationships based on experiments and have tried to extend the results to similar geographical regions. But the methods have to be tested with the data generated over the Indian subcontinent before applying them to the design of communication and radar system. To evolve better formulations suitable to tropical countries especially for Indian conditions, research efforts carried out in India can be broadly categorized into the following areas:

(i) Characterisation of tropospheric medium.

(ii) Fixed, mobile and marine communication

(iii) Rain, water vapour and cloud attenuation studies.

2. Characterisation of the tropospheric medium

The quality and reliability of radar and microwave communication systems are largely controlled by the Radio Refractivity profile in the lowest one or two kms of our atmosphere. The effects of the Indian seas and large landmasses dominate the atmosphere over the Indian subcontinent. An apriori knowledge of the total refractivity profile particularly of the refractivity gradient, at least in the form of monthly average, is a prerequisite for designing robust LOS and troposcatter systems and also to predict radar performance. Over-design beyond a certain level is as dangerous as under design, especially in the tropical zone, because of the high level of interference caused by super- refraction and ducting. An atlas of

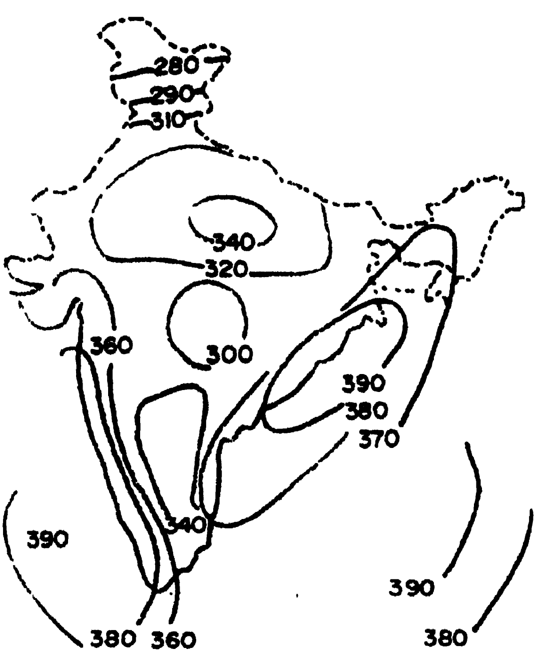

Figure 1. Refractivity over surface in May during 0000 GMT.

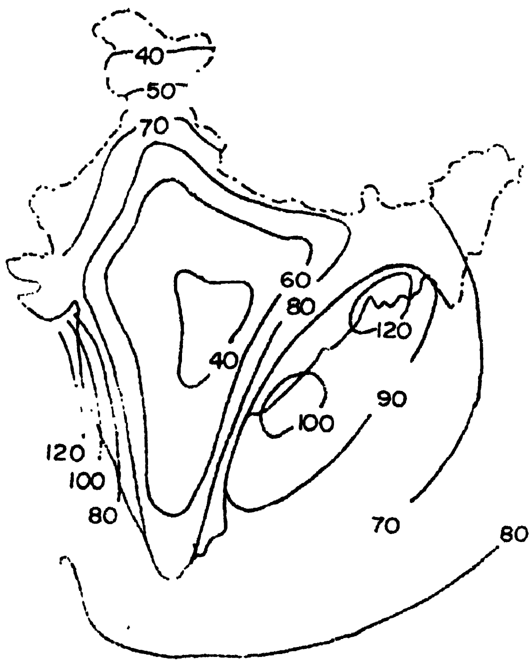

Figure 2. Refractivity gradient over surface in May during 0000 GMT.

tropospheric radio refractivity over the Indian subcontinent was developed in 1977 on the basis of data from 16 regular radiosonde stations and data collected from ships on special Indo-USSR ship expedition were used [1]. Another atlas of tropospheric radio propagation parameters over the Indian sub- continent was brought out in 1985 [2]. This atlas in fact is the upgrade version of the earlier atlas. The upgrade version was necessitated for a number of reasons. Data from a large number of radiosonde stations with more accurate sensors became available. For example, data from 32 radiosonde stations were used in this atlas as against 16 stations in the previous version. A survey of the users showed that due to the advances in system design, a number of new sets of data were required in addition to what was given in the previous atlas. This atlas was also primarily based on climatological data obtained from the India Meteorological department and depicts the average conditions in a month or season as the case may be. From an exhaustive analysis of meteorological data from 32 radiosonde stations, a detailed picture of radio climatology over India and adjoining sea areas has emerged. The aim is to provide, a detailed map over the entire Indian subcontinent of the structure of the vertical gradient of radio refractivity in the lower surface-based layers, effective earth's radius factor, sub refraction and ducting occurrence probability, occurrence characteristics of super refraction at higher levels and Cn^2 morphology. It is expected that the major features will hold good for other tropical areas as well. It is observed that the annual mean initial refractivity gradient (surface to 250 m) is large during all the twelve months along the West Coast (-90 N-units/km) followed by southeast coast (-80N-units/km). The gradient values along southwest coast covering Cochin and Trivandrum are less intense than the gradients observed along the other coastal lines of the country. As far as the plains of this subcontinent are concerned, the gradient values in northern plains are quite high (~-75N-units/km) while over central plains, the gradient values are rather low during all the twelve months. The gradient values are moderate over Southern plains of the country. The high initial refractivity gradients have been observed in Port Blair and Gauhati during pre-monsoon and winter. In the evening hours gradients are less intense than in the morning hours. The distribution of refractivity over surface and initial refractivity gradient (across surface-250 m) over India in the month of May during 0000 GMT is presented in Figures 1 and 2. However, the pattern of variation in the evening hours is similar to that of morning hours. In terms of seasonal variation, the highest gradient values are usually observed during pre-monsoon months while it is quite low during monsoon throughout the country. Significant changes of initial gradient occur during sunrise and sunset hours. The values of gradient start falling with sunrise, generally reaching the lowest value in the afternoon; after sunset, it starts rising usually reaching the peak value in the early morning hours. The surface duct occurrence probability in pre-monsoon period is about 30% over the coastal regions and decreases rapidly towards the central part of the country. Incidence of ducting is maximum during pre-monsoon and minimum during monsoon and is higher by a factor of 2 to 3 in the morning than in the evening. The meteorological parameters affect the ducting gradients in the following way: (i) Large magnitude of temperature inversions is associated with ducting. (ii) Majority of the ducting situations is associated with very high humidity gradients. (iii) Ducting gradients do not show any quantitative correlation with Richardson number, which is the measure of the stability of the atmosphere. The elevated layers occurrence probability is of the order of 50% over south east coast and is 10% over the central plains during pre-monsoon seasons Effective earth's radius factor k, exclusively depends upon the refractivity gradient The value of k perhaps is the prime parameter used by communication engineers in optimizing the terminal equipment characteristics In line-of-sight systems, for example, the k-factor uniquely determines the radio horizon distance for a given set of receiving and transmitting antenna heights This factor remains important even in the design of the troposcatter systems for the height of the common volume, which is solely controlled by the k-factor The distribution of mean value of the effective earth's radius factor observed over the Indian subcontinent during May at 0000 GMT indicates that in the pre-monsoon months, March to May, the highest mean values of the effective earth's radius factor is of the order of 4 3 over the coastal stations Over the plains, the mean value of the effective earth's radius factor is found to vary between 1.4 and 2 2 during pre-monsoon months while it is 1.4 to 1 8 during winter season The high values of k during the pre-monsoon months observed over the coastal stations are related to super refraction and ducting conditions The large values of k have also been observed over the Indian seas Some statistical studies on the variation of refractivity over Coastal area also have been carried out [3].

Kulshrestha and Chatterjee [4,5] showed that seasonal distributions of surface refractivity for the seasons winter (December to February) and summer (March to May) are in many respects similar. Again the distribution patterns for the monsoon (June to September) and post monsoon (October to November) are also similar to some extent

Kulshrestha [6,7] showed that radio refractivity at sea surface level (Arabian sea, Bay of Bengal and the north Indian ocean) varies between 340-400 N-units and it is the lowest in winter like the inland stations The work carried out at the India Meteorological Department, New Delhi indicates that the highest values of the radio refractivity at sea level occur during southwest monsoon In all seasons the lowest values occur in the northern and central parts of the Arabian Sea In Bay of Bengal, refractivity decreases from west to east except in winter months when it increases from west to east The refractivity gradient in the lowest 1 km varies between -50 and -80 N/km and is generally maximum in summer except over waters adjoining Somalia and SriLanka where the gradient is maximum during southwest monsoon months. It has been observed that over south Indian Ocean the refractivity decreases from equator towards south.

The coastal waters of Indian subcontinent did not have measurements of fine structure of radio refractivity especially in near real time basis, needed to mitigate the effects of anomalous propagation. Typical observations under normal and anomalous propagation conditions were taken over the coastal waters of India by a refractometer [8].

One of the techniques, used to characterize the boundary layer is the acoustic radar. A "SODAR" with a capability of probing thermal structures in terms of thermal plumes, inversion layers, ground-based layers, wavy like structures *etc.*, upto 1.2 km was developed [9,10] The sodar provides results on different form of atmospheric situations near the earth surface and is useful to study the effects of atmosphere on microwave propagation [11,12]. Sodar is also an useful tool to detect any atmospheric disturbance even in macro scale [13].

To measure the refractive index of the medium directly, microwave refractometer is used. A microwave refractometer was designed and fabricated [14]. The system had an accuracy of 0.2 N in its dynamic range of 400 N-units. The refractometer was flown over different places in India by using CESSNA aircraft and refractivity measurements were taken [8].

Kytoon measurements could identify the small-scale variations in RRI profile. Kytoon and radar measurements at a particular site in West Coast were also carried out [15]. The study shows that both ground-based and elevated layers with super-refractive and ducting gradients were found to exit for considerable time over that area. Correlation was tested between refractivity gradients across surface to 100m, surface to 200 m and surface to 300 m with ground clutter extent. It was seen, maximum correlation with clutter extent and refractivity gradient across surface and 300 m was used.

A three-dimensional ray tracing technique was developed for radar targeting error corrections and radar mapping of holes during different atmospheric conditions [16]. This programme was made also to evaluate the time delay through troposphere using global positioning satellite microwave transmission [16,17].

The work on radio climatology carried out so far over the Indian subcontinent in fact serves the purpose to design tropospheric communication circuits operating in VHF and UHF bands over any geographical region in India. Though some results on radio climatology over the Indian seas are available, still more are needed to be done. The radio climatologic variation at land (coastal) and sea junctions has to be understood more effectively. For such purpose, more and more simultaneous meteorological observations along the coast and sea are to be obtained preferably by using kytoon system and slow rising balloon in radiosondes.

3. Fixed, mobile and marine communication

Line of Sight (LOS) propagation studies:

A number of LOS links situated in the northern, eastern, western and southern sectors were monitored. Considerable work has been carried out on the field strength variations and their relationship with the observed meteorological conditions. LOS propagation characteristics observed at 6 GHz between DumDum and Andul situated on the Indian east coast, showed that scintillation frequency increases with the wind component and that the wavelength dependence in turbulence conditions varied between -1,3 and -0.08 whereas for layer conditions, it varied from 0.4 to 2.3 [18]. Atmospheric turbulence parameters were deduced from spectral analysis of LOS fading independently. It was found that the spectral slope is a measure of atmospheric structure [19]. Several studies were carried out from the experimental measurements of LOS field strength by using the link operating at 7.6 GHz situated between Sonepat and Delhi [12,20,21]. Studies were also made to show by using this LOS link data that the morning transition is characterized by an enhancement in the signal level for a short period of time and is associated with the rise of the ground-based inversion due to solar heating of the ground [22]. It was also seen that microwave signal levels are affected during solar eclipse time [23]. Using two links situated over Indian east coast and northern plains also carried simultaneous LOS microwave propagation studies. It was seen that the link situated over east coast suffers heavier fading than the link located over northern plains [24]. The amplitude fluctuations of both the links were studied in relation to meteorological conditions over the two regions.

Investigations of multipath fading affecting the performance of a LOS link situated in northern India at 2 GHz were also made [25]. The study included diagnosis of the fading problems, remedial measures to overcome the fading from radio meteorological point of view, and the implementation of these remedial measures. One of the remedial measures *i.e.*, tilting the antenna is found to be effective in reducing the fading due to surface based layers [26].

Mutipath fading affecting the performance of a digital microwave LOS link situated in western India was investigated [27]. The link operates at 8 GHz with a data transmission rate of 68 Mb/s and a part of propagation path falls over the sea. The analysis of the data showed that fade depth has no correlation with Bit Error Rate (BER) and linear amplitude dispersion is found to be good indicator of BER performance. In collaboration with Indian Southern Railways, field strength measurements were made using several communication links (Gooty-Penukonda, Guntakal-Adoni and Guntakal-Vadrahalli) situated in different locations of Indian southern region. The performance deterioration of such links operating at 7 GHz was investigated [28-30]. The performance of the links is

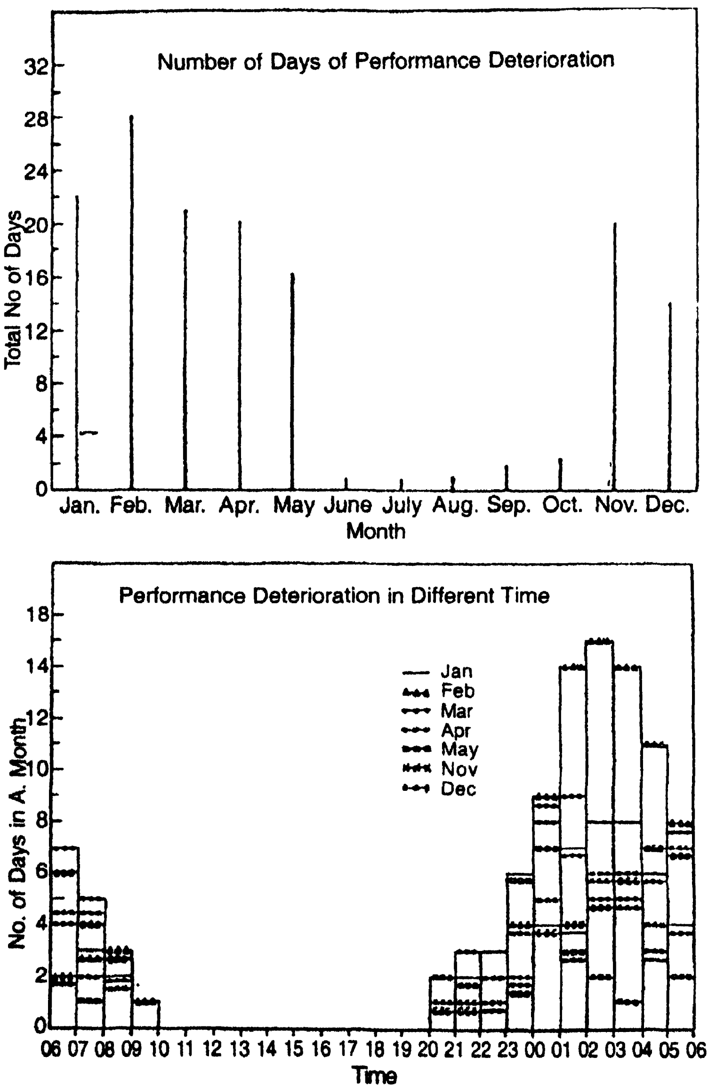

Figure 3. Performance deterioration of microwave link during different months and times.

satisfactory when the signal level is equal to and greater than -74 dBm, which is the usual satisfactory level of the signal. The link's performances start deteriorating when the signal level reduces to as low as around -75 dBm. The most problematic months and time during which the performance of each link was found not to be satisfactory, was investigated and is shown in Figure 3. On the basis of low signal level, causes of deterioration in relation to meteorological conditions have been determined. In order to counter multipath fading, some remedial techniques also have been looked into. Another microwave link of VSNL, situated in the Indian eastern sector was monitored and performance investigation was carried out [31]. Results on carrier intensity of another microwave communication link belonging to Indian Southern Railways situated between Raichur and Adoni having path length of 60 km and affected by three atmospheric conditions *viz.* clear air, fog and cloud have been deduced [32]. The low signals associated with deep fades were observed for large percentage of time during foggy and cloudy situations. It was seen that there is wide variation in signal level under foggy condition. The low signal associated with less than -70 dBm was found to occur for 74% of the time under foggy situation. The details of the results are shown in Figure 4. The change of meteorological situation (temperature or water vapour or liquid water content) from normal condition (level) leads to change in atmospheric condition and such change gives rise to change in signal level. For cloudy condition, the low signal ≤ -70 dBm has been found to occur for around 91% of the time. The low signal characterized with fades as seen in cloudy condition can only be explained on the basis of multipath propagation phenomena.

The effect of sea breeze on the performance of another line-of-sight (LOS) link operating at 6 GHz between Nellore and Chittedu was studied. Correlation of meteorological parameters and LOS records showed that onset of sea breeze induced heavy fading on the link and is shown in Figure 5 [33].

Some of the remedial measures to counter the multipath fading in microwave communication systems are path inclination, antenna tilting, space diversity, frequency diversity, route diversity etc. Such remedial measures have been tested [34] for various microwave communication links and it has been seen that the path inclination is one of the best measures to counter the multipath fading [35].

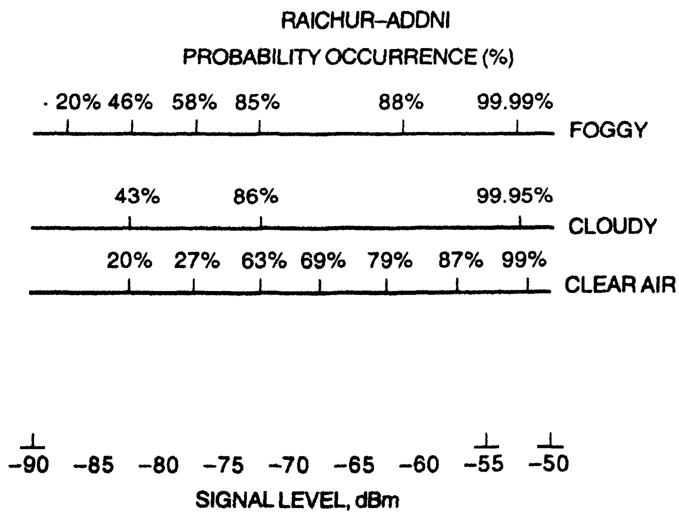

Figure 4. Probability distribution of signal levels under different atmospheric conditions.

All the aforesaid studies indicate that over the Indian subcontinent, many of the microwave communication links suffer frequent fade outs despite of the fact that all considerations are taken into account at the design stage of the links. The deterioration of the performance of some of the links is due to varied local meteorological condition. These studies infer that LOS microwave links situated in any part of our country may suffer total fade-outs in the months of pre-monsoon due to the stratified atmosphere.

VHF propagation studies:

Various investigators have carried out detailed work on VHF propagation by monitoring of TV signals at New Delhi, which is far beyond the primary service zone of many TV transmitters [36-40]. These transmitters include Jullunder, Mussorie, from India and TV stations situated in Pakistan. The study included the propagation characteristics of these signals, identification of their mechanisms with the help of various path loss prediction techniques and selected meteorological data for the specific days. Considerable number of studies also have been conducted on the influence of obstacles on VHF TV signal propagation over 13 paths in western India and evaluation of the suitability of various prediction techniques for path loss estimates by comparing their results with experimental data. Some of the techniques are suitably modified, based on the experimental values [36]. TV signal reception at VHF band was also studied in the light of meteorological parameters over transhorizon path in southern plains [37].

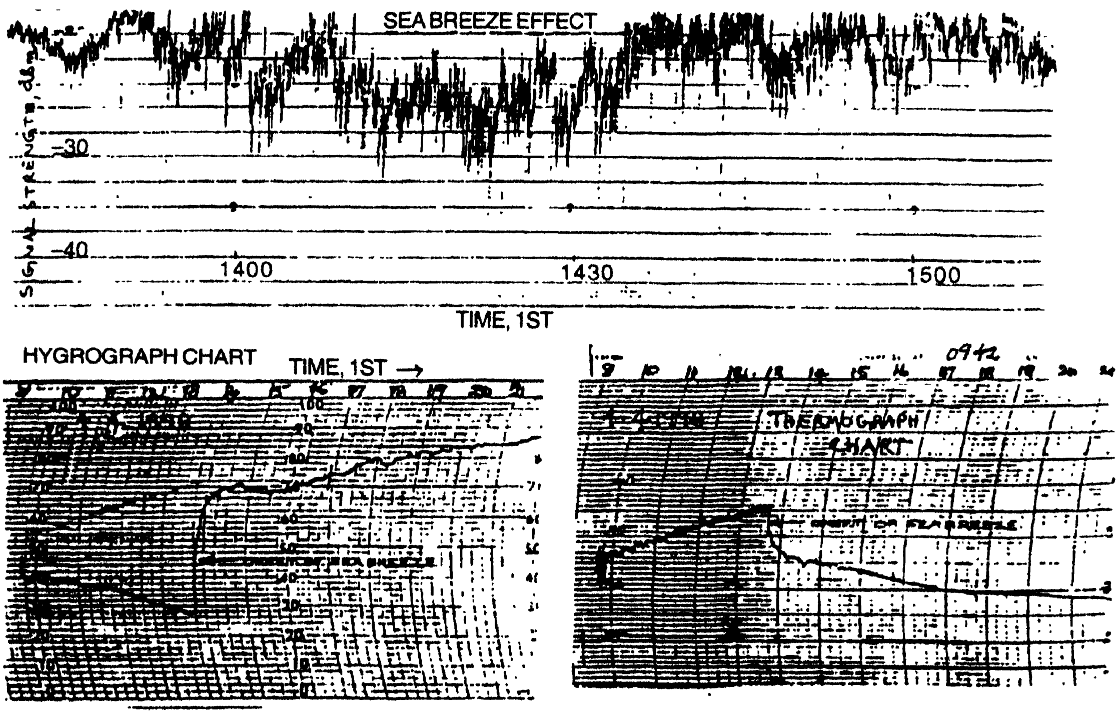

Figure 5. Effects of sea breeze on microwave propagation (after Rao et al, 1999)

TV signals originating from Narayana Giri Hill in the VHF band are monitored at 4 different locations of Tirupati to study the single knife-edge diffraction in the hilly terrain [38]. A comparison of double knife-edge diffraction prediction techniques is carried out by comparing the predicted losses against the path losses deduced from the experimental measurements conducted in western India [39]. The paths are (i) Mumbai-Kasara (ii) Mumbai-Karjat (iii) Mumbai-Chauk (iv) Mumbai-Bulsar (v) Pune-Mahabaleshwar. Whenever the number of knife-edges is more as in the case of Mumbai-Bulsar, the predicted path loss in the case of Epstein-Peterson and Edward-Durkins methods is much more than the observed path loss. Epstein-Peterson method gives good agreement when the knife edges are prominent. Out of all the methods Giovanel's method gives better agreement and can be used for designing diffraction links over mountainous regions. Unexpected large occurrences of anomalous TV receptions in channel 2 and channel 3 of Band I was observed at Delhi. In addition to tropospheric ducting and sporadic E, ionospheric heating was also suspected to cause such a long-range reception [40].

The results of propagation studies carried out at VHF band are useful particularly for FM broadcasting, which are in great demand in our country at present. In fact, these results are also useful for air to air and air to ground communication purposes where there is heavy increase of air services in our country. In fact, communication system in air service is using VHF frequency. The VHF propagation studies carried out in different parts of India are too useful for mobile communication users to get on hand results about the behavior of radio signals over different geographical regions in India.

Troposcatter :

Troposcatter systems are used for tactical purposes with 99.99% reliability. These systems are used over the transhorizon paths. Several studies were made on transhorizon propagation

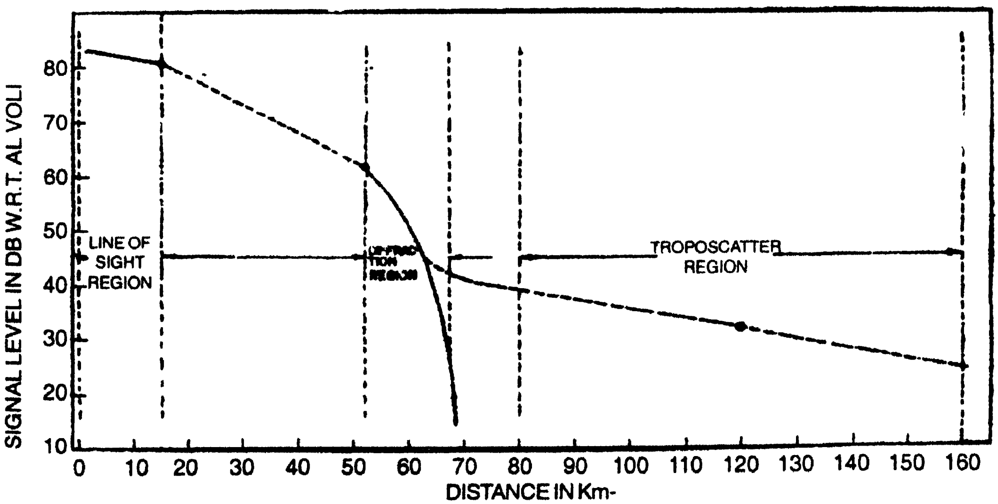

Figure 6. Distribution of observed signal levels in Line of Sight, diffraction and troposcatter modes of propagation

characteristics and the effects of different meteorological parameters over transhorizon signals. Results were also deduced of wavelength dependence and distance dependence with signal levels [41,42].

A troposcatter link for experimental studies at 4.6 GHz was established during the year 1980s between IIT, Delhi and CEERI, Pilani. Field strength trials were conducted along the route with mobile field intensity meter and the variations were studied as the link transcends from line of sight to scatter mode as shown in Figure 6. The results were compared with Met parameters and it was found that the link starts behaving in tropo-mode beyond 80 km [43].

Analysis of troposcatter field strength data conducted by researchers shows that the field strength reaches maximum around midnight when the reflection from Glints and Layers are stronger and it reaches minimum around noon when the field strength is entirely due to turbulence scatter. The observed correlation with Met parameters and field strength suggests the correlation to be better with the initial refractivity gradient than with the surface refractivity. [44,45].

The aperture to medium coupling loss in troposcatter systems was studied with a view of optimizing antenna sizes. An expression was developed for some Indian zones using a realistic model for atmosphere for the estimation of antenna gain degradation [46]. Effects of radioclimatology on correlation bandwidth of troposystems were also investigated [47].

The observed path loss values over two troposcatter links situated in northern India were also compared with the path loss values deduced from various prediction techniques [48]. The comparison showed that Yeh's method and ITU-R's (International Telecommunication Union-Radio Communication) method come closer to the observed results. The deteriorated performance of a troposcatter link situated in Indian desert was also tested [49]. The signal level was found to vary from -90dBm to -110 dBm during the disturbed period from 1800 to 2200 hrs LT in the pre-monsoon months. The deterioration was due to localized meteorological phenomena. Such disturbances are difficult to predict or to take into account at the design and installation stage.

The transhorizon propagation studies provide a detailed investigation of variation of signals on twenty-hour basis, monthly basis as well as in different seasons. Inference has also been drawn that different propagation phenomena, like scattering, reflection and ducting are associated with transhorizon radio signals. It has also been seen that propagation over some links is affected due to localized meteorological phenomena. Such problem of non-performance of the link caused due to localized met phenomena cannot be taken care at the design and installation stage of the link.

Mobile communications:

The communication scenario in the country took a quantum jump with the introduction of mobile communication services. To strengthen the work on mobile communication, experiments were conducted in VHF and UHF band [50]. Comparisons of various path loss prediction methods have also been tested (Figure 7) and the most suitable one has been identified for different environmental conditions [51].

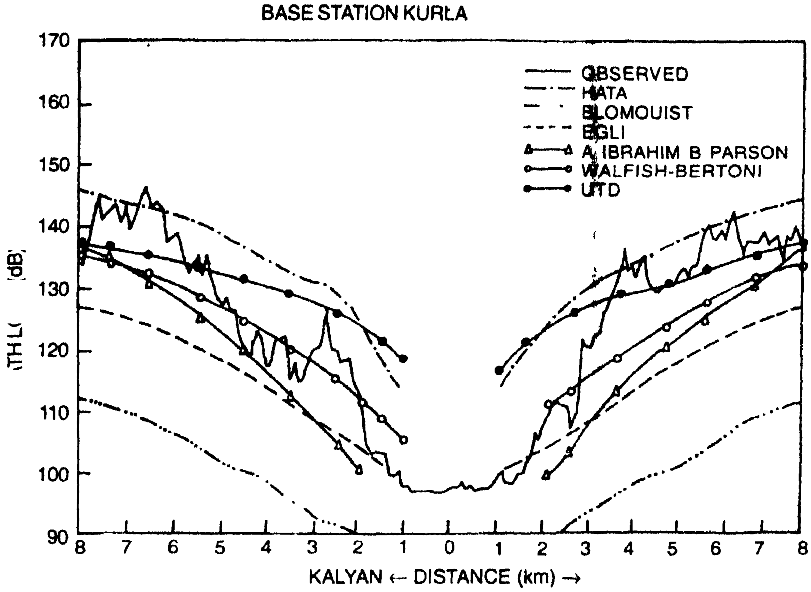

Figure 7. Comparison of various land mobile prediction models with experimental results of train mobile (western India) (after Prasad and Singh, 2000).

A major task of deducing path loss exponents from various data sets spanning northern, western and southern Indian zones including urban, suburban and rural areas was carried out in the VHF, UHF bands. The experiments included FM, TV measurements in different radials, mobile train measurements *etc.* [52]. This is a very useful design parameter for designing future mobile communications in these regions. These experimentally deduced values as functions of distance were compared with modeled values and the deviations were also brought out.

Various studies were also done to evaluate theoretically the antenna tilting effects on fixed and mobile communications and to reduce the interference in neighboring cells using the path loss exponents generated from previous data sets [53]. Also some experimental and modeling studies of widely varying urban environments on train mobile communication have been carried out and existing models were modified to suit Indian conditions.

Mobile communication is in extensively use in the country at present. The use of mobile communication is increasing day by day. The frequency, which is in mostly use, is 900 MHz. The other frequency used very sparsely, is 1800 MHz. With increasing density of mobile communication, reliability will be a major factor. To overcome this factor, more and more measurements of radio signals over different environments as well as different geographical conditions are to be carried out. Such measurements should form a database to evolve a most suitable mobile propagation model for our Indian conditions.

Marine communication:

Work also has been carried out on evaporation duct over Indian seas, both Bay of Bengal and Arabian Sea. Evaporation duct exists over sea on regular basis due to the excess evaporation of water vapour from sea water. The duct height variation over Indian seas during day time is presented in Figure 8. Such evaporation ducts affect the performance of microwave radio communication and radar propagation. Based on meteorological parameters evaporation duct height morphology over Indian seas have been prepared [54]. In addition to, refractivity gradient statistics over different locations in Indian seas have also been deduced. Such results can be used for the estimation of performance of radio systems over seas. Based on evaporation duct characteristics, the vertical and horizontal coverage diagrams are generated under different systems configuration. The coverage diagrams indicated shadow zones on radio holes *i.e.*, regions which are not illuminated by radio rays.

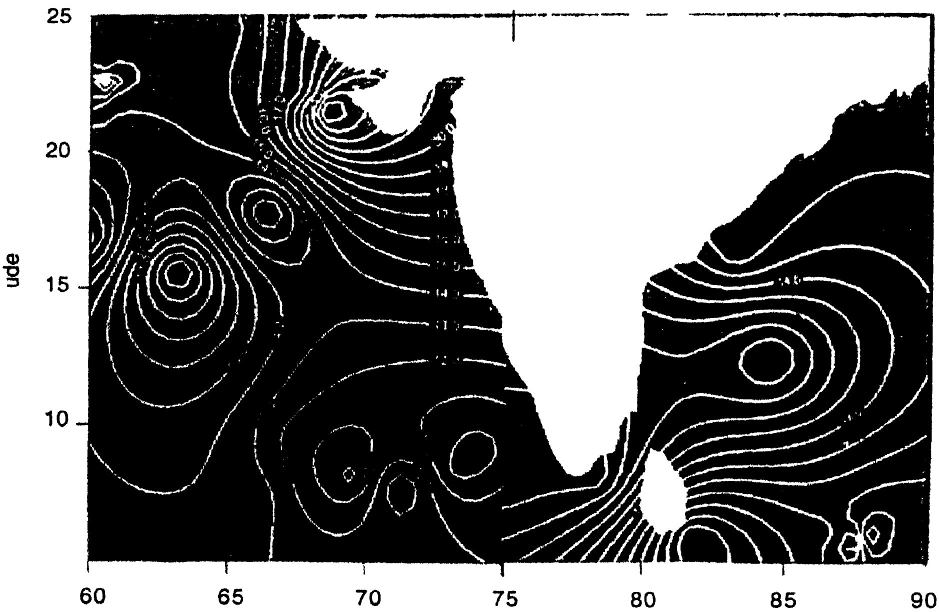

Figure 8. Evaporation duct height in metre during day time over Indian seas (after Pasricha *et al*, 2002)

The available model for estimation of evaporation duct height is to be validated from experimental observations. Simultaneous experimental facilities to obtain met data and microwave propagation are to be set up over the Indian seas.

4. Rain, water vapour and cloud attenuation

The frequencies more than 10 GHz are affected by the precipitation in terms of attenuation due to its high dielectric constant [55]. As far as Indian subcontinent is concerned, rain and cloud are the most important factors for precipitation. Thus, there is still tremendous need to develop a strong database on precipitation, which mainly includes cloud and rain

Systematic measurements of various precipitation parameters have been carried out over different geographical regions of India in recent years. The parameters, which affect the microwave communication and radar propagation, are mainly rain rate, horizontal extension of rain, rain height, rain drop size distribution, cloud characteristics and cumulus cloud cells responsible for formation of thunderstorm. All these parameters are taken as input parameters for estimation performance of microwave communication systems. Several techniques such as rapid response rain gauge, conventional rain gauge, radar, radiosonde etc., are used to deduce such results. In addition to precipitation measurements, communication links operating in Ku and K bands are also monitored to investigate the effects of rain on the performance of communication systems. Preferably, such links should be monitored where heavy rainfall occurs.

Rain statistics collected from the rapid response rain gauges with integration time 10 sec over Shillong, Calcutta, Delhi, Tirupati have been developed [56-59]. With the help of data obtained from slow response rain gauges having an integration time of 15 min, conversion factors are developed [56,59,60]. Worst month rain rate statistics were deduced for different regions of India using slow response rain gauge data [61]. Also extent of rain cells is estimated from simultaneous measurements of attenuation on a LOS link and rain rate measurements [59]. The investigations reveal that rain path is heavily dependent on rain rate. Rain rate distribution at different percentage levels from 0.001% to 0.1% of time including non-rainy period over the several aforesaid locations have been deduced. The rainfall rate is usually found to vary from 2.5 mm/hr to 200 mm/hr over India. Here in India, it has been observed that the rain rate is characterized with slow and rapid variations as shown in Figure 9. The variation of rain rate is similar to the amplitude variation of microwave radio signals and can give insight into the fade dynamics due to rain, for determining the fading margin and hence the performance of the link. It is seen that some time, the variation of rain intensity is fast. A mathematical formulation was derived to obtain rain rate distribution from total rainfall measurements [62].

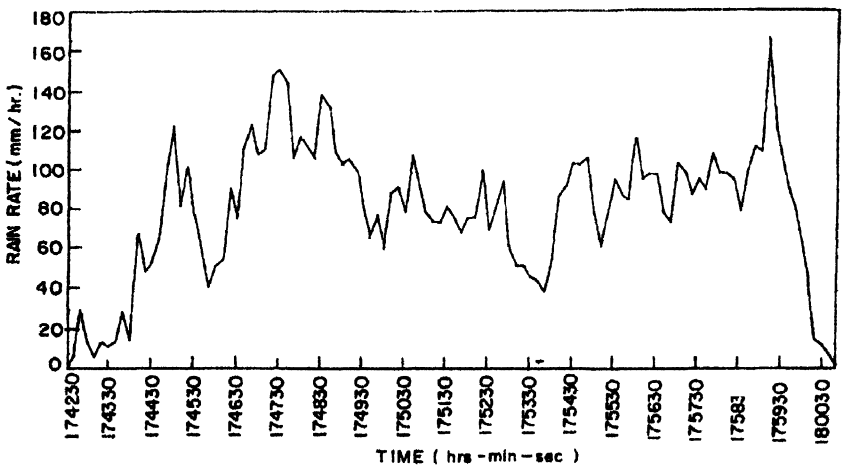

Figure 9. A typical rain rate measurements with rapid response rain gauge.

An attempt also has been made to derive results on raindrop size distribution (RDSD) at different rain intensities from radar reflectivity measurements [63]. In order to deduce RDSD, some Integral Rainfall Parameters (IRP) is used. The formulation obtained in terms of radar reflectivity factor and rain rate is quite simple. The well known equations, that relate radar reflectivity factor (Z) in dBz, effective radar reflectivity factor (Z_e) in mm^6 m^{-3}, rain rate (R) in mm/hr, rain drop diameter (D) in mm, drop size distribution $N(D)$ in m^{-3} mm^{-1}, back scattering cross-section (σ_b) in m^2, terminal velocity of rain drop (V) in m/s, dielectric constant of water (K_w) and the wavelength of the operating radar (λ) in m were utilized to deduce $N(D)$ over Kolkata [63].The most probable raindrop diameters at different radar reflectivity and rain rate have been estimated. It is seen in our study that the most probable raindrop diameter D varies exponentially with radar reflectivity dBz. The values of D vary from ~ 0.1 mm to 1.4 mm, while the radar reflectivity varies from 23 dBz to 58 dBz. The values of D have also been found to vary exponentially with rain rate. At higher rain rate of ~ 100 mm/hr, D is around ~ 1.25 mm. The values of $N(D)$, at rain rates ~ 49 mm/hr and 75 mm/hr were also estimated. It was seen that the maximum number of drops is around ~ 1800 per m^{3}mm^1 and they are associated with most probable raindrop diameter of ~ 0.75 mm at 49 mm/hr. Significant number of rain drops are associated with diameters greater than ~ 1.5 mm. Large number of small rain drops also have been observed at ~ 49 mm/hr. For rain rate ~ 75 mm/hr, the maximum number density, $N(D)$ per m^{3}mm^1 was observed to be ~ 640, while the maximum rain drop diameter was ~ 3.9 mm. A considerably large number of rain drops with large diameter have also been observed at ~75 mm/hr. The number of drops [$N(D)$] per m^{3}mm^1 associated with rain drop diameter ~ 1 mm, 1.5 mm, 2 mm, 2.5 mm and 3 mm have been found to be ~ 630 , 530, 300 ,150 and 10 , respectively at ~ 75 mm/hr. The results on rain drop number density measured by distrometer over other Indian locations also showed similar distribution and large raindrop size occurs for significant numbers at higher rain rates. A generalized mathematical distribution for raindrops of different rain intensities for radio wave application was also developed [64]. Some models on RDSD are available [65], but it is always useful to have more measured results on RDSD. The techniques for modeling of the distribution of raindrop sizes in relation to lognormal from multi-wavelength rain attenuation measurements at millimeter and infrared bands have been investigated by Maitra and Gibbins [66]. Some results on RDSD measured with distrometer have been reported over Dehradun by Jassal *et al* [67] and over Guwahati by Timothy *et al* [68]. The model developed by Verma and Jha [65] on RDSD is found to follow log normal distribution. The results on RDSD taken by using laser spectrometer over Ahmedabad have also been reported by Calla *et al* [69].

The statistical morphology of radar reflectivity as a function of horizontal and vertical extension of rain is of considerable interest to those assessing the possible interference between terrestrial links and earth-space satellite links. The horizontal and vertical extension of rain is also estimated from radar plan position indicator (PPI) and range height indicator (RHI) measurements [70]. These results of rain extension are deduced as a function of radar reflectivity factor (dBz). The radar reflectivity factor is the measure of the strength of the scattering cross section of the rain cells. The scattering cross-section is responsible for causing interference to the radio signals. The radar reflectivity measurements taken by X-band radar over Kolkata have been utilized to deduce rain cells extension. Taking all PPI measurements, horizontal extension of rain has been derived. It has been seen that the horizontal extension varies from ~14 km to 4 km, while the radar reflectivity varies from 28 dBz to 53 dBz. The large value of reflectivity is an indication of high rain rate and is associated with low horizontal extension of rain. The radar reflectivity of ~43 dBz (which is a measure of rain rate ~ 18 mm/hr), is associated with the horizontal extension of ~ 8 km, while the radar reflectivity of ~ 33 dBz (which is a measure of rain rate ~2.6 mm/hr) is associated with the horizontal extension of ~ 10 km. The low radar reflectivity is associated with large horizontal extension.

The results on the variation of vertical extension of rain with radar reflectivity suggest the height from where the rain of different intensities starts occurring. It has been seen that the vertical extension of rain varies from 9 km to 5.75 km. These measurements were taken in monsoon months. It is seen that the low vertical extension of rain ~5.75-km is associated with the radar reflectivity of ~ 53 dBz when the rain intensity is ~ 74 mm/hr. The vertical extension of rain from 8 km to 9 km is found to be associated with 28 - 43 dBz and the rain rate varies from ~ 2.4 mm/hr to 18 mm/hr.

The probability distributions derived from the observed radar reflectivity of the PPI and RHI measurements indicate that the probability distributions follow almost the same variation in both PPI (Figure 10) and RHI observations (Figure 11). The radar reflectivity of 40 dBz exceeds for around 28% of the time in PPI case, while it exceeds for around 34% of the time for RHI case. Similarly, it has been found that the radar reflectivity of ~53 dBz, which corresponds to ~ 75 mm/hr exceeds for 4% of time in PPI case while it exceeds also for around 4% of time in RHI case. It is also seen that both PPI and RHI follow similar

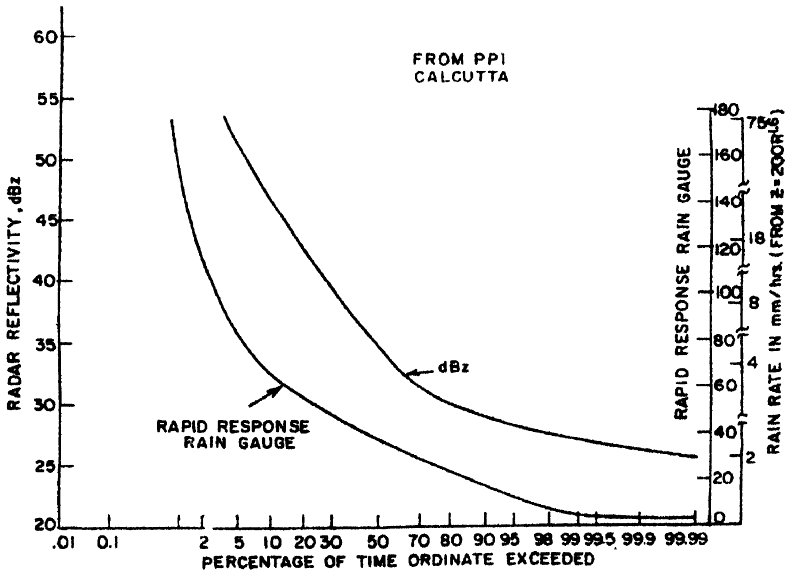

Figure 10. Distribution of radar reflectivity on Plan Position Indicator (PPI).

variation up to 30 dBz and above 50 dBz. There is a difference in variation of PPI and RHI between 30 dBz and 50 dBz. Such difference of variation is marginal. For instance at 50% probability level, the radar reflectivity is found to be 34.5 dB in case of PPI and for RHI it is 36.5 dB. The different radar reflectivities are associated with different rain rate. The rain intensity of different magnitude exists for equal percentages of time both in horizontal and

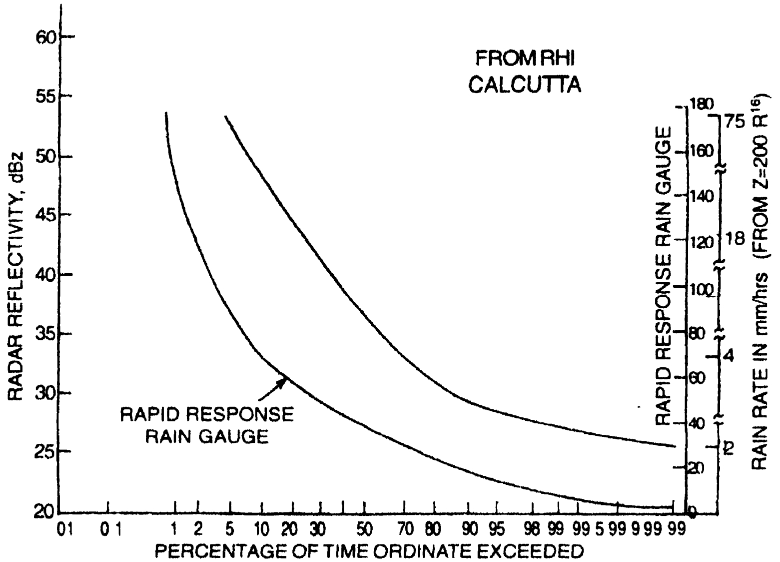

Figure 11. Distribution of radar reflectivity on Range Height Indicator (RHI).

vertical extension. In order to deduce the attenuation of rain, we need the probability distribution of rain rate. The probability distribution of rain rate derived from horizontal and vertical extension of radar reflectivity measurements by using the *Z-R* relation ($Z = 200R^{1\ 6}$) can be utilized for rain attenuation estimation for both horizontal and earth-space paths. However, such derived rain rate distribution from radar reflectivity observations is to be validated with the rain rate distribution derived from the ground-based rapid response rain gauge measurements.

The rain height is important for attenuation estimation in satellite communication. It is well established that 0°C isotherm height is taken as rain height. Detailed investigations of rain height have been made over India [71-77]. The variation of rain height is appreciable over different locations in India particularly during winter months. It is seen that rain height decreases in winter as the latitude increases while in monsoon, the variation is not substantial. The rain height is within 4.5 -5.5 km up to 30°N . This is due to the fact that the rainfall during monsoon is more or less uniformly distributed throughout India irrespective of the station latitude. Over Srinagar, H_i is around 0.25-1.60 km while over Minicoy, it is around 4.30-6.50 km and over Calcutta it is 3.20-4.70 km during winter season. In the months of monsoon season, the variation of H_i is not substantial particularly over inland. Rain height depends on rain rates and since rain rates during monsoon over these stations are almost similar, no significant variation in rain height with respect to latitude is observed. As far as topographical dependence is concerned, it has been found that rain height does not depend very much on topographical features, but it depends more on seasons. Seasonal dependence has been observed almost over all the stations. The latitudinal dependence has also been observed particularly in winter months (Figure 12).

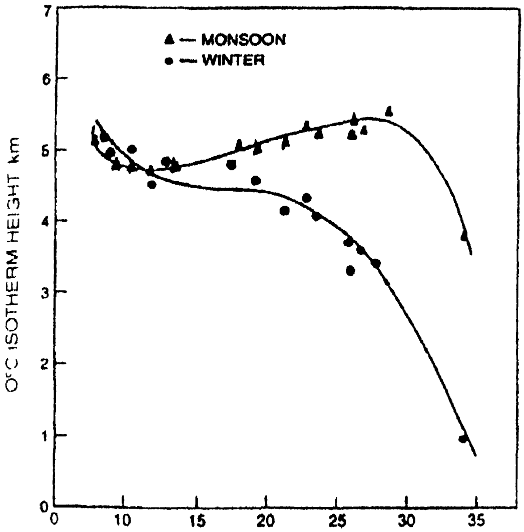

Figure 12. Latitudinal variation of mean 0°C isotherm height over India during winter and monsoon.

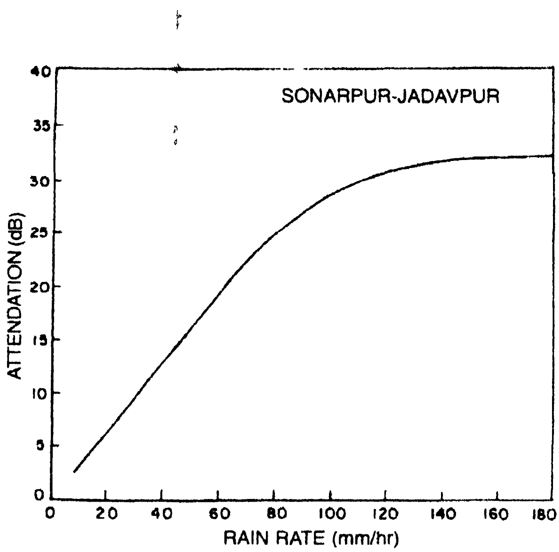

Figure 13. A plot of observed attenuation at 18 GHz due to rain for different rain rate.

To see the effects of all such climatic parameters, commercial communication links having different hop length operating at 13 GHz and 18 GHz are monitored along with rapid response rain gauge measurements [77-79]. The attenuation results over two different paths at 13 GHz at different probability levels are deduced. It is seen that under normal condition, when there is no precipitation, the measured signal level is ~ -44 dBm. The results on attenuation have been derived by taking the difference of the normal signal level ~ -44 dBm and the instantaneous signal level in dBm. If the observed signal level at a time is ~-54 dBm then the estimated attenuation is 10 dB. It is seen that the attenuation increases with rain rates. The observed attenuation is around ~ 6 dB at 20 mm/hr and it is 16 dB at 60 mm/hr. The attenuation ranging between ~ 15 dB and 27 dB is found to be associated with rain rate from 55 mm/hr to 145 mm/hr. The results on attenuation at different rain rate have also been deduced from the ITU-R model, $A = .02515R^{1\ 164}$.The attenuation results deduced from ITU-R model particularly at higher level, intermediate level, show quite good agreement with the measured results. But at very high rain intensities, the ITU-R model overestimates the attenuation results at 13 GHz.

The probability distribution of attenuation at 18 GHz over the communication link situated over Kolkata having path length 8km is deduced. It was observed that under normal condition when there is no precipitation the measured signal level is -48 dBm. It is seen that the observed attenuation is around 7 dB at 20 mm/hr and it is 18.6 dB at 60 mm/hr There is not much increase in attenuation from 120 mm/hr to 180 mm/hr It was seen that the attenuation is equal or more than 18 dB for 20% of the time It was seen that the attenuation is ≥ 18dB when the rain rate is ≥ 64 mm/hr for 10% of time The attenuation is around 30 dB for 1% of time when the rain rate is ≥ 160 mm/hr for 1% of time (Figure 13)

Rain attenuation studies were also made at 11 7GHz by utilizing INSAT-2C satellite signals over southern India during rain events [80] The observed cumulative distribution functions were compared with prominent predicted models and it was found that Garcia Lopez and Moupfouma methods fare better and the ITU-R method deviates largely from the observed rain attenuation

In India, a number of experimental studies have been carried out by different groups Several microwave radiometers to conduct rain attenuation measurements at 10 GHz and 11 GHz were fabricated at Delhi [81-83] The long term cumulative distribution of rain attenuation at these frequencies were obtained For about 0 01% of the time the attenuation during the monsoon period was as high as 14.4 dB Tewari *et al* [84] at Dehradun and Sen *et al* [85,86] at Kolkata have shown that the rain attenuation ~ 11 GHz and 17 GHz over Dehradun and that at ~ 11 GHz over Kolkata have good agreement with CCIR prediction

Water vapour attenuation studies at 22.235 GHz by using microwave radiometer were also conducted by Uppal *et al* [87] Recently liquid water content has been derived by using two radiometers one at 22 235 GHz and the other at 37 GHz Extensive work was also carried out by Sen *et al* [85,86], Maitra Amitabha [88] and Karmakar *et al* [89-91] in the area of millimeterwave propagation Several atmospheric parameters were deduced which affect radio wave propagation directly over Kolkata The relative contribution of 22 235 GHz and 183.31 GHz absorption lines on 94 GHz propagation was estimated and the role of 50 55 GHz millimeter wave band in atmospheric propagation in relation to remote sensing and rain attenuation in millimeter wave was determined [88]

Till now, efforts have been made to deduce database and results on rain related work including rain attenuation in patches with existing systems. But recently, very sophisticated systems are available to carry out such rain related studies on long-term basis over the entire subcontinent This has been highlighted in the subsequent section as well as the scope for future work.

Water vapour attenuation.

The results of water vapour morphology over the Indian subcontinent have been documented for the first time in the country in the form of atlas as maps of water vapour density for various fixed pressure levels and also as height profiles for specific regions of the country [92].

The study carried out on water vapour distribution over the Indian subcontinent indicated that water vapour densities in the south-west coast is the highest followed by west coast, etc [92-94]. These values are utilized to evaluate the water vapour attenuation from 1 GHz to 350 GHz at elevation angles from 1° to 10° . At 18 GHz the attenuation is 5 dB at 3° elevation angle using water vapour density of 26 gm/m³ while at another window region of 200 GHz, the attenuation is 85 dB at 20 g/m³ for 10° elevation (Figure 14). These studies are important for slant path communication systems operating at less than 10° elevation angle.

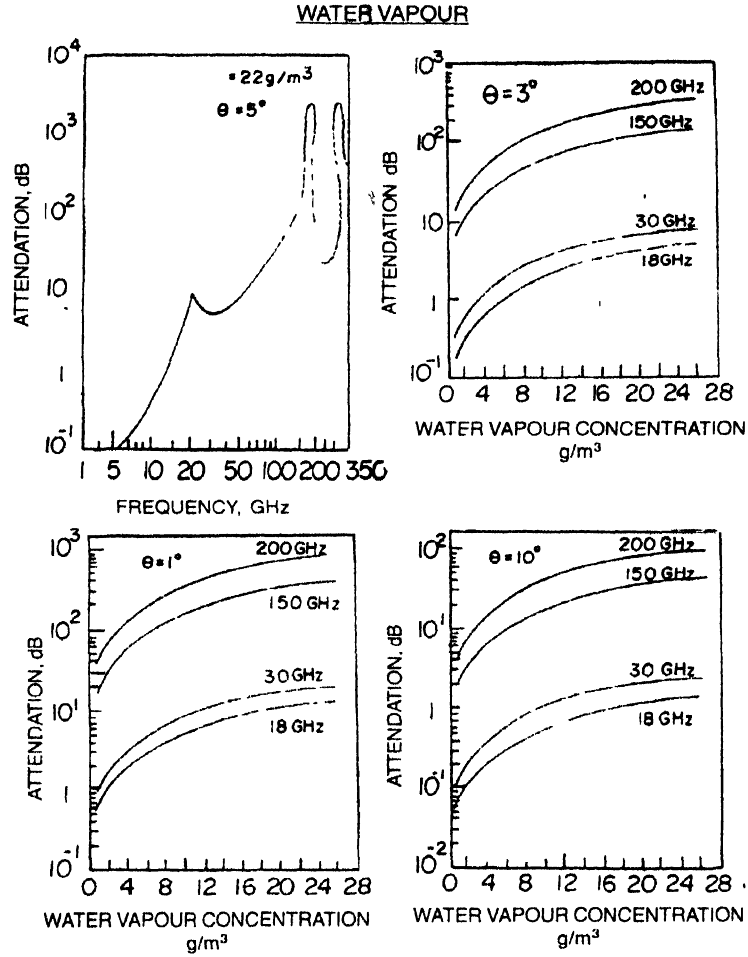

Figure 14. Water vapour distribution and water vapour attenuation

The water vapour studies over the Indian subcontinent have been done mainly by using radiosonde observations [92] which are being taken twice a day one in early morning and the other at late evening over India. The water vapour parameter is dependent strongly on time and space. Due to the availability of Global Positioning System (GPS) over various locations in India, efforts are to be made to deduce water vapour on twenty-hour basis. Such results can be obtained from the GPS path delay measurements. Such measurements have wide applications in relation to Civil Aviation in the country.

Cloud characteristics and cloud attenuation:

The effects of rain on radio wave are more than those cloud but the occurrence of cloud is more prevalent than rain. The frequent presence of cloud causes some amount of link degradation for significant percentage of time over the tropical Indian subcontinent. The cloud morphology particularly in relation to radio wave propagation over different geographical region of India is very essential and important. In view of this, systematic studies on cloud occurrence morphology over different geographical locations in India have been undertaken.

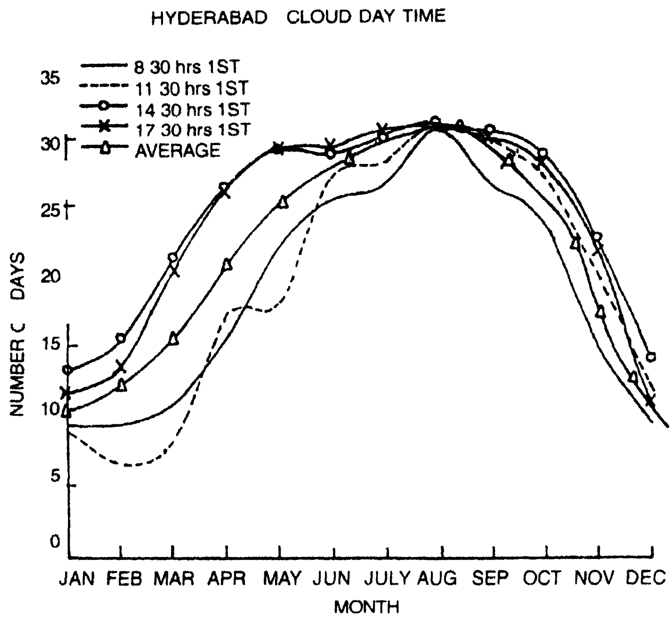

Figure 15. Cloud coverage in different months during day time over Hyderabad

Recently, some results on cloud occurrence statistics and attenuation of radio wave due to cloud over selected stations located in different geographical regions were derived and reported [95-97] The cloud characteristics have been derived from the low cloud data The cloud data was obtained from the India Meteorological Department The cloud observations are taken four times during day and four times during night. The daytime observations are taken during 0830 hrs IST, 1130 hrs IST 1430 hrs IST and 1730 hrs IST The nighttime observations are taken during 2030 hrs IST and 0530 hrs IST. The low clouds are found to occur between 2 km and 6 km heights. The times of observations of clouds were chosen in such a way that four-day time observations and four night time observations are good enough to be representative conditions of day and night Moreover, the results on cloud statistics have been provided on a monthly basis Similarly, the daytime and nighttime average cloud statistics of a month can be the true representative of the daily cloud statistics in that month. The day time and night time results on cloud derived from four observations in a day and night can again be said to be the true representative of cloud occurrence at any time of the day and night. In fact, such type of statistics is good enough for radio communication engineers and radio researchers for estimation performance or prediction of field strength for satellite communication It is seen from a recent study [97] that low cloud occurrence over Hyderabad is very significant particularly during June, July, August and September In the months of June, July, August and September, low clouds are found to occur for 29 days, 30 days, 30 days and 28 days and 28 nights, 28 nights, 31 nights and 28 nights respectively. In winter months, December, January and February, the clouds occur for 11 days, 10 days and 12 days and for 6 nights and 7 nights respectively (Figure 15). The specific attenuation of radio wave due to clouds at various frequencies ~ 10 GHz, 20 GHz, 30 GHz, 40 GHz, 50 GHz, 75 GHz and 100 GHz for summer and monsoon seasons has also been deduced The specific attenuation of radio wave due to cloud at 30 GHz for liquid water content ~1g/m^3 is 0.88 dB/km while at 75 GHz the specific attenuation is ~ 5.55 dB/km. The attenuation of radio wave due to cloud also has been studied recently by Sarkar *et al* [98] over an Indian coastal station.

The meteorologists of our country have done considerable amount of cloud studies related to weather forecasting [99-101]. But not much has been done so far in the country, on cloud characteristics in relation to radio wave propagation. The areas in which the concentration is needed have been highlighted in the subsequent section.

5. Scope of future work

Recently, in India there has been a shift, shift in use of frequency from UHF band to higher bands due to the requirement of larger bandwidth for high data transmission rate for communication purposes and for remote sensing application work to get the finer structures of the objects [102]. There is also a tremendous increase in demand of the use of radio systems in the form of telephone, internet, multimedia *etc*., by the people, particularly our youngsters. In earlier time, reliability of radio system used to be the only criterion of priority. Looking at the present scenario of microwave communication in India, one has to deal with a variety of other criteria [102]. Increasing the power of the system, particularly of the transmitter, we can increase the reliability of any radio system. In doing so, we are not only affecting the use of other radio systems in the vicinity of the receiving site in the form of radio interference, but also the performance of other systems like medical gadgets (such as pace maker, ECG machines), systems working on Nuclear magnetic resonance principle (NMR) *etc*., [102]. There has been a quantum jump in the use of such medical systems in recent years in India. It has also been seen recently that some user organizations have gone on increasing the size of transmitting antenna without realizing its effects on human lives. Another important point to be noted is that earlier the sites of installation of such transmitting towers particularly in metropolitan cities, were not much population. But, with time, population has also become denser in and around many transmitting towers. This is also an issue of great concern [102].

The other important issue of the present day's radio communication is the directivity of the transmitted and received power (signal) [102]. Increasing the antenna sizes, we can of course increase the directivity of the transmitted/received signal. But, increasing the antenna size beyond a point that we are not utilizing the contributions of maximum scatterers, which are usually atmospheric irregularities. In-fact, the scatterers decide the strength of the radio signal. So, a compromise between the size of the antenna and maximum radio signal is made in order to get maximum directivity.

In recent years, there has been tremendous advancement in electronics of radio systems. Such advancement has made possible, the regularization of transmitted power. These days in mobile communication, transmitted power is regulated depending on the requirement of the received radio signal [102]. A transmitter located in rainy and cloudy area has to be provided with more power than to a transmitter situated in non-rainy and non-cloudy area. Similarly, it may be questioned why people living on non-rainy and non-cloudy region should be exposed to electromagnetic effects due to the radiation of high power from transmitter [102].

In India, we have varied rainfall climatic regions [102]. For example, annual total rainfall over different geographical regions in India varies between ~350 mm and ~11,420 mm. We have region where the total rainfall is around ~ 11,420 mm (Cherrapunji) as well as region where we have total rainfall ~ 380 mm (Jodhpur). Mumbai, which is located over west coast, has a total rainfall of ~2700 mm while Kolkata which is another east coastal station has a total rainfall of ~1570 mm. Similarly, we have different geographical regions like Ahmadabad and Bangalore where total rain fall is around ~820 mm and over Nagpur, the total rainfall in a year is ~ 1127 mm. The total rainfall over an Indian island, Minicoy is ~ 1530 mm.

In view of these three issues, it is necessary to characterize our rain and cloud environment so that attenuation of radio wave due to rain and cloud can be estimated with good degree of accuracy for proper designing of satellite communication and remote sensing systems [102]. It is also important to mention here that such characterization work has to be upgraded whenever an opportunity arrives. All organizations in India where latest techniques, are available, should join hands to make comprehensive efforts to derive radio environment results. There is now enough evidence to support the idea that rain cells occurring in our country during high intensity rainfall events differs from that in temperate regions where most of the measurements have been carried out. It has been seen that most of the intense tropical rainstorms are of convective type (melting layer: bright band is missing). Vertical height of the stratiform rain is estimated from the height of the bright band or melting layer. The portion below the melting layer can be called rain. The layer above to it may not be in liquid form. In case of convective rain, the liquid form of hydrometeors can also be found above the melting layer because of the up and down drafts. Such type of rain can more often be seen in our country. Due to the availability of the large number of sophisticated computer controlled conventional radars operating in X-band over different Indian geographical regions, this aspect of rain cell size is to be looked into more rigorously by taking radar reflectivity measurements in PPI (Plan position indicator) as well as RHI (Range height indicator) mode. Few Doppler radars operating in C-band over different locations by the India Meteorological Department are also available at present. The Doppler radar system is very useful to investigate cloud characteristics including cloud coverage, cloud height, cloud thickness, liquid water content within the cloud, *etc.* Efforts are to be made to study all such cloud parameters by using extensive Doppler radar observations. Based on cloud height, cloud temperature and cloud liquid water content, attenuation of radio wave due to cloud at various frequencies are to be derived over different locations in India. Other important investigations should be carried out in the area of attenuation of radio wave like contributions from frozen and mixed phase fluctuations in addition to rain. Millimeter wavelength radiation is highly susceptible to scattering by large ice particles above freezing level and melting hydrometeors around the freezing level provide a significant contribution to total attenuation at frequencies above 10 GHz. In the past, meteorologists have carried out some of these studies but those were for weather forecasting and mainly for monsoon prediction [99-101]. The ITU-R techniques assume the rain height in relation to $0^{o}C$ isotherm height. This assumption holds well over the temperate region. This has been found to be unrealistic over tropical Indian stations. The rain height over the Indian stations has to be the effective rain height. This requires an effort of local data collection and this aspect is to be looked into immediately. This emphasizes the need for an effective rain height rather than simply the assumption of the 0°C isotherm height. In the coming years, satellite communication in Ku and Ka band will be used extensively for various purposes in India [102]. Apart from rain and cloud related work, another important area that needs attention is the measurement of radio signal in Ku and Ka band from satellites as well as by using terrestrial communication links belonging to various user organizations, wherever opportunities are available over different rain and cloud climatic regions [102]. Till now, we do not have much measurements over earth space paths as well as enough measurements over terrestrial paths in our country in these frequency bands.

If efforts are now made to work on rain and cloud, we will have detailed results on both rain and cloud for radio wave propagation work in the form of maps over the entire Indian subcontinent within a few years [102].

The other important area which needs to be investigated, is the biological effect due to electromagnetic radiation. Due to the increase in use of RF energy in our country, the people are more susceptible to the exposure of such radiation. Though some standards are available in terms of exposure time, specific absorption rate in terms of power flux density or field strength due to exposure to RF transmitting source in western countries, standards of such parameters are to be set in our country also. Study related to the diseases caused due to the exposure of RF energy is another area, which is also to be explored quite extensively in near future, in a tropical country like India.

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