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ATMOSPHERIC RESTRAINTS IN SPACE COMMUNICATIONS

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The last ten year period can be most appropriately called as the communication explosion decade. Satellites and computers are the two main players in this unprecedented technology revolution. With the tremendous leaps in electronic hardware and computer communications, the limitation to high reliability systems is our inadequate knowledge of effects of our atmosphere on radio propagation. The two regions, troposphere and ionosphere are not only characterised by significant departures in the Radio Refractive Index, but also are hosts to unpredictable weather, turbulence and rapidly moving irregularities. This paper presents a brief review of contemporary state of understanding of the problems and identifies problem areas where additional work is immediately needed to give appropriate inputs to system design in space communications.

Key Words: Space Communications; Rain Attenuation; Atmospheric Gas Attenuation; Scintillations

Introduction

Radio wave propagation, in principle, can be achieved around the Earth by using high power ELF and VLF transmitters. But the band width is so limited that even a single telephone line cannot be accommodated. As we move to higher frequencies to accommodate more channels, ground-based systems do not work because of the Earth's curvature. The earliest attempts to beat the curvature of the Earth was through ionospheric reflection;but the frequency was still limited to 30MHz, which means low channel capability, in addition to vulnerability due to the ionospheric variability and disturbances. The next generation of communication modes used tall microwave towers to increase the line of sight (LOS) distances with the radio wave refraction abetting increase in LOS distances due to a decreasing refractive index profile with height in the troposphere. Troposcatter was used for limited point-to-point applications with high reliability using frequencies upto a few GHz; the communication range can be increased beyond 1000km by exploiting omnipresent, turbulence-generated irregularities upto altitudes of a few kilometers—thus essentially locating the transmitters at high altitudes to increase the radio horizon distance. However, it is the advent of the satellite era that triggered an explosion in worldwide coverage of broadcast and telephone services with a very large channel capability.

Evolution of Space Communications

Interestingly, it may be noted that satellite communications in a way started in 1946. It was in 1946 that J.H.Trexler of Naval Research Laboratory, USA used Moon, the natural satellite of Earth, to bounce off UHF signals as part of project 'DIANA'[1]. Subsequently, it were these moon-bounce studies which enabled Browne *et al.*[2] to discover the trans-ionospheric Faraday rotation effect which is being successfully used now with transmissions from artificial earth satellites for a variety of studies related to the total electron content of the ionosphere. The passive ECHO satellite followed in 1960; even an artificial cloud of metallic dipoles were tried in the earth's orbit in 1963 which successfully aided communications. Several series of orbiting satellites such as TELSTAR, EARLYBIRD and SYNCOM by NASA and MOLNIYA by Soviet Union were tried for communications and surveillance with different degrees of success until the concept of geostationary orbit materialised and gave a quantum jump to space communications.

In addition to communications, the satellite-based radio systems are being used to study solar-terrestrial interactions, global change and a host of seminal scientific disciplines. Of course, they have become the mainstay for a number of civilian and military applications such as position-fixing, tectonic movements, earth resources survey, command, control and Intelligence gathering etc. All

these applications require stringent stability and accuracy of the systems.

Radio waves from all space-based radio systems will have to travel through the intervening environment, often several times to complete an intended task. The most important regions of interest in this context are the troposphere and the ionosphere where the refractive index can significantly depart from unity and the magnetosphere because it hosts the geostationary satellite whose stability of operation is compromised by a variety of particle effects. Several basic research efforts have been initiated over the last three decades to understand and quantify the deleterious effects imposed by the troposphere and ionosphere on the system performance of space communication systems and to develop statistical climatology over different regions of the world to build enough margins to achieve acceptable performance levels depending on the service requirements.

The Troposphere

Troposphere extends from ground level upwards to altitudes of about 16km at the equator and 8km at the poles. The percentage composition does not change with altitude except that of water vapour. It is characterised by a 6°C per km lapse rate on the average. Radiation, absorption, condensation, evaporation, advection, convection, turbulent diffusion and a number of complex and interacting meteorological phenomena make the troposphere a cauldron of nonlinear and unpredictable processes. The gradients of temperature, pressure and water vapour in the lowest few kilometers of the troposphere combine to produce significant Radio Refractive Index (RRI) gradients and under some circumstances even ducting which can restrict space communications coverage area at low elevation angles. But, by far, the most important degradations at satellite communication frequencies are caused by water vapour and by the general category of hydrometeors consisting of rain, hail, ice, fog, clouds and snow.

Effects of Hydrometeors

The most significant effects of hydrometeors, especially of rain are the following :–

(*i*) Attenuation caused by dissipation of radio wave energy as heat.

(*ii*) Scatter resulting in loss in the desired direction and consequently causing interference to other systems; scatter loss can dominate at extremely short wave lengths compared to the size of the hydrometeor.

(*iii*) Depolarisation due to the non-spherical nature of rain drops.

(*iv*) Rapid amplitude and phase scintillations caused by equivalent multipath propagation.

(*v*) Antenna gain degradation due to phase dispersion of ray paths reaching the antenna.

(*vi*) Bandwidth coherence reduction, especially in digital systems involving carriers spanning over large channel bandwidths.

It should be mentioned here that the primary cause of attenuation in liquid rain drops is the heavy displacement currents caused by the large dielectric constant of water and the high frequencies employed in space communications[3]. Consequently, the rain attenuation depends not only on the rain rate, but also on the rain drop size distribution and the temperature of the rain drops. In view of rain being the primary factor in degrading the Earth-space links above 4GHz, some additional details, especially for the tropics are in order.

Rain Attenuation

We should first appreciate that frequencies atleast upto 50GHz are going to be pressed into service in near future. Until 1969, the geosynchronous orbit hosted a small number of satellites. They included the seven INTELSATS in the 6/4GHz bands; SYNCOM-3, ATS- 1,3 and 5 of NASA, the SKYNET satellite of United Kingdom and the TACSAT of U.S. Airforce[4]. By 1979, another one hundred satellites were added. It is estimated that by the year 2000 A.D., there would be more than 600 active satellites in the geosynchronous corridor. Firstly, this proliferation will push the frequency spectrum upwards to gain more channels. Secondly, as the orbit gets crowded, inter-satellite interference will increase; to mitigate this problem, higher frequencies will be sought as the beam width for a given dish size decreases with decreasing wavelength. Indian satellites at 10 to 14 GHz are already on the agenda. The World Administrative Conference (WARC) had already provided bandwidths of over 500 MHz in the 12/14GHz Band, 3.5GHz in the 20/30GHz Band and 4.2GHz in the 40/43GHz region. The specific attenuation γ, in dB/km due to rain can be evaluated from the classical Mie scattering theory by using the complex RRI of water at the rain drop temperature, the terminal velocities and the rain drop size distribution.

$$\gamma = 4.343 \int_0^\infty Q_t(D) N(D)\, dD \text{ [dB/km]}, \qquad ...(1)$$

where $Q_t(D)$ is the extinction cross section and $N(D)dD$ is the number density of the rain drops of diameter D in the interval dD. The rain rate R is related to the drop size distribution as

$$R = 6\pi \times 10^{-4} \int_0^\infty D^3 N(D) V(D)\, dD \text{ [mm/h]}, \qquad ...(2)$$

where $V(D)$ is the terminal velocity of the drops in m/sec and $N(D)$ is in $mm^{-1} m^{-3}$. The specific attenuation has been found to be related to rainfall rate R by the relation (Olsen *et al.*)[5].

$$\gamma = KR^{\alpha} \text{ [dB/km]}, \quad \ldots(3)$$

where K and α are parameters depending on the wave frequency and polarization for a given distribution of rain structure. So, to be able to estimate the specific attenuation from measured or predicted rain rate, one requires the values of K and α for different polarizations and rain drop temperatures. As the drop size distribution is not unique for a given rain rate, we have to assume one of the available models; more detailed discussion follows in subsequent sections. Values K and α were calculated for rain drops of oblate spheriod in shape by using models of drop size distribution and terminal velocity for 20 °C temperature[6-9] and are shown in Table I.

Table I

Coefficient for estimating specific attenuation

	Frequency(GHz)	K_H	K_v	α_H α_V
1	0.0000387	0.0000352	0.912	0.88
2	0.000154	0.000138	0.963	0.923
4	0.00065	0.000591	0.121	0.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.31
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0335	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.03
30	0.187	0.167	1.021	1
35	0.263	0.233	0.979	0.963
40	0.35	0.31	0.939	0.929

Problems in Quantifying Rain Attenuation

Estimation of specific attenuation using relation (3) above which was originally derived on empirical basis by Gunn and East[10] was confirmed on analytical basis by Olsen *et al*[5]. A rigorous critical evaluation of the specific attenuation over different geographical regimes is possible only through coordinated experiments deploying fast response rain gauges, radiometers and radars; unfortunately such an exercise was never attempted in India. Some attempts have been made in India and in Nigeria using fast response rain gauges, but without simultaneous measurements by Radars and rain drop spectrometers[9]. To estimate even approximately the total slant path attenuation in satellite communications, we need to know the structure of the specific attenuation, the drop size distribution, the ground level rain rate and the height of the 0 °C isotherm. Convective precipitations are formed below 0 °C isotherm and the importance of this height is due to the high attenuation of liquid water compared to the other forms of hydrometeors. The mid-latitude rain pattern may be dominated by low rain rate caused by stratiform clouds extending to a few hundred kilometers with vertical heights of barely 5km. However, in the tropics, convective rains, often associated with thunderstorm events can extend to more than 10km in altitude due to convective upswelling; the horizontal extent and the duration of course are lesser. But the damage to the link is the worst in the tropics due to high rainfall rates, larger drop sizes and higher altitudes of 0 °C isotherm. Fortunately, the change in the rain drop size distribution with increasing rain rate can be predicted with a reasonable degree of accuracy as will be obvious in the following paragraph.

The three distributions used often in Earth-space attenuation calculations are those of Laws and Parsons[7], Marshall and Palmer[11] and Joss *et al*[12]. Fig. 1 shows the specific attenuation at frequencies from 1 to 1000 GHz for four specific rain rates obtained by a series expansion solution of the Mie scattering coefficients for the three drop size distributions mentioned above; these values have been confirmed by a large number of more recent investigations and a description of these results is beyond the scope of this paper. The authors here would like to emphasize that there are several lessons for the tropics including for India from Fig(1):—

(*a*) As rain attenuation increases rapidly with rain rate, even frequencies below 5GHz can be affected for short bursts of downpour lasting only a few seconds.

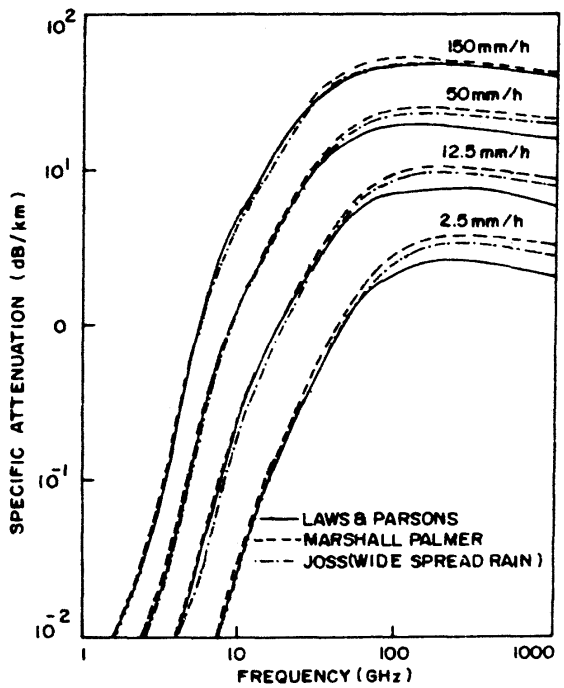


Fig 1 The specific attenuation of rain from 1 to 1000GHz at rain rates of 2.5, 12.5, 50 and 150mm/h for the drop size distributions of Laws and Parsons, Marshall-Palmer and Joss *et al*, with a rain temperature of 20 °C[4].

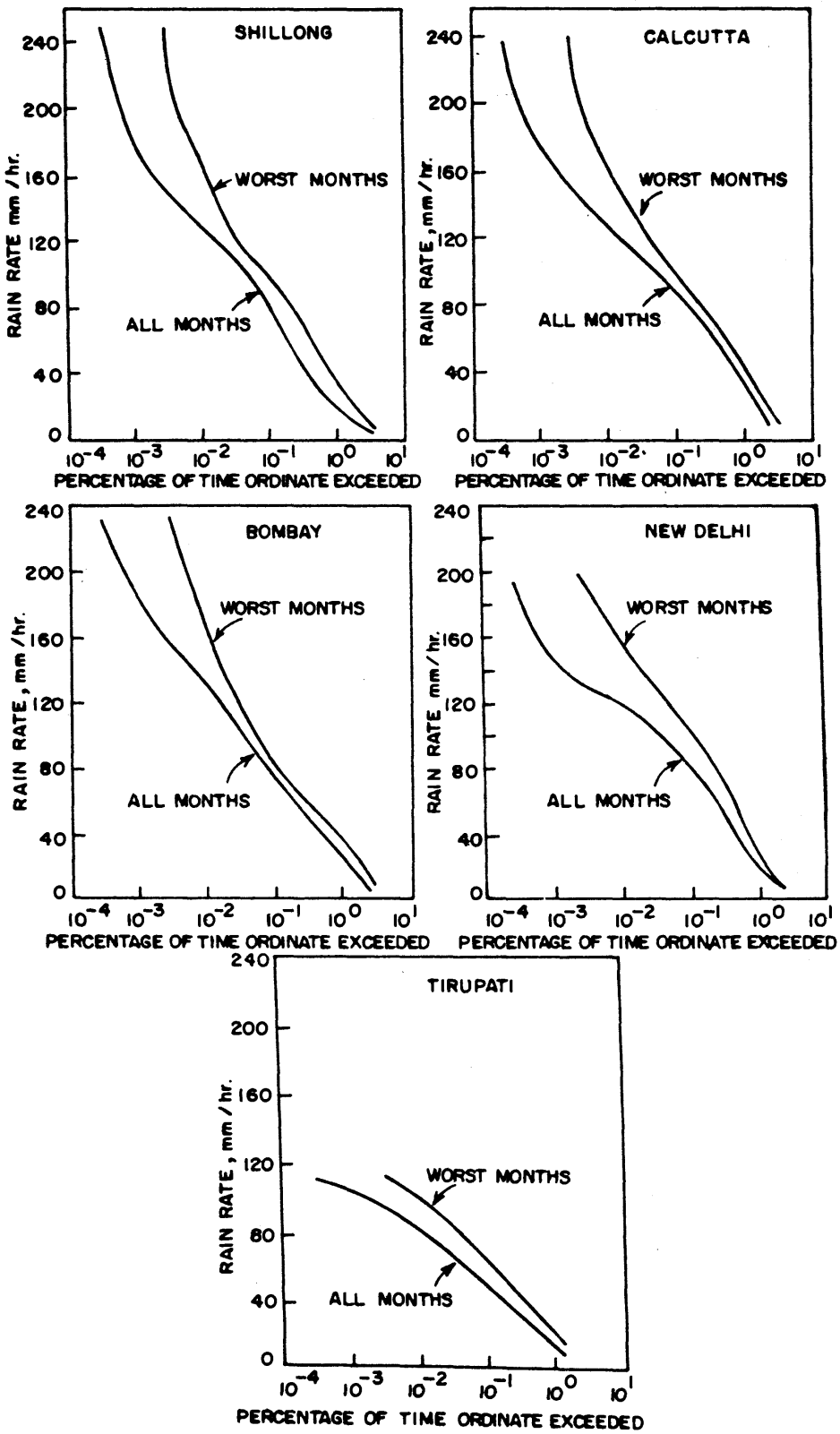


Fig 2 Rain rate distribution over various stations in India[14].

(*b*) Atleast upto 30 GHz (beyond which no plans exists in the near future), the drop size distribution is of little significance. Hence, we need not be bothered with studies of drop size distribution at this stage.

(*c*) The exceptions to (*b*) above are for basic studies of cloud physics in association with radars (preferably 3cm radars) and to decide on XPD (cross polarisation discrimination) in frequency reuse systems both in ground-based links and in earth-space links.

(*d*) The single most important data set required is a good morphology of rain rate at a large number of places in the country using fast response rain gauges (10 to 20 second integration times). Some preliminary information from Sarkar *et al.*[13] is already available, but it has to be augmented. Fig. 2 shows results obtained by Sarkar[14] at Delhi, Shillong, Calcutta, Bombay and Tirupati using 10-second response rain gauges. The rain rates measured show that in many places in India, the heavy rain rates can far exceed 0.01% probability level considering all months. This percentage of outage is unacceptable for many commercial and Defence services. In Fig. 2, the abscissa represents the probability percentage of time including dry spells over which rain rates exceed the ordinate values. Fig. 3 shows typical rain storms recorded in different locations in India. The features here are similar to those observed in amplitude variations of microwave and millimeter radio waves. Results on amplitude fade, its duration and the associated distributions are important for system planning, particularly for low elevation earth-space paths[15].

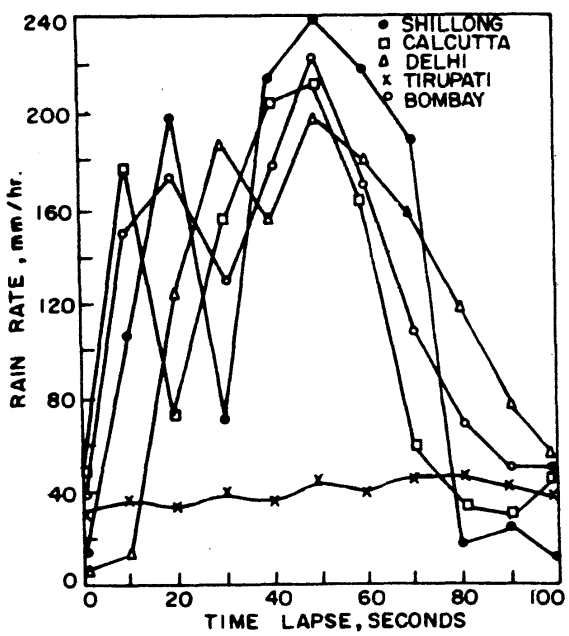


Fig 3 Typical rain storms in India.[14]

Future Possibilities in Rain Attenuation Work

The ideal method would be a direct and continous monitoring of actual rain attenuation over several years from a large number of locations. This is possible by having stable beacon transmitters on-board satellites with several operating frequencies from 5GHz to atleast 30GHz. These should be supplemented by ground-based fast response rain gauges and microwave radars. Future Indian satellites can carry such beacons as Piggy-back payload. As the pressure on the frequency spectrum builds up, frequency reuse systems will have to be employed with dual independent orthogonal polarisations providing two channels at the same frequency. But, such transmissions can be degraded in the propagation medium through a transferral of energy from one polarisation state to the other state with consequent ambiguity at the receiver. This problem known as cross-polarisation can be caused by (*i*) large rain drops which degrade to oblate spheriods and by (*ii*) multipath propagation usually in the ionosphere by the Faraday effect - and this is easily compensated in Earth-space. In high performance frequency reuse system, an adequate margin should be provided for cross polarisation discrimation.

Atmospheric Gaseous Attenuation

The second most important parameter, after the rain, in degrading Earth-space links is the attenuation due to atmospheric gas components, water vapour and oxygen. Unlike the rain parameter, the gaseous attenuation is characterised by resonance absorption peaks, in addition to the gradual increase of absorption with frequency. The first absorption band is due to water vapour and is centered at 22.2GHz. The electric dipole of the water vapour molecule interacts with the electric field of the passing radio wave producing a quantum jump in its rotational energy which is derived from the radio wave energy. In case of the oxygen molecule, its permanent magnetic moment interacts with the magnetic field of the radio wave and thus gaining in rotational energy at the expense of the radio wave. These oxygen absorption bands are centered around 60GHz and 118.8GHz. The frequency dependence of this absorption is a function of temperature, pressure and humidity in the atmosphere and hence is liable to significant spatial and temporal variability.

The total gaseous attenuation in the atmosphere 'A' over a path length r_0 (km) is given by

$$A = \int_0^{r_0} \{r_0(r) + r_w(r)\}\, dr, \text{ in dB}, \qquad ...(4)$$

where r_0 and r_w are the attenuation coefficients (in dB per km) for oxygen and water vapour respectively. Fig. 4

shows the attenuation coefficients for oxygen and water vapour for frequencies from 1 to 350GHz at a temperature of 20 °C and a humidity of 7.5g/m^3 (CCIR)[16]. The slant path attenuation in the atmosphere is given by the cosecant of the elevation angle down to about 6° below which the cosecant law breaks down because of the earth's curvature and refraction effects. Below 6°, the attenuation is obtained by ray tracing the path through the atmosphere, starting at the surface height and obtaining the line integral of attenuation along the ray path[4]. It is relevant to mention here that the water vapour attenuation problem in the tropics is a mixed bag. Firstly, the elevation angles will be rather high for geostationary satellites (unless a country is forced to use a satellite far away in longitude!). Secondly, the water vapour levels are much higher than the 7.5 g/m^3 used to derive Fig. 4; infact they may even exceed 30g/m^3 and this factor will greatly increase the slant path attenuation even at the modestly high elevation angles obtainable in the tropics. Fig. 5 shows that measured values (individual points) and those derived from zenith attenuation using the cosecant formula are in good agreement from the data obtained from China at 20.6GHz (Ajayi *et al*)[17]. Using a long series of Radio Sonde data from India, an Atlas of water vapour has been published by NPL[18] and Fig. 6 is a sample from the Atlas for Assam valley, desert area and southern plains during monsoon months at 0000 hours GMT. In conclusion, it can be stated that satellite system designers should estimate the slant path attenuation due to water vapour which can be the main debilitating consideration in the tropics at low elevation angles and give enough margin in the transponder power. As the attenuation due to oxygen reaches significant levels only above 35GHz, this may not be of immediate concern in India. The importance of gaseous attenuation can be appreciated if one realises that it is always there, unlike in the case of rain.

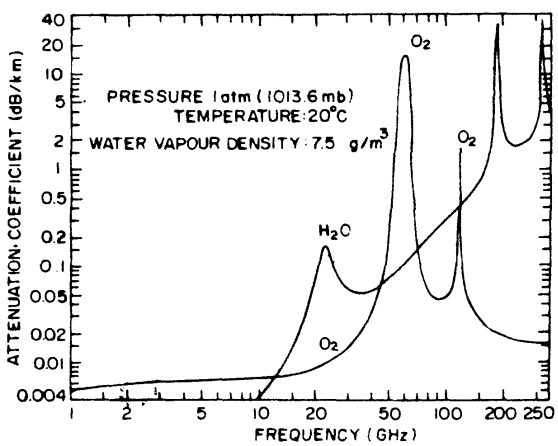


Fig 4 Attenuation coefficients for oxygen and water vapour from 1 to 250GHz[4].

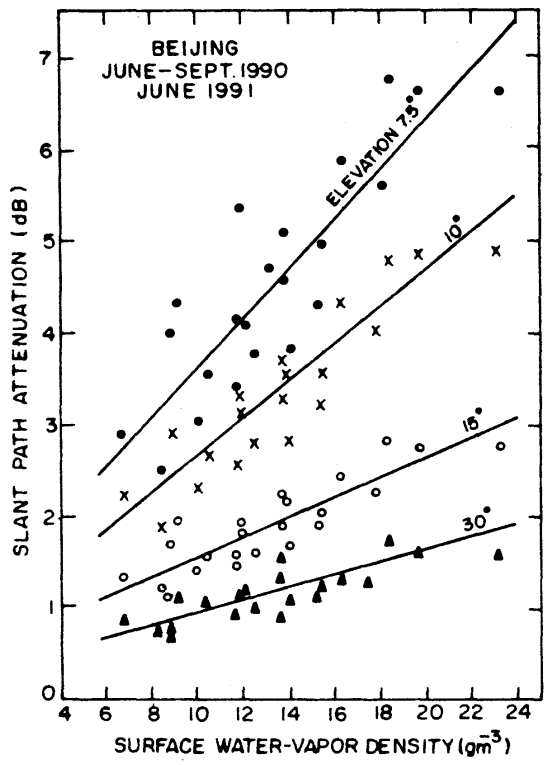


Fig 5 Slant-path attenuation at 20.6GHz[9].

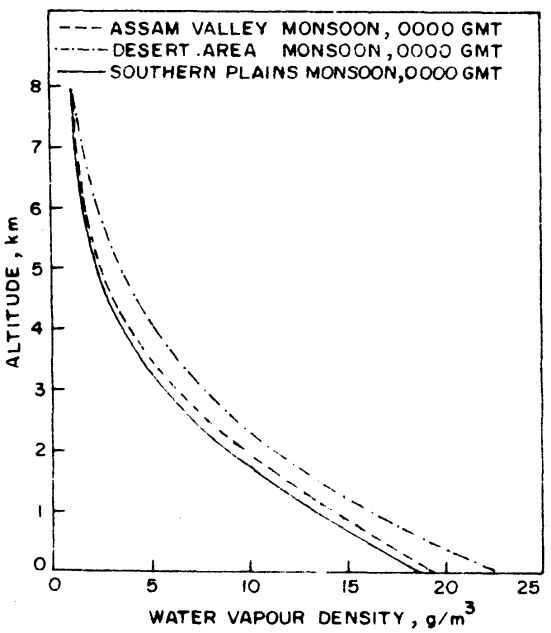


Fig 6 Height profiles of tropospheric water vapour concentration for Assam valley, desert area and southern plains during monsoon at 0000hrs GMT[18].

The Ionosphere

The ionosphere has dominated all long distance communications around the world until the sixties and continues to be an important mode of communications in the tropics even today. In the recent war "Desert storm operation", the biggest after the satellite era, the cutting edge in communications was provided by Ionoshere-reflected HF propagation. While the reliability factor is rather questionable, the advantages of HF communication in the tropics are very tempting[19]. A comprehensive review of this topic was presented by Lakshmi[20]. However, in space communications, ionosphere is a nuisance and can impose serious restrictions on the use of lower microwave bands for reliable systems. While it is a fact that the deleterious effects of trans-ionospheric propagation disappear above 10GHz, the tropospheric effects can be rather serious above 5 or 6GHz and as a trade-off, many users will have to use frequencies below 5GHz. For such users, an appreciation of the problems, quantification of the degradation and the techniques of mitigating the problems without increasing the cost of the space segment should be considered essential. The main effects of the ionosphere are scintillations due to irregularities, the group path delay caused by retardation due to the electrons, polarisation, and the doppler shift. For most of the satellite based systems, polarisation and doppler shift are insignificant and can be essentially ignored.

Scintillations

The most significant effect of the ionosphere is the degradation imposed through fluctuations in signal power and phase as a result of inhomogeneities in the refractivity

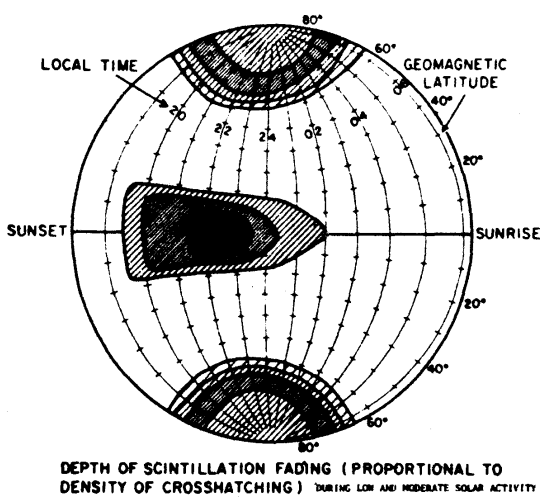


Fig 7 Global depth of scintillation fading (proportional to density of crosshatching) during low and moderate solar activity[21].

casued by a moving ionosphere embedded with irregularities. These irregularities responsible for scintillations are predominantly in the F layer, at altitudes between 250 to 450km. The global morphology of the depth of scintillations can be best described by Fig. 7 which shows the most intense scintillations near the equator for several hours after sunset[21,22,23]. Thus it is obvious that low latitude nations (most of which are the developing countries) should pay special attention to this problem. In fact, there have been several major groups in India which have contributed substantially in understanding the physics and developing reliable morphology[24-31]. During the early seventies, when scintillation measurements were made only in VHF and UHF, a distinctly decreasing trend was noticed with increasing frequency. Observations employing ten frequencies between 138MHz and 2.9GHz transmitted from one satellite, Freemouw *et al.* [32] showed a consistent wave length dependence of $\lambda^{1.5}$ for scintillation index values not exceeding 0.6. By extending such wave length dependence to microwave frequencies upto 12GHz, it was concluded that scintillations will not pose a problem above a few GHz. However, this state of complacence was short lived when several workers reported rather intense scintillations even around 10GHz during high solar activity periods.

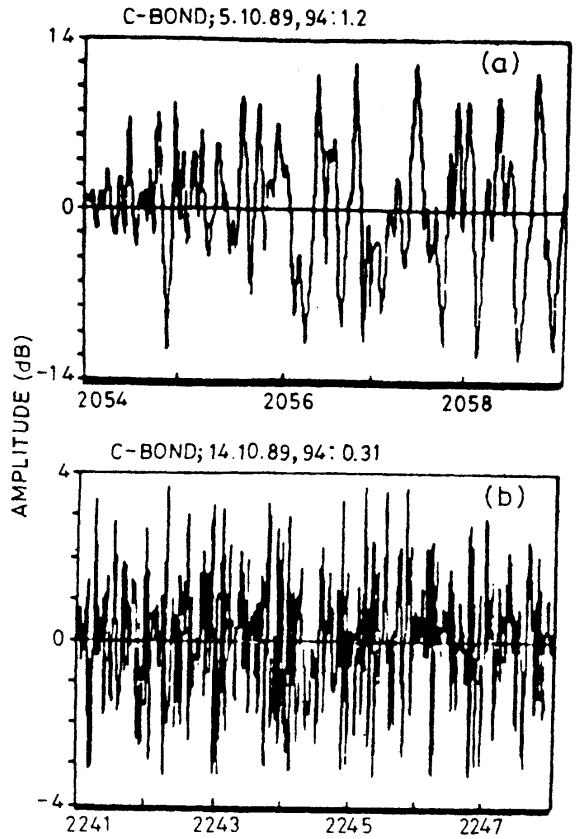
Dabas *et al.*[29] conducted detailed investigations of scintillations at 4GHz using the Indian satellites INSAT-IB(74° E) and INSAT-1C (94°E) simultaneously from two stations in India. The propagation geometry of these two stations, namely Sikandarabad (SKD) near Delhi and Chengalpet (CHPT) near Madras in South India is shown in Table II.

Table II

Details of propagation geometry

Station	Propagation Angle (degs.)	Subionospheric coordinates(400km)		
		Latitude (deg.N)	Longitude (deg.E)	Dip (deg.)
	INSAT 1B/1C	INSAT 1B/1C	1B/1C	
	159.89	26.82	77.82	
SKD				42.0
	153.43	26.68	78.90	
	110.86	10.41	79.49	
CHPT				7.0
	110.68	10.36	80.97	

From these investigations, several interesting features related to plasma dynamics and morphology were reported [29] and the details are not within the scope of this paper. However, two points of interest to space communications deserve to be mentioned here: even at 4GHz, peak-to-peak scintillations of 20dB were observed during the high solar activity equinoctial months. This is very



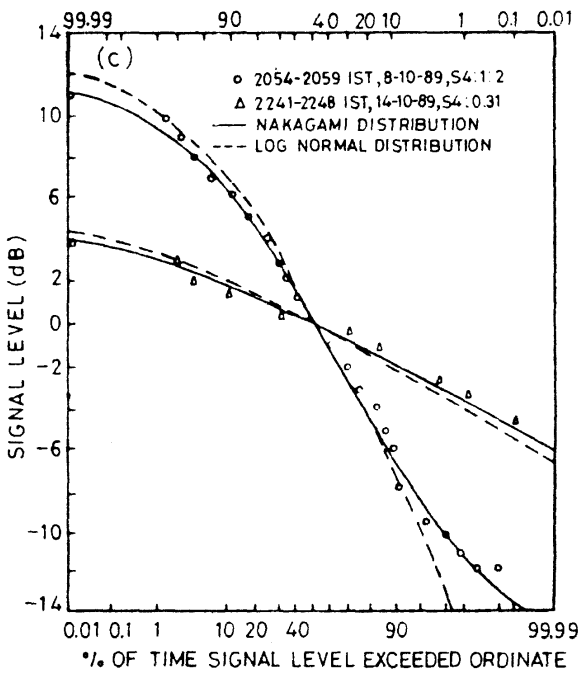


Fig 8 Computer plotted scintillation at C-Band: (*a*) 5 Oct. 1989, S4 : 1.2; (*b*) 14 Oct. 1989, S4 : 0.31; the corresponding cumulative distribution functions are shown in (*c*)[29].

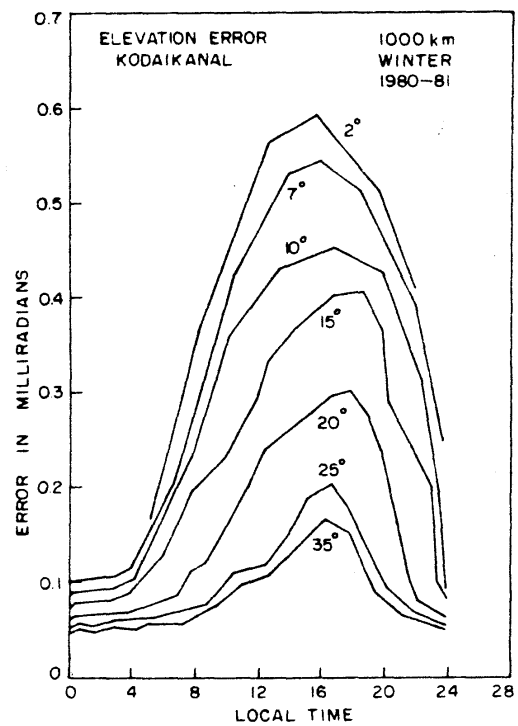


Fig 9 Ionospheric refraction errors for different elevation angles at Kodaikanal at a frequency of 500MHz using ray tracing techniques on model profiles calibrated by Ionosonde data.

large indeed and usually cannot be compensated by merely increasing the transponder power in the space segment and the only solution could be an appropriate diversity system or reducing the data transmission rate to avoid inter-pulse interference. The second point is that though the scintillation occurrences were less frequent near Delhi, by no means were they less severe. This has been attributed to the higher background electron density values at Delhi which is closer to the equatorial anomaly peak. Fig. 8 shows two computer plotted scintillation samples at 4GHz, one strong (index 1.2) and one weak (index of 0.31) near Delhi. The corresponding cumulative amplitude distribution functions (cdf) for the above two cases are also shown (Fig. 8*c*). The cdf is used in defining the fade margin requirements for communication systems as it expresses the probability of the signal either equally or exceeding a given decibel level depending on the service requirement. The reception of a message is ideal only when the signal level exceeds the fade depth, though there are special techniques such as CDMA (Code Division Multiple Access) and SSMA (Spread Spectrum Multiple Access) to mitigate the problem. By definition, the message reliability approaches the percentile given by the cdf as the message length approaches near zero levels; this implies that cdf gives the maximum value of reliability for a given fade margin.

Refraction in the Ionosphere

While this topic is not of much interest to space communications per se, this can be a rather serious trans-ionosphere effect in radio tracking of space objects like satellites or missiles. As the radio wave goes up into the ionosphere, it encounters rapidly increasing electron densities and hence the non-zenithal rays are bent away from the normal upto the peak of the F-region. Though the electron density decreases above the F-region, the profile in the topside is not a mirror reflection of the profile in the bottom side. As a result, the apparent elevation of the space object is higher than the real elevation. Actually, this error has to be added to the error introduced in the troposphere; the tropospheric error is independent of the frequency while the ionospheric error is a function of the frequency and decreases rapidly with increasing frequency. Fig. 9 shows the diurnal variation of the elevation angle erorr in milliradians for different elevation angles (only the ionospheric part of the error) for a target height of 1000km. The ionosonde data from Kodaikanal was combined with IRI (International Reference Ionosphere) model to obtain the electron density profile upto 1000km and ray tracing operation was performed to evaluate the elevation angle errors.

Conclusion

The advent of the satellite era has ushered in a whole series of high-tech space applications, the most important being telecommunications and broadcasting. At the lower end of currently operating frequencies, the ionosphere introduces serious problems while the tropospheric phenomena are responsible for degrading the performance with increasing frequency. A large number of groups in India had studied relevant ionospheric phenomena recently under the patronage of the Department of Science and Technology (DST) of Govt. of India and have collected a significant amount of data that can be harnessed to quantify margins in the space segment payload design. That apart, we will have no option except to go to frequencies above 10GHz where tropospheric processes, especially rain and water vapour will decide the reliability levels. As the Indian morphology of these parmeters is unique, it is imperative to initiate and expand experimental work to gather information on processes described in this paper to aid in robust space based systems that can deliver expected performance levels.

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