Atmospherics in Relation to Source Phenomena & Radio Wave Propagation in the VHF, UHF, Microwave & Millimetre Wave Bands

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Atmospherics originating from lightning flashes have been extensively studied by radio scientists for the last several decades, with a view to assessing and predicting the interfering effect on radio communication systems. Most of the earlier studies were confined to frequencies below about 30 MHz where ionospheric propagation can be exploited. The advent of satellite communication for a global coverage has, apparently changed the pattern of communication, which is now confined to frequencies above 30 MHz in the VHF, UHF, microwave and millimetre wave bands. A current trend is to use satellite communication for long distances supported by microwave LOS links for inland coverage. A study of atmospherics in these bands is, therefore, urgently needed to assess the radio noise potential of lightning flashes in operational communication and radar systems. This paper is an attempt to review the present state of knowledge in the area obtained from ground based and space borne instruments to detect and measure electromagnetic noise and interference due to lightning flashes.

1 Introduction
Interference to radio reception in the form of “crashes”, “sizzles” and “grinders” during a lightning flash is a common experience to the listeners of radio broadcasts, operating at frequencies below 30 MHz. The advent of satellite communication has greatly widened the application areas of VHF, UHF, microwave and millimetre wave bands for communication using satellite links supported by line of sight (LOS) links over the surface of the earth. Atmospherics, in these frequency ranges, therefore, necessitate a thorough investigation. It is, in fact, believed that most of the futuristic operational radio communication systems will also exploit these bands. Accordingly, this review is aimed at highlighting the work done on atmospherics in the VHF, UHF, microwave and millimetre wave bands.

2 Atmospherics
Electrical discharges accompanying lightning flashes in thunderstorms radiate a significant amount of energy over a wide range of the electromagnetic spectrum. These radiations are propagated through space in accordance with the known laws of radio wave propagation. The nature and magnitude of these radiations received at a point are determined by the source characteristics, viz. the location of thunderstorms, their growth and decay and the flashing characteristics of the lightning discharge. When these radiations from lightning flashes are picked up by a receiver tuned to a certain frequency with a specified bandwidth, the output in the receiver is heard as “atmospherics”.

Caton and Pierce1 have divided atmospherics into 4 main classes: (a) an irregular high frequency type, (b) a regular peaked type, (c) a regular smooth type and (d) a long oscillatory train type. Type (a) was considered to be originated from the stepped leader process while other types come from return stroke.

Laby et al.2 accounted for some features of atmospherics in terms of reflections at the ionosphere, and Hales3 and Budden4 considered the ground and ionosphere to form a waveguide. Budden3 pointed out that the reflection and waveguide methods of approach are essentially the same, but one or the other may be more suitable in a particular case.

3 Frequency Dependence of Atmospherics
Various investigations5-11 have shown that the noise field strength varies inversely with frequency and directly as the square root of the bandwidth of the receiver used. Atmospheric noise is the principal source of interference to the reception of radio signals at frequencies below 15 MHz (Ref. 12).

Taylor and Jean8 made an observation of the intensity of atmospherics at 1-40 kHz emitted from ground discharges at distances of 150-600 km. Watt and Maxwell5 recorded the intensity at 1-100 kHz at distances of 30-50 km and Horner13, at 11 MHz and 6 kHz at distances of 1.5-6.5 km, Takagi14 at 100 kHz and 500 MHz at 15-20 km, and Schafer et al.15 at 150 MHz at 1-32 km. These results have been summar-
Fig. 1—Field intensity of atmospherics (bandwidth = 1 kHz; distance = 10 km)

ized by Kimpara\textsuperscript{16} who normalized all the data at a
distance of 10 km for a receiver bandwidth of 1 kHz
and found the frequency spectrum as shown in Fig. 1.
From these observations it is seen that the characteris-
tics of atmospherics which define their frequency
spectra depend on the development of the thunder-
storms and other factors. The investigation of the fre-
quency spectra from ELF to UHF at various dis-
tances from the source will contribute to the study of
the mechanism produced in the thunderstorms.

Aiya\textsuperscript{17} from his model of stepped leader deduced
that the power in the high frequency range is $45/f^2$ W
in a bandwidth of 6 kHz, where the frequency $f$ is in
MHz. There is no explicit statement about which the
various power parameters this model represents, but
from a later paper\textsuperscript{18} by Aiya it seems probable that it
was intended to be the mean power over the duration
of one atmospheric.

4 Atmospherics from Nearby Storms

Studies of atmospherics from nearby storms during
the past few years, over a wide range of frequencies,
yield the representative values of the parameters\textsuperscript{13,19}
(Table 1) gives some properties of the vertically polar-
ized field near the ground at a distance of 10 km from a
typical lightning discharge. The quantities are based
mainly on measurements in England, but those for
10 kHz are well-substantiated by the results of work
elsewhere\textsuperscript{19}.

A typical duration in temperate latitude is 300 ms.
In the tropics the durations tend to be longer and
500 ms may be taken as more typical, but many at-
mospherics last for more than a second. At high fre-
quencies each atmospheric is more continuous and a
rate of occurrence much more than one per second
results in noise in which separate atmospherics or
even separate pulses are not readily distinguishable.
The amplitude data given in Table 1 refer to the elec-
tric field as measured in a short vertical rod aerial at
ground level. The field strength given in Table 1 for
each of the three highest frequencies represents the
vector sum of direct and ground reflected waves.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Peak energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10 \text{kHz}$</td>
<td>$1600 \text{ mV/m}$</td>
</tr>
<tr>
<td>$10 \text{MHz}$</td>
<td>$1100 \text{ mV/m}$</td>
</tr>
<tr>
<td>$100 \text{MHz}$</td>
<td>$80 \text{ \mu V/m}$</td>
</tr>
<tr>
<td>$500 \text{MHz}$</td>
<td>$8 \text{ \mu V/m}$</td>
</tr>
</tbody>
</table>

5 Atmospherics at Satellite Heights

We know that high frequency atmospherics penet-
rate the ionosphere and reach the satellite. Low fre-
quency atmospherics propagate through the ionos-
phere in the whistler mode.

The estimated\textsuperscript{20} peak amplitude of the field
strength of a single atmospheric at 500 MHz is 0.08
\mu V/m when the receiver is directly above a typical dis-
charge. This is almost the same as the rms amplitude
of galactic noise. Reduction of the frequency to
100 MHz increases peak amplitude to 0.8 \mu V/m
while rms value of galactic noise now becomes 0.12
\mu V/m. At 10 MHz the corresponding values are 11
\mu V/m and 0.21 \mu V/m and the peak would, therefore,
be about 50 times greater than the rms galactic noise,
if there were no ionosphere. Particularly by day, the
atmospherics may be partly absorbed or may fail to
penetrate the ionosphere when the critical frequency
is high.

Table 2 (Ref. 20), where relevant data for galactic
noise are also given, summarizes the characteristics of
the field which would be expected in a bandwidth of 1
kHz at a height of 1000 km over one of the main thun-
derstorm areas if there were no ionosphere. These val-
ues, however, take account of reflection from the ion-
osphere below the receiver. The 10 MHz values for
galactic noise are rather uncertain and a compromise
has been made between values extrapolated from
measurements at higher frequencies\textsuperscript{21} and somewhat
larger values quoted by Ellis\textsuperscript{22} and Hartz\textsuperscript{23}.
It is interesting to note that the atmospheric noise intensities at 10 MHz are nearly the same as those near the ground in the main thunderstorm area.

6 Atmospherics from Other Planets

Many observers have recorded noise burst from Jupiter with a flux density of the order of $5 \times 10^{-12} \text{ W m}^{-2} \text{ Hz}^{-1}$ at about 20 MHz (Ref. 25). The estimated power radiated from terrestrial thunderstorms at this frequency, with assumed 100 discharges per second, is $4 \times 10^{-4} \text{ W m}^{-2} \text{ Hz}^{-1}$. If these storms were transferred, without change, to the minimum distance of Jupiter ($6.2 \times 10^8 \text{ km}$), the flux density received on the earth would be $8 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ or a factor of nearly $10^8$ smaller than the noise actually observed.

Terrestrial thunderstorms transferred to Venus would produce a flux density of $4 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ on the earth at 10 MHz. This is much smaller than the flux of galactic noise ($H \times 10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1}$) and would be very difficult to detect from the earth, even using radiometer techniques and high gain aerials.

7 Radio Noise from Atmospherics

At frequencies below about 10 MHz the atmospherics originating from lightning flashes usually propagate to great distances and the radio noise is received by antennas near the earth's surface omnidirectionally from all around. The radio noise levels due to atmospherics have been studied extensively in different countries and the results reported in the publications of the National Bureau of Standards and CCIR. The results are typically given in terms of a quantity $F_u$, in dB, which is given by

$$F_u = 10 \log_{10} \frac{P_w}{kTB}$$

where $P_w$ is the noise power available from a perfect short vertical monopole and $B$ the bandwidth. Equating $P_w$ with $kTB$, where $T (288 \text{ K})$ is the effective brightness of the environment due to atmospherics, we have

$$F_u = 10 \log_{10} \frac{T_b}{288}$$

The measured values of $F_u$, in dB, are plotted in Fig. 2 in the form of effective brightness temperature $T_b$ against frequency over a range of 10 kHz-10 MHz. Since the atmospherics are received from all directions, the brightness temperature is also the effective antenna temperature for any antenna above and near the surface of the earth, irrespective of the antenna directive pattern.

It may be mentioned here that the atmospherics radio noise level drops above 10 MHz, exhibiting a sort of cut-off around 15 MHz due to the elimination of distant atmospherics propagated by reflection in the ionospheric layer at higher frequencies. According to Homer, the radio noise levels at VHF, UHF microwaves and millimetre waves are rather low and originate mainly from local sources of lightning flashes within the line of sight (LOS) range of the receiving antenna.

8 VHF Atmospherics at Various Distances from a Lightning Flash

Measured data in VHF atmospherics by different workers are mentioned below.

1. The rms29 field strength at 100 MHz per burst at 1 kHz bandwidth at 1 km from the source = 127 $\mu$V/m.
2. Peak power radiated by the equivalent isotropic radiator corresponding to a flash at 1 kHz bandwidth = 8.5 mW.

According to Aiya and Bhat, the high intensity hour is most frequent for thunderstorm during 1620 hrs LMT. Median duration of flash is 0.5 s, the burst form of the noise occupies about 10% of that during this high intensity hour and it is assumed that flashes occur between 5 and 50 km.

The VHF noise radiation from lightning flashes can travel to distances of the order of 500 km via the sporadic E-layer or by troposphere. This is estimated to give rise to continuous noise of the order of 0.1 $\mu$V/m at 100 MHz and 1 kHz passband.

Schafer and Goodall observed near storms and their results show that at 10 km distance the peak value of noise was 1.2 mV/m in a bandwidth of 1.5 MHz at 150 MHz. This peak value was measured on a cathode ray tube.

According to Homer, peak amplitude in 1 kHz bandwidth at a distance of 10 km at frequency 100 MHz is 0.1 mV/m, peak radiated power in 1 kHz bandwidth is 3 mW and mean power over 200 ms in 1 kHz is 160 $\mu$W.

Ghosh and Saksena measured the field strength of atmospherics at 95 MHz in $\mu$V/m for 1 kHz band-
Table 3—Radio Noise Field Strength under Various Conditions

<table>
<thead>
<tr>
<th>Condition of observation</th>
<th>Total no. of hrs of observations</th>
<th>No. of occasions</th>
<th>Average field strength for 1 kHz bandwidth, $\mu$V/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>600</td>
<td>Most of the time</td>
<td>0.03</td>
</tr>
<tr>
<td>Rain</td>
<td>7</td>
<td>6</td>
<td>0.15</td>
</tr>
<tr>
<td>Thunderstorm</td>
<td>5</td>
<td>3</td>
<td>0.20</td>
</tr>
<tr>
<td>Abnormal propagation</td>
<td>10</td>
<td>8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

width during various seasons. According to their observations, radio noise field strength (RNFS) values are higher during the summer and lower during the winter, while the spring and autumn values are in between. These values are less than 0.1 $\mu$V/m for kHz bandwidth and are lower than the values predicted by the empirical formula based on the ARN field strength data between 2.5 and 9.5 MHz (Ref. 32). According to Ghosh and Saksena, at 95 MHz, there is normally no propagated noise and therefore lower values of RNFS are expected.

Ghosh and Saksena recorded the RNFS not on a normal day (Table 3). After 1500 hrs IST, the thunder was heard for about two hours and the noise record due to this could be recognized. During rain between 1645 and 1715 hrs IST, the noise heard was different from the one which was due to thunderstorm.

9 Generation of Atmospherics

Brook and Kitagawa measured atmospherics at frequencies 420 and 825 MHz and found that these are associated with the development of streamers in breakdown processes both in leader strokes and inside the clouds. No effect is found ascribable to the main return stroke itself and a dart leader gives no effect during the last 100 $\mu$s of its movement.

There have been several reports of high frequency radio emission from clouds at times when there are no lightning flashes. For example, Gibson found radiation on a wavelength of 0.86 cm ($3.5 \times 10^4$ MHz) from clouds without lightning. Sartor considered the phenomenon and suggested that the origin of the radiation might be the collision of charged water drops, and carried out laboratory experiments to confirm this.

Every lightning flash can give rise to a noise burst. As is now known, lightning flashes are of different types. There are lightning flashes in which the electrical discharge strikes the ground (ground flashes), those in which the discharge occurs within the cloud only (cloud flashes) and those occurring between the cloud and the air. But in all types of flashes, there are electrical discharges occurring inside the cloud. It is now known that these discharges inside the clouds are responsible for the radiation giving rise to a noise burst at any frequency in the LF, MF, HF and VHF bands.

10 Propagation Mechanisms of Atmospherics in the VHF Bands

Short distance VHF noise reaches the receiver directly. Radiation from long distance flash may be received via sporadic-E or by troposcatter. Such propagations in long distance TV signals in band I have been reported by Smith and Smith and Hamer, to be due to sporadic-E and tropospheric ducting, and by Saha and Saksena and Sarkar in India to be due to artificially modified ionosphere and tropospheric ducting, respectively. Saksena, in fact, examined the TV signal propagation due to various modes.

11 Microwave Atmospherics

The widespread use of radar for meteorological purpose, i.e. for the detection and study of rain and thunderstorms has led to many observations of radar echoes from lightning and, to a lesser extent, to observations of atmospherics at the radar frequency, generated by some process in the lightning discharge. Reports of radio noise from lightning observed on other types of telecommunication equipment at frequencies of 200 MHz or higher are relatively rare.

11.1 Observed Characteristics of Radio Noise at Frequencies Used in Radar

The majority of radar equipment used for the observations of lightning echoes and radio noise from lightning has been the conventional high performance radar, normally used for weather observations.

11.2 Intensity

The subject has been treated in some detail by Atlas who observed radio noise at a wavelength of 10.7 cm of an intensity corresponding to a field strength in excess of $1.5 \times 10^{-4}$ V/m normalized to 1 mile and 1 kHz bandwidth.

Hewitt observed noise on 600 MHz and calculated the power flux of this radiation to be at least $10^{-12}$ W m$^{-2}$ in a bandpass of 1 MHz centred on 600 MHz within a range of 8-16 km from typical lightning stroke. Atlas extrapolated the spectrum calculated by Watt and Maxwell to the microwave region and concluded that the stronger spherics at 10.6 cm and at 600 MHz fall very close to the predicted ones.

11.3 Waveform

Published information on the waveform of radio noise from lightning above 600 MHz is relatively rare.
It is generally in the form of intensity modulation of PPI (Plan Position Indicator) type display, where saturation is deliberately arranged in the design of the equipment.

Atlas\textsuperscript{34} observed a large number of spherics during a 6-hr period on a 1200 MHz radar. These averaged a duration of 480\,\mu s, the most frequent ones were 92\,\mu s long and the longest one was 2310\,\mu s. At 600 MHz, using fixed multiple beam radar with continuous recording, Hewitt\textsuperscript{52} obtained a large number of records of noise from lightning over several summer seasons.

It is interesting to compare the waveform information obtained by Atlas\textsuperscript{34} at 1200 MHz with that obtained by Hewitt\textsuperscript{52} at 600 MHz, particularly, for the duration of the individual pulses, which according to Atlas averaged 27.5\,\mu s. Hewitt’s records indicate a fine structure, more in the region of 1\,\mu s superimposed on the general rise in noise level.

The durations of the noise bursts observed by Atlas\textsuperscript{34} and Hewitt\textsuperscript{52} are in good agreement, though Atlas does not appear to have observed the long duration noise bursts of 10 ms or more, that Hewitt associates with cloud flashes or air discharges.

### 11.4 Source in Vertical Cross-section

Published information on the precise region in the discharge from which the noise originates is relatively sparse. Atlas\textsuperscript{34,49} observed a storm with a vertically scanning radar. Among the thirty frames which displayed lightning echoes, only five simultaneously displayed what could be classified as probable “spherics”. At 600 MHz, Hewitt\textsuperscript{52} was able to observe, with some limitations, the angle of elevation of the source of noise. On a number of occasions this angle has been observed to increase as the stroke number increases in ground flashes. But there is no obvious correlation between the observed angle of elevation and the location of the source of the echoes that follow, for, with a display of this type, only short duration samples (about 50\,\mu s) at intervals of 500\,\mu s are available for study. It appears, nevertheless, that the noise can come from comparatively localized sources.

### 11.5 Sources in Horizontal Cross-section

Having observed 489 spherics during a 6-hr period on a severe squall line Atlas\textsuperscript{34,49} conducted an intensive study of spherics activity in relation to lightning echo rate.

Hewitt\textsuperscript{52} has not made any specific study of horizontal distribution at 600 MHz, but followed the practice of pointing his aerial at regions of lightning activity observed visually or, in the event of local rain obscuring vision, by using the appearance of lightning echoes or of atmospherics on a monitor scope as a guide.

### 11.6 Rate of Occurrence

Atlas\textsuperscript{34,49} concluded that with a FPS-20 radar at 1200 MHz, counts in excess of 10 spherics observed per hour per 5° sector are indicative of rather severe electrical activity with a probability of 1 in 64.5 of detection in a 5° azimuth sector with the 1.3° beam of the FPS-20. This is equivalent to 645 spherics per hour actually occurring, but not necessarily observed, in the 5° sector. Hewitt\textsuperscript{52} has not made a particular study of activity, but 5-10 separate bursts of noise per ground flash are common and up to 20 separate bursts are observed (not frequently) per cloud discharge.

This relatively high number of discrete noise bursts per lightning discharge observed by Hewitt\textsuperscript{52} may be due to the fact that there is a tendency to ignore radar records where only a small number of strokes is observed, i.e. 2 or 3. The short duration record gives the impression that weaker signals may be missing due to the possibility of the discharge being partially off-beam, whereas when more strokes are observed it is assumed that the discharge was well within the coverage horizontally. However, as the received noise power is expected to be proportional to range\textsuperscript{43} (according to Marshall\textsuperscript{45} the received echo power is proportional to range), the ratio of noise burst to echoes observed for any equipment is a function of range and, therefore, no simple conclusion can be drawn regarding this at this stage.

### 11.7 Origin of Radio Noise at Frequencies Used in Radar Observation

Hewitt’s information\textsuperscript{52} is relatively sparse and not very conclusive. Atlas\textsuperscript{34,49} observed that 4 out of 9 spherics originated near the storm top, suggestive of a restricted altitude zone for each (the ice crystal region appears to be preferred). He adds that the best spherics appear along a line which just grazes or slightly exceeds the top of the weak precipitation echo, while the lightning echoes usually extend from this region upward.

Hewitt\textsuperscript{52} observed that the deduced height of the source of noise commenced at 12,500 ft approximately for early strokes and ended at 1600 ft, although the radar echoes extended to a maximum height of 30,000 ft.

### 11.8 Cloud Flashes

These are the sources of relatively strong and long duration bursts of radio noise at 600 MHz. As the cloud flash mechanism has a strong similarity to that of stepped leaders, Hewitt\textsuperscript{52} suggests that the noise from cloud flashes is associated with the development of the streamers in the cloud flash.
12 Millimetre Wave Atmospherics

Although the millimetre waveband covers the frequency range of 30-300 GHz, from practical considerations the range has been extended to cover a wider band of 18-400 GHz. Atmospherics at millimetre waves are in general, too weak to interfere with the most sensitive receiving system. However, on certain occasions, peculiar noise spikes associated with electrical discharges within the cloud have been observed at Calcutta in radiometric receivers operating at 22.235 and 94 GHz bands. Typical records obtained are shown in Figs 3 and 4. The sensitivities of

Fig. 3—Typical records of noise spikes associated with electrical discharges at the operating frequency of 22.235 GHz

Fig. 4—Same as Fig. 3 but for operating frequency of 94 GHz
the radiometers are 1 K and 5 K, respectively, at 22.235 and 94 GHz bands. Why some clouds radiate such spiky millimetre wave atmospherics, while most of the other electrically active clouds are relatively quiet at millimetre waves, is a question of great significance in the understanding of the mechanism of generation of the millimetre wave atmospherics. Further studies in this direction are in progress at the Institute of Radio Physics and Electronics, University of Calcutta, the results of which will be reported in due course.

Besides the atmospherics, millimetre wave radiometers also show the increase of random emission noise from the clouds crossing their antenna beams. Some of the results obtained in UK and at Calcutta are shown in Figs 5 and 6. The UK results (Fig. 5) obtained at 22.95 and 123 GHz bands clearly indicate that an enormous increase of the antenna temperature during a cumulonimbus thundercloud development is more prominent at the higher millimetre wave frequencies. Observations at Calcutta also show a similar trend during the cumulonimbus thundercloud development, as shown in Fig. 6. It is interesting to note that no spiky noise associated with discharges
within the cloud is noticeable in the record, although it is certain that a large number of cloud flashes occurred during the thundercloud development as noticed by radio receivers at lower frequencies. This suggests that the spiky millimetre wave noise shown in Fig. 4 must be ascribed to some special type of discharges in the cloud having a spectral peak in the millimetre wave bands.

Acknowledgement

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