Current Moments at ELF of Lightning Discharges Associated with a Mature Tropical Hurricane

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Abstract

The mean spectrum of negative polarity 'slow tail' ELF atmospherics received during daytime from the area of a distant mature tropical storm (Hurricane Blanca, August 1966) is presented. The mean amplitude spectrum is used with established attenuation rates to calculate from zero-order mode theory the mean current moment associated with the waveform sources. It is suggested that the waveforms may be greatly controlled by intracloud lightning discharges associated with the degree of vertical development of the hurricane.

1. Introduction

At extremely low-frequencies (ELF) it is necessary to consider only the zero-order mode of propagation in the earth-ionosphere waveguide to describe the radiated electric fields of distant lightning discharges. Thus, electric field measurements of 'slow tail' atmospherics (Liebermann, 1956) provide a mechanism for studying lightning discharge source characteristics at distances of several thousands of kilometers. This, of course, is possible only if the source distance and propagation parameters of the earth-ionosphere waveguide are known along the path from source to receiver.

During the month of August 1966, simultaneous recordings of 'slow tail' vertical and horizontal electric field components were made in a remote area of the Hawaii Volcanoes National Park, Hawaii. The measurements were made using a vertical antenna and a set of orthogonal earth-probes oriented parallel and perpendicular to the local geomagnetic meridian. The detailed description of the instrumentation and method of source location has been reported elsewhere (Hughes. 1967). The system voltage transfer functions are shown in Figure 1 for the Hawaiian measurements.

Subsequent analysis of the recorded data indicated an area of intense 'sferic' activity located at approximately $\lambda 120°W$; $L22°N$. An examination of synoptic meteorological data indicated that at the times of recording this was the approximate location of a mature tropical storm, Hurricane Blanca. Recordings had been made during the period of local noon on 3, 4 and 5 August 1966 such that the propagation path from the disturbance was under full daytime conditions. A typical example of the 'slow tail' waveforms received from the storm area is shown in Figure 2A. The differences in appearance of the earth-probe signatures and those of the vertical antenna can be attributed mainly to the differences in frequency response of the three systems. There is approximately a 45° phase difference between the vertical electric field in air and the horizontal electric field in the earth,
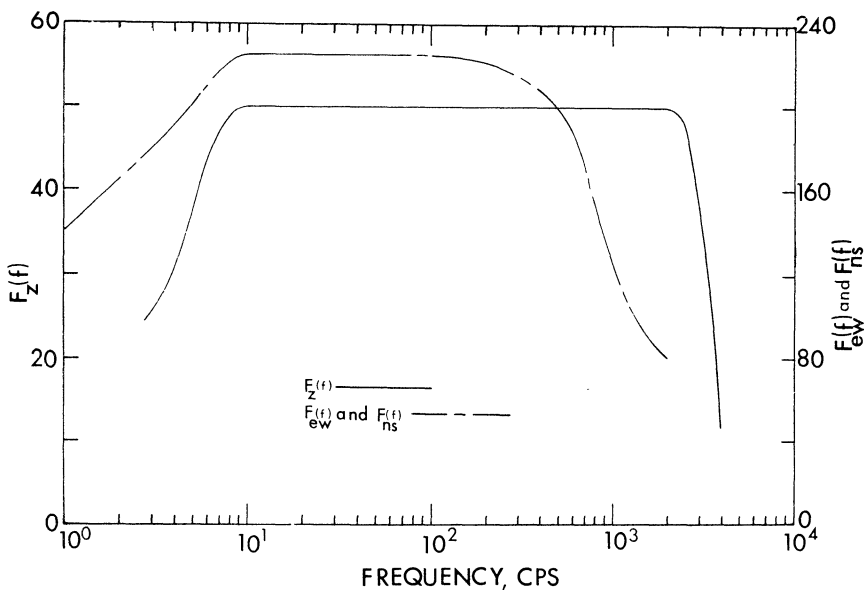
Fig. 1. Voltage transfer functions versus frequency for the vertical antenna system,
$F_Z(f)$, and for the E-W and N-S earth-probe systems, $F_{ew}(f)$ and $F_{ns}(f)$, res-
tively.

Fig. 2. (A) Example of typical negative 'slow tail'
waveforms received from Hurricane Blanca
under daytime conditions. The first and third
traces in each example are the vertical anten-
na signature of the same waveform and the
second and fourth traces are of the E-W and
N-S earth-probe signatures, respectively. In
each case, the horizontal scale represents
time increasing to the right and each major
division corresponds to 2.5 msec. The vertical
scale is the system output voltage and corres-
ponds to 1.0 volt per major division in each
case.
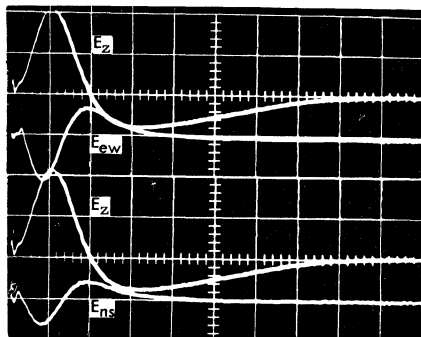
(A)

(B) Approximate locations of the waveform
A with respect to Hurricane Blanca.
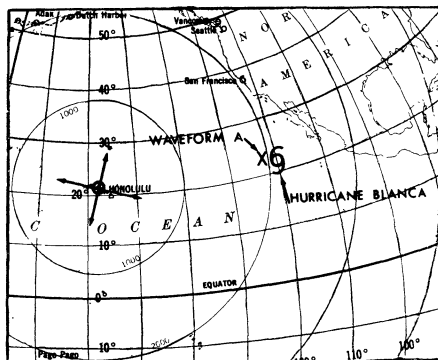
(B)

and the ratio of the frequency spectra of the two components is proportional to the square root of the frequency. These two factors account for some of the differences in appearance of the vertical and horizontal waveforms. The approximate location of the received wave-form with respect to the reported storm position at 0000Z, 4 August 1966 is shown in Figure 2B. The storm location agrees well with the source distance estimated from the rise time of the vertical antenna signature (Wait, 1962) and the bearing estimated from the ratio of the peak amplitude of the earth-probe signatures. Ideally, the source location should have been shown on an azimuthal-equidistance map with the measurement site at the center. The measurement site on the island of Hawaii was approximately 200 nautical miles east of Honolulu, Oahu.

The vertical antenna signature shown in Figure 2A is of negative polarity. The initial portion of 'slow tail' waveforms may be of either positive or negative polarity (Hepburn, 1957; Tepley, 1961). The term 'negative polarity' is here taken to mean that the electric vector of the initial portion of the waveform is directed downward at the receiving antenna and 'positive polarity' means that the electric vector of the initial portion of the waveform is directed upward. At ELF, the change in phase upon reflection at the boundaries of the earth-ionosphere waveguide is small and the spectral components of the 'slow tail' move down the waveguide in an almost coherent fashion. The initial portion of the waveform has a polarity in the direction of current flow in the lightning discharge and this polarity does not change during propagation (within the distance under consideration) through the waveguide. Because of the dispersive properties of the waveguide only the rise time, am-plitude and duration of the pulse change as the distance to the source increases.

Tepley (1961) and Hepburn (1957) have suggested that the 'slow tails' of positive polari-ty have their origin in the return stroke to cloud of a cloud-ground (CG) discharge and Tepley (1961) has suggested that the 'slow tails' of negative polarity are caused by intra-cloud (IC) discharges which result from the transfer of positive charge at the top of a cloud to its base. However, an attempt to identify from elementary theory the positive waveforms with CG flashes and the negative waveforms with IC flashes can be misleading. From studies of the 'fine structure' of lightning discharges, Brook and Kitagawa (1960) point out the possibility that the K-changes (generated when an advancing junction streamer en-counters a region of minor charge concentration) of a lightning discharge contribute con-siderable energy to the radiated field at ELF. K-changes occur for both IC and CG dis-charges and can be both positive and negative polarity. There is some evidence that the total field change is actually the integrated sum of the individual K-changes (Kitagawa and Brook, 1960). However, from the correlations of near field measurements and visual obser-vations of lightning discharges (Bruce and Golde, 1941; Ishikawa, 1961; Müller-Hillebrand, 1963; Pierce, 1955; Smith, 1957) it must be concluded that 5 percent of CG flashes and 20 percent of IC flashes do not follow the elementary rule for the direction of current flow.

During the measurement period, the waveforms received from the storm area were predominately of negative polarity. It is estimated that the number of negative waveforms exceeded the number of positive waveforms by at least one order of magnitude. The number

of positive waveforms from frontal and convective thunderstorm activity may be expected to be greater than the number of negative waveforms by a factor of 2 or 3 (Hepburn, 1957; Pierce, 1955). It is possible, however, that the data of Hepburn (1957) may have also included waveforms of hurricane origin. A positive statement cannot be made at this time as to the origin of the waveforms analyzed in this paper. However, the degree of vertical development of a hurricane can be great and the intracloud activity can be expected to be intense. It is therefore highly probable that the negative waveforms reported on in this paper are associated with intracloud type lightning discharges.

2. Data Analysis

25 waveforms of negative polarity emanating from the area of Hurricane Blanca were analyzed from data recorded around local noon on 4 August 1966. The mean rise time and duration of the sampled daytime waveforms was 2.2 and 21.3 msec with standard deviations of 0.37 and 1.4 msec, respectively. The peak amplitudes of the various waveforms were between 3 and 30 mv/m.

The vertical antenna system output voltage, $V(t)$, for each waveform was sampled at a time interval, Δt, of 0.25 msec. The frequency content of each waveform was then determined by numerical evaluation of the complex Fourier transform equation given by

$$\left.\begin{aligned} E(f) &= \int_0^\infty \frac{V(t)}{F_z(f)l} e^{-i2\pi f t} dt \\ &\cong \sum_{n=0}^{\tau/\Delta t} \left[\frac{V(n\Delta t) + V[(n+1)\Delta t]}{2F_z(f)l} e^{-i2\pi f\left(n+\frac{1}{2}\right)\Delta t} \right] \Delta t. \end{aligned}\right\} \qquad (1)$$

$F_z(f)$ is the vertical antenna system voltage transfer function, l is the effective half-length
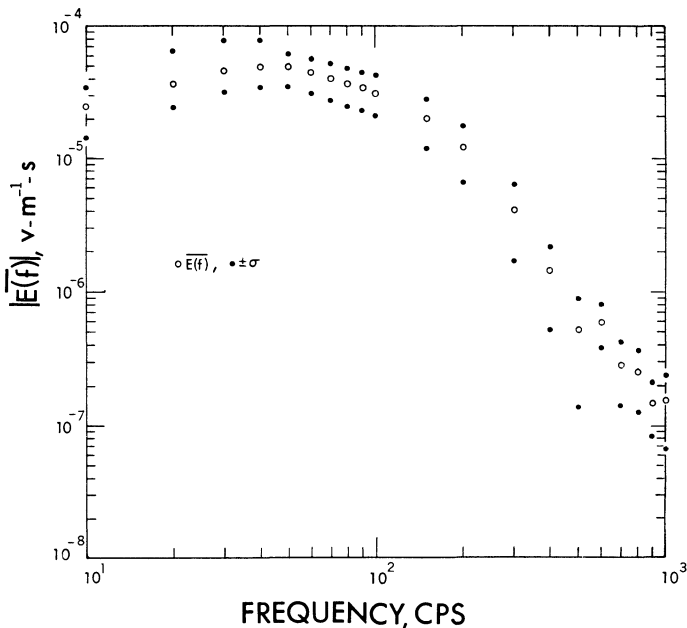

Fig. 3.   The mean amplitude spectrum of the waveforms emanating from the area of Hurricane Blanca.

of the antenna, τ is the duration of the waveform and f is the frequency. The spectrum of each waveform was then used to synthesize the sampled waveforms by means of the inverse Fourier transform. Truncation errors in sampling the waveforms were found to be small since the synthesized waveforms differed from the sampled waveforms by negligible amounts. Figure 3 shows the mean value $|\overline{E(f)}|$ and standard deviation σ of the 25 unsmoothed spectra. The form of the mean spectrum in Figure 3 would be expected from zero-order mode theory assuming a realistic (electron) ionosphere (Galejs, 1966; Wait, 1962).

3. Formulation of Current Moment

The modulus of the frequency spectrum of the received vertical electric field, $|E(f)|$, is related to the modulus of the current moment, $|Ids(f)|$, by the expression for the zero-order mode (Wait, 1962)

$$|E(f)| = \frac{\eta \sqrt{f}}{4\pi h \sqrt{\rho c}} |Ids(f)| \cdot |S_0(f)|^{3/2} e^{-\alpha(f)\rho} \qquad (2)$$

where η is the impedance of free space, h is the effective height of the ionosphere, c is the free space speed of light, f is the wave frequency, ρ is the distance to the source, $\alpha(f)$ is the attenuation per unit distance and $S_0(f)$ is the sine of the complex angle of incidence on the lower ionosphere given by

$$S_0(f) \cong 1 - \frac{i^{3/2}c}{2^{3/2}h\sqrt{\pi f \omega_r}} \qquad (3)$$

where $\omega_r = \omega_0^2/\upsilon$ in terms of the plasma frequency ω_0 and electron collision frequency υ. The expression for $|E(f)|$ is valid in regions corresponding to the radiation field of the source. From the experimental data of Hepburn (1957), Wait (1962) deduced values of ω_r and h for daytime conditions of 1.2×10^5 sec^{-1} and 70 km, respectively. Using these values, $|S_0(f)|$ can be determined from equation 3. The mean current moment of the waveform sources is then computed from equation 2 using the values of $|\overline{E(f)}|$ shown in Figure 3. A source distance to Hurricane Blanca of 3500 km and the measured daytime attenuation rates of Chapman and Macario (1956) were used in the calculations. Figure 4 shows the spectrum of the mean current moment for the frequency range of 100 c/s to 1000 c/s. Data are not presented below 100 c/s because this is the lower limit of the Chapman and Macario attenuation
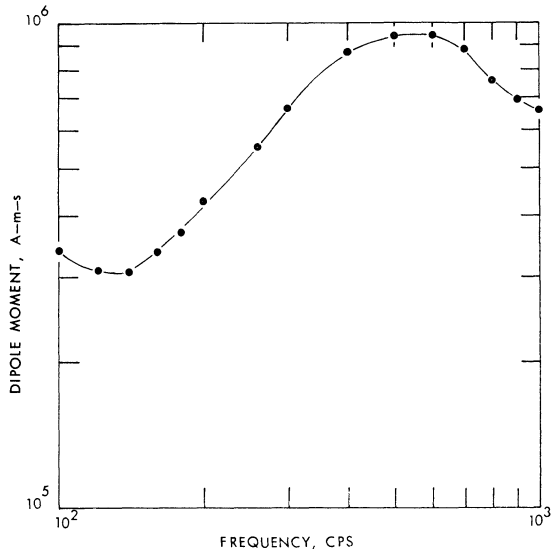

Fig. 4. The mean current dipole moment versus frequency.

rates.

4. Discussion

Information concerning measurements of lightning discharge current moments below 1 kc/s is scarce in the published literature. However, assuming free-space radiation, Galejs (1967) has transformed the current of williams (1958) (derived from VLF radiation field measurements) to obtain an expression for the current moment of a median lightning flash (also see Raemer, 1961). Only the waveform signatures of large amplitude lightning discharges are apt to be received above background noise at a large distance from the source, and the current moment of Galejs (1967) is not of sufficient amplitude to explain the waveforms presented here (private communication, Janis Galejs). The current moment of Galejs had to be increased approximately 40 dB over the frequency range from 100 c/s to 1 kc/s to reasonably predict the measured field strengths using the attenuation rates of Chapman and Macario (1956). At a frequency of 10 c/s the calculated current moment of Galejs is approximately 20 dB lower than the mean current moment determined by Rycroft (1965) from electric field measurements of the earth-ionosphere cavity resonances. Also, at VLF the radiation fields calculated by Galejs using his mean current moment were approximately 26 dB lower than the radiation field measurements of Taylor (1960).

The current moment shown in Figure 4 cannot be interpreted as being representative of the median of all lightning flashes, but only as the mean current moment responsible for the waveforms analyzed here. The waveforms analyzed here may be associated with intracloud discharges in Hurricane Blanca; and the large values of the current moment in Figure 4 may possibly be due to the exceptionally long discharge channel length associated with the vertical development of the storm. The present technique of source location does not allow sufficient range resolution to determine if the waveforms emanated from the storm periphery or the regions of intense winds. However, the waveforms were received during the mature stage of the hurricane.

5. References

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