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Measuring lightning-induced ionospheric effects with incoherent scatter radar or with cross-modulation

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Abstract

Measurements have been made of the ionosphere during lightning storms using the incoherent scatter radar at Arecibo, Puerto Rico. Attempts were made to detect the expected increases in the D-region electron number densities, and possible changes in the plasma line echoes in the F-region. No D-region density changes were detected, to a limit of under 200/cc. This upper limit on possible lightning-induced ionization is not necessarily in conflict with predictions, which are of the same order as this limit and depend on assumptions of the strength and duration of the lightning. Spectral plasma line measurements of the incoherent scatter in the F-region, which are a sensitive indication of E-field variations also did not show any changes associated with individual lightning strikes. An alternative method of searching for D-region changes due to lightning is a cross-modulation or riometer experiment, which is modeled here. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

This paper contains the results of an attempt to measure the effects of lightning on the ionosphere using an incoherent scatter (IS) radar. Additionally, calculations of an alternative method using a cross-modulation or riometer technique are presented, and we speculate that this method may be more sensitive to D-region effects from lightning than the IS radar has proven to be.

The experiment was performed at the Arecibo Observatory in Puerto Rico in the autumn of 1994 during the monsoon rain season. Significant thunderstorm activity was present on several occasions while the radar was operating. We ran two special programs employing both IS echo mechanisms—the ion line and the plasma line. These programs were designed to determine if there were any measurable transient effects in the ionosphere associated with lightning. Usually, the ionospheric radar data is averaged over many seconds to improve the statistical accuracy of the results. This is the proper strategy when attempting to improve estimates of slowly varying geophysical quantities derived from the measurements. Here, we used little or no averaging to attempt to detect lightning-induced transients.

Lightning flashes have duration of typically 1 s, With each flash containing several strokes of duration under 1 ms (Uman, 1969). The effects on the ionosphere from these very intense and impulsive stimuli are also expected to be brief, with large D-region increases in electron temperatures and small changes in electron number density. Inan et al. (1991) and Rodriguez et al. (1992) have shown that heating and ionization due to lightning can be significant in the nighttime D-region.

2. D-region investigations

The duration of the postulated increased electron number density caused by lightning EMPs is many seconds to minutes. For daytime conditions, predictions (Taranenko, 1993) show that only minimal energy is deposited below about 60 km, while at night, larger depositions at altitudes up to nearly 100 km is possible. However, the IS radars cannot routinely detect ionization below 80 km

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at night, except for occasional narrow layers. Hence early evening is the best time to secure conditions favorable to detecting effects and, fortunately, the afternoon monsoon storms often extend into the early evening.

The IS radar at Arecibo was configured to make D-region density measurements using either 40 μs uncoded or 52 μs Barker-coded pulses. The integration time used was 0.25 s or 2 s, which is significantly less than the density relaxation times expected. Measurements were made in the afternoon, early evening, and nighttime during heavy lightning conditions. Frequently, the strongest echoes at slant ranges corresponding to the D-region were aircraft, and these could be distinguished by their change in range with time on intensity vs time and range gray-scale plots. No changes in electron number density profiles were detected due to the lightning strikes on these plots. During the best conditions which occurred on two days between 18.00 and 21.00 local time, the sensitivity was 100 to 200 cm^{-3} that is, any abrupt increase of that magnitude due to lightning would have been detectable. This sensitivity was reached by integrating over several seconds and several kilometers.

If lightning flashes often occur in the nighttime and produce increased ionization, then there may be little chance for a decay in ionization before the next flash occurs. Therefore, a slight accumulated density buildup from many flashes may occur, resulting in absorption of electromagnetic energy at lower altitudes than those associated with the initial strike (Taranenko, 1993; and Taranenko et al., 1993). Also depletions of density can occur due to changes in attachment rates at altitudes near 80 km, below where the more significant increases are predicted to occur at 90 km. While these predicted density changes are of the order 100% of the ambient, since the nighttime ambient density is likely to be well under 1000 cm^{-3} at 90 km, the difficulty of measuring these changes with the radar is considerable.

The lightning on the island of Puerto Rico in the late summer is due to tropical monsoon conditions. The lightning strikes are impressive, yet they are not as large as the mesoscale convective storms in the continental US, which produce induced changes in VLF propagation and blue jets, red sprites, and elves. The highest cloud top recorded at the San Juan weather radar was 41 kft, and the tops were usually under 33 kft, which is less than for the continental storms which can reach to 60 kft (Uman, 1969).

An effort was made to detect the Puerto Rican sferics at Stanford's VLF receiver at Palmer Station, Antarctica. Simultaneous VLF records from the observatory and Palmer were inspected over many minutes on two days when strong local storms occurred. The Palmer data routinely contain sferics from continental storms, but the island sferics were not detectable, possibly because the Puerto Rican storms are weaker than the continental storms.

3. F-region investigations

Strong electric fields and superthermal ions or electrons from lightning are thought to penetrate to the F-region. The evidence for such penetration was provided by Kelley et al. (1990), Bell et al. (1993), and Burke et al. (1992). The superthermal particles would be expected to influence the strength of Langmuir waves producing the plasma line echoes, and to last longer than the short, 1 ms duration of the impulsive E-fields.

F-region measurements using a lightning-triggered spectral plasma line program were taken on many occasions. Because it was impractical to record all the non-integrated spectral data over several hours of observations, groups of 225 IPPs (data from each Inter Pulse Period) were saved around a lightning trigger. The program used a thresholded VLF receiver output to trigger the saving of data from 0.5 s before to 4 s after the threshold event. Up- and down-shifted plasma line spectra were collected in a 5 MHz span offset by roughly f_0F_2 above and below the 430 MHz radar frequency.

An example of a triggered group of plasma line spectra is presented in Fig. 1. The vertical axis is time running downward, with the trigger event appearing in IPP #26, followed by 5 more sferics, the last of which is at IPP #75, one second later. The strongest sferic at IPP#57 goes off scale by a factor of 4. The sferics were measured at 426 MHz. The upshifted plasma line spectra is given as an instantaneous gray scale and as a summary line plot. Only 120 kHZ of the spectra is shown, and the cutoff edge [for explanation see Showen (1979)] is near the f_0F_2 of 6.3 MHz. The gray scale shows a speckled variability matching the averaged spectra shape and showing the effect of the strong contamination in time by the sferics. Except for this sferic contamination, no amplitude effects from lightning are visible.

An additional test made of a potential change due to lightning in the difference of the up- and down-shifted cutoff frequencies—the up-down asymmetry [Showen (1979)]. The asymmetry is directly related to the bulk velocity of the electrons as well as more weakly to the photoelectron distribution function (Showen, 1995). The electron velocities are in turn related to the average E-field present at the peak of the F-layer. This in turn could be related to the unbalanced charge distributions of the thunderstorm clouds underneath the ionosphere. When the cloud charging builds up, the far field E-field may slowly change and upon a lightning strike, the pre-and post-strike charge distributions will also be different. Both of these effects were potential observables, and might have been expected to be visible in the asymmetry.

The asymmetry can be measured to a fraction of the frequency resolution of the plasma line spectra if the cutoff edge is sharply defined, has a strong SNR, and is averaged over many IPPs. In the best case investigated, 10 groups were processed, with the 225 IPPs averaged

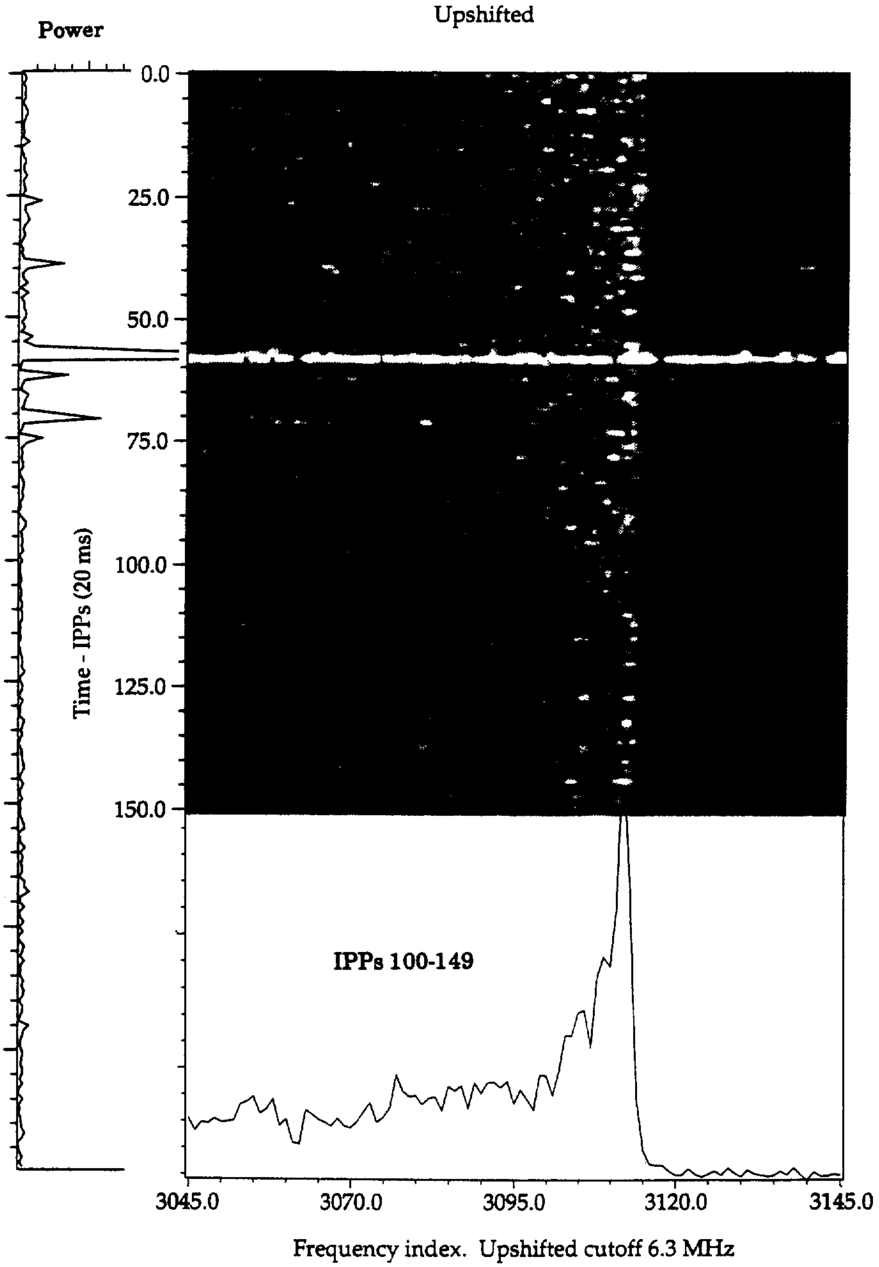

Fig. 1. Illustration of plasma line power near the F-region peak during a lightning flash. The vertical axis is time progressing downwards in units of 20 ms radar pulse periods. Lightning strokes occurred beginning at IPP #26 and continuing until #75. The horizontal axis is an upshifted-frequency span of 120 kHz near 436.3 MHz, the sum of the radar frequency plus f_0F_2. The gray-scale shows sferic contamination, but no changes in the spectra data due to the lightning. Comparison of up- vs down-shifted cutoff asymmetries shows that they are constant to within 100 Hz before and after the lightning.

over 5 IPPs, to give 5 pre- and 40 post-integrated samples. Looking at the groups individually and collectively, there is no pre- to post-lightning variation in the asymmetry value of 1.1 ± 0.1 kHz. Showen's eqn (6) (1979) shows the relation between the asymmetry ∂f, (kHz) the radial electron velocity Ve, (m/s) and temperature Te: $\partial f = 5.733Ve - 0.869Te$. If we assume that the uncertainty in ∂f is due to an uncertainty in Ve, the 100 Hz uncertainty in the above asymmetry sets an upper limit on the Ve of 17 m/s due to a possible impressed difference by the static E-field. Since the plasma drift velocity is $Vd = |ExB|/B^2$, the change in steady state E-field before and after the lightning strikes is less than 1 mV/m at the F-region peak, assuming the curl of E and B is not orthogonal to the vertical radar beam.

No lightning effects were noted on any of the more than 20 groups inspected which had strong sferics and strong, uncontaminated cutoffs.

4. Cross-modulation and riometer experiments

An assessment has been made of an alternate method to observe ionospheric D-region changes due to lightning. Cross-modulation takes advantage of the fact that while lightning-generated E-fields produce only a small change in number density, they produce enormous changes in electron temperature. That increased electron temperature elevates the local electron collision frequency and hence the absorption of radio waves. A practical problem is that the temperature changes last an exceedingly short time, from 10 μs to a few ms at altitudes between 60 km and 100 km. The sferics produced by the lightning at the received frequency need to be short enough or weak enough to not overlap the short-lived absorptive effect due to the increased temperatures.

Two types of wave interaction experiments are proposed—the first uses a radio wave propagating through the D-region, while the second uses down coming celestial radio noise in a riometer-type measurement. Both types would use the lowest practicable frequency, as the absorptive effect scales as f^{-2}. The former method could use terrestrial radio sources of opportunity or dedicated radio links. An example of a dedicated experiment would use a few continuous wave HF transmitters separated far enough from a central receiver site so that ground-wave propagation would not interfere with sky waves reflecting off the E- or F- region. The first cross-modulation experiment was done by Fejer (1955), and the presently proposed experiment would use E-fields from lightning to heat the D-region instead of a 'disturbing wave'.

To make these calculations, a model of the lower ionospheric parameters and an energy deposition formalism is needed. The model and formalism selected is that used in Showen (1972) which successfully calculated the magnitude of the temperature rise and the decay time constants in an artificial heating experiment.

Two results are presented here in Fig. 2. The top panel gives the expected fractional absorption of a 5 MHz wave making a double pass through the D- and E-regions due to E-field pulse from a lightning strike producing at least a 10 times change of ambient temperature at 60 km in the daytime. The absorption calculation uses the eqns on page 214 of Davies (1990). The decay time begins at 0.4 ms, giving time for the heating effects to reach an altitude of 60 km before becoming effective.

The absorption model presented above can be checked with results from an experiment conducted in 1963 at the Jicamarca Observatory. The bottom panel of Fig. 2 reproduces a figure from Klemperer (1963) using the 50 MHz (Mc/s) main radar transmitter to cross-modulate the cosmic noise. The points correspond to the recovery of the sky noise after the transmission of a 3 ms 4 MW pulse. (the first 4 points of the original figure have been removed, as they correspond to recovery after the main pulse (R. Woodman, private communication, 1995), and because the riometer effects could not begin to occur until the pulse arrives at ~ 60 km.) The experiment was run with a receiver bandwidth of 2 MHz, and the IS returns were filtered out. The solid line is the calculated absorption, with the curve normalized to give the sky noise at 20 ms, and offset in time by 0.4 ms. The model is quantized in 10 km steps, and the thermal relaxation times are hence also quantized, with the longest being 1, 10, 20 and 40 ms. These superimposed time scales can be faintly recognized in the curve.

The amount of absorption is surprisingly independent of the amount of heating if the heating is over 10 times ambient, as is expected from Inan et al. (1991) for a variety of lightning strengths. That is, for lightning which causes either 10 × or 100 × electron heating, the absorption effects will be similar after waiting 0.5 ms to begin observations.

Comparing the two panels of Fig. 2, we note that the fractional absorption of 50 MHz is 0.57%, and is 50% at 5 MHz, due mostly to the ratio of the received frequencies. Klemperer (1963) also reported cross-modulation experiment using a 3 MHz 'wanted wave' and the Jicamarca 50 MHz transmitter at half power which attained up to 25% induced amplitude change. If the contaminating sferic duration would be under 2 ms, either type of cross-modulation experiment—riometer or 'wanted wave' absorption—should be feasible.

5. Conclusion

Unfortunately, no evidence of lightning-induced effects in the ionosphere was seen in the September and October 1994 measurements at Arecibo Those measurements were conclusive for potential transient changes in the D-region density and spectral plasma line data at the F-region peak. We were not able to check for the potential effects of longer term variability as storms moved closer or further away from the observatory. We were also not able to run the coded long pulse technique (Djuth et al., 1994) during times of both strong lighting and strong plasma lines, in order to obtain a test of possible plasma line effects below the F-region peak. A better examination of this possibility is the most important unfinished experimental task in order to be able to make a more definitive conclusion.

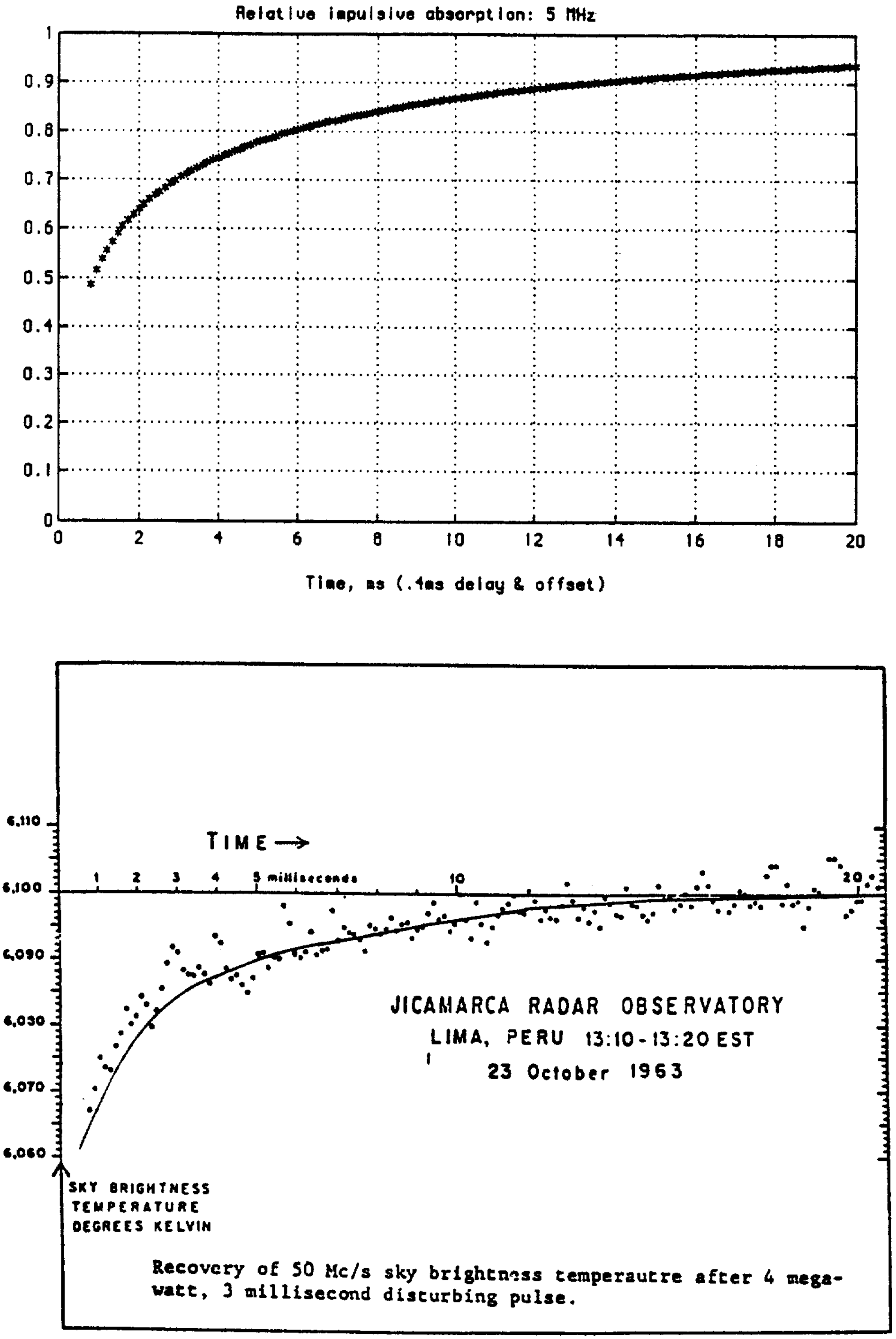

Fig. 2. D-region absorption effects on propagation after radio wave heating. Top panel shows expected absorption of 5 MHz wave after a lightning EMP heats the lower ionosphere. The relaxation of the absorption is longer than the expected sferic durations of 1 ms, so this effect might be monitored in a cross-modulation experiment using lightning EMP as the 'wanted wave'. The bottom panel shows a comparison of old data and the present model of the recovery of cosmic radio noise after a strong 50 MHz radar pulse.

There should be further attempts to measure the effects of lightning on ionospheric densities, beyond the radar work reported by R. Tsunoda (private communication, 1996), and K. Groves (private communication, 1996). Tsunoda claims radar detection of lightning-induced events at 27 MHz at a range of 600 km or more, in line with the results of Rumi (1955), but there is no optical confirmation that these are related to sprites. Groves has made radar experiments at 28 MHz, with no detectable ionization changes under ideal lightning conditions simultaneous with known optical emissions or positive-to-ground lightning strikes.

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