The Potential for Remote Sensing of a Tornado Vortex

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ABSTRACT

Plasma has a unique characteristic that can be detected remotely. If there is such a plasma at the interior of the tornado's vortex, then there exists a new method of tornado detection.

1. Introduction

For centuries starting with Lucretius (60 B.C.) observers have hypothesized an electrical force connected in some way with tornadoes. The numerous eyewitness accounts that report unusual electrical activity coinciding with the appearance of a tornado seem to support this hypothesis. However, because of a lack of good scientific data there is still some debate over this phenomenon. This paper presents a method for obtaining this needed data if the phenomenon does actually exist.

2. Plasma model

Colgate (1968) asserts that because of the reduced atmospheric pressure at the interior of the tornado, the atmospheric electrical breakdown potential is reduced by a factor of 4. Under these conditions the tornado becomes the preferred breakdown path for cloud to ground electrical discharges. Assuming this actually happens, we can then hypothesize the existence of a plasma column due to the continuing electrical discharges.

Colgate (1967) argues for such a plasma column and Vonnegut (1960) reports some eyewitness accounts of plasma within the tornado's vortex. Assuming this plasma column is a nominal cylinder of 1 km in height and 25 m radius gives a volume of

$$V = h\pi r^2 \approx 2 \times 10^{12}\ \text{cm}^3. \qquad (1)$$

From Brook (1967) we can assume an average current flow of 225 A. Computing the plasma's average electron density gives

$$N_{\text{av}} = \frac{QA}{V} = 7 \times 10^8\ \text{electrons cm}^{-3}. \qquad (2)$$

Since few atmospheric objects have abrupt boundaries, it seems reasonable to give this plasma model a nonuniform electron density distribution. Choosing a normal distribution within this cylinder gives

$$n = N_0 e^{-(2R/R_0)^2}, \qquad (3)$$

where R_0 is the radius of the model and N_0 the axial (at $R = 0$ m) electron density. The average value of the function $Y = e^{-x^2}$ is $y = 0.43$ at $x = 0.92$. Substituting these values and the average electron density into Eq. (3), gives N_0 a value of 1.66×10^{10} electrons cm^{-3}. From Tonks and Langmuir (1929) the plasma resonance frequency is

$$f_p \approx (9 \times 10^3) n^{1/2}. \qquad (4)$$

Using Eqs. (3) and (4) at the longitudinal axis of this vertical cylinder gives a resonance frequency of $f_p = 1160$ MHz. Beyond the edge of this model where the plasma is immersed in the tornado ($R = 27$ m) the resonance frequency is $f_p \approx 110$ MHz. Thus, we have a somewhat arbitrary plasma model that has an electron density gradient and whose outer surface is coupled to the mechanical movement of the tornado.

3. Observational method

Now we face the question of how to collect data from this model that has these two features. Fortunately, Stern (1965) has shown that at the plasma resonance frequency there exist strong nonlinear effects due to the close coupling between an incident electromagnetic wave and the plasma. He observed the second harmonic frequency of an electromagnetic wave incident on a bounded plasma column at its resonance frequency. Under the same conditions he also observed the mixing (summing) of two incident frequencies.

Fig. 1 (from Stern, 1965) shows the dependence of second-harmonic power on the incident power at resonance. The approximate dependence is

$$P_{\text{2nd}} \approx P_i^2 (5 \times 10^{-12})\ \text{mW}. \qquad (5)$$

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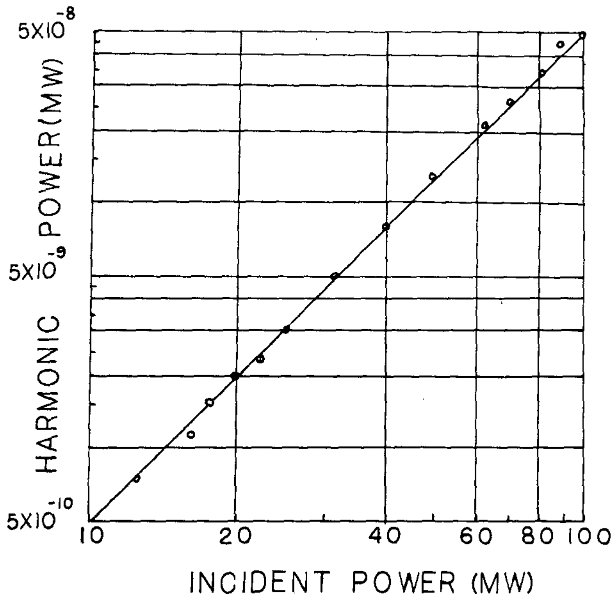

FIG. 1. The dependence of the second-harmonic power on the incident power at resonance.

The conversion efficiency is remarkably low but the resultant second harmonic power can still be detected using currently available techniques and hardware as shown in the Appendix.

The model has an electron density gradient and hence a resonance frequency gradient. Thus, an electromagnetic wave whose frequency is less than 1160 MHz will propagate into the plasma column until it reaches a point in the electron density gradient where the plasma frequency equals its frequency. At this point the second harmonic is generated and the remaining energy is reflected. A quasi-dual-wavelength radar can be used to generate the transmitted signal, receive the second harmonic return, and provide the range and azimuth. Provisions would have to be made to insure the spectral purity of the transmitted signal. The actual density gradient can be determined by increasing the transmitted frequency each successive pulse over the estimated resonance frequency limits. Taking magnetometer measurements at the same time and then calculating the average current following Brook (1967) will allow the calculation of the physical size of the plasma column.

4. Excess rf emissions

The plasma model also assumes a mechanical coupling between the tornado and the plasma boundary. This coupling could generate plasma space charge or electromechanical waves as described by Heald and Wharton (1965). The upper limit of the frequency radiated by the model due to this effect is

$$f_{co} = f_p/(1 + K_D)^{1/2}, \quad (6)$$

where K_D is the relative dielectric constant of the medium. Thus, at a radius of 27 m, f_p is ~110 MHz and the cutoff frequency of the radio emission is close to 80 MHz, for $K_D \approx 1$. This frequency lies very close to channel 5 in the TV broadcast band. Various popular magazines have published articles on using a TV set as a tornado detector and the radio emissions generated by the space charge waves at the plasma boundary could be the source of these TV signals. Low-level rf measurements will provide data on the frequency spectra of the tornado's excess radio emissions.

5. Conclusion

If there is a plasma column in the interior of a tornado there is a method for its positive detection by using the unique plasma characteristic of frequency multiplication (and mixing) at its electron resonance frequency.

This method will also detect the plasma sheath surrounding lightning strokes but the plasma density gradient should differ somewhat from that found in a tornado.

APPENDIX

Radar Detection Range

The familiar radar equation

$$P_r = \left(\frac{P_t G_t}{4\pi R^2}\right)\left(\frac{\sigma}{4\pi R^2}\right)A_r \quad (A1)$$

can be rearranged into the maximum range equation

$$R^4_{\max} = \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 k T_s B_n L (S/N)_{\min}}, \quad (A2)$$

where

$$G_t = \frac{4\pi A_r}{\lambda^2},$$

$$P_r = (S/N) k T_s B_n.$$

The conversion loss is

$$L = \frac{P_i}{P_{2nd}}. \quad (A3)$$

Using Eq. (5) gives

$$L = \alpha^2 \frac{P_n}{P_i} 2 \times 10^{11}, \quad (A4)$$

where P_n is a normalization factor and α is the real part of the propagation coefficient $\gamma = \alpha + j\beta$.

The incident power at the plasma column is

$$P_i = \frac{P_t G_t}{4\pi R^2}. \quad (A5)$$

Using (A5) in A3, the conversion loss then becomes

$$L = \left(\frac{4\pi R^2}{P_t G_t}\right)\alpha^2(0.688 \times 10^{11}). \quad \text{(A6)}$$

Substituting (A6) into the maximum range equation gives

$$R_{\max} = \left[\frac{P_t^2 G_t^3 \lambda^2 \sigma}{(4\pi)^4 k T_s B_n \alpha^2 (6.88 \times 10^{10})(\mathrm{S/N})_{\min}}\right]^{1/6} \quad \text{(A7)}$$

or

$$R_{\max} = 80\left[\frac{P_t^2 G_t^3 \sigma}{f^2 T_s B_n \alpha^2 (\mathrm{S/N})_{\min}(6.88 \times 10^{10})}\right]^{1/6} \text{km}, \quad \text{(A8)}$$

where P_t is peak power (kW), f is frequency (MHz), T_s is temperature (K) and B_n is the receiver bandwidth (kHz).

The collision frequency as derived by Nicolet (1959) is

$$\gamma_c = 3.5 \times 10^9\, PT^{-1/2}, \quad \text{(A9)}$$

which, for $P = (760/4)$ mm Hg and $T = 300$ K, becomes

$$\gamma_c = 3.8 \times 10^{10}\ \text{Hz}.$$

The attenuation of the electromagnetic wave is given by Drummond (1961) as

$$\alpha = \frac{\omega}{c}\left\{-\frac{1}{2}\left(1 - \frac{\omega_p^2}{\omega^2 + \gamma_c^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_p^2}{\omega^2 + \gamma_c^2}\right)^2 + \left(\frac{\omega_p^2}{\omega^2 + \gamma_c^2}\frac{\gamma_c}{\omega}\right)^2\right]^{1/2}\right\}^{1/2}. \quad \text{(A10)}$$

For our example we will use the characteristics of the Marconi S670 radar which are

Frequency	610 MHz
Power, peak	500 KW
Power, average	800 W
Antenna gain	32 dB
Pulse width	4 μs.

With a 1.0 rpm antenna scan speed and a Swerling case 3 target characteristics we enter the tables in Skolnick (1970) to arrive at a $(\mathrm{S/N})_{\min}$ of 1.

Using the computed collision frequency and the radar's transmitter frequency in Eq. (A10) gives an attenuation of $\alpha \approx 0.016$ dB m^{-1}. If the distance into the plasma column using Eq. (3) is 14 m for $f_p = 610$ MHz, then $\alpha = 0.224$ dB. Assuming that only the upper half of the plasma column is illuminated, then the cross section is $\sigma \approx 10^4$ m^2. Substituting these computed values and radar parameters into Eq. (A8) gives

$$R_{\max} = 80\left[\frac{(500)^2(1585)^3 10^4}{(610)^2 300(250)(6.88 \times 10^{10})(2.805)}\right]^{1/6} = 28\ \text{km}.$$

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