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Title:

RADIO FREQUENCY OBSERVATIONS OF LIGHTNING DISCHARGES BY THE FORTE SATELLITE

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BY THE FORTE SATELLITE

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ABSTRACT

FORTE-observed VHF signatures for different lightning discharges are presented. For in-cloud discharges, a pulse pair is typically recorded and is named a "transionospheric pulse pair" (TIPP). Many intense TIPPs are coherent and polarized, whereas initial and dart leaders do not show a recognizable degree of polarization. TIPPs are optically weaker than cloud-to-ground (CG) strokes, and stronger VHF TIPPs are optically darker. About 10% of CG strokes, mostly over seawater, produce extremely narrow, powerful VHF pulses at the very beginning of the return strokes. These narrow pulses are found to form an upward beam pattern.

INTRODUCTION

The FORTE (Fast Onboard Recording of Transient Events) satellite was launched on 29 August 1997 and has been in continuous operation since then. FORTE is in a circular, 800-km-altitude orbit inclined 70 degrees from the Earth's equator. FORTE carries a suite of radio-frequency (RF) and optical instruments for the study of lightning. The RF payload comprises (1) a multi-channel-coincidence trigger system, (2) a wideband (300 Megasamples/sec) RF receiver operating in any of three positions within the very-high-frequency (VHF), and (3) a pair of medium-bandwidth (50 Megasamples/sec) simultaneous RF receivers also operating anywhere in the VHF. The RF payload derives its signals from two mutually orthogonal, linear polarization, moderate-gain log-periodic antennas (LPA) on a nadir-directed deployed boom. The optical payload comprises (1) a photodiode detector (PDD) sampling an 80-degree field-of-view (FOV) throughout the visible and near-IR and sampled every 15 microseconds, and (2) a 128 x 128 pixel CCD array imager (LLS) whose square image inscribes the circular PDD FOV, and whose input is the bright narrow-band-filtered line emission at 0.7774 microns wavelength. FORTE has recorded millions of VHF and optical signals produced by lightning discharges since it was launched. In this report, we will present some recent results and will focus mostly on the VHF observations.

OBSERVATIONS AND RESULTS

FORTE VHF Signatures for Cloud-to-Ground (CG) and in-cloud (IC) Discharges

During the summers of 1998 and 1999, cooperative lightning observations were conducted between the FORTE satellite and the National Lightning Detection Network (NLDN) over the contiguous United States [1]. Fig. 1 shows typical FORTE-detected VHF signatures for several different discharge processes, with the types of discharges verified by the time-correlated NLDN observations.

Fig. 1a shows VHF radiation produced by an in-cloud discharge in a spectrogram format. The record is 400 μs long and the RF receiver was tuned to a 26-51 MHz band. The colors indicate the received radiation power in dB scale. The dispersion or chirping of the signal is due to the Earth's ionosphere between the terrestrial source and the satellite. The dispersion is common for all FORTE-detected lightning signals, and the extent of the dispersion is proportional to the total electron content (TEC) the signal traverses [2], as also shown in Fig. 1b, 1c, and 1d. In Fig. 1a there are a pair of similar pulses separated by several tens of microseonds. The first is associated with a signal that travels directly from the source to the satellite and the second is a reflection of the same signal off the Earth's surface. This observational phenomenon was first reported by [3] with our previous Alexis satellite observations and was named as a "transionospheric pulse pair" or a TIPP. In-cloud discharges are commonly observed as TIPPs if the width of the original pulse is narrower than the time separation between the pair. A majority of the FORTE recorded lightning signals are this type. Fig. 1b shows observations for an initial ground stroke in a –CG flash. The return stroke started at 110 μs into the beginning of the record, as marked by the arrow. It is evident that the return stroke produced stronger

VHF radiation than the preceding leader process. The VHF enhancement associated with the initial return stroke agrees with ground-based observations [4,5]. Fig. 1c shows observations for a dart leader to ground. The abrupt absence of VHF radiation after the start of the return stroke is characteristic, and is also consistent with previous ground-based observations. For positive ground strokes, the opposite was observed, as shown in Fig. 1d, in which the arrow indicates the start of the return stroke. There appears to be no detectable radiation associated with the positive leader process (0-100 μs in the record). This again agrees with previous ground-based observations [6].

Detailed analysis of different types of discharges in conjunction with simultaneous onboard optical observations were reported by [7]. Based on the different VHF and optical signatures, it is possible to independently distinguish different types of lightning processes from the FORTE observations.

Polarization Studies of Lightning VHF Signals

With the two orthogonally mounted, nadir-directed, linear LPA antennas, FORTE is able to detect the state of polarization for received signals [8]. Fig. 2 shows such an observation for an in-cloud TIPP event. In this figure, the signal is “de-chirped” before the polarization analysis, according to the nature of the ionospheric VHF propagation. From the signals received by the two antennas, a full set of Stokes parameters are computed. Based on the Stokes parameters, the total power, the degree of polarization, the orientation of the polarization ellipse, the corresponding ellipticity, and the direction of the E-vector rotation can be obtained. Fig. 2a shows the spectrogram for the total received power from the two antennas. Fig. 2b shows the degree of polarization, the ratio of polarized power over the total signal power. As can been seen, each of the TIPP pulses is highly polarized and each shows an unpolarized region at the middle of the pulse. When a VHF signal propagates through the ionosphere, a linear polarization signal will split into two near-circular polarizations with opposite senses of E-vector rotation, i.e., the “ordinary” and “extraordinary” modes. The two modes travel at slightly different group and phase velocities, and results in “mode splitting”. Fig. 2b shows that for each TIPP pulse, both modes are highly polarized. The gap at the middle is due to the incoherent temporal mixing of the two modes. The mode splitting can also been seen from Fig. 1a at frequencies below 35 MHz. Fig. 2d shows the ellipticity of the polarization ellipse in terms of an open angle formed by the minor and the major axes. Zero is for linear polarization and 45° is for circular polarization. The positive and negative signs are associated with clockwise and anticlockwise E-vector rotations, respectively. In the figure, the two opposite modes are clearly detected. Finally, Fig. 2c shows the orientation of the polarization ellipse, as referenced to one of the two linear LPA antennas. Since each mode is nearly circular polarization in this case, the corresponding orientation is not well defined. However, for signals arriving from large nadir angles, the detected polarization will become more elliptical due to the FORTE antennas’ directional responses.

We have studied the polarization properties for hundreds of TIPP events and for many other lightning processes. We found that most narrow TIPPs are highly polarized, indicating that the associated discharge processes are well organized

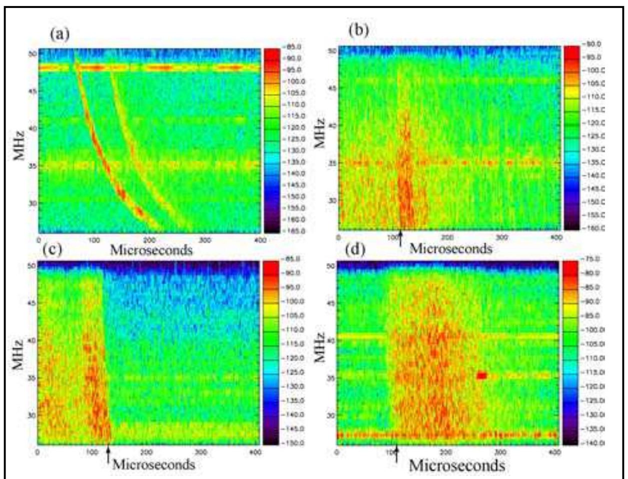

Fig. 1. VHF radiation signatures for (a) in-cloud discharge, (b) negative initial stroke, (c) negative dart leader, and (d) positive stroke.

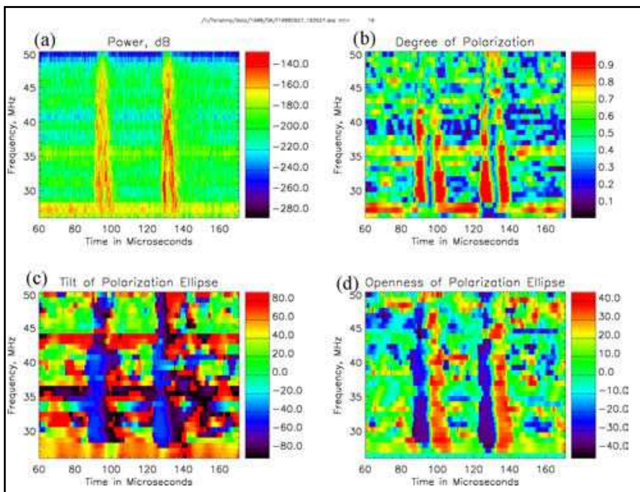

Fig. 2. State of polarization: (a) total power, (b) degree of polarization, (c) ellipse orientation, and (d) ellipse open angle and sense of rotation.

and coherent. On the other hand, leaders of initial and subsequent strokes to ground, as well as of K-changes, are found to be unpolarized.

Comparisons of VHF and Optical Observations

Detailed comparison studies between FORTE-observed VHF and optical signatures were reported by [7, 9, 10], for various types of lightning discharges. We present here very briefly the most recent findings. Fig. 3a shows the percentage of TIPPs and non-TIPPs that have a coincident optical signal, as a function of the peak VHF radiation power. It is evident that for a non-TIPP event, the stronger the VHF peak radiation, the more likely it is to have a coincident optical signal. For TIPP events, the opposite trend is detected, that is, for VHF peak power above 0.1 $(mV)^2/m^2$, it is less likely to have a coincident optical signal for stronger VHF TIPPs. Nevertheless, for VHF power below this threshold, the likelihood of optical coincidence increases roughly the same for TIPPs and non-TIPPs. Also from FORTE observations, it appears that TIPPs are more likely to have stronger VHF radiation than that of non-TIPPs. This, together with Fig. 3a, suggests that in-cloud lightning processes that produce stronger VHF radiation tend to generate weaker optical signals.

Fig. 3b shows the height distribution of the TIPP events (dashed line) and the TIPP events that are coincident with optical signals (solid line). The height for each TIPP is computed based on the time lag between the pulse pair, the longitude and latitude of the source (inferred from NLDN or FORTE LLS), and the instantaneous position of the FORTE satellite [2]. We note the clear optical cutoff for TIPPs below 10 km altitude, perhaps due to cloud scattering and attenuation.

Very Narrow VHF Pulses Associated With Return Strokes

About 10% of FORTE-NLDN detected return strokes contain a very narrow (< 100 ns), powerful, and well-polarized VHF pulse at the very beginning of the stroke. This type of return stroke is more likely to occur over the seawater than over the land, as shown in Fig. 4a. Statistical analysis in terms of probability of detection indicates corresponding VHF radiation beams upward, consistent with a model of current-pulse propagating at a speed close to the speed of light (i.e., with the $[1- v/c \cos\theta]^{-1}$ factor for E field). In Fig. 4b, the red line shows the inferred beam pattern for the narrow return strokes, and the other three thin black lines show the modeled beam patterns for (1) a propagating current pulse in free space, (2) same as (1) but with a simultaneous image source due to the conducting ground, and (3) a conventional dipole, respectively. The inferred beam pattern is obtained by comparing the occurrence of the narrow return strokes to that of all the detected, background events, as a function of the zenith angle. The background events can be treated as having an isotropic radiation pattern. Fig. 4b shows that the narrow return stroke radiation is in favor of the free space model with a propagation speed of 0.6c. This suggests that the radiation source is a few tens of meters above the ground, so that the ground reflection will arrive to the satellite ~100 ns later and the reflected pulse will not contribute constructively to the original pulse.

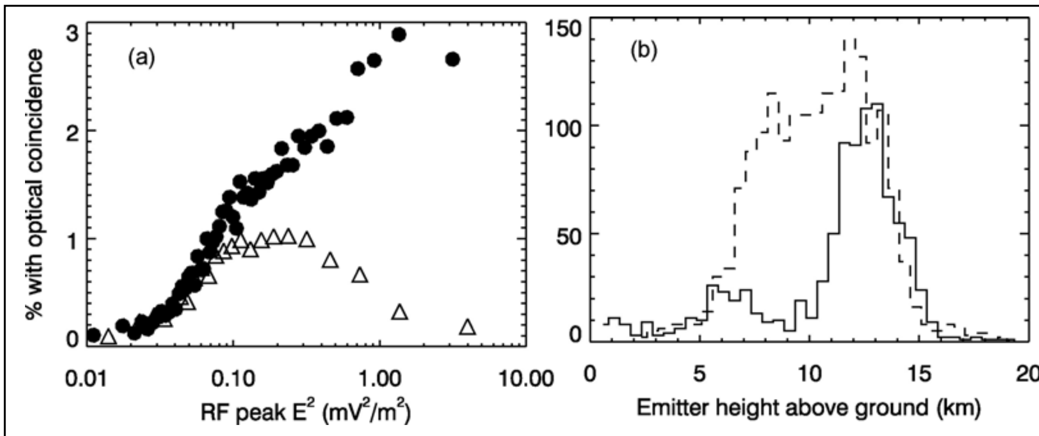

Fig. 3. (a) The percentage of VHF TIPPs (triangles) and non-TIPPs (circles) that have a coincident optical signal, as a fundtion of peak power. (b) Distribution of TIPP height above ground, for the optically-coincident TIPPs (solid) and NLDN-coincident TIPPs (dash).

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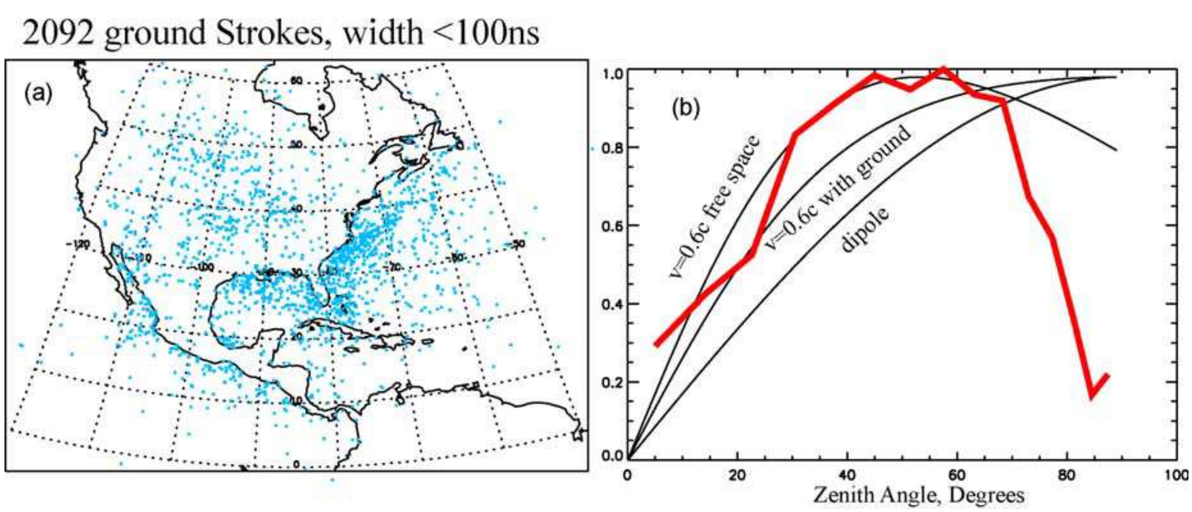

Fig. 4. (a) Locations of ground strokes that produced very norrow (<100 ns), powerful, and well-polarized VHF pulses. (b) Inferred radiation beam pattern of the narrow-pulse return strokes (red), compared with three different modeled beam patterns.