FORTE Satellite Observations of VHF Radiation from Lightning Discharges

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Abstract: The Los Alamos National Laboratory/Sandia National Laboratory FORTE satellite is described and its capabilities for global remote sensing of lightning in the radio regime are described. Some results from 7 years of successful operation are presented. A future global lightning monitoring mission, VGLASS, is described.

Key words: Lightning, remote sensing

1. Introduction

The FORTE (Fast On-orbit Recording of Transient Events) satellite was launched on 29 August, 1997, into a 70° inclination, nearly circular orbit at 800 km altitude. The radio package on the satellite was designed and constructed by Los Alamos National Laboratory. The satellite posseses two linearly polarized, log-periodic dipole array antennas that are orthogonal to each other and lie along the same 10 m-long boom which points to the satellite's nadir. There are three radio receivers on board covering the frequency range 30 to 300 MHz. Two of these are medium bandwidth systems, 22 MHz wide, and are tunable anywhere in the 20–300 MHz range. The third receiver is a wideband system (300 MSamples / sec) which can operate in any of three positions in the available frequency range. Space-based observations of RF emissions from lightning can only be done at frequencies sufficiently high that the signals are not heavily attenuated or very strongly dispersed by the ionosphere.

The signal from each antenna can be fed into a separate broadband receiver. The two medium bandwidth receivers can acquire data coherently using a common reference signal. The FORTE data acquisition system typically captures a waveform record several hundreds of μs long. Usually, this consists of 100 μs of pre-trigger records and 300 μs of post-trigger data. The onboard memory (160 Mbytes) can hold many thousands of events. The data are acquired in two modes: time-triggered or signal-triggered. In the latter mode, the capture is initiated by a trigger which requires coincidence of signals in 5 out of 8 of 1 MHz-wide sub-bands, spaced by 2.5 MHz. The acquired data is digitized at 50 MHz and stored on-board for future download to a ground station at either Los Alamos National Laboratory or at Fairbanks, Alaska. The trigger can re-arm and acquire new data within a few μs. The data records are timestamped to 1 μs accuracy with an on-board GPS clock. Since the satellite orbit lies above most of the ionosphere, the coincidence time window is set to allow for a suitable range of delays due to dispersion in the ionosphere. The trigger threshold levels are adjustable; typically, these are 15–18 dB above the noise floor in each sub-band. The noise floor varies with satellite location. Industrialized regions usually present higher noise levels to the FORTE system.

The system is sensitive to impulsive source on the Earth's surface which are within $\approx$ 3000 km of the subsatellite point. Signals from the Earth's limb are attenuated by the antennas' gain patterns and by the increased range. Consequently, the spatial location of the impulsive signals seen by FORTE is limited unless augmented by information from other instruments — for example, the Los Alamos Sferic Array [13, 1]. It is possible to derive some information about the sources from geographically-dependent ionospheric effects.

There is a parallel optical payload onboard, built by Sandia National Laboratory. This has a fast time response photodiode detector (PDD) which samples an 80° field of view in the visible and near-IR, and a 128×128 CCD array imager (LLS) whose narrow band (0.77 μm) image lies within the PDD field of view. The radio and optical payloads can be either triggered independently or cross-triggered.

A comprehensive description of the technical results from this project can be found at the web site [3].

2. Analysis

The large volume of data from the FORTE system has required automation of data handling, processing, analysis and sorting. The signals in each band are each subjected to a spectrogram. Typically, the spectrogram's moving Fourier time window is 128 samples (or 2.56 μs) and is advanced in steps of 8 samples (or 0.16 μs). This gives a spectral resolution of 0.39 MHz. Each spectrogram is then "pre-whitened" to largely remove CW carrier signals.

The impulsive signals show a distinctive ν^{-2} ionospheric dispersion (or "chirp") which is described approximately by a group delay, τ, versus frequency, ν, given by:

$$\tau(\mu\, s) = 1.34\times\left[(N/10^{17}\,\mathrm{m}^{-2})\times(\nu/100\,\mathrm{MHz})\right]^{-2}$$

where N is the electron column density.

3. FORTE Results

Figure 1 shows typical pulsed signals illustrating the essentially bimodal character of the FORTE recordings.

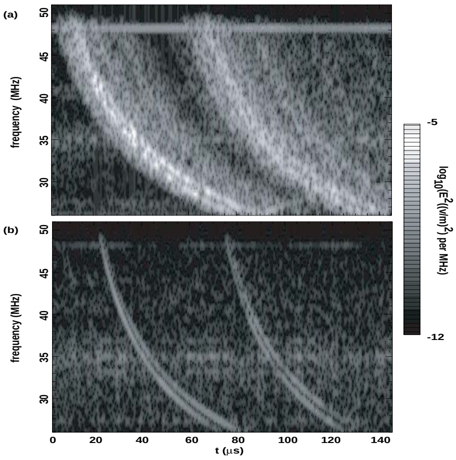

Figure 1: Spectrograms of **(a)** strong intracloud pulse, and **(b)** polarized/coherent intracloud pulse. The ground echo is seen at a delay of ≈50–60 μs relative to the main pulse in each case. The spectrogram is computed with a sliding short-period Fourier transform having ≈1 μs width. Grey-scale key is shown at right and is common to the two examples.

For the case of narrow RF pulses having clear ground-reflection echoes, it has been shown [8] that these pulses tend to belong to one of two general classes. The first class ("strong pulses") are the brightest RF signals recorded by FORTE. They have somewhat extended width (typically 2-4 μs), have random amplitude variations within the pulse at sub-microsecond timescales, and usually have a several-microsecond coda of weak emission extending after the main pulse. The strong pulses have been shown sometimes, but not always, to be associated with narrow bipolar events (NBEs) [12]. (Narrow bipolar events are caused by intracloud discharge processes and give rise to an intense RF pulse. NBEs are accompanied by weaker optical pulses than other lightning processes [9].)

The second class ("coherent pulses"), by contrast, are two to three orders-of-magnitude weaker, are narrow (on the order of 0.1 μs when suitably measured), are coherent (that is, they consist of a simple pulse with no random amplitude variations versus either time or frequency within the pulse), and are perfectly linearly polarized. These coherent/polarized pulses are associated with steps in a progressive leader breakdown [5, 8].

Figure 1 (after Jacobson and Light [8]) shows examples of the two classes of pulses in moving-window-spectrogram form. The top signal (Figure 1a) is from the strong-pulse class. The bottom signal (Figure 1b) is from the coherent/polarized-pulse class. The logarithm of the spectral density is coded in grey-scale; the same scale is common to both signals. The spectrograms' sliding Fourier window is about 1 μs wide, so the coherent/polarized pulse's 0.1 μs intrinsic width is artificially broadened by the Fourier windowing in Figure 1. The strong pulse shows extended width compared to the coherent/polarized pulse. The strong pulse also shows a low-power coda that is lacking in the coherent/polarized pulse. Finally, the strong pulse has irregularly varying spectral amplitude but is much more intense overall, compared to the coherent/polarized pulse.

In addition to lightning in these signals, there is some interference (horizontal bands) from anthropogenic narrow-bandwidth radio transmissions. In each spectrogram, the ground-reflection echo is delayed ≈50 μs from the primary pulse. This implies that the echo has propagated ≈50 μs/c ≈17 km further than the primary pulse. If the satellite were at zenith relative to the lightning, this would imply a height above ground of ≈8.5 km. This height is a lower estimate; if the satellite is not at zenith, the implied RF-emission height must be greater [6]. Each signal exhibits obvious spectral dispersion from ionospheric propagation [6, 11], with most of the group delay varying as TEC × ν^{-2}, where TEC is total electron content, that is, the path integral of the electron density along the line-of-sight, and where f is the radio frequency. (The TEC is inferred to be $5.36\times10^{17}\mathrm{m}^{-2}$ in Figure 1a and $3.43\times10^{17}\,\mathrm{m}^{-2}$ in Figure 1b, using the automatic data reduction described in Section 2 and in [6]). In addition, each signal shows pulse splitting at finer time-scales due to ionospheric birefringence in the geomagnetic field [7, 10].

Using a variety of techniques [4, 8], FORTE event sources have been geolocated in many cases. Together this geolocated-source database permits us to tally the spectrum of amplitudes of effective radiated power (ERP) in the observing passband. Figure 2 shows both the square of the received electric field (E^2) and the at-source ERP within the FORTE low band (26-48 MHz) as seen from 800 km altitude.

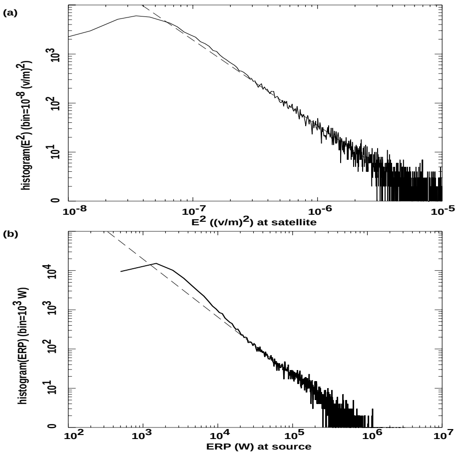

Figure 2: **(a)** Histogram of E^2 (intensity) at satellite, with binwidth $10^{-8}\,(V/m)^2$. Dashed line has log-log slope of -1.74. **(b)** Histogram of ERP in band 26-48 MHz at source, with binwidth 10^3 W. Dashed line has log-log slope of -1.05. Data include all 67,578 intra-cloud discharges for which horizontal location is known.

4. The Future

We have proposed the development of a satellite-based global lightning detection and total electron content (TEC) monitoring system called V-GLASS (VHF Global Lightning And Severe Storm Monitor). The proposed system would be a secondary application of an already-funded constellation of broadband VHF receivers to be flown on the upcoming Block IIF Global Positioning System (GPS) satellite constellation beginning in 2006. Although the space segment of V-GLASS is already funded and scheduled for deployment, the development of a global ground station array and a formal development of the scientific foundations for the detection and analysis process is needed before V-GLASS can become operational.

Satellite-based global lightning monitoring is based on the idea of using lightning detection as a proxy for identifying and locating strong convective activity. Convective updraft is a basic concern for both civilian and military aviators. It is also the driving mechanism for several forms of severe weather on the earth and a primary means by which energy in the form of latent heat drives the large-scale atmospheric circulation. In addition to lightning detection, a determination of the line-of-sight TEC as a by-product of the VHF lightning detection process will provide a valuable global TEC mapping product. An accurate assessment of global TEC is essential in fore-casting and now-casting conditions that affect VHF/UHF communications and in determining GPS single-frequency range errors. The global lightning and TEC monitoring missions both have strong support from the civilian, scientific and military communities (*e.g.* [14]) although, to date, we have yet to secure formal program funding.

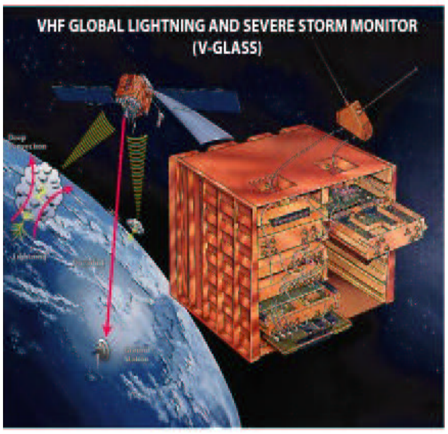

Figure 3: Artist's rendition of V-GLASS mission on the future GPS Block 2F.

For the past few years, LANL/ISR-1 has made good progress in defining the conceptual design and expected performance parameters of an operational V-GLASS system [15]. An important tool in this work has been the availability of a V-GLASS-like VHF receiver aboard the SVN 54 GPS satellite. Studies of this database and the use of ground-based "truthing" tools such as the LANL Sferic Array in Florida [1] and the National Lightning Detection Network have been instrumental in determining that a V-GLASS system will be most sensitive to an impulsive type of in-cloud lightning called a Narrow Bipolar Event (NBE). NBEs have been shown to be excellent generic indicators of thunderstorm convective activity [16]. Analysis of data from a second recently launched V-GLASS-like GPS satellite (SVN 56) has shown that satellite-based NBE detection is an efficient means of monitoring the progression and evolution of individual thunderstorm cells, particularly over oceans. The extraction of TEC and TEC uncertainty measurements associated with each detected lightning event has also been demonstrated and appears to be a viable means of TEC monitoring.

5. Conclusions

The FORTE satellite program has provided a powerful tool for the observation and understanding of the natural RF background due to thunderstorm activity. Unfortunately, because of hardware failures, the satellite ceased operation in late summer of 2003 after 6 years of very successful operation.

Acknowledgements

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