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Title: SATELLITE OBSERVATIONS OF TRANSIENT RADIO IMPULSES FROM THUNDERSTORMS

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Satellite Observations of Transient Radio Impulses from Thunderstorms

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ABSTRACT: ~~Electromagnetic~~ Transient radio emissions from thunderstorms detected by satellites were first reported in 1995 (Holden, et al., 1995). The nature and source of these emissions remained a mystery until the launch of the FORTE satellite in 1997. FORTE, with its more sophisticated triggering and larger memory capacity showed that these emissions were connected to major thunderstorm systems. The analysis reported here, connecting FORTE RF events with ground based lightning location data from the National Lightning Detection Network (NLDN), shows that localized regions within thunderstorms are responsible for the creation of the satellite detected rf signals. These regions are connected with the areas of strong radar returns from the NEXRAD Doppler radar system, indicating that they are from regions of intense convection. We will also show data from several storms detected in the extended Caribbean, in which the height profile of the source regions can be determined. Although as a single low earth orbit satellite FORTE cannot provide global coverage of thunderstorm/lightning events, follow-on satellite constellations should be able to provide detailed information on global lightning in near real-time.

INTRODUCTION

Over the past several years we have reported observations of transient radio impulses observed by Earth-orbiting satellites. The first reported observations, from the ALEXIS/Blackbeard satellite, indicated the existence of brief (a few microseconds long) pulses, often seen as pairs of pulses that were dispersed in such a way to imply that they had undergone trans-ionospheric propagation. Blackbeard's memory and triggering limitations constrained detections to a few events per orbit. With the limited data set available from the Blackbeard observations it was not clear whether the source of these pulses was anthropogenic or natural. With the advent of the FORTE satellite, with its multi-channel triggering, increased sensitivity and enlarged memory configuration, our observations have shown that often there were thousands of narrow pulse events observed during a single transit of the tropics, or a few tens to hundreds of events observed during transits of the United States. From these events we were able to show that the pulse dispersion and pulse pair separation are consistent with a model of an initial pulse at high altitude (8-20 km) and a subsequent reflection from the ground (Jacobson, et al., 1998). In addition, we often detected more classical structured emissions believed to come from normal lightning activities.

The FORTE observations have allowed us to collect a wealth of data on RF emissions emanating from thunderstorm regions. With the multi-channel trigger we are able to detect not only the very bright TIPP events observed by Blackbeard, but also weaker distinct pulses and even diffuse RF emissions from the lightning processes. A complex and involved analysis routine has been used to sort through the FORTE data, and to identify various forms of RF lightning returns (Jacobson, et al, 1999). These tend to fall into three categories: 1) the pair of narrow Rf pulses believe to be representative of a high altitude (8-20 kilometer) discharge and its reflection from the ground (TIPPs); 2) an extended train of apparently distinct and discrete pulses (believed to correspond to recurrent leader emissions); and 3) many dispersed traces, overlapping with each other and with poor contrast between peak and median instantaneous intensity, typical of diffuse lightning emissions.

This paper is intended not to provide rigorous scientific observations on the development or the characteristics of thunderstorms, because the sparseness of FORTE overpasses (both temporally at one location and in global coverage) do not lend themselves to that. Rather we will try to show how a follow-on system capable of global coverage could provide a rich data set in both individual storm development and in global storm conditions.

It is important to note that the lightning flashes discussed in this paper are not just the TIPP events usually discussed in the FORTE data, but also include the more classical structured and diffuse emissions. We will show that there are distinct differences between the continental thunderstorms and those detected in the tropical Caribbean.

OBSERVATIONS

The ground based lightning detections and locations in this study are done using historical data provided by the National Lightning Detection Network (NLDN) (Cummins et al.,1998). This network, using more than 100 sensors, has a median location accuracy of about 500 meters, and a flash detection efficiency of 80% to 90%. The wide-band

magnetic direction finders were designed to optimize detection of cloud-to-ground strokes, and in fact detect and locate very few intracloud strokes.

In this paper we will discuss a subset of the FORTE detections are coincident with lightning strokes detected and geolocated by the National Lightning Detection Network. Using this coincidence to attach a location to the source of the FORTE detected signal, we find that the sources of these events are not only connected to the thunderstorm, but also usually come from very localized regions within the thunderstorm. For storms over the continental United States, where complete Doppler radar data is available, the localized regions of FORTE detected are spatially coincident with regions of strong Doppler radar echoes gotten from continental images from the NEXRAD weather radar system. Since the strong radar echoes come from the regions of intense convection within the thunderstorm, we surmise that these same regions are responsible for the FORTE events, indicating that the lightning activity creating strong FORTE RF signatures is occurring in the strong convective regions within thunderstorm systems. Although in most cases the NLDN network is detecting lightning from an extended region around these discrete patches of strong Doppler radar convection, the majority of NLDN lightning locations also come from this strong Doppler core.

May 26, 1998

At approximately 0500UT on May 26 the FORTE satellite was descending along the West Coast of the United States, and detected a pair of storms in Texas. Figure 1 is the Doppler Radar map taken at 0500UT and the combined NLDN and FORTE lightning detections during the overpass period. In Figure 1 the black pluses are the geolocated FORTE detections, and the contours show the NLDN strike density. In Figure 1 the NEXRAD data for echo strengths above 45 dBZ are plotted in gray. Note that generally there is an indication that the FORTE detections occur in the regions of highest radar return. During this time, as seen in the NEXRAD map, most of east Texas was undergoing stormy conditions. Two larger regions showed strong Doppler echoes, one just east of the panhandle (on the Oklahoma border), and the other was north of Dallas. Smaller regions of strong echoes trailed westward across the state. The FORTE and NLDN returns come from the two regions connected to the high Doppler echoes. The closeness of detected locations is striking in this case, where the time differences between maps were only a few minutes. In this case not a single TIPP event was identified and localized to this storm.

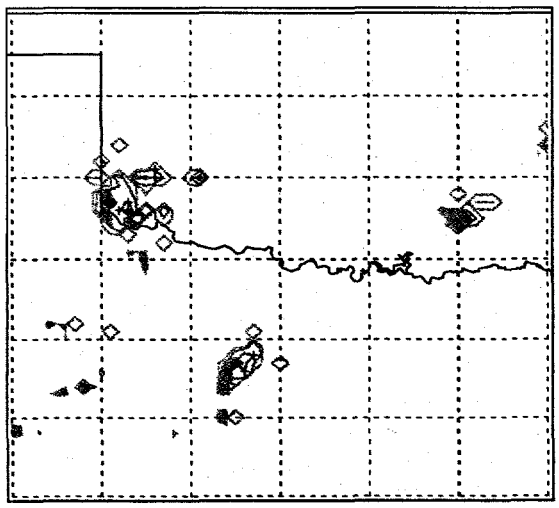

Figure 1. A map of the Texas panhandle region for 0500UT May 26, 1998 showing the relationship of the strong (>50dBz) NEXRAD radar echoes in gray, the NLDN lightning strike density (contours), and the FORTE detections (+'s).

Caribbean Storms

We were also able to use FORTE/NLDN coincidence data for lightning events occurring over the extended Caribbean region. In this area the NLDN data has reduced accuracy, and is unable to classify events, but still has

geolocation capabilities within the requirements of this study. The lightning events observed over this Caribbean region were parts of larger ensembles of events clearly coming from storm systems, as observed both by NLDN and the FORTE overpasses. Using a geolocation technique described by Argo et al (1999) and the few FORTE/NLDN coincidence geolocations, we could connect a larger set of FORTE lightning detections to the given storm. Using this larger data set we will show how FORTE could be used to study macro-scale storm characteristics.

We chose nineteen (19) storm systems within the extended Caribbean tropics (including the Western Atlantic and the Eastern Pacific) that had distinct and separable FORTE lightning data as well as NLDN/FORTE coincidences. Figure 2 shows the locations of these storms, as the black asterisks. In all these cases the amount of FORTE data far exceeded the number of coincidences with the NLDN system, and we used the geolocation technique described in Argo, et al (1999) to include this larger data set. In all of these events the ratio of TIPP events to total lightning events was at least 50%, and in several cases was greater than 70%. This is distinctly different from the continental storms discussed above, where this ratio was generally less than 10%. By using the time differences between the pair of pulses in the TIPP events we determine the height of the RF emission region, using the model discussed in Jacobson, et al (1999). Figure 2 also shows the height distributions for these emission regions for all of the events. Although the values are normalized to the maximum in the height distribution for each event, the maximum values ranged from twenty to almost one hundred. There is a tendency for the peak heights to be greater than 12 kilometers, in agreement with Jacobson, et al (1999), and distinctly different from what they found for the ensemble of continental storms, where the height of the peak was about 8 km. In almost all profiles there is evidence of a bimodal distribution, with a lower peak at 5 to 7 kilometers. We are not sure whether this is real, or is an artifact of not isolating storm data sufficiently. One storm region was observed several days after the first observation. These observations are marked in Figure 2 by letters **a** and **b**. Another storm, marked as **c** and **d** in Figure 2, was observed at two times separated by almost 24 hours. In both cases the storm height profiles were very similar.

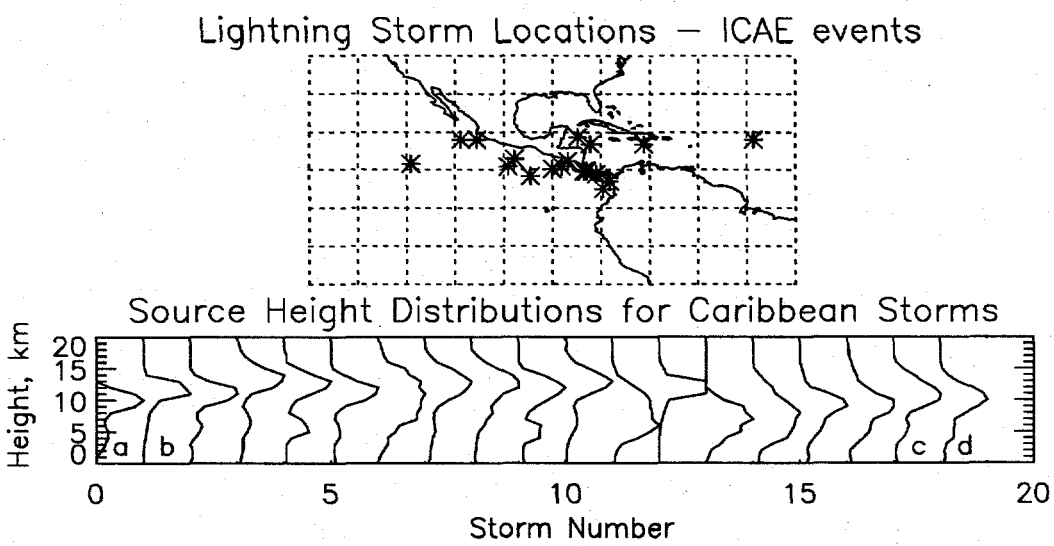

Figure 2. Nineteen storms in the extended region selected both by NLDN/FORTE coincidences and the use of recurrent-emission characteristics to do autonomous geolocation. The map shows the storm locations, the lower figure shows the height distributions of the discrete emissions that we could identify. Note that most storms have the most emissions at heights significantly above 10 kilometers.

DISCUSSION

We have studied several storm cases where many of the FORTE RF detections are coincident (to within several hundred microseconds) of an NLDN located flash. In each case the locations of the FORTE/NLDN detected flashes are nearly coincident with the strong radar echoes detected by the NEXRAD Doppler radar system, indicating that this lightning activity is occurring in the locations of strong convective regions.

FORTE overpasses of tropical regions show a distinctly different character than those found in continental U.S. storms. We see far more RF triggers (often thousands), and many more are the narrow TIPP events. Smith (1998)

determined that the source height from the one tropical storm observed was significantly higher than those observed in local thunderstorms (15 to 17 kilometers as opposed to 8 to 10), and Jacobson has shown for the ensemble of NLDN coincidences that the southeastern maritime storms had similar differences in height distributions than the inland continental storms. In the nineteen storms observed in this study we found a variety of height distributions, with most showing peaks well above ten kilometers. In addition, the tropical storms are far more rich in the TIPP events (50-75% of the detections were TIPPs), again different from the inland continental storms where usually fewer than 10% were identified as TIPPs.

SUMMARY

The FORTE satellite observations of the RF emanations from thunderstorms have significantly increased our understanding of the phenomenology of these events. The ability to detect and store several thousand events between downlinks has allowed us to observe complete passages by major thunderstorm systems. This in turn led to the corroboration of the model that the twin TIPP pulses were actually a single pulse and its reflection off of the ground. With this knowledge, we could then study the causative thunderstorm sources.

In this paper we have studied a subset of the FORTE detections that are coincident with lightning strokes detected and geolocated by the National Lightning Detection Network. Using this coincidence to attach a location to the source of the FORTE detected signal, we are able to show that the sources of these events are not only connected to the thunderstorm, but come from very localized regions within the thunderstorm. A further connection, using continental images from the NEXRAD weather radar system, was shown between the FORTE sources and strong Doppler radar echoes. Since the strong radar echoes come from the regions of intense convection within the thunderstorm, we conclude that these same regions are responsible for the FORTE events. This result is similar to that found the earlier work done by Smith (1998), in which he showed that TIPP events are produced by singular, isolated, intracloud electrical discharges that occur in intense regions of thunderstorms. These intense regions appear to support electric fields an order of magnitude higher than those previously expected, or detected. Smith postulates that these large fields have not been detected by *in situ* measurements primarily because the regions are so compact that instruments have not reached them.

Although the FORTE satellite RF detection capabilities have extended the understanding of the VHF emissions from thunderstorms, and have shown that satellite borne RF detectors can provide lightning measurements of the convective core of the thunderstorm, the use of a low earth orbit satellite for global synoptic studies of thunderstorm morphology is hampered by the fact that such a satellite passes a thunderstorm at best a couple of times a day for durations of less than fifteen minutes. Early next century (~2003) a constellation of FORTE-like sensors will be flown by DOD/DOE for national security reasons, but will have the possible offshoot of providing global lightning detection coverage. Because the use of multiple coincidence detections will allow the constellation to unambiguously locate each lightning event, we will not have the problems of separating out closely co-located storms. In addition, the possibility of measuring TIPP time separations would allow us to follow the time evolution of the source altitude profiles, as well as the global differences in source altitude characteristics. We hope to be able to provide hourly maps of the global lightning, along with information such as the source height distributions.

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