P2.5 VHF LIGHTNING DETECTION AND STORM TRACKING FROM GPS ORBIT

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1. INTRODUCTION

1.1 Background

Over the last few decades, there has been a growing interest to develop and deploy an automated and continuously operating satellite-based global lightning mapper [e.g. *Christian et al*., 1989; *Weber et al*., 1998; *Suszcynsky et al.*, 2000a]. Lightning is a direct consequence of the electrification and breakdown processes that take place during the convective stages of thunderstorm development. Satellite-based lightning mappers are designed to exploit this relationship by using lightning detection as a proxy for remotely identifying, locating and characterizing strong convective activity on a global basis. Global lightning and convection mapping promises to provide users with (1) an enhanced global storm tracking and early warning capability [e.g. *Weber et al*., 1998] (2) improved ability to optimize aviation flight paths around convective cells, particularly over oceanic and remote regions that are not sufficiently serviced by existing weather radar [e.g. *Weber et al*., 1998], and (3) access to regional and global proxy data sets that can be used for scientific studies and as input into meteorological forecast and global climatology models.

The physical foundation for satellite-based remote sensing of convection by way of lightning detection is provided by the basic interplay between the electrical and convective states of a thundercloud. It is widely believed that convection is a driving mechanism behind the hydrometeor charging and transport that produces charge separation and lightning discharges within thunderclouds [e.g. see chapter 3 in *MacGorman and Rust,* 1998]. Although cloud electrification and discharge processes are a complex function of the convective dynamics and microphysics of the cloud, the fundamental relationship between convection and electrification is easy to observe. For example, studies have shown that the strength of the convective process within a thundercell can be loosely parameterized (with large variance) by the intensity of the electrical activity within that cell as measured by the lightning flash rate. *Williams* [2001] has provided a review of experimental work that shows correlations between the total lightning flash rate and the fifth power of the radar cloud-top height (i.e. convective strength) of individual thunder cells. More recently, *Ushio et al.*, [2001] used a large statistical sampling of optical data from the Lightning Imaging Sensor (LIS) in conjunction with data provided by the Precipitation Radar (PR) aboard the Tropical Rainfall Monitoring Mission (TRMM) satellite to conclude that the total lightning flash rate increases exponentially with storm height.

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Lightning activity levels have also been correlated to cloud ice content, a basic product of the convective process. For example, *Blyth et al.* [2001] used the Thermal Microwave Imager (TMI) aboard the TRMM satellite to observe a decrease in the 37 and 85 GHz brightness temperatures of upwelling terrestrial radiation during increased lightning activity. This reduction in brightness temperature is believed to be the result of increased ice scattering in the mixed phase region of the cloud. *Toracinta and Zipser* [2001] have found similar relationships using the Optical Transient Detector (OTD) satellite instrument and the Special Sensor Microwave Imager (SSM/I) aboard the DMSP satellites.

1.2 Satellite-based VHF Lightning Mapping

To date, efforts to develop a global lightning mapping capability have primarily focused on the deployment of optical sensors that can provide cost-effective, single-platform, two-dimensional geolocation of conventional lightning flashes [e.g. *Christian et al*., 1989]. Over the last several years, measurements of radio-frequency lightning radiation using very high frequency (VHF) radio receivers aboard the Fast On-Orbit Recording of Transient Events (FORTE) satellite have suggested that satellite-based VHF lightning detection may also present a practical means of global lightning mapping [e.g. *Suszcynsky et al.*, 2000a; *Jacobson*, 2003a]. VHF lightning detection can provide geolocation of lightning events into the third dimension (altitude) and can easily discriminate between cloud-to-ground (CG) and intra-cloud (IC) activity based on the powerversus-time profile of the signal [*Suszcynsky et al*., 2000b; *Light et al*., 2001]. The opportunity to locate lightning sources in altitude can be particularly useful in deducing vertical charge distributions and quantifying the vertical extent (strength) of the convective surge [*Suszcynsky and Heavner*, 2003; *Jacobson*, 2003a]. The availability of these features suggests that VHF lightning detection can function as a stand-alone lightning mapper or as a complement to an optical lightning mapper.

An operational radio frequency (rf) global lightning mapper would most likely employ a constellation of geosynchronous or Global Positioning System (GPS)-based radio receivers that would detect and geolocate intense rf lightning transients with a multiple-sensor time-difference-of-arrival (TDOA) technique. Ideally, the receivers would operate in the VHF portion of the radio frequency spectrum (30 – 300 MHz) above the local ionospheric plasma frequency (~ 10 – 20 MHz). This frequency range is high enough to allow detection of those frequency components of the signal that propagate through the ionosphere without reflection, but not so high that the signal strength is overly compromised by the natural roll-off of the power spectral distribution of lightning with increasing frequency. Although this "high-pass-filtered" signal acquires a frequency-dependent dispersion as it propagates through the ionosphere to the satellite receiver, the dispersion does not significantly affect the detection or time-tagging accuracy of the event. In fact, if the event is detected by a broadband or multi-channel receiver with sufficient temporal resolution, the degree of dispersion can be quantified (and removed) and used to deduce the line-of-sight total electron content (TEC) of the ionosphere between the lightning event and the receiver (e.g. see *Jacobson*, 1999). In this manner, a global VHF lightning mapper could also be used as a global TEC mapper [e.g. *Pongratz et al.,* 2000], the acquisition of each TEC measurement being only dependent upon the occurrence of a detectable lightning event.

A satellite-based VHF lightning mapper would also require an on-board discrimination capability and/or a multi-channel triggering scheme such as that used with the FORTE receivers in order to avoid excessive triggering on anthropogenic single-frequency emissions. The FORTE receiver triggering scheme requires that at least five out of eight frequency channels simultaneously trigger before a signal is tagged as an event. This approach virtually guarantees that the receivers only detect broadband signals. The detected signal must also be sharp enough in time and in structure to provide an unambiguous triggering feature that can be accurately time-tagged and geolocated.

The geolocation accuracy of a TDOA-based VHF lightning mapper is driven by a combination of satellite viewing geometry (quantified by the Positional Dilution of Precision or PDOP of the system) and sensor timing errors [*Judd and Fugate*, 2003]. The expected geolocation accuracy is well within the scale size of typical convective cells and would be sufficient to address most lightning mapping applications.

1.3 Narrow Bipolar Events (NBEs)

FORTE lightning studies have shown that satellite-based VHF lightning sensors are uniquely and primarily sensitive to a ubiquitous and meteorologically important type of in-cloud lightning known as a Narrow Bipolar Event (NBE). Because of the dominance of NBE activity in the VHF portion of the frequency spectrum, the success of a future VHF lightning mapper is to a large extent dependent upon the viability of using NBEs as generic and robust indicators of thunderstorm convective activity.

The phenomenology of NBEs has been extensively characterized by numerous ground-based studies [e.g. *Willet et al*., 1989; *Smith et al*., 1999, *Thomas et al*., 2001] and satellite-based studies [e.g. *Holden et al*., 1995; *Jacobson*, 1999, 2003a; *Jacobson and Light*, 2003b]. NBEs were originally reported by *LeVine et al.* [1980] and are named for the temporally narrow (~ 10 μs) bipolar waveform structure that they exhibit when observed by ground-based very low frequency (VLF) electric-field-change meters. They appear to be ubiquitous features of strong convective thunderstorm activity, have source altitudes in the range of about 5 to 15 km [*Smith et al*., 1999], are optically weak (*Light and Jacobson*, 2002) and produce the strongest VLF and VHF signatures associated with lightning. They can occur as temporally and spatially isolated events, or can occur as initiators of more generic intracloud activity [*Thomas et al., 2001; Jacobson, 2003c*].

More recent and ongoing work has focused on establishing the meteorological context of NBEs, particularly as it relates to satellite-based VHF lightning mapping. NBEs have been observed to occur near and within the convective cores of thunderstorms [*Smith et al*.,1999] and their effective radiated powers have been correlated to the altitude at which they occur in the cloud [*Jacobson*, 2003a]. NBE flash rates and source heights have also been shown to be statistically correlated to the convective strength of the storm, the inference being that NBEs can serve as proxy for strong convection [*Suszcynsky and Heavner*, 2003]. A similar relationship has been observed between NBE occurrence and GOES-8 satellite-derived infrared cloud-top heights [*Jacobson and Heavner*, 2004]. Additional work is needed to address the generality of these findings over more varied geographical regions and storm types.

This paper presents the scientific and technical foundations for satellite-based VHF lightning detection and storm tracking from GPS orbit. After the introduction and discussion of the technical justification for satellite-based VHF lightning mapping, data from experimental VHF receivers currently in orbit aboard two GPS satellites is used to (a.) quantify and characterize the detection of VHF lightning from GPS orbit (section 3) and (b.) demonstrate the use of VHF lightning detection in mapping and tracking the evolution of thunderstorms (section 4). The paper concludes with a brief discussion of a proposal to use a planned deployment of VHF radio receivers on the upcoming Block IIF GPS constellation as a real-time global lightning mapper beginning in 2006.

2. INSTRUMENTATION

2.1 GPS VHF Receivers

The analysis in this paper uses data from an experimental VHF receiver aboard the GPS constellation that is capable of routinely monitoring lightning activity in the western hemisphere. The receiver was launched on January 31, 2001 aboard the SVN 54 GPS satellite and provides approximately 7.5 hours of lightning detection coverage per day. The collected lightning event data is downlinked to the ground in real time for as long as the satellite remains in direct line-of-sight contact with the ground station located in Albuquerque, New Mexico. Figure 1 illustrates the temporal evolution of the approximate "field-of-view (fov)" of the SVN 54 receiver/antenna system over the course of one day (two 12-hour orbits). The sensor fov is shown for the start, mid-point and end of the contact interval with the ground station. The receiver fov progresses eastward along the subsatellite track (red) repeating this track once per day and passing over a given point on the earth approximately 4 minutes earlier each day. In the course of one year, the satellite will sample exactly one 24-hour period of local time for each point along the ground track. GPS satellites lie at about 20,000 km altitude and have an orbital inclination of 55°.

The SVN 54 VHF receiver was not specifically designed for lightning detection and cannot be reconfigured or optimized for formal lightning detection campaigns. However, it provides continuous coverage of lightning activity while in contact with the ground station and is generally similar to receiver designs recently flown on the FORTE low-earth-orbiting satellite [e.g. *Jacobson et al*., 1999]. The receiver covers the 50 MHz to 150 MHz frequency range and operates with a multi-channel amplitude-threshold triggering scheme similar to that of FORTE. Detected events are GPS time-stamped and their waveforms are made available for analysis on the ground shortly after the end of each pass over the ground station.

Since four or more satellite receivers are required for an unambiguous three-dimensional geolocation of an event, the current single experimental receiver aboard SVN 54 cannot autonomously geolocate detected lightning events. Instead, it is necessary to employ a ground-truthing system such as the Los Alamos National Laboratory (LANL) Sferic Array (LASA) to both geolocate and type GPS-based lightning detections. LASA has a high detection efficiency and can establish the framework needed to confidently interpret the GPS-based observations.

2.2 LASA

The LANL Sferic Array (LASA) was developed as a ground-truthing tool for the FORTE satellite and consists of eight capacitively coupled electric-field change sensors located throughout Florida [*Smith et al*., 2002]. The array is sensitive to both IC and CG lightning activity and also provides excellent ground-truthing for the on-orbit GPS VHF receivers. The LASA stations used for this study are located in Tampa, Gainesville, Boca Raton, Kennedy Space Center, Daytona, Tallahassee, Ft. Meyers and Orlando.

The array is designed to collect 8.192-ms duration waveforms at a 1 MHz sampling rate from each station where the local signal strength exceeds a pre-set amplitude threshold. If three or more stations are found to trigger on a lightning event within a 20-ms time window, the GPS timestamps from those stations are used to calculate a two-dimensional geolocation of the event using the TDOA technique described in *Smith et al.,* 1999. Once the events are geolocated, an automated measurement routine is used to parameterize the waveforms and determine a lightning type (CG, NBE or unknown) and polarity [e.g. *Smith et al*., 2002].

LASA detection efficiencies are greatest for events that occur within 625 km of the center of the array and are estimated to be about 85% for CG lightning strokes and a few percent for generic IC lightning flashes. The majority of LASA-detected IC activity is due to NBEs.

(a.)

(b.)

(c.)

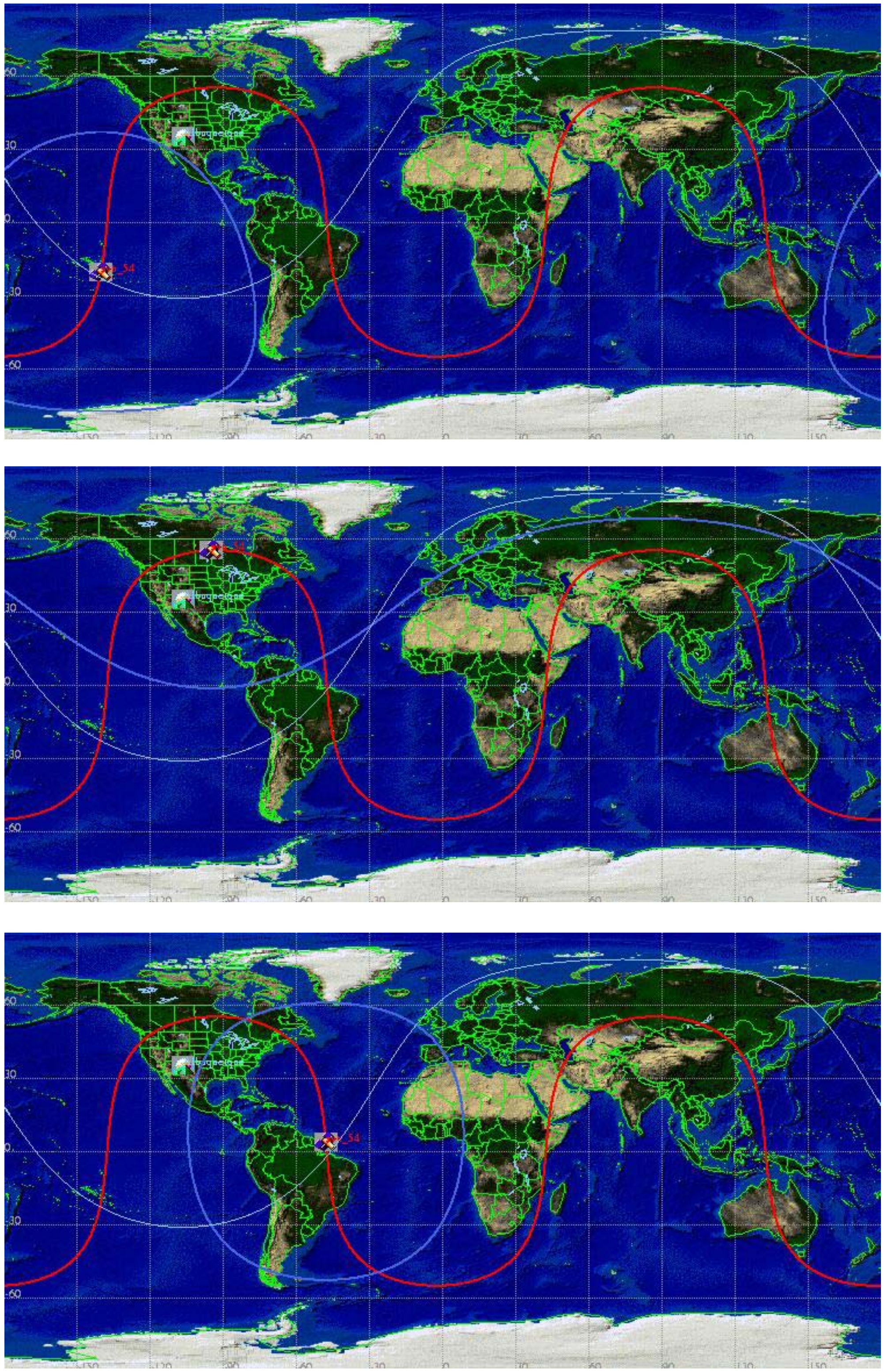

Figure 1. SVN 54 (satellite icon) field-of-view for the (a) start, (b) middle and (c) end of ground-station contact time. Ground-station horizon and satellite track are also shown.

The LASA detection efficiency for NBEs is unknown although we assume that the array collects a significant and relatively unbiased sampling of the total NBE population. LASA is optimally tuned to the detection of NBEs and as a consequence, provides an ideal ground-truthing tool for individual GPS-detected lightning events.

3. GPS LIGHTNING DETECTION

As a first step in quantifying the lightning detection capabilities of the GPS VHF receivers, LASA-detected lightning events were temporally correlated to GPS-detected events over the periods from June 1, 2001 to Sept. 30, 2001 and from April 1, 2002 to July 31, 2002. The LASA dataset provided geolocation information for the GPS events and the LASA waveforms were used to identify GPS-detected lightning types based on an interpretation of the collected VLF waveform profiles.

Figure 2 shows a histogram of lightning types for the 4664 events that were simultaneously observed by both LASA and GPS during the study period. About 75 % of the correlated events were identified as NBEs, the vast majority of these having a positive-polarity. The remaining 25 % of the correlated events are due to intense VHF negative return stroke attachment transients occurring primarily over sea water [*Jacobson and Shao*, 2002]. The results illustrate the fact that satellite-based VHF lightning mapping is primarily dependent upon the detection of NBEs.

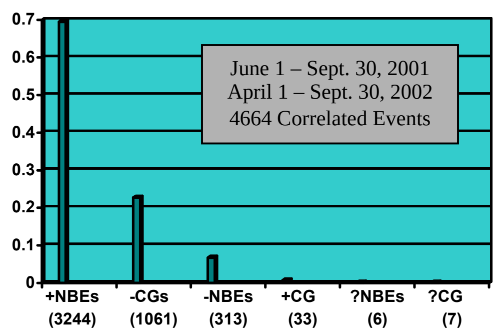

Figure 2. Histogram showing the percent occurrence of each lightning type for the 4664 events simultaneously observed by both GPS and LASA.

4. GPS STORM TRACKING

As a case study of a strongly convective storm that was observed by both LASA and GPS, figures 3 and 4 summarize the LASA-detected and GPS-detected lightning activity from Tropical Storm Edouard in 2002 as a function of its convective development. To date, Edouard is the only named storm that has occurred in the Florida area during a time when both the LASA and GPS sensors were simultaneously functional. Edouard was fairly disorganized, reaching tropical storm status for a three-day period from about 0600 UT on Sept. 2, 2003 until about 0600 UT on Sept. 5, 2003 shortly after it reached landfall. Convective activity intensified significantly on the morning of Sept. 3 and reached maximum strength by about 1200 UT. This main surge of deep convection decreased by midday but the storm continued to have occasional convective bursts until its demise on Sept. 5 [*National Hurricane Center*, 2003].

Figure 3 shows the location of LASA and GPS lightning events with respect to GOES-8 (imager 4) infrared (IR) cloud imagery from 1030 – 1230 UT on Sept. 3, 2002. Each panel represents 0.5 hours of accumulated lightning activity and the time of each IR image occurs at the midpoint of the associated 0.5-hour time interval. LASA-detected lightning events are marked as CGs (green), NBEs (red) or unknown (yellow). The symbols are further defined as "+" or "-" to indicate the polarity of the events. Fortuitously, the SVN 54 receiver rose above Edouard's horizon at 10:40 UT just as the main convective development of the storm was taking place. For the next three hours, the SVN 54 receiver recorded over 100 NBEs that were associated with the main convective surge. Those NBEs that were simultaneously detected by both GPS and LASA (and geolocated by LASA) are shown as blue dots. All GPS-detected events were identified as +NBEs by noting the polarity and characteristic shape of the temporally correlated LASA waveforms.

Three conclusions can be immediately drawn from figure 3. First of all, the LASA-detected conventional (i.e. non-NBE) lightning events map out the general convective region of the storm (as indicated by the cold cloud tops) quite well. Secondly, the LASA-detected NBE events occur over a more limited area of the storm and clearly announce the arrival, location and persistence of the main convective surge. Finally, the SVN 54 receiver detected a significant portion of the LASA-detected NBE activity during the surge.

The above observations are better quantified in figure 4 which shows the (a) LASA "total" lightning flash rate, (b) the LASA NBE flash rate, (c) the GPS NBE flash rate, and (d) the measured "best track" wind speed (kt) and mean sea level pressure (MSLP – 1000 in mBars) of the storm over the Sept. 1 through Sept. 8 time period. The flash rates are averaged over two-hour bins and the wind speed and pressure measurements are top-of-the-hour "best track" values. In general, the

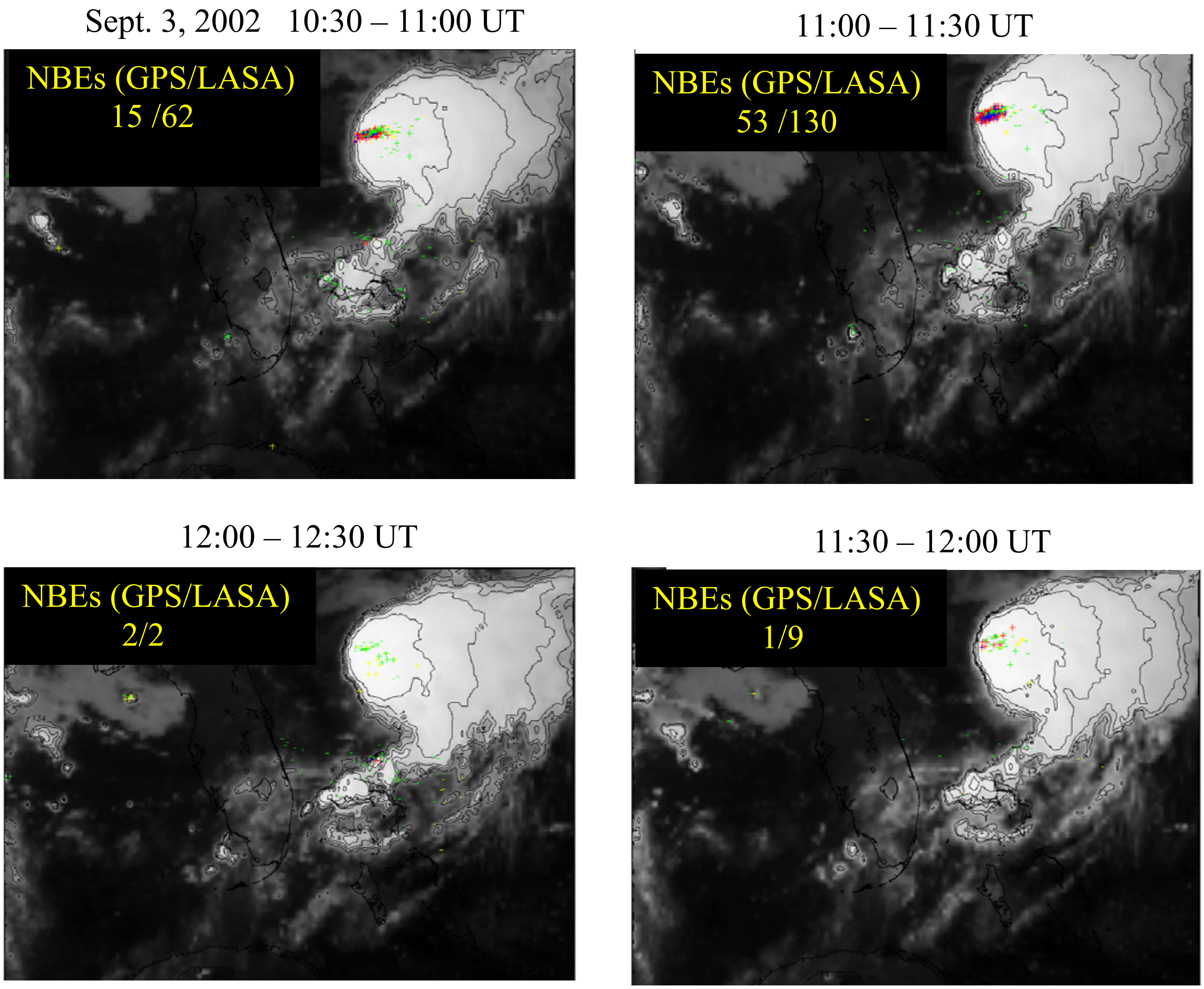

Figure 3. Temporal evolution of Tropical Storm Edouard on Sept. 3, 2002 from 10:30 UT through 12:30 UT in 0.5-hour increments. LASA-detected lightning events are identified as CGs (green), NBEs (red) and unknown (yellow). Those NBEs also detected by LASA are shown in blue. Lightning polarities are indicated by "-" or "+" symbols.

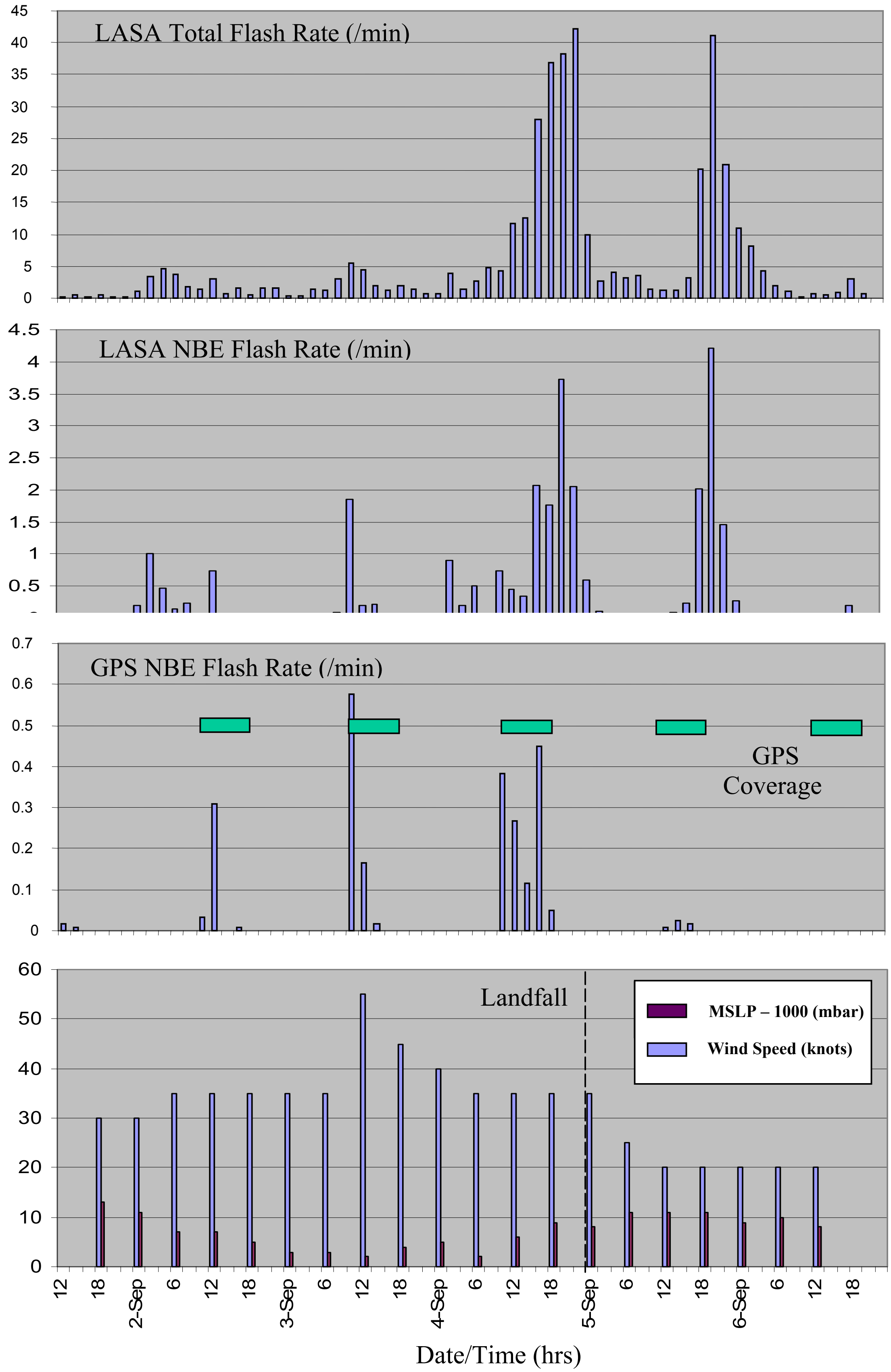

Figure 4. Storm history for Tropical Storm Edouard showing (a.) LASA-detected total lightning flash rate, (b.) LASA-detected NBE flash rate, (c.) GPS-detected NBE flash rate, and (d.) "best track" wind speed in knots and MSLP-1000 in millibars, all as a function of date and time. GPS coverage times are shown as green bars.

lightning activity was localized to the central part of the storm prior to landfall (see figure 3) and became much more dispersed over a larger geographical region once the storm neared landfall and began to dissipate (starting late on Sept. 4).

Figure 4a shows a sustained production of lightning over the entire history of the storm with daily flash-rate enhancements centered at 0400 UT on Sept. 2, 1100 UT on Sept. 3, 2100 UT on Sept. 4 and 1900 UT on Sept. 5. The Sept. 4 and Sept. 5 enhancements have significantly higher flash rates than those on Sept. 2 and Sept. 3. This is probably due to the combined effect of (a.) a significant increase in the CG flash rate once the storm reached land and dispersed and (b.) the fact that prior to Sept. 5 the storm is outside of the 625-km radius "high-detection-efficiency" range of the LASA array as discussed in *Suszcynsky and Heavner* [2003]. Figure 4b indicates that the LASA NBE flash rate history is similar (proportional) to the "total" flash rate history.

Figure 4c demonstrates that the GPS receiver was able to successfully track the storm by way of NBE detection. The fov bars in figure 4c indicate the times when GPS was above Edouard's horizon. Fortuitously, these times corresponded quite closely to lightning enhancements for each day, particularly on Sept. 3 and Sept. 4 when GPS detected the majority of its events. The routine detection of NBE events during these times provides strong evidence that GPS-based VHF lightning detection can be used to effectively track storm electrical activity.

The linkage between the electrical activity shown in figure 4abc and the convective state of Edouard is illustrated in figure 4d. The maximum measured wind speed of 55 kt and minimum pressure of 1002 mbars occur at about 1200 UT on Sept. 3 in direct temporal coincidence with the lightning flash-rate enhancement (and numerous GPS NBE observations) for that day. "Best track" wind speeds and pressures present a preliminary indication of the convective state of the storm. One must keep in mind that these "best track" values are inferred values for the storm center wind speed and pressure based on numerous satellite, aircraft and surface measurements. These measurements can be highly dependent on local conditions and may or may not capture temporally and/or spatially localized surges.

Despite these limitations, several conclusions can be drawn. First of all, it is clear that the LASA-detected total flash rate is consistently active over the entire time period that Edouard retained tropical storm status. The total flash rate enhancements seem to be generally aligned in time with increases (decreases) in wind speed (pressure), the notable exception being the enhancement on Sept. 5 which was well after the storm became disorganized and dispersed across Florida. Also, NBE flash rates occur at a rate proportional to the total flash rate. The conclusion is that both total lightning and NBE lightning are good generic indicators of convective activity in Tropical Storm Edouardo. Secondly, when available, the GPS receivers detected NBE activity at a rate that was proportional to the LASA rates, demonstrating that the convective development of Edouardo was also successfully tracked at GPS orbit.

5. CONCLUSIONS

More work is needed to generalize the results of sections 3 and 4 over a larger geographical region and variety of storm types. However, the work to date suggests that satellite-based VHF lightning detection can serve as a powerful proxy tool for identifying and tracking storm activity and strong convection.

Recently, we have developed a concept definition to use a constellation of VHF radio receivers aboard the upcoming Block IIF/III Global Positioning System (GPS) satellite constellation to monitor VHF lightning emissions on a global and continual basis [*Suszcynsky et al.;* (2000a, 2001)]. The system would be a secondary application of an already-funded constellation of FORTE-like receivers scheduled for launch beginning in 2006. The system will be capable of detecting, geolocating and reporting VHF lightning activity on a global basis in near real-time. Preliminary work is now underway to develop tools and data products for potential users.

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