J2.5 OVERVIEW OF CAPABILITIES AND PERFORMANCE OF THE U.S. NATIONAL LIGHTNING DETECTION NETWORK

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1. INTRODUCTION

The motivation for this paper is to provide a consolidated overview of current and future capabilities of the U.S. National Lightning Detection Network (NLDN) to users who may be somewhat familiar with the system but not all of its capabilities. The three major capabilities to be discussed here are over-land cloud-to-ground (CG) lightning detection, long-range CG detection, and cloud lightning detection. The first two are current capabilities, while the third is to be implemented by spring 2006. To some degree, this paper also discusses evaluations of the performance of the network in each of these three categories, although in this paper we focus more on the latter two capabilities. Cummins *et al.* (2006, paper 6.1 in this conference) give a thorough discussion of recent field campaigns to validate the performance of the NLDN's over-land CG detection aspect.

This paper concentrates on the NLDN and is not designed to provide a detailed comparison between the NLDN and other lightning detection technologies, ground-based or otherwise. That said, however, we do mention the strengths and limitations of the NLDN relative to other detection systems where appropriate. For specific details of the performance characteristics of other systems, however, we refer the reader to the references.

2. CURRENT COMPOSITION OF THE NLDN

In 2002 and 2003, the NLDN was upgraded in order to improve maintainability by eliminating outdated sensor technology. Another objective of the upgrade was to improve detection efficiency along the southern border, along the Gulf coast, and in some areas of the interior western US. To satisfy this goal, the sensor type was made uniform across the network, and the number of sensors was increased slightly. The network now consists of 113 sensors, all of which are the most recent model of the IMPACT-type sensor (Cummins *et al.*, 2006 this conference), which measures both the angle and arrival time of each signal. The former configuration, by contrast, was a mix of LPATS-type sensors, which measured arrival time only, and IMPACT-type sensors (Cummins *et al.* 1998). The change to a homogeneous IMPACT network means that discharge locations can now be produced by as few as two sensors throughout the entire network. The new sensor model, called the IMPACT-ESP, has significantly faster processing capability than the former version of the sensor. This, together with the ability to compute locations with only two sensors, fulfills a third goal of the upgrade, which is to give the network a limited cloud lightning detection capability.

The NLDN is jointly operated with the Canadian Lightning Detection Network (Burrows *et al.* 2002) in order to provide seamless detection efficiency and location accuracy performance across the northern border of the US. The combined network is often referred to as the North American Lightning Detection Network (NALDN). In sections 3 and 4 below, we primarily refer to the NLDN, although much of the discussion refers equally well to the combined network. Section 5, on cloud lightning detection, refers just to the NLDN because of the recent upgrade of the US NLDN portion of the combined network.

3. CG LIGHTNING DETECTION IN THE INTERIOR OF THE NETWORK

The original purpose of the NLDN is to detect CG lightning over the interior of the US with high efficiency and good location accuracy. The quality-controlled, real-time CG lightning data stream is the one most users have today and are most familiar with. The satellite-delivered real-time data stream consists of CG flash data, but flashes are reconstructed from the positions of individual CG return strokes, according to the algorithm discussed by Cummins *et al.* (1998). Both stroke and flash data are available via Internet delivery.

Most real-time applications of the data are concerned with the flash level, so we often quantify the network's flash detection efficiency. However, a more fundamental performance metric is the stroke detection efficiency, since individual strokes are what are actually being detected and located. Field campaigns to validate network performance take both strokes and flashes into account in the detection efficiency analysis. Verification of location accuracy is always done at the stroke level. Two major categories of validation studies exist: coordinated video camera and electric field recordings (e.g., Idone *et al*. 1998a,b; Kehoe and Krider 2004), and rocket-triggered lightning studies (Jerauld *et al.* 2005). Prior to the 2002-3 upgrade, Idone *et al.* (1998a,b) demonstrated that the network detected 85-90% of CG flashes with peak currents of at least 5 kA, and the median location accuracy in the network interior was 500 m. As a result of the upgrade, location accuracy is about the same as before, but detection efficiency has been improved. The current NLDN detects 90-95% of CG flashes within the continental US, without restriction by peak current. Cummins *et al.* (2006) gives a detailed discussion of recent validation campaigns and their results.

4. LONG-RANGE LIGHTNING DETECTION

Cloud-to-ground lightning can be detected at distances of up to several thousand kilometers via signals that have been propagated through the earth-ionosphere waveguide. Beyond a distance of a few hundred km, propagation effects remove nearly all of the higher frequency components of the original signals, but those frequencies below about 40 kHz are still present. Some ground-based networks, such as the U.K. Met Office's ATD network (Lee, 1986), the WWLLN (Lay *et al.* 2004), and ZEUS (Papadopoulos *et al.* 2005) have specifically been designed around detecting VLF signals. In the NALDN, this detection capability is a benefit of sensing across a broad frequency band that encompasses both the LF and VLF. Discharges that are detected and located using predominately VLF signals are processed along with CG strokes from the network interior, but the former are filtered out of the standard quality-controlled data set. Very long distance detections are also produced over the northern Atlantic and Pacific oceans by blending data from the NALDN with networks of similar sensors in western Europe and Japan. More recently, a special VLF-only version of the IMPACT-ESP sensor was installed at 4 island sites in the Pacific ocean to improve transoceanic detection in that region (Pessi *et al.*, 2004).

In the NLDN, a long-range detection capability using widely-separated sensors was first quantified by Cramer and Cummins (1999). They used sensors on the west and east coasts of the US to locate lightning in the Great Plains (propagation path lengths of 1200-1600 km) and compared the quantity and accuracy of lightning locations obtained that way to the standard NLDN data set. Figure 1 shows a time series of the NLDN-relative detection efficiency of the long-range configuration over a five-day period in the summer of 1997. In general, Cramer and Cummins (1999) showed that this long-range configuration had a flash detection efficiency of about 10% during nighttime on both sides of the network and about 1-2% during daytime, with intermediate values when one side or the other was in darkness. Primarily large peak current discharges (> 30 kA) were detected. The median NLDN-relative location accuracy for the long-range configuration was 5 km, and the 95th percentile accuracy was in the 15-20 km range.

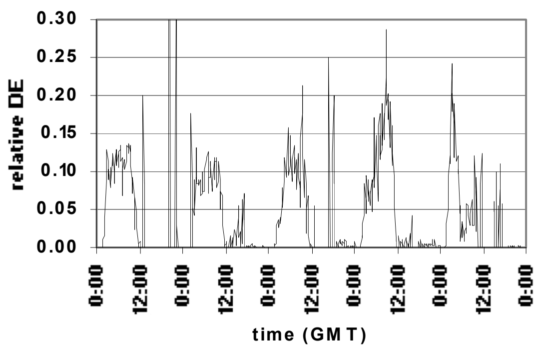

Fig. 1. NLDN-relative detection efficiency of long-range data over 5 days in summer, 1997, as a function of GMT time.

The transoceanic performance of the NALDN was studied by Boccippio *et al.* (1999) and Boeck *et al.* (1999) using satellite-based optical lightning detection (both OTD and LIS sensors). The OTD-relative detection efficiency of the NALDN was determined as a function of distance from the edge of the NALDN for both daytime and nighttime conditions, as well as propagation over land and over ocean. Satellite-based optical sensors detect both cloud flashes and CG flashes, whereas the ground-based long-range systems detect almost exclusively CG flashes. The OTD-relative detection efficiencies are therefore low relative to a true measure of CG flash detection efficiency, but an approximate correction can be made by taking into account a typical value for the ratio of cloud flashes to CG flashes, which is around 3-4. With this correction, the approximate distance at which the NALDN detection efficiency dropped to 10% could be estimated. This distance was found to vary from a low of about 1700 km for

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propagation over land during the day to about 3000 km for propagation over the ocean at night.

Samples of recent data from the long-range system and PacNet are presented in Figs. 2 and 3. Both of these images are subsets of larger satellite-lightning overlays generated by the Aviation Weather Center. In Fig. 2, we see some of the abundant lightning that was produced by Hurricane Katrina, both in the eyewall and in the outer rainbands. We also detect lightning in the central Atlantic Ocean to about 50° W, as well as over Central America, as far south as the image goes. Figure 3 was taken from a small storm that generated convection north of Hawaii. The addition of the PacNet sensors provides many more flashes than we would detect from the continents alone in this storm.

5. CLOUD LIGHTNING DETECTION

Up to now, processing of the operational NLDN data set has been configured to reject as many cloud discharges as possible, although the performance assessments discussed by Cummins *et al.* in paper 6.1 of this conference show that a large fraction of low-amplitude discharges that the NLDN detects today are cloud discharges. We are working toward a greater capability to detect cloud discharges in the NLDN and classify them correctly. This capability should be available in real time by spring 2006. The Canadian network has had a very limited (1-4% estimated detection efficiency) cloud lightning detection capability from its inception in 1998.

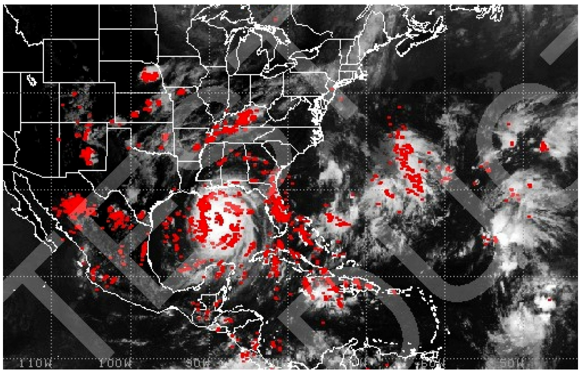

Fig. 2. Subset of long-range lightning overlay with IR satellite image showing lightning in outer rainbands and eyewall of Hurricane Katrina on August 28, 2005.

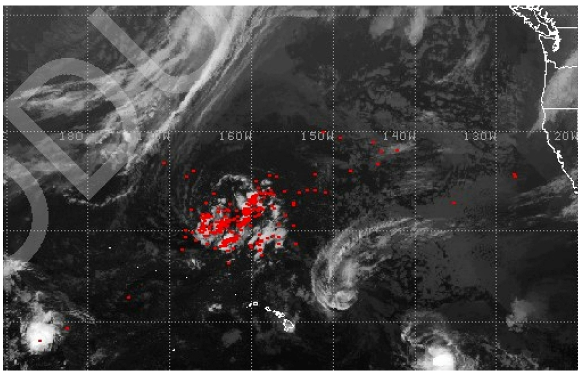

Fig. 3. Long-range lightning data overlaid on IR satellite image on Sept. 23, 2005. Convection was associated with a small storm system north of Hawaii.

With a widely-spaced network of LF sensors, it is only possible to locate the larger amplitude pulses generated by cloud flashes. This is primarily because LF signals from cloud flashes are much smaller in amplitude than those from CG return strokes. Although Ogawa and Brook (1964) observed that the K changes in cloud flashes had current amplitudes of typically 1-4 kA, our experience with running an LF sensor at close range to small storms in Florida that were observed by the LDAR VHF lightning mapping system (Mazur *et al.*, 1997) shows that most pulses are much smaller (Murphy and Cummins, 1998). Figure 4 shows cumulative distributions of range-normalized signal amplitudes from our Florida analysis for all cloud discharge pulses, the largest cloud discharge pulses, and a sample of first return strokes in CG flashes. The majority (about 70%) of all LF pulses from cloud discharges have amplitudes less than 1% of the typical first return stroke in a CG flash (equivalent to about 0.2 kA). Only the largest 1-2 pulses in each flash were consistent with an amplitude equivalent to about 1 kA. On the basis of the data in Fig. 4, we estimate that the NLDN's cloud flash detection efficiency will be around 10% over the interior of the network.

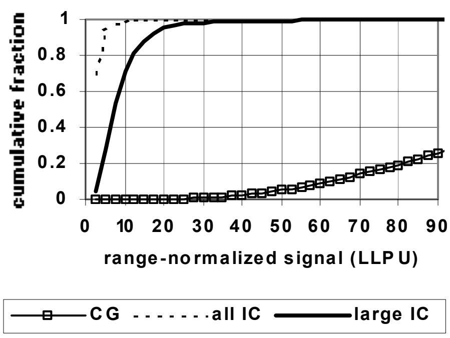

Fig. 4. Cumulative distributions of range-normalized signal amplitude in LLP Units for all LF cloud pulses ("all IC"), the largest LF pulse within a cloud flash ("large IC") and a sample of 1st return strokes in CG flashes ("CG"). Note that the CG distribution is cut off in order to highlight the IC distributions.

To test cloud discharge detection, we have operated a regional network of specially-configured IMPACT-ESP sensors near Dallas, Texas, over the past couple of years. We also operate a VHF total lightning mapping network in that region, the LDAR II system (Demetriades *et al.* 2002). The LDAR II network serves as the reference system for the cloud lightning detection capability of the regional IMPACT-ESP network. Because of the relative density of the regional test network in Texas, the expected detection efficiency of this network reaches above 25% in a region of about 100-km radius surrounding Dallas-Fort Worth and in the corridor between Dallas and Houston. The performance of the regional IMPACT-ESP system was evaluated against the LDAR II for several storms in the Dallas area during 2004. This analysis took advantage of prior NLDN validation field work by classifying all positive-polarity events with peak currents less than 10 kA as cloud discharges, even if they were originally classified as CG strokes. In this analysis, when multiple LF cloud discharge events were associated with a single LDAR flash, they were grouped together and counted as a single flash. In this way, the analysis provides a value for the cloud flash detection efficiency. Table 1 shows that the LDAR-relative cloud flash detection efficiency varied between 16-38% for a sample of 4 storms, and that those values are roughly consistent with the modeled detection efficiency.

Table 1. Summary of analysis of LF cloud detection efficiency relative to LDAR II for four isolated storms near Dallas, Texas, in spring 2004.

date	VHF flashes	LF cloud	relative DE (%)	modeled DE (%)
5/1 A	537	72	16.7	15-25
5/1 B	122	35	38.5	> 25
5/1 C	381	101	36.7	> 25
5/13	58	9	23.1	> 25

From the results presented above, it can be seen that cloud flash detection by an LF network is not nearly as good as that provided by other sensing technologies. Ground-based VHF mapping systems such as LDAR and the Lightning Mapping Array (Thomas *et al.* 2004), as well as VHF interferometry (Kawasaki *et al.* 1994) are capable of detecting almost all flashes over most of the network coverage area. The geostationary lightning mapper described by Christian (2006, this conference) will have similarly high detection efficiency over a much larger coverage area. As part of the new (2005) NLDN data delivery contract with the US government, and particularly the National Weather Service, low-level cloud flash detection capability is being added to the operational NLDN data stream.

LF cloud lightning detection is also related to satellite-based VHF detection (Suszcynsky *et al.*, 2006, this conference). The high-power VHF events seen from space are sometimes, but not always, accompanied by a short, relatively high-amplitude LF pulse often referred to as a Narrow Bipolar Event or NBE (Jacobson, 2003). NBEs typically have a much higher amplitude than the bulk of cloud discharge pulses shown above in Fig. 4 – about 70% of a typical return stroke (Smith *et al.* 1999). This means that detection efficiency in networks like the NLDN is much higher for NBEs than for ordinary cloud discharge events. These events are relatively rare; they are likely at the very upper end of the distribution labeled "large cloud" in Fig. 4, and they likely constitute less than 1% of that distribution. NBEs are apparently quite rare compared to common cloud pulses, but they appear to be closely associated with deep convection. These events are the subject of ongoing research.

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