EVALUATION OF PEAK CURRENT POLARITY RETRIEVED BY THE ZEUS LONG RANGE LIGHTNING MONITORING SYSTEM

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ABSTRACT

This study presents the first assessment of a newly developed polarity retrieval scheme augmenting a Very Low Frequency (VLF) long-range lightning detection network (named ZEUS). The polarity scheme uses the Extremely Low Frequency (ELF) in conjunction with the VLF waveform. The measured ELF signal is compared with simulated ELF signal to extract the polarity sign. This comparison also produces correlation coefficients that are used to assign four confidence index categories on the polarity sign. In this paper we present polarity results for a period (November 26 to December 15 2004) of ZEUS network operation. Assessment of the polarity measurements is conducted through comparisons against the Brazilian lightning network–RINDAT that uses a well established lightning location technology. Contingency test analysis shows that the algorithm performance is consistent with the assigned confidence level: e.g., at medium confidence level the algorithm has a 5% bias, while at high level perfect agreement is shown with RINDAT. Peak current strength was found not to influence the accuracy of the polarity retrieval.

1. Introduction

Lightning measurements have been widely used by power plant companies, meteorological offices, and by the scientific community in general. Power plant companies use these observations to protect their transmission lines and electronic circuits, while meteorologist use lightning data as a diagnostic tool for the strength of convection and to improve quantitative precipitation forecasting (Papadopoulos et al. 2005). Nowadays, besides measuring the time and location of cloud-to-ground (CG) lightning; the polarity of the current to ground is an important parameter characterizing lightning in severe storms. As noted in a recent study of severe and
non-severe thunderstorms in the central region of United States (Carey and Rutledge, 2003), severe storms have up to three times more positive CG than negative CG discharges. Moreover, the polarity of storm’s electrification has been speculated to relate to the updraft strength (Williams, 1995), which controls the all-important ice microphysics (Williams et al, 2005).

Positive CG lightning flashes typically present a continuous current that lasts hundreds of milliseconds with high current amplitude. They can cause short circuit in electronic devices, which is a major concern for power companies. Beyond this impact, observational studies reveal that the temporal evolution of both positive and negative discharges in thunderstorms can be used to indicate the life cycle stage of the storm. For example, positive discharges begin to occur during the dissipating stage of a storm (Holle et al. 1994) and in the stratiform precipitation regions of mesoscale convective systems. Furthermore, an increased frequency of positive discharges is noted in regions of extreme updrafts and during the growth of graupel and hail from super-cooled cloud water in severe storms (Stolzenburg, 1994; Carey and Rutledge, 2003) and tornados (MacGorman and Burgess, 1994).

At present moment the systems capable to retrieve charge polarity and peak current (strength and polarity) are electric field mills and IMPACT/LPATS sensors. The field mills are limited to 40-50 km range, while the IMPACT/LPATS technology is limited to 400-500 km. Both systems adopt a transmission line or a bi-polar charge structure to retrieve the strength and polarity of the peak current.

Currently available long-range lightning detection systems, such as WWLLN (World Wide Lightning Location Network--Dowden and Rodger, 2002) and ZEUS Long-range Lightning Detection System (Chronis and Anagnostou 2006; Anagnostou et al. 2002), use VLF radio receivers to locate sferics over large areas. Sferics is the radio noise emitted by lightning in
the ELF/VLF (10Hz-30 kHz) range of the electromagnetic spectrum, which can propagate over thousands of kilometers in the earth-ionosphere wave-guide. “Long-range receivers primarily detect sferics emitted from major CG lightning strikes associated with large (of either polarity) peak current amplitude” (Morales 2001). They sample the vertical electric field of the propagating sferics wave in the atmosphere, while location is then performed on the basis of the Time Of Group Arrival (TOGA) (Dowden et al. 2002) and Arrival Time Difference (ATD) techniques (Lee 1986a,b). Although long-range lightning systems have been recently demonstrated by a handful of studies (Morales 2001; Wood and Inan, 2002; Chronis and Anagnostou 2003, 2006; Rodger et al. 2004) to reach a satisfactory level in terms of locating accuracies and detection efficiencies, the ability to retrieve polarity information from these systems has not been explored yet. In another hand, the Long-Range and Trans-Oceanic Lightning Detection (Cramer and Cummins, 1999), which combines the National Lightning Detection Network (NLDN) and the Canadian Lightning Detection Network (CLDN), besides locating CG lightning it estimates the peak current strength based on the LPAT/IMPACT technology but it is limited to Northern America, and parts of North Atlantic and Pacific Oceans.

This paper presents a first attempt to evaluate the current polarity on the basis of combined VLF and ELF measurements and assess the proof of concept using preliminary ZEUS long-range network data. The algorithm developed is tested here against polarity data obtained in South Brazil from a local network of IMPACT/LPATS sensors. In the following sections we discuss ZEUS long-range network characteristics and the characteristics of the polarity algorithm. The experimental data, assessment methodology and evaluation results are presented in Section 4. Our conclusions are offered in Section 5.
2. **ZEUS Long-Range Lightning Detection Network**

The ZEUS long-range lightning detection system, fabricated by Resolution Displays, Inc., consists of a network of ten Very Low Frequency (VLF) receivers [1-Birmingham, UK; 2-Roskilde, Denmark; 3-Iasi, Romania; 4-Larnaca, Cyprus; 5-Evora, Portugal; 6-Addis Ababa, Ethiopia; 7-Dakar, Senegal; 8-Dar es Sallam, Tanzania; 9-Bethlehem, South Africa; and 10-Osum State, Nigeria] measuring radio noise emitted by lightning in the frequency range of 7-15 kHz (Anagnostou et al. 2002) based on the original concept developed by Lee (1986). In each receiver, the VLF signal is pre-amplified at the antenna site and the signals are synchronized to GPS time and encoded by Analog-to-Digital (A/D) converters. The receiver hardware has a dynamic range exceeding 100 dB with a timing accuracy within 1 microsecond of GPS time. The noise floor is typically 100 nano Volts/meter/root-Hertz RMS. The digitized data are sent to a PC with a Digital Signal Processor (DSP). The PC executes the identification algorithm that detects a probable sferics candidate and then sends compressed files to a central station over the Internet. The identification algorithm is designed to exclude weak signal and noise, and is capable of capturing up to 70 sferics/second. The receiver bandwidth is defined by a finite impulse (FIR) digital filter extending 4 kHz above and below its center at 11 kHz. Each sferics waveform is contained in a 4.5 millisecond window. The waveshape information is heavily compressed to about 160 bits per sferic. This compressed sferic data are accumulated into files of 16 seconds duration. The files are backed-up locally and transmitted to the central station.

At the central station the waveforms observed at the different outstations are compared to extract the Arrival Time Difference (ATD), as presented by Lee (1986a, 1986b). In this comparison, the 4.5 milliseconds waveform signal from two receivers are analyzed and the time lag with the highest cross-correlation value defines an ATD. Accordingly, ATD values are
computed for all possible combinations of receiver pairs. Currently the 10-receiver ZEUS network is operated on a two-continent configuration with 7 receivers (there are two common receivers) each, which represents 21 ATD values. These ATD values represent positions between two outstations with same time difference and their intersection defines a sferic fix. An interested reader is referred to Chronis and Anagnostou (2003 and 2006) for details on the ZEUS locating algorithm and its locating error evaluation.

On the evaluation of the STARNET system, precursor of ZEUS network, compared to the National Lightning Detection Network (NLDN) of USA, Morales (2001) presented a theoretical and an experimental model to determine the system’s CG detection efficiency (DE). In that study it was found that the CG DE decay is exponential with distance, where at the center of the network the system gives 100% efficiency that drops below 20% beyond 4,000 km. Morales et al. (2004) on a validation study for the current ZEUS network over southeast Brazil (~5,000 km range from ZEUS network) have found that the detection efficiency of ZEUS varied between 2% (daytime conditions) and 21% (nighttime conditions), while the mean sferics location error was found to be 62 km.

3. **The Polarity Algorithm**

The ELF and VLF regions of the electromagnetic spectrum are naturally separated by the waveguide cutoff frequency that ranges between 1.6 kHz (nighttime) and 2 kHz (daytime). Below this cutoff frequency, only one waveguide mode can propagate, i.e., the TEM mode. The initial excursion in this ELF signal is known to be a reliable indicator of the polarity of lightning (Burke and Jones, 1995; Huang et al, 1999). Above the waveguide cutoff in the VLF region, multiple modes are known to be present (Galejs, 1972), which interfere with one another. These interferences make the use of the initial excursion of the wideband signal ambiguous as to
polarity. In light of these theoretical considerations, ELF signal-processing was added to the existing VLF lightning locating system by Resolution Displays, Inc.

In the VLF frequency range used for locating, 7 to 15 KHz, the sferics propagation velocity is approximately the speed-of-light. However at frequencies below the earth-ionosphere waveguide cutoff near 2 kHz, propagation is much slower and there is large frequency dispersion causing the ELF signal to arrive several milliseconds later than the VLF burst. The delay is strongly dependent on the propagation distance and ionospheric effects of the diurnal cycle. With these parameters well defined a model can be used to predict the ELF signal, and correlation with the measured signal can be used to extract the polarity. Figure 1 illustrates VLF and ELF sferics waveform recovered from a single lightning stroke located 2,000 kilometers from receiver A and 8,000 kilometers from receiver B. At receiver A the VLF knot is received 6.7 milliseconds after the stroke while the ELF signal peak is delayed an additional 0.7 milliseconds. Receiver B detects the VLF knot 27 milliseconds after the stroke and the associated ELF signal is received 3.5 milliseconds later. The ELF signal delay and shape are modeled according to the parameters for phase velocity and amplitude attenuation listed in Table 1, which are in general agreement with those presented in the literature (Galejs, 1972).

The VLF detection distance of the existing ZEUS receivers extends to 10,000 kilometers. To detect polarity at this distance the ELF frequency range from 100 to 1000 Hz is used with a detection window extending 10 milliseconds after the VLF burst. The existing receiver hardware is unchanged and has 100 dB dynamic range in this region as well as in VLF. A large amount of power line harmonic noise exists in the ELF spectrum, which required implementing a complex filter in the receiver software. Along with VLF data stream, the filtered ELF signal captured by each receiver is sent to the central locating processor (CLP). The ratio of ELF-to-VLF signal
amplitude is also reported. At CLP the lightning location and time is first computed from VLF data as discussed in Section 2, thereby indicating the propagation path to each receiver with its diurnal conditions. On the basis of the measured propagation path and diurnal conditions we model the ELF signal. The measured ELF signal from each receiver is then correlated with the modeled signal, and the correlations are combined into weighted average among the different receivers. The resulting magnitude reveals polarity and an associated confidence level from 0 (no correlation) to 3 (high correlation). Preliminary thresholds for the confidence levels have been set empirically at 0.35, 0.55 and 0.70 to approximate the performance of the system. The sign of correlation indicates if it is positive or negative polarity, since the modeled ELF signal assumes a “Positive discharge”.

4. **Experiment & Results**

To evaluate the retrieval of lightning polarity with ZEUS, this study adopted an existing lightning detection technology developed by former Global Atmospherics Inc. (Cummins et al. 1998), and presently operated by Vaisala, Inc. This technology is able to estimate peak current polarity, in addition to locating lightning discharges. For this evaluation, we used lightning measurements in south Brazil available by RINDAT (Rede Integrada Nacional de Detecção de Descargas Atmosféricas). RINDAT is the Brazilian integrated lightning detection network deployed on the basis of cooperation between two power companies, CEMIG and FURNAS, and two research institutes, SIMEPAR and INPE (Pinto Jr. et al. 2004). This network is currently operating 24 IMPACT/LPATS sensors that are installed along the center and southeast regions of Brazil. These sensors measure the electromagnetic radiation emitted by lightning in the VLF/LF spectrum. The LPATS sensors measure the vertical electrical field component and the IMPACT sensors measure both the vertical electrical field and magnetic component. After
combining Time of Arrival (TOA) and Magnetic Direction Finder (MDF) techniques, the system is able to detect atmospheric discharges with 0.5-2 km locating accuracy and 80-90% detection efficiency (with stroke detection efficiency of 50-60%) within the RINDAT network (Naccarato et al. 2004a and 2004b).

RINDAT data for this study were available for the period November 26th to December 15th of 2004. Figure 2 presents the lightning accumulation of both ZEUS and RINDAT for the above period. As expected even though the two systems measure similar lightning properties their varied detection efficiency directly influences the spatial patterns. Specifically, RINDAT system has high detection efficiency inside the network coverage, but it is limited to a few hundred kilometers outside the network periphery. Consequently, the study area is limited to within south Brazil where during the period of this intercomparison, RINDAT observed 945,850 strokes while ZEUS measured 758,935 sferics.

To evaluate the ZEUS polarity determinations, we adopted time and space constraints to assure that both systems, ZEUS and RINDAT, are measuring the same lightning event. These constrains were set as a time window of 1 mili-second and 100 km distance between the lightning measurements. With these conditions we have found 12,178 RINDAT and ZEUS matches of which 1778 had polarity with confidence level 1, 510 with 2 and 62 with 3. The verification scores used in this study are derived using the contingency table approach. This is a two-dimensional matrix where each element counts the number of occurrences in which the two networks (ZEUS and RINDAT) agree or disagree on the lightning polarity. The table elements are defined as: A—ZEUS and RINDAT measure positive polarity; B—RINDAT measures positive polarity but ZEUS negative; C—RINDAT measures negative polarity but ZEUS positive; and D—ZEUS and RINDAT measure negative polarity. Table 2 shows the
contingency table elements A through D for the different polarity confidence levels (0 through 3).

Considering the above elements the skill of the ZEUS polarity algorithm is assessed by evaluating the bias score (BS), equitable threat score (ETS), and Heidke Skill Score, HSS (Heidke, 1926) for the different confidence levels. The bias score is defined separately for positive and negative polarity signs as,

\[
BS_{\text{POS}} = \frac{A + C}{A + B} \\
BS_{\text{NEG}} = \frac{D + B}{D + C}
\]

The ETS and HSS scores are defined as,

\[
ETS = \frac{A - (\frac{A + B}{A + B + C + D} \cdot (A + C)/(A + B + C + D))}{A + B + C - (\frac{A + B}{A + B + C + D} \cdot (A + C)/(A + B + C + D))}
\]

\[
HSS = \frac{2 \cdot (A \cdot D - B \cdot C)}{(A + C) \cdot (C + D) + (A + B) \cdot (B + D)}
\]

For a given confidence level the bias score represents the systematic overestimation (when BS>1) or underestimation (when BS<1) for positive and negative polarity, while ETS and HSS represent the accuracy of polarity retrieval, ranging from low (when ETS=0 or HSS≤0) to perfect agreement (when ETS and HSS are equal to 1). HSS and ETS scores combine the effects of probability of detection, false alarm rate and occurrences by chance.

Results for the above statistical scores are presented in Table 3. A first observation is that the confidence index used in this algorithm is a good proxy of the expected uncertainty in the retrieved polarity sign. Mainly, as the confidence index increases the ZEUS retrieval is shown to be more accurate relative to RINDAT. At high ZEUS confidence (level 3) we show perfect agreement between ZEUS and RINDAT. At medium confidence (level 2) ETS and HSS
are above 0.85 (indicating very good performance) and bias is within 7%. At poor confidence (level 1) ETS and HSS drop to moderate levels of performance (0.44 & 0.61) primarily due to erroneously assigning negative strokes as positive. Note that the positive strokes are now overestimated by 55%, while negative strokes are underestimated by 7%. At no confidence (level 0) ETS and HSS scores are nearly zero indicating no agreement between ZEUS and RINDAT. Another presentation of ZEUS-RINDAT comparison is shown in Figure 3a, which plots the peak current measured by RINDAT and the correspondent ZEUS match, i.e., the estimated confidence polarity sign. A point to note is the lack of dependency on the peak current strength. These results indicate that even the weak lightning strokes travel large distances and can be detected in the ELF waveforms. The figure further confirms the contingency table statistics in that ZEUS-RINDAT polarity sign agreement is strongly associated with the confidence index assigned by the ZEUS polarity algorithm.

Figure 3b shows the relative frequency (in %) of each confidence level index in the retrieved polarity values as a function of distance from the center of ZEUS network in Africa [20N and 20E]. The range rings (of 2000 km resolution) are presented in panel (d) of the figure. Results indicate a strong range dependence on the polarity retrieval quality. It is noted that the relative frequency of high quality indices (2 and 3) fall exponentially with range. For example at about 2,000 km range we get more that 50% (70%) of the ZEUS polarity measurements to be associated with confidence index 3 (3&2) indicating very good performance. On the other hand the probability of no agreement (index 0) is about 7%. At long ranges (>10,000 km) the high performance indices (2&3) drop below 10%, while the no agreement index (index 0) goes above 70%. Finally, Figure 3c presents the percentage of negative and positive sferics of confidence level 2 & 3 classified by range from the centre of the network. It is clear an exponential decay of
this classification with range, which can be attributed to the signal strength decay due to attenuation. It is also important to note that there is more negative sferics than positive which is consistent with several studies that have found that more than 80% of CG discharges have negative polarity [e.g., Carey and Rutledge, 2003]. In these data we note an average negative-to-positive ratio of 5 to 1 for ranges below 4000 km, which drops to about 3 to 1 at far ranges.

5. Conclusions

The paper evaluated an experimental ELF-based algorithm designed to assign peak current polarity to the lightning fixings retrieved by a VLF long-range lightning detection network. The results indicate that the application of the ELF associated with the VLF waveform signal is a good proxy to depict the polarity signal of sferics measurements. The analyses showed that the higher confidence indices (2 & 3), assigned by the polarity algorithm on the basis of correlation between simulated and measured ELF signal, are strongly associated with the agreement of ZEUS with RINDAT network polarity signs. At high confidence, ELF-based polarity assigned by ZEUS algorithm reach perfect agreement with the polarity sign provided by the local RINDAT network located 5,000 km away from ZEUS. It is also important to notice that there is no peak current strength dependence on polarity detection accuracy. Moreover, the study showed that the relative frequency of the high quality polarity indices (2 & 3) would decrease exponentially with range from the network. It was shown that the algorithm is able to retrieve sferics polarity up to 10,000 km range with significant portion associated with a good-to-high quality index. Beyond that range the fraction of good-to-high quality indices drops below 30%. 
Acknowledgments. The study was supported by NSF through a Water Cycle Program grant to Prof. Anagnostou. Zeus data from the European network are available on the basis of Memorandum of Agreement between the University of Connecticut and the National Observatory of Athens. RINDAT data were obtained from FURNAS Centrais Elétricas under a scientific cooperation.
6. References


Dowden R.L., Brundell J.B., Rodger C.J. (2002), VLF lightning location by time of group arrival (TOGA) at multiple sites, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 64, Number 7, May 2002, pp. 817-830(14)


Table 1: Modeled ELF phase velocity and attenuation as a function of frequency and diurnal conditions (day versus night).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>c/v (daytime)</th>
<th>c/v (nighttime)</th>
<th>Attenuation (daytime) (dB/Mm)</th>
<th>Attenuation (nighttime) (dB/Mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.33</td>
<td>1.20</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>300</td>
<td>1.25</td>
<td>1.15</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1000</td>
<td>1.15</td>
<td>1.09</td>
<td>16.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Table 2: Contingency table elements for the different confidence index categories.

<table>
<thead>
<tr>
<th>Confidence Index</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>430</td>
<td>3039</td>
<td>1429</td>
<td>4930</td>
<td>9828</td>
</tr>
<tr>
<td>1</td>
<td>173</td>
<td>144</td>
<td>32</td>
<td>1429</td>
<td>1778</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>9</td>
<td>3</td>
<td>417</td>
<td>510</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>44</td>
<td>62</td>
</tr>
</tbody>
</table>
Table 3: Contingency table statistics for the different confidence index categories.

<table>
<thead>
<tr>
<th>Confidence Index</th>
<th>BIAS_POS</th>
<th>BIAS_NEG</th>
<th>ETS</th>
<th>HSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.51</td>
<td>0.33</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>1</td>
<td>1.55</td>
<td>0.93</td>
<td>0.44</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>1.07</td>
<td>0.99</td>
<td>0.85</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 1: Illustration of VLF and ELF sferics waveforms from a lightning stroke located 2,000 kilometers from receiver A and 8,000 kilometers from receiver B. The VLF knots are cross-hatched to emphasize the independence of VLF phase from polarity. Peak amplitudes have been normalized.
Figure 2: Lightning activity observed from November 26th through December 15th 2004 by (a) ZEUS (left panel) and (b) RINDAT (right panel).
Figure 3: Panel (a)—ZEUS confidence and polarity sign versus coincident RINDAT peak current measurements. Panel (b)—Relative frequency (in %) of the different polarity confidence levels classified by range from the center of ZEUS network [20N, 20E]. Panel (c) Frequency of negative (black) and positive polarity as a function of range from the center of ZEUS network [20N,20E], assuming confidence levels 2 and 3. Panel (d) rings of 2000-km from the center of ZEUS network [20N, 20E].