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WWLL global lightning detection system: Regional validation study in Brazil

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[1] An experimental lightning detection network, the World Wide Lightning Location network (WWLL), is being developed to provide real time global coverage with 10 km location accuracy and at least 50% detection efficiency. This paper provides a "worst case" analysis of WWLL location accuracy in Brazil where the VLF lightning receivers that make up the network are very distant (>7000 km). Through comparison to a local lightning detection network, we analyze the detection accuracy in Brazil with respect to time, location, and peak current of lightning strokes. In this study, we find that WWLL detection is highly dependent upon the peak return stroke current, resulting in detection of about 0.3% of the total lightning strokes. However, the detected strokes have a location accuracy of 20.25 ± 13.5 km and a temporal accuracy of 0.06 ± 0.2 ms, providing a good overview of regions of overall global lightning activity in real time. *INDEX TERMS:* 2494 Ionosphere: Instruments and techniques; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Lay, E. H., R. H. Holzworth, C. J. Rodger, J. N. Thomas, O. Pinto Jr., and R. L. Dowden (2004), WWLL global lightning detection system: Regional validation study in Brazil, *Geophys. Res. Lett.*, *31*, L03102, doi:10.1029/2003GL018882.

1. Introduction

[2] A global lightning detection system has a variety of applications in the scientific, commercial, and governmental sectors. Scientifically, it could provide a better understanding of the global electric circuit [*Volland*, 1984] or provide better global tracking of severe storms. Its seasonal and yearly averaged data could be used as an indicator of global climate change [*Schlegel et al.*, 2001]. Data on global variation in "strong lightning" would be extremely helpful in estimating the direct impacts on the local regional and global atmosphere of transient luminous events (TLEs), such as sprites, elves, and halos [*Rodger*, 1999]. Lightning estimates in areas with poor radar coverage can be used to estimate convective rainfall as well as to predict flash flooding [*Tapia et al.*, 1998]. Global lightning data could be used in the commercial sector (e.g., shipping) or in the governmental sector (e.g., forest fire management and the initialization of weather forecast models).

[3] Current lightning detection techniques cannot provide continuous global coverage. Satellite lightning detection systems can only observe each point on the earth for about 15 hours each year [*Christian et al.*, 2003], and thus cannot make continuous real time observations. Ground-based commercial lightning detection networks provide the real time observations that satellite measurements lack [e.g., *Orville et al.*, 2002], but their coverage is limited to a few continental locations. The cost and logistics of ground-based networks makes them unlikely to be implemented over oceans or in areas of low population density.

[4] The World Wide Lightning Location network, just now coming online, overcomes the limitations of satellite-based or regional-based lightning detection systems. In its trial stage, this relatively low cost network continuously detects strong lightning anywhere in the world and should eventually provide real time global coverage of a majority of lightning events with location accuracy to within 10 km [*Rodger and Dowden*, 2003]. Here, we provide an analysis of WWLL in a region where the VLF lightning receivers are very distant (>7000 km) to determine its stroke location accuracy in a worst-case scenario.

2. WWLL Network Description

2.1. Configuration

[5] During data collection for this paper (March 2003), the WWLL consisted of 11 active VLF receivers, with several new receivers in the process of deployment. Table 1 shows locations of active receivers. *Dowden et al.* [2002] describe the instrumentation at each site and present data from the initial six receiving sites spanning from New Zealand to Japan. The VLF receiver stations each consist of a short (1.5 m) whip antenna, a GPS receiver, a VLF receiver, and an Internet connected processing computer. The antennas are mounted on ferro-concrete buildings. Because they are adequate conductors at VLF, these buildings remain at ground potential and shield the antenna from local man-made noise. In addition, the vertical electric field from strong CG lightning dominates over power line noise. WWLL receivers thus have relative freedom from the restriction of noise-free receiver locations required for other long-range lightning location techniques [e.g., *Fullekrug and Constable*, 2000].

[6] The antennas measure radio wave pulses (spherics) in the VLF band (1–24 kHz) radiated by lightning discharges. Lightning generated waves in this frequency range can

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Table 1. Station Locations

Station	Latitude (deg)	Longitude E (deg)
Dunedin, New Zealand	−45.8639	170.514
Darwin, Australia	−12.3718	130.868
Perth, Australia	−32.0663	115.836
Singapore	1.2971	103.779
Brisbane, Australia	−27.5534	153.052
Osaka, Japan	34.8232	135.523
Tainan, China	22.9969	120.219
Budapest, Hungary	47.4748	19.062
Seattle, USA	47.654	−122.309
Cambridge, USA	42.3604	−71.0894
Durban, South Africa	−29.8711	30.9764

Map of receiver locations can be found at http://ritz.otago.ac.nz/~sferix/TOGA_network_global_maps.html.

propagate many thousands of kilometers in the Earth-ionosphere waveguide because of low attenuation and high power spectral density [*Crombie*, 1964]. When a station measures a spheric exceeding a threshold level, it sends that event trigger time back to the central processing point. If four or more stations detect an event, the location and time of the discharge is determined by minimizing the differences in station arrival times [*Lee*, 1986]. The minimization routine produces a location and timing "residual" that indicates an accuracy estimate of the measurement. The global data are then posted to the internet every 10 minutes (see http://ritz.otago.ac.nz/~sferix/TOGA_network.html).

[7] The time of group arrival (TOGA) processing software, discussed by *Dowden et al.* [2002], had not been implemented during the time of our study, such that the network relied upon simple time of arrival (TOA) observations. Beginning August 2003, TOGA software is being trialed in the network.

2.2. Coverage

[8] A global flash rate of 0.5 flashes/sec is estimated from April and May 2003 WWLL data, using the conservative criterion of "good data" as WWLL locations with residuals ≤20 microseconds. Yearly averaging from satellite measurements approximates a total global flash rate of 44 ± 5 flashes/sec, while April and May averaging alone gives about 42 flashes/sec [*Christian et al.*, 2003]. A quick calculation shows that the WWLL was providing good quality locations for approximately 1.1% of all lightning.

[9] Although this percentage is quite low, one must realize that it is a global average. Because of the positioning of detection stations, the WWLL does not provide equal coverage of all regions of the Earth. Four stations must detect an event for it to be recorded, so detection efficiency is likely to be lower in regions of low receiver density (i.e., the Americas) in comparison with regions of higher receiver density (i.e., Asia and Australia). Many stations are currently clustered in Asia and Australasia, so the WWLL measures a much greater percentage of lightning discharges in that region. In March 2003, only two operational stations in the Americas and one station in Europe result in less than 1.1% of total lightning discharges measured in those regions [*Rodger and Dowden*, 2003]. Here, we look at WWLL detection in Brazil, a region where the closest VLF lightning receivers are more than 7000 km away. Through this analysis we determine a "worst case" accuracy measurement of WWLL.

[10] A detailed consideration of global variation in the WWLL network detection efficiency is to be undertaken after the network reaches a more mature state.

3. WWLL Comparison

3.1. Method

[11] We compare WWLL lightning events with residuals less than 20 microseconds that occurred on 6, 7, 14, 20, and 21 March 2003 in the range of 40° to 55°W, 15° to 25°S to events in the same range measured by a land-based local Brazil lightning detection network, the Brazilian Integrated Network (BIN) [*Pinto and Pinto Jr.*, 2003; *Pinto Jr. et al.*, 2003b]. Figure 1 shows the region of interest in Brazil. We study these data because the BIN data had already been procured by our group for use in the sprite balloon campaign in 2002–2003 in Brazil [*Holzworth et al.*, submitted, 2003].

[12] BIN consists of 21 sensors in the region of interest, with an overall stated detection efficiency of 80% of all cloud-to-ground lightning strokes. However, return stroke peak current affects efficiency in certain ranges. Detection efficiency of events with peak current greater than 50 kA is 90% with a location accuracy of less than 1 km. For events with peak current less than 10 kA, detection efficiency could be as low as 30% with approximately 5 km location accuracy. The return stroke peak current measurement also includes uncertainty due to assumed lightning return stroke speeds, as expected for detectors of this type [e.g., *MacGorman and Rust*, 1998]. BIN cites an uncertainty of 20–30% for strokes with peak current greater than 10 kA and up to 100% uncertainty for strokes with less than 10 kA peak current [*Pinto Jr.*, personal communication, 2003].

3.2. Results

[13] In the five day time period, 671 WWLL events and 63,893 BIN events were reported in the region of interest. Taking into account the 80% accuracy of BIN and the limitation that BIN measures only CG lightning strokes [*Pinto Jr. et al.*, 2003a], a rough estimate of the percentage of all lightning events measured in this region is about 0.3%. The percentage is slightly lower in this "worst case" region than the 1.1% average global detection efficiency calculated above. To measure the accuracy of WWLL, we

Figure 1. Boxed area of Brazil shows the region of comparison between lightning location networks used in this study. As there were no WWLL receivers in South America, this region of Brazil is a low-coverage region of the WWLL network.

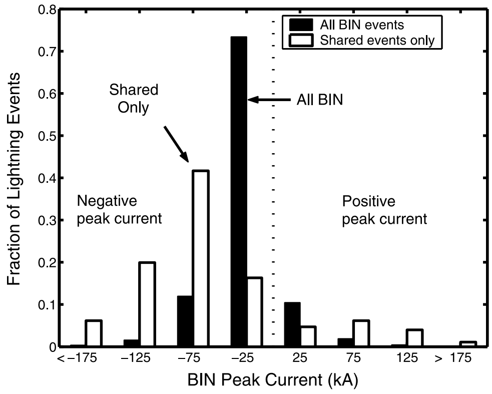

Figure 2. Histogram of return stroke peak currents measured by the BIN, shown in 50 kA bins centered on the single peak current value noted beneath them. The two outermost bins contain data for all strokes with peak current greater or less than 175 kA. Distributions are shown for shared WWLL-BIN events (white) and all measured BIN events (black).

compare the data sets from the two networks to find "shared" events. A lightning stroke is assumed to be shared if each network measures an event within the same 3 ms and 50 km. According to these criteria, 289 of the 671 WWLL events are common to the BIN stroke data.

[14] The shared events have an average return stroke peak current of 85.7 kA, as measured by BIN. In contrast, the average peak current of the entire BIN dataset is 33.3 kA, suggesting that the WWLL network only detects large discharges that exceed an approximate "threshold" in return stroke peak current. The histogram in Figure 2 represents this threshold by comparing the BIN peak current distribution of the entire BIN data set to only the BIN events which were also observed by WWLL. Overall, a greater fraction of the strokes have negative polarity, as expected. However, for discharges with an absolute value of peak current less than 50 kA the figure shows that there is a larger proportion of such low-current lightning in the overall BIN dataset (black) than in the subset made up of only shared events (white). For events with peak current greater than 50 kA, the relative pattern is reversed. This pattern illustrates that WWLL detection is biased towards lightning strokes with large peak currents.

[15] Next, we estimate the spatial and temporal accuracy of WWLL by analyzing the shared events. Time differences between shared strokes are on average 0.06 ± 0.2 ms. Note that the time resolution of the WWLL is 1 microsecond, while the BIN time resolution is 1 nanosecond. To calculate location offsets for WWLL strokes relative to their shared BIN events, we plot each shared BIN event at (0, 0) and determine the east-west and north-south deviation of the WWLL positions (Figure 3). WWLL events have a mean deviation of 3.2 km north (dashed-dotted line), 7.3 km east (dotted line) from BIN events. The plotted ellipse of one standard deviation encompasses (0, 0), indicating no statistically significant difference in the location of the shared events. The elongation of the data spread is possibly a systematic error due to VLF propagation in the Earth-ionosphere waveguide, although this matter must be investigated further. Location errors might be improved by using an enhanced location finding algorithm that incorporates ionospheric propagation. In analyzing the data for random error, we find that the absolute location error is 20.25 ± 13.5 km for WWLL network observations in this part of Brazil.

[16] In addition to shared events, we consider the unshared WWLL events to determine if they are valid measurements of lightning discharges. By plotting unshared WWLL locations with all BIN locations on each individual day, we find that 300 of the 382 unshared WWLL events lie within 30 km of BIN locations. Because 30 km is of the order of magnitude of a storm system, it seems reasonable that WWLL positions within this range represent valid lightning discharges.

[17] WWLL events farther than 30 km from any BIN event were classified as outliers, well separated from known storm centers. Data from the 5 days we consider contains 82 outliers. In order to verify whether the outlier events are likely to be valid lightning discharges, we use independent VLF measurements from the balloon campaign [*Holzworth et al.*, Submitted, 2003] as well as raw data from the BIN network.

[18] The data collection period of the 7 March 2003 balloon flight overlaps with only a few measured WWLL outliers. Even so, balloon data indicate the arrival of a lightning spheric by a spike in AC electric field strength within a millisecond of one of the WWLL outliers (Figure 4) [*Holzworth et al.*, Submitted, 2003; *Thomas et al.*, Submitted, 2003]. As such, we can be confident that this WWLL position was due to a lightning discharge located near the balloon.

[19] Having found independent data that verified the existence of lightning associated with one outlier event, we look into better determining the validity of the remaining 81 outliers. By using raw data from the BIN network, we can compare WWLL events to data that may have been discarded in the measurement algorithm, but still contains valuable information. For example, if the minimum number of BIN stations did not detect an event, one or two stations may still

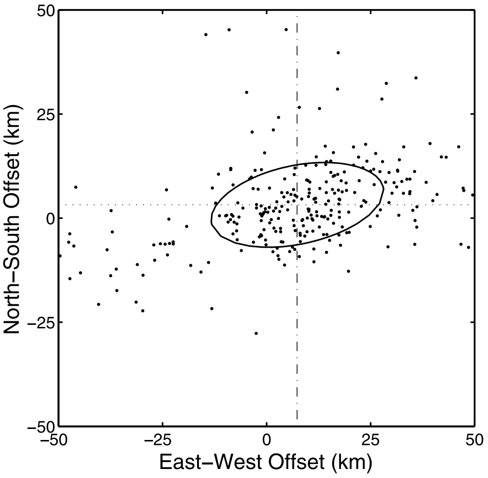

Figure 3. Location offsets of shared WWLL-BIN events relative to the BIN-determined discharge position. Each shared BIN event is taken to be at (0, 0) and the corresponding WWLL event is plotted relative to (0, 0). Mean location offset is 3.2 km north (dashed-dotted), 7.3 km east (dotted). One standard deviation (ellipse) encompasses (0, 0).

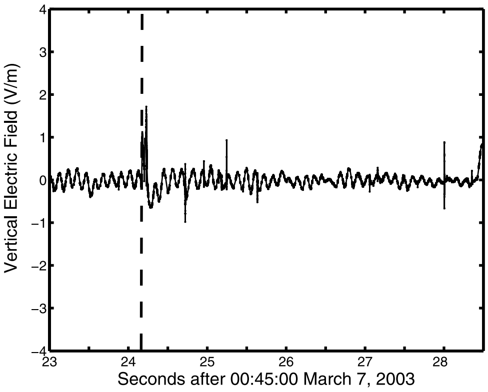

Figure 4. Vertical AC-field measurements beginning at 00:45:23 UT from a balloon flight on 7 March 2003. The timing of a WWLL reported outlier event is marked at 00:45:24.173 UT (dashed-dotted line), coinciding to within a millisecond of the spike in the balloon-measured AC-field.

have recorded a time and approximate location. The processed data would exclude such an event in the final lightning positions due to large uncertainties in the location. BIN algorithms also exclude IC lightning based on waveform shape, since the network is only interested in measuring CG lightning accurately [*Pinto Jr.*, personal communication, 2003].

[20] We found that the event at 00:45:24.173 UT on 7 March 2003, measured by WWLL and verified by VLF balloon data, was also present in the raw BIN data, but not in the final processed BIN data. The raw BIN event occurred within 1 millisecond of the WWLL event time, but separated by a distance of 63.3 km. Since raw BIN data has low location accuracy we cannot use these locations for comparison with the WWLL positions. However, we can confirm that the WWLL events are associated with real lightning discharges occurring in the region.

[21] Of the 82 outlier events, 43 occurred within 1 millisecond of a BIN raw data event. Of these 43, 75% were reported by WWLL to be located within 30 kilometers of the roughly located raw BIN event.

[22] For the remaining 39 outliers, we analyze the raw BIN data that has been classified as IC lightning and hence discarded. Of these remaining outliers, 25 of the WWLL events occurred within 1 millisecond of BIN-measured IC flashes while 7 were within 10 milliseconds. This information leads us to believe that WWLL can measure IC lightning as well as CG, and is not currently configured to distinguish between the two types.

[23] Only 7 of the outlying events were not matched to BIN data in some way. Since BIN claims an 90% efficiency for the high peak current events, it is probable that BIN simply missed a few events that WWLL measured.

[24] This analysis of BIN observations provides good evidence of coincident lightning for ~99% of the WWLL events. Thus, while the detection efficiency may be low, the false-positive rate is also very low.

4. Discussion

[25] This analysis has shown that WWLL provides lightning location of about 0.3% of lightning events in Brazil with an accuracy of 20.25 ± 13.5 km and 0.06 ± 0.2 ms. WWLL detection efficiency, while low compared to BIN, suffices to mark storm occurrence due to the large number of total lightning strokes that occur in storm systems.

[26] The greatest advantage of WWLL is global lightning coverage in real time at low cost. By comparison with a regional network on the outskirts of the current WWLL coverage zone our analysis indicates that WWLL-reported lightning events have excellent temporal accuracy and spatial resolution on the order of magnitude of an isolated thunderstorm. For many applications, the benefits of a global overview in real time may outweigh the fact that a very low percentage of the total lightning activity is reported. The WWLL is shown to be an important scientific and operational tool for lightning and severe-storm researchers to characterize remote storms, and should prove to be a highly useful tool for the atmospheric sciences community.

5. Future

[27] Two improvements are in the process of implementation to increase the total percentage of lightning events measured by the WWLL. The first is the installation of additional stations in the low coverage region. The second is the implementation of new timing algorithms that will account for wave dispersion by measuring time of group arrival (TOGA) of the spheric instead of the current algorithm that simply measures time of arrival. This system should make the long propagation distance of VLF waves from Brazil less important and thus increase location accuracy of lightning events. It is hoped that with further development the WWLL will meet the goal of >50% of global lightning detection efficiency, reported to within 10 km location accuracy.

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