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CALCULATING LIGHTNING DETECTION NETWORK EFFICIENCIES

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1. INTRODUCTION

Gated, wideband magnetic direction finder networks (Krider et al. 1976) have been in operation in most Canadian provinces for a decade. Produced by Lightning Location and Protection (LLP) of Tucson, Arizona, these systems have provided provincial fire protection agencies with reliable lightning data, valuable for predicting lightning-caused forest fire occurrences.

Lightning is a major cause of fire occurrence and loss in Canada. According to statistics compiled from 1980 to 1989 (Ramsey and Higgins 1992), lightning caused 38% of the nearly 11,000 fires that occurred annually in Canada. Yet, these fires accounted for 82% (2,086,091 ha) of the total area burned nationwide each year. The reason for the disparity in proportions is that most lightning-caused fires occur in remote areas. This results in longer detection times and, when fire fighting resources arrive, the fires are often large, increasing the difficulty of containment and likelihood of escape. Also, dispatched resources must be transported by air, increasing the costs to contain these fires.

To reduce the risk of large fires, efforts are now being placed in building fire occurrence prediction models. Predicting the number and locations of these ignitions could allow agencies to be prepared for high risk days and, conversely, avoid expensive preparedness costs on low risk days. Data from lightning detection networks will be used by these models but reliable estimates of the actual numbers of lightning flashes would be necessary. Current lightning detection networks have attenuation effects and as a result, fail to detect flashes, especially on the fringe of the network.

This paper will present various methods to estimate the efficiency of a gated, wideband magnetic direction finder network. Efficiency maps will be produced for the province of Manitoba and the methods will be compared to reveal the deficiencies of each approach.

2. METHODOLOGY

Three methods were used to estimate the detection efficiency of a gated, wideband magnetic direction finder network. These include the Canadian Electrical Association (CEA) detection efficiency model, Cummins' average number of sensor reports (ANSR), and the average range-normalized signal strength (RNSS). Each method was spatially calculated for the province of Manitoba and results were compared.

2.1 *CEA Detection Efficiency Model*

Under contract for the Canadian Electrical Association (CEA), Janischewskyi and Chisholm (1992) developed a model to calculate direction finder efficiencies based upon lightning amplitudes and the threshold detection levels of two of the LLP direction finders (models DF80-02 and ALDF).

In the CEA model, the direction finder efficiency is calculated as the probability of the second closest direction finder detecting a lightning flash. This is based on the probability of a flash exceeding a minimal observable current, as described by the Anderson IEEE approximation (Anderson 1982)

$$P(I > I_{min}) = \frac{1}{1 + \left(\frac{I_{min}}{31}\right)^{2.6}} \quad (1)$$

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where $P(I > I_{min})$ is the probability of the peak current I of a lightning flash exceeding the minimal observable current, I_{min}, with all currents measured in kiloamps.

The CEA model uses the threshold trigger level of the two LLP direction finder models to determine the minimal observable current. Both direction finders have a trigger level of 16 "LLP units" (the arbitrary units that LLP direction finder signal amplitude is measured in) along the north-south and the east-west axis to detect a lightning flash. Between these two directions, the DF80-02 uses the analog sum of the amplitude of the two signals received by the two orthogonal loop antennae

$$(2) \qquad A_{min}(\theta) = \frac{16}{|\sin\theta| + |\cos\theta|}$$

where A_{min} is the trigger level in LLP units and θ is the bearing from the direction finder to the lightning flash. The ALDF uses the maximum signal from either of the loop antennae

$$(3) \qquad A_{min}(\theta) = \frac{16}{\max(|\sin\theta|,|\cos\theta|)}$$

The amplitude of the signal can be related to peak current. Using triggered lightning, Orville (1991) found a linear relationship between the peak current I, in kiloamps, and the signal strength A (normalized to 100 km), measured in LLP units

$$(4) \qquad I = 2.3 + 0.19\,A$$

The CEA model uses a source/propagation model of the form

$$(5) \qquad I(D) = \frac{I\,D\,e^{D/\chi}}{100}$$

where D is distance in km and χ is an attenuation constant, typically set to 621 km.

In summary, using equations 2 or 3, one can take the trigger level for either the DF80-02 or the ALDF. With equations 4 and 5, this value is converted into the minimal current required to trigger the direction finder, or the minimal observable current, at a distance D. Using this current in equation 1 yields the probability of detection by a direction finder.

2.2 *Average Number of Sensors Reporting*

Cummins et al. (1992) described a method of determining detection network efficiency by calculating the average number of sensor reports (ANSR). The ANSR is not measurable directly because a minimum of two direction finders is needed to register a lightning flash. It is possible to measure the observable ANSR, which is the ANSR with the exclusion of less than two reporting stations.

The observable ANSR is an indirect measurement of the efficiency of a lightning detection network. With a greater number of sensors reporting flashes on average, the more likely low current flashes will be detected.

Cummins' paper shows a strong relationship between the observable ANSR and detection efficiency for the U.S. National Lightning Detection Network (NLDN). This was relationship was built using the LLP optimal location algorithm (Hiscox et al. 1984) and based on the assumptions that (1) the direction finder reports are independent, and (2) the peak current distribution detected by the network is uniform over all regions covered by the network.

2.3 *Average Range-normalized Signal Strength*

The signal strength is the peak amplitude of the signal received by a direction finder, which is a measure of the peak magnetic field radiated from a lightning flash measured at the direction finder's location. The range-normalized signal strength (RNSS) is the signal strength normalized to a predetermined distance, assuming an inverse relationship between distance and magnetic field strength.

This predetermined distance, known as the signal normalization can vary from 50 km to 298 km. Manitoba's system is currently set to 298 km.

The RNSS has a strong relationship to the peak current of a lightning flash (Orville 1991) and, as demonstrated by the CEA model, the peak current determines the probability of detection. The average RNSS is inversely related to network efficiency, as fewer weak flashes will be detected at greater distances from the network producing a bias in the average RNSS towards higher values.

2.4 *Spatial Calculations*

Manitoba has been running a lightning detection network since 1983. Until 1990, data were stored on tape cartridges, providing both individual direction finder reports and lightning flash locations.

For this study, the year 1989 was chosen. The data for the year were fairly complete with 115,019 flashes recorded between May 1 and August 28. At the time, Manitoba had seven DF80-02 direction finders in its detection network.

To conduct spatial estimates of detection network efficiencies, the province was divided into a set of grid-cells, 0.125 degrees latitude by 0.250 degrees longitude in dimension (approximately 200 square km each). The three efficiency algorithms were applied to each cell to determine the detection efficiency for that cell.

The CEA detection efficiency model was calculated for the central point of each grid-cell. Default values were used for the baseline (10.0), trigger level (16 LLP units), internal angle (10 degrees), bearing error (2 degrees) and attenuation (621 km), as defined in the CEA report.

The observed ANSR and average RNSS were calculated by averaging the values of all lightning flashes recorded within each cell.

2.5 *Scatter Plots*

Scatter plots were made of the negative flash density, i.e., the number of flashes recorded within each cell, plotted against each of the efficiency methods. This was done to compare the predicted efficiencies with the overall population of lightning events.

Also scatter plots were made of the efficiency methods plotted against each other to reveal any correlations between them. To reduce the influence of random sampling errors when comparing methods, the observed ANSR and the average RNSS were calculated only for cells where 10 or more flashes had been recorded.

3. RESULTS

3.1 *Manitoba Lightning for 1989*

Figure 1 shows the lightning flashes recorded within Manitoba in 1989 as a density, i.e., the number of flashes per cell.

Though flash density not an measure of detection efficiency, the affect efficiency has on it is pronounced. The general activity level observed is quite high in the southern half of the province and gradually decreases towards the north. A large density of flashes north of Thompson, the northern most direction finder, is indicative of an intense storm that moved through the region.

3.2 *CEA Direction Finder Efficiency*

Figure 2 shows the calculated CEA direction finder efficiency. Most of southern and central Manitoba was covered by 95% detection efficiency or greater. Corridors of poorer efficiency show up along the baselines of the network.

3.3 *Average Number of Sensors Reporting*

Figure 3 shows the observable ANSR for each cell within Manitoba. The highest values occurred in the central and the eastern regions of the province, which corresponds well with the calculated CEA model values. In the northern half of the province, ANSR values gradually decrease.

Lower values between the three northern direction finders do not match the high efficiencies predicted by the CEA model.

The map also shows the local high observable ANSR values directly between direction finders. This also contrasts the low values in the CEA model, which predicts low probabilities due to baseline errors.

3.4 *Average Range-normalized Signal Strength*

Figure 4 shows the average RNSS for each cell within Manitoba. The average RNSS values

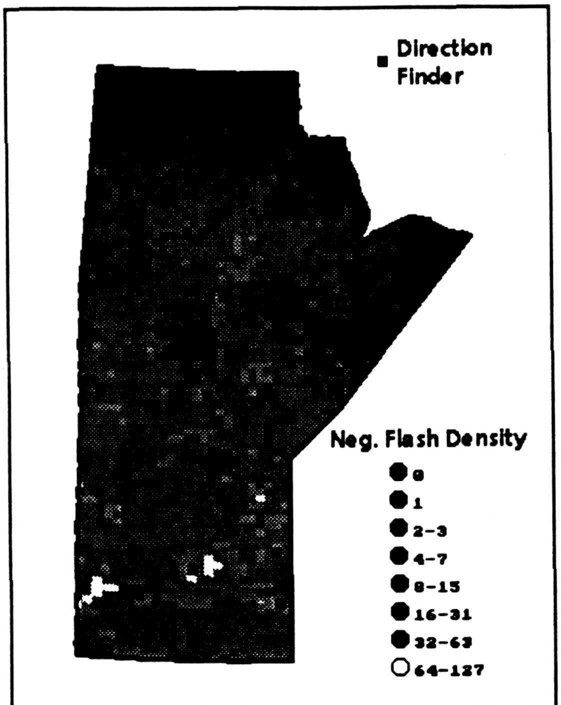

Figure 1. Negative lightning flash density for Manitoba, 1989.

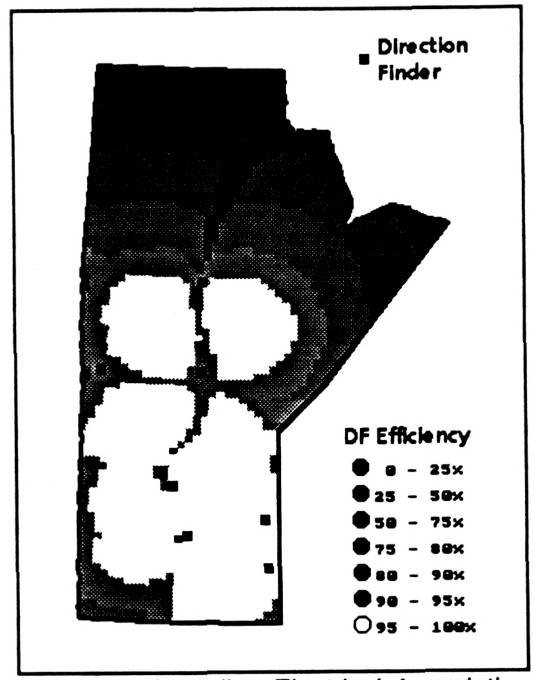

Figure 2. Canadian Electrical Association modelled theoretical maximum detection efficiency for Manitoba, 1989.

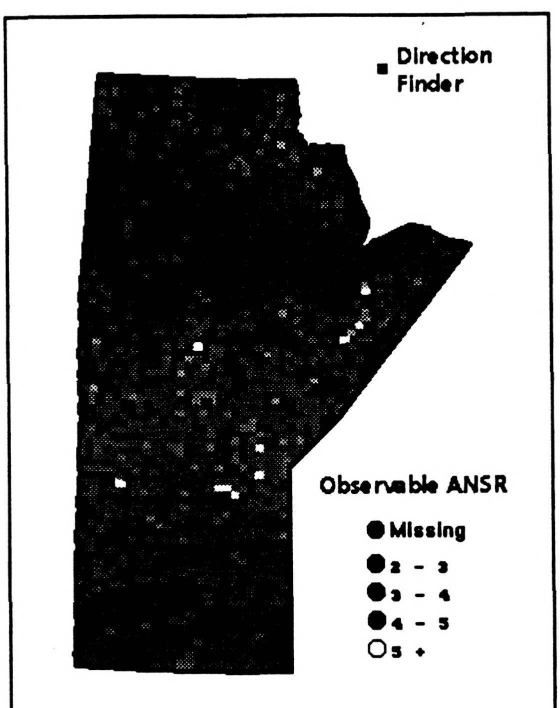

Figure 3. Average number of sensors reporting for Manitoba, 1989.

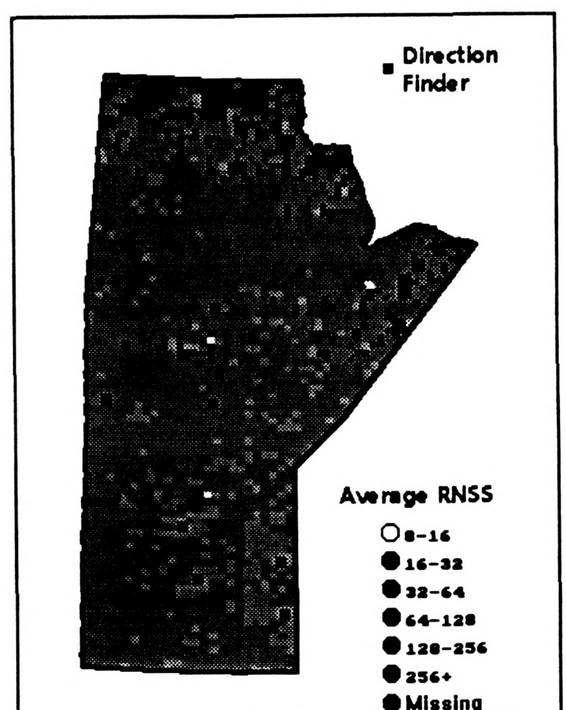

Figure 4. Average signal strength (LLP units) for Manitoba, 1989.

follow the same general efficiency trend as the ANSR. Low average RNSS values in the south that gradually increase to the north2 coincide with the peak ANSR values that decrease in the north. The region of high efficiency between the three northern direction finders as calculated by the CEA model, does not show up in the average RNSS data.

Local minimum average RNSS values, corresponding to peak detection efficiencies, tend to occur around direction finder locations, with lower values between. This contradicts the observable ANSR results but supports the CEA model's baseline error assumption.

3.5 *Scatter Plots*

Figures 5, 6, and 7 show scatter plots of calculated CEA model values, observable ANSR, and average RNSS, respectively, plotted against the number of negative flashes in each cell. The CEA model and the average RNSS show peak lightning densities at highest detection efficiencies, but the observable ANSR shows greater scatter.

Plots comparing the three methods show a great degree of scatter. Clearly, there are poor correlations between the methods, although appropriate trends appear. An exponentially increasing trend between the CEA model and the observable ANSR is apparent, which agrees with Cummins' paper. Likewise, an inverted parabolic pattern can be seen, though less clearly, between the CEA model and the average RNSS, which follows the shape described by equation 1. No trend can be seen between the average RNSS and the observable ANSR.

4. DISCUSSION

Each of the methods is, in theory, a measure of how well a lightning detection network operates. General trends shown both spatially and through scatter plots support the theory that each is a measure of this network efficiency, yet, when looking at local spatial characteristics, contradictions arise. These are reflected in the poor correlations between the methods shown in the scatter plots.

The CEA model, though based on sound physics, may have weaknesses in its assumptions regarding baseline errors and its requirement for only two direction finders to register a flash. The weakness in the latter assumption is clearly shown in the high efficiencies predicted for the mid-northern portion of the province, between the three northern direction finders, which are not supported by either of the other two methods. Incorporating more than two direction finders in the calculations could fix baseline error under-predictions and reduce the over-predicted efficiency of relatively independent direction finders on the fringe.

The apparent contradiction in local trends between the observable ANSR and the average RNSS brings into question the validity of both methods. Each method is an indirect method of measuring network efficiency and weaknesses inherent in the assumptions may be manifesting themselves through the data.

One issue that has not been addressed is that of data quality. A large number of records were garbed by the recording apparatus and rejected from this study. Missing data would have a large impact on the quality of observable ANSR measurements and may account for much of the noise in its values. Likewise, no site error analysis has been conducted on the Manitoba data, which, if present, would account for more noise.

This analysis was a first step in comparing various methods of estimating lightning detection network efficiencies. A more rigorous comparison could yield clearer correlations and explain some of the apparent contradictions among them.

5. ACKNOWLEDGEMENTS

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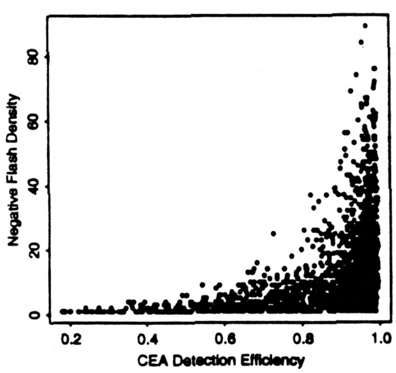

Figure 5. Canadian Electrical Association model detection efficiency versus negative flash density.

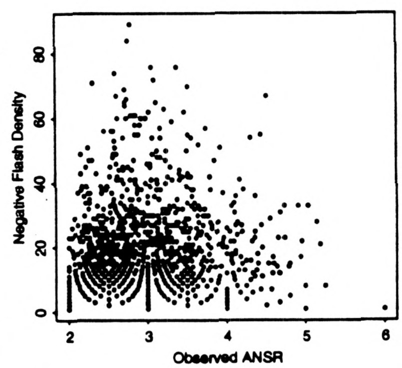

Figure 6. Observed average number of station reports versus negative flash density.

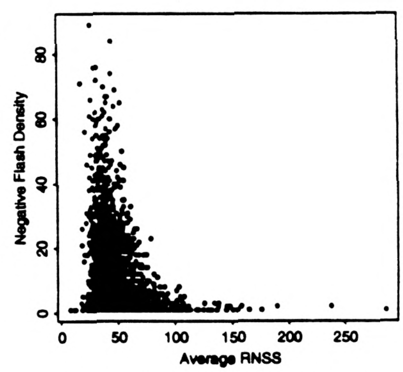

Figure 7. Average range-normalized signal strength versus negative flash density.

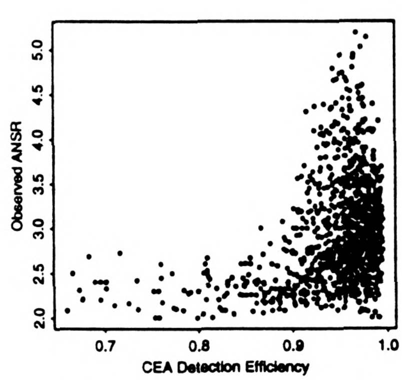

Figure 8. Canadian Electrical Association model detection efficiency versus observed average number of station reports.

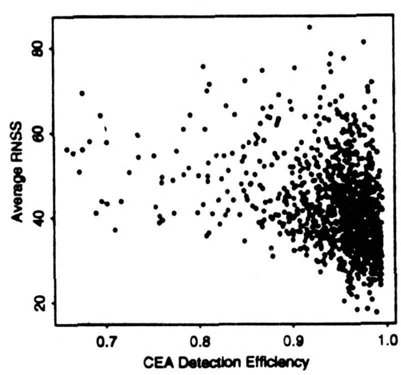

Figure 9. Canadian Electrical Association model detection efficiency versus average range-normalized signal strength.

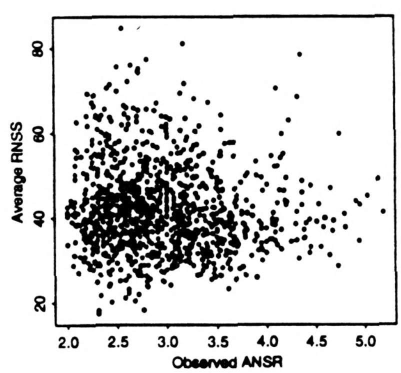

Figure 10. Observed average number of station reports versus average range-normalized signal strength.

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Front Cover: This picture of a tornado and a lightning stroke over Lake Okeechobee was taken at approximately 10 p.m. on 15 June 1991. This dramatic and unusual photograph is particularly appropriate for the cover of this preprint volume as this year's Conference on Severe Local Storms is collocated with the Conference on Atmospheric Electricity. The photograph was taken and kindly supplied by Mr. Fred Smith (3800 SW 35th St., Okeechobee, FL 34974) who retains all rights. Unauthorized duplication is prohibited. For copies and/or authorization, please contact Mr. Smith Directly.

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