A RELIABILITY STUDY OF THE LIGHTNING DETECTION NETWORK IN BRITISH COLUMBIA

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ABSTRACT

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To combat the major problem of lightning-caused forest fires in British Columbia, the B.C. Ministry of Forests operates a lightning locating system developed by Lightning Location and Protection Inc. As of 1985, this network consisted of eighteen magnetic direction-finders located throughout the Province. Lightning strike data collected by the network over three fire seasons (1983-1985) were analyzed to estimate the distribution of lightning signal strength and the component detection efficiencies. The analysis was based on more than 165,000 lightning strike records. In the mountainous terrain of British Columbia the detection efficiencies of the lightning sensors were found to be somewhat lower than earlier results obtained from similar networks in Florida and Oklahoma. Corrective actions have been taken on five detector sites found to have significantly worse than average detection efficiencies. A long-range program to improve the system by refurbishing with upgraded equipment and adding several new detector sites is underway. The statistical results vividly demonstrate the importance of archiving and analyzing the lightning strike data to provide comprehensive local-environment field tests.

In future years the data preparation and analysis techniques will be implemented annually.

1. INTRODUCTION

Lightning is the single largest cause of forest fires in British Columbia. In the last ten year period, 1976 - 1985, lightning caused 48% of all forest fires, an average of 1,156 [2,396][1] fires per year. These fires cost 184.5 [321.1] million dollars (1986$) to suppress. Lightning-caused fires burned 596,000 [985,000] hectares during the same period, resulting in 140.1 [223.4] million dollars in damage to timber, mobile equipment and structures.

The detection of lightning-caused fires is a major concern of the B.C. Ministry of Forests. Over the last six years, a high gain lightning locating system developed by Lightning Location and Protection Inc. was installed in B.C. As of 1985 this network consisted of eighteen magnetic Direction Finders located throughout the Province and at shared sites in the Yukon Territories and Alberta (see Map 1).

The lightning location system detects and analyzes electromagnetic signals in the 1 kHz to 1 MHz frequency range. An electric field antenna captures the polarity of the signal, and the azimuth bearing is sensed by a cross-loop magnetic field antenna. The antennas are connected to an analog signal processor, called the Analog Direction Finder (ADF), which filters background noise, compares all incoming signals against the "known" lightning signature profile, and forwards valid lightning data through an analog-to-digital converter to the

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[1] Data in square brackets give corresponding totals from all causes.

Digital Direction Finder (DDF). The Digital Direction Finder calculates the azimuth angle and amplitude of the incoming lightning signal and forwards these data upon request from the host computer, the Position Analyzer (PA). Upon receiving data from two or more Direction Finders, the PA performs a triangulation calculation and pin-points the most probable location of the lightning strike on the surface of the earth. The system operates in "real time" with the elapsed time from lightning event to triangulation being no more than 3 seconds. Lightning strike frequencies in B.C. have approached 4,000 lightning strikes per hour.

Basic research in the atmospheric science field led to the understanding and development of the system. Detailed information can be found in the literature published by Krider & Noggle (1975); Krider, Noggle & Uman (1976); Noggle *et al.* (1976); Krider *et al.* (1980a); Krider, Pifer & Uman (1980b).

All electromagnetic radiations are subject to certain propagation distortions (reflection, refraction and diffraction) and local direction or site errors. Site errors are defined as the difference between the observed azimuth bearing angle and the actual bearing. Methods to detect and correct these sources of errors have been developed by Hiscox *et al.* (1984) and Mach *et al.* (1986).

Detection efficiency is defined to be the proportion of lightning events detected to those actually occurring. Until recently, methods for determining the detection efficiency of a network of direction finders have relied on visual observation techniques compared with the data sensed by the network. From tests carried out in Florida and Oklahoma using these photo-visual techniques, the direction finders were reported to have 80 to 90 percent detection efficiency at 200 miles (320 km) (Byerly, 1980). The original design of the B.C. network was based on this specification, but it was unknown whether the mountainous terrain of British Columbia would adversely affect detection efficiency.

This paper describes the approach used to develop B.C. environment detection efficiency functions for each Direction Finder (DF) in the B.C. network. These functions are based on a statistical analysis of 165,132 complete lightning records compiled from network operation over three fire seasons (May 1 to September 30 for the years 1983 to 1985). Although there was no independent monitoring device to evaluate network efficiency, the extensive data proved to be very useful for estimating reliability of component DF's and uncovering weaknesses in the network. Sections 2, 3 and 4 deal with the two main objectives of the study, namely:

(i) to estimate the true distribution of range-normalized signal strengths for lightning events occurring in British Columbia during May through September periods, and

(ii) to estimate the detection efficiency for each of the eighteen direction finders in the network.

In response to the findings of the statistical analyses, the Ministry has undertaken corrective actions and network modifications which are discussed briefly in Section 5.

2. PRELIMINARY DATA REDUCTION

The following computations were made for each lightning event record:

(i) the eighteen distances from the strike position to each of the eighteen DF sites were computed using Robbins' algorithm for an oblate spheroid (see Bomford, 1971, p. 136) to correct for the earth's curvature;

(ii) the average range-normalized (ARN) signal strength as detected by the observing DF's and the associated standard error were calculated as described in Section 3; and

(iii) the record of which DF sites detected the strike was maintained (A lightning strike is typically detected by three or four Direction Finders; on rare occasions fourteen DF's have detected the same event.).

For each DF site a separate two-way data table was created which classified the lightning event data according to range (10 km width zones) and ARN signal strength (10 SSU[2] width zones). For each range r (with respect to DF site #j) and signal strength s category, the following two strike counts were recorded:

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[2]The signal strength units (SSU) are the digitized output of the peak amplitude as detected by the magnetic field antenna.

$N_j(r,s)$ = number of strikes having range r from DF site #j and signal strength s that were located by the network;

$n_j(r,s)$ = number of strikes counted in $N_j(r,s)$ that were detected by DF site #j.

The detection efficiency of DF site #j is estimated for range/signal category (r,s) by the relative frequency $n_j(r,s)/N_j(r,s)$. From these initial two-way tables the data were further reduced to produce the summary table of component detection efficiencies (see Table 2), and the detection efficiency probability curves (see Figures 2 and 3). Details of these data reductions are given in Section 4.

3. DISTRIBUTION OF RANGE-NORMALIZED LIGHTNING SIGNAL STRENGTH

As the electromagnetic radiation generated by a lightning event propagates over the surface of the earth, the signal amplitude attenuates inversely with the distance travelled (Lin *et al.* 1979). To remove the inverse range dependence of the lightning radiation field at each DF site, the DF signal strengths were normalized according to the following formula:

$$[1] \quad \text{Normalized Signal} = \frac{\text{(DF Signal Strength)(Distance from Strike to DF)}}{\text{Normalization Range of 200 km}}.$$

Thus, the normalized signal is the output signal that would be generated by a DF located 200 kilometres from the lightning strike. To approximate peak current (kA), the normalized signal should be multiplied by the conversion factor of 0.62. Thus, a lightning strike with peak current 62 kA would produce a DF output signal of approximately 100 SSU at 200 km range (Guillo, 1985).

For each observed lightning event, the Average Range-Normalized (ARN) Signal Strength, $\bar{U}$, was computed by the formula

$$[2] \quad \bar{U} = \frac{\text{Sum of Normalized Signals from all detecting DF's}}{\text{Number of detecting DF's}}$$

$$= (1/n)\sum U_i .$$

Also, the standard error of $\bar{U}$ for estimating normalized signal strength was computed by the formula

$$[3] \qquad SE(\bar{U}) = \frac{\sum (U_i - \bar{U})^2/(n-1)}{n} .$$

The distribution of observed ARN signals, grouped into 20 SSU width class intervals, is displayed in Table 1. The right-hand column of this table gives the Average Standard Error computed according to the formula

$$[4] \quad \text{Av Std Error} = \frac{\text{Sum of } SE(\bar{U})\text{'s associated with ARN Signals in class interval}}{\text{Number of ARN Signals in class interval}}$$

A graphical representation of the frequency distribution for ARN Signals is given in Figure 1 by a frequency polygon. The large data set of 165,132 observations produced a distribution that provides a good approximation for the true distribution of Normalized Signals that will be detected by the existing system during May through September periods. The distribution given in Table 1 and Figure 1 is of general interest because it gives at least a first approximation to the true amplitude distribution of a natural lightning source.

4. DETECTION EFFICIENCY COMPARISONS

To analyze the detection efficiency of a given DF site, the lightning events located by the network were classified according to range and ARN signal strength as discussed in Section 2. Within each range-ARN signal category, those events detected by the given DF were called successes of the DF; all others were called failures. From appropriate relative frequencies, detection efficiency probability curves as a function of range were constructed for each DF site. The graph for each DF contained three curves over three representative ARN signal zones (40 - 60 SSU, 80 - 100 SSU, 180 - 200 SSU). The choice of these three zones was made on the basis of representing different regions of the ARN signal strength distribution, data sufficiency, and low redundancy in presenting the information.

The first zone corresponded to the mode of the ARN signal strength distribution, the second to the steep region of the trailing edge, and the third to the leveling off region of the trailing edge. To improve reliability of these curves, a shift-and-average smoothing technique was used. The detection probability estimate for each range interval of width 10 km was computed as the average of seven relative frequencies of detection for seven overlapping range intervals, each 70 km wide, that contain the 10 km range interval. For example, the detection probability for the 100 - 110 km range interval was estimated by the average of the relative frequencies of detection for the seven range intervals (40 - 110 km, 50 - 120 km, 60 - 130 km, 70 - 140 km, 80 - 150 km, 90 - 160 km, 100 - 170 km) that contain the 100 - 110 km interval. Although the probability curves may have given somewhat inflated estimates, because any lightning events missed by the entire network could not be counted, these estimates provided powerful tools for comparing the relative efficiencies of the eighteen different DF sites in the network. Two of the eighteen graphs have been included in this paper as examples (see Figures 2 and 3). The DF at Lumby (Figure 2) achieved one of the best detection efficiency ratings; while in dramatic contrast the Bear Lake DF (Figure 3) recorded one of the worst performances. The other sixteen graphs can be found in Johnson and Zala (1985).

Instead of including all eighteen graphs here, a composite summary table is given (see Table 2) to conserve space and facilitate comparison. Each detection probability estimate in this table is based on the relative frequency of detection for those lightning events located by the network, and having ARN signal strengths larger than 30 SSU. Listed beside each estimate in parentheses is the standard error, computed by the formula

[5] (rel. freq.)(1-rel. freq.)/(sample size).

The observations with signal strengths in the 0 to 30 SSU zone were not used here, because analysis of these observations showed that the network probably had failed to detect a sizable proportion of low strength signals. The analysis that led to this decision was based on the assumption that within the immediate vicinity of a DF (160 km) the lightning flash density is uniform. In the long-run 25% of those lightning events occurring within 160 km of a given DF should fall within 80 km of the DF, as the area of a circle is reduced by a factor of 4 when its radius is halved. The observed percentage was computed for each of the seventeen circular regions centered at the different DF sites except Teslin, then averaged over the seventeen sites to obtain a figure that theoretically should be near 25%. (The Teslin site was excluded because of insufficient data.) This calculation was performed first for those lightning events with signal strengths above 30 SSU, and again for those below 30 SSU.

For the above 30 SSU group the percentage was 25.9%; but for the below 30 SSU group it was 39.1%, well over the theoretical 25%. This suggested that the network probably failed to detect a sizable proportion of low strength signals occurring more than 80 km from the nearest DF.

From the information provided in Table 2, it is clear that the results of reliability tests carried out in Florida and Oklahoma are not valid for the B.C. environment. Although the estimates in Table 2 may be somewhat inflated, all except for Peace River are well below the 80 - 90% at 320 km figure suggested by the Florida/Oklahoma results. The results in B.C. are consistent with other recent findings which have indicated average detection efficiencies of 50 - 70% (Mach *et al.*, 1986). Location appears to play a large role in DF reliability as indicated by the wide variation in performance levels among the eighteen Direction Finders in the B.C. network.

These results vividly demonstrate the importance of archiving and analyzing these data sets to provide comprehensive local-environment field tests.

5. UPDATE OF MINISTRY RESPONSE

The B.C. lightning detection network's lower detection efficiency has been attributed primarily to the mountainous terrain of British Columbia. For example, if the detection efficiency of the Peace River DF in the 0 to 80 km range (see Table 2) at 93% is compared to the Dawson Creek DF at 78%, an estimated 15% reduction in detection efficiency is observed. The Dawson Creek DF is 180 km due west of Peace River and situated in the eastern foothills of the Rocky Mountain trench. We have concluded that the reduction of detection efficiency can be attributed to the presence of mountains.

From results of the statistical analysis, five DF's were identified as having significantly worse than average performance. A detailed problem analysis was performed on each of these Direction Finders. Decisions resulting from this process are discussed below.

Marguerite: Analysis identified a problem with the telecommunication line servicing this site. As a result B.C. Tel. modified the communication circuit and placed a high priority status on all trouble reports. No significant failures of this circuit occurred during the 1986 lightning season.

Dease Lake: Initial analysis suggested the problem may have been caused by the site being heavily treed. However, a more significant problem was uncovered during the spring field check, when the alignment of the looped magnetic field antenna was checked using "solar" noon. (At local solar noon the south and north arms of the magnetic field antenna are superimposed casting a single shadow). The antenna alignment was found to be approximately 30 degrees in error. Surveyors originally had aligned the antenna to magnetic north instead of true north.

Pink Mountain: An analysis of antenna systems located on mountain tops close to microwave sites suggested that the electric field antenna was being shielded by the microwave tower. The electric field antenna has been moved approximately 200 m away from the microwave antenna structure.

Bear Lake: This site has had a history of no detections in the northwest quadrant. Despite extensive efforts the cause was not found. Subsequently, the Bear Lake DF was moved 80 km north to McKenzie for the 1986 lightning season.

High Level: This DF is an Alberta Forest Service site, which is heavily treed. Alberta has been aware of the poor detection efficiency of this site and will be moving it in the fall of 1986.

To improve network detection efficiency, two new DF's were installed in 1986 at Creston and Jasper (see Map 2). Also, three new sites are planned for 1987 at Pemberton, Anahim Lake and Meziadin Lake.

The manufacturer of the lightning location equipment has produced an upgraded version with an integrated design of the antenna systems, analog and digital computers. Benefits of this new design are the improvement in detection efficiency at extremely low signal strengths, improvement of the dynamic range, and better diagnostic and maintenance characteristics. This new equipment will be used to refurbish the network over the next five years.

The preparation and analysis techniques will be implemented annually to analyze the most recent lightning season data and compare the results to this benchmark.

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TABLE 1. Distribution of average normalized signal strengths

AVERAGE NORMALIZED SIGNAL INTERVAL (SSU)	NUMBER OF OBSERVATIONS (frequency)	RELATIVE FREQUENCY	AVERAGE STANDARD ERROR (SSU)
0.0 to 20.0	2702	0.0164	3.57
20.0 to 40.0	21528	0.1304	3.70
40.0 to 60.0	34315	0.2078	5.24
60.0 to 80.0	28790	0.1743	7.40
80.0 to 100.0	20743	0.1256	9.74
100.0 to 120.0	14810	0.0897	12.15
120.0 to 140.0	10667	0.0646	14.95
140.0 to 160.0	7765	0.0470	17.16
160.0 to 180.0	5746	0.0348	19.78
180.0 to 200.0	4210	0.0255	22.99
200.0 to 220.0	3106	0.0188	27.01
220.0 to 240.0	2183	0.0132	31.08
240.0 to 260.0	1733	0.0105	35.98
260.0 to 280.0	1337	0.0081	42.63
280.0 to 300.0	1025	0.0062	45.56
300.0 to 320.0	802	0.0049	54.81

TABLE 1. Distribution of average normalized signal strengths (continued)

AVERAGE NORMALIZED SIGNAL INTERVAL (SSU)	NUMBER OF OBSERVATIONS (frequency)	RELATIVE FREQUENCY	AVERAGE STANDARD ERROR (SSU)
320.0 to 340.0	598	0.0036	62.04
340.0 to 360.0	497	0.0030	67.37
360.0 to 380.0	391	0.0024	70.72
380.0 to 400.0	301	0.0018	86.92
400.0 to 420.0	239	0.0014	87.97
420.0 to 440.0	207	0.0013	89.91
440.0 to 460.0	162	0.0010	90.61
460.0 to 480.0	163	0.0010	113.76
480.0 to 500.0	129	0.0008	118.06
500.0 and up	983	0.0060	330.23
Total	165132		

Table 2. Component Detection Efficiencies. First entry is lightning detection probability estimate; entry in parentheses is standard error.

DF NO.: LOCATION	RANGE ZONES (km) 0 to 80	80 to 160	160 to 240	240 to 320	320 to 400	400 to 480
1: BRISCO	.77 (.0073)	.73 (.0045)	.73 (.0035)	.62 (.0034)	.45 (.0036)	.26 (.0034)
2: LUMBY	.74 (.0055)	.77 (.0033)	.74 (.0036)	.68 (.0039)	.55 (.0039)	.32 (.0035)
3: VAVENBY	.79 (.0065)	.77 (.0042)	.64 (.0037)	.60 (.0030)	.47 (.0032)	.28 (.0033)
4: LAC LE JEUNE	.79 (.0069)	.77 (.0039)	.72 (.0035)	.63 (.0039)	.48 (.0040)	.32 (.0032)
5: DUNCAN	.79 (.0189)	.72 (.0118)	.58 (.0095)	.34 (.0053)	.23 (.0036)	.13 (.0025)
6: CAMPBELL RIVER	.85 (.0189)	.68 (.0174)	.57 (.0116)	.38 (.0068)	.14 (.0032)	.06 (.0018)
7: MARGUERITE	.59 (.0083)	.65 (.0049)	.58 (.0049)	.46 (.0042)	.32 (.0032)	.15 (.0022)
8: VANDERHOOF	.72 (.0086)	.69 (.0056)	.59 (.0050)	.49 (.0043)	.34 (.0038)	.18 (.0030)
9: SMITHERS	.80 (.0127)	.81 (.0076)	.74 (.0068)	.57 (.0063)	.40 (.0048)	.26 (.0038)
10: DEASE LAKE	.36 (.0411)	.27 (.0234)	.13 (.0122)	.16 (.0097)	.08 (.0048)	.05 (.0030)
11: WATSON LAKE	.84 (.0296)	.67 (.0235)	.54 (.0214)	.44 (.0163)	.21 (.0088)	.10 (.0048)
12: FORT NELSON	.85 (.0100)	.75 (.0069)	.64 (.0058)	.57 (.0050)	.37 (.0049)	.17 (.0037)
13: PINK MOUNTAIN	.33 (.0087)	.30 (.0051)	.38 (.0050)	.38 (.0043)	.26 (.0035)	.18 (.0030)
14: DAWSON CREEK	.78 (.0069)	.75 (.0040)	.71 (.0036)	.64 (.0034)	.53 (.0035)	.38 (.0038)
15: BEAR LAKE	.54 (.0093)	.43 (.0051)	.37 (.0040)	.31 (.0034)	.23 (.0032)	.14 (.0027)
16: TESLIN	.56 (.1656)	.74 (.0757)	.82 (.0822)	.76 (.0705)	.36 (.0543)	.42 (.0562)
17: HIGH LEVEL	.68 (.0160)	.63 (.0094)	.47 (.0093)	.25 (.0075)	.12 (.0048)	.06 (.0034)
18: PEACE RIVER	.93 (.0081)	.94 (.0039)	.90 (.0041)	.80 (.0055)	.60 (.0067)	.43 (.0074)

CAPTIONS

MAP 1. Provincial lightning detection sites 1985

MAP 2. Provincial lightning detection sites 1986.

FIG. 1. Line graph of frequency distribution of average normalized signal strengths.

FIG. 2. Detection efficiency curves for direction finder number 2.

FIG. 3. Detection efficiency curves for direction finder number 15.