LIGHTNING DETECTION IN BRITISH COLUMBIA: AN EXAMPLE OF USING SYSTEM OPERATION OF UNKNOWN RELIABILITY TO ESTIMATE COMPONENT RELIABILITY

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LIGHTNING DETECTION IN BRITISH COLUMBIA; AN EXAMPLE OF USING SYSTEM OPERATION AT UNKNOWN RELIABILITY TO ESTIMATE COMPONENT RELIABILITY

(*abbreviated title*: LIGHTNING DETECTION IN BRITISH COLUMBIA)

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ABSTRACT

Lightning data collected over three dry seasons from the detection system operated by the British Columbia Ministry of Forests were analyzed to estimate the distribution of lightning signal strength and component detection efficiencies. The analysis was based on more than 165,000 lightning strike records where component detectors served both as lightning finders and as data collectors for evaluating the performance of other component detectors in the network. In spite of the unusual feature of this application involving a system evaluating itself, much was revealed to identify weaknesses and suggest improvements. A post-analysis system modification update is included.

1. INTRODUCTION

Each dry season lightning-caused fires are responsible for extensive damage to the vast forest regions of British Columbia. During the ten-year period, 1976 to 1985, lightning-caused fires burned 596,000 hectares of B.C. forests. To combat this problem the B.C. Ministry of Forests operates a lightning location detection network which as of 1985 consisted of eighteen field detectors, called direction finders, located throughout the Province and just beyond its northern and eastern boarders (see Map 1). These direction finders monitor electromagnetic radiation and filter out all but cloud to ground lightning signals. They measure azmuith, time, and signal strength of all detected cloud to ground signals and send this information to a central computer, called the position analyzer. Whenever a lightning signal is located by two or more direction finders, its triangulated position is computed for appropriate evaluation and investigation.

When constructing the network the direction finders were spaced from 110 to 430 kilometres apart. An important factor in determining their initial positions was a published specification that each direction finder had 80 to 90 percent detection efficiency at 200 miles (320 kilometres) range. This specification was based on tests carried out in Florida and Oklahoma using an expensive, independent photo-visual monitoring process. The question of whether or not this efficiency rating was appropriate for direction finders located in the rugged terrain of British Columbia remain unanswered. Because of the enormous cost, a comprehensive independent field test of the entire B.C. lightning detection network was not feasible.

From network operation during three dry seasons (May 1 to September 30 for the years 1983 to 1985) 165,132 complete lightning event records were compiled.

In the fall of 1985 Barrodale Computing Services Limited, with this author as consultant, was awarded a contract to carry out a statistical analysis of the B.C. lightning data. Although there was no independent monitoring device to evaluate network efficiency, the extensive data proved to be very useful for estimating component reliability and uncovering weaknesses in the network.

Section 2 discusses the dual roles played by the individual direction finders in this investigation. Sections 3, 4 and 5 deal with the two main objectives of the study, namely:

(i) to estimate the true distribution of 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 findings of the statistical analysis, the B.C. Ministry of Forests has undertaken corrective actions and network modifications which are discussed briefly in Section 6.

2. DUAL ROLES FOR DIRECTION FINDERS

Because the detection network consisted of eighteen direction finders (DF's) and only two sightings were needed to position any given lightning strike, each individual DF could serve dual purposes. In addition to its normal function as part of the network, each DF was used to collect data for the purpose of evaluating the detection efficiency of the other DF's.

For a lightning strike occurring in a specified range-signal strength category with respect to a given DF site, let A denote the event that the strike is detected by the given DF and B the event that the strike is located by the network. If sufficient observations occur in this category, we are able to obtain a good estimate of $P(A|B)$. Of course, a good estimate of $P(A)$ would be preferred, but at least $P(A|B)$ provides an upper bound because

$$\begin{aligned} P(A) &= P(B)P(A|B) + P(B^C)P(A|B^C) \\ &\leq P(B)P(A|B) + P(B^C)P(A|B) \\ &= P(A|B). \end{aligned}$$

This follows from the intuitively obvious inequality

$$P(A|B) \geq P(A|B^C).$$

Since

(1) $$P(B)P(A|B) \leq P(A) \leq P(A|B),$$

the term $P(A|B)$ gives only a slightly inflated approximation of $P(A)$ for those range-signal categories where $P(B)$ is near 1. More importantly, the estimates of $P(A|B)$ provide a valid means of comparing the detection efficiencies of the different DF sites in the network.

3. 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 Robbin's algorithm for an oblate spheroid (see Bomford, p. 136);

(ii) the average normalized (AN) signal strength and the associated standard error was calculated as described in Section 4;

(iii) the record of which DF sites detected the strike was maintained.

For each DF site a separate two-way data table was created which cross-classified the lightning event data according to range (10 km width zones) and AN signal strength (10 v width zones). Two entries were recorded in each range-AN signal strength category; the first entry in each category gave the total count of lightning events detected by the network, and the second entry recorded the count of those first entry events that were detected by the given DF. Thus, the ratio of second entry to first entry estimated the DF's detection efficiency for the category. 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 5.

4. DISTRIBUTION OF NORMALIZED LIGHTNING SIGNAL STRENGTH

As the electromagnetic radiation generated by a lightning event propagates over the surface of the earth, the signal varies inversely with the distance travelled. 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:

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

Thus, the normalized signal is the output signal that would be generated by a DF located 200 kilometres from the lightning strike.[1]

For each observed lightning event, the Average Normalized (AN) Signal Strength, $\bar{V}$, was computed by the formula

$$\bar{V} = \frac{\text{Sum of Normalized Signals from all detecting DF's}}{\text{Number of detecting DF's}}$$
$$= (1/n)\sum V_i .$$

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

$$SE(\bar{V}) = \frac{\sum(V_i - \bar{V})^2/(n-1)}{n} .$$

The distribution of observed AN signals, grouped into 20 v 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

$$\text{Av Std Error} = \frac{\text{Sum of } SE(\bar{V})\text{'s associated with AN Signals in class interval}}{\text{Number of AN Signals in class interval}} .$$

A graphical representation of the frequency distribution for AN Signals is given in Figure 1 by a frequency polygon. The huge data set of 165,132 observations produced a beautifully smooth distribution. This line graph provides a good approximation for the true distribution of Normalized Signals that will be detected by the existing system during May through September periods.

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[1] To convert Normalized Signal (volts) to Peak Current (kiloamperes), the conversion factor is 0.62. Thus, a lightning event with peak current 62 kA would produce a DF output signal of 100 v at 200 km range.

AVERAGE NORMALIZED SIGNAL INTERVAL (volts)	NUMBER OF OBSERVATIONS (frequency)	RELATIVE FREQUENCY	AVERAGE STANDARD ERROR (volts)
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
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 1. Distribution of average normalized signal strengths.

5. DETECTION EFFICIENCY COMPARISONS

To analyze the detection efficiency of a given DF site, the lightning events located by the network were cross-classified according to range and AN signal strength as discussed in Section 3. Within each range-AN 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 AN signal zones (40 - 60 v, 80 - 100 v, 180 - 200 v). The choice of these three zones was made on the basis of representing different regions of the AN signal strength distribution, data sufficiency, and low redundancy in presenting the information. The first zone corresponded to the mode of the AN 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 based on the average of estimates for seven overlapping range intervals each 70 km wide. 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, as explained in Section 2, they 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 AN signal strengths larger than 30 volts. Listed beside each estimate in parentheses is the standard error, computed by the formula

(rel. freq.)(1-rel. freq.)/(sample size).

The observations with signal strengths in the 0 to 30 volt zone were not used here, because analysis of these observations showed that the network probably had failed to detect a sizable proportion of low voltage signals. The analysis that led to this decision was based on the assumption that in the long-run approximately 25% of those lightning events occurring within 160 km of a given DF should fall within 80 km of the DF, because the area of a circle is reduced by 75% 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 volts, and again for those below 30 volts. For the above 30 v group the percentage was 25.9%; but for the below 30 v group it was 39.1%, well over the theoretical 25%. This suggested that the network probably failed to detect a sizable proportion of low voltage 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% @ 320 km figure suggested by the Florida/Oklahoma results. 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 comprehensive local-environment field tests.

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)

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

6. UPDATE OF USER RESPONSE

The B.C. lightning detection network's lower performance level, when compared to the results obtained in Florida and Oklahoma, 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 foothills of the Rocky Mountain trench. Thus, the reduction of detection efficiency is attributed to the presence of mountains.

From results of the statistical analysis, five DF's were identified as having significantly worse than average performances. 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. The antenna was found to be approximately 30r0e 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 compensate for detection efficiency problems caused by mountainous terrain, the network web is being tightened with the addition of two new DF sites in 1986 and three more in 1987. Also, over the next five years the existing equipment will be refurbished with an upgraded design which improves the dynamic range and the detection efficiency at low signal strengths.

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