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THE ROLE OF A HIGH ALTITUDE AIRBORNE INFRARED FOREST FIRE DETECTION SYSTEM IN EASTERN CANADA - PROGRESS REPORT

by

Peter Kourtz

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The Fire Detection Problem

Forest fire statistics indicate that existing detection systems and levels of suppression activities are adequate to control all but a relatively few fires. These few fires, however, usually result in large damage and suppression costs (Table 1). Furthermore, a detailed examination of fire statistics reveals that a significant percentage of fires remain undetected for long periods of time (Table 2). Often these fires are detected only after conditions are suitable for rapid spread (Table 3). The near simultaneous detection of many such fires frequently strains suppression organizations to the limit -- all too often resulting in large fires and corresponding high costs and losses (Tables 4 and 5).

An Infrared Detection System

Recently an airborne infrared detection system capable of detecting most incipient fires has been developed by Project Fire Scan of the U.S. Forest Service (Hirsch, 1971). It is a combined optical and electronic system that collects transmitted energy from a target by a rotating prism and reflects this onto infrared detectors that are sensitive to radiation in the 3 to 4 and 8.5 to 11 micron ranges. (Maximum energy is emitted from a smouldering fire in the 3 to 4 micron wavelength

Table 1

STUDY AREA FIRES BY YEAR AND COST AND LOSS CLASS

(60,000 square mile area in northwestern Ontario)

(July - August)

Year	Cost and Loss Class (Upper Bound) ($)								
	500	1,000	5,000	10,000	20,000	50,000	100,000	+	Total
63	43(57)*	14(18)	16(21)	2(3)	0	1(1)	0	0	76(100)
64	58(63)	12(13)	15(16)	2(2)	1(1)	4(4)	1(1)	0	93(100)
65	87(75)	14(12)	10(8)	1(1)	1(1)	1(1)	1(1)	1(1)	116(100)
66	127(76)	23(13)	13(8)	1(1)	3(2)	0	0	0	167(100)
67	76(69)	18(16)	15(14)	1(1)	0	0	0	0	110(100)
68	32(91)	2(6)	1(3)	0	0	0	0	0	35(100)
69	27(90)	2(7)	1(3)	0	0	0	0	0	30(100)
70	109(68)	20(13)	29(18)	2(1)	0	0	0	0	160(100)

* Per cent of horizontal total.

Table 2

STUDY AREA FIRES BY YEAR AND ELAPSED TIME TO DETECTION

(July - August)

Year	Elapsed Time (Hrs.) from Ignition to Detection (Upper Bound)										
	1/4	1/2	3/4	1	2	4	8	12	24	+	Total
63	5(7)*	0	2(3)	2(3)	7(9)	11(15)	4(5)	1(1)	11(14)	33(43)	76(100)
64	11(12)	3(3)	3(3)	1(1)	5(5)	5(5)	10(11)	8(9)	14(15)	33(36)	93(100)
65	5(4)	4(3)	6(6)	0	8(7)	10(9)	8(7)	7(6)	35(30)	33(28)	116(100)
66	11(7)	2(1)	10(6)	8(5)	22(13)	24(14)	15(9)	18(11)	39(23)	18(11)	167(100)
67	3(3)	16(14)	8(7)	2(2)	17(15)	15(14)	15(14)	3(3)	14(13)	17(15)	110(100)
68	8(23)	1(3)	2(6)	1(3)	7(20)	5(14)	1(3)	0	5(14)	5(14)	35(100)
69	2(7)	0	1(3)	1(3)	6(20)	5(17)	3(10)	3(10)	4(13)	5(17)	30(100)
70	5(3)	7(5)	6(4)	1(1)	30(19)	23(14)	15(9)	7(4)	37(23)	29(18)	160(100)

*Per cent of horizontal total.

Table 3

STUDY AREA FIRES BY YEAR AND SIZE AT DETECTION

Year	Detection Size Class Upper Bound (Acres)							
	1/4	1	5	10	100	500	+	Total
63	40(53)**	10(13)	22(29)	2(3)	2(2)	0	0	76(100)
64	45(48)	16(17)	20(22)	2(2)	6(7)	3(3)	1(1)	93(100)
65	-*	-	-	-	-	-	-	116
66	-*	-	-	-	-	-	-	167
67	79(72)	20(18)	9(8)	0	2(2)	0	0	110(100)
68	29(83)	5(14)	1(3)	0	0	0	0	35(100)
69	25(83)	4(13)	1(4)	0	0	0	0	30(100)
70	130(81)	18(11)	10(6)	1(1)	1(1)	0	0	160(100)

*Missing data.

**Per cent of horizontal total.

Table 4

STUDY AREA FIRES BY ELAPSED TIME TO DISCOVERY AND COST AND LOSS CLASS

(1963-1970, July - August)

Number of Fires

	Cost and Loss Class Upper Bound ($)			
	1,000	10,000	+	Total
Discovered same Day as Ignition	421	49	6	476
Not Discovered Same Day	243	60	8	311
	664	109	14	787

Percent of Fires

	Cost and Loss Class Upper Bound ($)			
	1,000	10,000	+	Total
Discovered same Day	88.4	10.3	1.3	100.0
Not Discovered same Day	78.1	19.3	2.6	100.0

Table 5

RELATION OF MULTIPLE FIRE DETECTIONS
AND COST PLUS LOSS IN THE STUDY AREA

(1963-1970, July - August)

Number of Fires

Number of Fires Detected on a Single Day	Cost Plus Loss Class (Upper Bound) ($)			
	1,000	10,000	+	Total
1 - 2	193	29	1	223
3 - 5	194	24	0	218
6 - 9	184	31	5	220
10 +	93	25	8	126
	664	109	14	787

Percent of Fires

Number of Fires Detected on the Same Day	Cost Plus Loss Class (Upper Bound) ($)			
	1,000	10,000	+	Total
1 - 2	86.5	13.0	0.5	100.0
3 - 5	89.0	11.0	0	100.0
6 - 9	83.6	14.1	2.3	100.0
10 +	73.8	19.8	6.4	100.0

region and from the terrain in the 8.5 to 13 micron wavelength region.) With each revolution of the scan mirror, radiation is collected from a narrow strip of terrain. This strip or scan line is perpendicular to the heading of the aircraft. A radiation source along a scan line that results in an electrical energy level above a predetermined threshold value is identified as a potential forest fire location. The energy that is collected along each scan line is converted into light and projected onto a film.

The speed of the aircraft, the rate of rotation of the prism and the movement of the film before the printer are synchronized to result in a thermal map of the terrain. An electronic device automatically marks the location of potential fires on the film.

Large distortions in imagery result when a turn is made and because of this, it is impossible to obtain an accurate fire location while the aircraft is turning. For this reason detection patrols usually consist of a number of parallel flight lines.

The ideal aircraft for this system appears to be the turboprop executive-class aircraft capable of speeds of at least 250 mph for a duration of about four hours at an altitude above 20,000 feet MSL. Such an aircraft equipped with a detection system similar to that developed by the U.S. Forest Service and the necessary doppler navigation equipment should cost less than 250 dollars per hour to operate if owned by the fire control agency and about 350 to 400 dollars per hour if leased.

Objective of the Study

Experience gained by the U.S. Forest Service while operating this system during the fire seasons of 1970 and 1971 in Idaho and Montana clearly indicates its feasibility in areas of high lightning fire occurrence and light cloud cover. The objective of this study is to determine the future role of this type of detection system in Eastern Canada where there is frequently heavy cloud cover and a relatively low incidence of lightning-caused fires. Specifically the study is designed to answer the question: is it economically feasible to supplement the existing visual detection system of northwestern Ontario with one airborne infrared forest fire detection system similar to that developed by the U.S. Forest Service?

Study Area

A 60,000 square mile area in northwestern Ontario was selected for this study. This area is bounded on the west and east by the 95 and 88.55 degree longitude lines. The north and south boundaries were the 11th base line and the 49 degree latitude line. This area includes most of the Dryden Fire Zone and is made up of portions of the Kenora, Sioux Lookout, Fort Francis, Thunder Bay and Geraldton Forest Districts (Figure 1).

FIGURE 1

STUDY AREA DESCRIPTION

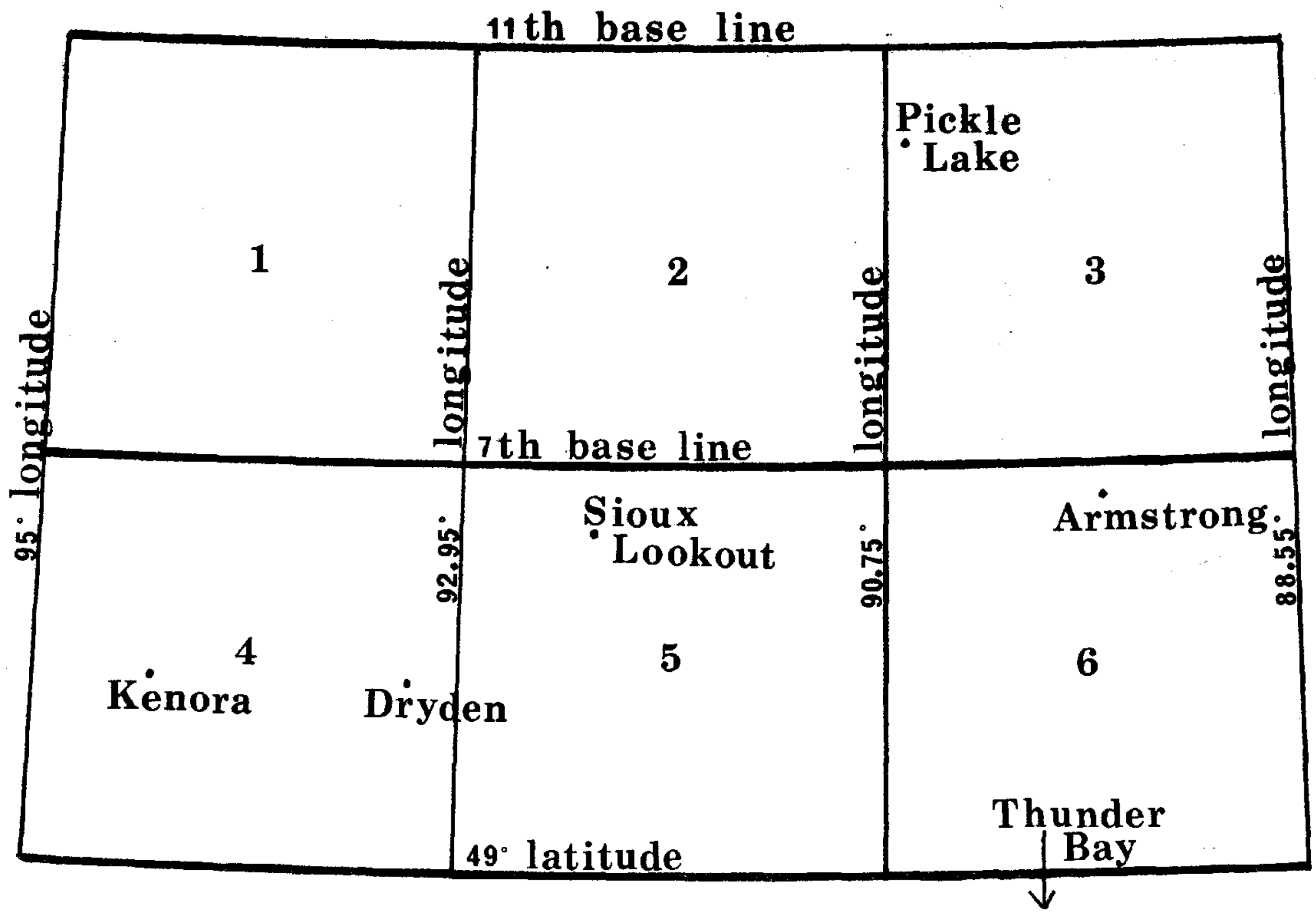


Table 6 gives the percentage of fires by general cause for the 1965 through 1970 fire seasons. Table 7 gives the percentage of fires by fuel type.

Table 6

STUDY AREA PERCENTAGE OF FIRES BY GENERAL CAUSES
(1965-1970, July and August)

Cause	Percent
Lightning	52.8
Recreation	29.1
Residents	2.1
Miscellaneous	5.7
Railway	7.8
Forest Industry	.2
Other Industry	1.6
Incendiary	.5
Unknown	.2
TOTAL	100.0

Table 7

STUDY AREA PERCENTAGE OF FIRES BY FUEL TYPE
(1963-1970, July and August)

Fuel Type	Percentage
Pine	35.4
Spruce	19.9
Fir	2.8
Mixed	4.8
Hardwood	2.2
Slash	5.3
Grass	18.3
Other	11.3
TOTAL	100.0

The Simulation Model

This report describes the initial simulation model that was developed and the results obtained from its use. It was intended that this initial model would be unsophisticated and that this phase of the study would lead to an improved analysis technique as well as a more realistic model.

The question that the simulation model was designed to answer was -- would it have been worthwhile to have operated a single high-altitude, infrared-equipped aircraft in the study area during the fire seasons (July and August) of 1963 through to and including 1970? (It was felt that if this system did not prove effective during this 62 day period, it would not be effective during the remaining part of the fire season.) The major factors considered in the model follow.

1. Patrol Characteristics

The 60,000 square mile study area was divided into six sectors each 10,000 square miles in area (Figure 1). Only one infrared patrol was to be flown each day and this was a night patrol in one of the six sectors.

The patrol route for a sector consisted of eight evenly spaced parallel flight lines the direction of which alternated with each successive patrol. For example, even numbered patrols within a sector had eight flight lines running in the north-south direction while flight lines for odd numbered patrols ran in the east-west direction.

Each patrol was started between 12 midnight and 4 a.m. depending on cloud conditions. The specific starting hour was that hour between 12 midnight and 4 a.m. that began the lowest five hour average cloud cover sequence.

Each patrol was carried out along the flight path at an altitude of 25,000 feet MSL at a speed of 250 miles per hour. An additional 150 miles were allowed to reach and return from the sector of interest. Thus, each patrol was 950 miles in length. The average terrain height was assumed to be 1,500 feet and this resulted in a 15.4 mile strip being covered along each flight line.

2. IR as a Supplementary System

The single infrared-equipped aircraft is intended to be a supplement to the existing visual detection system. The simulation model incorporated this concept in the following manner:

(a) The actual relevant past history of the eight fire seasons for the study area was reconstructed based on fire report and weather data.

(b) A fire was "available" for detection by a simulated infrared patrol only if its ignition occurred before the aircraft's arrival and the fire had not been previously detected by the existing organized or public systems. Dates and times of ignitions and actual detections were taken from the historical records.

3. Measure of Effectiveness

The criterion used to evaluate effectiveness was the expected number of fires first discovered by the simulated infrared patrols. The factors that were considered in determining detection probability follow:

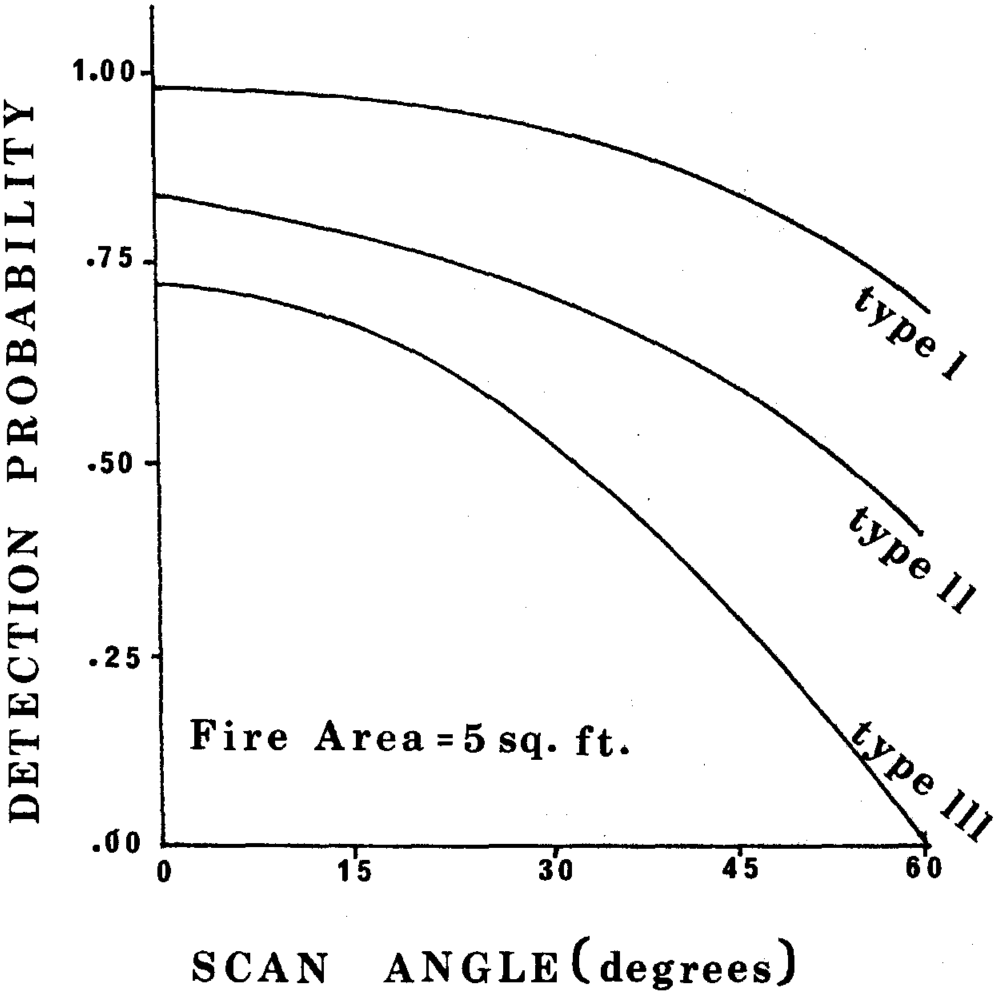
(a) Each fire was assumed to have a burning area of five square feet.

(b) Each fire was assumed to be burning on flat terrain at an elevation of 1,500 feet MSL.

(c) The scan-angle, timber-type detection probability function that was used is presented in Figure 2. These curves apply to fires with a burning area of five square feet located in moderately dense stands of timber. Forest Type I includes all pine types of the study area, spruce, poplar, birch and tamarack (intolerant species). Forest Type II includes Balsam fir, cedar and mixed conifer and hardwoods of moderate tolerance. Forest Type III includes hemlock, maple, beech, and ash (tolerant species). These curves were based on results from experiments conducted in dense mature stands of similar forest types (Hirsch, 1968).

(d) Each patrol was carried out at an altitude above most clouds. Since infrared radiation does not penetrate clouds the probability of detecting a fire along a patrol route is significantly influenced by the amount of cloud along the route. Figure 3 presents the relationship between the probability of seeing through cloud and the cloud amount and scan angle from an aircraft above the cloud layer. Note that cloud amount here is defined as the amount (in tenths) of the whole sky (celestial dome) that is observed to be covered by cloud. Often a large proportion of the sky near the horizon will appear clouded when only scattered amounts of cloud appear overhead resulting in high estimates of cloud cover using this method of observation.

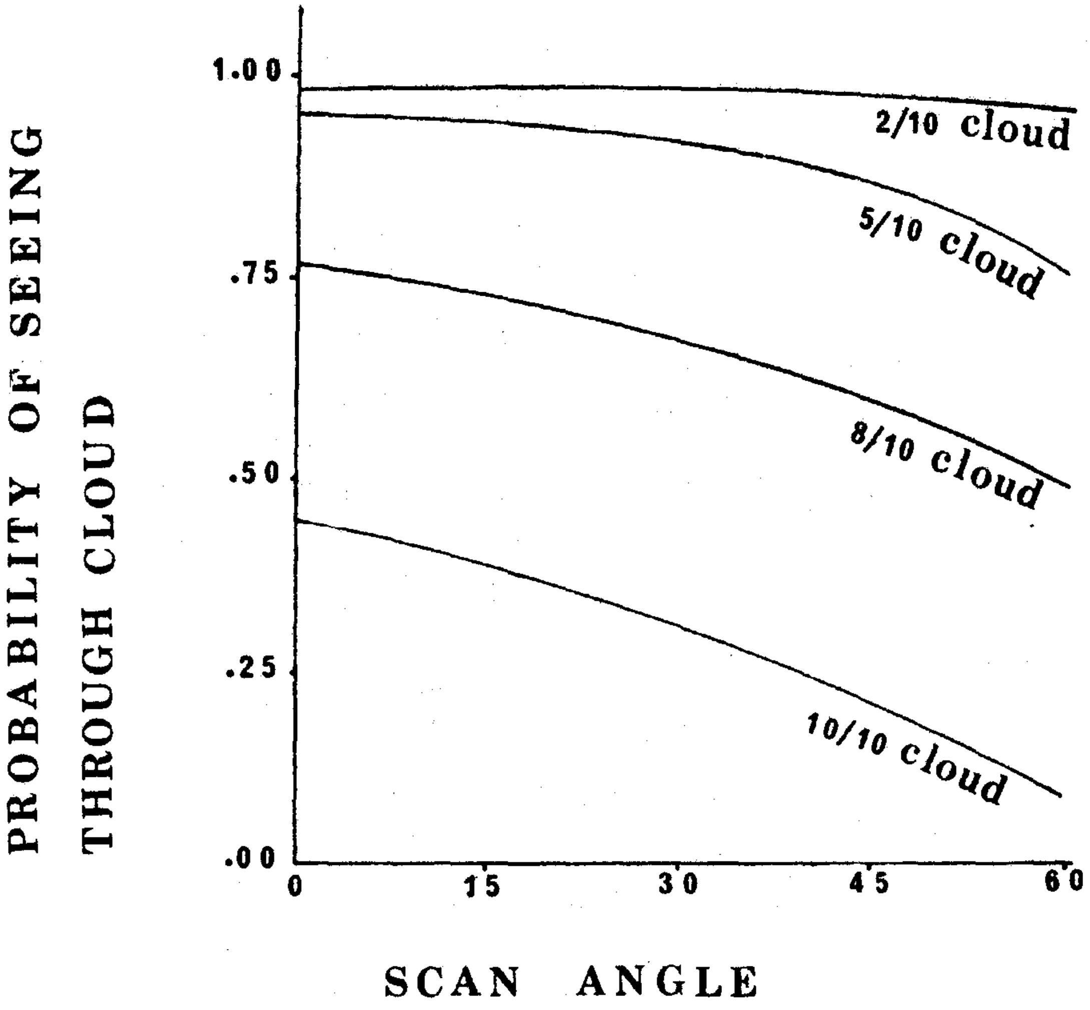
FIGURE 2



DETECTION PROBABILITY CURVES FOR TIMBER DETECTION TYPES

FIGURE 3

RELATION OF PROBABILITY OF SEEING THROUGH CLOUD, CLOUD AMOUNT, AND SCAN ANGLE



NOTE THAT CLOUD AMOUNT IS DEFINED AS THE CLOUD OBSCURED PROPORTION (in tenths) OF THE <u>WHOLE</u> SKY(celestial dome)

Hourly cloud cover data were obtained from the following weather stations in or near the study area: Kenora, Pickle Lake, Sioux Lookout, Armstrong and Thunder Bay (the only stations in or near the study area that recorded hourly cloud data). Hourly cloud amounts were assigned to each of the six patrol sectors (Figure 1) based on the data from the above stations. Table 8 shows how these data were assigned.

Table 8

ASSIGNMENT OF HOURLY CLOUD AMOUNTS TO PATROL SECTORS

Sector No.	Cloud Data Used
1	Kenora
2	Pickle Lake and Sioux Lookout*
3	Armstrong and Pickle Lake
4	Kenora
5	Sioux Lookout and Thunder Bay
6	Thunder Bay and Armstrong

*(A mean of the two stations was calculated for each hour's cloud cover.)

Table 9

CLOUD DATA SUMMARY

Hour	Mean Cloud Amt. (1/10ths)
1	2.25
2	2.15
3	2.20
4	2.51
5	2.93
6	3.45
7	3.78
8	3.79
9	3.77
10	3.86
11	4.09
12	4.50
13	4.86
14	4.84
15	4.80
16	4.79
17	4.68
18	4.62
19	4.45
20	3.93
21	3.68
22	3.24
23	2.75
24	2.38

Percent of total hours between 7 and 19 hours that had cloud amounts greater than 5/10ths = 37.2.

Percent of total hours between 1 and 6 and 20 and 24 hours that had cloud amounts greater than 5/10ths = 20.8.

The mean for all reporting stations was used for a station with missing data. These data (71,424 numbers) were arranged by season, day, sector and hour and stored on magnetic tape. Table 9 presents a brief summary of this cloud data.

The following calculations were made for each 'available' fire during a patrol in a sector.

(a) The scan angles to the fire from each of the eight flight lines were determined based on the aircraft and fire positions.

(b) The timber type detection class was determined based on the species type given in the fire report.

(c) The detection probability (D_i) was determined for each flight line (i) using the function given in Figure 2. Detection probability for a scan angle greater than 60 degrees was assumed to be 0.

(d) The arrival time opposite the fire was calculated for each flight line with a scan angle less than 60 degrees (based on take-off time, aircraft speed, and distance along the patrol route). This was used to determine the cloud cover amount at that time and to determine the corresponding probability of seeing the fire (S_i) through the cloud (Figure 3).

(e) The overall probability of detecting the fire on the Kth patrol (P_k) after its ignition assuming the fire was still burning was:

$$P_k = 1.0 - \prod_{i=1}^{8} (1.0 - S_i . D_i)$$

(f) The probability of the fire being detected by the end of the mth patrol during the time that it was 'available' for detection (E_m) was:

$$E_m = 1.0 - \prod_{k=0}^{m} (1.0 - P_k)$$

The E value associated with the last infrared patrol carried out during the time period when the fire was available represented the overall probability of detecting the fire. The sum of such values represented the expected number of fires detected by the infrared system and was used as the measure of effectiveness for evaluation of the system.

Fire Data Required for the Simulation Model

Fire data for the seasons 1965 through 1970 were obtained from the Ontario Department of Lands and Forests. These data contained the fire report records for fires that occurred in the Kenora, Fort Francis, Sioux Lookout, Geralton and Thunder Bay forest districts. Fire data for 1963 and 1964 were obtained from Al Simard of the Forest Fire Research Institute. From these records the following were taken or calculated for each fire:

(a) Year

(b) Starting date

(c) Discovery date

(d) Starting hour

(e) Discovery hour

(f) General cause

(g) Final size class

(h) Fuel-species type

(i) Discovery size class

(j) Total cost class

(k) Latitude and longitude

Latitudes and longitudes for the fires were calculated, where possible, using a specially developed computer program. Fires in irregular shaped townships were first located on maps and converted to latitude and longitude manually. This version of the model does not require all factors listed however, it was felt that they might be useful later.

These data were stored on magnetic tape by ignition year, day and sector and later merged with the corresponding cloud data.

The major problem encountered with the fire data was that elapsed times to detection greater than 24 hours were not recorded. Therefore, ignition dates and times for "holdover" fires could not be estimated. These fires were assumed to have been ignited 48 hours before they were detected.

An Optimizing Procedure

The simulation model provided the means for evaluating the effectiveness of a series of infrared patrols in a given sector. But the problem remained to determine which sector should be patrolled each night. The first of two possible approaches to this problem involved the defining of an operating rule which automatically assigned a patrol to one of the six sectors each night. The factors considered by such a rule presumably would be available to a detection dispatcher prior to the patrol assignment. For example, such a scheme might involve the construction of an index number for each sector based on a weighted combination of the sector's forecasted cloud cover and burning index, whether or not a thunderstorm occurred recently, and the number of fires recently detected in the sector. The sector with the highest index number would be patrolled that night.

An effective operating rule could be found by using a trial and error process to define a series of interesting rules and the simulation model to evaluate the worth of each rule. The advantage of this approach would be that a real-world operating procedure would be devised in the process of evaluating the infrared system.

The second possible approach to the problem, and the one used in this phase of the study, was to find the sector-patrol allocation that resulted in the highest number of expected first detections by the infrared system. No rule was devised to send the patrol to a specific sector but instead, this approach assumed the detection dispatcher could accurately forecast the expected number of first detections in each sector each night. This approach was simple and avoided the time consuming and costly search for an effective operating rule that was required for the first approach.

A dynamic programming formulation was devised to allocate one patrol to one of the six sectors each night in the fire season in a manner that would result in the highest number of expected first discoveries by the infrared system. The formulation had the following characteristics:

(1) The dynamic programming stage was the date of the fire season. There were 62 such stages.

(2) The formulation assumed that the reward for patrolling a sector on a given night (in terms of the expected number of first detections) was dependent on whether or not that sector had been flown the previous night and/or two nights previous (altogether eight possible dependence states). Note that it was earlier assumed that no available fire burned for more than 48 hours. Four of the eight dependence states involved a patrol in the sector on the night of interest. The simulation model was modified slightly in order to produce the rewards associated with these four states for each sector and each night in the fire seasons.

(3) The dynamic programming state was the dependence situation existing in each of the six sectors.

(4) Definitions:

(a) R_n (Z,S) was the number of expected first discoveries given stage n and dependence state Z for sector S.

(b) F_n (Z,S) was the cumulated number of expected first discoveries obtained by arriving in an optimal manner at stage n in sector S in dependence state Z.

(c) The maximum number of expected first discoveries for a fire season was found by: max F_{62} (Z,S) over all Z and S since the season length was assumed to be 62 days.

(d) The recursive relation was: $F_n\ (Z,S) = R_n\ (Z,S) + \max\limits_{(P,Q)} \{F_n-1\ (P,Q)\}$ where dependence state P in sector Q in stage $(n-1)$ is compatible with dependence state Z in sector S in stage n.

Test problems were devised that showed that this algorithm did select the optimum set of sectors for patrolling.

Results Obtained from use of the Simulation Model

Table 10 gives the results produced by the model.

Discussion

The model produced for this phase of the study is relatively unsophisticated. Three of its major shortcomings are:

(a) It is unrealistic to restrict the number of patrols to only one per day. Up to three, 3-hour patrols likely could be carried out throughout a 24-hour period.

(b) It is unrealistic to restrict the patrols to specific sectors. In a real-world operation the system's primary role likely would be that of 'thunderstorm-chasing'.

(c) The criterion used to evaluate effectiveness is only distantly related to total cost and loss as Table 4 and 5 point out.

Several general conclusions can be made based on this phase of the study.

(a) Cloud cover amounts are not sufficiently high to rule out the use of an infrared system. Night cloud amounts are such that few patrols would be cancelled.

(b) An infrared system likely would detect at least a quarter of the fires sooner than the existing detection system.

It has been estimated that the type of infrared detection system described by this model would cost approximately 250 dollars per hour to operate if owned by the fire control agency. This price considers the costs of operation and depreciation of equipment and aircraft plus pilot wages. Each patrol would cost about 1,000 dollars. During July and August therefore such a system would cost about 60,000 dollars if one patrol per day was averaged.

Table 10

RESULTS OBTAINED FROM THE INFRARED DETECTION MODEL

Fire Season	Number of Fires	Total Fires Available*	Available Fires With Uncertain Ignition Dates**	Expected IR First Discoveries	First Discoveries % of Total
1963	76	45	28	33	43
1964	94	45	20	28	30
1965	116	65	33	42	40
1966	167	53	18	36	22
1967	110	31	17	23	21
1968	35	10	5	9	26
1969	30	7	5	7	23
1970	160	55	28	40	25

* Fires that burned at least throughout one night before being detected by either Ontario Lands and Forests or the public.

** Fires that burned more than 24 hours undetected.

The average direct suppression cost (taken from fire reports) of all fires that occurred between 1965 and 1970 in the study area and that were detected on the same day that they were ignited was 429 dollars. The average direct suppression cost of all fires that were not detected on the same day that they were ignited was 1,658 dollars. The simulated IR system averaged 26 first detections between 1965 and 1970. Assuming that the average savings per IR first detection was the difference between the average cost of the fires discovered the same day as their ignition and the average cost of fires detected after the day of their ignition ($1,229), the savings from the IR patrolling would be $31,954. Therefore, there would be an expected loss in out-of-pocket funds of about 30 thousand dollars per two month season.

Future Work

Future work will be aimed at the development of an improved IR detection model for the study area. The following will be attempted.

(a) Improvement in fire data -- original fire reports will be examined in detail in order to more accurately establish each fire's history.

(b) A new criterion will be used. An attempt will be made to identify "critical" fires -- fires that the elapsed times to detection are important in determining their ease of control at initial attack time.

(c) The model's framework will be revised.

(1) The sector concept will be dropped in favour of a uniform grid

over the study area. The grid intersections will be 15 miles -- the approximate strip width covered by the IR scanner.

(2) An algorithm will be devised to determine the best patrol route through this grid structure given:

(a) The airport for take-off and landing (a point on the grid).

(b) A aircraft fuel constraint in terms of a maximum number of grid points to visit.

(c) Rewards associated with each grid point for one or more visits.

(d) Penalties for turns along the patrol route.

(3) An attempt will be made to develop an indexing scheme to assign rewards to grid points in a manner that will route patrols to high-risk areas in an attempt to quickly detect critical fires. This indexing scheme will be based on information available to a detection dispatcher.

(4) Day time patrols and more than one night patrol will be tried.

(5) The 'available' fire concept (used in the initial model) will be retained since the IR system is intended to supplement the existing system.

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____________ 1971. Application of infrared scanners to forest fire detection. Paper presented at International Remote Sensing Workshop, May 1971, Ann Arbor, Michigan.