

ANALYSIS OF AN
INFRARED FOREST FIRE DETECTION SYSTEM

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Introduction

It has long been recognized that combined early detection and fast initial attack is the key to reduced acreages burned, suppression costs, and damages. Fire control agencies for many years have operated elaborate visual detection systems and alert suppression organizations in an attempt to achieve this goal. However, the technology was never available in the past to truly meet or perhaps even approach this goal. Recent developments in the use of airtankers, retardants, and large helicopters seem to indicate that fast and effective initial attack may now be possible for the first time. These new developments appear so successful that we are currently undergoing a significant change in the form of our suppression organizations. Many are changing or have changed from a dispersed network of small fire control centres to regional initial attack bases requiring large capital investments.

It seems clear that our initial attack capability has far outstripped our ability to achieve rapid detection. In fact the question might well be posed - can we justify such large capital expenditures on these modern initial attack organizations knowing that the effectiveness of these initial attack systems is intimately related to our ability to detect fires quickly and this detection capability has changed very little over the last 30 years?

The Fire Detection Problem

There is general agreement among fire control officials that lightning-caused fires currently present the major problem to most organizations. This is true even in areas of high man-caused fire occurrence. Often a single thunderstorm or series of thunderstorms will start numerous fires. A significant number of these fires remain dormant until burning conditions are suitable for rapid fire spread. A study of lightning-caused fires in the Clearwater National Forest (Hirsch, 1966) revealed that 12 hours after ignition 40 percent remained undetected by the visual detection system and 24 hours later 22 percent still remained undetected. Existing visual detection systems detect many such fires only after they become large enough to present serious control problems. The large number of fires that may be detected almost simultaneously over-taxes the initial attack organizations resulting in high costs and losses.

An Improved Fire Detection System

The U.S. Forest Service recognized the potential of an improved detection system and initiated project Fire Scan in 1961 (Hirsch, 1962).

Project Fire Scan's primary objective was to investigate and develop a system 'capable of detecting both man-caused and lightning-caused fires day or night through all normally encountered atmospheric conditions and in the wide variety of fuel and topographic conditions encountered in the various forests of the United States' (Hirsch, 1962). This project's research in the last ten years has produced an airborne infrared fire detection system that can detect and locate from high altitudes small smouldering or flaming fires under dense forest canopies.

Results from field trials of this system provide ample evidence that this system has the potential for solving at least our major detection problem -- the holdover lightning fire.

Need for Economic Evaluation of the Infrared System

There are many unanswered questions concerning the use of an infrared detection system. How should such a system be operated to obtain maximum effectiveness under a budget constraint? What are the effects of cloud cover, timber canopy, topography and fire occurrence pattern, and how can their influences be considered? How does the effectiveness of an infrared system compare to that of a visual system? Also, an infrared detection system will be expensive. It is estimated that a single unit consisting of an aircraft capable of long-duration, high altitude flights, an accurate navigation system, and the infrared equipment will cost in the neighbourhood of 500,000 dollars. Clearly such expenditures will require sound justification, likely in the form of a detailed cost-effectiveness study.

The Simulation Model

A study of an 8,280 square mile area of the Nezperce and Clearwater National Forests of Idaho and Montana was begun in 1967. On the average 220 lightning fires occurred per year within the area selected over a 20 season period. The study was designed to answer the previously mentioned questions and provide the framework for future cost-effectiveness studies of infrared detection systems.

The study consisted of two parts. The first part dealt with relationships between environmental conditions, patrol timing, and detection results in terms of the measure of effectiveness. The traditional method of discovering these relationships is by experimentation. However constraints on time and budget prevented this approach. Instead, a simulation model was constructed to provide responses (in terms of the measure of effectiveness) to differing patrol schemes.

The second part of the study dealt with the use of these patrol-response information to determine the efficient allocation of a limited number of patrols.

Quadratic and dynamic programming, statistical design of experiments, and response surface procedures were all necessary parts of this study.

The Measure of Effectiveness

Ideally the goal of this study should have been to define the operating procedures for an infrared forest fire detection system that minimized the total of loss plus presuppression and suppression costs. Two major items, however, prevented the use of this ideal criterion. First, the relation between a detection system's output and the final area burned by fires for a given amount of fire control resources was not known. Second, problems involving non-market values, joint costs, and poor accounting schemes prevented the evaluation of suppression and damage costs.

The criterion that was chosen to evaluate the effectiveness of each set of operating rules was the number of fires that could not be controlled by the initial attack forces. Such fires are potentially expensive. The primary goal of the study was to find the set of operating rules that minimized this number over a long period of time for a given annual budget. This goal was assumed to be directly related to the ideal goal of minimizing the total of costs and loss but avoided the difficulties in measuring costs and losses.

In the simulation model, a fire-growth model was used to predict fire perimeters at the times when initial attack forces arrived (Barrows, 1951). This model considered fuel type in terms of a 'rate of spread' classification (Hornby, 1935) and slope in the vicinity of the fire and hourly burning index levels between ignition and attack times. Total energy in BTU per second being given off around the perimeter was calculated for each fire at attack time using the fire perimeter, rate of fire spread, weight of available fuel and the heat energy per unit of fuel. The weight of available fuel was assumed to be related to the 'resistance to control' fuel classification (Hornby, 1935). When this energy exceeded 50,000 BTU per second the fire was classified as potentially dangerous.

Factors Affecting Infrared Radiation Detection Considered in the Model

Timber Canopy Effect

For an infrared detector to sense a forest fire an unobstructed view of at least part of the heat source is needed. As the point of observation above a moderately dense timber stand on flat terrain approaches tree top level and the line of sight to the fire approaches 180 degrees, the probability of viewing a portion of a distant ground fire rapidly approaches zero.

Project Fire Scan conducted field experiments to determine the relation of detection probability to timber type, stand characteristics,

fire area, and scan angle. A function was derived, based on the results of these experiments, with which the probability of detecting a fire given the area of the fire, the timber species and density, and the scan angle to the fire could be estimated.

Topographic Effect

Topographic variation affects the probability of detection in two ways. First, as the elevation of a fixed ground point increases, the angle measured from the vertical beneath the aircraft to that point increases. Second, and most important, is the effect of the interaction of topography and vegetation. Trees tend to stand vertically no matter what the slope may be. The amount of area obscured by tree boles and the amount of timber canopy through which radiation must pass becomes a function of terrain slope relative to the scan line as well as the scan angle and timber characteristics. The function expressing this relationship, given the slope, aspect, and elevation of the point of interest and relative aircraft position, was developed and incorporated into the detection probability equation. In general, the detection probability increases as the degree of uphill slope relative to the scan line increases and decreases as the downhill slope relative to the scan line steepens.

Cloud Effect

No infrared radiation will pass through clouds or fog due to the character of water droplets. Therefore it becomes important to consider cloud cover in the operating rules that determine the time of each patrol. A patrol above scattered cloud will not detect a fire if a cloud lies between the fire and the detection device.

McCabe (1965) studied the problem of cloud interference with aircraft observation of ground points. He presented a function representing the probability of a direct line-of-sight to the ground given the look angle and the total sky cover beneath the observer. This function was used in the model to determine the probability of the detector 'seeing' through the cloud layer. This value was multiplied by the probability of detecting the fire, resulting in the probability of the joint event of seeing through the cloud and detecting the fire.

The Information System

A grid of points, spaced at one-mile intervals, was established over the study area. It was assumed that if a fire was to occur anywhere within a mile square area represented by a point in the grid, it would be located at the point. Thus there were 8,280 possible fire locations in the study area. More than one fire could occur at a given point.

A computer program was written to pack the elevation, slope, aspect, timber species, diameter, stocking, rate-of-spread, and resistance-to-control

data for each of the possible fire locations into a matrix of 8,280 elements. A subroutine for the simulation model was written to unpack these data given the X-Y coordinates of the point of interest.

Small Scale Fire Model and Fuel Beds

A computer based model of a small creeping or smouldering ground fire was used to produce estimates of burning area at the time when the aircraft passed in its vicinity (Kourtz and O'Regan, 1970). The model assumed that each ground fire spread in a grid whose squares were homogeneous fuel types of one square foot in area. Fuel type was defined in terms of rate-of-spread and fire persistence characteristics. Such terms as litter, duff, grass, punk, and rock outcrop were used to describe fuel types. Persistence time was defined as the length of time that the fire continues flaming or smouldering after the fire front has passed.

Each ground fire was started in the centre square of the grid. The arrangement of fuel types within each grid for a specific cover type was determined by using three probability distributions and the Monte Carlo sampling procedure. Five fuel types within each of seven cover types were recognized in the study area. Sample data from each cover type were collected to construct these distributions. The pattern of fuel types described in the generated grids was similar to the pattern in the area where the fire occurred.

A dynamic programming algorithm was used to determine the minimum time required for the fire to reach and burn each square in the grid. The rate-of-spread of fire through a given square of the grid was determined by the fuel type of the square and its corresponding moisture content at the time when the fire passed through. It was assumed that fuel moisture content changed as the hourly spread index class changed. A rate-of-spread value was used for each fuel type for each of six 4-hour periods in each of four spread-index class days. These rates-of-spread values and fuel data were provided by Hal Anderson, Jim Brown and Dick Rothermel of the U.S. Forest Service's Northern Fire laboratory, Missoula, Montana.

The Environment Portion of the Model

Many seasons of data from the study area concerning burning indices, cloud cover and altitudes, thunderstorm and lightning fire occurrence, and fire locations were summarized in terms of probability distributions. These, in turn, were used in the Monte Carlo sampling technique to produce a series of events similar to those which might be expected to occur in the future and upon which the design of efficient operating procedures could be based.

During a simulated fire season, thunderstorms occurred at specific times, each storm produced a specific number of fires at specific locations, each hour was assigned a specific spread index class, and each fire spread at rates governed by spread index and fuel conditions at its location.

The Design Portion of the Stimulation Model

Operating Rules

The design portion of the model was concerned with the simulation of infrared detection patrols and the interaction of these patrols with the environmental factors. Basic to this portion of the model were the operating rules. These rules were used to determine when each patrol was to takeoff and the route of each patrol. Many rule forms were possible. The following describes the general rule form that was used:

- a) Each patrol was carried out at 23,000 feet (MSL) and consisted of eight parallel flight lines. The best positions of the eight flight lines were found using dynamic programming and a criterion that considered the location of the previous flight lines, the fire occurrence pattern, the scan angle-detection probability relationship, cloud cover and overlap of flight strips. The cycle of flight patterns started over after every storm.
- b) The rule to determine the time of the next patrol considered the following:
 - 1) Whether or not a storm occurred since the last patrol.
 - 2) The number of fires detected on the previous patrol.
 - 3) The elapsed time since the last patrol. Here time was weighted by burning conditions.
 - 4) The cloud cover present at a potential takeoff time.
 - 5) Whether or not the proposed patrol would be carried out during the night or day (it was estimated that to obtain a daytime detection probability equal to that of the night approximately ten times the fire area was required).

This rule was reduced to a series of five functions; each containing a unique 'K' parameter. The rule used was:

- 1) If one or more fires were detected on the last patrol, fly as soon as the current amount of cloud, measured on a 0 to 10 scale, was less or equal to $(10-K1/B)$ provided that this takeoff time resulted in a daylight patrol and $(10-K2/B)$ otherwise. B was the number of burning index hours that had elapsed since the previous takeoff time. Each low, moderate, high, and extreme spread index hour was assigned the value of 1, 2, 3 and 4 respectively.
- 2) If a storm occurred since the last patrol, the next was begun as soon as the current amount of cloud was less or equal to the minimum of $(10-K1/B)$ and $(10-K3/T)$ for daylight patrols and the minimum $(10-K2/B)$ and $(10-K4/T)$ for night-time patrols. Here T was the number of elapsed burning index hours measured from the occurrence time of the storm.

3) If no fires were detected on the last patrol and no storm occurred since, the next patrol was carried out as soon as the current amount of cloud was less or equal to $(10-K5/B)$ provided that this was a night-time patrol. No daytime patrols were carried out in this condition. A set of values for the five 'K' parameters was required at the beginning of each simulation run. These values completely defined the time of each patrol throughout each simulated fire season.

Processing of a Fire

The model processed individual fires during each patrol. For a given fire and flight line, the corresponding scan angle and arrival time of the aircraft were calculated. The small scale fire model predicted the size of the fire at that time and the information system provided the necessary data to calculate detection probability. The amount of cloud beneath the aircraft was determined at that time and this was used in the McCabe (1965) function to determine the adjustment factor for detection probability. The Monte Carlo procedure and the adjusted detection probability were used to determine if the fire was detected.

It was assumed that smoke jumpers would be used in the initial attack on each fire and their arrival times would be two hours after detection provided that their forecasted arrival time was during the daylight hours. The arrival time for fires detected during the night was assumed to be two hours after daylight occurred. The energy at attack was calculated using the large scale fire model, the spread index, and data from the information system. If this energy exceeded 50,000 BTU per second the fire was classified as dangerous.

Runs and Results

Twenty seasons were generated with the environmental portion of the model. These same 20 seasons of data were used with each trial of a new operating rule (new set of 'K' values). The model produced the resulting cost and effectiveness that corresponded to each set of 'K' values.

Use of the Model

An experiment was designed to determine how cost and effectiveness values changed as changes were made in the set of K values. Eighty-one trials, each with different K values, were run. Regression equations were fitted to the cost data and to the effectiveness data. The best fitting cost equation was a linear form and the best fitting effectiveness equation was a quadratic form.

The efficient operating rules, or equivalently, the values of the five 'K' parameters, that resulted in the fewest expected annual number of dangerous fires for a given annual budget were found using the technique of quadratic programming. Table 1 presents the results obtained.

Table 1

Annual Infrared Detection Budgets
and Corresponding Minimum Number
of Dangerous Fires

<u>Detection Budget (Air Hrs)</u>	<u>Detection Budget (Dollars)</u>	<u>Number of Dangerous Fires</u>
100	20,000	45
150	30,000	43
200	40,000	41
250	50,000	39
300	60,000	38
350	70,000	37
400	80,000	37
450	90,000	36
500	100,000	36

Economic theory suggests that the detection budget should be set so that the total cost of detection, suppression, and loss should be minimized. A crude approximation to the optimum detection budget can be found by assuming that dangerous fires result in B, C, D and E class fires (fires over 0.25 acres). Records of fires in the study area for the past decade indicated that a conservative estimate of the average cost and loss of B, C, D, and E fires was \$25,000. Using this number and the values in Table 1, it can be calculated that the infrared detection budget should be about 70,000 dollars to obtain the minimum cost plus loss of approximately 1 million dollars. The current visual detection budget for the study area is approximately 200,000 dollars and the last ten seasons of fire records from the study area indicate that on the average there are 55 B, C, D, and E fires per season. The approximate total cost plus loss value for the existing visual system is approximately 1.5 million dollars.

Conclusions

The major weaknesses in the model should be pointed out and discussed before conclusions are made concerning the results. Attempts were made to correlate the occurrence of thunderstorms, amount of cloud cover, and burning index. These correlations were unreasonably low and thus conditional probability distributions relating these factors were not used in the generation of storms, clouds, and burning indexes. In effect, these factors were generated independent of each other.

Clearly there exists a relationship between cloud cover and thunderstorm occurrence. Before conclusions are made about the results consideration must be given to the fact that this relationship was not present in the model.

The reason for the low correlations likely was that the observations for each of the three factors were taken at widely separated locations within the study area. It appears that the study area should be divided into smaller segments, each with its own set of storm, cloud, and burning index data.

Three other items in the model that should be mentioned are the fuel classification scheme, the large scale fire model, and the snag fire model. These could stand improvement in the model.

Keeping all these items in mind in evaluating the results produced by the model it may be concluded that if the existing visual detection system were replaced in the study area by an infrared system, substantial savings likely would be obtained.

Results of the study must not be generalized to other areas. The cloud cover history of an area is a major determinant of the frequency of patrols and the effectiveness of each patrol. Even within the study area, which was picked partly for its low cloud cover history there have been periods of several days after severe storms during which dense clouds would have prevented infrared patrols. This seems to indicate that for areas of similar cloud and fire history as that of the study area the ideal detection system with to-day's technology may be a combined infrared-visual air patrol system.

It is not known how effective an infrared system would be in an area where a large number of man-caused fires occur. The problem here presumably is that most of these fires begin rapid spread shortly after ignition. If this is indeed the situation, an effective airborne detection system can only be achieved by very frequent patrols.

Future modelling work will be concerned with improvements in the existing model and sensitivity analysis. A new "storm chasing" model to examine the role of an infrared detector as a supplement to an existing visual system has begun. The area selected for this study is in northern Ontario, Canada, where there are relatively high amounts of cloud cover and few lightning fires.

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