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An approach for measuring the effectiveness of fire detection systems in different dimensions

One of the key elements of the cheap but effective fire suppression is early fire detection and quick initial response. There are many ways of fire detection; in many cases taking an overview of the effectiveness is not useless.
First the paper describes the basic principles of the economic effectiveness of the fire management. Then it treats the different dimensions of fire detection and calculates the possibility of aerial flight patrol. Looking at the monitored forest as a flat area makes the analysis 2-dimensional but as an articulated area requires 3-dimensional analysis. If research counts with the time scale, i.e. changing weather conditions, the analysis becomes 4-dimensional.
Research proves that in the 2-dimension model the aerial flight patrol cannot be effective; a tower based fire detection system is required. In case of the 3-dimension model what decides between aerial flight patrol and the tower based fire detection system is the type and rate of the area articulation. The 4-dimensional analysis shows that the choice between the aerial flight patrol and the tower based fire detection system depends on the fire weather index of the area.
Keywords: aerial patrol, UAS application, tower based fire detection system, dimension analysis

Introduction

One of the key elements of the cheap but effective fire suppression is early fire detection and quick initial response. There are many solutions for fire detection, such as satellites equipped with special sensors, manned or unmanned aerial (UAV) flight patrols at different altitude, many kinds of tower based automatic fire detection systems, or mobile human surveillance. Each of them has operation costs, in many cases not negligible; therefore taking an overview of the effectiveness is not useless.

The satellite can be a very effective tool for fire detection but there are some problems with the application. Satellites in geostationary orbit can monitor huge areas but the distance is too far from the Earth to detect hot spots of small sizes. Sensors with higher resolution could help to detect a smaller fire but there are other problems, like higher price or false alarms (Pennypacker, 2013). Satellites with closer than geostationary orbit could be an effective solution but keeping the distance from the Earth requires higher speed meaning that the same area is monitored cyclically (Giglio at al., 2008). In this case we can count a *monitored time* and a *blind time*; the latest means that the area is not monitored continuously (Restas, 2012). This type of satellite can be a good solution for huge forested areas such as North and South America, Africa or Siberia.

Human surveillance is also a kind of fire detection method; however, the effectiveness is accidental in many cases. The effectiveness of human surveillance is more or less similar to the tower based fire detection systems. Assuming continuous monitoring and taking into account the horizontal position of the "sensor" human surveillance and satellite sensor are the two extremes in the range of different fire detection solutions.

All the above mentioned methods represent strategic solutions for hot spot detection; however, at the beginning of the intervention managers also require tactical solutions. It can mean horizontal observation from the ground or a fire fighter with special technical equipment like a fire truck or a UAS.

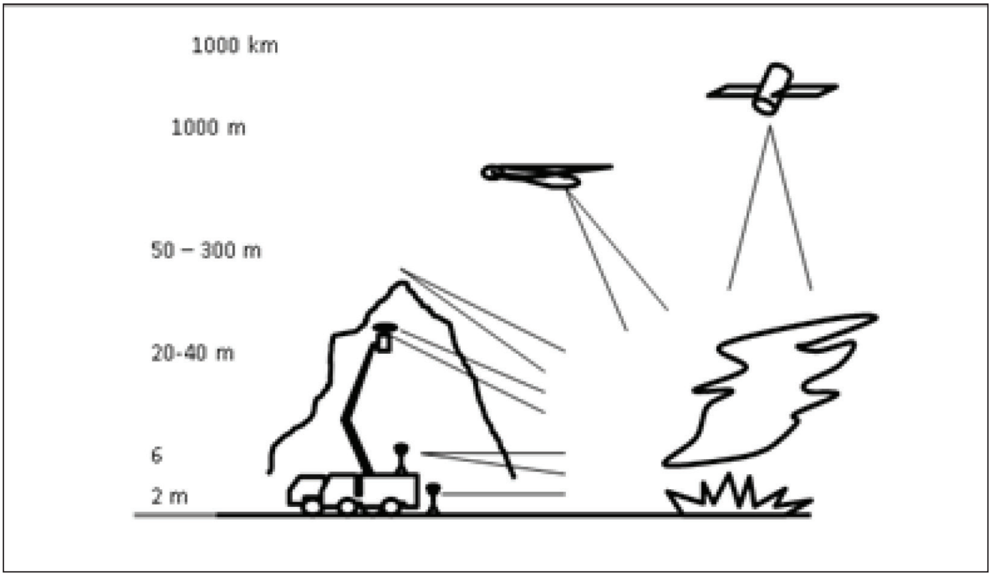

Figure 1 – Different solutions for fire detection: from human on ground to satellite sensors

Damage – time function analysis

When assessing efficiency usually two factors are taken into account: the returns on the investment and the period of time required for such returns to be realized. The concept of efficiency is applicable to firefighting as well, but the way it is applied differs from the traditional interpretation mentioned above. In the case of firefighting and other interventions, efficiency is measured either by the quantity of saved value or by the actual damage, which, of course, should be as small as possible.

The value of a forest is not homogenous; it depends on variety, age, quality, etc. However, the value of forests is not only economic, they have social, biological, goodwill, etc. value as well. The goodwill value is much higher than the simple economic value. It applies even more to national parks. Despite the above remark our method only takes the economic value into account.

The value of a saved forest is also not homogenous, neither in time nor in space. Usually it does not take into account the total price of the forest. Destruction depends on the age of the forest, the type of the trees, the combustible materials and weather parameters. They are calculated not at a discrete value but as a complex continuous function.

On the other hand, there are years when the risk is very high, the value of destruction is extreme and in other years much less. Let us look at this curve in the case of a forest fire. The damage-time function gives an exponential curve that diverges to infinity.

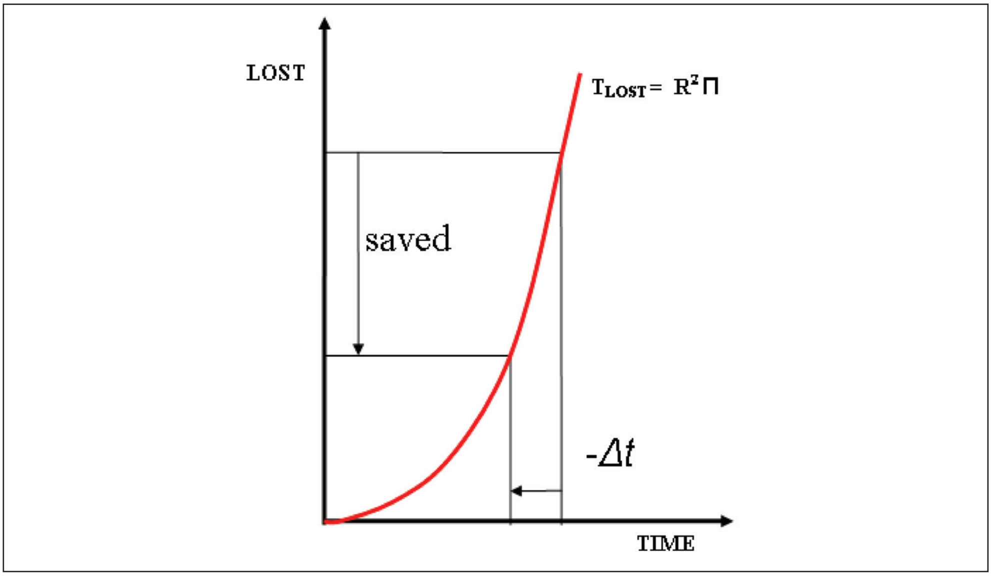

Figure 2 – Damage-time function. Basic shape at uncontrolled forest fire

It is easy to recognize if Δt is reduced, the area burnt and thereby the damage caused is exponentially reduced. The smaller the area affected by the fire, the smaller the quantity of resources needed to extinguish it.

Aerial patrol for hot spot detection – 2 dimensional analysis

Basic elements of effectiveness

The basic assumption is that by using aerial patrol the fire service can save forest of more value than without it. The economic efficiency will materialize if the value of the saved forest is more than all the fire services' expenditure on aerial surveillance. At a strategic level, e.g. at a government level, we have to take into account all the expenditure on aerial surveillance and all the saved forest of the country.

Aerial patrol can detect hot spots very quickly and it is able to give the first fire report to fire brigades; it can reduce the time of the first intervention.

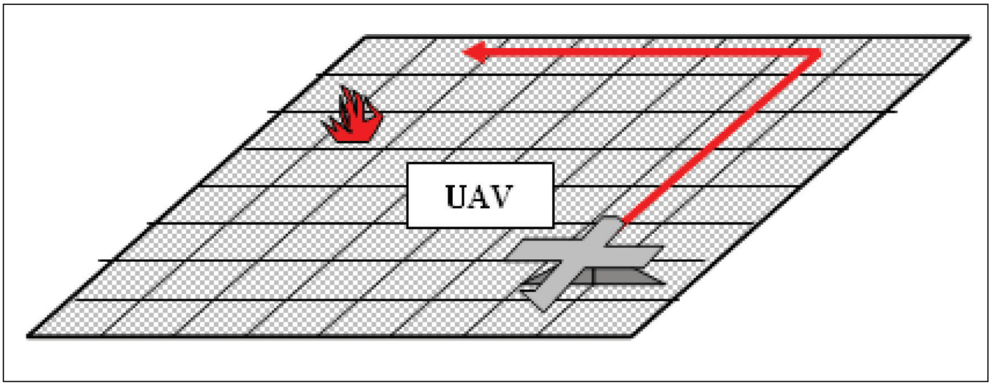

Figure 3 – Aerial surveillance e.g. using UAV for hot spot detection

For a patrol following the pre-programmed flight path hot spot detection is a routine task. Obviously, the average delay of the aerial fire report must be less than the average delay of the civil report. This condition is necessary, though not sufficient for satisfying the requirements of economic efficiency of aerial surveillance, in this example of a UAV flight.

The time between the ignition of the fire and the aerial based fire report can differ depending on the position of the UAV, the position of the ignited fire and the planned flight path. Based on a large number of fire detection events (statistical data base) the average time of the fire report is half of the UAV patrol time. This statement can be reached also by logical conclusion.

$$\bar{t}_{UAV\_report} = \frac{1}{2} t_{UAV\_patrol} \qquad (1)$$

$$\bar{t}_{UAV\_report} < \bar{t}_{Civil\_report} \qquad (2)$$

- t_{UAV_patrol} - full time of a flight patrol made by UAV;
- t_{UAV_report} - average time of fire report given by UAV on fire patrol;
- t_{Civil_report} - average time of fire report given by civilians.

As another criteria, for a satisfying the economically efficient operation the fire service must save forest of more value with the assistance of aerial surveillance (e.g. UAV use) than the costs of surveillance (aerial patrol). A quick fire report results in a quick response; shorter uncontrolled fire means less damage and more saved value. If the intervention starts very soon after ignition, the savings will come not just from the saved forest but also from the shorter use of the special equipment required to suppress the fire (figure 4).

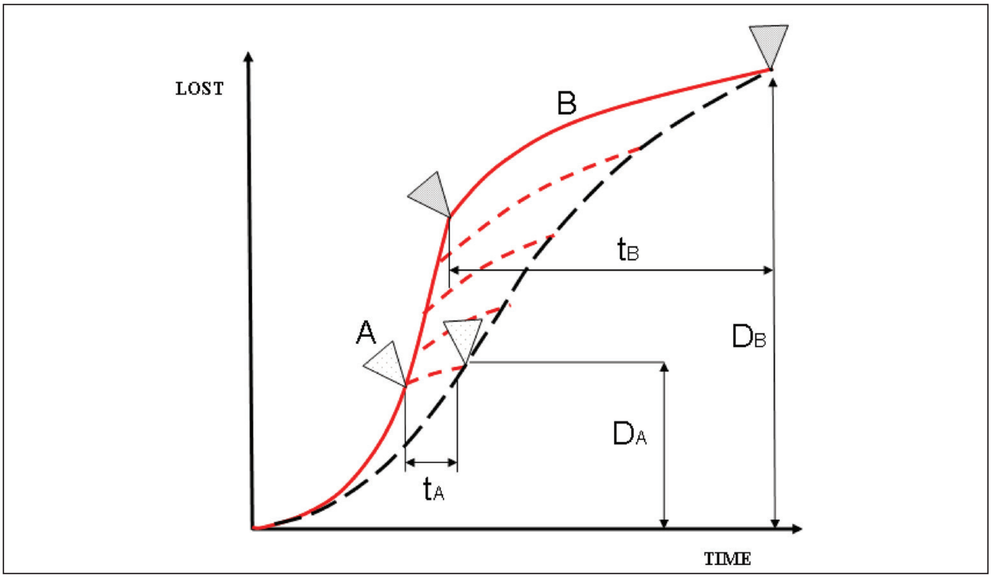

Figure 4 – Structure of damage – time functions taking into account the quick fire report

Modelling the extinguishing of the fire by the damage – time functions the beginning of the response will break the fire curve (figure 2 →figure 4). The intensity and the length of the modified fire curve will depend on the time between the ignition and the beginning of the intervention. In case A the time is shorter than in case B therefore in case A the intensity is lower and the length of the modified fire curve is shorter than in case B (figure 4). The response in case A results in less damage and shorter time of intervention; this latest one results also in lower intervention costs. The shorter the time is between the ignition and the beginning of the response, the lower the intensity and the shorter the modified fires curve is. The above criteria can be expressed also by the next formulas:

$$S \Rightarrow D\left[\bar{t}_{Civil\_report} - \frac{1}{2}t_{UAV\_patrol}\right] > \Sigma C_{UA} \qquad (3)$$

$$\int_{\frac{1}{2}t_{UAV\_patrol}}^{\bar{t}_{Civil\_report}} D \;>\; \Sigma C_{UAV\_patrol} \qquad (4)$$

S (D) - damages between the average term of civil report and aerial report;
A - characteristics of suppression using UAV support;
B - characteristics of suppression without UAV support.

As long as the above formulas are valid the criterion of economic efficiency is satisfied for the UAV assisted fire management.

Moving to higher effectiveness – flight speed analysis

Since the efficiency depends on the difference between the civil based and aerial supplied report's time, the question spontaneously arises, how can we make the time difference longer between these reports? Based on the above formulas the delay of civil report is relatively stable, while the aerial based hot spot detection depends mainly on flight regimes. Therefore, to make the aerial based hot spot detection more efficient we must examine the flight parameters. Logically, we can test the flight speed, the altitude and the visual or camera (UAV) focus. During the analysis ideal circumstances are supposed: there is no wind, it counts just with one hot spot, the price of the technical equipment, like camera does not change, weather does not limit the visibility, area is flat, etc. This latest one, the flat area means that we monitor 2 dimensional extensions.

In order to reduce the average detection time, flight speed needs to be higher. With this process the flight path will not change but the time of aerial patrol will be reduced. In case of a 24 km x 24 km area, with about a 180 kmh^{-1} flight speed and about a 3 km x 3 km monitored grid at a time (e.g. UAV) the monitored time for 1 grid is 1 minute then 63 minutes are blind; the ratio between the monitored and blind area is 1:63. By raising the speed the cycle will be reduced but the ratio between the monitored and blind area will not. The problem is that raising the flight speed is objectively limited.

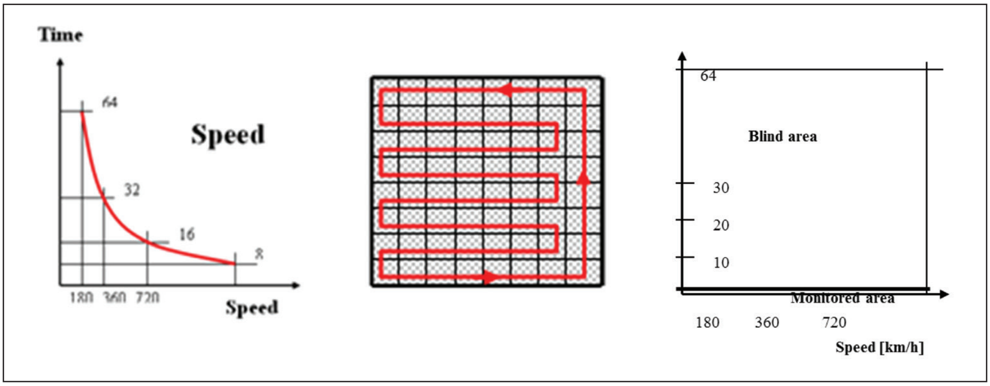

Figure 5– Example for moving towards higher effectiveness of the fire detection.
By raising the flight speed neither the flight path nor the ratio of monitored and blind area change

Moving to higher effectiveness – camera focus and altitude analysis

The analyses of camera focus and altitude gives a little bit different results. By raising the altitude the camera on board can monitor a larger area (grid). If the frame of the supervised area remains and the monitored grid is larger than earlier, then the flight path can change; obviously, it will be shorter. The flight path will move to the center of the area. Continuing this process step by step we reach the shortest route when the flight path concentrates on the middle point of the supervised area. It means that our aerial surveillance vehicle hovers over the central point of the area without flight speed! Logically this position does not require a manned or unmanned plane; in this case a tower based camera system can be an alternative solution with the same effectiveness.

Without further explanation it can be accepted that a similar analysis of the camera focus gives the same results. In this case there is no or only insignificant difference between the altitude of the aerial "surveillance" – hovering over the center point of the area – and the tower based fire detection system.

In both cases the ratio of the monitored to the blind area changes; it becomes more and more efficient. At the end of the process the ratio is 1:0, which means the whole area is monitored continuously. Even though the effectiveness of the two systems – the aerial surveillance and the tower based fire detection system – is similar, it might not be true for efficiency. If the total cost of the tower based fire detection system and the aerial surveillance is similar, then their efficiency is also similar. For the sake of simplicity we assume the same technical parameters – i.e. the same camera installed on board or on the tower – therefore the difference in efficiency comes from the cost of running the systems. This is true for UAV use too, even if it is supposed to be a cheaper solution than manned aircraft. In this case the tipping point – meaning the balanced costs – can be lower.

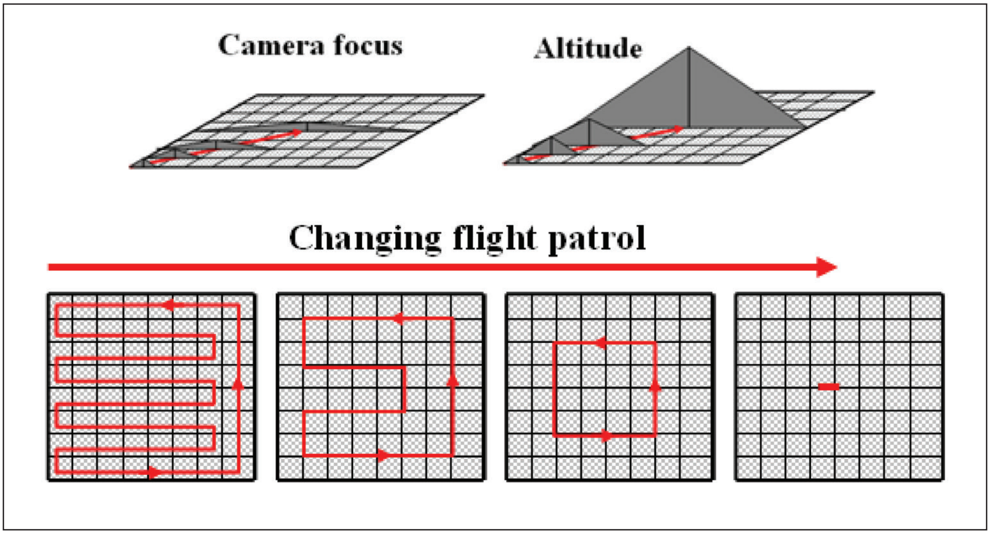

Figure 6– Example for moving towards higher effectiveness of the fire detection. Raising the angle of camera focus or the altitude the flight path changes; it moves to the center of the monitored area

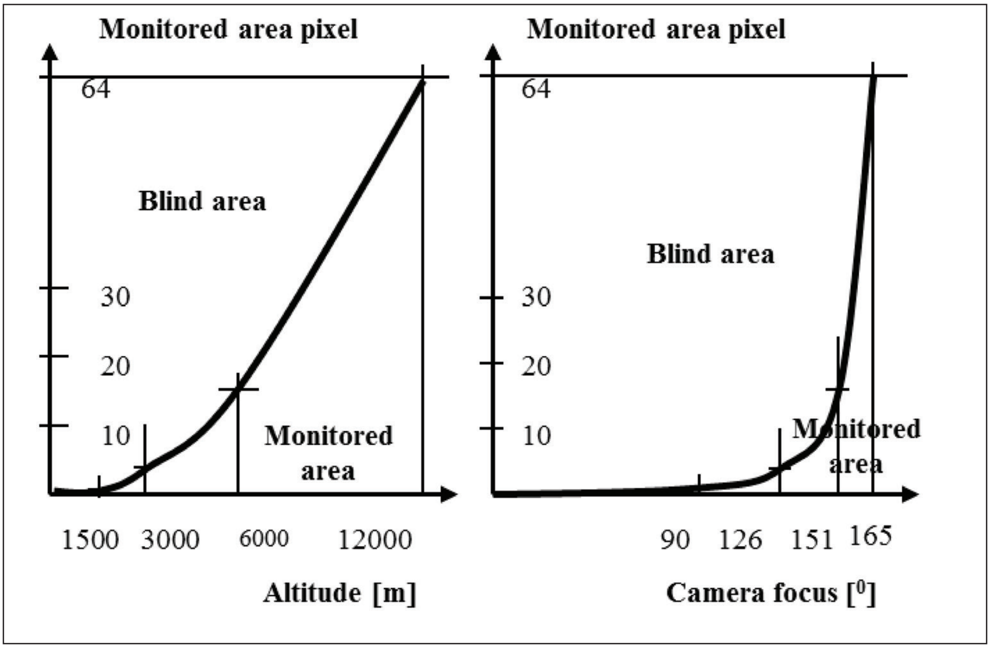

Figure 7– The ratio of the monitored and blind area changes drastically in a positive way

Geographically high articulated area – 3 dimensional analysis

The tower based fire detection system in a flat area – two-dimensional extension – is more effective. The question is when and how its efficiency is limited. As a first step, let's change the two-dimensional, flat area to a geographically high, articulated, three-dimensional area.

In case of a flat area the tower based fire detection system can detect hot spots directly, i.e. there is no natural or manmade barrier for the camera or sensor to detect hot spots. In case of articulated areas the way of fire detection is different. If the ignition point is located in a valley or at the bottom of a slope it might be hidden by the hills. Therefore the tower based fire detection system can only detect this fire indirectly, i.e. the fire is shielded by the hill, so the camera or the sensor can only detect the smoke column or the plume.

Understandably, the indirect detection of smoke occurs later than the direct detection of fire. Depending on different circumstances – power and direction of the wind, inversion, fire intensity, height and direction of the articulation, etc. – the detection of the smoke column can delay significantly. Therefore not just the effectiveness but also the efficiency of the tower based fire detection system is reduced. The degree of delay depends on the height and direction of the articulation; this is a circumstance that does not change in time. In case of high articulation the reduction of effectiveness is surely higher; however, the correlation between them requires advanced research. Moreover, the direction of the articulation is also important.

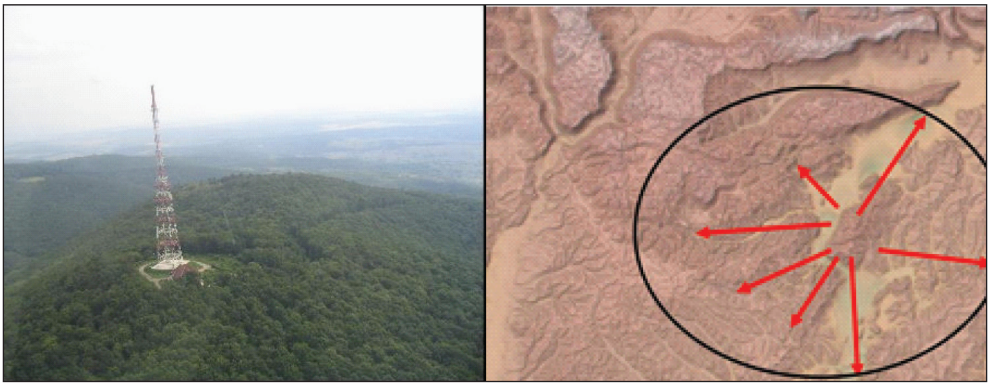

Figure 8– Example for a geographically good positioned tower based fire detection system.
Aggtelek National Park - Szendro Fire Department, Hungary, Installation: 2005

In one example the tower based fire detection system was installed in such an advantageous way that the whole valley became visible (Restas, 2006). The right positioning of the tower is very important; it basically determines the effectiveness and efficiency of the system. Good positioning – even if just in a limited way – can reduce the shadow effect of hills.

In a highly articulated area direct detection and indirect detection can also be very ineffective. The smoke coming from a valley fire can be detected only with such delay that the low costs of annual maintenance evaporate.

Obviously, the mission costs of aerial surveillance do not, or only to a limited extent, depend on terrain articulation. On the other hand, during flight patrol the shadow effect of hills is relevant only for the grid where the aircraft flies. Naturally, this effect is much lower than in case of the tower based fire detection system. Since the effectiveness and efficiency correlate to each other, the higher costs of aerial surveillance can be balanced by the lower effectiveness of the tower based system. In other words, hot spots are detected earlier by aerial surveillance than by the tower based system. The disadvantageous ratio of monitored to blind area is balanced by the higher rate of quick fire report regarding screened areas. The above criterion can be expressed by formula (1) and (5) too.

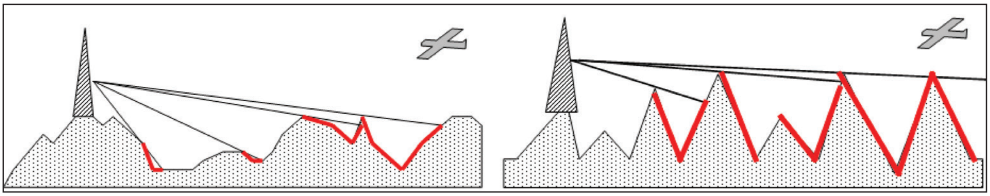

Figure 9– High articulated area: direct detection versus indirect detection (red colored slopes). Aerial surveillance versus tower based fire detection system

$$\bar{t}_{UAV\_report} = \frac{1}{2} t_{UAV\_patrol} \qquad (1)$$

$$\bar{t}_{UAV\_report} < \bar{t}_{delay\_tower\_report} \qquad (5)$$

– $t_{delay\_tower\_report}$ – average delay of fire report, given by the tower based fire detection system.

As the time factor of formulas (1) and (3) are the same, the cost factor of formulas (3) and (6) are also the same.

$$S \Rightarrow D\left[\bar{t}_{delay\_tower\_report} - \frac{1}{2} t_{UAV\_patrol}\right] > \Sigma C_{UAV\_patrol} \qquad (6)$$

There is another basic criterion to be met, namely, providing a quicker fire report on average than the civilian report. As long as the above formulas are valid the criterion of the economic efficiency is satisfied in the comparison of the aerial surveillance versus the tower based fire detection system.

Extremely High Fire Weather Index – 4-dimensional analysis

The above analysis focused on the physical extension of the given area; 2 dimensions meant flat areas, 3 dimensions were articulated areas. But there was no difference in the time range; it was taken as a constant value. However, areas are usually threatened by fire cyclically during the so-called fire seasons. If the fire risk is cyclical, can the monitoring of the area be also cyclical? If we take into account the fire seasons as a time factor the analysis becomes four-dimensional.

It is known that fire seasons strongly correlate to weather conditions and a fire weather index (FWI) was created for its measurement, e.g. Canada: McArthur FWI (Dowdy at al., 2010), Germany: Waldbrandgefahrenindex WBI (König, 2007). Obviously, the higher the fire risk (as shown by FWI), the more area monitoring is required, because the probability of hot spot detection is higher. There should be a correlation between FWI and the effectiveness of fire detection.

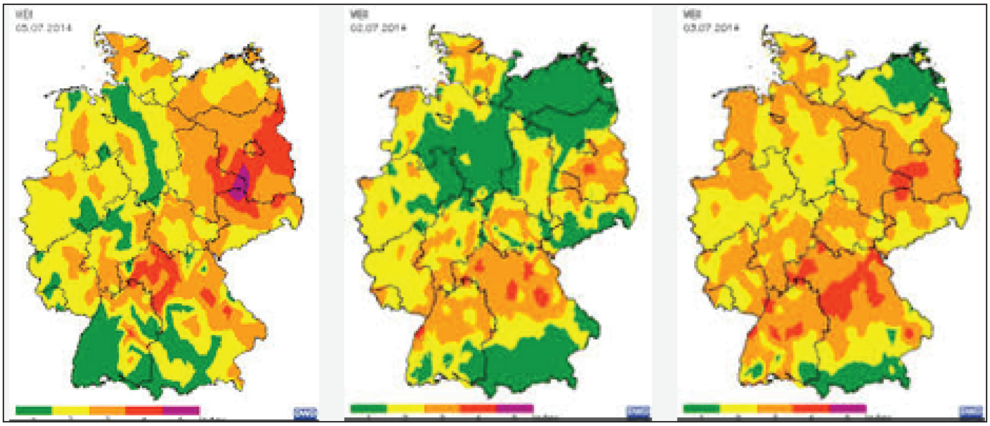

Figure 10 – Examples for Waldbrandgefahrenindex, July 2014, Germany

Following the correlation, the FWI based fire detection planning does not require area monitoring all year round. This condition is not relevant for the tower based fire detection system because its installation is fixed and it is able to work during the whole year. Consequently, we need to count with maintenance costs for the whole year. In case of aerial surveillance we have to count with costs only for the period when it is occasionally demanded.

There are some options for analyzing the efficiency: area extension can be taken as 2 dimensional or 3 dimensional; however, both results must be essentially similar.

In case of identical effectiveness – the average rate of fire detection is the same – the cheaper solution is more efficient; however, this rarely happens. In the other scenario there are differences between the two methods both in the speed of fire detection and also in the operational costs. Obviously, the costs of aerial fire detection are higher. The higher costs of aerial fire detection might be balanced by the higher rate of detecting hot spots; which gives us the tipping point between the two methods. Above this threshold – calculating with a fix price per flight hour – the aerial fire detection is more efficient, otherwise it is not.

If there is a difference in hot spot detection we have to calculate the difference between the saved forest and costs. Under normal circumstances the criterion can be expressed by the following formula:

$$\Sigma C_{UAV\_occasionaly} < \Sigma C_{Tower\_yearly\_\mathrm{costs}} \qquad (7)$$

$\Sigma C_{\mathrm{UAV\_occasionally}}$ - occasional costs of UAV used by extremely high FWI;
$\Sigma C_{\mathrm{Tower\_yearly\_costs}}$ - yearly costs of the tower based fire detection system.

As long as the above formula is valid the criterion of economic efficiency is satisfied at an extremely high FWI value.

As can be seen, this latest analysis contains the most changeable variables. Therefore, this paper only provides suggestions for further research, e.g. the exact definition of the tipping point, or the correlation between the higher rate of detecting hot spots and the efficiency.

Summarizing

There is no doubt that one of the key elements of the cheap but effective fire suppression is the early fire detection and quick initial response. There are many fire detection solutions; however, in many cases taking an overview of the effectiveness is not useless.

This paper firstly described the basic principles of the economic effectiveness of fire management. Then it treats the different dimensions of fire detection and calculates the possibility of aerial flight patrol. Looking at the monitored forest as a flat area makes the analysis 2-dimensional but as an articulated area requires 3-dimensional analysis. If research counts with the time scale, i.e. changing weather conditions, the analysis becomes 4-dimensional.

Research proves that in the 2-dimension model the aerial flight patrol cannot be effective; a tower based fire detection system is required. In case of the 3-dimension model the type and rate of the area articulation decides between aerial flight patrol and the tower based fire detection system. The 4-dimensional analysis shows that the choice between the aerial flight patrol and the tower based fire detection system depends on the fire weather index of the area.

The paper emphasized that the applied analysis contains a number of schangeable variables. Therefore, this paper only provides suggestions for further research, e.g. the exact definition of the tipping point, or the correlation between the higher rate of detecting hot spots and the efficiency require further study.

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A tűzdetektálás hatékonyságának vizsgálata különböző dimenziókban

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Az olcsó, de hatékony tűzoltás egyik kulcseleme a korai tűzdetektálás és az oltás gyors megkezdése. A tűzdetektálásnak számos lehetősége ismert, ezek hatékonyságának áttekintése nyilvánvalóan nem haszontalan.

A cikk elsőként a tűzoltás gazdaságossági szempontú hatékonyságnak alapelveit mutatja be. Ezután a kutatás különböző dimenziókban végez elemzéseket, és alapvetően a légi őrjáratozásra fókuszál. A megfigyelt erdőterületet síknak tekintve az elemzés kétdimenziós, míg dombos-hegyes területnél háromdimenziós modelleket alkot. Amennyi-

ben egy hosszabb időintervallumot is figyelembe veszünk, vagyis tekintettel vagyunk az időjárás változására is, úgy az elemzés négydimenziós.

A kutatás alapján a kétdimenziós modellben a légi őrjáratozás nem lehet hatékony, a toronyra szerelt tűzdetektáló kamerák előnyösebbek. A háromdimenziós modellben a fenti rendszerek hatékonysága a domborzat átszegdeltségének mértékétől függ. A négydimenziós modellben végzett vizsgálatok azt mutatják, hogy a légi őrjáratozás, valamint a toronyra szerelt tűzdetektáló rendszerek hatékonysága korrelál a tűzveszélyességi indexhez.