Detecting and Localizing Forest Fires from Emitted Noise

Claus Blaabjerg
Brüel & Kjær, Claus.Blaabjerg@bksv.com
Karim Haddad
Brüel & Kjær, Karim.Haddad@bksv.com
Wookeun Song
Brüel & Kjær, Woo-Keun.Song@bksv.com
Ignazio Dimino
CIRA, The Italian Aerospace Research Centre, i.dimino@cira.it
Vincenzo Quaranta
CIRA, The Italian Aerospace Research Centre, v.quaranta@cira.it
Alessandro Gemelli
D'Appolonia, alessandro.gemelli@dappolonia.it
Natalia Corsi
D'Appolonia, natalia.corsi@dappolonia.it
D. X. Viegas
ADAI, xavier.viegas@dem.uc.pt
L. P. Pita
ADAI, luis.pita@adai.pt

Abstract

It is well known that forest fires emit characteristic sounds and in some circumstances, when the fire spread conditions are very intense the level of this sound can be perceived even from large distance as a loud roar as it is reported in many cases (Mannix 2008, McGourty 2009).

An original study on the measurement of the characteristics of the sound emitted by natural vegetation burning in the open air in the conditions of usual forest fires was carried out with the objective of determining characteristic features of this sound and of assessing the viability of developing acoustic sensors that could be used to detect the presence or proximity of a forest fire for field and operational applications.

The acoustic emission of fires was measured and analyzed to assess the feasibility of a novel acoustic system for the early detection of fire in a forest. In a series of preliminary tests in the well controlled conditions of an enclosed Fire Laboratory the acoustic signal emitted by the burning of different fuel beds composed by forest species characteristic of Mediterranean and Southern European countries were carried out. A wide range of fire spread conditions was considered in these experiments at they showed that the spectrum of the noise emitted by the fire has characteristic features that are useful to recognize its acoustic signature.

In a second step a series of tests in the open air in an airfield close to the Laboratory were performed. The effects of type of fuel and background noise were considered in these outdoor experiments in order to design a system suitable in operative conditions.

In a third step, acoustic sensors were used in the field experiments of Gestosa in 2009. The experiments were carried out in the Mountain of Lousã, in Central Portugal and consisted in the controlled burn of plots of shrub vegetation of one hectare of area. The experiments were encouraging mainly because the loud noise produced by some of the burns was clearly received by the sensors and identified positively as originated by a forest. The effect of distance to source were identified as a limitation to the use of the system in wide areas especially to detect the presence of relatively small fires spreading with very low intensity.
Keywords: fire noise, forest fire, early fire detection system

1. Introduction

Different solutions exist for detecting forest fires at early stage: visual surveillance, cameras, infrared cameras, LIDAR technique, and satellite as examples. But these approaches show some limitations when the goal is to monitor, continuously in time and space, an area with assets (villages, infrastructures…). In the context of the project EUFIRE (European Project FP6-IST-35299), other technological solutions have been investigated in order to overcome these limitations (D. X. Viegas, 2009). One of the new approaches explored in this project concerns the detection and the localization of forest fire thanks to the emitted noise. It is well known that a fire generates an acoustic emission, and in some cases, the generated noise is intense (Mannix 2008, McGourty 2009). Also, in many cases, the noise is easily recognized by humans as originated from fires. Therefore, the fire noises have signatures which could be detected by an adapted processing. One advantage of using the noise to detect a forest fire is related to one property of acoustic propagation: there is no need for line of sight between the fire and the acoustic sensors for detection purpose.

In the first part of the article (section 2), we show results and analysis from tests performed in laboratory conditions: acoustic measurements were performed to obtain noise signature for different type of fuels. In the second part (section 3), a description of the fire detection system is given. Validations tests results are also reported. In the third part (section 4), we report results of tests performed in real conditions.

2. Forest fire noise signatures

Humans can recognize in most cases a fire noise; therefore a signature of the fire noise could be obtained. One way to check the presence of a signature is to look at the spectrum of the acoustic pressure measured when there is a fire and process these data by an Artificial Neural Network replicating the decision making process typical of humans. All these tests described in this section have been performed at ADAI facilities, at Lousã in Portugal.

Tests in laboratory

In order to obtain these spectra, tests have been performed in laboratory conditions. The first tests were done in an enclosed laboratory with different species. From the tables containing different fuels to burn, different microphones at different distances were used to acquire the fire noise. The different tested fuels are: straw, shrubs, pines and slash. Two microphones at different distances were placed close to the test table.

The spectra concerning the tests with 1x1 m^2 table are reported in Figure 1. The X-axis of the figure is the frequencies expressed in 1/3 octaves. The Y-axis is reports the acoustic level in Decibel (dB).

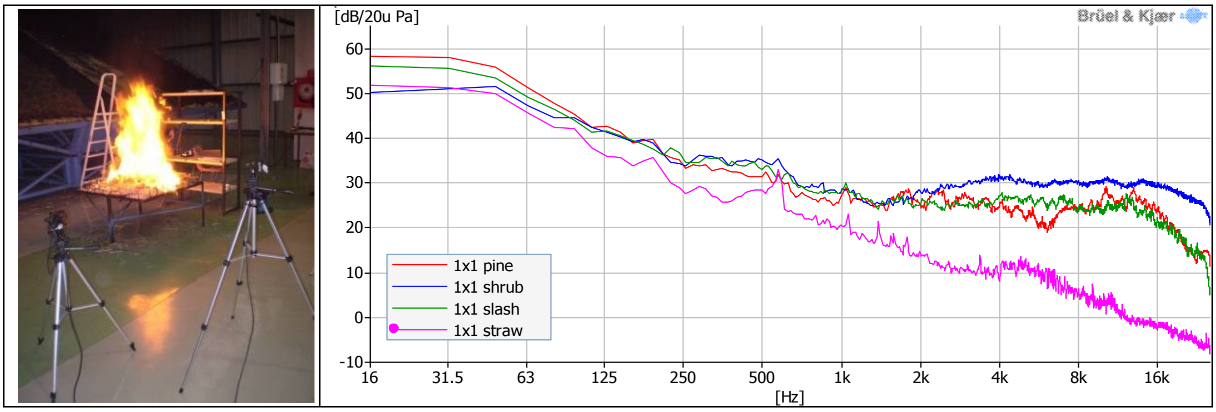

Figure 1: Left: Setup. Right: spectra of fire noise for different fuels.

Looking at these spectra for the different fuels, we notice little differences in low frequencies (below 1 kHz), the dissimilarities are more important in higher frequencies. This part of this spectrum is in great part related to the crackling noise.

Airfield tests

To get a more realistic signal of the fire noise, outdoor measurements were done at the Lousã airfield, where 8 plots with different fuels have been set up. Again, we put microphones at different distances, but we used finally results from microphones close to the fires, to get signals containing, as much as possible, only the noise from fire, in order to get an accurate spectrum. Pictures of the setup are shown in Figure 2.

Figure 2: Pictures of the setup for the tests at Lousã airfield. Left: a plot, right: a microphone

The closer microphones were put at approximately 50 meters from the plots for the plot 1 to 6 (plots with slash and shrubs) and at about 10 meters from the plots 7 and 8 (plots with straw). To emphasize the effect of the fire noise on the acoustic signals, we compare the spectra obtained in three different times: just before the fire has started, during the fire activity, just after the fire has died. Results are shown for a few plots in Figure 3. As in figure 1, the Y-axis represents the level in Decibels, but X-axis corresponds to frequencies on a linear scale.

The comparison of the three curves (before, during and after the fire) shows that in all cases the fire presence is obvious in almost the full frequency range: the red curves, corresponding to the cases when the fire is active, are always higher than the two other curves. It is the case for high frequencies (above 1 kHz approximately), as already stated in previous section. But the fire contribution is also attested in low frequencies (for the plot 5, the increase of level in low frequencies due to fire is little, but it is present).

This differentiation between low and high frequencies is important when it comes to design a system based on acoustic measurements to detect forest fires. From the spectra, the contribution of fire noise is definitely more important for high frequencies. This is also the range where the fire noise could be easily recognized (range where the crackling noise is present). But absorption of acoustic waves in the air is increasing with frequencies, meaning that high frequency noise is rapidly attenuated as function of distance. Microphones at relatively long distance from fires have little chance to capture the high frequency part of the signal. Therefore, it is important to focus on the low frequency part of the fire noise spectrum, in order to design a system which would be able to detect fires at long distance. An estimation of the maximum distance to detect a fire from acoustic measurements is discussed in last part of the article.

Looking at all the results in Figure 3, we can target especially the range 200 – 500 Hz to detect a fire. This frequency range is used below to design the detection system based on microphone measurements.

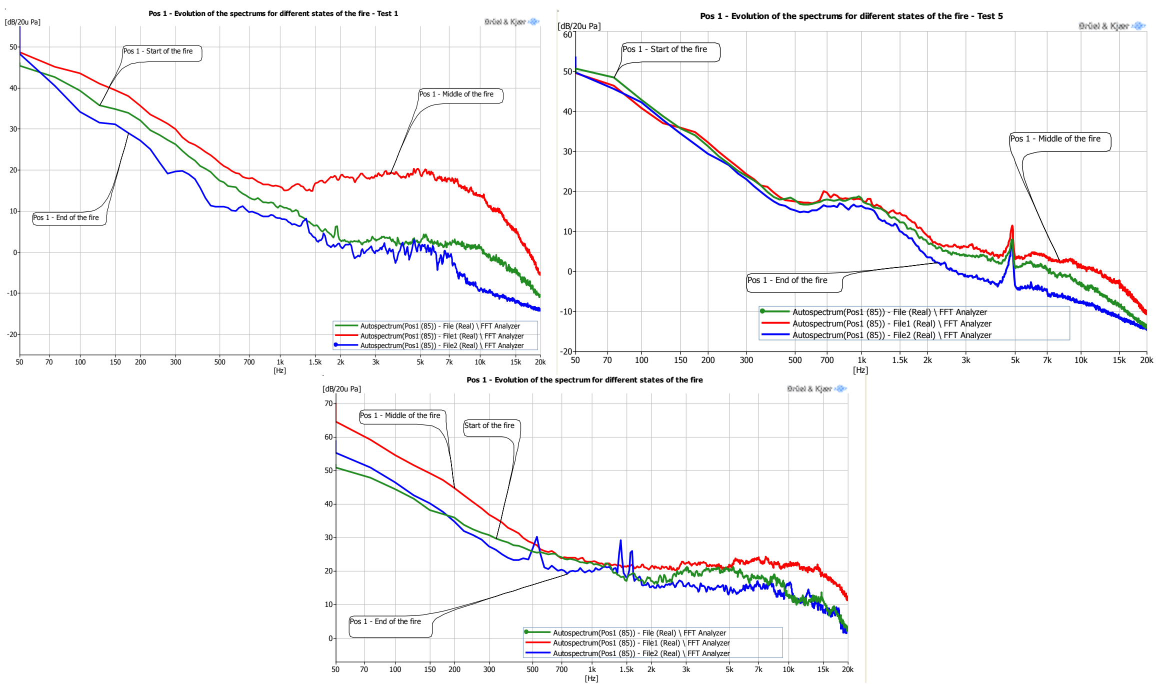

Figure 3: Spectra obtained during tests at Lousã airfield. Top left spectrum: Test 1, Top right spectrum: Test 5, Bottom spectrum: Test 7. Green curves are spectra obtained just before fire has started, red curves are obtained when fire is active and blue curves are obtained at the end of the fire.

3. Design of the Volumetric Acoustic System (VAS)

The purpose of the Volumetric Acoustic System is to detect and localize forest fires as soon as possible in a given area. From the previous section, we know what frequency range we target to design such system. But we need other requirements to fully design the system. The first question is: in what conditions do we want to use the Volumetric Acoustic System. Secondly, the VAS has to perform two tasks:

- Localization: at what position is the acoustic source? Requirements concerning this task are the resolution and the dynamic range.
- Detection: is the detected source a fire noise or something else? The requirements are the rates of false alarm and of good answer.

In this section, we describe the VAS prototype and present the validation tests.

Scenarios

Different types of design could be done, depending on the scenario, in particular the morphology of the terrain. The scenario we have chosen to consider is the one close to the field test (results reported in the last part). The figure 4 illustrates a typical case of the chosen scenario.
In this scenario, assets are distributed around the forest; therefore the VAS system should be able to monitor all directions around. In other types of scenario (not considered in this paper), only a limited area needs to be monitored (edge of a canyon as an example): in this case, the geometry of the VAS would be different from the scenario of the Figure 4.

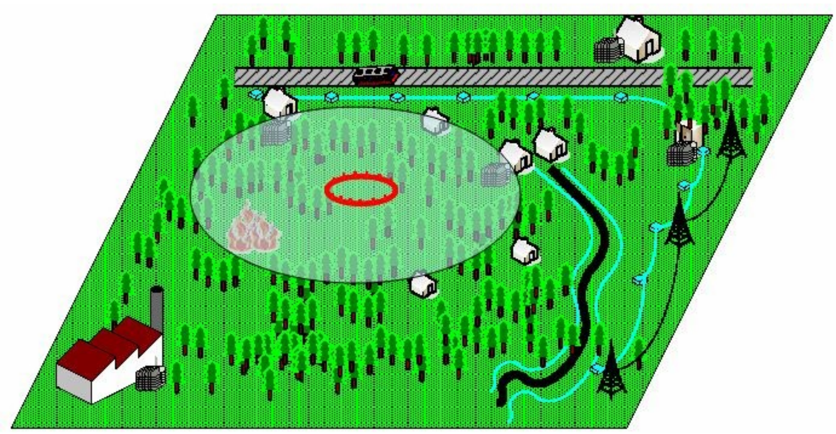

Figure 4: Typical scenario for the design of the Volumetric Acoustic System. The red circle indicates the VAS system, and disk around the VAS corresponds to the inspected area.

Localization

To achieve the localization of acoustic sources, a set of microphones is necessary. A single microphone can provide the frequency content, the level of a sound field, but without separation of the different sources, which contributes to this sound field. At least two microphones can constitute an acoustic localization device, even if the performances in term of resolution are poor. This set of microphones is called ‘acoustic antenna’,

'microphone array' or simply 'array'. A key parameter, which plays a major role in the imaging performances, is the arrangement of the microphones ('array design').
One popular technique to localize acoustic sources based on microphone arrays is called 'beamforming' (Christensen, 2004). For this processing, the signals from each microphone are summed up in an optimal manner to give enhancement to the sound from a specific direction. This processing is actually a spatial filter. As an example, we consider below the localization of a source based on a linear array (Figure 5).
In this example, we consider one single source emitting a specific sound. The microphones output are related to the distances from the source to each sensor of the array: longer is the distance, more the output signal originating from the source is delayed. The role of the beamforming processing is to correct these delays in order to align all the signals for the chosen direction (see Figure 5), and then sum up all the contributions. If the looking direction is toward this source, we will obtain a local maximum output signal. Thus, by scanning all directions, we can find where the sources are.
But the beamforming processing cannot give a perfect image of all the sources, because it is based on discrete sensors and the array has a limited size. The complete sound field is thus not fully captured and then, information is missing. The consequences are a limited resolution and the presence of ghost (or false) sources on the acoustic map. These effects can be understood in a similar way as the Discrete Fourier Transform (the time step and the time length are equivalent respectively to the spacing between sensors and to the size of the array).

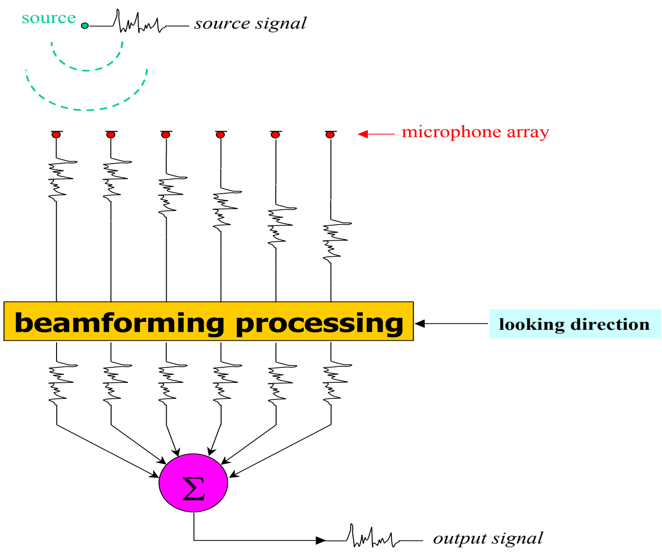

Figure 5: Beamforming processing

To characterise a microphone array, two main parameters are used: the resolution and the dynamic range. The resolution is defined as the minimum distance between two sources which can be separated by the microphone array. As stated before, the processing introduces ghost sources which do not have any reality. Their presence limits the dynamic range of the system, because sources which have levels lower of these ghost sources cannot be detected. Therefore the dynamic range is expressed as the difference of level between the main source level (true source) and the maximum level of the ghost sources.

For a given frequency range, the resolution is mainly related to the size of the microphone array, and the dynamic range is more connected to number of microphones and their distribution.

According to the chosen scenario, all directions (in azimuth) should be monitored. Therefore we have chosen a circular microphone array to fulfil this requirement.

Based on this shape and the chosen frequency range, 200 – 500 Hz, simulations has been carried out to meet initial requirements in terms of resolution and dynamic range.

The designed microphone array is shown in Figure 6. The radius is 3 meters and the number of microphones is 39. This microphone array fulfil the initial requirement in resolution (11.4 degrees corresponding to a separation of two sources distant of 200 meters at 1 km from the array) and in dynamic range (10 dB).

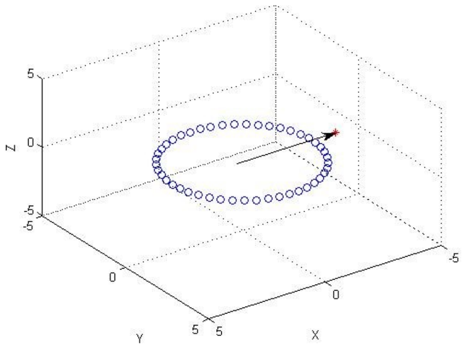

Figure 6: Microphone array selected for VAS: 3 m radius, 39 microphones

However the resolution along the elevation does not fulfil the requirement. Therefore this array can be used only to detect sources in azimuth. Moreover simulations show also that the resolution in azimuth decreases and does not meet the resolution requirement for sources which have an elevation higher than +/- 35 deg from the array plane. In conclusion, the designed array is mainly able to localize sources only in azimuth and for sources which are approximately in the same plane as the microphone array. This is in line with the chosen scenario.

Thus the microphone array can localize acoustic sources in azimuth, providing directions of the sources. In case more precise localisation is needed, a triangulation technique could be used in connection with others microphone arrays to get access to spatial coordinates. To overcome the lack of resolution in elevation, a terrain model would help to have a greater accuracy in the source localization. To illustrate how it could be done, we consider the case depicted by the figure 7. In this figure, microphone arrays 1 and 2 localize a source. By triangulation, we obtain the coordinates of the point C. But to get the real position of the source, we can use a terrain model which would give the real altitude of the source, so the point D. This situation has been met during the field tests, see the last part.

Detection

Once a source has been localized, the system analyzes the signal from that specific source in order to establish a decision on the nature of the emitter (*fire* or *no fire*). The processing module we are using to make this decision is called pattern recognition. To set up this module, there is an initial stage where the internal parameters are calculated based on a training set. It means that we train the module based on an Artificial Neural Network to make the right decision (*fire* or *no fire*) on a known training set of signals. Then the internal parameters are validated on different set of signals.

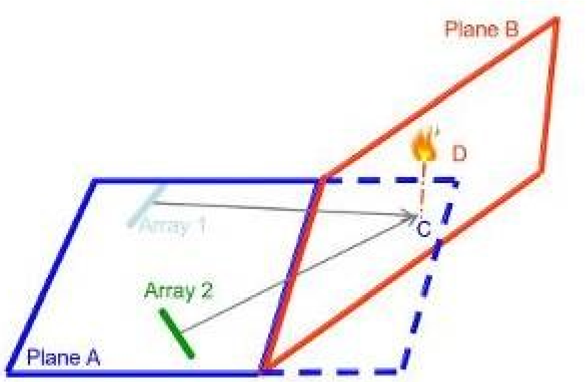

Figure 7: Illustration of how to precisely localize a fire thanks to the triangulation technique and to a terrain model.

To evaluate the pattern recognition performances, we have to consider criteria, according to what is most important for such system. One important objective of a fire detection system is the reliability: what is the probability to detect correctly a fire during an amount of time? What is the risk of false alarms during the same amount of time?

This amount of time should be relatively small for a system aiming to detect fires as early as possible. We consider 1 minute as reasonable. A criterion is therefore the probability to detect a fire *for the correct direction* within 1 minute, if the beamforming processing has localized a source. The result is called *Fire Detection probability* below.

Another criterion to evaluate the pattern recognition performances is the probability to detect a fire when there is none (error about the direction or when the noise is only background noise). The result is called *False Alarm probability* below.

Prototype and validation

A complete prototype has been built, based on the design choices:

- Two microphone arrays, 3 m in radius and 39 microphones (Figure 8 shows one of them),
- Acquisition boards,
- Software for acquisition of signals, processing (localisation and detection) and communications with a control Unit.

The basic validation of the system consists in checking that the localization of a source at a known azimuth is performed accurately. The microphone array of Figure 8 has been used to localize the noise emitted by a loudspeaker in the frequency range 200 – 500 Hz (white noise signal) and at distance 50 meters. The result is shown in Figure 9. It shows that the dynamic range is relatively high (12.6 dB, so higher than the 10 dB required), and the experimental resolution is 5.9 degrees (better than the required 11.4 degrees).

Figure 8: view of the microphone array

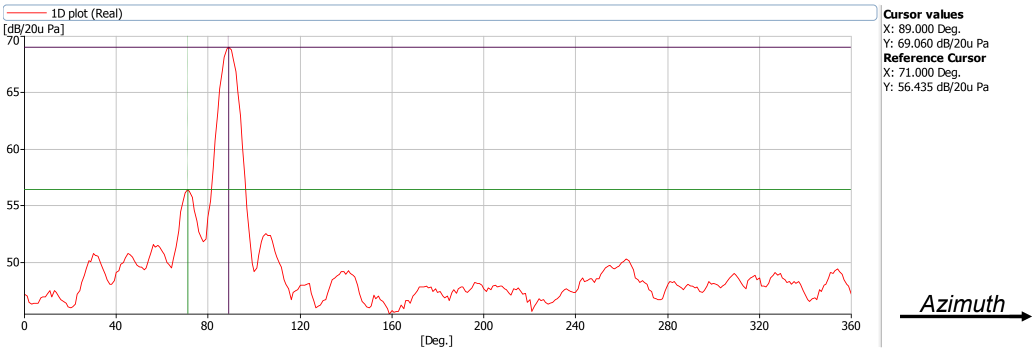

Figure 9: Validation test for one microphone array: localization of a source at a known azimuth.

VAS validation on a real fire at Lousã Airfield

The full VAS has been tested in Lousã airfield. The purposes of these tests are:

- Test of the integration with other components: two microphone array (one was simulated), and communications with the control unit.
- Localization and detection of real fires.

The positions of the different elements are reported in Figure 10. The result of localization for one plot is given in Figure 11.

In conclusion, concerning the localization capabilities of the VAS, it was shown that the fire was correctly localised for 4 different plots, meaning that the acquisitions and the beamforming components are working properly. For the other plots, signal-to-noise ratio was an issue in the sense that background noises were relatively high compared to the noises from the fire. The amount of noise from a fire is directly linked to the fuel and also to the size of burning area; therefore a noisier plot would improve the signal-to-noise ratio. This was the case during the field tests discussed below.

Concerning the detection, the results are:

	Fire Detection probability	*False Alarm probability*
Plot 11514	87 %	0 %
Plot 11515	100 %	0 %
Plot11516	50 %	37.5 %
Plot11517	100 %	25 %
Overall	77 %	17 %

The performances of the pattern recognition module are very good for the two first plots. For the plot 11516, the performances are lower compared to the other plots, but the overall performances are reasonably good. Nevertheless, pattern recognition module has been improved for the field tests described below.

Figure 10: Positions of the different elements for the VAS validation in Lousã airfield. SPU2#2 emulates VAS#2. VAS #1 has been put in two different positions. LCU: it is the Local Control Unit, driving and receiving data from all sensors.

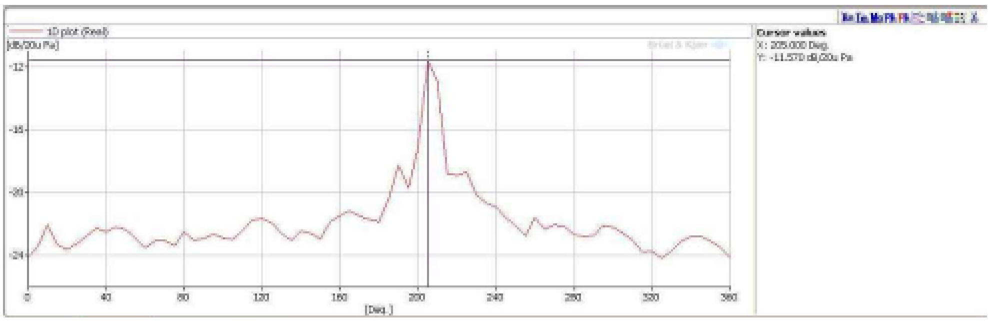

Figure 11: Localization from VAS#1 (at position 2, see figure 10) of fire noise from plot 11514. X-axis represents the azimuth.

4. Field tests

Field tests have been carried out at Gestosa. The test conditions were very similar to a wildfire scenario with the exception that the burns were carried out in controlled conditions in pre-prepared plots with defined borders and with the support of fire fighters to avoid fire escape, Figure 12. The test site was situated in the mountain at 1000 m altitude with access to all terrain vehicles and exposed to the elements; the deployment of the equipment required safety procedures.

Figure 12: Field Tests

The tests setups are indicated in figure 13. The burnt plots are shown in red, and the positions of the two VAS systems are indicated by the labels VAS#1 and VAS#2.

Figure 13: Setups for the field tests. Left: test setups for the plots 11501, 11502 and 11503. Right: test setups for plots 4 and 5 (plot 4 has been finally cancelled for safety reason).

The characteristics of the plots 11501 to 11503 (plot 5 is small part of 11501) are:

P11501 L8	40x30 m^2	Live Shrubs	10º	Linear	30-75	15-30	35-75	2-7	SW
P11502 L9	40x30 m^2	Live Shrubs	17º	Linear	30-75	15-30	35-75	2-7	SW
P11503 L10	40x30 m^2	Live Shrubs	21º	Linear	30-75	15-30	35-75	2-7	SSW

(Respectively the dimension of the plot, type of fuel, terrain slope, ignition pattern, humidity, temperature, fuel moisture, wind speed and wind direction).

Results concerning the plot 11503

The fire on this plot has been detected by the two microphone arrays. As an example, figure 14 show one result of localization for VAS#1 and VAS#2.

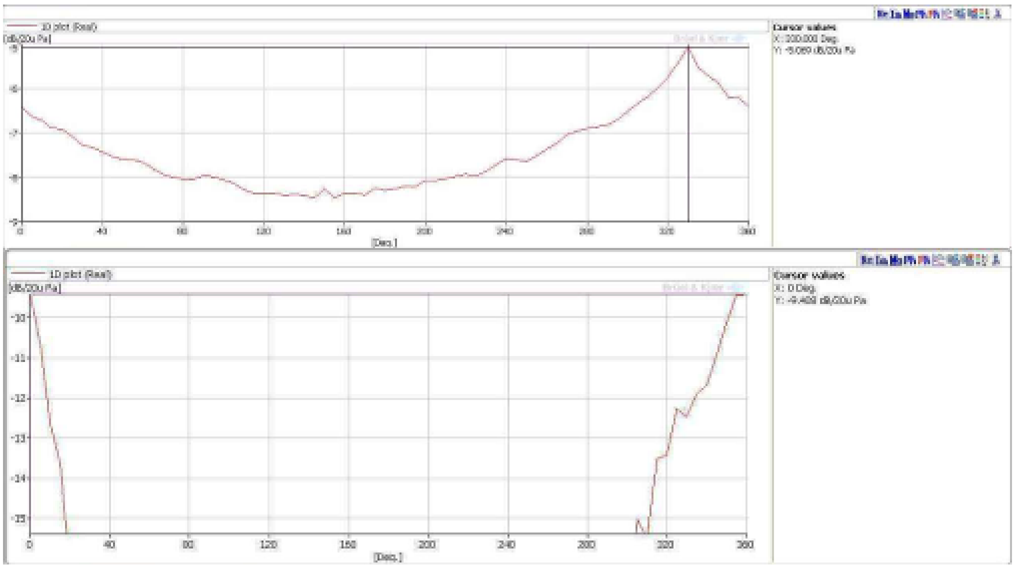

Figure 14: Top: localization of the fire on plot 11503 from VAS#1 at 330 degrees. Bottom: localization of the fire on plot 11503 from VAS#2 between 355 and 0 degrees.

Applying the triangulation technique from the results of VAS#1 and VAS#2 gives a position on the plot 11503 as expected (Figure 15).

Figure 15: Plot 11503. Fire localization by triangulation using the outputs of the two arrays.

For the other plots, we obtain the same type of results (figures 16 to 18). Therefore, all the fire plots were successively localized. Nevertheless, the result of the case from the plot 5 (Figure 18) is fragile: the location of the burning plot was between the two microphone arrays; then the triangulation technique does not perform very well in such situation. In this case a better solution would have been to put the arrays in different positions or to use a third microphone array.

Figure 16: Plot 11502. Fire localization by triangulation using the outputs of the two arrays.

Figure 17: Plot 11501. Fire localization by triangulation using the outputs of the two arrays.

Figure 18: Plot 5. Fire localization by triangulation using the outputs of the two arrays.

Detection performances

The results are summarised in the following table.

	Fire Detection probability	*False Alarm probability*
Plot 11503 – VAS#1	100 %	40 %
Plot 11503 – VAS#2	75 %	41 %
Plot 11502 – VAS#1	86 %	0 %
Plot11501 – VAS#1	89 %	50 %
Plot 5 – VAS#2	100 %	0 %
Overall	92 %	30 %

The performances of the pattern recognition module were improved compared to the results obtained at Lousã airfield (see previous section). The results are globally excellent, except for a too high False alarm probability for plot 11501 (VAS#1) and plot 11503 (VAS#1 and VAS#2). Nevertheless, such a drawback can be solved by implementing an enhanced value for the threshold of detection. In addition, it should be noticed the very excellent results for plot 5, but in this case, the arrays are relatively close to the fire.

Discussion about the acoustic measurement distance

In all investigated cases, exhibiting fires at distances between 20 to 110 meters from the microphone arrays, the VAS system localized the fire. But it is difficult to express a definitive opinion for greater distances. The crucial issue is how far can propagate a fire noise. It is dependent on the fuel but also on the size of the burning area (bigger is the area, more noisy it would be). Another important aspect is the background noise. In our field tests at Gestosa, the dynamic range of the plot are relatively low, except for plot 5, where the arrays were very close to the burning area. A lower dynamic range makes difficult to localize sources. Some elements of the tests we have performed confirm our opinion that long range localization and detection is very challenging:

- The fire at plot 11513 (Lousã airfield, see previous section) has not been detected (pattern recognition) and localized (beamforming) because of an other dominating source. The distance from plot 11513 to the array was 111 meters.
- During the tests at Gestosa (plot 11503), fire has been localized by the second array (VAS#2) a few minutes later than the first array. Though the distances from each array to the plot are very similar (80 meters from VAS#1 to plot 11503, 110 meters from VAS#2 to same plot). This difference in time for the localization could be explained eventually by the wind. Nevertheless, it shows the difficulty to localize a fire for a relatively short distance (110 meters).
- In the pattern recognition analysis from the tests at Gestosa, it has been pointed out that for the current state of VAS, the levels of the sources should be relatively high compared to the background noise to be localized by the beamformer, and then analyzed by the pattern recognition (therefore the signal to noise ratio is an important element). If the noise from a fire is relatively low (because too far away or too small), it may not be localized and detected.

In such conditions and unless the burning area is very noisy, tests demonstrated that it would be difficult to detect and localize a fire at 1 km distance, at least when the fire size is relatively small.

5. Conclusion

This campaign of measurements at Gestosa, in mountain conditions, has shown that the Volumetric Acoustic System is able to localize fires thanks to its acoustic sensors and processing tasks (beamforming and pattern recognition). It justifies the different design orientations we have made for the VAS prototype: the frequency range, the design of the array, the hardware and the software. The question remains about how far a fire can be detected and localized by such system. The tests performed at Gestosa and at Lousã airfield in Portugal did not give a definitive answer. But some results tend to show that for long distances (for example 1 km or higher), the localization and detection of a fire are strongly influenced by the signal-to-noise ratio (ratio between the fire noise levels and the the background noise level). These particular aspects should be addressed more precisely since they significantly depend on many factors like wind, fuel, size of the burning area and terrain morphology.

Nevertheless, the system has proven it capability to localize fires: It could therefore be suitable for short distances fire detection: to protect small forest areas, facilities, houses.

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