PASSIVE MICROWAVE FIRE DETECTION: A SURVEY AND ASSESSMENT

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INTRODUCTION

Recent research at The University of Tennessee has demonstrated that the science of using passive microwave engineering technologies in detecting both flaming and smoldering fires has been shown as a promising technique. This technique relies upon the fact that thermal radiation from fires generates a detectable signal in the microwave portion of the electromagnetic spectrum.

Earlier research revealed several attractive advantages of the use of microwave-based flame detection and intelligent sensors. The first and primary advantage is that microwave radiation penetrates optically thick smoke and water vapor. A second attractive feature is that microwave fire detection might be viable through non-metallic walls.

Low-cost, hand-held microwave detectors could be useful for fire investigators who conduct on-scene assessments of post-fire smoldering debris. Microwave detectors could also assist fire investigators when identifying and confirming multiple sources of ignition during full-scale fire tests, particularly during the generation of optically dense smoke.

This paper conducts a (1) survey and assessment of the use and science of microwave detection as applied to fire detection; (2) includes the results of bench top and enclosure experiments; and (3) presents a gap assessment of further short- and long-term research areas.

MICROWAVE SCIENCE

Electromagnetic waves consist of charged particles, such as electrons, changing their speed or direction. These waves are also characterized as photons (massless particles of energy), traveling at the speed of light. The oscillations of these electromagnetic waves, consisting of both an electric and magnetic field, form their ***frequency*** and ***wavelength***. The frequency is the number of waves per second.

The following simple mathematical relationship exists between the ***energy*** of electromagnetic waves, their frequency, and wavelength:

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$$\lambda = \frac{c}{f} = \frac{hc}{E}$$

where

$\lambda = wavelenth\ (meters)$
$c = speed\ of\ light\ (3 \times 10^{8}\ meters\ per\ second)$
$f = frequency\ (Hertz)$
$h = Planck's\ Constant\ (6.63 \times 10^{-27}\ ergs\ per\ second)$
$E = Energy\ of\ the\ electromagetic\ wave\ (ergs).$

Note that the energy of the electromagnetic wave is proportional to the frequency and inversely proportional to the wavelength. Therefore, the higher the energy of the electromagnetic wave, the higher the frequency, and the shorter the wavelength.

The spectrum of electromagnetic waves is generally divided into regions, classified as to their wavelength. These bands of wavelengths range (from short to long) generally consist of gamma rays, x-rays, ultraviolet, visible light, infrared, microwave, and radio waves.

The ***radiation*** from electromagnetic waves can be by ***thermal*** and ***non-thermal*** means, depending upon the effect of the temperature of the object emitting the energy. ***Non-thermal emission*** of radiation in general does not depend on the emitting object's temperature. The majority of the research into non-thermal emission concerns the acceleration of charged particles, most commonly electrons, within magnetic fields, a process referred to in the astrophysics field as ***synchrotron emission***. Astrophysicists and radio astronomers look for synchrotron emissions from distant stars, supernovas, and molecular clouds.

Thermal emission of radiation from electromagnetic waves depends only upon the temperature of the object emitting the radiation. The common forms of this radiation can be ***blackbody radiation***, ***free-free emission***, and ***spectral line emission***. For the purposes of this paper, we concentrate on the thermal radiation from the microwave regions of electromagnetic waves.

Blackbody radiation is the central and most basic form of thermal emission of electromagnetic radiation from an object whose temperature is above absolute zero (0 Kelvin). A blackbody is a theoretical object that will completely absorbs all of the radiation falls upon it and will not reflect away any of the radiation. Practical examples of blackbody radiators include the Sun and other stars in the galaxy.

Raising the temperature of an object causes atoms and molecules to move and collide at increasing speeds, thus increasing their accelerations. The acceleration of charged particles emits electromagnetic radiation which forms peaks within the wavelength spectrum. There is a direct correlation in changes in temperature impact the accelerations of the particles with the frequency of the radiation and peaks within the spectrum. Once an object reaches its equilibrium temperature, it re-radiates energy at characteristic spectrum peaks.

The use of passive high-gain microwave antennas and receivers to measure the temperature of a remote object is a field commonly known as ***microwave radiometry***. A microwave radiometer can produce a measureable voltage output which is proportional to the temperature of the target. The typical users of microwave radiometry are radio astronomers scanning extraterrestrial objects and orbiting satellites pointed back towards the earth conducting remote sensing of the earth's surface.

FIRE DETECTION BY MICROWAVES

The first prominent mention of the use of microwave technologies in fire detection appeared in a 1995 National Institute of Standards (NIST) report which conducted a comprehensive review of measurements and candidate signatures for early fire detection.[1] The NIST report suggested that the concept of multispectral electromagnetic wave sensing might become a viable fire detection technology. Cited was a modified microwave motion detector used to monitor the presence of flames in a gas furnace.[2] The device trained microwaves to interact with the ions produced in the flames to form a measureable Doppler signal. Note that this would be considered an active device.

The German 2001 NIST paper mentioned that the first experiments in fire detection by microwaves was conducted by Daimler Chrysler Aerospace AG. These experiments, which are not cited, were to detect fires in garbage bunkers. The reported success of these initial tests motivated the Germans to pursue their own experiments.

Tests by German Researchers

The science of using microwave engineering technologies in passive detection of both flaming and smoldering fires was first cited at a NIST Conference in 2001 by German researchers presenting it as a promising technique.[3] This technique relies upon the fact that thermal radiation from fires generates a detectable signal in the microwave portion of the electromagnetic spectrum. Their later research in 2006 identified a second attractive feature in that microwave fire detection might be viable through non-metallic walls.[4]

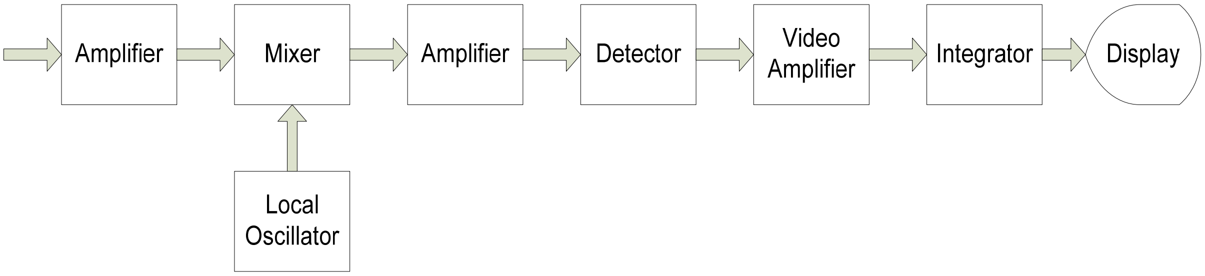
The German tests in 2001 used a commercial satellite dish and superheterodyne low noise converter to measure the microwave radiation of both the walls and the targeted fire. The experimenters chose a center frequency of 11 GHz with a bandwidth of 1 MHz. Their seven tests were described as an open wood fire, pyrolysis, open polyurethane, liquid heptanes, liquid spirit, and dekalin fires. The distance from the microwave dish antenna to the fire ranged up to 7 meters. Their findings showed that fires having glowing materials could be easily detected by the microwave apparatus. In contrast, fires consisting of only flaming combustion could not be detected.

The follow-up German tests published in 2006 expanded the frequency range of the initial experiments from 2 to 40 GHz. They reported that thermal radiation was measurable in this expanded range of frequencies. Their test apparatus used four broadband antennas to cover 2-12, 12-18, 18-26, and 26-40 GHz bands of operation. These researchers used a "hot load" of 100 ^{o}C (373 K) to calibrate their apparatus.

Recent Testing by U.S. Researchers

Research and development testing conducted during 2006-2007 in the United States by the authors also reveal similar results as were obtained by the German researchers. A 48 cm (19 in) Ku band (typically in the 12.4 - 18 GHz range) commercial satellite dish antenna with a low noise amplified blocked converter fed to a superheterodyne receiver.

Apparatus and a method for radiometric temperature measurement consists of a radiometer class superheterodyne receiver coupled to an antenna/calibration array that produces a brightness temperature signal (Figure 1). The typical calibration of such an array uses the Dicke switch[5] method with a known temperature source. However, due to the varying conditions, particularly with outside conditions, the authors chose to use other stable temperature sources (Sun, sky, ground) which also slowly changed with the surrounding environment.



<u>Figure 1</u>. Superheterodyne Receiver with Signal Amplifier

The output of the amplified signal, also referred to the literature as a brightness temperature signal, is interfaced to a laptop computer displaying a voltage reading which is converted to a temperature. The target source is was located up to 2.5 meters away from the dish.

The tests consisted of shredded paper, smoldering shredded paper, and Isopropanol pan fires. Rather than use a "hot load" for calibration, the ground and sky temperatures are used instead. A two-bulb portable battery-powered fluorescent light was used to help aim the antenna onto the location of the test fires. The results of the United States and German tests were similar as to the types of fires detected. Both the burning and smoldering shredded paper were easily detected; however, the flaming pan fire was not. This reported phenomenon is most likely linked to the fact that burning and smoldering fires share more in common with blackbody radiation and smokeless flaming fires do not.

Further experimentation demonstrated other security related applications in the area of intrusion detection. The first tests showed that overhead approaching aircraft provided a reflective interference easily detected by the apparatus that has been recently documented by other researchers.[6] In this situation, several radio observatories reported interference from frequency bands allocated to aviation pulsed radar transmissions. Since this application of microwave fire detection might be subject to false alarms by spurious accidental or intentions jamming signals on or surrounding the operational frequency, the authors have studied this phenomenon and recommend the use of protected radio astronomy frequencies. The authors are exploring the use of the 1.400-1.427 GHz band set aside for radio astronomy, since this band is one of the internationally protected passive frequencies.[7]

Another intrusion detection problem is the detection of humans and other objects at varying temperatures that come within the receiving aperture of the microwave antenna. Experiments conducted in 2007 showed that a human could be detected as far away 15 meters (50 feet). Other experimentation by the authors includes the most practical method to self-calibrate the detector. In the German tests, they used a "hot load" of 100 °C (373 K) to calibrate their apparatus. This would not be practical for a field deployable unit, for example, which would require

The authors suggest that various calibration sources already exist in the environment, both inside and out. Outside references could include the temperature of the Sun, the earth, foliage of large trees, and the ground beneath the unit. Within an enclosure, such as a warehouse, the floor temperature would be the most stable source.

ADVANTAGES OF MICROWAVE FIRE DETECTION

There are several advantages of using microwave radiometry for detecting fires. These conclusions are based not only upon scientific knowledge, but also the results of testing by both German and U.S. researchers:

- **Detection –** This technique relies upon the fact that thermal radiation from fires generates a detectable signal in the microwave portion of the electromagnetic spectrum.

- **Attenuation –** Due to the very nature of microwaves, molecules suspended in the air such as oxygen, water vapor, dust, and smoke do not attenuate the microwave radiation from the targeted object.

- **Temperature and climatic conditions –** Microwave antennas which remotely separated from their electronic instrumentation are less likely to be impacted by extreme temperature and climatic changes.

- **Penetration –** Due to the ability of microwave radiation to penetrate most materials, with the exception of metals, it may have future role in through-the-wall fire detection.

- **Cost –** Due to the mass production of commercial microwave antennas and associated electronics, the cost is relatively low when compared to other technologies, such as infra-red thermal imaging.

Furthermore, the underlying scientific basis for the use of microwave thermal detection is firmly set in the field of radio astronomy.

GAP ASSESSMENT

A gap assessment is a foundation for measuring the investment of time and resources to improve a product or process. The assessment considers both the potential individual usage as well as the number of consumers. Finally, the assessment often sets forth a financial plan to make prudent decisions of how to maximize the return-on-investments.

First the technology gaps need to be addressed in the potential use of microwave technologies for fire detection.

- **Antenna size and configuration –** The size of the antenna must be examined, particularly in terms of cost, maintenance, and configuration. At the present, parabolic dish antennas have been used; however, other configurations such as horn and flat arrays should be explored.

- **Frequency of operation –** Microwave fire detection is a passive technology that may be subject to accidental or intentional interference on or surrounding the operational frequency. Thought might be given to explore the 1.400-1.427 GHz band set aside for radio astronomy. This band is an internationally protected passive frequency.

- **Hand-held devices –** Low-cost, hand-held microwave detectors could be useful for fire investigators who conduct on-scene assessments of post-fire smoldering debris. Microwave detectors could also assist fire investigators when identifying and confirming multiple sources of ignition during full-scale fire tests, particularly during the generation of optically dense smoke.

The authors’ conception of the visualization of the complex data formed by several microwave receiver arrays can be integrated into a fire and intrusion detection system, such as shown in Figure 2. Obviously, the key technology involves the coordination and signal processing of the detector arrays along with the reference array.

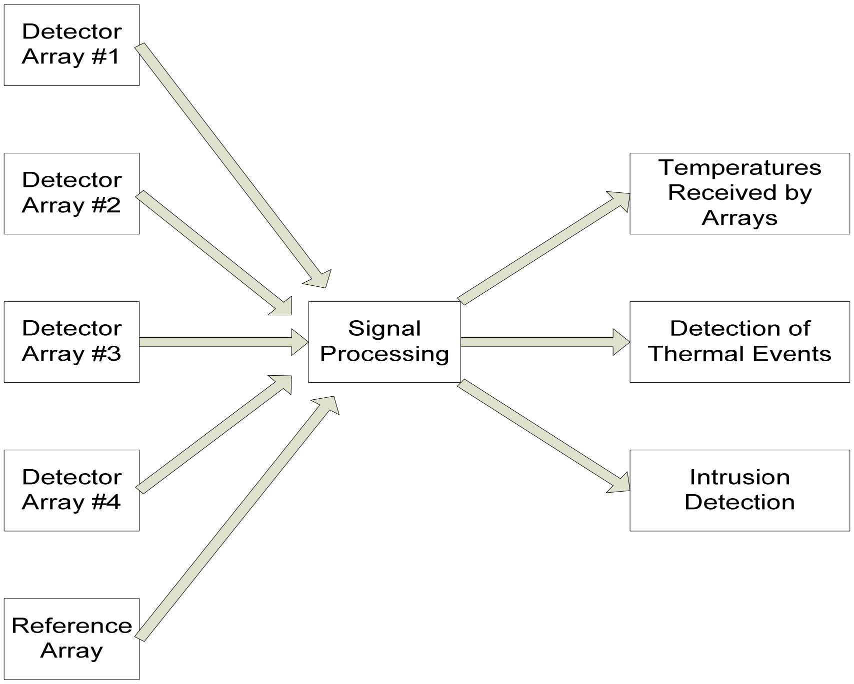


Figure 2. **An Integrated Fire and Intrusion Detection System**

SUMMARY AND CONCLUSIONS

This paper has conducted (1) a survey and assessment of the use and science of microwave detection as applied to fire detection; (2) included the results of bench top and enclosure experiments; and (3) presented a gap assessment of further short- and long-term research areas.

Researchers should recognize that the science of using microwave engineering technologies in detecting both flaming and smoldering fires has been shown as a promising technique. This technique relies upon the fact that thermal radiation from fires generates a detectable signal in the microwave portion of the electromagnetic spectrum.

We have seen that earlier research revealed several attractive advantages of the use of microwave-based flame detection and intelligent sensors. The first and primary advantage is that microwave radiation penetrates optically thick smoke and water vapor. A second attractive feature is that microwave fire detection might be viable through non-metallic walls.

Finally, low-cost, hand-held microwave detectors could be useful for fire investigators who conduct on-scene assessments of post-fire smoldering debris. Microwave detectors could also assist fire investigators when identifying and confirming multiple sources of ignition during full-scale fire tests, particularly during the generation of optically dense smoke.

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