Open-area Light Scattering Smoke Detection (OLSD)

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BACKGROUND

The OLSD technology is derivative of the familiar and well established method of smoke detection using light-scattering by smoke particles.

> *In traditional photo-electric detectors an air sample is either forcibly drawn or allowed to diffuse into a detection chamber. Labyrinths are used to keep out as much as possible of the ambient light from the external environment. Within the chamber a beam of light from an internal light source is directed toward the air sample. This light source is typically an LED or a laser diode, though other light sources such as incandescent lamps and Xenon discharge lamps have been used in the past. Also in the chamber there is a light-sensitive element such as a photo-diode. This photo-diode is positioned such that its view includes the section of the light beam where the air sample is positioned (known as the region of interest, ROI). However, the design ensures that both direct illumination of the photo-diode, and indirect illumination by reflections from the chamber walls are minimized. When smoke particles enter the light beam at the region of interest, some of the light is scattered onto the photo-diode. The amount of light and the resultant electrical signal are dependent upon the scattering characteristics of the particles, and the smoke density.*

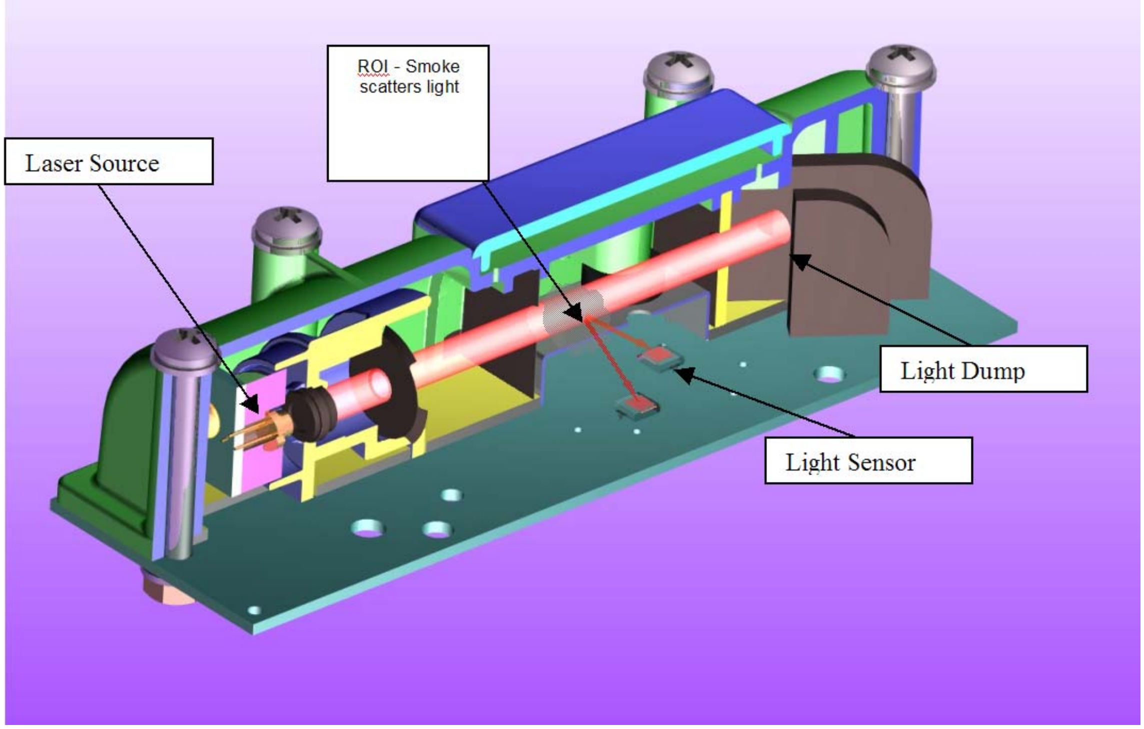


Figure 1: An example light scattering smoke detector chamber

OLSD PRINCIPLE OF OPERATION

The basic operating principle of OLSD is to turn the whole room into a light scattering detection chamber by directing a beam across it, as shown in the plan view of Figure 2.:-

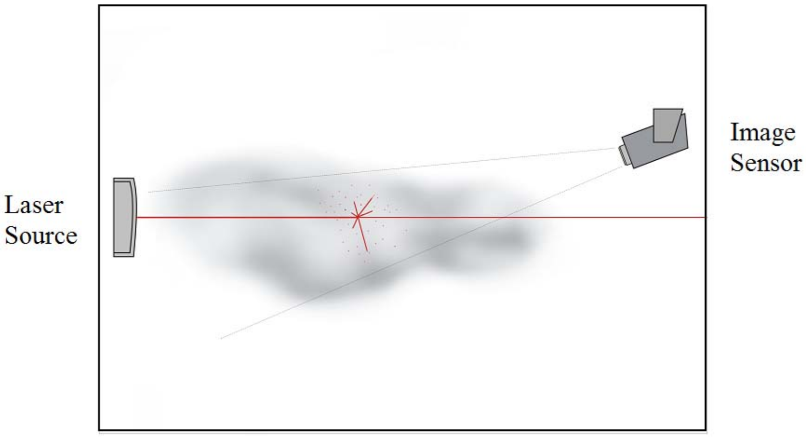


Figure 2 – Basic layout plan of OLSD

Rather than using individual photo-diodes, any light scattered by smoke in the beam is detected using a special type of “video camera” placed off-axis from the beam. In practice, a standard camera is unsuitable and a purpose-built image sensor using filtering optics, a highly configurable 2-dimensional CMOS imager and a very powerful programmable logic chip are required.

For greater clarity, in the perspective view of Figure 3 the laser source is projecting a beam onto a square target. The image sensor has a field of view, represented by the shaded triangular area, which includes the laser source and almost the entire length of the beam.

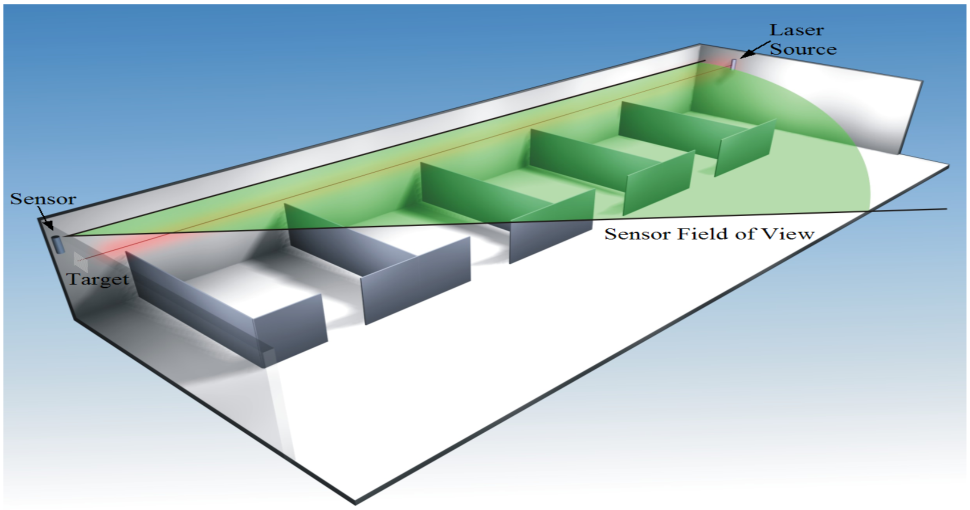


Figure 3 – Perspective view of an OLSD installation

Processing the captured image reveals where the smoke is along the beam by simple geometry, while the signal strength at each CMOS pixel can be used to calculate the smoke density at each point.

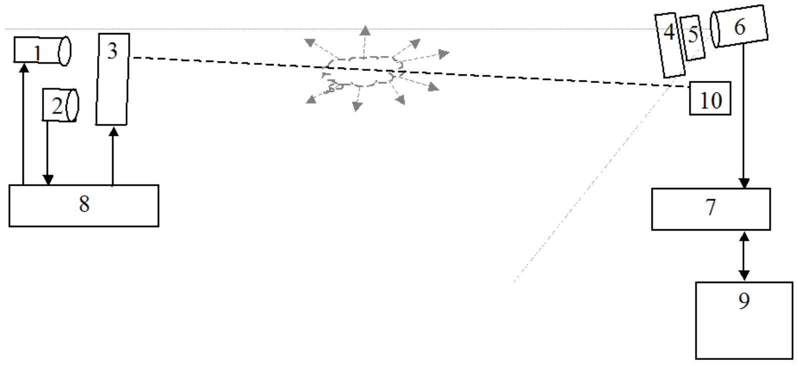
The primary benefit of such a system is that no equipment has to be mounted at the measurement position and that multiple measurement positions can be generated along the path between the two units. This provides for low cost of installation and maintenance, and gives early warning smoke detection for large open spaces, high-ceiling areas, aesthetic applications and applications with limited access.

This simple principle can be made to work readily in complete darkness, but the *main* challenge is to achieve high sensitivity under uncontrolled lighting conditions. Excessive background light can saturate the image sensing element, effectively drowning out the relatively tiny scattered-light signal.

Varying background due to flickering from artificial lighting (which is often very strong although too fast to be seen by the human eye) or movement within the scene makes the wanted signal difficult to identify. An extreme example is when sunlight entering a building has passed through a tree canopy that is moving in the wind. This rapidly changing light signal may be many thousands of times brighter than the wanted scattering signal.

One “brute-force” solution is to simply increase the power of the light source. However, this is a limited option for a practicable product as the laser used must meet stringent international eye-safety standards. Since the equipment runs unattended it cannot use the very powerful lasers that are familiar in laser light shows, since in many jurisdictions these are legally required to have constant supervision by an operator.

Instead, a combination of techniques are used to address these problems. These are described below with reference to Figure 4 which shows a simplified block diagram of the major components of one implementation of an OLSD system.



1. Laser light source
2. Photo-diode receiver
3. Steering mechanism
4. Interference filter
5. Polarization filter
6. Sensor lens & imager
7. Sensor processor
8. Source processor
9. External interfaces
10. Reflective target

Figure 4 - Overall OLSD system block diagram

- **Optical filtering**

Laser light has two optical characteristics that may be used to enhance rejection of ambient light:

- It is monochromatic – i.e. it is a single wavelength (color). A narrowband color filter selected to pass only that wavelength will block out a large majority of other ambient light. An interference filter (4) is the best available mechanism, though simple dye filters work at a lower level of performance

- It is polarized - i.e. the light-waves are oriented in a specific direction. A polarization filter (5) will block out half of all the randomly-polarized ambient light.

- **Synchronous detection**

This is the key mechanism that is used to “tune-in” to the wanted light source while disregarding other random light. To achieve this the laser (1) is modulated on-and-off precisely in phase with the image capturing device (6) and at half its frame rate.

That is, for one frame the laser is on and for the next frame it is off.

In the processor (7) each “on-frame” image is added into an accumulator and each “off-frame” is subtracted until eventually the uncorrelated background image disappears entirely and only the scattered light signal from the laser beam remains.

The strength of this signal combined with its location in the image, and knowledge of the optical gain of the system and the power of the laser allows both the concentration of smoke to be calculated and its position in space to be identified.

In order for the laser source processor (8) and the sensor processor (7) to synchronize and to support installation and maintenance functions a communication path between them is required. This could take the form of wires or radio communications or may conveniently utilize the existing optical components.

➢ Image processing

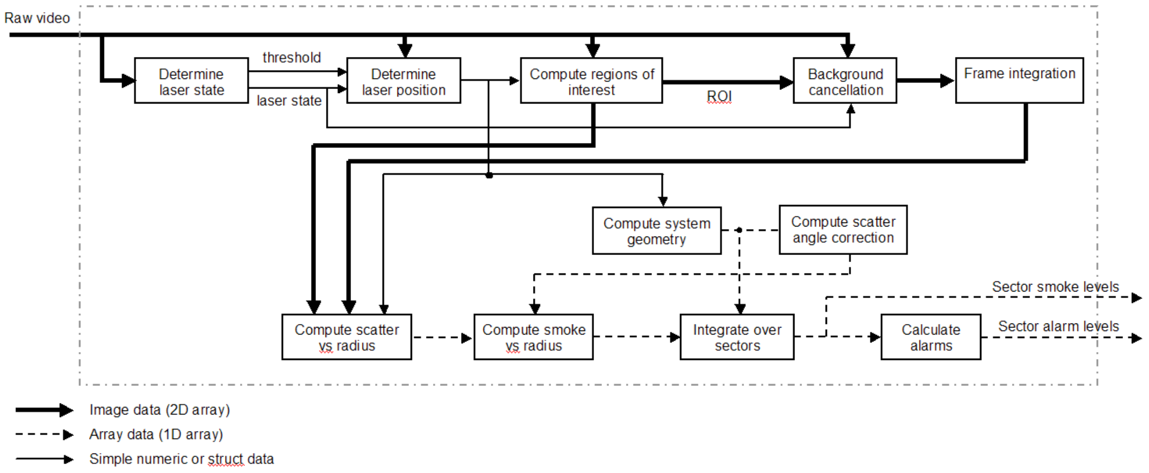


Figure 5 – Signal processing flow of the OLSD sensor.

To optimize the detection of the wanted light-scattering signal while preventing interference from ambient light it is desirable to sample images with a wide aperture and a short “shutter” time (actually an electronic sampling time in modern imagers). The exposure time is preferably short enough to just avoid saturation of the imager in the brightest lighting conditions feasible. This is generally full direct sunlight.

At the same time, it is preferable to operate at the maximum frame rate achievable. This both deals with rapid rates of ambient lighting change and allows for the largest possible number of “on-frames minus off-frames” to be correlated in a given time, thus reducing the signal noise.

Fortunately, CMOS image capture devices are available that can operate at very high speed and that permit selected sub-sections of the image to be transferred for signal processing. In the OLSD system the required sub-images are those that fall within the “Region of Interest” (ROI) i.e. the slice of the image that is occupied by the laser beam. In the current prototype the system runs at 600 frames per second, about 20 times faster than a conventional video camera, providing immunity to saturation by a sunlit scene.

CALIBRATION

It is very desirable that a smoke detector is calibrated in an ‘absolute sense’ – i.e. that the reading of actual smoke concentration is traceable back to an industry/scientific standard. This is especially so when a smoke detector is used at a high sensitivity level to provide early warning pre-alarms.

Traditionally, smoke concentration in the fire industry is expressed in terms of light extinction with units of percentage obscuration per unit length (foot or meter). Detectors based on light scattering do not actually make a direct measurement of this light extinction; instead it is estimated from the scattered component alone. The reason that light scattering is nonetheless favored over the extinction method, especially for early warning detection, is simply that it can be made very much more sensitive in practice. This is because it is measuring a large increase in a small signal rather than a small decrease in a big signal. This gives an inherently lower noise, higher stability reading.

Light extinction occurs for two reasons; when light impinges on a smoke particle some of the light is scattered (actually diffused, refracted and diffracted) and some is absorbed. The proportion that is absorbed determines the color of the smoke – i.e. white smoke appears white simply because it is made up of particles that primarily scatter light and do not absorb it; while black smoke has a relatively high absorption component. Nonetheless even black smoke scatters a substantial proportion of the light that impinges on it. One particularly black smoke type is generated by flaming n-Heptane which tends to produce a disproportionately strong light-extinction reading compared to its scattered-light reading.

Traditional photo-electric smoke detectors collect light at a fixed angle of scattering (or more precisely over a fixed range of angles) and are calibrated for this.

This would be ideal if smoke always scattered light isotropically (i.e. at the same intensity in all directions, producing a circular polar-plot) but as the wavelength of light in use is in the same order of size as the particle diameters of concern then Mie Theory applies and correctly predicts that the scattering is more often non-uniform. Consequently, a compromise range of scattering angles is generally selected where the variation in reading from one smoke type to another is acceptable when referenced against a true extinction measurement.

One aspect of the OLSD detection method that requires consideration is that the scattering angle varies from one point to another along the laser beam. In particular, the scattered light from particles in proximity to the laser source is received at a very narrow scattering angle, which would tend to make it particularly responsive to larger particles.

This would be undesirable as false alarms could be triggered by mechanically generated nuisance particles like dust. To preclude this effect, a number of well known approaches based on Mie Theory are available to determine the particle size distribution, such as measurement at multiple angles of scattering and/or beam polarizations (e.g. Ref 5) and at multiple wavelengths (Refs 6,7,8). Another approach is to make a measurement of the transmission path loss and use this in combination with the scattering signal to reduce the contribution from large particles. This can be achieved by employing a retro-reflective target, (Figure 4, 10), and a photo-receiver (2) housed with the laser source. This enables the direct light extinction measurement capability in the same way as a conventional beam detector, while also permitting the much higher sensitivity of light scattering measurement. The scattering measurement also enables continuous real-time re-zeroing of the drift that normally limits beam detectors, while providing addressability equivalent to a row of point detectors.

In order to compensate for the varying scattering angles of the OLSD system geometry, non-isotropic scattering, effects of absorption of light by smoke and for system gain variables such as optical and imager conversion losses, a theoretical model has been derived[1] which is expressed in the formula:

$$G = \kappa \frac{2^{N_{ADC}}}{16} \frac{\left(\eta_q \eta_{CCD} \eta_{lens} {d_{lens}}^2\right) \lambda T P_{laser} Obs S(\theta)}{c h N_{well} d} \frac{w}{F} \cos^2 \alpha \cos \beta \cos \gamma$$

The parameters in this equation and its derivation are in Ref 3.

In order to verify this model and to determine specific parameter values for actual equipment and smokes, empirical measurements were made against trusted reference devices. One example reference is a nephelometer that has been calibrated using clean nitrogen gas and a span gas such as FM200 (Heptafluoropropane, CF_3CHFCF_3 –Ref 4).

Another example is a light extinction measurement device or “obscurometer” like that detailed in Ref 3; this has the specific benefit of providing an inherently ratiometric measurement so that sources of error can be restricted to precisely controlled and measurable parameters such as length and wavelength, while drift is removed by cyclic flushing and re-zeroing with clean air.

ADDRESSING SCHEME

Potentially, the OLSD technology may be applied in several ways.

The simplest is the “*linear*” approach where a laser source and sensor operate as an independent pair to give coverage along the length of the beam that is within the field of view of the camera. The first planned product release will utilize this approach and is named the “VESDA QUANTUM™ ”.

In the future more sophisticated OLSD products may be developed which support multiple sensor and laser beams which can be steered to provide detection in 2 dimensions (a “*planar*” system) or even 3 dimensions (a “*volumetric*” system).

In the meantime, a scheme is required to allow interfacing to legacy fire systems to utilize the ability of OLSD to identify the location of smoke. To accomplish this, the beam is divided along its length (in software) into “regions”. The length of each region is user-configurable and may be mapped to a “virtual” high sensitivity point-detector address.

For example, if a line of equipment racks are to be protected over a length of 200 feet then the line could be divided into 10 regions, each of 20 feet in length. Each region can then be allocated an address equivalent to one point detector. A loop interface card can then communicate the address of the “virtual” detector as if it were a point detector on a proprietary communications loop.

In addition, scattering from the whole beam length can be integrated to give a single reading for the whole protected length. This provides an even greater sensitivity for the

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[1] Karl Boettger – 2005 Xtralis Pty Ltd

detection of very slow growth fires that gradually permeate smoke throughout the entire space, providing the same advantage as an aspirated air-sampling system's accumulated smoke sensitivity, where smoke enters at a number of holes. This very high sensitivity measurement can be mapped to a further "virtual point detector" address.

If required, a different threshold setting may be allocated for each individual "virtual point" along the beam - for example to avoid alarms from specific local nuisance sources such as a door to a kitchen area.

FAULTS MODES AND SELF-SUPERVISION

In order for any smoke detection technology to be developed into a safe and approved product it needs to meet standards for reliable operation. It must also be able to detect conditions that would prevent correct operation and to indicate a trouble signal to the fire alarm control panel.

These failures modes could be internal, such as a component fault, or could be as a consequence of unusual external environmental factors.

As with any sophisticated electronic product, good circuit and software design practice can manage the avoidance and detection of internal component failures.

Internal components such as the laser power output and the correct operation of every pixel in the CMOS imager may be supervised and/or automatically tested at regular intervals by built-in mechanisms.

For OLSD there are a number of external environmental issues that must be monitored to ensure that the system remains fully operational.

- **Direct Sunlight** - While an OLSD system could operate in lighting conditions from complete darkness to a fully sunlit room, as with any CCTV camera or indeed the human eye, it would not be expected to function reliably if the sun were allowed to shine directly onto the imager lens, so it should be mounted so as to avoid this possibility. However, if the situation should arise, a trouble condition would be flagged and logged. Even then, it is possible that the system would continue to provide some level of protection over part of the beam, and the trouble will clear as soon as the sun is no longer shining directly into the lens.

- **Obstruction detection**

  Obstruction of Laser Beam:
  this can be readily recognized in a number of ways; in the case of the VESDA QUANTUM the laser beam is directed onto a six-inch square reflective target and the received reflection is measured. If this beam is interrupted the rapid change in reflected intensity can be used to immediately detect this.

Obstruction of Imager Field of View (FOV):
To be able to detect smoke the OLSD imager must have a clear view of the active length of the laser beam. If any object blocks that view then it must be detected. There is a triangular area of concern formed between the laser beam and FOV of the imager, shown in Figure 6 as the triangle A-B-C.

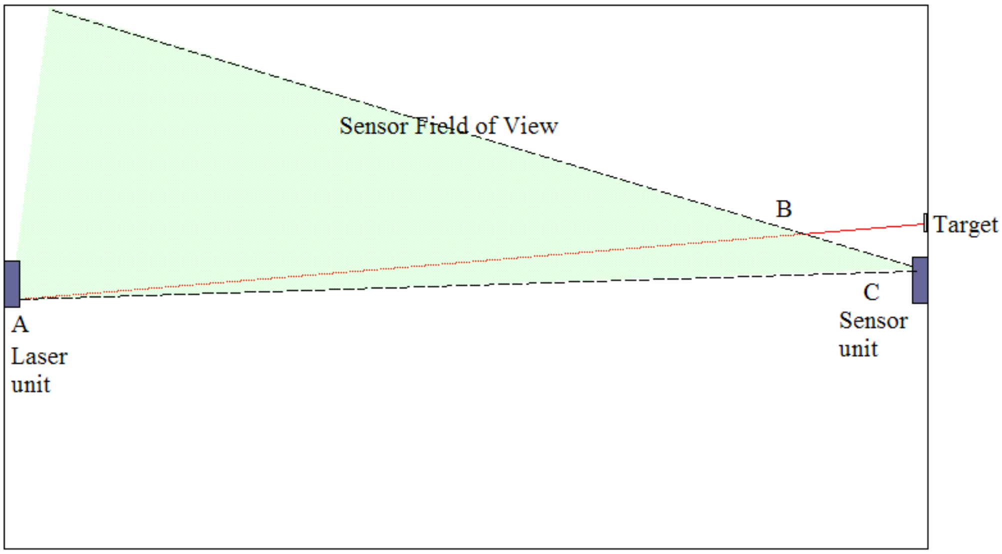

Figure 6 – Plan view of area of concern for object intrusion

Three optical mechanisms may be used to protect the triangle A-B-C:

- any object that touches the line A-B (i.e. the laser beam) may be immediately detected as described above.
- any object that intrudes between C (the sensor unit) and A (the laser source unit) can be seen by the sensor because it would block the view of the LEDs mounted on the front panel of the laser unit.
- periodically, the laser beam may be swept between the Target position and the Sensor unit. Any object in the remaining part of the triangle can be detected by strong scattering ("glint") from at least one edge.

Contamination
Excessive dirt build up, or objects such as insect crawling onto the window of the unit may be detected by a built in illuminator which can periodically check for backscatter from such objects. Servicing of the units would consist of wiping with a clean damp cloth.

Misalignment
This issue may be avoided by the use of active steering of both the laser beam and the imager field of view using an electro-magnetically driven pan-tilt mirror. Initial alignment of the units requires only that they be placed facing one another within the range of movement of the mechanism (for exaample +/- 15 degrees horizontally and +/- 5 degrees vertically). Precise alignment may be made and maintained automatically under software control.

LABORATORY RESEARCH

It was recognized that the envelope of performance capabilities of the OLSD method needed to be quantified in order to develop products that can be applied successfully in a wide range of environments. The responsiveness to a wide range of true fire threats needed to be verified, while methods to reduce the impact of nuisance particle sources, interfering light sources and other unwanted phenomena had to be developed and quantified.

Since the OLSD technology operates in a manner that is novel in approach, the capabilities, limitations and risks associated with the system were largely theoretical.

While the basic theory of light scattering is well described, the models are based on simplistic assumptions of spherical particles of known refractive index. In practice, smoke may consisting of many particle sizes and compositions generated from the many materials and conditions of combustion that create real world fire threats. The light scattering characteristics of these are poorly documented, particularly at the very wide range of angles that the OLSD technique can utilize. This is especially true for the extremely narrow forward scatter angles (<4º) that have been difficult to measure experimentally in the past.

To this end a program of laboratory research testing was conducted using the OLSD principle itself; with 8 lasers; 4 wavelengths ranging through infrared (808nm), red (532nm), green (650nm) and violet (402nm) each at the 2 planes of polarization. These were sequentially modulated synchronously in time with 3 separate video camera systems. Conventional off-the-shelf video capture equipment was able to be used since the testing was conducted in complete darkness in a large fire test room. This testing program identified many problems and solutions which have contributed to the realization of a practicable implementation; as well as enabling optimized and fully characterized products to be designed, with well understood fire detection and nuisance rejection capabilities.

Further OLSD research testing is in progress, at an increased range of wavelengths and yet narrower angles. Much of the detail of the early testing conducted and results obtained are presented as supporting text in a Master’s Degree thesis by one of Xtralis Research Engineers (Ref 3). Copies of this can be made available by permission of Xtralis.

REFERENCES

1. Knox et al; International Patent Number WO2004/102498 “Particle Detector” Nov 2004.
2. Knox, Boettger, Ajay; International Patent Number WO2006/050570 “Particle Detector, System and Method” 2006
3. Georgiev; Master of Engineering Thesis “Laser video particle detection system” 2005
4. Great Lakes Chemical Corporation; www.e1.greatlakes.com – FM200 data sheet 2005
5. Gravatt; US Patent 3,901,602 “Light scattering method and apparatus for the chemical characterization of particulate matter” 1975
6. Runciman; Patent WO 00/07161 “Smoke Detectors” July 1998
7. Cole; “Laser Monitor” US Patent 5,392,114 1988
8. TSI; Three Wavelength Integrating Nephelometer; http://www.tsi.com/ ; http://www.cmdl.noaa.gov/aero/instrumentation/neph_desc.html