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THIS ISSUE: Muon Scattering Tomography | Nuclear Forensics | The GBL Laboratory | London 2012 | Seismology | Detection Techniques | Infrasound

Contents

It is a great pleasure to write the foreword for this issue of Discovery highlighting the work of the national nuclear security field at AWE.

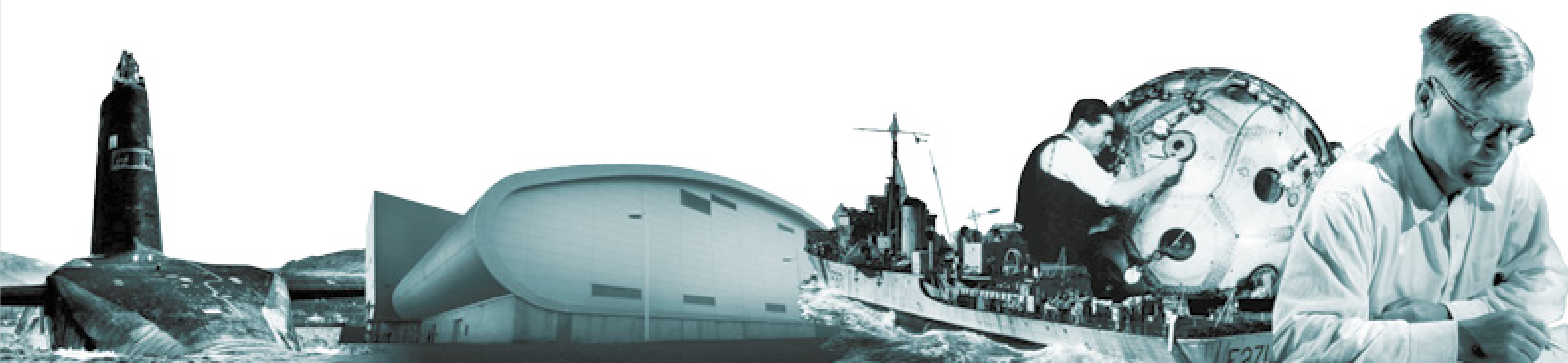
The role of AWE and its technical experts to protect the UK is as important now as it has ever been. We have outstanding and internationally recognised scientists and engineers at AWE, as well as those from other key organisations, to provide MOD and other Government departments with the technical skills, knowledge, advice and capability on a 24/7 basis.

In this issue of Discovery, there are many interesting and fascinating examples of the research that is undertaken by AWE's scientists and engineers in the area of supporting the UK's national security agenda, ensuring that we have a minimum credible UK nuclear deterrent both now and in the future.

I am seeing for myself the excellent science that is being done at AWE. An example of this was AWE's contribution to the Global Initiative To Combat Nuclear Terrorism conference in January 2014. I had the privilege to attend and listen to AWE's technical presenters on a variety of issues concerning the threats we face and how through a concerted approach, working with our international partners, we can protect the UK to keep our world safe.

I do hope you enjoy reading the articles and get a sense of the exciting science and technology at AWE.

Dr Bryan Wells
DST Head, MOD



Introduction

In March 1994 three men were arrested in St Petersburg, Russia for attempting to sell approximately three kilograms of 90% enriched uranium. 500 g of material was found in a glass jar in the refrigerator of one of the individual's homes. This is not an isolated incidence of criminal activity associated with radiological or nuclear material. Since 1993 over two thousand confirmed incidents involving radiological and nuclear materials have been reported to the IAEA "international trafficking database". Sixteen of these incidents involved highly enriched uranium or plutonium.

This edition of Discovery is focused on some of the work undertaken by AWE in support of the United Kingdom's efforts to combat the threat of nuclear terrorism and proliferation.

The UK deploys technology around its borders to detect potential radiological and nuclear materials being smuggled into the country. The technology detects gamma and neutron radiation and will alarm at low radiation levels. This technology was used at the **London 2012 Olympic Games**, where AWE supported UK security agencies.

A cross government effort has instigated a research programme coordinated through AWE to investigate enhanced methods to detect radiological and nuclear materials with particular emphasis on the detection of shielded material. This UK effort complements wider international efforts which have increased greatly over the previous decade, driven by the US Departments of Energy, Defence and Homeland Security. AWE has also been collaborating with scientists across a number of universities in the UK and with the UK Home Office with the goal of prototyping a number of new technologies which should provide a significant enhancement to capabilities to detect shielded radiological and nuclear materials. A number of projects are also being pursued within the European Union.

The first area investigated was improvements to the current radiation detector technologies. The technology currently deployed at UK borders utilises plastic scintillator materials to detect gamma radiation, ^{3}He detectors to detect neutrons and algorithms which take account of background radiation produced by naturally occurring radioactive materials. The benefits of new gamma and neutron detector materials are being assessed but, in addition, some significant improvements may be made by the use of more sophisticated data acquisition and data analysis algorithms. Some of the challenges presented in the analysis of the data are presented in the **Digital Data Acquisition** article.

Even though significant improvements can be made to the detection of the natural radiation emissions from radiological and nuclear materials, it becomes problematic for very highly shielded materials. A more radical approach to detecting nuclear material is to use an external source of radiation to stimulate fission within the material.

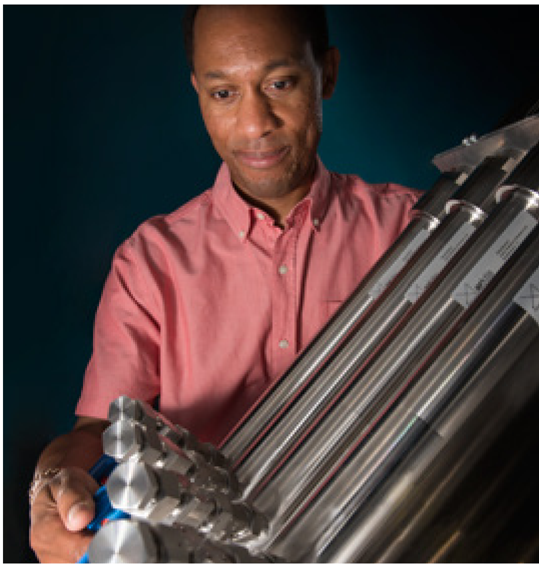
If the material is irradiated with photons of energy greater than about 6 MeV or by a neutron source then this will make some of the material fission. As the material fissions it will emit prompt gamma and neutron radiation followed by delayed gamma and neutron radiation production as the fission fragments decay. This will generally result in an enhanced emission of radiation for a period of a few seconds following the irradiation. The **Active Detection** article provides more detail on techniques to detect this stimulated radiation signature.

Another technique being developed is the use of naturally occurring cosmic ray muons to detect nuclear material. Muons are produced in the upper atmosphere as high energy cosmic ray protons collide with air nuclei to form pions which subsequently decay into muons. Muons are charged particles, two hundred times the mass of an electron, with one passing through an adult's hand every second. Muons can have very high energy, up to TeV, but most are a few GeV in energy. This means they can penetrate huge amounts of shielding. The **Muon Scattering Tomography** article describes how this technology could be implemented.

Longer term techniques which could result in better detection, or technologies which could be incorporated into future designs of detector systems are also considered. Recent workshops have enabled a series of innovative projects to commence in UK universities and industry to look into new ideas. Some of these projects are described in the **Novel Detection Concepts** article.

AWE supports a number of other UK efforts which are related to the detection and analysis of nuclear material and events. AWE has the UK Radionuclide laboratory, which supports the UK commitment to the Comprehensive Test Ban Treaty (CTBT). The **GBL laboratory** article provides an overview of this capability and its use.

AWE also supports the CTBT efforts by undertaking analysis of seismological events to determine if they are naturally occurring or man made. The **Seismology** article provides an overview of the global international monitoring system and the role the UK and AWE play. Another capability used for the detection of nuclear events is infrasound. This was heavily used during the age of atmospheric testing and has been re-invigorated at AWE to support the UK CTBT efforts and is described in the **Infrasound** article.



Muon Scattering Tomography

The University Of Sheffield.

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University of BRISTOL

Following their discovery in 1909 by Wulf[1], studies of cosmic rays have provided insights into fundamental physics and, in recent years, have been applied to the detection and imaging of special nuclear materials (SNM)[2], nuclear waste scanning[3], and volcanology[4]. AWE is primarily interested in understanding the feasibility of using the scattering of cosmic ray muons passing through cargo to detect SNM.

Primary cosmic ray particles impinge upon the upper atmosphere with very high energies, many in excess of those produced on Earth by man-made particle colliders such as the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN). When these primary particles interact with the Earth's upper atmosphere, a variety of secondary particles are produced. Highly energetic secondary muons compose the largest component of this natural radiation source and have an average energy around 3 GeV. Due to these very high energies, muons are extremely penetrative and difficult to effectively shield against, making them an ideal tool for detecting SNM. This source of cosmic ray muons is discussed in more detail in Box 1.

As muons pass through materials, they scatter and the outgoing trajectory may not necessarily be in the same direction as the incoming one. The probability that a muon scatters through a large angle increases with the materials' density and atomic number (the number of protons in the nucleus). By measuring muon trajectories through a small region inside a cargo container, it is possible to infer the spread in angle due to the material present and locate high density, high atomic number materials. This concept is shown in Figure 1. This process is repeated at all regions inside the cargo container to obtain a 3D image, which is analogous to medical tomography scans but without the high radiation hazard.

Muon Scattering Tomography (MST) techniques utilise the natural background radiation to inspect cargo for nuclear materials. MST does not introduce man-made radiation, poses no risks to human operators or cargo, is easier to deploy and has a lower regulatory burden than other detection techniques. These unique benefits have generated much interest in scientific communities concerned with homeland security since it was first proposed by a Los Alamos team[2].

AWE in partnerships with a number of UK universities and the UK Government has undertaken research into MST techniques [5,6]. AWE work in MST has considered issues in the following technical areas:

- **Potential of the technique to enhance the detection of shielded SNM and image cargo containers**
- **Up-scaling and integration of prototype detector tracking technology to large areas**
- **Providing information on the relative location and shape of objects, even when shielded**

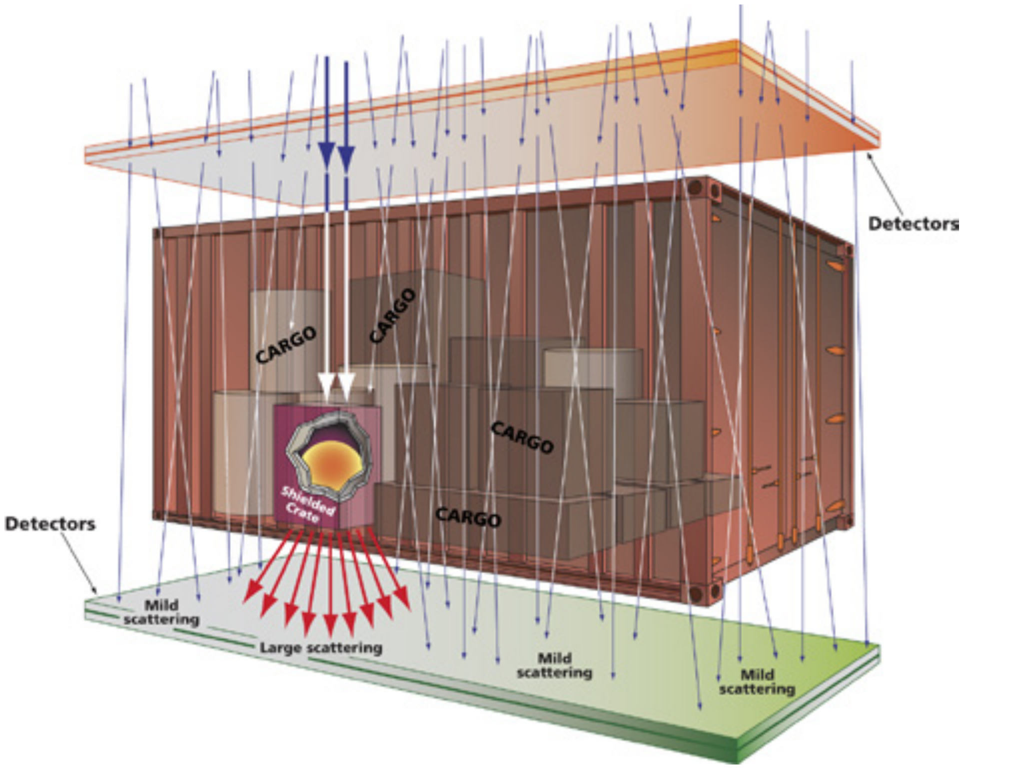
The MST technique requires the use of many tracking detectors which give the crossing position of a cosmic ray muon. A stack of these tracking detectors is used to measure multiple crossing positions along the muon trajectory. A straight line is then fitted to the crossing points to measure the trajectory. These detector stacks are typically positioned above and below the inspection volume to measure the incoming and outgoing muon trajectory from which, using the 3D tomographic reconstruction techniques detailed in Box 2, information about the volume's contents can be inferred.

There are some unique experimental challenges with the large areas and high position resolution needed to perform muon tomography, which are also faced by particle physicists in the design and development of detectors for large-scale experiments at CERN where the products of colliding proton beams are tracked. AWE research has focused on two detector technologies, resistive plate chambers (RSP) and drift chambers; these are described in Boxes 3 and 4 respectively.

Both of these detector technologies have been developed into small test systems and have been used to produce images of various materials.

Figure 1

An illustration of a muon scattering tomography cargo screening system.

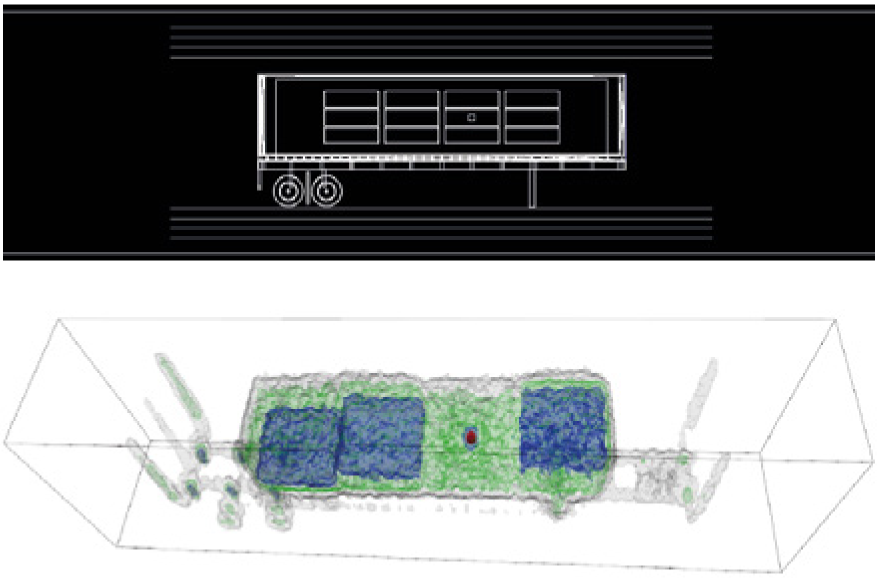


In parallel with efforts to understand the design of these detector systems, many simulations and small scale experiments have been performed. Figure 2 shows the results of a simulation of a cargo container showing the inferred local scattering at each point within the container. The simulation geometry set-up is in the upper panel and reconstruction in the lower panel. A high density and high atomic number target, shown in red, is clearly visible in the centre of the cargo container. The boxes contain materials of different densities; higher density materials are shown with a blue transparent surface, whereas materials with lower densities are shown in green and grey (lowest). This 3D image can be interrogated by the user to discern where the target is, the density of the materials in the cargo container and any contextual information derived from the shape of individual items.

Cosmic ray muon scattering tomography is a novel and completely passive imaging technique. MST is well-suited to a growing number of applications. AWE, in collaboration with its academic partners, have shown that it can demonstrably improve the detection of shielded SNM in cargo containers.

Figure 2

A muon scattering tomography reconstruction of a simulation of a cargo container (lower panel) and geometry (upper panel).



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Box 1

Where do muons come from?

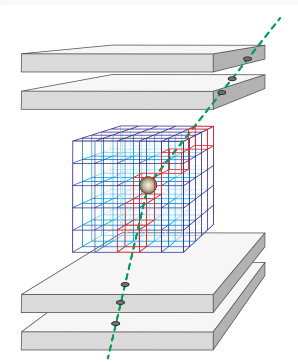
Muons are charged, subatomic particles created by energetic cosmic rays high in the Earth's upper atmosphere. Primary cosmic rays are charged particles, mostly hydrogen and helium nuclei, which have been accelerated to very high energies in astrophysical sources. These cosmic rays continuously bombard the earth and collide with air nuclei to create cascades of less energetic particles. As they travel through the atmosphere, most of these secondary particles interact or decay producing further particles, including positive and negatively charged muons, which may reach ground level. Cosmic ray muons decay with an avaerage life time of 2.2 μs, but their high velocities and relatavistic time dilation mean that a significant fraction reach the Earth's surface.

The number of muons reaching the surface is about one per square centimetre per minute, roughly equivalent to one through an area the size of a hand every second. These muons have energies in the GeV range; a muon with kinetic energy of about 4 GeV will pass through more than 2 m of steel.

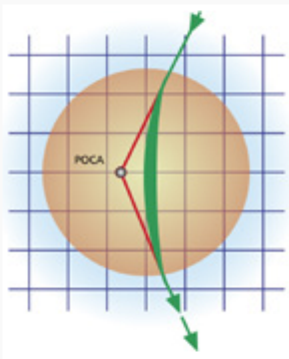
Box 2

Reconstruction Techniques

Tomographic reconstruction is the analysis process used to infer a 3D image from data measured by a muon tomography system. The data comprises information about the muon's trajectory as it entered and left the inspection volume. The task of a reconstruction algorithm is to determine the amount of scattering that took place in regions visited by each muon inside the inspection volume. Computationally, the inspection volume is split up into voxels, the 3D analogue of pixels in images, as illustrated in the figure below. The reconstruction algorithm therefore estimates the average scattering density within each voxel.



An illustration of the dissection of the inspection volume into voxels. The green dashed line indicates a muon trajectory, which is deflected as it passes through a sphere within the inspection volume.



An illustration of the point of closest approach (PoCA); the approximated muon path (red line) and the path with scattering included (thicker green lines).

The simplest reconstruction algorithm, and one that is widely used, is the point of closest approach (PoCA) algorithm. It assumes that points where a muon scatters occur at a single point; the point of closest approach between the incoming and outgoing tracks. The PoCA is calculated and the voxel containing that point is given a score, usually equal to the square of the measured scattering angle between the tracks. The final density for each voxel is then taken to be the average of all the scores assigned to it.

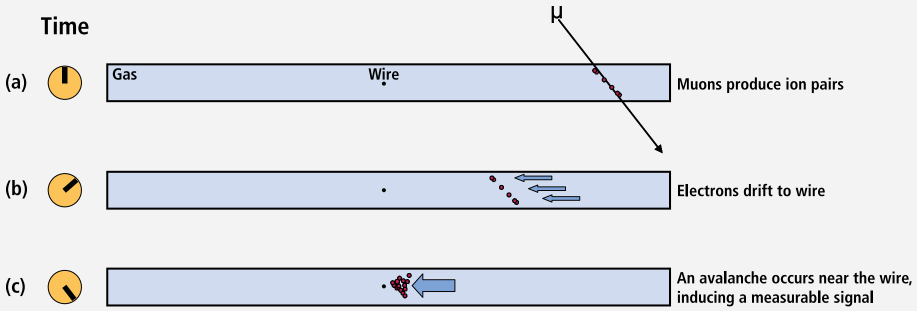
There are numerous difficulties which limit the effectiveness of the PoCA algorithm. For extended objects, the muon actually scatters in multiple locations so the PoCA approximation is less accurate. Detector noise can cause the PoCA to vary wildly as it is given by the intersection of two nearly parallel lines. Other algorithms have been proposed to circumvent these problems, such as the expectation maximisation / maximum likelihood approach[7] and angle statistics reconstruction[6], which show marked improvements to PoCA. However, uncertainties in the muon path and momentum hinder performance. Efforts to understand the tradeoffs between algorithm complexity and robustness to these sources of uncertainty are underway.

Box 3

Drift Chambers

Drift chambers are inert gaseous detectors constructed with an anode sense wire positioned along the length of the detector and two cathode plates on the top and bottom surfaces. The location of a muon interaction can be determined from the time taken from electrons, ionised within the gas mixture, to reach the anode wire if the initial interaction time is known. Ionised electrons drift towards the anode wire at a constant velocity until they arrive close to the wire surface where the electric field increases by several orders of magnitude causing drifting electrons to produce a large electron avalanche that induces a detectable signal in the wire. The initial interaction time is subtracted from the measured time of the signal from the wire to calculate the longitudinal location of the muon interaction. Two crossed layers of drift chambers can be used to measure a 3D interaction point.

The figure below demonstrates the principle of drift chambers. A muon passes through the gas volume producing ion pairs, as illustrated in panel (a). The electrons drift towards the centre, due to the presence of a drift field, shown in panel (b). In panel (c), an electron avalanche is shown occurring some time later. The time taken to observe the signal on the wire is converted to the crossing position through the chamber calibration.



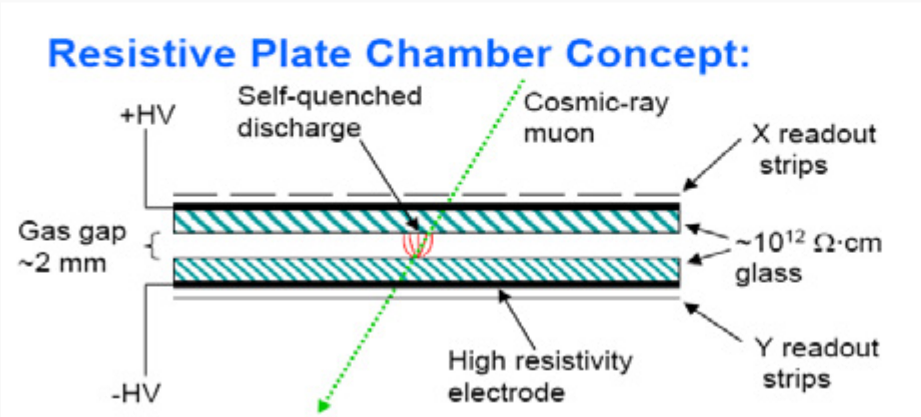
The position measurement principle of drift chambers.

A close-up view of a drift chamber, with an upper PCB removed, where the centrally-placed thin wire and copper cathodes, that are used to establish the drift field, can be seen. In the foreground the white Delrin supporting frame that holds a pin which crimps the wire under tension, can also be seen.

Box 4

Particle Tracking Technologies 2 – Resistive Plate Chambers

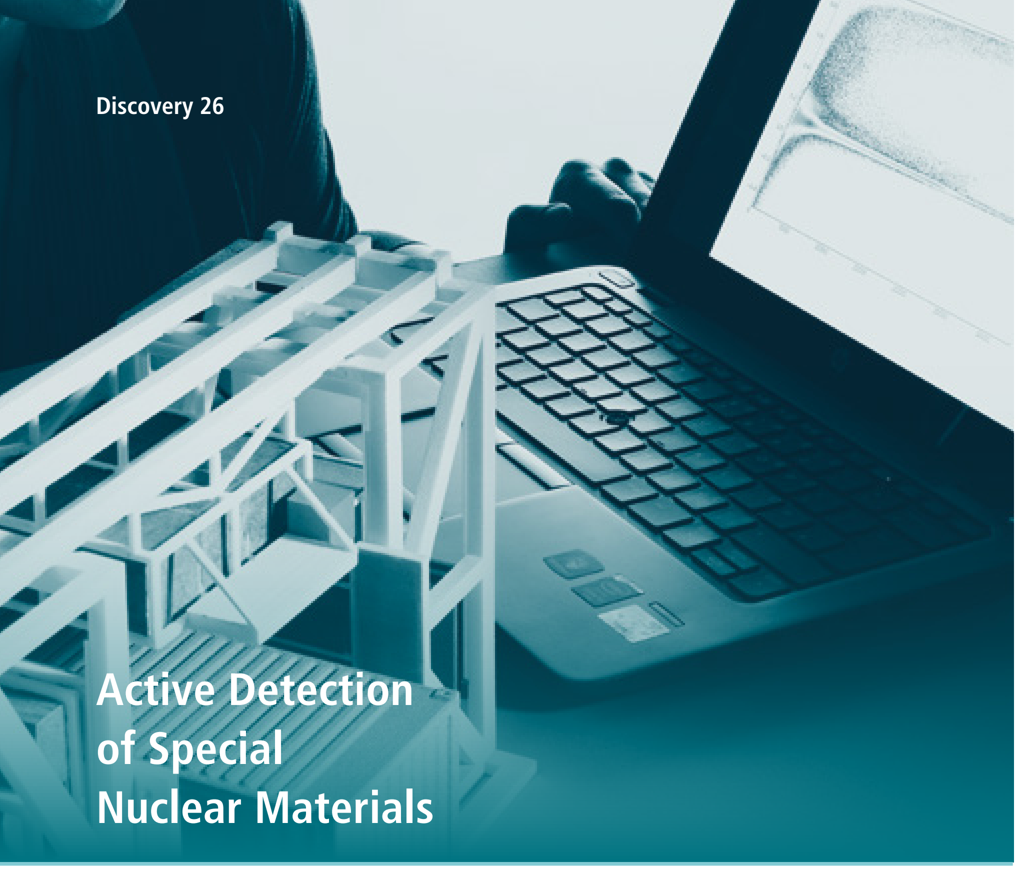
Resistive plate chamber (RPC) detectors measure the crossing point of a muon trajectory by ionising gas between two sheets of glass. The electrons and ions are separated and avalanche, in a similar manner to drift chambers (see Box 3) and are accelerated towards the sides of the glass volume. This charge impact induces a current on PCB strips laid on top of the glass and a pulse is observed by the detector readout on the strips corresponding to the crossing position of the trajectory as shown in the figure below.



A schematic of the measurement concept of the resistive plate chamber.

AWE and the University of Bristol have produced one of the first RPC-based muon tomography systems, see figure below. The figure below clearly shows the upper and lower detector cassettes. These contain RPC detectors which have a high efficiency and excellent position resolution. The objects to be imaged were placed between these detector cassettes.

RPC-based muon tomography demonstration system developed in collaboration with the University of Bristol.



Active Detection of Special Nuclear Materials

A major concern for national and international security is the detection and interdiction of trafficked radiological materials and special nuclear material (SNM)[1]. The simplest way to do this is to detect the emitted gamma or neutron radiation from the material of interest. This becomes more problematic when deliberate or unintentional shielding is included in a given cargo container.

An alternative to passive radiation detection is the use of an active interrogation technique. In active detection, an external source of radiation is used to stimulate fissile material to fission and the subsequent measurement of the prompt and delayed neutron and gamma radiation associated with the fission process is used to increase the probability of detection as shown in Figure 1.

A generic active detection system will comprise an accelerator sub-system and a detector sub-system with associated data acquisition. There is a wide choice of technologies developed for each subsystem and selecting the most appropriate has been the basis of research performed by AWE.

There exist a huge variety of options of energies and types of radiation which could be used to generate fission in SNM. Fissile actinides such as ^{235}U and ^{239}Pu may undergo fission following interaction with high energy photon radiation (>6 MeV) or neutron radiation, of any energy, as shown in Figure 2.

Figure 1

Schematic of active detection using two different source production methods.

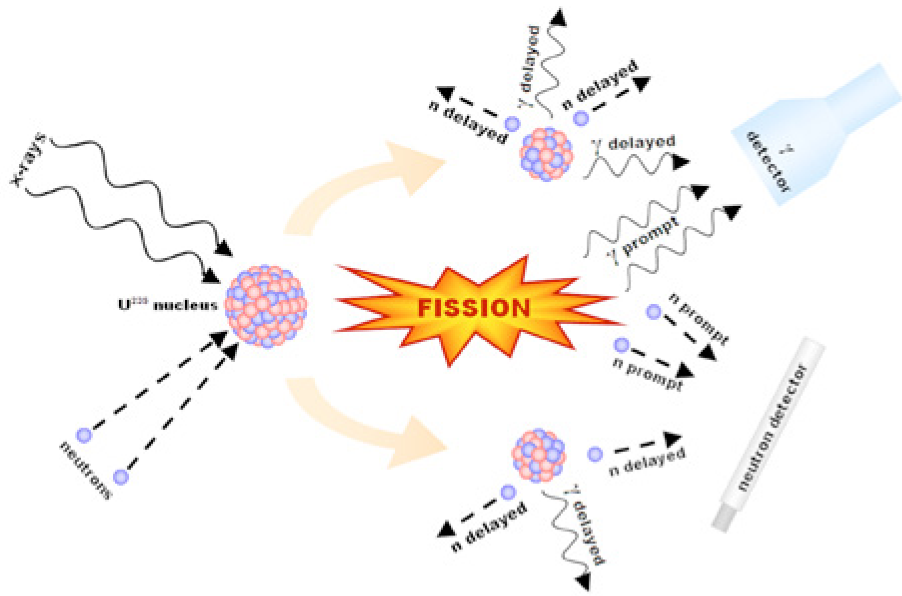


Figure 2

Thresholds for photon and neutron induced fission in actinides of interest[2].

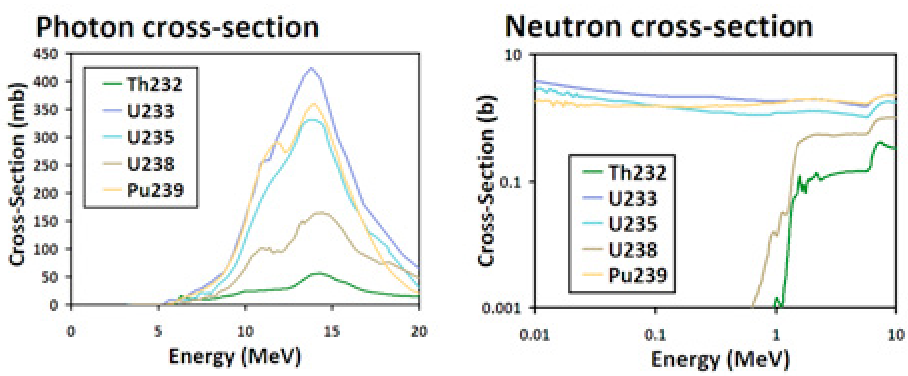
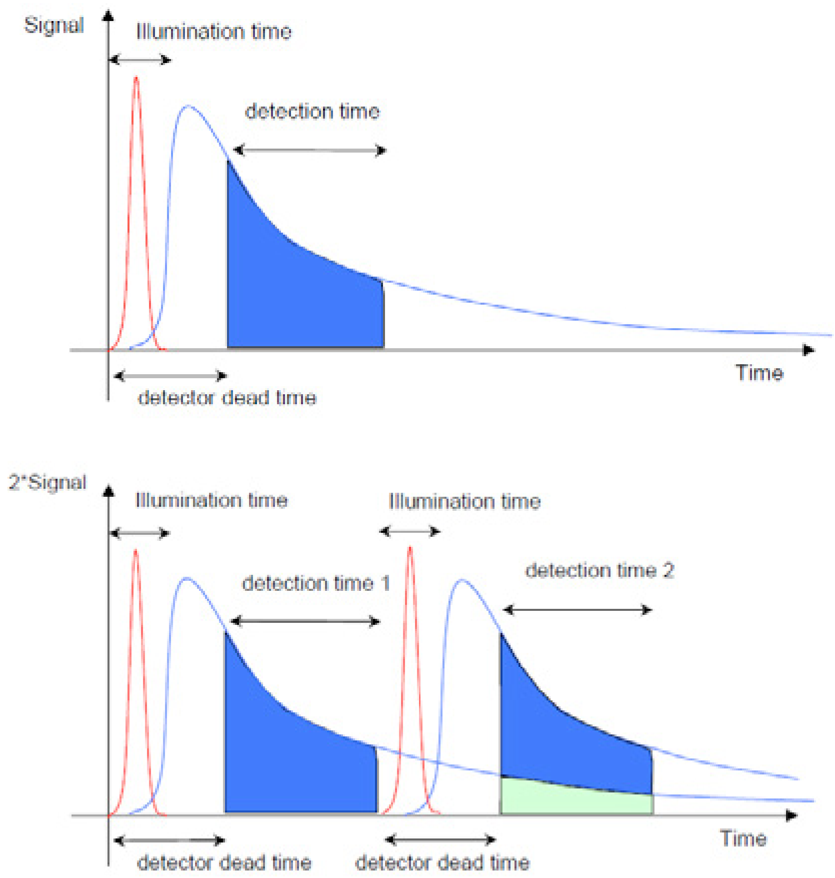


Figure 3

Schematic of difference between flash and continuous wave irradiation.



An important consideration is the time period within which this radiation should be delivered to a target volume. A very brief, intense, 'flash' of radiation might offer the potential to better discriminate prompt or delayed fission signatures temporally. Alternatively less intense, high repetition frequency or continuous wave (CW), 'non-flash' sources such as a linear accelerator (LINAC) may use other methods such as energy cuts in detectors to discriminate signals from background. These systems may also offer benefits in terms of reduced dose to cargo. Figure 3 provides a schematic view of the difference in the two approaches.

Detector selection is a critical part of any active detection system as they will be subjected to high fluxes of photon and neutron radiation and as such will need to be able to both withstand such harsh environments and also discriminate useful fission signals from the source particles used.

The deployment strategy for any active detection system is a considerable challenge. Introducing a large system with a substantial source of radiation to normal port operations without detrimentally affecting the flow of commerce or introducing a hazard to the public or employees is challenging. The amount of time between successive irradiations and the reliability of the source system is critical in determining the practicality of its use. Consideration also has to be given to potential cargo contents and the effects the interaction of the interrogating radiation may produce.

Table 1

Source production methods considered for active detection.

Energy (MeV)	"Particle"	Source
10	photon	Bremsstrahlung x-ray radiation.
6.1, 6.9, 7.1	photon	Characteristic of the $^{19}F(p,\alpha\gamma)^{16}O$ reaction.
~14	neutron	DT fusion reactions.
~7	neutron	Accelerated DD beam target interactions.
~2.5	neutron	DD fusion interactions.
~3.5 - 7	both	Photonuclear interactions between a 10 MeV bremsstrahlung x-ray spectrum and D_2O or Be.
<1	neutron	Kinematically collimated by the use of the $^{7}Li(p,n)^{7}Be$ reaction, using a proton beam.

Prototype Source Selection

In order to scope the range of potential radiation types which could be deployed in active interrogation systems a number of radiation types were considered, shown in Table 1. This list is not exhaustive but represents a realistically achievable range of source options which would be deployed in a usable timescale. An important consideration is the photon energy limit where sources with photon energies above 10 MeV were ruled out in the initial scoping[3]. While the photofission threshold for fissile materials continues to increase above 10 MeV, many photo-neutron thresholds are crossed for abundant materials such as oxygen. This introduces a large background term which makes determination of the fission signatures more complicated.

In all cases both flash and non-flash production of the different radiation types were considered. For $^{19}F(p,\alpha\gamma)^{16}O$ and $^{7}Li(p,n)^{7}Be$, these specific interactions were used to quantitatively bench mark the maximum yield of useful interrogating radiation that could be delivered with due consideration of the wider range of other proton and deuteron interactions which could have been deployed to achieve alternative line gamma or neutron sources.

A number of experimental tests have been conducted in the period 2010 to 2013 to investigate the range of source options. The experimental tests can be roughly grouped into two sets. The first set concerned measurements of photofission signatures for both bremsstrahlung and characteristic gamma radiation[4,5]. The second set concerned quantification of the output of interrogating neutrons from $^{7}Li(p,n)^{7}Be$ reactions with pulsed power generated proton sources[6].

Four important results were derived from these experiments. Firstly, the experimental campaigns provided data with which modelling studies could be validated. This established a degree of confidence in simulated comparisons of the signals produced by different interrogating source radiation types[3].

Secondly the experimental data provided important practical experience in utilising pulsed radiation sources with the kinds of sensitive neutron and gamma radiation detector sub-system technologies necessary to measure fission signals in an active detection system. The importance of detector recovery was established. Practical experience from the range of detectors used in these experimental campaigns suggested that typically radiation detector systems might be unresponsive for a 'dead time' of a few ms post flash of interrogating radiation due to saturation of the detector or electronics. During this dead time any prompt neutron radiation from fission, or delayed gamma or neutron signals could not be recorded and these data were useful in the interpretation of predicted levels of neutron and gamma signal from flash sources.

Thirdly, it was clear in the characteristic gamma experiments that the pulsed ion beam diodes used with the pulsed accelerators generated a small population of accelerated deuterons. This resulted in a background of neutrons being generated from the source (via. interactions with carbon or fluorine components in the diode) and these, in turn, confused signature fission neutrons from material under detection[5]. This deuteron induced neutron background represents a disadvantageous feature of beam-target generated sources (such as $^{19}F(p,\alpha\gamma)^{16}O$) in comparison with bremsstrahlung sources where relatively few ions are accelerated in the diode.

Fourthly and most importantly the experimental studies on photofission enabled a direct quantitative comparison between signals generated from bare and shielded DU with flash bremsstrahlung vs. flash characteristic gamma sources. The use of characteristic gammas was found to be a factor of 30 to 200 times less effective than the use of bremsstrahlung radiation per mC of accelerated charge dependent upon whether gamma or neutron signatures were being used.

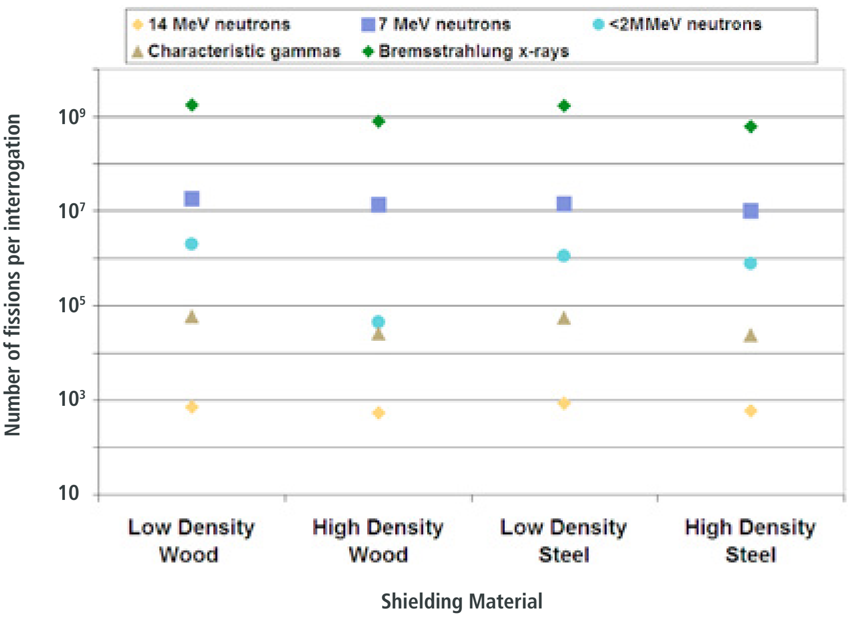
In addition to the empirical experimental measurements a series of systematic modelling sets were generated to investigate the performance of different interrogation sources in the detection of different types of fissile object within different shielding configurations. Several different sources were modelled using Monte Carlo transport codes. These included 10 MeV end-point energy bremsstrahlung and characteristic gamma sources from $^{19}F(p,\alpha\gamma)^{16}O$ but also a number of neutron sources. The neutron sources considered included two different distributions of neutrons from the $^{7}Li(p,n)^{7}Be$ reaction (based on the kinematics associated with two different incident proton energies) and 14 MeV neutrons to represent a DT source. Later calculations also included an intermediate energy, 7 MeV neutron source to represent an accelerated target DD source.

In these simulations, a simplified maritime (2TEU) shipping container mock up was placed 5 m from the interrogating sources. This steel shipping container was filled with different homogenous fills of typical shipped goods representing a broad variation in hydrogen content, atomic number and density. The cargoes modelled were fertiliser, neoprene rubber, nylon, PVC, styrofoam, stainless steel and wood. Each of these materials was modelled at four densities ranging from 0.1 gcm^{-3} to 0.4 gcm^{-3} in 0.1 gcm^{-3} steps.

Information from these calculations was used extensively in making quantitative assessments of the relative efficacy of different radiation sources. Figure 4 shows the relationship between the number of fissions that can be generated in a representative object for each source type, given the present day constraints of the technologies which produce them, as a function of shielding type and density. It is clear from this graph that 10 MeV bremsstrahlung outperforms all of the other sources despite a large proportion of the x-rays produced being less than the photo-fission threshold. This is primarily because of the sheer number of photons that can be produced given today's technology. Future developments in source architecture may enable other source options which are more favourable. Interestingly at this stage, no clear benefit was observed in delivering the pulse in a single intense burst over a LINAC style approach.

Figure 4

Variation in the number of fissions produced in a given special nuclear material object with different shielding materials.



Detectors

Assuming that the interrogating beam is bremsstrahlung x-rays, a substantial neutron return signature would be a good indicator of fissile material. After the irradiating pulse, the number of neutrons is expected to decrease with time, at a rate specific to the actinide of interest. A variety of proportional counters would offer the ability to detect such neutron die away characteristics.

Experiments using ^{3}He tubes have shown them to be the obvious choice for active interrogation as they suffer little dead time in the interrogation beam, and when used with the correct shielding and moderation, can provide a good measure of the die-away of neutrons following an interrogating pulse as shown in Figure 5.

Such detectors would be swamped with indistinguishable background if a neutron source was used. Detectors with sufficient energy resolution to determine broad groups of incident radiation would provide an advantage.

Liquid scintillators offer a significant gain in their ability to discriminate the energy of the incident radiation, the time of interaction and the type of particle (gamma or neutron) via pulse shape discrimination (PSD) as shown in Figure 6. In addition, specific threshold activation detectors (TAD) such as fluorocarbon liquid scintillators[7], offer the interesting possibility of detecting prompt neutrons via the gamma and beta decay of ^{16}N following the $^{19}F(n,\alpha)$ interaction.

The sheer abundance of gamma radiation produced from fission makes it a useful signal to measure when either photons or neutrons are used as the interrogating radiation. Prompt gammas which are emitted within femtoseconds

Figure 5

Die away of neutron signal as a function of time after irradiation with a bremsstrahlung source.

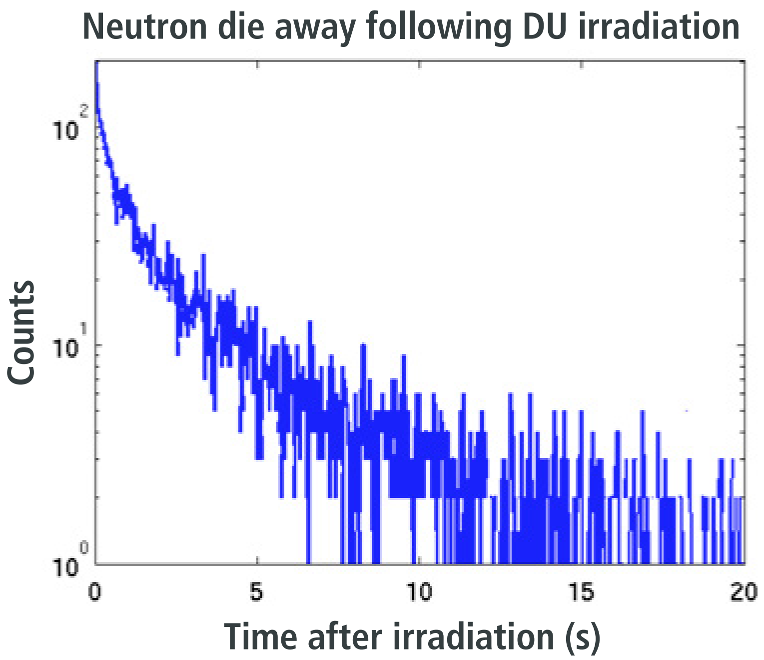
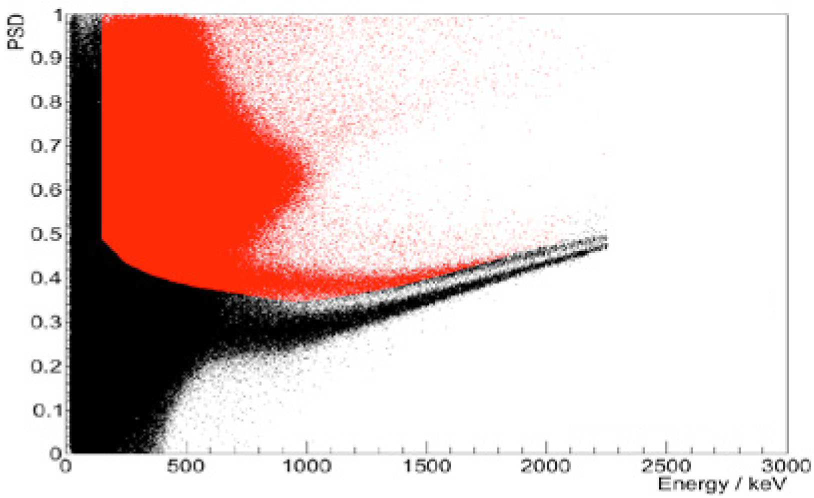


Figure 6

A scatter plot of liquid scintillator pulses showing neutron (red) and photon (black) separation via pulse shape discrimination.



of a fission event are very difficult to distinguish from the interrogating source and, dependent of the intensity of the source, may be lost in any dead time experienced by failure of electronics or pulse pile up within the detector acquisition chain.

Delayed gammas released from the fission product, following the thermal neutron fission process with half lives ranging from fractions of a second to several minutes are much easier to discriminate. Suitable detectors for delayed gamma measurement range from plastic scintillators with poor energy but good time resolution, to high purity germanium (HPGe) with good energy resolution but for an associated cost burden.

The suitability of a number of technologies for use as gamma and/or neutron detectors for an active interrogation system were assessed. A selection of criteria and requirements was used to evaluate detector performance against. No single detector was found to excel in all categories.

Plastic scintillators and sodium iodide detectors were best when judged against the criteria for gamma detection. Liquid scintillators were found to be the best overall for neutron detection. Gamma-neutron sensitive hydrocarbon-based and fast neutron sensitive fluorocarbon-based threshold activation detectors also scored well.

Current work within AWE is focussing on selecting suitable detectors from the identified technologies and testing their performance in an actual system. The performance in neutron die away measurements compared to the ^{3}He tubes can then be assessed.

Concepts of Deployment

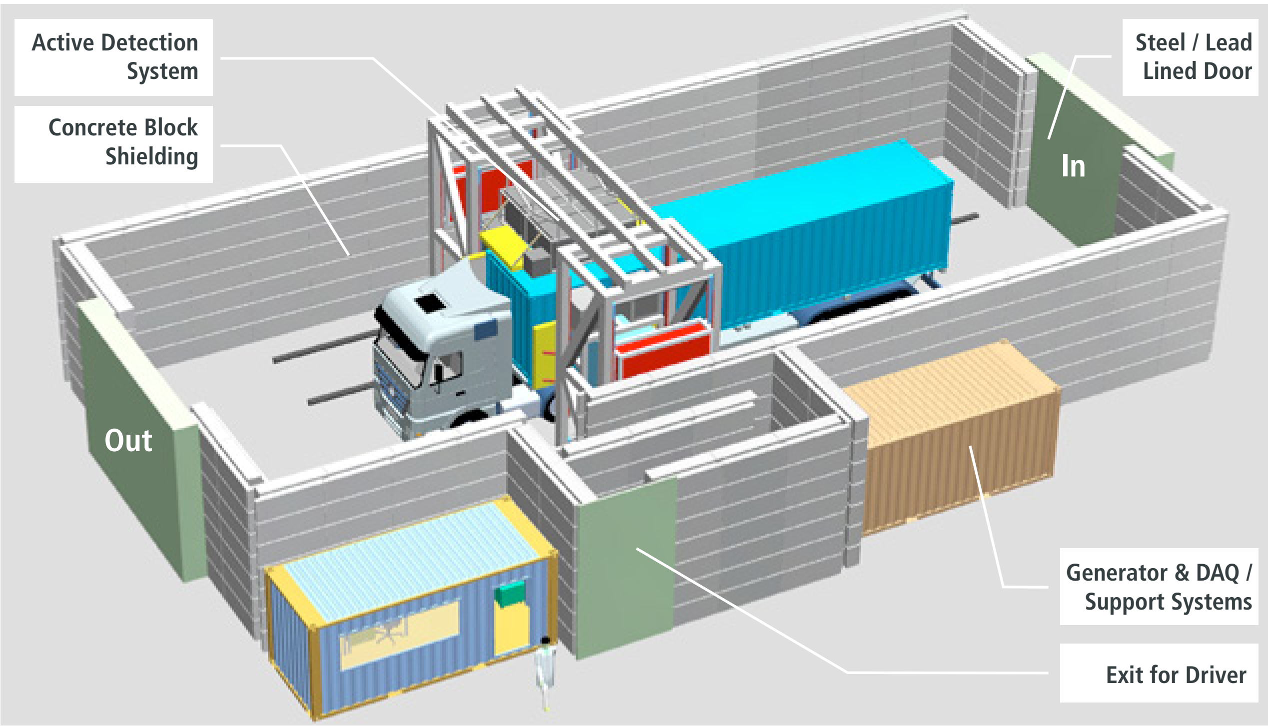
The principal objective of this part of the investigation is to inform the deployment requirements for a shielded SNM detection system. The requirements are concerned with meeting both the customers' strategic need but also the constraints associated with the operation of the system in realistic scenarios. In order to determine the deployment requirements for a particular detection system, the performance of that system must be assessed against different operational scenarios that address the customer requirements. The preferred operational scenario(s) for a particular detection system will then allow the associated constraints and performance criteria to be agreed.

The first logical task is to align the problem space associated with the illicit movement of SNM and the capability challenge associated with detection of shielded SNM with the customer requirement to detect shielded SNM at UK borders. From this a number of operational scenarios can be developed and criteria for their assessment determined. Each scenario is then assessed for each prototype, be it active, passive or muon technology. The scenarios are scored for each technology and the best fits to the customer and operational requirements as a whole are selected.

Active detection presents many deployment difficulties. Primarily the driver of any vehicle needs to leave the vehicle before it is scanned to avoid receiving a dose of radiation. In addition, the system requires a significant amount of shielding to ensure port employees are also within the allowable radiation limits. This makes mobile and primary deployment concepts very challenging for active interrogation. For these reasons, a secondary deployment concept was selected. In this scenario cargo that has been flagged for further investigation during primary inspection is taken aside for more in-depth investigation by active interrogation techniques. Given the large size and relatively low repetition rate of active systems this is a more practical use of the technology. Figure 7 shows an illustration of an active detection system in a secondary port location.

Figure 7

Concept of deployment for a LINAC based active detection secondary system.



Future Work

Throughout the last few years a large amount of work has been carried out to investigate the best way in which active interrogation can be applied to the problem of interdiction of illicit radiological material. Through a combination of modelling and experimental research the work has indicated the optimum radiation source production and radiation detector technologies as well as suitable deployment concepts.

Future work will continue to refine these choices and focussing on fielding sizeable detectors of the suitable technologies on a full scale active interrogation system during a full test campaign.

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Novel Detection Concepts

Illicit radioactive and nuclear (RN) materials can be detected and identified through emitted neutrons and gammas; however, other characteristics are measurable. AWE works closely with academia and international partners, identifying and developing innovative approaches to RN detection.

Research is conducted across three key themes:

- **Identification, measurement and characterisation of RN signatures**
- **Growth and development of new RN detection materials**
- **Improved application of signal processing and data analysis methods**

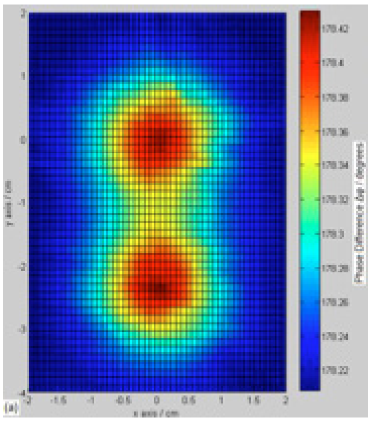
Electromagnetic Detection

Magnetic induction tomography (MIT) is a non-contact electromagnetic imaging technique with potential applications in security, industry and medicine. The method can be used to detect shielded objects. The sample object is imaged via phase variance measurements between the driver and sensor coils, due to inductive coupling between the coils and the sample object. Working in partnership with University College London (UCL), the team is exploring a range of methods to generate and utilise electromagnetic imaging. Figures 1a and 1b show early results from a commercially available 680 μH inductor.

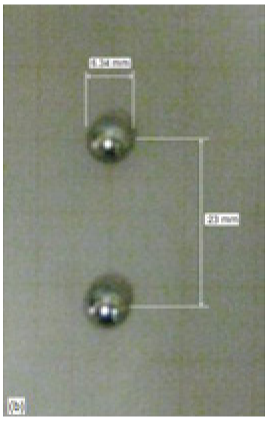
Figure 1

(a) Two dimensional magnetic induction tomography surface plot of 2 x 6.34 mm diameter steel ball bearings separated by 2.3 cm. (b) Photograph of ball bearings.

(a)



(b)



Raster scanning and large coil array imaging methods are under investigation within the collaboration. Operating at 500 Hz, early results imaged a set of pliers within a wooden box, see Figure 2.

Recent results have demonstrated that it is possible to capture magnetic images of conductive objects through a set of metallic ferromagnetic enclosures.

Distributed Radiation Detection Network

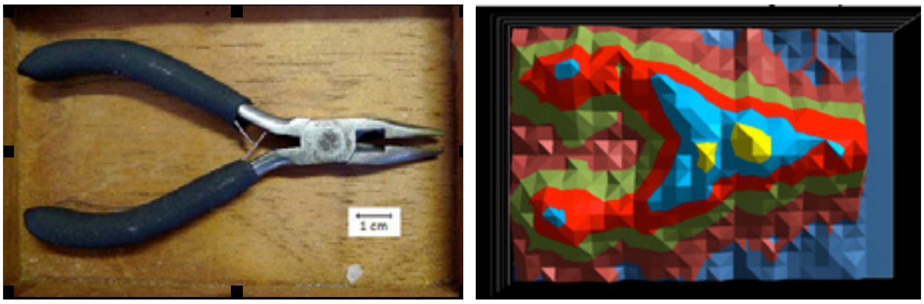
The advancement of wireless technology has made the use of low cost wireless detector nodes a flexible deployment solution with significant advantages over their larger more expensive counterparts.

The idea of multiple networked radiation detectors is not new; however, traditional sensor networks can operate around a central processing unit, see Figure 3. The central processing unit assimilates information from each individual node, accumulating the data to form a single threat decision. It is the network reliance upon central processing which raises concern. Removal of this unit, either through malfunction, accident or malicious intent, will render the network inoperable.

AWE has developed a Distributed Radiation Detection Network (DRDN), where local threat decisions allow the system to be operated in a truly de-centralised process; removing any single point of failure, see Figure 4.

Figure 2

Electromagnetic raster imaging applied to a set of pliers concealed within a wooden box.



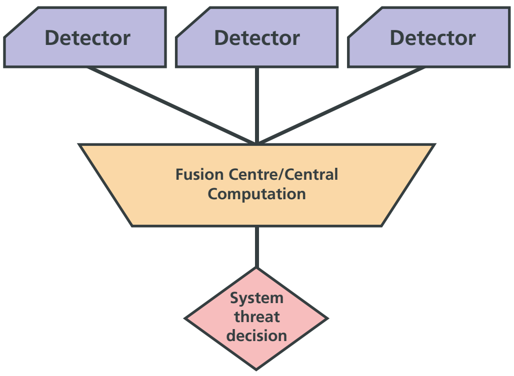
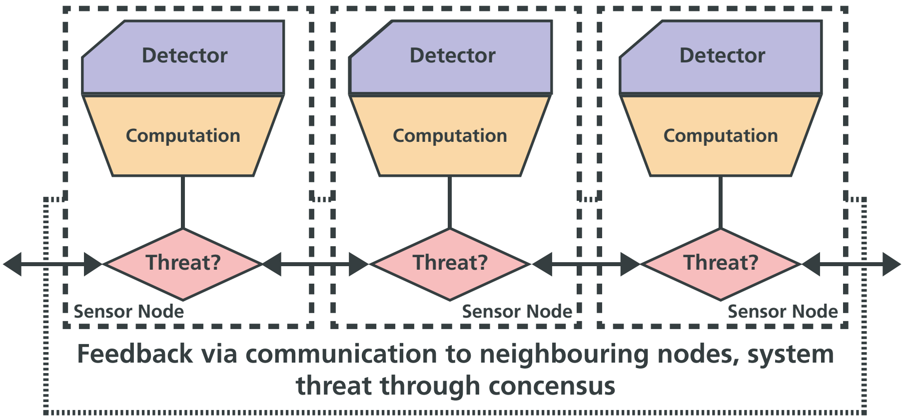


Figure 3

Traditional radiation detection architecture.

Figure 4

AWE distributed radiation detection architecture.



Network topology is a major energy constraint; the nodes must broadcast their data in a structured manner to minimize energy consumption. It is also important that the communication hierarchy is determined in real-time to enable network reconfiguration should a node or communication link fail.

Existing distributed detection algorithms include kSigma, Bayesian hypothesis testing and sequential tests. These algorithms can accentuate the use of a data fusion centre. Consensus algorithms offer an alternative approach suitable for a distributed network; examples include the Parley method and Gossip approach.

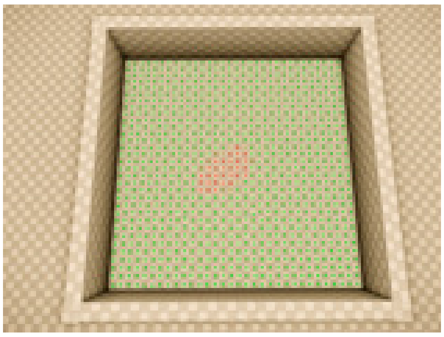
The Parley algorithm is a feedback-based consensus algorithm. A likelihood ratio is calculated by each node as a local test statistic based on its sensor measurement. A detection decision is made based on this likelihood ratio, which is then broadcast to every node in the network or designated neighbourhood. Each sensor then makes a new decision based on its own data in combination with the decisions of the other sensors.

This Parley procedure continues until a consensus is reached, at which point the decisions at all detectors agree. The approach is a truly decentralised scheme, with no requirement for a fusion centre.

AWE tested and compared the performance of the Parley algorithm alongside the other methods listed above both at AWE and using facilities at the University of Surrey. In-house simulation software was utilised and a series of Waspmote detectors customised and ruggedised to enable in-field testing. Modelling and experimental performance tests showed good agreement, further sustained when 1024 nodes were tested within the Virtual Reality suite environment at AWE, see Figure 5.

Figure 5

Simulation containing 1024 detector nodes applying a Parley consensus method to locate a threat (shown in red).



Both 2D and 3D analytical and numerical methods were applied to calculate the coverage afforded by various network configurations. Random sequential deposition methods provided good sensor coverage for simple test motion paths.

Present research is exploring the use of evolutionary algorithms to optimise both sensor coverage and communication topology, this could aid in the deployment of distributed radiation detection networks across a variety of defence sector applications.

Pockels Effect

In recent years there has been increased interest in the Pockels electro-optic effect for use as a radiation detector. A Pockels detection system has the potential to operate at room temperature, locate the sensitive electronics outside the radiation field and requires minimal signal processing equipment.

The Pockels effect describes the birefringent properties induced within an optically isotropic material by the application of an external electric field. The electric field modifies the refractive index along the axis parallel to the field, causing the sample to behave as an anisotropic material.

The University of Surrey and AWE have developed a detection system utilising the Pockels effect. Comprising of a CdZnTe crystal, positioned between two polarisers crossed at 90°, the detector operates on the principle that radiation incident on the CdZnTe sample will liberate charge carriers and perturb the internal electric field. Perturbation of the field alters the birefringence induced and changes the overall polarization of the probe beam and therefore the fraction of light transmitted through the assembly, shown in Figure 6.

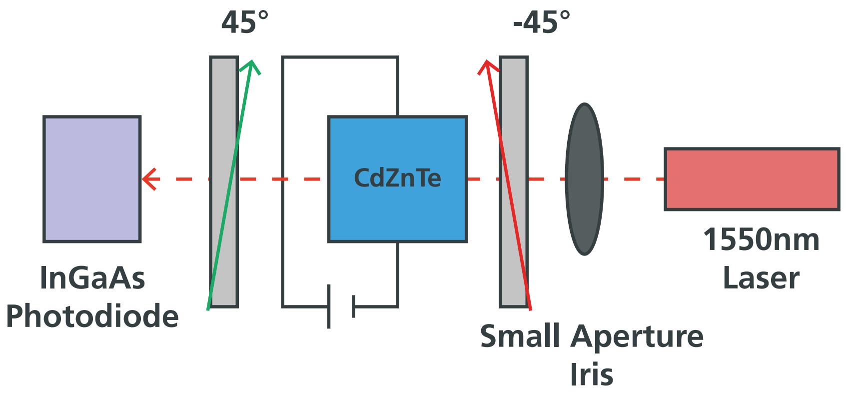
A series of studies were conducted, exploring areas including:

- **Crystal quality, in particular focusing on surface finish and measurement of inclusions**
- **Optimisation of the applied voltage to improve sensitivity to radiation**
- **Contact design, comparing strip, planar and dot contacts**
- **Ability to target the interrogating laser through specific regions of CZT to maximum performance**

The validation of the work is on-going and is presently supported through a three year STFC funded PhD hosted at the University of Surrey.

Figure 6

Example of the University of Surrey/AWE radiation Pockels test cell.



Radiation Portal Monitors Exploiting Time Correlation

One of the areas being investigated at AWE in support of the development of prototype technologies for the Enhanced Detection programme is the application of sophisticated data acquisition and processing techniques to increase the probability of detecting materials when compared with traditional gamma ray and neutron detection methods that are typically employed in radiation portal monitors (RPMs).

A key element of this activity is the 'FLASH' portals programme. FLASH is a collaboration between AWE, Arktis Radiation Detectors Ltd (Switzerland), and the Joint Research Centre (European Commission). FLASH is primarily funded by the US Technical Services Working Group (TSWG), part of the Combating Terrorism Technical Support Office (CTTSO). The programme's goal is to develop a technology to detect shielded SNM more efficiently and less ambiguously by exploiting the time correlation of neutron and gamma ray emissions, which are created through fission radioactive decay.

The underlying technology of FLASH has its roots in research programmes performed at CERN involving cryogenic noble gas detectors. By demonstrating that many of the properties offered by cryogenic detectors can be harnessed at room temperature using pressurized noble gas, an important milestone was achieved, making the detectors better suited for field applications.

Traditionally, RPMs typically use plastic scintillators (Polyvinyl toluene or PVT) to detect gamma radiation and ^{3}He counters for neutron detection, but rely predominantly on gross counts of radiation events and do not fully exploit the time correlation information of detected radiation events. FLASH uses ^{4}He fast neutron detectors to trigger PVT scintillators, exploiting the fact that fission events produce a very high degree of time correlated radiation. This method holds the potential to obtain highly selective, low background detection results from cost-effective, scalable, large area detectors such as plastic scintillators.

The FLASH collaboration has been running since January 2012 and in that time there have been significant developments in the detector hardware, data acquisition electronics and digital signal processing algorithms for time correlation and neutron-gamma discrimination.

The first of two experimental phases was conducted in June 2012 at the European Commission Joint Research Council (JRC) test facility in Ispra, Italy. A second phase of testing, also at Ispra, was completed in a full scale RPM prototype configuration. This rapid timescale has enabled AWE to gain valuable experimental data over a relatively short timescale.

Figure 7 shows the FLASH radiation monitoring system used at the Phase II experiments: it contained eight ^{4}He fast neutron detectors (steel tubes) and two PVT detectors (black) in a RPM-type configuration. The signals of all detectors were fed into data acquisition electronics with sub-nanosecond time synchronisation across all channels. Early analysis of the results indicated a two-fold increase in detection performance compared to neutron counting. Furthermore, the results suggested that these detection signatures to be less susceptible to shielding than both neutron counting and gamma spectrometry. Results and detailed analysis of the FLASH experimental campaigns and the time correlation detection technique have been published in the open literature and presented at a number of international conferences[1-3].

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Figure 7

FLASH radiation monitoring system used at the Phase II experiments.

Figure 8

FLASH PHASE II experiments at JRC, Ispra (January 2013).

Photo courtesy of Neue Zürcher Zeitung (Switzerland)

The Benefits and Challenges of Digital Data Acquisition

Gamma rays are high energy photons (wavelengths typically less than ten picometres), which can interact directly with the electrons of an atom. Although a large number of possible interaction mechanisms are known for gamma rays in matter, only three major types play an important role in radiation measurements: photo-electric absorption, Compton scattering and pair production[1]. In all cases photon energy is transferred to electron energy, which can be directly or indirectly detected in an electronic circuit.

Neutrons are uncharged particles and so cannot be detected through interactions with the electric field from the electrons within an atom. Instead, neutrons are detected through interactions with the nuclei of atoms.

There are two primary interaction types: absorption reactions, where the neutron is absorbed and charged particles are emitted, and proton recoil reactions, where the neutron elastically scatters with the nuclei. Both of these reactions produce charged particles that deposit their energy within a detection medium that can be detected with an electronic circuit[1-3].

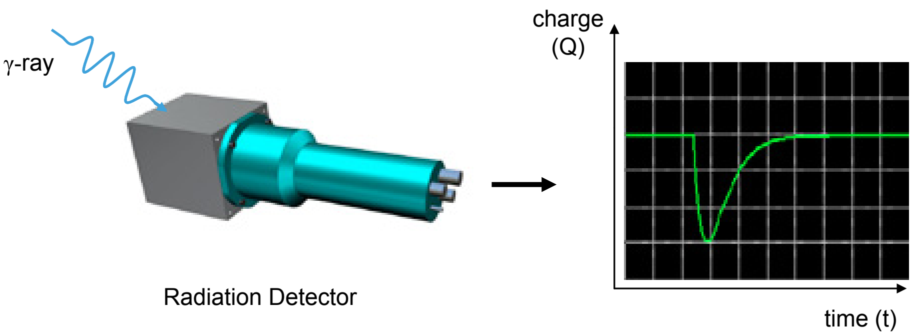
Data Acquisition

A data acquisition (DAQ) chain is required for each radiation detector element in a given system. When a radiation particle interacts with a detector element, a certain amount of charge is liberated, which is typically collected across a high voltage (HV) bias. This results in a charge pulse at the detector element output.

The detector system will be configured in such a way that the amount of charge liberated is directly proportional to the particle energy. The function of the DAQ chain is to first detect the radiation event and then measure certain properties such as the particle energy. The charge pulse (Q) at the detector output will be similar to that shown in Figure 1.

Figure 1

Charge pulse from detector (resulting from a gamma ray interaction) as viewed on an oscilloscope.



The traditional method for measuring the particle energy is an analogue DAQ chain. This has the steps of charge integration, pulse shaping (to improve signal-to-noise) and then detecting the peak height of the resulting waveform; see Figures 2 and 3. This method has been the mainstay of gamma ray spectrometry for many years.

Gamma Ray and Neutron Data Acquisition

Typical applications for gamma ray data acquisition include spectrometry, simple event counting and event timing. The basic chain described above is generally all that is required. The recorded events can be processed and presented in whatever format is required. For example, in spectrometry, gamma-ray events are plotted as an energy spectrum as shown in Figure 4.

For neutron detectors that employ one of the three main nuclear absorption reaction materials (^{3}He, ^{10}B and ^{6}Li), the data acquisition chain is very similar to that described previously for gamma rays.

All commonly used neutron detectors have some sensitivity to gamma rays (photons) and so the output events attributed to neutron and gamma rays must be separated. For this type of neutron detector, the separation can be done relatively simply by energy discrimination, as neutron events and gamma ray events deposit different amounts of energy.

Figure 2

Traditional analogue data acquisition chain.

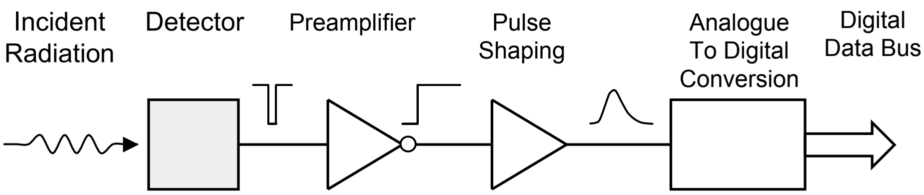


Figure 3

Typical electronic units in a data acquisition chain.

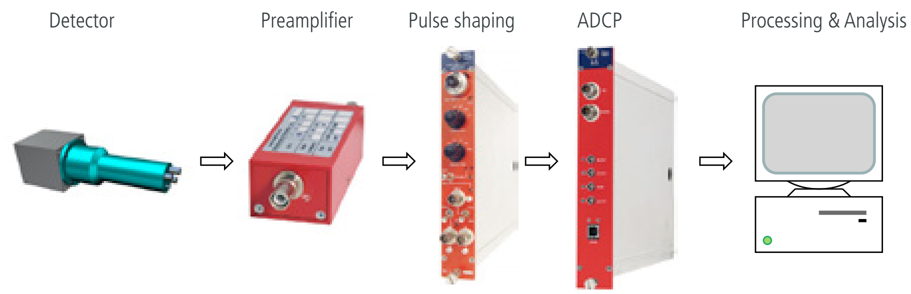
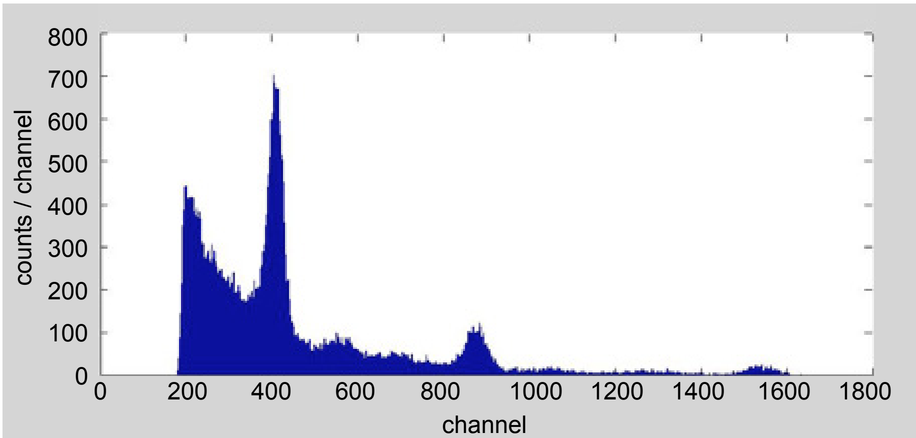


Figure 4

Gamma ray energy spectrum from sodium iodide detector with ^{137}Cs source.



Modern Digital Data Acquisition

Analogue data acquisition systems are adequate for a small number of detectors but the system becomes rapidly cumbersome and costly as the number of detector channels is increased.

The detector systems currently being developed at AWE will typically be made up of large area detector arrays of which each element will require its own data acquisition channel. Digital DAQ systems are particularly suited to these multi-channel implementations and significantly out-perform their analogue counterparts.

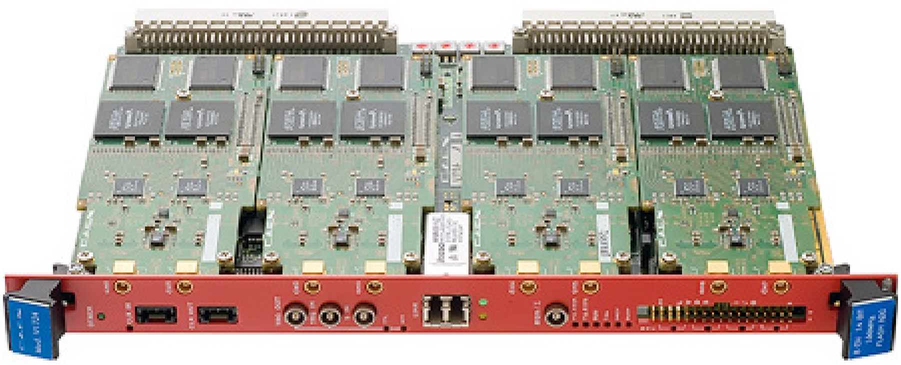
Another significant advantage of digital processing is that the detected radiation events can be analysed in far greater detail opening up the possibility of sophisticated detection algorithms thereby increasing overall detection performance.

Recent developments in high-speed digitisers have paved the way for a more elegant solution to the multi-channel DAQ problem. The analogue DAQ chain is replaced by a digital DAQ chain. The essential difference between the analogue and digital systems is that the latter digitises the detector output signals very early in the chain (usually at the detector output) and then performs the pulse processing in the digital domain. The main advantages are a significant reduction in hardware, consistency across channels, reliability and flexibility.

Digitisers represent the cutting edge of high-speed multi-channel DAQ and higher performance boards at lower and lower cost are continually being introduced to the market.

Figure 5

A typical plug-in multi-channel digital data acquisition card (Caen V1724[4]).



One example of a multi-channel digitiser is the CAEN V1724[4], which samples at 100 MHz at a resolution of 14 bits (16,384 gradations). 100 MHz is sufficient to capture the microsecond time-constant signals from detectors such as sodium iodide (NaI), high-purity germanium (HPGe) and silicon (Si). The 14 bit resolution is necessary to resolve the exceptional energy resolution of the germanium detector.

Sampling rates in excess of 500 MHz are required to capture the nanosecond timescale charge pulses from, say, liquid scintillator neutron detectors. A suitable digital DAQ solution for a liquid scintillator might have a sample rate of 500 MHz or 1 GHz and an ADC resolution of 8 or 10 bits since the energy resolution that can be achieved from a liquid scintillator is quite poor.

Fortunately, most commonly used detectors require either a high sampling rate and low ADC resolution or vice versa; this is quite fortunate since a high resolution, high sampling rate digitiser is (today) technically challenging to implement and could end up being prohibitively expensive.

However, processing in the digital domain at such high fidelity introduces its own challenges of data throughput, handling and storage.

Challenges of Digital Data Acquisition

A digitiser running at 100 Msamples/sec at 14-bit resolution produces something in the order of 200 Mbytes/sec of data output. When multiplied by, say, 64 channels (i.e. for an 8 x 8 detector array), this is around 13 Gbytes/sec. This is an impractically large amount of data to send on to the host computer for processing and analysis. To get around this problem, firmware (software configurable hardware) implementations are used to do some of the processing 'on-board' the digitiser to reduce the amount of data passed to the host computer. In its most basic form, this firmware does a 'peak-detect' of the signal from each detector channel and just passes two parameters to the computer; the detected particle energy and the time at which it occurred (time stamp). More sophisticated firmware algorithms can be used to output parameters such as the shape of the detector charge pulse or to look at, say, the time correlation of radiation events and perform functions such as particle coincidence.

This method of data acquisition is known as time stamp list mode (TSLM). The amount of data passed to the computer is directly proportional to the detection event rate (as opposed to a raw digitiser, which continually sends data to the computer irrespective of whether there are any detection events or not). Despite this huge reduction in data being passed to the host computer, the data rates can still be challenging for the communication link from the hardware to the computer (which typically may be USB, Ethernet or optical).

Neutron Gamma Discrimination

Neutron detectors based on elastic scattering do not enjoy a separation of neutron and gamma-ray events by energy deposition and so some other method must be used to discriminate. For certain detection materials like liquid hydro-carbons, neutrons and gamma rays give up their energy in different ways as they traverse the detection medium, which manifests as a difference in the shape of the charge pulse from the detector.

Figure 6 shows how the light pulse (and hence the charge pulse from a detector) in a scintillation material will vary according to the particle type. This technique of separation is known as pulse-shape discrimination (PSD).

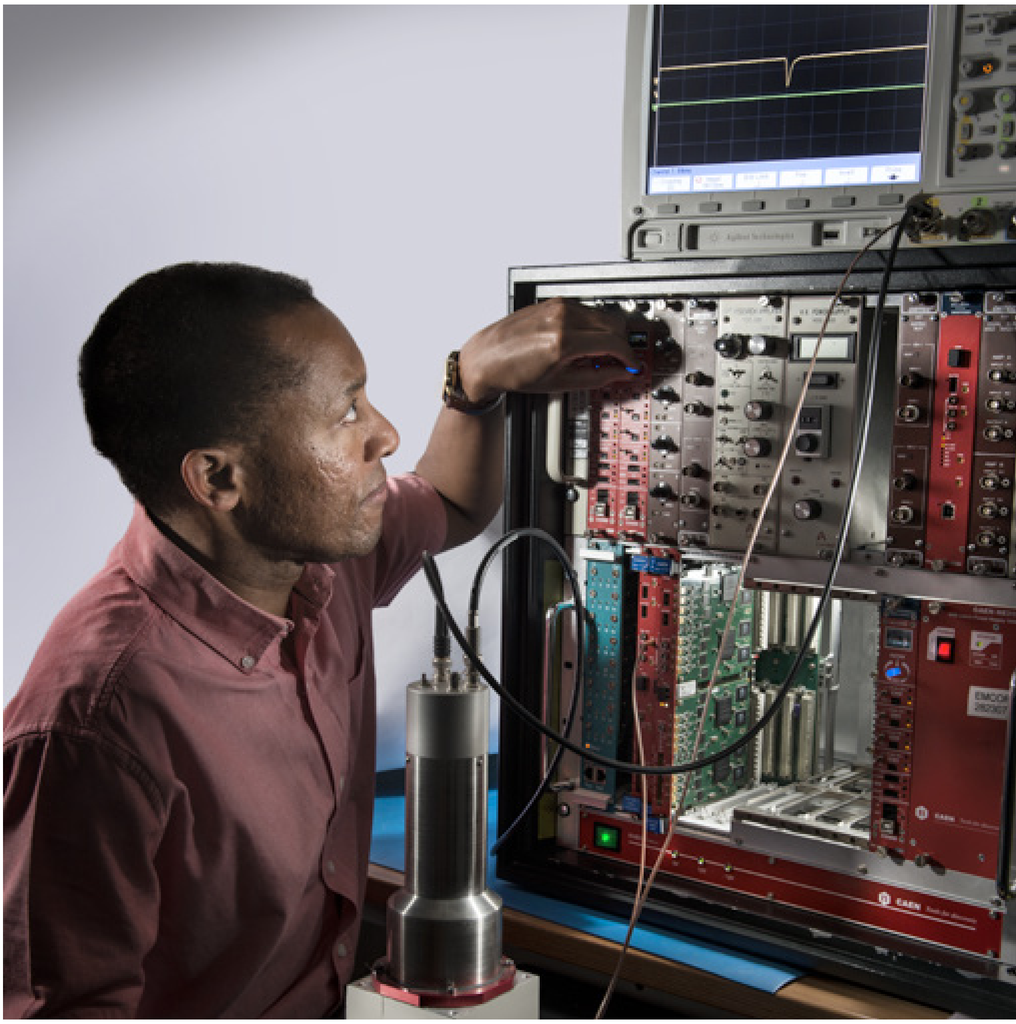
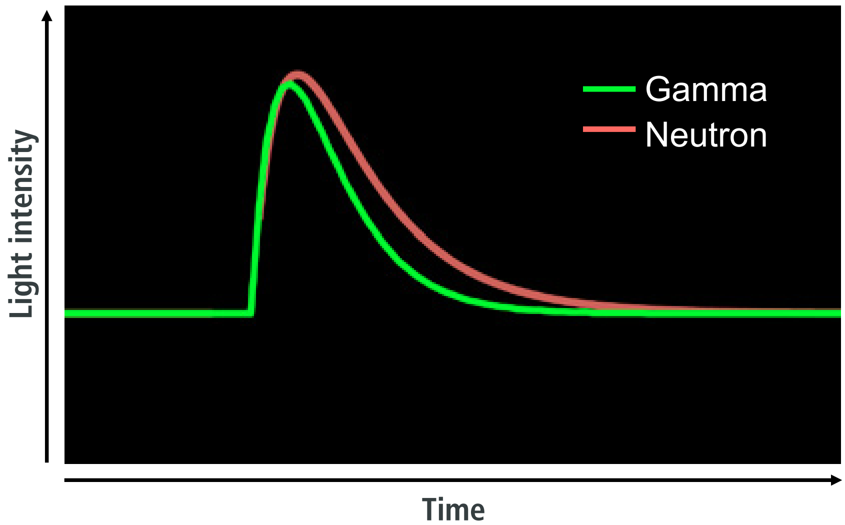


Figure 6

Pulse shape variation from gamma rays and neutrons.



Performing PSD in the data acquisition chain is particularly challenging but the onset of digital systems has simplified the situation significantly.

For PSD, the DAQ chain is modified to include a method of determining the shape of the pulse as well as its height (energy). There are many well established methods for neutron-gamma pulse shape discrimination[5-8] but all are essentially looking at either the charge pulse decay gradient or comparing the amount of charge in the whole pulse compared to that in the pulse tail (a short pulse for a gamma and a long pulse for a neutron). The simplest implementation of this is illustrated conceptually in Figure 7. Every output pulse is integrated over a short time gate and a long time gate; the relative value of the charge in these integrated gate periods determines whether the event is a neutron or a gamma ray.

Although simple enough to understand, the method presented in Figure 7 is not so easy to implement in traditional analogue electronics. Digital PSD can be much simpler to implement in hardware/ firmware and is one of the key reasons AWE, Detection Science has moved to digital systems.

With a PSD digital DAQ implementation employing time-stamp list mode output it is possible to tag each radiation event and represent it in a two dimensional plot (as shown in Figure 8) where relatively simple algorithms can be used to separate neutrons from gamma rays.

Figure 7

Double gate charge integration PSD method (red trace - gamma, blue trace - neutron).

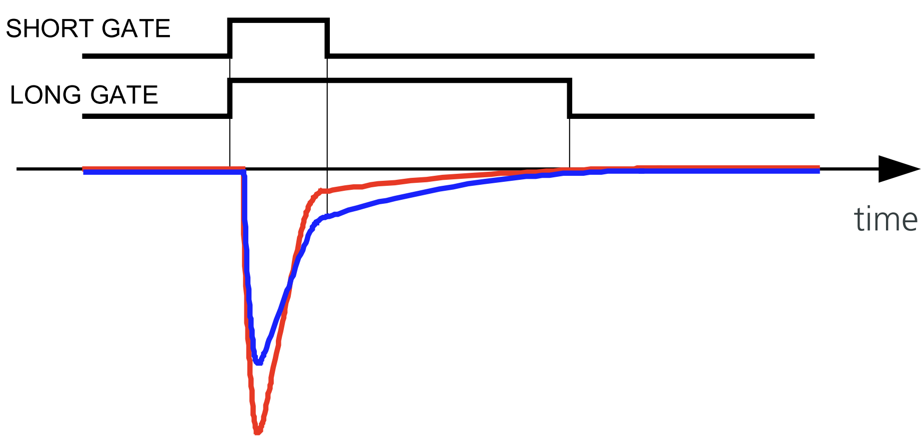
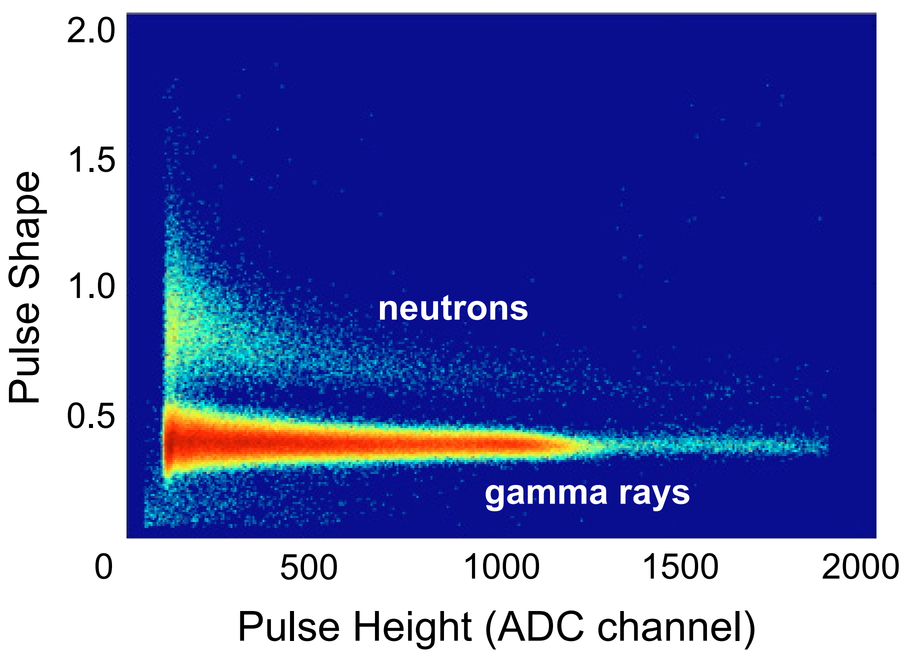


Figure 8

Neutron gamma separation by pulse-shape discrimination (for a five inch liquid scintillator detector).



In practice, there is a wide statistical variation in the pulse shapes for both gamma rays and neutrons and separation can only ever be performed to some value of statistical significance. Moreover, the degree of separation that can be achieved varies with energy.

The degree of separation between gamma rays and neutrons is a function of many parameters including the detection medium itself, the charge collection process performance, detector geometry, PSD algorithm implementation, noise environment and others. This makes the detector and DAQ system selection for a particular application particularly challenging. This is really the crux of the problem; the composition of the radiation fields being measured must be sufficiently well understood and the detector/DAQ combination must be well matched to achieve best performance.

System Implementations

A single digitiser plug-in card measuring no more than 26 cm x 16 cm can perform 16 channels of PSD DAQ simultaneously. It is an improvement over the analogue solution in just about every aspect. The equivalent analogue solution would require some eighty or so individual electronics modules with an estimated cost per detection channel of £11,000. The cost per channel for the equivalent digital solution is around £600; a factor of 18 difference.

The potential down-side of digital solution is the software development time and the detailed understanding that is required of the digital algorithms. These types of digitisers are relatively new to the market and there is typically no standard software offered so this has to be developed in-house. One would expect that this situation would be quite different in years to come as digital DAQ systems become the norm. Even so, AWE has made great progress in software development though links with technology developers such as Caen S.p.A and also the Space Sciences Division of the US Naval Research Laboratory (NRL) amongst others.

However, once the software is written, operation of the system can be quite trivial; certainly much simpler than an equivalent analogue system.

Future Research

AWE, Detection Science have been researching and developing digital data acquisition systems and techniques over the past 4 years as the hardware technology has matured and have been involved in a significant number of collaborations internationally with current publications focussing on PSD performance[9-11], and future publications in progress.

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Nuclear Forensics

Nuclear Forensics is a relatively new discipline that seeks to answer the questions that will be asked following a nuclear security event involving nuclear or radiological material. It is essential that the data derived from a nuclear forensics investigation are able to be presented in a court of law.

Nuclear Forensics, in conjunction with traditional forensics and other information, is instrumental in the process of identifying the nature, source, pathway and perpetrator associated with a radiological or nuclear event, which is known as attribution.

Whilst AWE has a strong background in the analysis of nuclear and radioactive materials, nuclear forensic scenarios bring new technical challenges. Existing analytical methods have been developed to handle different analytes, matrices and the requirement for initial data within shortened timescales.

The key capabilities that may be required for nuclear forensics are gamma spectrometry, alpha spectrometry, mass spectrometry and radiochemistry. The International Atomic Energy Agency (IAEA) Nuclear Security Series[1] gives examples of analytical tools for nuclear forensics, refer to Table 1.

High resolution gamma-ray spectrometry (HRGS) and alpha spectrometry can be used to determine the radioactive nuclides present. A brief explanation of the different types of radioactive nuclides and counting techniques is provided in Box 1 at the end of the article. Thermal ionisation mass spectrometry (TIMS) is mostly used for the detection of actinides but can be used for many elements.

Inductively coupled plasma mass spectrometry (ICP-MS) is used as a complementary technique to HRGS and alpha spectrometry; ICP-MS can provide information pertaining to a sample's isotopic and elemental composition without the need for prior radiochemical separation or sample preparation such as electro-deposition or filament loading.

This isotopic information can be used to complement the data provided by radiometric counting techniques and isotopic information provided by TIMS. X-ray fluorescence (XRF) is a non-destructive elemental analysis technique which can complement ICP-MS for elemental composition determinations.

Secondary ion mass spectrometry (SIMS) is also used for particle analysis and can provide response times of hours/days rather than weeks/months when compared to fission track thermal ionisation mass spectroscopy (FT-TIMS).

Infrared (IR) spectroscopy is utilised to provide chemical/molecular information about a sample, producing information on the source of production and what materials have been in contact with the sample. Microscopy techniques, such as optical and scanning electron microscope (SEM), can provide details on microscopic appearance including structural properties such as scratches and marks.

Where possible existing AWE capabilities have been evaluated as to their applicability to nuclear forensic requirements. Where new equipment has been bought to replace old equipment the requirements for nuclear forensics have been incorporated into the consideration of which specific item to purchase. The analytical capability has thus been enhanced in a focused way to benefit both nuclear forensics and the overall AWE analytical capability.

AWE participates in inter-laboratory comparisons or 'Round Robin' exercises. One such exercise was arranged by the Nuclear Forensics International Technical Working Group (NF-ITWG) in 2010. Laboratories used their available techniques to analyse the supplied sample in an attempt to answer the questions posed (refer to Box 2). The results were then compared with other international laboratories to determine which techniques were the most reliable and which gave the most information on the sample analysed.

AWE performed extremely creditably in this exercise and, overall, the experiences from the Round Robins, when allied with other areas of AWE expertise in nuclear security, mean that the UK is better prepared for the challenges that may present themselves in the future[2].

AWE's capability has been enhanced since the 2010 Round Robin exercise by the procurement of new instrumentation.

Table 1

Examples of analytical tools for nuclear forensics adapted from IAEA Nuclear Security Series[1].

Measurement Goal	Technique	Type of Information
Survey	High Resolution Gamma Spectrometry	Isotopic
Elemental and isotopic bulk analysis	Chemical Assay Radiochemistry / RA counting methods Thermal Ionisation Mass Spectrometry Inductively Coupled Plasma – Mass Spectrometry Glow Discharge – Mass Spectrometry X-ray Fluorescence X-ray Diffraction Gas Chromatography – Mass Spectrometry Infrared	Elemental Isotopic / Elemental Isotopic / Elemental Isotopic / Elemental Isotopic / Elemental Elemental Elemental Molecular Molecular
Imaging	Visual Inspection Optical microscopy Scanning Electron Microscopy Transmission Electron Microscopy	Macroscopic Microscopic structure Microscopic structure Microscopic structure
Microanalysis	Inductively Coupled Plasma – Mass Spectrometry Thermal Ionisation Mass Spectrometry Secondary Ionisation Mass Spectrometry Scanning Electron Microscopy with energy or wavelength dispersive sensor X-ray diffraction	Isotopic / Elemental Isotopic Isoptopic / Elemental Elemental Molecular

The CAMECA IMS 1280-HR, shown in Figure 1, is a large geometry secondary ion mass spectrometer (LG-SIMS), capable of providing rapid isotopic data free from many of the mass interferences that limit small geometry SIMS instruments. It is not reliant on particle irradiation in a reactor followed by the picking of individual particles with micromanipulators, as is the requirement with FT-TIMS.

As the only IMS 1280-HR instrument within the UK it provides significant opportunities for collaborative work with academia and other scientific institutes.

Provenance

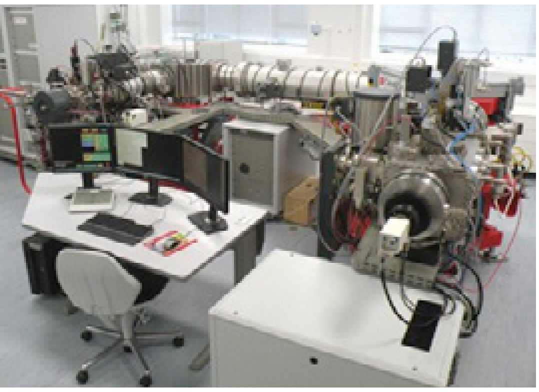
Assessing the provenance or source of nuclear materials has received much international attention through the IAEA[3] and the Global Initiative to Combat Nuclear Terrorism (GICNT)[4]. A proposed mechanism for determining the origin of nuclear materials found outside regulatory control is by comparison to nuclear data of material holdings held within a Nuclear Forensic Library. This would enable a country to rapidly declare if any unknown material is consistent or inconsistent with its current nuclear material holdings. Other countries have presented their progress in developing Nuclear Forensic Libraries for this purpose[5].

AWE has supported the development of a Nuclear Forensic Library and delivered a proof-of-concept Forensics Library in 2014. AWE has held assessment exercises in support of this capability.

In addition to the availability of material data for nuclear forensics it is vital to have subject matter expertise. Experts need to have insights on nuclear material processes related to enrichment, manufacturing, handling etc to be able to determine the origins of a material.

Figure 1

The CAMECA IMS 1280-HR instrument.



Concurrent Traditional Forensics

In addition to the analytical measurements providing identification of the unknown radionuclide outside regulatory control, law enforcement investigators would need to investigate associated materials or marks, such as packaging, pollen, hairs, fibres and finger marks that might provide further insights into the perpetrators, linking individuals to scenes, reconstruction of an event and potential pathway history of how the unknown radionuclide reached the point of interdiction. As a result it is important to be able to perform conventional forensic as well as nuclear forensic techniques on items arising from any given security incident[6].

Undertaking conventional forensic science examinations on materials or items that have become contaminated with radioactivity presents an extremely difficult challenge. Laboratories traditionally associated with conventional forensics do not have the required facilities and are not licensed to handle radioactive material. Equally laboratories involved in radio-analytical chemistry are able to handle radioactive material but do not have the appropriate equipment or experience to undertake the examinations traditionally associated with forensic science, e.g. developing fingerprint markers[7].

In response to this challenge a specialist conventional forensic science laboratory to enable the safe examination of materials and items contaminated with radioactivity[8] has been built at AWE. The laboratory is equipped to support conventional forensic science examinations and enabled to undertake work to the standard required by the UK Justice system. The laboratory has been developed in collaboration with forensic practitioners from the Metropolitan Police Service, Forensic Access Ltd, the Forensic Explosive Laboratory (FEL) at Dstl and the Home Office Centre for Applied Science and Technology (CAST).

The Conventional Forensic Analysis Capability (CFAC) laboratory was officially opened by the Home Office Security Minister, James Brokenshire MP in May 2012, see Figure 2. The CFAC laboratory is one of only a limited number of specialist laboratories around the world that is able to support conventional forensic examinations on items contaminated with radioactivity. The current and future activities in the CFAC laboratory are focussing on validation of traditional forensic methods in the laboratory, gaining the appropriate accreditation for the laboratory and supporting ongoing nuclear forensic science research and development.

The laboratory is equipped with modern instrumentation, including a comparison microscope and electrostatic imaging system, to support a range of examinations including hairs, fibres and questioned documents. In addition to these instruments the laboratory has two glove-box containment units, as shown in Figure 3.

The glove-box units have been specially designed around the requirements of the different disciplines of the forensic practitioners. Therefore it is possible to undertake photography of items, swabbing of an item for DNA, capture of detailed images using a fully integrated digital microscope and recovery of data from electronic devices such as mobile phones.

The most comprehensive forensic science examination capability integrated into the glove-box units is for fingerprint identification. While it may be possible to identify a visible fingerprint mark, e.g. composed of blood or ink, latent fingerprint marks require additional processing for detection and subsequent imaging.

To enable this, the glove-box units have built-in chambers for cyanoacrylate vapour fuming of items, the ability to perform chemical staining of items and a range of alternative light sources to aid in visualising the developing fingerprint mark, see Figure 4.

The operating model for the laboratory is that the forensic science practitioners from Forensic Access Ltd, the Metropolitan Police Service, South East Counter Terrorism Unit and Dstl FEL are, after suitable training, able to operate in the laboratory with AWE providing technical and safety advice relating to the radioactive contamination.

Figure 2

Security Minister, James Brokenshire MP being shown one of the glove-box containment units within the CFAC laboratory during the opening of the laboratory.

Figure 3

A glove-box unit within the specialist forensic laboratory.

Figure 4

The cyanoacrylate fuming chamber integrated into the glove-box. An example of a plastic bottle undergoing cyanoacrylate fuming to assist in developing potential fingerprint marks. An example of a fingerprint mark that has been imaged after an item has undergone cyanoacrylate fuming.

Box 1

Radioactive counting techniques

Each radioactive isotope emits radiation of known types and energies at a known rate. By measuring the radiation emitted by a sample, it is possible to quantify the amount of each measured isotope present. There are three types of radiation that are usually considered for measurement: alpha, beta and gamma radiation.

Each type of radiation has its own properties and methods of detection. Silicon surface barrier detectors commonly detect alpha radiation, scintillation techniques or gas ionization detectors are used for beta radiation and germanium crystals for the detection of gamma radiation.

References

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Box 2

Round Robin

The 2010 Round Robin exercise involved each of the participating laboratories receiving two pieces of metal, each piece being five to seven grammes. To mimic a police enquiry it was requested that three reports be produced to 'The Authorities' – at timescales of one day, one week and two months. The reporting timescales were scheduled to support the requirements of the justice system; one day to arrest and hold in custody, one week to charge, and two months to prosecute. The questions to be answered were:

1. **The country of Texmex has a statute that prohibits the unauthorised transport of uranium materials in excess of 1 gram and more than 1% enriched in the isotope uranium-235 (^{235}U). Do the measurements of Sample A as well as Sample B materials indicate that the statute was exceeded?**
2. **Can the characteristics of the materials be used to say that the two seized materials (Sample A and Sample B) are reasonably from the same source?**
3. **Is there any reason to believe that there may be more of this metallic material at large? What is used to technically justify the statement?**

In field analysis provided an initial set of values to allow packaging and transport, thus completely unknown samples did not arrive at the laboratory. The materials were identified as uranium enriched in ^{235}U.

To address the requirements of the investigators an analytical plan was developed to determine the types of analyses and their order. Conventional forensic techniques, such as fingerprints, DNA and fibres, were also considered. The properties of the samples that were measured can be broken down into four main categories:

- **physical characteristics**
- **isotopics**
- **morphology**
- **elemental composition, both bulk and trace quantities**

The packaging was inspected prior to opening, as it could have revealed voids or areas of different materials. Inspections, radiography and gamma spectrometry in the laboratory allowed the in-field conclusions to be confirmed (that the material was uranium enriched in ^{235}U). The items were photographed, measured and weighed. The analysis showed that both samples exceeded the mass and enrichment characteristics of question 1.

In answer to question 2, the conclusion from the analysis showed that the pieces of metal were similar; it was further concluded that they were probably made by the same process but came from different batches, made some time apart. It was not possible to state that they were from the same facility as they could have been made by the same process in two different facilities.

From the information available to the technical community in the scenario, it was not possible to answer question 3; it may have been that a larger piece was still in its proper location. From a legal perspective, it is a reminder that answers to questions need to be based on known facts and speculation should be avoided.

The GBL Laboratory

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) bans any nuclear explosions, for military or civil purposes. A robust International Monitoring System (IMS) is being established to monitor treaty compliance. The radionuclide network of monitoring stations will perform high resolution gamma spectrometry on air filter samples at 80 global locations, as shown in Figure 1.

Measurements to identify 85 radionuclides indicative of nuclear weapons tests and reactor incidents are undertaken. If the sample is found to contain multiple anthropogenic radionuclides at anomalously high concentrations, and at least one is a fission product, then the sample is sent to a certified laboratory for more sensitive gamma-spectrometry analysis. The UK Radionuclide Laboratory (GBL15) is based at AWE and was certified by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in 2004.

The radionuclide technology is complementary to the three waveform verification technologies - seismic, infrasound and hydroacoustic - employed by the CTBTO verification regime. The technology measures the abundance of natural and anthropogenic radionuclides in the air. The natural radioactivity originates from both terrestrial e.g. ^{238}U and ^{232}Th series, ^{40}K and extraterrestrial sources e.g. ^{7}Be. Anthropogenic radionuclides are generated by nuclear reactors, particle accelerators, radionuclide generators or nuclear explosions e.g. ^{140}Ba, ^{95}Zr, ^{99}Mo, ^{141}Ce, ^{147}Nd, ^{131}I, ^{134}Cs and ^{137}Cs.

During a nuclear explosion large quantities of debris, including radioactive materials, are produced. In an atmospheric or surface test these can be dispersed as plumes high into the troposphere, which

Figure 1

The CTBT International Monitoring System.

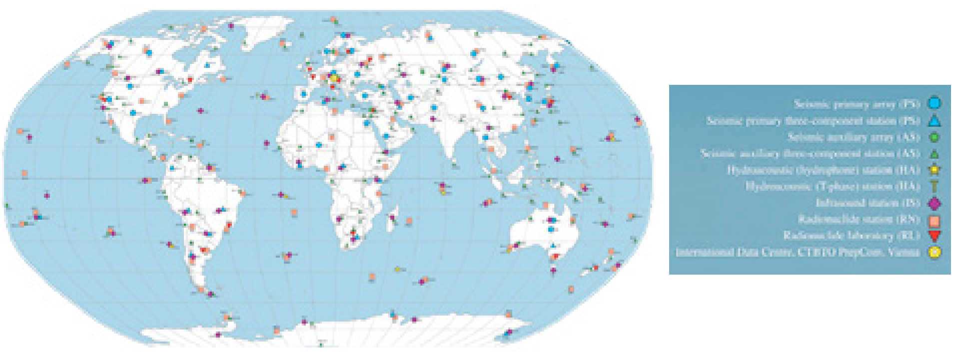


Image courtesy of the CTBTO

can be transported many thousands of miles away. In the case of an underground test, some of the fission products and gaseous debris may be vented into the atmosphere.

Fission products from a nuclear explosion are highly radioactive and contain a mixture of radionuclides with half-lives ranging from a few seconds to many thousands of years. Meteorological models can predict the dispersion of the debris with time, and are used to track the debris back to the detonation location. In most cases the time of the detonation can be deduced from the gamma spectrometry results from early radioactivity measurements.

Radionuclide Monitoring Network

The network has been designed to provide a minimum 90% probability of detecting any above ground nuclear weapon detonation with an explosive yield equivalent of 1 kiloton TNT or above, within 10 days. This design was based on requirements for particulate monitoring, where there was already much global experience in monitoring airborne radioactive materials. The system has been upgraded to detect venting of underground tests by the addition of noble gas monitoring with equipment to be installed at half of the 80 particulate monitoring stations (see Figure 2), to provide the possibility of detection of vented xenon isotopes in the atmosphere (^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe). Box 1 provides further information on noble gases and how they are used to detect underground nuclear explosions.

The objective of the CTBTO's radionuclide monitoring network is to detect this residual radioactivity in the form of radioactive particles or gaseous releases, even if only in miniscule amounts. By collecting and analysing the debris of a nuclear explosion, the radionuclide technology is the only one of the four technologies employed that can provide evidence that an explosion has been nuclear in nature and provide ultimate proof for the nuclear nature of an event. Radionuclide technology is of crucial importance to the entire verification effort.

The CTBTO does not determine whether an explosion has been nuclear in nature or not. It is the prerogative of Member States to make an assessment on the nature of a conspicuous event, based on monitoring data and analysis provided by the CTBTO.

Radionuclide Laboratories

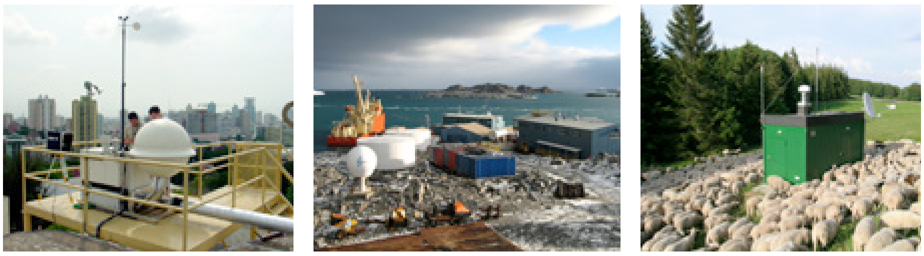
The 80 station radionuclide monitoring network enables a continuous worldwide observation of aerosol samples of radionuclides. The network is supported by 16 radionuclide laboratories hosting expertise in environmental monitoring and providing independent additional analysis of IMS samples. The laboratories analyse samples suspected of containing radionuclide materials that may have been produced by a nuclear explosion. They also conduct routine analyses of regular samples to provide quality control of a station's air sample measurements.

In December 2004, the laboratory was certified by the Provisional Technical Secretariat (PTS) of the CTBTO and commenced working on a fee-for-service as part of the IMS. Since certification the laboratory has been required to participate in annual proficiency test exercises and has consistently obtained A grade results as a top performing laboratory.

Since certification the UK Radionuclide Laboratory has analysed over 320 IMS samples. The particulate samples are prepared using cleanroom facilities and analysed using high resolution gamma spectrometry. The laboratory currently has two ultra low-background detectors for routine analysis and one experimental detector for research and development. Routine samples are measured for seven days for the detection of 85 radionuclides indicative of a nuclear event. After measurement, the results are processed and securely transmitted to the International Data Centre (IDC).

Figure 2

IMS radionuclide stations. Left: RN50, Panama. Middle: RN73, USA. Right: RN33, Germany.



The Fukushima Incident

The UK Radionuclide Laboratory was extensively involved in monitoring the global transport of radionuclides released from the Fukushima Daiichi reactor after the 9.0 magnitude earthquake on 11 March 2011, see Figure 3.

The laboratory analysed over 40 IMS samples to determine the radioactive emissions which spread across the northern and southern hemispheres. The majority of these samples contained iodine (^{131}I) and caesium (^{137}Cs, ^{134}Cs) isotopes released from the reactor, see Figure 4.

Further Research

The use of advanced gamma spectrometry systems has been investigated to reduce background radiation and improve detection sensitivity. This includes a Compton suppression system[1] that provides background reductions of 28-59% and removal of interferences by factors of up to 147. A cosmic veto system[2] has also been developed to provide background reductions of 81% with mean sensitivity improvements of 46%.

Further research has examined the use of coincidence measurements to provide up to 99% background reduction for radionuclides of interest. Much of this research has been disseminated in support of the CTBT in the form of over 30 peer-reviewed journal publications.

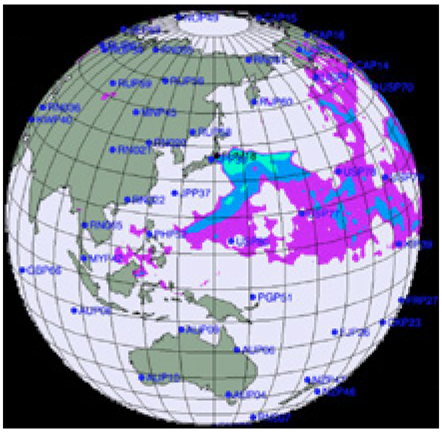
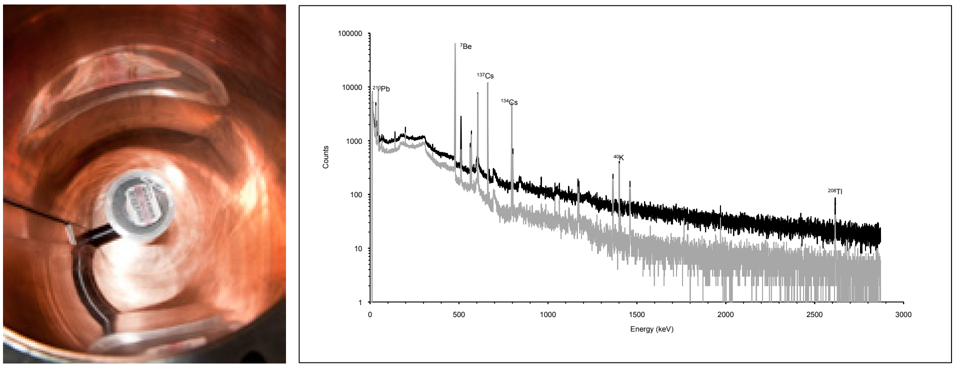


Figure 3

Atmospheric transport modelling of the Fukushima release.

Figure 4

Left: A CTBT gamma spectrometer. Right: Measurement of a Fukushima sample.



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[2] J L Burnett and A V Davies AV, Further development of a cosmic veto gamma-spectrometer, Journal of Radioanalytical and Nuclear Chemistry, Volume 298, Issue 2, 2013

Box 1

Noble Gas

If a nuclear explosion takes place underground, the probability that the solid particulates will enter the atmosphere and be available for collection on the Radionuclide Particulate stations is extremely low. Radioactive products, specifically noble gases, that have extremely low levels of reactivity to surfaces of underground cracks and fissures nor will dissolve appreciably in water, are good candidates for the detection of an underground test. The radioactive noble gas isotopes formed after a nuclear explosion include isotopes of argon (^{37}Ar), krypton (^{85}Kr) and xenon (^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe). Argon-37 is produced by neutron activation of calcium content in the surrounding rocks or soils. Although useful for an on site inspection, it has limited application for the IMS due to measurement difficulties against an ambient naturally occurring background. There are also a number of krypton isotopes formed during an explosion; however these are almost all too short-lived for CTBT use, with the exception of ^{85}Kr which is too long-lived (half-life of 10.7 years) and consequently present at high levels in the ambient background from multiple sources, meaning that it could mask a clandestine test. There are several isotopes of xenon produced in nuclear fission with suitable half-lives and radiations to be detected in the CTBT verification system. The CTBT relevant radioxenon isotopes are ^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe with the half-lives of 11.934, 2.19, 5.243 days and 9.14 h, respectively.

To enhance the radionuclide particulate capability at GBL15 a modified SAUNA II radioxenon measurement system was purchased from Scienta Sweden in 2012. This gives GBL15 the capability to provide continuous radioxenon monitoring of the local atmosphere to increase knowledge of radioxenon background levels. The equipment can also operate in a laboratory mode where IMS station samples can be analysed. This has been used to help certify noble gas stations on the IMS network and will act as part of GBL15's wider effort to improve its noble gas measurement and that of the CTBTO. The radioxenon emissions from medical isotope production for ^{99}Mo are very similar to those signatures from a nuclear explosion and rely on accurate atmospheric transport modelling (ATM) along with measurement of isotopic ratios to differentiate the source and potential location. This ATM capability is being developed at GBL15 using a Bayesian inference system for the non-parametric inference of world-wide radioxenon releases.

Infrasound

The Forensic Seismology team at AWE is tasked to develop and maintain expertise in the analysis of seismic signals generated by suspected underground nuclear tests. Over the past twenty years this expertise has been utilised in helping to develop an effective verification regime for the Comprehensive Nuclear Test Ban Treaty. As part of these verification measures a global network of monitoring stations is being installed, known as the International Monitoring System (IMS).

The IMS includes three waveform technologies in addition to radionuclide monitoring: seismology (to detect waves propagating through the solid Earth), infrasound (to detect low-frequency acoustic waves propagating through the atmosphere, see Box 1) and hydroacoustics (to detect acoustic energy propagating in the oceans).

In 2006 the Forensic Seismology team was tasked to widen its expertise such that it could provide credible analysis of infrasound recordings. AWE had a historical capability in such analysis, which was lost after the cessation of atmospheric nuclear testing in the early 1980s (see Box 2 for some historical context).

The IMS global infrasound network will consist of 60 stations, each with a sensor array, with nearest station separations of between 1000 and 3500 km. Currently 47 arrays have been certified by the Comprehensive Nuclear Test Ban Treaty Organization. Figure 1 shows the locations and current status of the stations.

IMS infrasound arrays consist of a number of sensors distributed within approximately 3 km of one another. The distributed sensor arrays are used to detect possible acoustic signals; fluctuations generated by acoustic waves are coherent across the array, while shorter wavelength wind generated pressure fluctuations are incoherent at the

Figure 1

The current status (February 2014) of the International Monitoring System (IMS) infrasound array network. Of the 60 planned arrays (all triangles), 47 have currently been certified for use (red triangles).

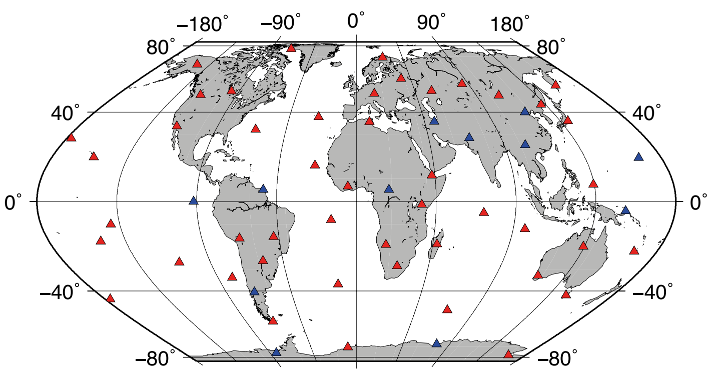
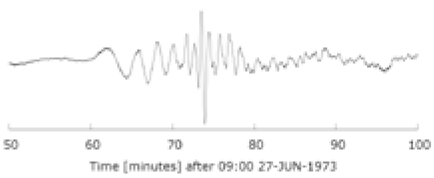


Figure 2

A pressure time-series, recorded at one element of the Blackness microbarograph array, of the Chinese atmospheric nuclear test that occured on 27 June 1973.



separated instruments. Array processing also assists in improving signal-to-noise ratios by optimally combining the records from different sensors, and allows the direction of arrival of a given signal to be estimated. Figure 2 shows a sample of historic data captured at the Blacknest microbarograph array. The estimated yield of this explosion was 2.5 MT at high altitude[1]. The test location was approximately 6600 km from the recording instrument. Exact amplitudes are not available, but pre-signal mechanical calibration signatures suggested a maximum peak-to-trough amplitude of approximately 20 Pa.

With the expanding IMS network of infrasound sensors, a large number of infrasound signals from diverse sources are being detected. These sources include volcanic eruptions, meteorite terminal airbursts, accidental industrial explosions, military activity, sonic booms, and the interaction of ocean waves during storms.

Two notable events, the Chelyabinsk meteor and the 2013 DPRK announced nuclear test, are used to illustrate some of the challenges faced by infrasound analysts.

The Chelyabinsk Meteor

The fragmentation of the superbolide meteor above Chelyabinsk, Russia, on 15 February 2013 generated the most widely observed infrasound signals of the IMS era. Localization of the acoustic source confirmed that the majority of energy was deposited during a single fragmentation event. It was also the first event since the inception of the infrasound network in the early 2000s to generate acoustic-gravity waves comparable in size to the atmospheric nuclear tests of the 1960s and 1970s.

The pressure disturbances were large enough that the passage of the wave was detected after multiple orbits of the globe[2]. Figure 3 shows an example from an array in Fairbanks, Alaska, where the final arrival (Ig5) took almost three and a half days to arrive. This wave train had orbited Earth two and a half times, resulting in a total path length of approximately 86,700 km. These results highlight both the extremely low acoustic attenuation at low frequencies within Earth's atmosphere, and the efficient propagation of acoustic waves within atmospheric waveguides.

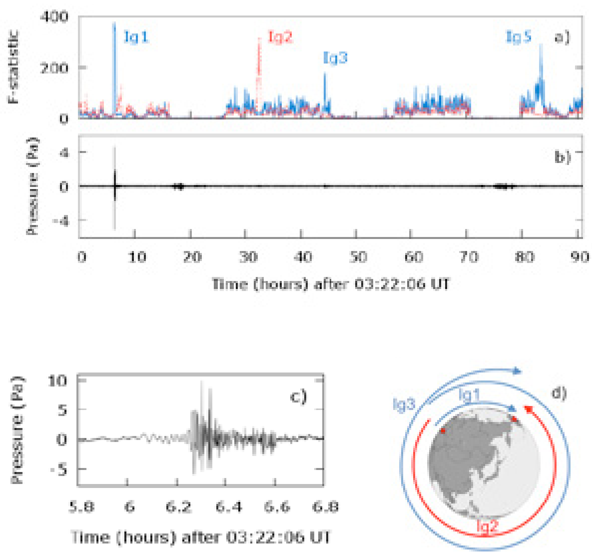


Figure 3

Infrasound generated by the Chelyabinsk meteor recorded at array IS53, Fairbanks, Alaska. Panel a) shows the results of array processing the data within the 0.03 to 0.05 Hz passband. The F-statistic value is an indicator for the presence of coherent acoustic signals passing across the array; high F values indicate signal. The blue trace indicates the F-statistic obtained when the array is steered to look for signals from the Chelyabinsk region; the red trace is the result when the array is steered to look in the opposite direction.

Panel b) shows the array beam in the 0.03 to 0.05 Hz passband aligned from the array back to the meteor's terminal explosion location.

Panel c) shows the details of the initial arrival on the unfiltered beam.

Panel d) is a cartoon showing the nomenclature for the arrivals impinging upon the array.

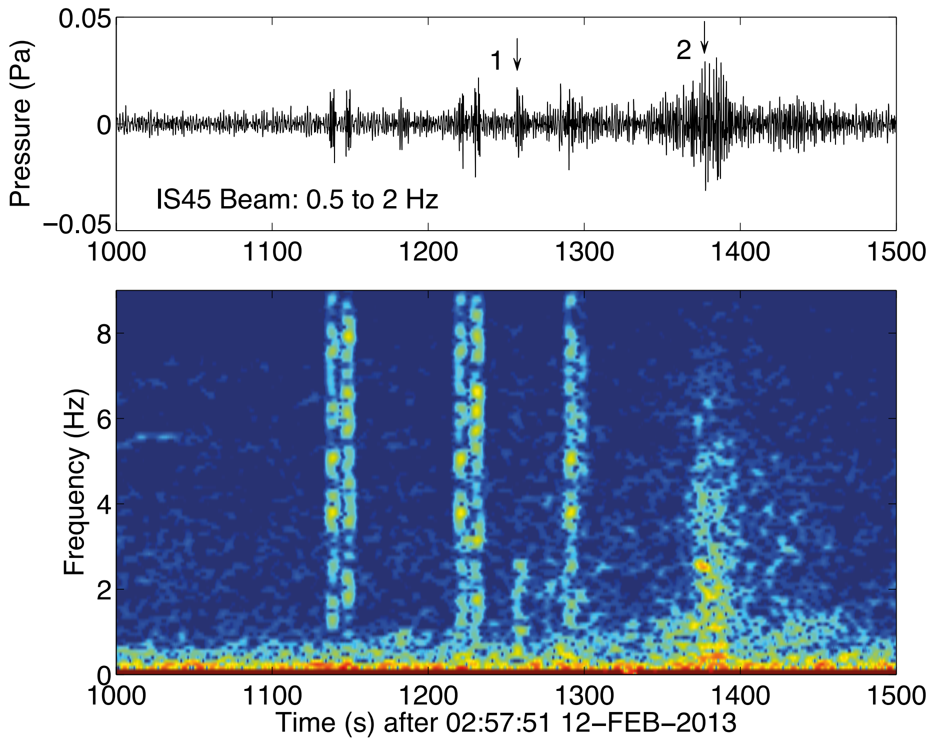
These arrivals are indicated within the processed data in panel a).

Due to the effects of the meteor's terminal burst upon the infrastructure surrounding Chelyabinsk, there was great interest in estimating the amount of energy deposited into the atmosphere by the airburst. Using relationships derived from atmospheric nuclear test generated signals, it was shown that infrasound period measurements from 12 IMS stations were comparable with those expected from a chemical explosion of approximately 500 kilotons of TNT[3].

The results illustrate another important consideration for infrasound analysis. In Figure 3a it is observed that during local night time at the array there are constant low levels of acoustic detections, while during daytime the detection statistic indicates there are almost no detectable acoustic arrivals. This is the result of increased daytime turbulence within the lower atmosphere that generates large amplitude pressure disturbances, local to the station, that mask acoustic signals of interest. Such noise is broadband in nature and major efforts are underway to design arrays and detectors to reduce the impact of wind-generated noise on the IMS infrasound network capability.

Figure 4

Infrasound recorded at station IS45, Grigoryevka, Russian Federation following the announced DPRK nuclear test of 12-Feb-2013. The station is located 412km to the North-East of the DPRK nuclear test site. The top panel shows the beamed waveform in the 0.5 to 2Hz passband, the bottom panel shows a spectrogram of the unfiltered beam (bright warm colours indicate regions of high pressure timeseries power, dark cold colours indicate low power). The three clear broadband double pulses are locally generated noise, the signals marked 1 and 2 have arrival times and propagation azimuths consistent with an origin at the test site.



Announced DPRK Nuclear Test 12 February 2013

The announced Democratic People's Republic of Korea (DPRK) nuclear test, on 12 February 2013, was conducted underground. Yet, at a distance of over 400 km from the test site, an infrasound signal was recorded at a Russian IMS array, see Figure 4. This signal is an example of a ground-to-air coupled wave.

The test generated large amplitude seismic waves in the vicinity of the source that shook the mountainous terrain surrounding the explosion. This ground shaking acts in the same manner as a loudspeaker cone, generating a pressure disturbance in the atmosphere that then propagates as infrasound.

The detection of infrasound from the DPRK announced nuclear test qualitatively confirms the event is shallow and occurred within a region of pronounced topography. Understanding of air-to-ground coupling mechanisms is not yet sophisticated enough to provide well constrained quantitative estimates of explosion depth and location from infrasound signals.

The detection of the DPRK explosion illustrated an important issue regarding IMS infrasound data. The air-to-ground coupled signal from the DPRK test site arrives at array IS45 coincident with a separate infrasound signal that appears to have been generated close to the array, either by military or industrial processes, see the broadband signals in Figure 4.

This is not uncommon; there are almost always a significant number of signals arriving at any infrasound array. For example, at Eskdalemuir, Scotland, signals are often observed from mining explosions throughout Scotland, sonic booms from military activity in the North Sea, continuous signals from local windfarms, and storm activity in the North Atlantic.

The challenge in interpreting small amplitude signals is two-fold. Firstly, we wish to identify the signal of interest from within the background signal 'clutter'. Research at AWE into improving array processing techniques for this task is ongoing. Secondly, with such a large number of signals, how does one take detection lists from separate stations and identify the signals that are associated with a particular, usually unknown, source?

This problem is closely connected to the problem of event location, and work in collaboration with Los Alamos National Laboratory is underway to better understand the uncertainties within event association and location algorithms[4].

Ongoing Research

To improve our infrasound analysis capability we need to better understand acoustic propagation through the atmosphere. At the stratospheric altitudes (30 - 60 km) where infrasound propagation paths are most sensitive to small-scale atmospheric structures there are few observational meteorological constraints to assist us. Such altitudes are higher than those that are important for operational meteorological forecasting, but lower than those that are probed by satellite-based instruments concerned with space weather.

Research is being undertaken to better constrain stratospheric atmospheric dynamics using variations within both observed infrasound signal arrival times and directions of arrival.

Such research is undertaken using a variety of methods: using serendipitous signals from events of known location[5-7], recordings of air-to-ground coupled waves on dense networks of seismometers deployed for other purposes[4], and the deployment of high-density networks of microbarometers.

This increase in infrasound research marks a shift from the strategic use of infrasound to understand atmospheric nuclear explosion sizes in the 1960s and 70s, and the nuclear test ban treaty monitoring efforts of the past 15 years. Infrasound is now being recognized as a useful scientific tool, both for research into upper atmospheric dynamics[8] and for civilian monitoring applications, such as the identification of large volcanic eruptions in regions of high risk to aviation routes[9].

Infrasound can provide useful information as part of multi-parameter event assessments. Research is focusing on how to combine information from seismic and infrasonic arrivals to jointly estimate source yield and height-of burst/depth-of-burial of explosions close to the ground surface.

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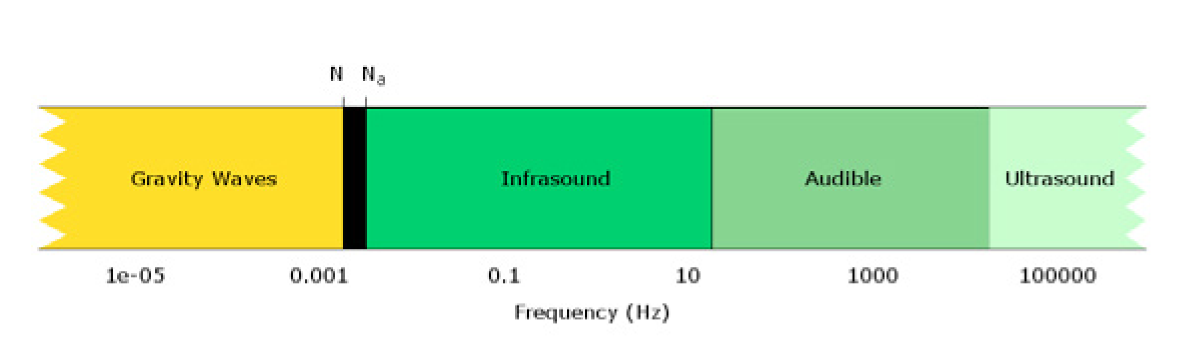
Box 1

Infrasound is the low-frequency region of the acoustic spectrum (<20 Hz) to which the human auditory system is insensitive, see figure below. These low frequency, long wavelength waves undergo little attenuation, so infrasound can propagate many thousands of kilometres and retain pressure amplitudes that can be detected by microbarographs above background wind pressure fluctuations.



The acoustic-gravity wave spectrum for the atmosphere. At frequencies below the Brunt-Väisälä Frequency, N, the restoring force is buoyancy and waves travelling in this regime are described as gravity waves. Above the acoustic cut-off frequency, Na, pressure disturbances propagate as sound waves. Infrasound is that part of the spectrum that is below the audible cut-off frequency at about 20 Hz.

In addition to the lack of attenuation, infrasound is measureable at long distances because the waves propagate within waveguide structures that channel the sound. These waveguides are generated by vertical changes in the sound speed structure which is controlled by temperature and horizontal winds. The most efficient waveguide for long distance propagation exists between the ground surface and the stratopause. The sound waves skip through the atmosphere, propagating upwards until refracted downwards at an altitude of approximately 50 km. After reflection at the ground surface the propagation cycle repeats. These waveguides vary over time; the stratospheric meteorology determines whether a waveguide is present and how efficiently it propagates acoustic energy.

Box 2

Infrasound from the atmospheric nuclear testing era

Atmospheric nuclear test explosions generate large amplitude atmospheric pressure fluctuations that propagate many thousands of kilometres. Indeed, many of these tests were so large that the atmosphere responded at frequencies lower than those that can support acoustic propagation. In this regime, motions of the atmosphere are large enough that buoyancy acts as the restoring force; such waves are referred to as gravity waves (see Box 1). Infrasound analysts become adept at looking at both acoustic and gravity waves as both sets of pressure disturbances are recorded by microbarometers.

In the era before accurate satellite based nuclear explosion detection technologies, ground based monitoring of infrasound was used extensively to detect, locate and assess the size of atmospheric nuclear explosions. In the late 1960s, scientists at AWE Blacknest built a microbarograph array, with a maximum aperture of 30 km, for the purpose of detecting signals generated by atmospheric nuclear explosions.

US analysis of an extensive atmospheric explosion dataset found that for these large explosions, the cube of the dominant signal period is proportional to the explosive yield (where period is the inverse of frequency). In the Comprehensive Nuclear Test Ban era it is not expected that we will record man-made signals of such a size. Yet, as the analysis of the Chelyabinsk superbolide event shows, the knowledge gained in the atmospheric testing era can now be used to estimate the explosive yield of meteoritic terminal airbursts.

Seismology

The Comprehensive Nuclear Test Ban Treaty (CTBT) bans all nuclear explosions. At the present time the treaty has yet to enter into force, but since the treaty was opened for signature in 1996 there has been a dramatic reduction in the number of nuclear tests. Between 1945 and 1996 over 2000 nuclear tests were carried out, whereas since 1996, announced nuclear tests have been carried out only by India and Pakistan in May 1998 and by the Democratic People's Republic of Korea (DPRK) in 2006, 2009 and 2013.

Since 1996 a major international effort has led to the establishment of the monitoring regime for the CTBT. The International Monitoring System (IMS), a global network of 321 seismic, infrasound, hydroacoustic and radionuclide stations, is now over 85% complete. These stations send data to the International Data Centre (IDC) in Vienna, Austria. The IDC then processes the data to produce a daily event bulletin. As well as explosions which potentially may be of interest under the treaty, the bulletin includes many other types of events such as naturally occurring earthquakes, mining explosions and bolides entering the atmosphere.

AWE hosts the UK National Data Centre (UK NDC) for the CTBT and the Forensic Seismology team which is tasked with carrying out analyses of events of interest, using waveform data from the IMS and UK recording stations. In recent years, the most high profile events have been the three explosions announced by the DPRK government as nuclear tests. This article describes what seismology can tell us about these explosions and provides a summary of the main areas of seismology research at AWE.

Detection

It is perhaps not obvious but seismology can sometimes provide the only physical evidence that an explosion has occurred when a nuclear test is announced. Separating signals generated by explosions or earthquakes from the continuing background seismic noise is the problem of signal detection.

Explosions of the size of the three DPRK announced tests generate seismic waves which can be detected across the globe, the most easily detected being P waves, which are body waves that travel through the interior of the earth and arrive at seismic stations within a few tens of minutes of the explosion. A key component of the IMS is the use of seismometer arrays, which are sets of typically 10 to 20 seismometers grouped within a few kilometres of each other. These arrays can be used to enhance signal detection capabilities by optimally combining the recordings to construct a beam, and to estimate the bearing and distance of the source that generated the signals. AWE has been a centre for research into the use of seismometer arrays for over 50 years.

AWE operates a small network of stations, known as UKNET, across the UK. Figure 1a shows the location of the stations that make up UKNET; most of these stations consist of single, three-component seismometers. AWE is also responsible for the operation of the seismometer array at Eskdalemuir, Scotland (EKA), which forms part of the IMS. EKA has been operating since 1962 and has detected signals from hundreds of underground nuclear explosions. EKA consists of 20 seismometers in two crossing lines with an aperture of about 8 km. Figure 1b shows the layout of the arrays at EKA.

Seismograms recorded in the UK containing P wave signals from the 2013 DPRK announced nuclear test are shown in Figure 1c. The seismogram from EKA is the array beam, formed by combining the outputs from the 20 seismometers in the array in an optimal way. The other three seismograms are single, vertical component seismometer traces. The seismograms have been converted to a common response which is essentially velocity in nms^{-1}.

Clear signals are seen in the beam calculated using the EKA array and at the UKNET stations at LLW, north Wales; LPW, south Wales; and WOL, north Hampshire. The seismograms are converted to a common response so the variation in the amplitude of signals and background noise is a genuine characteristic of the data; it should be noted that the background noise at EKA is clearly lower than at WOL.

Recent research at EKA on signal detection has focused on the use of the Fisher F statistic in providing confidence that a signal detection is real. Methodology developed by Selby[1-3] reduces the number of false alarms while maintaining the ability to detect small signals. Trials with this new method with IMS data show promise for improving the bulletin products produced by the IDC.

Figure 2a shows the EKA beam for the 2013 DPRK explosion together with some of the detector output. The F statistic has an expected value of unity when only background noise is present, but rises with increased signal-to-noise ratio. The detection method also outputs the azimuth (bearing) and slowness (or equivalently the vector slowness) with the

Figure 1

a) Map showing the seismometer stations in the UK operated by AWE.

b) Map showing the geometry of the seismometer array at Eskdalemuir (EKA) and the UKNET station EKB.

c) P seismograms from the 2013 DPRK announced nuclear test recorded at the stations EKA, LLW, LPW and WOL.

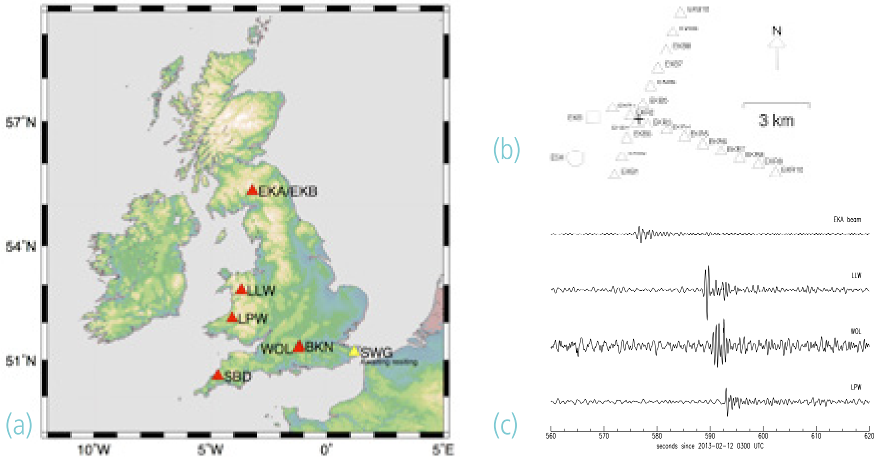
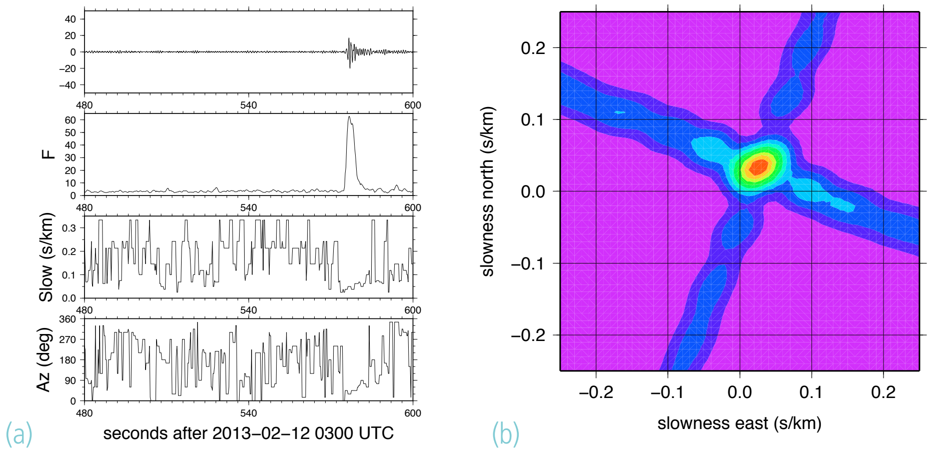


Figure 2

a) The four panels from top show: EKA beam signal from the DPRK 2013 explosion; time-domain F statistic trace showing the clear arrival; slowness (inverse speed) with maximum F statistic as a function of time and azimuth (bearing) with maximum F statistic as a function of time.

b) F statistic as a function of vector slowness for a five second window encompassing the arrival time of the signal.



maximum value of F for each time step. In Figure 2a it can be seen that the azimuth and slowness varies randomly when only background noise is recorded, but settles to consistent values when the signal arrives.

Figure 2b shows the F statistic as a function of vector slowness. The red area in the plot shows the peak F, indicating that the signal arrived at the station from a bearing of 35 degrees east of north and a speed of approximately 20 km/sec, consistent with a source in the region of Korea.

Location

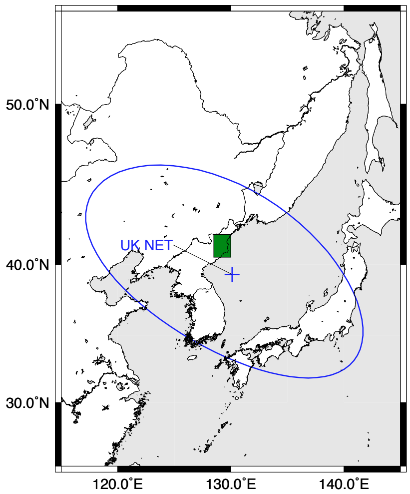
Seismic events are located using measurement of the arrival time, bearing and slowness of seismic signals, most commonly the P wave. Typically a set of arrival observations is inverted using an iterative least-squares technique to minimize the misfit between observations and predictions generated from a model of the earth. The accuracy of an estimated location and its precision depends upon the accuracy and precision of the observations, the accuracy of the earth model used and the geographical distribution of the stations used.

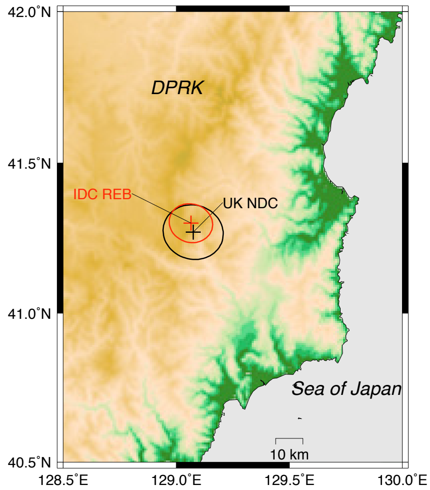
Using UK stations only is sufficient to demonstrate that the signals from the 2013 explosion originated in the Korea/Japan region. Figure 3a shows locations using the times of P seismograms shown in Fig 1c, and also the bearing and slowness measured at EKA as shown in Figure 2b. The ellipse shown is the 90% uncertainty region for the location, estimated by propagating prior uncertainties assigned to the observations and earth model predictions.

Figure 3

a) Location using UK stations (EKA and UKNET).

b) Location found by the UK NDC using IMS data (black), and the location given by the IDC in the Reviewed Event Bulletin (REB, in red). In each figure the ellipses show the uncertainty in the location at the 90% level.





While the UK stations are able to indicate the general region from which the signal originated, the result is not sufficient to identify the country in which the event occurred.

Although this result could perhaps be improved with a more careful assessment of the data, a much more precise result can be obtained using a global distribution of stations from the IMS network. Figure 3 shows the location and uncertainty for the DPRK 2013 explosion estimated using several array stations from the IMS. The uncertainty in the location is reduced to around 10 km.

An uncertainty in the location of seismic events of around 10 km is typical. This is due to lack of knowledge in the three-dimensional structure of the earth, which results in systematic uncertainties in travel time predictions.

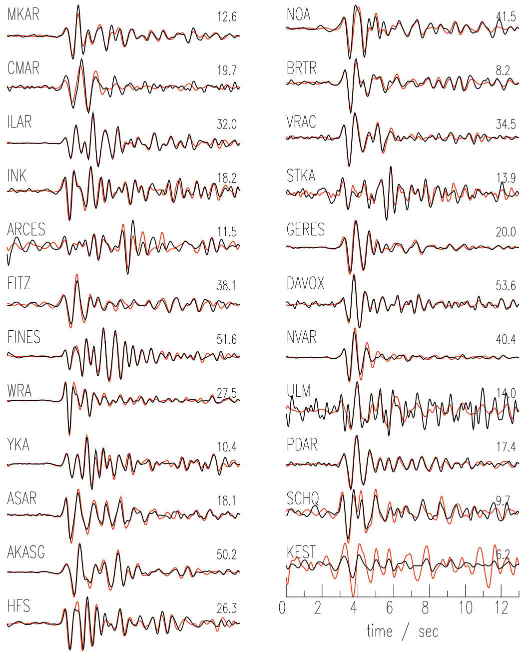
If multiple seismic events are sufficiently closely co-located that the systematic travel time variations can be assumed to be identical for all events, then the relative locations can be estimated with much higher precision.

Figure 4a shows the P seismograms at IMS stations for the 2009 (black) and 2013 (red) DPRK explosions. Other than a common scaling factor, the

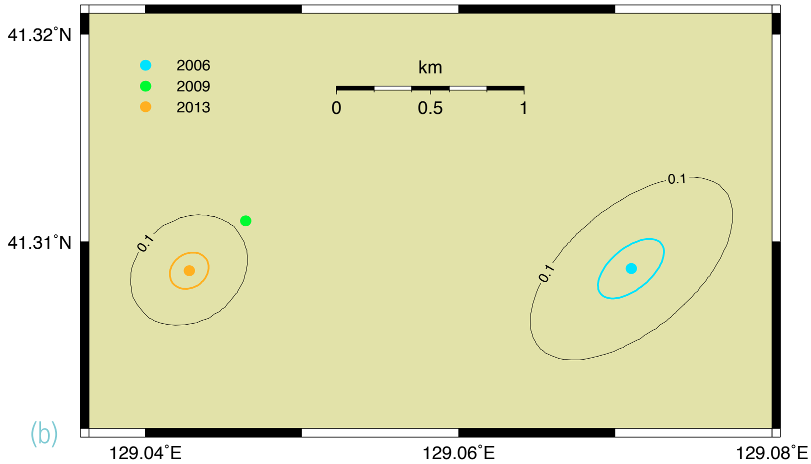
Figure 4

a) P wave seismograms at IMS stations for 2009 (black) and 2013 (red) shown overlain. A scaling factor of 2.4 is applied to the 2009 seismograms.

b) Result of applying an array cross-correlation technique to calculate the relative locations of the three DPRK explosions. The ellipses show the uncertainty in location using two different assumptions.



(a)



(b)

seismograms are almost identical. This immediately suggests that the two explosions were closely co-located. The seismograms from the 2006 explosion (not shown) were also similar to those for 2009 and 2013.

Using an array cross-correlation approach[4] it is possible to very precisely measure the relative arrival times of these signals. Making the assumption that systematic uncertainties are in common for all three DPRK events, the relative locations can be estimated with a precision of hundreds of metres.

Figure 4b shows that the 2009 and 2013 explosions were spatially separated by approximately 500 m, whereas the 2006 explosion occurred around 2 km to the east.

The uncertainties in these measurements depend on the assumptions made during the location process. Figure 4b shows two sets of uncertainty ellipses, based on two different assumptions, for the locations of the 2006 and 2013 events relative to the 2009 location. Even with the most conservative assumptions, the 2009 and 2013 locations can be separated.

It should be noted that the ellipses shown in Figure 4b are only for the relative locations; the uncertainty in the absolute location of the whole group of three explosions remains around 10 km.

Characterisation

Once an event has been detected and located the next stage is to characterize it i.e to determine whether it is of natural origin e.g. an earthquake or potentially an explosion.

While seismology can potentially identify a seismic event as an explosion rather than an earthquake, it cannot differentiate between a chemical and nuclear explosion.

Under the CTBT, the treaty organization cannot make a positive identification of an event as a nuclear test, as this is a matter for the States Parties. The approach used at the IDC is Event Screening, which is to screen out events for which the null hypothesis that they are single explosion sources can be rejected e.g. by positively identifying an event as an earthquake. As the treaty has not entered into force, all criteria for event screening at the IDC should be considered experimental and provisional.

Event screening and characterization in general is a complicated subject with a long history. Efforts are ongoing at AWE with a current focus on combining different types of data[5].

The ratio of body wave magnitude to surface wave magnitude (m_b:M_s) is one of the experimental provisional screening methods used in routine processing at the IDC.

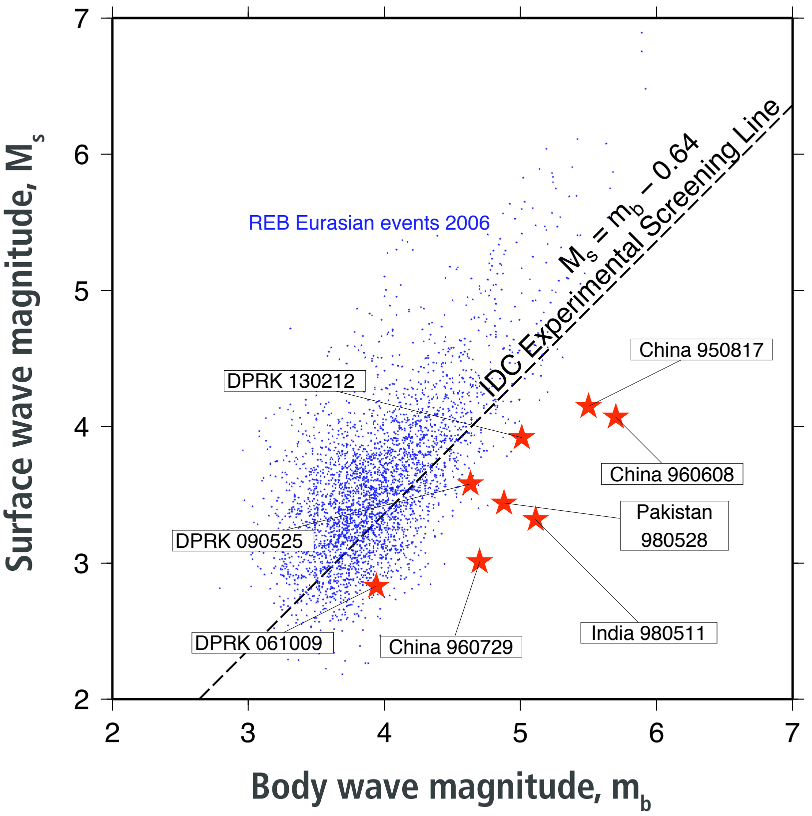
Seismic magnitudes are essentially measures of the amplitude of different seismic wave types, with corrections made for the effect on the amplitude of propagation through the earth. m_b is the magnitude measured from teleseismic P waves such as those shown in Figure 1c, whereas M_s is the magnitude measured from surface waves. Surface waves travel guided by the surface of the earth and are typically longer period than P waves. Surface waves from underground explosions typically have peak amplitudes in the 10 to 40 second period range, rather than 0.5 to 1 second for P waves. A long standing observation is that the seismic energy released from explosions tends to have a higher frequency content than for earthquakes of a similar size i.e. the ratio m_b/M_s is larger for explosions than earthquakes.

Figure 5 shows m_b plotted against M_s for recent announced underground nuclear tests and a typical selection of earthquakes.

For the 2006 and 2009 DPRK events the m_b:M_s signatures were unusual[6,7]. While the mb:M_s ratios were unusual for earthquakes, the 2006 and 2009 explosions plotted very close to the then experimental m_b:M_s screening line used at the IDC. As a result a reassessment of the screening line[8] was accepted to replace it. While this line now reduces the danger of mistakenly screening out an explosion, this is at the cost of failing to screen a larger number of earthquakes.

Figure 5

Body wave magnitude mb plotted against surface wave magnitude Ms using the revised IDC experimental provisional screening line. The red stars are recent announced underground nuclear tests and the blue dots a set of earthquakes from the IDC REB.



Magnitude

Estimation of the size of an underground nuclear explosion is a difficult problem, as it is a function of the exact emplacement conditions, local geology and wider earth structure between the source location and the receivers.

As with the location problem, for closely spaced sources that are likely to have similar emplacement conditions, the relative sizes of the yield can be more precisely estimated.

A widely used model of the explosion source[9] gives a relationship, for explosions with constant depth of burial, between body wave magnitude and explosive yield as

$$m_b = 0.87 \log Y + c$$

where Y is the yield and c is some constant which varies with region and emplacement conditions. Since the body wave magnitudes for the 2006, 2009 and 2013 DPRK explosions were 3.94, 4.63, and 5.01 respectively, we find that the 2009 explosion was about six times bigger than 2006, and the 2013 explosion about 17 times bigger than that of 2006.

Ongoing Research

Research into the DPRK explosions is still ongoing. In particular, investigations continue to extract as much information as possible about the explosions from the available data, and to compare the seismograms from the explosions with those from the extensive historical archive of explosions maintained at AWE. Understanding the unusual mb:Ms signature of the three explosions would lead to greater confidence in the event screening criterion.

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London 2012

The London 2012 Olympic Games was a globally significant event, watched by billions and scrutinised in every detail like no other event before. Over 2.6 million spectators attended the Olympic Park Site in Strafford, East London. As such the Olympic Park was designated a Tier 1 security venue, which meant that the risk of a terrorist related event and the consequences of such an event would be both 'High' and 'Catastrophic'. As a result of this assessment securing the Olympic Park against all conceivable threats was of the highest priority to the Cabinet Office and the Home Office, who oversaw all security arrangements.

While there were no specific chemical biological radiological and nuclear (CBRN) threats to the UK at the time, it was deemed prudent to plan for any eventuality. Securing the safety of all participants, spectators and staff for such an event was always going to be a challenge.

The Olympic site had to be completely ring-fenced with restricted and controlled access points. At every point of entry to the site, every single person and vehicle entering was required to be fully checked, verified and screened. At peak ingress the spectator flow rate of entry to the site would be higher than the flow rate of passengers through Heathrow airport.

Entry was allowed to pre-sold ticket holders only, baggage checks via x-ray scanning and metal detection via walk through portals along with random searching was required. What was not publicly acknowledged, was that a comprehensive multi-layered radiation detection screening system, capable of detecting and identifying a range of threat materials was also deployed, the likes of which had never been deployed before, and which would set the gold standard for future events.

This system was the culmination of a cross-Government approach to integrate this system into wider response planning for the mitigation of radiological and nuclear attacks. At the start of 2011 a team of subject matter experts (SMEs) from AWE attended preliminary meetings with the London Organising Committee for the Olympic Games (LOCOG) and the Olympic Delivery Authority (ODA), in collaboration with the Home Office and with support from Home Office Centre for Applied Science and Technology (CAST) and NUVIA Ltd.

The purpose of these meetings was to develop the requirements, identify the technologies, Concept of Operations (ConOps) and deployment of a radiation screening capability for the Olympic Park. The Olympic Park was pre-screened for radioactive material during construction and prior to lock down - no threat material was identified during this screening.

The role of AWE was to provide technical guidance, alarm mitigation and threat assessment to insure that the provided capability was proficient at meeting the requirements that LOCOG/ODA and the Home Office set.

One of the principal challenges was to develop a system that was both capable of detecting and identifying radiological material yet would not slow down the flow rate of people entering the Olympic Park. It was deemed to be of vital importance to get people through security and on to the park as quickly as possible. By late 2011 a system had been developed that would deploy a variety of commercial off the shelf radiation detection equipment that would be fully integrated into one complete system.

The final arrangement was a multi-layered radiation screening system comprising large sodium iodide (NaI) crystals with integrated identification algorithms, along with large area plastic scintillation based technologies, to provide both low gamma count rate detection as well as identification capability, backed up with a range of handheld style radiation detectors for more discrete searching. The fully integrated network allowed full monitoring, detection, identification and reachback from one manned terminal within the Operations centre, thus allowing immediate alarm resolution and consultation with all military and blue light services in attendance at the Olympic Park.

The capability was deployed for testing at a series of test events held at the Olympic Park prior to the games. These test events helped identify any shortfalls in capability and ConOps and highlighted the challenge of high flow rates. Some of the key components for the system were also subjected to technical analysis of their identification capabilities at AWE, which was then followed by an intensive period of installation and final acceptance testing and validation, all of which was overseen by AWE.

AWE provided a team to undertake the role of Scientific Liaison Officer (SLO). Their primary role was to man the system at the Olympic park on a 24/7 basis for the duration of the games. They would monitor the systems performance, fault find and rectify any problems, analyse all the data generated by the system and distinguish between a non-threat radiological material, such as a person bearing a medically used isotope, and any potential threat materials identified. A reachback capability to gamma spectrometry specialists at AWE was also available to provide further assurance to the ODA. Finally in any incident they were required to liaise with local security services over any potential threat to the park.

The SLO role relied on a team of specialist logistics experts from AWE who provided round the clock transportation, accommodation and logistical support. In addition, a dedicated team of AWE duty desk officers provided additional reachback capability support and deployment organisation in the event of any untoward incident at the park.

On Friday 27 July 2012 the opening ceremony started, for what would prove to be a fantastic time for team GB, London, the UK and AWE. Manning the system for the duration of the games and, therefore, providing alarm mitigation to LOCOG/ODA now became a priority. Lessons learnt in the pre-games test and deployment phase led to improvements to the system.

The AWE SLO team were required to provide their judgement and scientific expertise to analyse all the incoming data in a proficient manner. Their contribution to the event cannot be over stated; during peak times they had to assimilate large amounts of data in very short time periods and liaise with on site security and military teams to make decisions as to what was a threat or not.

This proved to be a challenging and pressurised environment to work in. It has since been recognised by all involved in the planning, including Ministers at the Home Office, that the role that AWE and the SLOs played was invaluable to the success of the system deployed, and the Games as a whole.

By the 17th day of the games more than 2.6 million people had been screened by the system, generating a vast amount of data. Up to 1000 vehicles per day drove through the fixed vehicle portals. The system performed as expected, detecting many instances of people bearing a medical issue, or vehicles carrying naturally occurring radioactive material; there were no instances of illicit material entering the park. AWE personnel provided to the ODA/LOCOG a very successful monitoring, assurance and alarm resolution capability.

Outreach

In this section, we cover a number of high-profile events and conferences in which AWE scientists and engineers have been involved in recent years.

Inaugural UK-US PONI

Around 90 scholars and experts including AWE scientists gathered at the inaugural UK-US Project On Nuclear Issues (PONI) conference at Wokefield Park near Reading, November 2014.

Sponsored by AWE and led by defence think-tank the Royal United Services Institute, the two-day conference examined subjects of mutual interest to the UK and US.

Nuclear Forensics Aids National Security

More than 80 scientists from the National Nuclear Security Centre of Excellence, accompanied by experts from UK law enforcement and other key organisations, came together in November 2014 to better understand nuclear forensics using a video-enriched scenario.

The one-day event called Exercise Blue Beagle, and facilitated by legal training firm Bond Solon, involved an expert panel of counter-terrorism investigators from the Metropolitan Police and other forces, forensics detectives, the Crown Prosecution Service, and the London Fire and Rescue Service.

Panellists discussed the various stages of a radioactive crime scene investigation. Exercise Blue Beagle formed part of the Global Initiative to Combat Nuclear Terrorism (GICNT) Nuclear Forensics Symposium in London.

Blast and Shock

More than 150 international experts in the science of blast effects and shock waves gathered in the UK for the first time in 14 years at the 23rd International Symposium on Military Aspects of Blast and Shock (MABS) – held on 7-12 September 2014 at Pembroke College, University of Oxford.

Last hosted in the UK in 2000, MABS has evolved over nearly six decades from nuclear blast simulators and experimental methods to include the burgeoning field of computational simulation, then expanding its membership to NATO and beyond.

The blast threat has also evolved for this now-global community so MABS has expanded to consider all explosive threats. It brings together the world's foremost scientists and engineers working in the field. In the opening address, DE&S Head of Weapons Engineering, Air Commodore Mike Quigley, spoke about the vital role of the MABS community in understanding and responding to the threats faced across the world.

Nineteen nations were represented at MABS 23 and responsibility for hosting the next symposium has transferred to Canada for 2016.

Royal Visit to Orion

The Duke of York visited the world-leading Orion laser facility at AWE in November 2014. The Duke toured Orion as UK Patron of the International Year of Light 2015 – a United Nations initiative to raise awareness of light science and its applications.

Orion is a high-powered laser in a room the size of a football pitch and one of the largest capital science investments in the UK. The laser can create conditions similar to those at the heart of the sun and provides opportunities for building and sharing knowledge. Laser physics is essential to maintaining the UK's nuclear warhead stockpile in the nuclear test ban era.

While Orion was designed to support the UK's Trident programme, it will also drive developments in fundamental science and support laser fusion energy research which could play a key role in developing clean and affordable energy.

The MOD has agreed that up to 15% of Orion's system time can be used by the UK academic research community for experiments which also contribute to AWE's core programme. This helps encourage and excite a new generation of physicists.

Global Initiative to Combat Nuclear Terrorism

Nearly 80 experts in nuclear forensics from around the world, including a number of AWE National Nuclear Security scientists, gathered at the Nuclear Forensics Workshop – held on 7-9 January 2014 at Lancaster House, London.

The three-day event was co-sponsored by AWE, MOD, the Home Office and the Foreign Office under the aegis of the Global Initiative to Combat Nuclear Terrorism (GICNT). The event shared vital knowledge in nuclear forensics between the GICNT Member States to support global security efforts.

The mission of the GICNT is to strengthen global capacity to prevent, detect, and respond to nuclear terrorism by conducting multilateral activities that strengthen the plans, policies, procedures, and interoperability of partner nations. The GICNT is co-chaired by the US and the Russian Federation.

The Royal Society

The jointly hosted AWE-Imperial College London stand called 'Set the controls for the heart of the Sun' had thousands of visitors at The Royal Society week-long Summer Science Exhibition on 1-6 July 2014.

The interactive display, supported through our engagement with Imperial College London under the aegis of the Centre for Inertial Fusion Studies, showcased how the world-leading Orion laser can recreate the conditions close to the centre of the Sun.

The Summer Exhibition, held annually since 1769 without exception, is undoubtedly The Royal Society's premier opportunity to present to visitors pioneering science and engineering from across the UK that can truly change lives and the way we think about science and our understanding of the world.

Support for the Comprehensive Test Ban Treaty

Image courtesy of the CTBTO

On-site inspection is one of the key elements of a global system to detect clandestine nuclear explosions worldwide and provides a third pillar to the comprehensive verification regime complementing the other two, namely the International Monitoring System and the International Data Centre in Vienna.

In 2008 a major Integrated Field Exercise, IFE08, demonstrated the integration of the on site inspection phases and was, at the time, one of the most ambitious projects conducted by the Comprehensive Test Ban Treaty Organisation (CTBTO).

The location chosen for the inspection area was the former Soviet Union test site at Semipalatinsk (now in Kazakhstan) previously the location of some 450 nuclear tests (both underground and above ground) which were conducted between 1949 and 1989. The remoteness of the site raised logistic challenges in deploying over 50 tonnes of equipment.

The UK provided a Mobile Field Laboratory (MFL) which allowed sensitive gamma spectrometry laboratory equipment to be operated in field conditions.

The MFL enables anomalies and artefacts to be identified which support the gathering of facts to help determine if a nuclear test explosion has actually been conducted in the inspection area. Some of these features can arise naturally so on their own are not nuclear explosion indicators. Some can be utilised in the initial period of the inspection and some more intrusive techniques in the continuation period.

The inspection team in the field included three trainee inspectors from AWE who supported the radionuclide laboratory where the analyses of samples were undertaken as well as contributing to other roles in the team.

A second Integrated Field Exercise, IFE14, was held in the Royal Hashemite Kingdom of Jordan in 2014. The scenario was that the fictitious country of Maridia had conducted a clandestine nuclear test. The resulting seismic body wave, magnitude 4, was detected by the CTBTO International Monitoring System and suspicious radio-xenon noble gases by the radionuclide stations.

The on site inspection team successfully narrowed down the initial inspection area of 1000 km^2 to the site of the fictitious test.

AWE personnel, along with experts from the P5 nations and other countries, helped define and implement the scenario. AWE also provided contribution in kind equipment, including the MFL, two surrogate inspectors in the initial inspection and was part of the control and inspected state teams.

Contributors

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Active Detection of Special Nuclear Materials

Cassie Hill on behalf of the Active Detection Team

Novel Detection Concepts

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The Benefits and Challenges of Digital Data Acquisition

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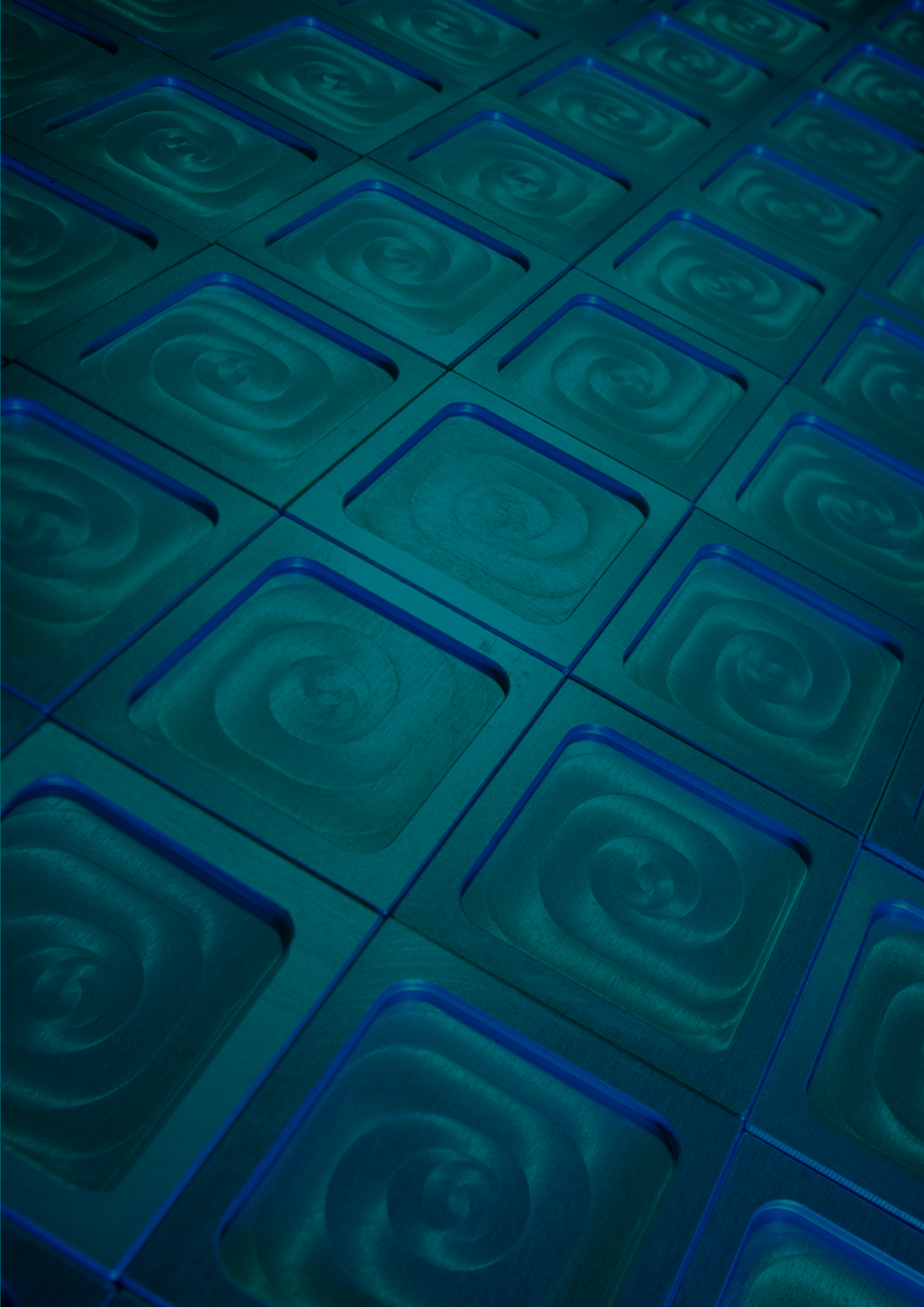

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