Trial of electro-optic technologies for the electro-magnetic remote sensing defence technology centre

A trial to evaluate the novel electro-optic imaging technologies produced by MOD's industry-led Electro-Magnetic Remote Sensing Defence Technology Centre (EMRS DTC) was held at Dstl's outdoor facility at Porton Down 15–18 March 2008. Imaging sensor technologies which were used to detect and identify targets at ranges of 1.4 km and 4.2 km. The technologies tested included polarimetric, hyperspectral, and multi-band imaging in different wavebands, active laser imaging (including covert photon-counting techniques), lucky imaging, and panchromatic VNIR and thermal imaging. The target set included mannequins, vehicles, decoys, and buildings with various levels of concealment. Weather conditions during the trial varied from clear skies to heavy rain, and the different conditions vividly illustrated the strengths and limitations of the different sensors. The paper reviews the sensor technologies and presents highlights from the trial.

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Introduction

The Electro-Magnetic Remote Sensing Defence Technology Centre [1] (EMRS DTC) is a programme of innovative research managed on behalf of the UK Ministry of Defence by an industrial consortium led by SELEX Galileo. It provides devices, components and techniques for sensing in both electro-optic (EO) and radar wavebands. This paper describes a major trial of EO technologies that was held 15–18th March 2008 to demonstrate and evaluate the products of DTC research. The sensors tested included a variety of discriminative imaging technologies (including spectral, polarimetric, and range-resolved active laser imagers), operating in different optical wavebands. The trial was hosted by Dstl at Porton Down, and was attended by 13 teams from 7 different organisations. The paper outlines the structure of the trial and presents its highlights and achievements. Additional details of individual sensors and their performance will be found in separate papers referred to in the text, or in companion papers in this issue.

The trial used a comprehensive target set including both military and civilian targets, and the opportunity was taken to include some emerging sensor technologies from non-DTC programmers. The performance of the new sensors was benchmarked against existing sensors including high-performance TV and thermal imagers. The imagery generated was used to assess algorithms for target detection and data fusion, some of which were themselves developed by the DTC. Commercially-available hyperspectral imagers were also included in the trial for this purpose.

Sensor technologies

The sensors broadly fell into two classes: wide-field devices to assist the detection of difficult or camouflaged targets within a wide search area, and narrow-field devices for target identification. A variety of "discriminative imaging" technologies, providing images based on information other than radiant intensity, were tested. Testing of new image processing algorithms that detect and locate targets within the multi-dimensional image also formed an important part of the trial.

The sensors and their providers are summarised in tables 1 (wide-area search) and 2 (target identification). Most of the individual technologies have been described in separate publications in reference [1], or in companion papers within this issue. Different technologies were at very different stages of development: for example, the LWIR polarimetric QWIP was incorporated in a MILSPEC imager body whereas the combined multispectral-polarimetric imaging was performed using a very preliminary prototype incorporating interchangeable band-pass filters and mechanically-rotated polarisers.

Table 1

Class	Technology	Waveband	Provider
Polarimetric imaging	On-chip polarimetric QWIP array	LWIR	Thales
	3-CCD polarimetric camera (COTS)	VNIR	Dstl
Spectral imaging	hyperspectral imagers (COTS)	VNIR, SWIR	BAE Systems
	IRIS multi-spectral imagers	VNIR	QinetiQ, Selex
Combined spectral + polarimetric imaging	InGaAs camera with filters & polarisers	SWIR	BAE + QinetiQ
High-performance thermal imaging	HgCdTe focal-plane array	LWIR, MWIR	Selex
	QWIP focal-plane array	LWIR	Thales
TV camera (baseline)	Si focal-plane array (COTS)	VNIR	Dstl

Wide-area search technologies. COTS = commercial off-the-shelf.

Table 2

Class	Technology	Waveband	Provider
Laser imaging	Dual-mode, BIL + passive TI	SWIR BIL; MWIR TI	Selex
	3-D laser imaging	SWIR	Selex
Turbulence suppression	Lucky imaging	VNIR	QinetiQ
Covert laser techniques using photon counting	range-resolved imaging	VNIR	Heriot-Watt university
	range finding	VNIR	QinetiQ

Target identification technologies.

Trial site and targets

The trial was conducted at Dstl's outdoor range at Porton Down. Most of the sensors were housed in the facility's main building which provided three spacious laboratories overlooking a wide valley; additional sensors operated from a Portakabin alongside the main building. The view from the sensor building is shown in Figure 1. Targets were placed around two tree-lines at ranges 1.4 km and 4.2 km. The location enabled several complementary sensors to operate simultaneously from a common viewpoint. Most of the sensors were divided into two batches operating for 5 days each; certain "benchmark" sensors operated throughout the trial.

The targets deployed at 1.4 km and 4.2 km included a variety of buildings, vehicles, decoy vehicles and artillery pieces, mannequins, resolution charts and other objects. Camouflage netting was used to cover some of the targets. A selection of the targets, photographed from close range in their tree-line environment, is shown in Figure 2. A variety of smaller metallic objects lying on and beneath a patch of disturbed earth was also viewed from much closer range (~10 m). Comprehensive local ground truth measurements were performed on all targets in their environments. Fiducial markers were provided to assist registration of imagery from different sensors; the markers were tungsten filament lamps whose copious broadband emissions were detectable by all sensors.

The trial experienced a wide variety of weather conditions ranging from clear skies to prolonged heavy rain, typical of March in the south of England. The visibility range varied between <1 km and >20 km. On the sunniest days, the structure constant of the atmospheric turbulence was estimated as $5 \times 10^{-15}\ m^{-2/3}$ by measurements of the distortion of a beacon at 4.3 km. Temperature, wind, and other meteorological parameters were monitored continuously.

1

The trial site (Dstl copyright).

2

A selection of targets (Dstl copyright).

Technologies for wide-area search

Polarimetric imaging

Polarimetric imaging highlights man-made objects, whose smooth, less textured surfaces exhibit reflections that are more strongly polarised than the natural background. The degree of polarisation is monitored using pre-sensor polarisers to determine the intensity difference between different polarised components of each pixel.

The Thales polarimetric QWIP (quantum well infrared photodetector) array[2] performs all the polarimetry on the sensor chip, without any additional bulk optics. All QWIP detectors incorporate diffraction gratings to couple in the radiation at the appropriate angle, and the polarimetric array exploits these gratings as discriminative elements. Each pixel incorporates four differently-polarised sub-pixels (horizontal, vertical, and two diagonal polarisations) which are sampled sequentially by micro-scanning around the four pixels at 25 Hz. The array outputs 640 x 512 pixels in "polarimetric mode", or 1280 x 1024 pixels in raw "intensity mode". At the trial, the device was incorporated into the company's existing Catherine MP imager body, and was tested alongside an unmodified Catherine imager. The device imager successfully highlighted polarised reflections from vehicles, roads, and other smooth surfaces (Figure 3), in spite of the limited discrimination of its tiny diffraction gratings. Moreover, the polarimetric mode was shown to be fairly immune to confusion by movements in the scene components, in spite of the sequential manner in which the different polarisations are sampled. Since the trial, the polarimetric camera has been exploited extensively in other trials and studies. The hardware has been improved by an update from 8-bit to 14-bit processing and by doubling the frame rate. Processing software is also developing rapidly.

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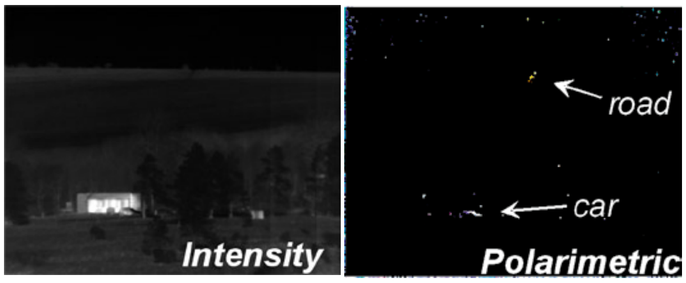

Polarimetric discrimination of man-made targets by polarimetric QWIP (Thales copyright).

Polarimetric discrimination was observed between real vehicles and decoys – the smoother surface of the decoy provides a stronger signature. However, the extent to which polarimetric imaging can highlight targets was found to depend quite strongly on the nature of the illumination. Targets in the open experienced illumination that was more directional, particularly in sunny conditions, and this dramatically enhanced the degree of polarisation. Targets under tree cover received relatively diffuse illumination and exhibited considerably weaker polarisation.

Hyperspectral imaging

Hyperspectral imagers exploit the inability of man-made targets to match predictable spectral reflectance features of the surrounding background. The spectral contrast cannot easily be removed completely because targets and camouflages contain different materials from the background terrain and vegetation. For example in the VNIR band, vegetation exhibits a "chlorophyll edge" around 700–800 nm, while water absorption bands around 1150 nm and 1400 nm provide valuable contrast. During the trial, commercially-available hyperspectral imagers operating in both wavebands were used by BAE Systems to provide imagery with which to test target extraction algorithms.

The best detection performance was achieved in the VNIR band, where the imagers had the advantage of high-performance Si arrays with close pixel spacing. Reliable detection of vehicle targets around the tree line was achieved at 4.2 km range (see Figure 4) using industry-standard anomaly detection algorithms in conjunction with a subsequent clutter-rejection algorithm which used a matched filter to reject "anomalies" whose spectra resembled vegetation. In this way, efficient target detection was achieved at false alarm rates as low as 10^{-4}/pixel, and the anomaly detection found targets that were completely indiscernible on a conventional image. This 4.2 km demonstration represents a significant advance beyond previous trials. Spectral unmixing algorithms, which seek to separate the mixed spectral composition of each pixel into a superposition of pure "end member" spectra representing particular classes of material (sky, trees, scrub, etc), were less successful. Industry-standard algorithms needed to adopt different end-member spectra in different regions of the image, and this complexity made it all too easy for the target to be concealed as a mixture of end-members rather than something different. The more advanced MUF2 spectral unmixing algorithm produced by the EMRS DTC achieved better target detection, although some false alarms were still recorded around edges where different end-members were mingled.

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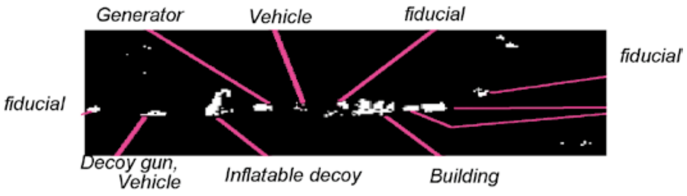

VNIR hyperspectral anomaly detection at 4.2 km (BAE Systems copyright).

SWIR hyperspectral imagery achieved efficient anomaly detection at 1.4 km. Maximum target-background contrast was observed at wavelengths around 100 nm, 1250 nm, and 1600 nm. Figure 5 illustrates how false-colour imagery based on these wavelengths makes targets stand out clearly from the vegetative background.

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False-colour presentation of SWIR imagery makes targets stand out clearly (BAE Systems copyright).

In the VNIR, searches for known material spectra were achieved at the shorter 1.4 km range. A matched filter algorithm, constructed from the spectrum of a vehicle in one image, was successfully used to track subsequent movements of that vehicle around the scene. The filter was also able to detect the spectrum of the vehicle under a camouflage net.

Multiband imagery

Both Selex and QinetiQ provided IRIS (image replicating Imaging spectrometer) multiband imagers which subdivided the focal plane of a large VNIR array (1920 x 1280 for the QinetiQ system) into 16 sub-band images (approximately 480 x 270 pixels) using a series of prisms and spectral filters. The spectral and spatial resolution was coarser than that of the hyperspectral systems (which sampled 100–200 spectral channels), but the signal/noise was correspondingly higher. Moreover, the IRIS systems used no mechanical scanning, and recorded truly simultaneous 2D images across all sub-bands with stable boresight alignment. Accurate registration of the sub-band images was required, and this was performed using industry-standard correlation techniques.

Anomaly detection using the 1.4 km IRIS imagery successfully highlighted a wide variety of targets including vehicles, mannequins and human subjects, although it missed some camouflaged targets. Matched filter processing detected the camouflaged targets, although it could only be performed once a region of interest had been located within the image.

Operation at 4.2 km range was very challenging because a very long focal length was required to provide adequate spatial resolution. Image collection became very slow; nevertheless, anomaly detection efficiently located vehicle targets in and around the tree-line.

Combined multispectral-polarimetric imaging

Since both spectral and polarimetric imaging have their separate limitations and trade-offs, the potential of an imager combining both discriminants in a simple form was investigated in a collaboration between BAE Systems and QinetiQ. Imagery was collected sequentially in different wavelengths and polarisations using a SWIR-band prototype incorporating an InGaAs camera fitted with manually-interchangeable spectral filters and polarisers. Six spectral sub-bands, each 100 nm wide, were recorded across the 1000–1600 nm spectral window. Most imagery was collected at short range (~100 m) in view of the limited performance of the prototype.

Spectral studies using a variety of targets revealed useful levels of spectral contrast at most wavelengths except around 1400 nm, where strong water absorption left little detectable signal. The polarimetric contrast exhibited very different spectral dependence, strong at short wavelengths around 1000 nm but much weaker around 1600 nm. The two signatures are quite complementary, and anomaly detection indeed improved considerably when both signatures were used together. This encouraging study invites the production and testing of an improved prototype.

A combined spectral-polarimetric version of the Thales LWIR polarimetric chip is already under development within the EMRS DTC.

High-performance thermal imaging

Both QWIP (Thales) and HgCdTe (Selex) imager technologies were tested during the trial. The systems and their characteristics are summarised in Table 3.

Table 3

System / mode	Waveband	Array size
HgCdTe imagers (SELEX)		
Hunter	LWIR	640x512
Hawk	MWIR	1024x768
QWIP imagers (Thales)		
standard mode	LWIR	1280x1024 (with microscan)
polarimetric mode	LWIR	640x512

The trial amply demonstrated the ability of thermal imagery to highlight vehicles, human figures and other targets in which power dissipation elevates the temperature. Even passive targets are detectable provided the environment is sufficiently non-equilibrium that the emissivity Figure 6 illustrates a collection of vehicles, decoys, and other targets at 4.2 km recorded by the Hunter imager. Many of the objects were completely invisible in a wide-field visible-band image. “Warm” targets are highlighted as least as clearly as in the best hyperspectral anomaly detection, and “passive” targets such as mannequins are at least detectable although not highlighted. Imagery at 1.4 km range was even more impressive: rabbits stood out clearly, and the Catherine imager with its large QWIP array could discern some of their features.

6

Targets at 4.2 km range, recorded by Hunter LWIR imager (Selex copyright).

Although the thermal imagers provided valuable imagery throughout most of the trial (including night operation, heavy showers, and even some mist and smoke), their performance was degraded very severely by prolonged heavy rain. After several hours, the rain effectively removed the temperature differences that render the thermal scene useable.

Technologies for target identification

SWIR Active Laser Imaging

The range resolution feature of active laser imagery provides valuable discrimination of targets from vegetation and other clutter. Systems operating in the SWIR waveband have reduced ocular hazard and form an important tool for target identification. Two Selex systems were tested at the trial:

- A "dual-mode" imager incorporating both wide-field passive thermal imagery and narrow-field active imagery. The active imager used a range-gated detector array to isolate the return from a chosen range window.
- A new "3D" laser imager based on a new detector array architecture that provided a complete range-intensity profile on each pixel. The trial provided the first outdoor test of this new technology and a comprehensive and valuable set of imagery was produced covering different targets, different orientations and concealments, and different operating parameters.

Figure 7 shows a range-gated images of a vehicle at 1.4 km recorded by the dual-mode system. The active image discriminates the vehicle clearly from the trees and undergrowth behind it, although it is not distinguished from the wire fence just in front. Figure 8 shows a "3D" laser image of another vehicle in a similar location, exhibiting much greater range resolution. The image is colour-coded by range, and the vehicle stands completely clear of the foreground and fence. Different views of the same data-set clearly show the 3D relief of the vehicle itself: the wheel arches, spare wheel, and even features inside the cab are shown clearly as being at different range from the side of the vehicle. The data-set generated by the trial has proved a valuable stimulus to the development of processing software to best exploit the powerful data contained in the 3D image cube.

Both systems operated successfully in a wide variety of atmospheric conditions, including considerable levels of rain and mist.

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Range-gated laser image (Selex copyright).

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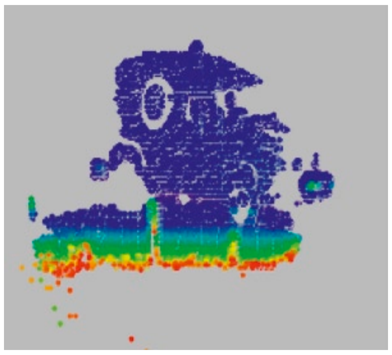

3D laser image (Selex copyright).

Lucky imaging

Lucky imaging provides a means of defeating the image blurring caused by atmospheric turbulence, which otherwise limits the effective range of ground-based imaging. The technique selects and exploits high-quality image fragments grabbed during the brief "lucky" periods when part of the imaging path is undistorted, and assembled to integrate a complete image. Most groups perform the sub-frame selection by post-detector analysis of the original image. QinetiQ's DTC-funded work uses a pre-detector wavefront curvature sensor that directly measures the distortion of each sub-frame and dramatically reduces the computation burden. Lucky sub-frames are selected using a "phase diversity metric" that has accommodates noise efficiently and is tolerant of a wide variety of different image contents. On the other hand, the existing wavefront sensor requires a monochromatic input because it incorporates diffraction gratings, and this reduces the optical efficiency in passive sensor systems. The QinetiQ prototype operates at a green wavelength selected by a band-pass filter.

At the trial, imagery was recorded using resolution charts and similar targets, with narrow field-of-view (~0.3 mrad). Dramatic improvements were achieved, particularly at range 4.2 km where the effects of turbulence were most severe. The "lucky" sub-frames were combined after applying the appropriate corrective lateral displacement which was estimated from analysis of edges and other recognisable features. Figure 9 illustrates the improvement in clarity of lettering with 100 mm characters at 4.2 km range, under the most turbulent conditions with $C_n^2 \sim 5 \times 10^{-15}$ $m^{-2/3}$. The angular height of the characters is about 25 μrad and they are clearly resolved in the lucky image; the resolution is obviously close to the 4.6 μrad Rayleigh diffraction limit of the input telescope.

Lucky imaging using the wavefront curvature sensor could form a logical extension of active laser imaging (see below). The monochromatic laser source is an obvious way to provide the required monochromatic input, and the incorporation of lucky imaging could enable a valuable extension of range.

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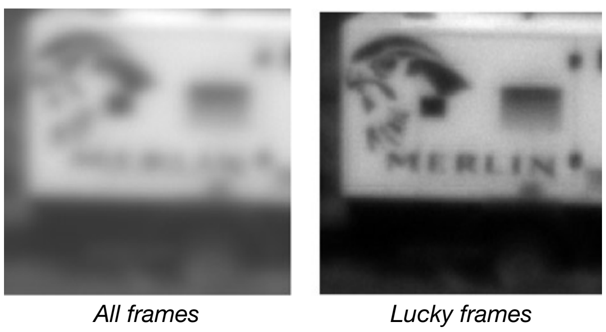

Defeat of turbulence-induced blurring using lucky imaging (QinetiQ copyright).

Conclusions and way ahead

The trial enabled the evaluation of several new EO sensing techniques, which provided a real advance in supporting the detection, discrimination and ID of military targets. Whilst high-performance thermal imaging provided impressive levels of performance, more advanced discriminative imaging techniques provided significant benefit especially for camouflaged targets and other objects that were in thermal equilibrium with their surroundings. Particularly successful new techniques included:

- **LWIR polarimetric cameras:** The on-chip polarimetric QWIP enables discriminative imaging capability to be incorporated into an existing imager unit, and opens up routes for rapid technology insertion. At the outset of the programme, several challenging technical risks had been identified surrounding the sequentially-scanned polarimetric sub-pixels of the device, and the trial convincingly demonstrated that these challenges had been overcome to provide a polarimetric mode that operates robustly under outdoor conditions. The prototype is now being exploited strenuously in other programmes, and processing techniques are developing rapidly.
- **SWIR multi-band and polarimetric systems:** The spectral and polarimetric signatures are complementary in nature and their combination significantly improves the detection statistics. The preliminary study, with data collection by a simple prototype based on mechanically interchanged polarisers and filters has made a convincing case for the production of a more advanced demonstrator. A LWIR combined polarimetric + spectral version of the polarimetric QWIP (described above) is also currently under development within the EMRS DTC.
- **Lucky Imaging:** The optical techniques for selection of "lucky" sub-frames pioneered within the EMRS DTC are faster and more efficient than existing techniques. The trial demonstrated suppression of turbulence-induced distortion to levels that enabled 100 mm characters to be read at 4.2 km range.
- **SWIR Active laser imaging:** The trial provided the first substantial test of the new "3D laser imaging" which provides complete range-intensity information at each pixel and represents an important step forward from established BIL imaging techniques. The trial provided an extensive set of valuable new imagery of vehicles and other targets at different orientations and under different conditions, and has provided a valuable stimulus to the development of processing/display techniques to exploit the powerful new capability.

Several of the technologies exhibit valuable complementarities which are particularly promising for future exploitation. For example, on-chip polarimetric imaging is a valuable extension to a high-performance thermal imager, lucky imaging could further extend the range of active laser imaging, and spectral and polarimetric signatures have been shown to complement each other.

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