Detector and Camera Technologies for 3D Active Infrared Imaging

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SUMMARY

Active systems, using a near-infrared pulse laser and a fast, gated detector, are now adopted for most long range imaging applications. This concept is often called burst-illumination LIDAR or BIL. The SELEX solid state detector is based on an array of HgCdTe avalanche photodiodes, and a custom-designed CMOS multiplexer to perform the fast gating and photon signal capture. These hybrid arrays produce sensitivities as low as 10 photons, due largely to very high, almost noise-free avalanche gain in the HgCdTe diodes. One of the strengths of laser gated imaging is the segmentation of objects from their background providing a signal-to-clutter advantage. However, in complex scenes, with camouflage and concealment, a major systems enhancement is the ability to generate 3D images. Here the detector senses the range, as well as the laser pulse intensity, on a pixel-by-pixel basis, providing depth context for each laser pulse. The 3D data enables objects to be extracted from background clutter far more effectively. The range information is less affected by excess contrast, coherence and scintillation effects so the images can be much cleaner than conventional 2D BIL images. In airborne applications, especially, it is useful to have 3D information to provide agile, feedback control of the range gating in a dynamic environment. This report describes some detector techniques that can be applied to produce 3D information and the arguments that led to the selection of the SELEX detector concept. The camera and prototype system is described along with preliminary trials results.

Keywords: LADAR, LIDAR, active imaging, HgCdTe, avalanche photodiode, APD, SW, 3D imaging

1 MOTIVATION FOR 3D IMAGING

The benefits of laser gated imaging have been established in the UK over the past 6 years in a large number of trials, encompassing ground-based, naval and airborne scenarios. The ability to perform detection, recognition, identification and intent over long ranges, day and night, is an essential modern requirement. Several factors give laser-gated imaging a performance advantage. Firstly the illumination by a collimated, pulse laser can give instantaneous brightness levels far in excess of passive infrared emission levels even at extreme long range. The brightness levels allow the use of long focal length telescopes made from glass (because of the 1.55µm wavelength). Also at 1.55µm there is better optical resolution compared with the longer wavelengths of passive IR systems. It is therefore fairly straightforward to achieve resolution improvements of over an order of magnitude compared with standard thermal imaging. The temporal gating function can help to reduce clutter in the scene by extinguishing signals outside of the gate. Another advantage stems from the short laser pulse (typically 20ns wide) which has the effect of freezing the scene, including any own-platform jitter, and any atmospheric effects. There will be distortion from frame to frame but work at SELEX, Edinburgh has shown that images can be de-rotated and re-registered in real time to provide stable video, for instance: Duncan et al (2006). Figure 1 shows some typical BIL images and the opportunities for segmenting objects in the scene.

There are also some well understood disadvantages with BIL that can limit the interpretation of images. They tend to suffer from scintillation and speckle effects which requires frame co-adding to make acceptable displayed images. Also the different reflectivities of common materials at 1.55µm compared to visible wavelengths, combined with the illumination source being placed along the sightline (which flattens the scene), can make scene interpretation difficult without training. In complex scenes it may not be practical to place a gate around a potential target and segment it from its background, especially in a dynamic environment, where there is relative movement between the camera and scene. The ability to identify outlines and edges is strongly compromised by these artefacts. It is worth noting that these issues relate to the intensity image only.

There are many motivations for adding a 3D capability to laser gated imaging. With 3D data, there is no longer a need for accurate gate placement, since segments of range can be isolated in software, and outlines generated readily by signal processing. Figure 1 illustrates how the outline of a man can be extracted from the deep gate by knowledge of the individual pixel ranges. Also, there may be opportunities for improving identification and automatic target recognition, by presenting an image in depth only, as this has the potential for defeating camouflage and concealment. For man-in-the-loop applications, 3D data can be manipulated to present images with perspective, false distance attenuation, and shadows. This can make distant, flat images appear close and more natural, providing the human cognitive system more chance of interpreting complex scenes. For the human observer the separation of objects and outlines is strongly enhanced by rotating the scene in software, creating a false parallax, and even presenting the scene as a plan view. Finally, for airborne applications in particular, the 3D data can be used for automatic tracking, essentially by holding the target in the centre of the gate. Many of the possible benefits of 3D imaging for long range identification have not been quantified yet, because of the absence of suitable detectors and trials data.

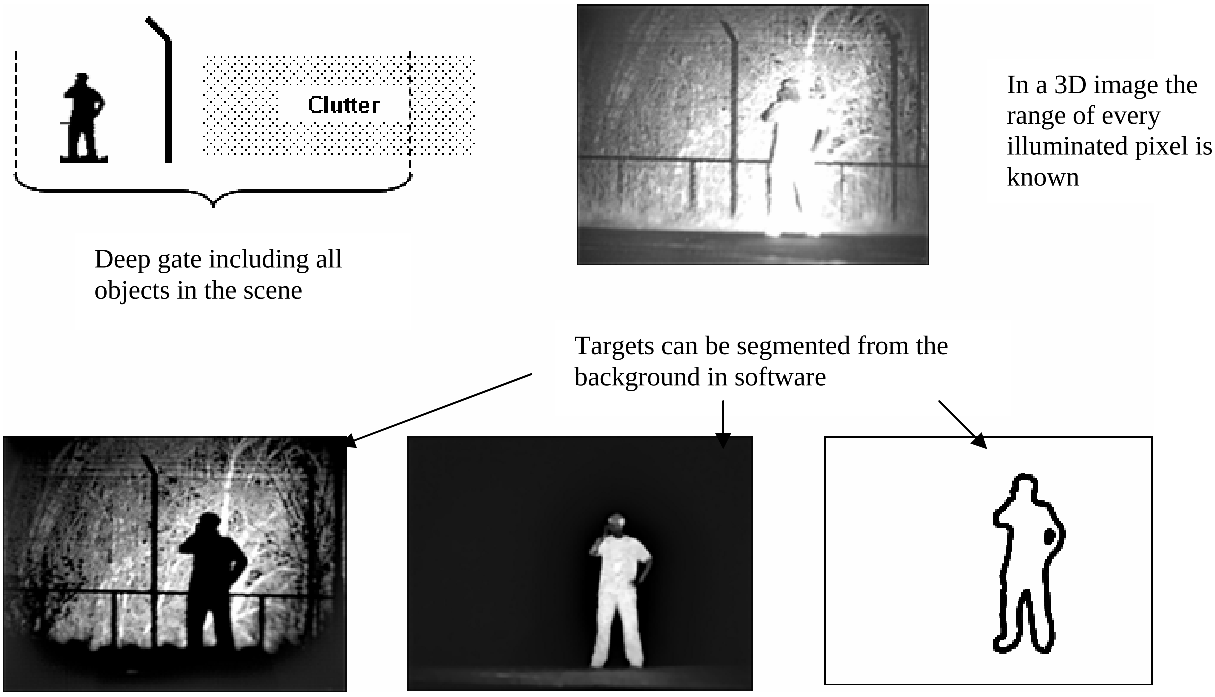

Figure 1 Example of some image manipulations enabled by 3D data

3D data can be gathered by sweeping the gate of a standard 2D BIL imager through the scene. The back of the gate in the SELEX detector is very sharp and the resolution is limited by the width of the laser pulse. By subtracting frames and colour encoding the differences it is possible to build up a false-colour image as is illustrated in Figure 2. The 2D picture shows a ruined cottage on a hillside. The four pseudo 3D images are slightly rotated in software and quite clearly the outline and edge definition is much improved over the intensity-only image. The processed 3D image has a limited range resolution because of the laser pulse width and the range gate sweep distance but illustrates the concept very well.

In the research at SELEX the goal has been to add-on the 3D capability to the existing 2D cameras with the minimum of compromise to the performance so that the sensitivity, frames rates and gating response is all preserved. Additionally, one of the topics we intend to study is the combination of 3D imaging with gate sweeping to provide better discrimination from multiple returns in the same pixel.

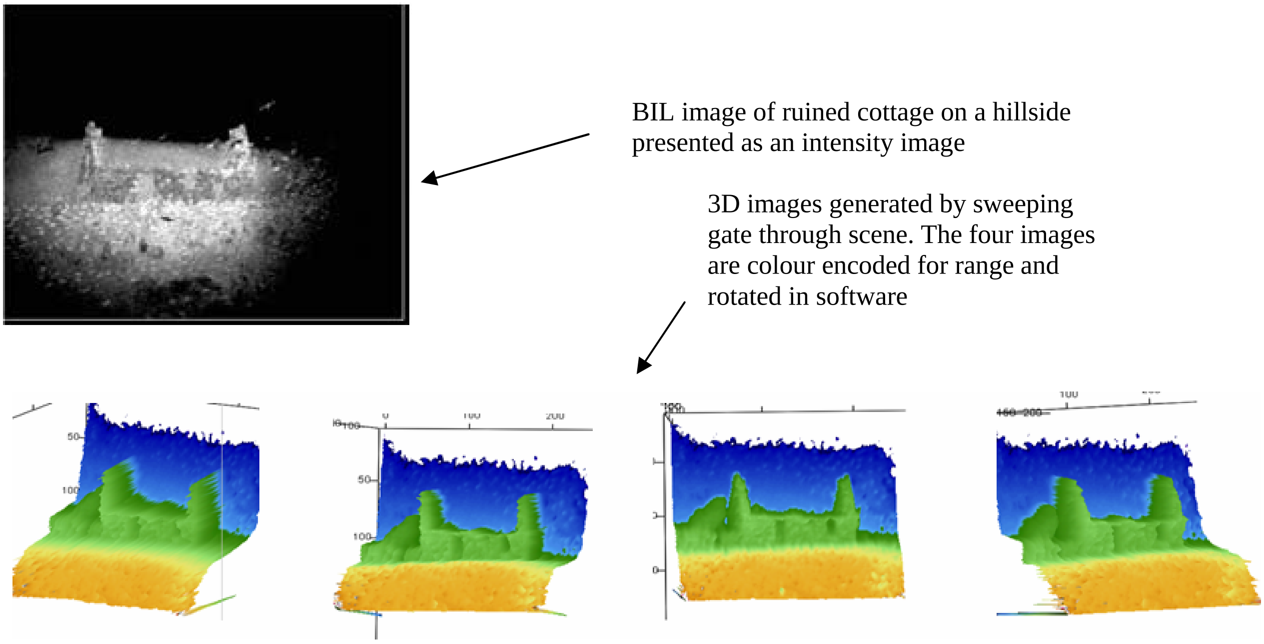

Figure 2 2D Image from range-gate sweep sequence, and processed 3D images

2 REVIEW OF THE SELEX FPA TECHNOLOGY FOR BIL APPLICATIONS

In previous papers on laser-gated imaging technology at SELEX S&AS, Baker et al (2004 and 2006) described in detail the approach used for the sensor. For laser-gated imaging, the detector needs to be about 100x more sensitive than a conventional thermal imaging detector, and to have a response time around 10,000x faster. In our solution, the sensitivity is met by using avalanche gain (up to 150x) in the HgCdTe photodiode, and a fast interface circuit in the CMOS multiplexer. The speed of response is achieved by having pixel-level gating circuits to switch the detector on and off. In operation, the gating circuits are controlled directly by the host computer for the laser system, to obtain accurate image-based range gating. Solid state sensors have near-ideal modulation transfer function (MTF) as a result of the strong optical absorption and limited cross-diffusion of minority carriers, and images from trials have shown characteristic sharpness.

There are two main HgCdTe technologies available for BIL detectors, including the 2nd generation loophole process, Baker et al (1994 and 2003), or 3rd generation processes based on MOVPE, bump bonded hybrids. Up to the present, all of our laser-gated imaging arrays have used the loophole or via-hole process, but MOVPE arrays are in advanced development. The diode arrays are typically biased at up to 8V to stimulate avalanche multiplication of the laser signal. In HgCdTe at a wavelength of around 4.0µm this process is very effective, largely stemming from the solid state characteristics of the HgCdTe system, which provides a very high electron to hole mobility ratio and nearly ideal cascade-like avalanching. Beck et al, (2001) provides a more detailed description of this process. The via-hole technology uses HgCdTe grown by the liquid phase epitaxy process, which is believed to give the lowest material dislocation densities. Our work indicates that this is crucial to maintain low noise and defect levels in detectors biased to many volts. Laser-gated imaging usually employs very short integration times, typically less than a microsecond, and there is not enough time to accumulate leakage current and excess noise. Because of this, the array defect levels and excess noise under high avalanche gain can be remarkably low, and similar to that of standard thermal imaging arrays without avalanche gain. Avalanche gains of up to x150 are used but for most practical situations a gain of around x20-x40 is more than adequate. The main drawback of using 4.0µm cut-off HgCdTe is that the best performance is at cryogenic temperatures and a Stirling engine is needed. However, we have not found any logistical problems with the use of engines, particularly in airborne applications, as modern engines and encapsulations are small and consume little power. Figure 3 illustrates the basic technology.

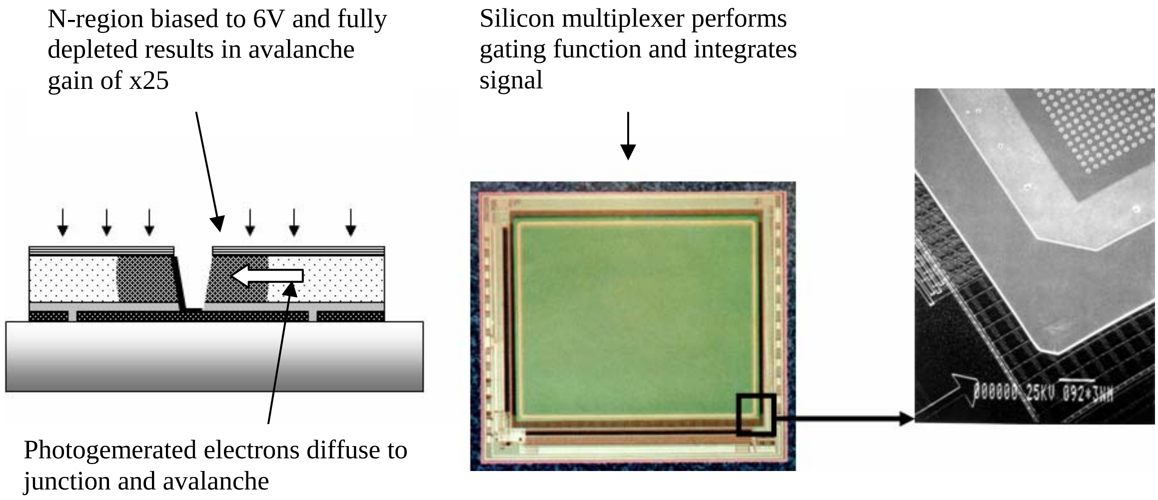

Figure 3 HgCdTe technology used for avalanche photodiode arrays

The SW detectors have a standardised array size of 320x256 and a pixel size of 24µm (to meet the Fraunhoffer diffraction conditions in the slow optical systems commonly used in BIL applications). The FPA is typically integrated into a cryocooler assembly using a small Stirling engine and is fitted with a notch filter for transmission at 1.55µm. The BIL cameras are based on SELEX SiGMA electronics modules. The avalanche gain is made variable in the camera, to control the sensitivity and the photon saturation level.

3 APPROACHES FOR 3D DETECTORS

A fundamental aim was to retain the 2D BIL detector and camera legacy technology, as much as possible, while upgrading to the 3D functionality. This included retaining the array size of 320x256 and pixel size of 24um. Also we wanted to retain the 2D intensity signal at the same sensitivity, i.e. at 10 photons rms, so that the default setting of the 3D detector emulated previous 2D detectors. The retention of existing cryogenics and vacuum packaging meant placing a power consumption limit of 50mW on the FPA and a maximum clocking rate of 10MHz. The laser pulse width is a key consideration because high energy pulse lasers of the types used at 1.55µm (e.g. OPO converted Nd_YAG) have an optimum efficiency at pulse widths of circa 20ns and a further reduction in efficiency to achieve a very narrow pulse is highly undesirable. There is therefore a strong drive to develop a FPA that is not sensitive to the laser pulse width. Because the intensity signal is strongly affected by coherence effects, and there is no correlation between laser pulses, it was a requirement to gather both the range and intensity signal for each laser pulse. For the camera there is a need to produce a similar electrical interface to the 2D detector both in terms of signal dynamics and clocking speeds. A final condition was to incorporate a variable “range depth” function so that the range information could be acquired over a depth in space determined by the camera operator. In this way relatively coarse data could be gathered over a deep scene or higher resolution data gathered over a shallower scene.

By definition, a 3D imaging detector produces two signals in response to a laser pulse return. The first is a conventional photon intensity signal, and the second is a range signal. To clarify this, a typical application may set up a 10m deep range gate around a vehicle, say. The detector will provide the depth of each pixel on the vehicle relative to the back of the range gate, so the shape can be determined absolutely. For 3D detectors, some new parameters need to be defined, reflecting the measurement of range. The sensitivity parameter for range we call “range accuracy”, to prevent confusion with the intensity figure of merit noise-equivalent-photons. Likewise, we need a new definition for spatial noise in the range data. Spatial noise in intensity is understood as the incomplete cancellation of non-uniformity by the processing electronics. A similar effect occurs in range, and we call this “range scatter”.

The 3D detector design represents one of the most difficult challenges in infrared detector design. There have been two classes of detectors considered for 3D imaging, namely: trigger based circuits and multiple binning circuits.

Trigger-based circuits sense the arrival time of the laser signal and produce a signal that corresponds to the delay in that arrival time. There are a number of ways to sense the timing of the event. The photodiode can be operated in the so-called Geiger mode, a state of unstable equilibrium. This technique relies on the collapse of the bias across the sensing diode when a photon burst occurs. Electronic equivalent circuits include, for example, Schmidt trigger circuits which change state at some critical signal level. However, our studies show that electronic trigger circuits need prohibitive power to respond adequately to the small signals typically found in BIL applications. In conjunction with Geiger mode there may be a solution but the approach requires an innovative step to overcome the main limitation of a variable delay dependent on the laser pulse shape and amplitude. Trigger based circuits do not produce an intensity image for the same laser pulse and this was a final reason for not following this approach.

Multiple binning solutions offer the most complete set of 3D data and this is particularly valuable to identify objects under translucent cover. This is the “data cube” concept which has the benefit of retaining all the intensity data over a set of range bins. Most realisations use a bank of sample and hold circuits and each one is switched at a particular time delay within the gate, freezing the signal at that point. Typically between 10 and 20 bins are needed in each pixel. The main draw is the pixel size. Also there is a data bottle-neck problem for the FPA. For our camera we wanted the pixel size to match the diffraction limit of the optics so that there was a minimal chance of receiving several return signals from different ranges. Such a situation would be nearly impossible to resolve by post-processing. Also the electronic clocking and data output rate would call for a complete redesign of the front-end camera electronics and possibly the cryogenic encapsulation so that the concept of upgrading current cameras to 3D would be unachievable.

SELEX have proposed a different approach driven by the main objectives of preserving the standard 24um pixel size and retaining the existing legacy HgCdTe technology, cryogenics and electronic modules. These conditions forced a solution where the main step forward was analogue signal processing within the pixel to produce a range signal output and an intensity signal output in consecutive frame readouts. We call this technique the “3D autocorrelation method” for reasons to appear later. The main development challenge was the pixel design and the post-processing of the data to extract and correct the range and intensity signals.

4 TOPOMORPHIC DESIGN FOR THE 3D DETECTOR

The incorporation of analogue circuitry in the pixel to produce both a range and intensity signal is only possible if some radical compaction strategies are used. As we have adopted 24μm as the standard pixel size for the short wavelength family of detectors it would seem that, for more complex pixel circuits, the designer would simply choose a denser CMOS process, in order to obtain a larger number of active devices and interconnects in the pixel. In digital circuits this is true but, when designing analogue circuits, voltage range, noise and uniformity are performance-driving factors. BIL detectors require a high voltage tolerance, and this is not generally compatible with dense CMOS processes. Also, MOSFET noise and threshold voltage uniformity both scale with an approximate inverse square-root law, so some components cannot be shrunk without compromising the noise floor and uniformity of the pixel circuit, and ultimately the camera performance.

The constraints imposed by a small pixel size, and components that cannot be shrunk, would seem to limit the development potential of solid state arrays. Nevertheless, there are strong pressures to develop more complex circuits in the focal plane for multifunctional arrays. The approach we have adopted has similarities to an uncommitted gate array in the digital world. In our case, the pixel components are assembled together in the best compaction geometry, but with uncommitted connections. Tiny switches are then used to connect the components into the required circuit function. At the same time, the metal tracks serving the pixel (there may be up to 10 of them) are also switched, so the function of each track can change radically. This combination of variable stimuli and circuit topology allows the functionality to be determined by a software instruction. We call this practice topomorphic design (from topology morphosis), and it is devised to break the natural design limits of dense pixels. The switches have no significant specification for noise or uniformity, and can be the minimum geometry for the CMOS process, so they usually take up little space. Topomorphic design can be exploited very effectively to create a 3D functionality.

5 AUTOCORRELATION PRINCIPLE FOR 3D IMAGING

A conventional solid state imaging device has an integration time for converting the photons to electrons and a readout time to scan the pixels and convert the voltage signals to digital. In the 3D detector there are two readouts per integration time. They both produce an intensity-dependant signal, the difference being that the pixels in the first frame are multiplied by a factor dependant on the range. This fairly simple concept provides for autocorrelation of some of the noise sources. In particular, coherence or scintillation effects in the image are common between the two frames and eliminated in signal processing so that accurate and stable range data can be acquired in the presence of a high degree of image noise. The same correlation also applies to the largest of the electronic noise sources: notably KTC noise (the thermal noise arising from switching a capacitor), so that the range accuracy can be independent of the key multiplexer noise source. The multiplication factor depends on the timing of the laser return pulse with reference to the end of the gate, so for instance, the range information can be gathered over the last 100ns of the gate period giving 3D information over 15m of space. The range depth, in this case 100ns, can be controlled by an applied voltage. Experimental pixel circuits have been assessed at low temperature to establish the noise and sensitivity parameters. Simulation and modelling has then been used to predict the range accuracy and intensity sensitivity (noise equivalent photons). The range accuracy depends on the signal strength in volts, which is in turn controlled by the avalanche gain, so avalanche gain is a useful variable for controlling for range accuracy, as well as the photon sensitivity.

There are a number of ways of realising the analogue multiplication function. We have selected a technique that is fairly insensitive to the shape of the laser signal return. At first it may seem counter-intuitive that laser pulse delays of less than a nanosecond can be obtained from a laser pulse of 20ns width but the circuit responds to the centre of gravity of the laser pulse. Figure 4 shows a typical prediction for the range accuracy and illustrates a very small loss of range accuracy away from the edges of the gate. In fact there could still be advantages in chopping the tail of the laser pulse to provide more accurate data near the gate-end but this is not essential.

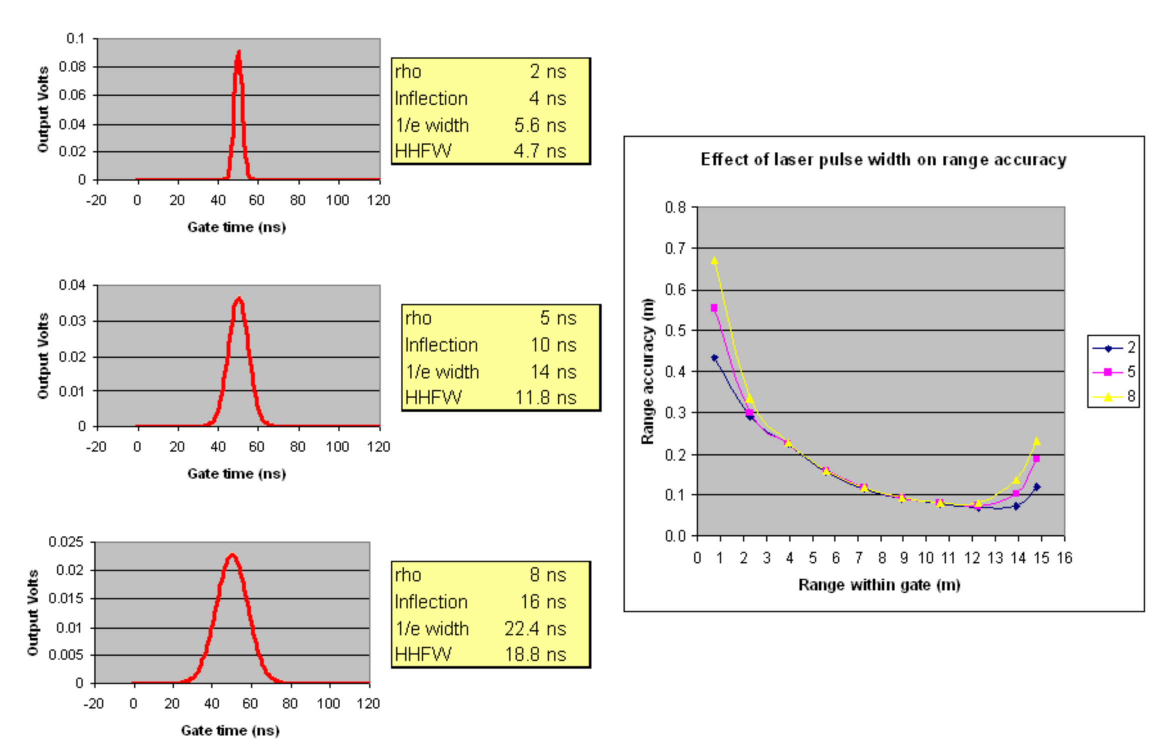

Figure 4 **Analysis showing small dependence of range accuracy on laser pulse width**

The 3D array produces 2 frames of data from which the photon signal and range signal need to be extracted. At the simplest level a comparison of frame 1 against frame 2 gives a parameter called “range ratio” and this is dependent on the actual range for that pixel. Because of non-idealities in the circuit realisation there are some extra corrections to be made to extract a true range value. Firstly the range value depends on the strength of the return signal so that brighter objects appear closer. Secondly the range is not linearly proportional to the range ratio so some gamma correction is needed. Thirdly the pixel to pixel values of range ratio can be dispersed due to simple variances in the silicon components. Since all of these features depend on silicon properties the aberrations should be stable in time and software correction should be effective. However the post-processing of the image data is essential to make full use of the range and intensity data to produce accurate 3D representations and is a key area in the camera development.

6 FPA AND CAMERA REALISATION

A prototype multiplexer, called Swallow, has demonstrated the correct range and intensity functionality, and has been invaluable in providing early experience of 3D imaging. The multiplexer has the same electrical and mechanical interface as previous SW detector products, so it is backward compatible. It has a 320x256 array size on 24µm pitch. In 2D mode, it has the same imaging sensitivity as a dedicated 2D SW detector, such as Swift. The Swallow device, hybridised with HgCdTe avalanche photodiodes, has been assessed in laboratory-based laser trials in Southampton and Edinburgh. The Edinburgh work was aimed at establishing the characteristics of the range data, in particular, the uniformity and influence of laser pulse intensity. This data is crucial for developing signal processing algorithms, to extract accurate range data from the raw array output.

The test kit for 3D detectors measures the range performance as well as the radiometric performance so understandably creates a large volume of data. An integrating sphere is used to illuminate the arrays. The pulse laser driving the integrating sphere is delayed in 10ns intervals with respect to the gate-end pulse, to simulate various target depths within the gate and a complete set of array data is acquired at each laser delay. The aim is to present a uniform signal delay to the whole array, in order to establish the distribution of range ratio values for the whole array and the range contrast. Typical results are presented in figure 5. Each distribution shows the variability of range ratio for a different laser pulse delay for the whole array and it shows that the range contrast is very large and significant compared with the variability.

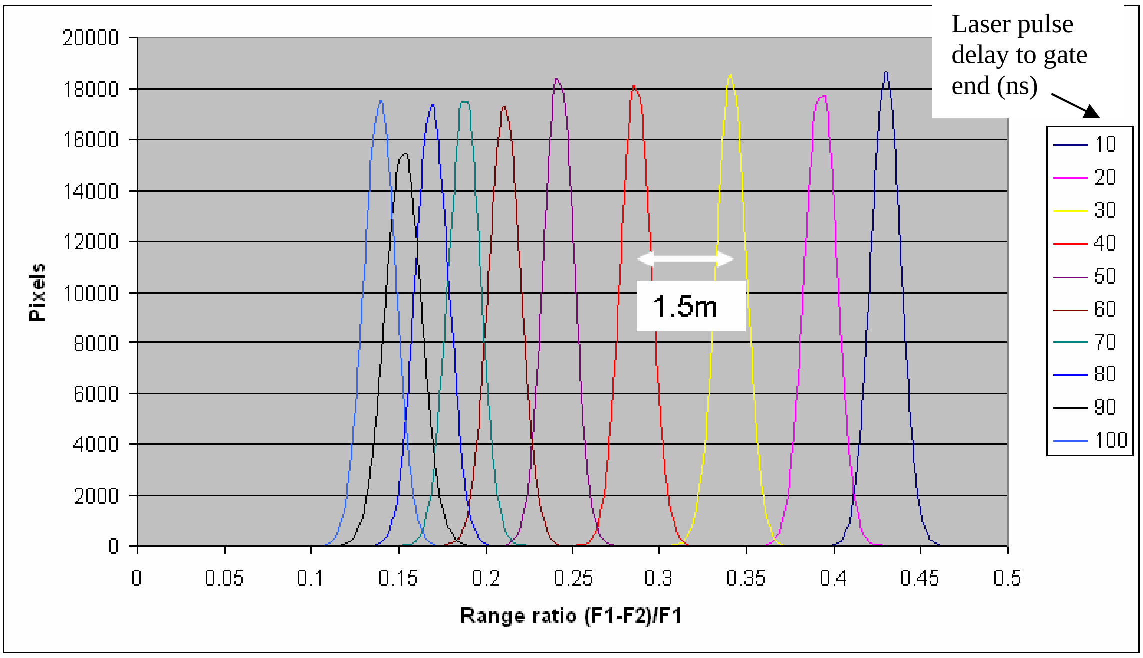

Figure 5 Histograms for range ratio data as a function of delay of signal from gate end

The camera has modified firmware to generate the extra frame of data but is otherwise similar to that used in standard 2D laser gated imaging systems. The need for two frames introduces the possibility of camera noise affecting the range ratio value as clearly the readout noise and analogue to digital conversion (ADC) noise is uncorrelated between the two frames. The ADC noise in particular is important and the voltage window is kept as small as practical to minimise it.

7 PRELIMINARY 3D IMAGING RESULTS

Imagery of real scenes has been collected using a SELEX BIL imaging equipment. The imaging rig incorporates a SELEX laser, delay generators (to control the gating function of the camera with respect to the laser firing time) and control PC for the collection of imagery, and for control of the system functionality. The 3D-enabled camera has been integrated with the BIL imaging rig, with appropriate optics to enable a sufficiently high resolution image of the scene. The laser output energy and divergence are controllable parameters, and were adjusted in order to maintain a sufficient energy density on the target.

3D imagery of a vehicle and building has been collected. When the frame 1 and frame 2 data is analysed the intensity and range can be separated. The intensity image is similar to a standard 2D BIL image and is presented to the left in figure 7. The range information is presented as a point cloud to the right, with the range coded in false colour, with blue being nearest to the observer and red furthest away.

Figure 6 – Intensity Image of Vehicle and Building

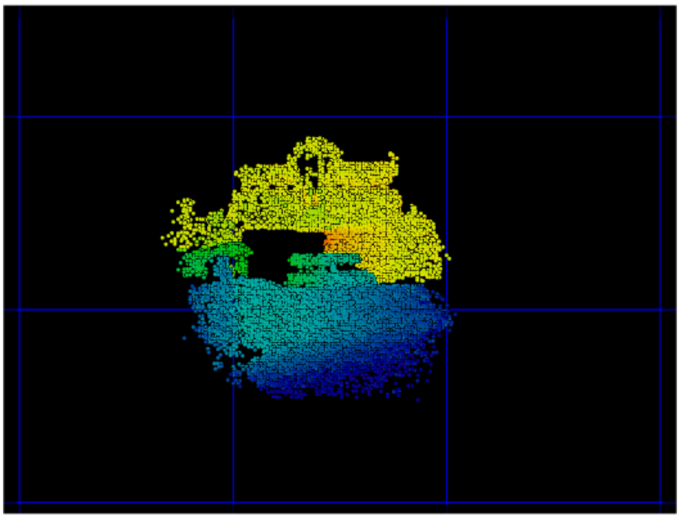

Figure 7 – Range Image of Vehicle and Building

The range image can be seen to yield information which is not apparent from the intensity image alone. The relative placement of the building, vehicle and front wall are clearly discernible from Figure 7 by the colour changes between the various elements. A major benefit of the 3D information is that the image can be manipulated in software, and Figure 8 shows the effect of rotation of the point cloud range image.

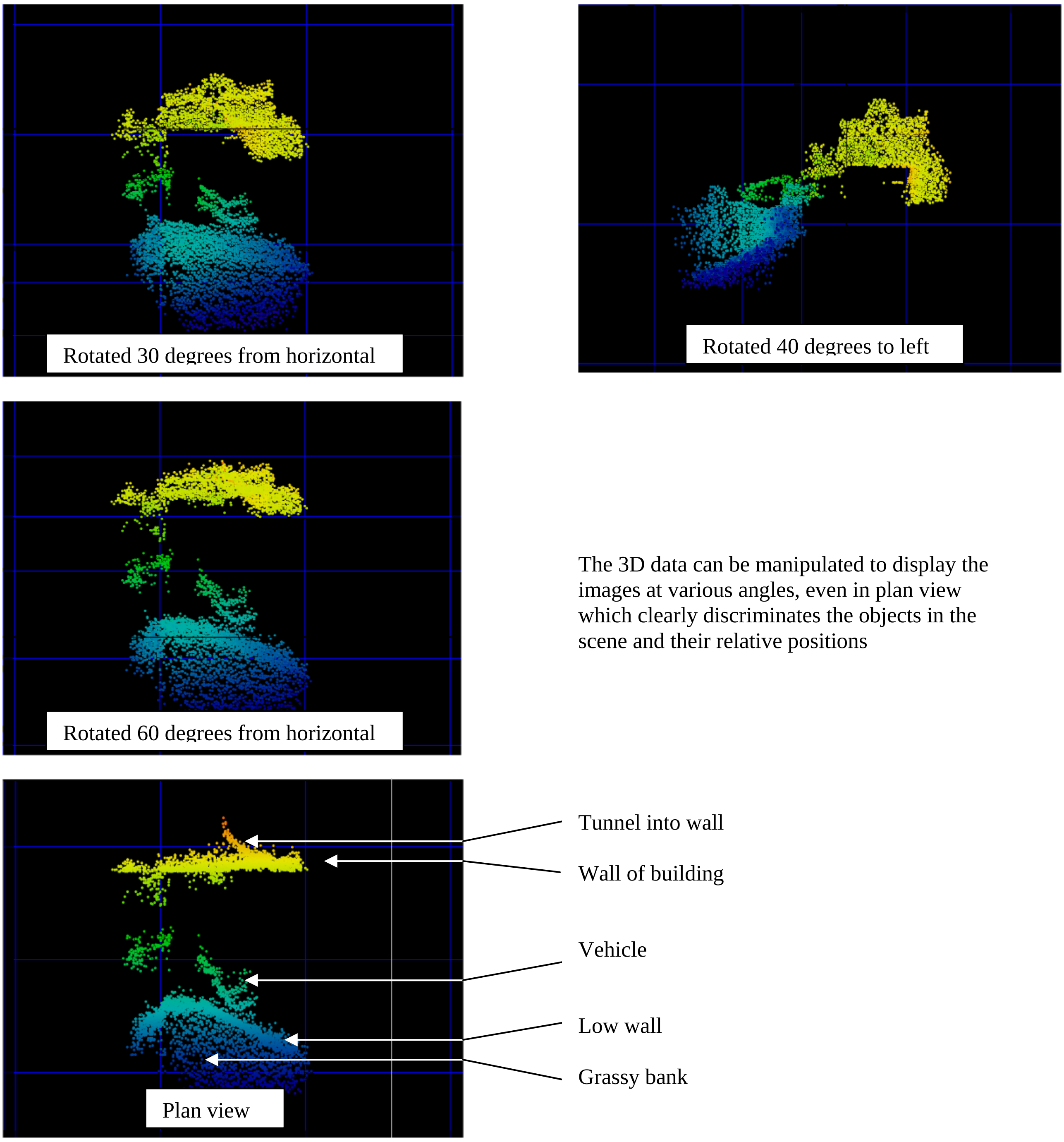

Figure 8 Range images with sightline rotated in software

In figure 8, the relative placement of the building, vehicle and front wall are more clearly seen, as is the orientation of the various elements. In the plan view, the front wall and vehicle orientation are very apparent. The returns in front of the wall represent a grass slope which is not obvious from the intensity image. The building can be seen to be orthogonal to the sightline, and the nature of the wall receding into the opening in the building can be seen. Notice that the far wall of the castle has a point scatter even though it is a flat surface. This is due to variances in the MOSFET parameters within the silicon which create small range errors. There is no correction applied to the images in figure 8 – it is the raw range data produced by the detector. With further development of the 3D software we will introduce corrections to the range data and errors due to the silicon should be very amenable to correction.

The 3D imaging activity has presented a whole new set of challenges and there are some artefacts where correction is unreliable because the magnitude of the effect can depend on the image content.. In conventional FPAs, real world problems, such as, power supply bounce, oscillations from inductance in and around the focal plane and debias effects are usually stationary from frame to frame, and have little effect on the image quality. However when measuring small analogue signals in the 1ns to 100ns range as is required by 3D detectors these real world problems are significant. For instance, this investigation showed that under some conditions (such as flood illumination) the prototype detector was limited at the 10s of nanoseconds level due to the finite resistance of the HgCdTe earth plane, which interfered with the measurement of range. The HgCdTe debias will be solved by a distributed metal grid in the short term and by MOVPE devices in the longer term with a more highly doped (lower resistance) earth plane. In parallel, current development of the 3D detector is concentrated on stabilising the pixel circuits at the 1-100ns level by careful high frequency design of the multiplexer, encapsulation and proximity electronics.

8 CONCLUSIONS

Laser-gated imaging has been shown to be a valuable tool for long range imaging, and the field is growing rapidly as new detectors, lasers, platforms and signal processing techniques are developed. The emergence of 3D detectors, will further augment the recognition, identification and intent for systems in ground based, naval and airborne scenarios. A 3D laser-gated imaging detector based on a new principal has been shown to produce simultaneous intensity and range data. The new detector (Swallow) shares the same array size (320x256) and pixel size (24μm) as the existing 2D SW products, and has identical encapsulation and proximity electronics, thus providing a fast exploitation route.

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REFERENCES

Baker I.M., Crimes G.J., Parsons J.E. and O'Keefe E.S., (1994), "CdHgTe-CMOS hybrid focal plane arrays – a flexible solution for advanced infrared systems", *Proc. SPIE*, Vol **2269**, p.636

Baker I.M. and Maxey C.D., (2003), "Summary of HgCdTe 2D array technology in the UK", *Jn. Elec. Mat*, Vol **30**, No.6, p.682

Baker I., Duncan S. and Copley J., (2004), "Low noise laser gated imaging system for long range target identification", *Proc. SPIE*, Vol **5406**, pp.133-144

Baker I.M., Thorne P., Henderson J. et al, (2006), *Proc. of SPIE*, Vol. **6206**, pp 620608-1 to 10.

Beck J.D., Wan C-F., Kinch M.A. and Robinson J.E., (2001), "MWIR HgCdTe avalanche photodiodes", *Matls for IR Detectors, Proc. SPIE*, Vol **4454**, pp.188-197

Duncan S., Copley J., Harvey G., Humphreys D., Gonglewski J. and Baker I. (2006), "Advances in Laser Gated Imaging in an Airborne Environment", *Proc SPIE*, Vol **6206**, pp.620607