LARGE FORMAT InSb INFRARED DETECTOR WITH 10 μm PIXELS

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ABSTRACT:

We report a new infrared detector named Blackbird, for the MWIR atmospheric window. The detector features an InSb Focal Plane Array (FPA) with a 1920×1536 format of 10 μm sized pixels housed in a stiffened Dewar and accompanied by an electronic proximity board. The FPA includes a new digital Readout Integrated Circuit (ROIC) and is based on SCD's matured planar InSb diode technology that provides excellent quantum efficiency and dark current performance. The ROIC has two Analog to Digital (A/D) converters per-column (total of 1920×2) to allow full format readout at 13 bit resolution and a high frame rate of up to 120 Hz. Such on-chip A/D conversion eliminates the need for several A/D converters thereby avoiding fairly high power consumption at the system level. The ROIC features a wide range of pixel-level functionality such as several conversion gains and 2×2 pixel binning. The design makes use of advanced 0.18 μm CMOS technology, which allows for high functionality and a relatively low power consumption of less than 400 mW at maximum bandwidth. The Flip-chip bonded FPA is mounted on a Cold-Finger and is housed in a stiffened Dewar that can withstand harsh environmental conditions while minimizing the environment contribution to the overall heat load of the Integrated Detector Cooler Assembly (IDCA). The resultant heat load of the Dewar and ROIC at an ambient temperature of 71 ºC is about 0.9 Watt. The Dewar is integrated with either a linear or a rotary 1-Watt cryogenic cooler, and the FPA is cooled down to 80K. The proximity electronics board is designed for easy integration into a system with a single power supply, a standard serial communication protocol, and a standard video output. In this work we present in detail the characteristic electro-optical performance of the new detector.

1. INTRODUCTION

Over the last years there has been a growing demand for infrared detectors with a large format, in order to increase the system spatial resolution. This trend naturally involves a shift towards smaller pixel size, which allows higher resolution and wider field of view (FOV) in infrared imaging systems [1]. A smaller pixel size thus enables the overall size of an FPA with a specific format to be reduced, or alternately, it allows a higher resolution for a given FPA dimension. SCD's roadmap of two dimensional (2D) InSb array detectors reflects these demands and follows the trend of pixel shrinkage and format growth in 2D infrared arrays. The roadmap started in 1997 with the introduction of 320×256 format, 30μm pitch detectors, and continued with the larger format of 640×512 elements and pixel sizes of 25, 20, and 15μm [2,3]. The shift to a smaller pixel dimension required the migration from a 0.5μm CMOS process to a more advanced, 0.18μm CMOS technology, in order to allow a higher value of capacitance per unit area, a lower operating voltage for reduced power consumption, and a denser device layout for maintaining a high level of functionality. The trend to larger format and smaller pitch continued with Hercules, an InSb detector with 1280×1024 pixels of 15μm pitch [4, 5]. The new Blackbird detector is a natural step in this roadmap with 3 million pixels in the FPA and a pixel dimension of 10 μm. The Blackbird design takes advantage of the knowledge and experience gained from its predecessors, to ensure maximum exploitation of the 0.18μm CMOS technology in terms of integration capacitance, power consumption, pixel readout rate, functionality, and readout noise. It features a self-controlled and self-initializing ROIC with several conversion gains and an option for 2-by-2 pixel binning, all implemented at the pixel level. The ROIC with its 13 Bit sub-LVDS video output at a 120Hz frame rate combined with the newly designed 10μm pitch InSb diode array, makes Blackbird an attractive new Mid Wave Infra-Red (MWIR) detector for a wide range of High-End applications. In this paper, the measured electro-optical performance of the new detector is presented. We describe the basic components and technologies which comprise the detector, as well as the detector's performance and special features.

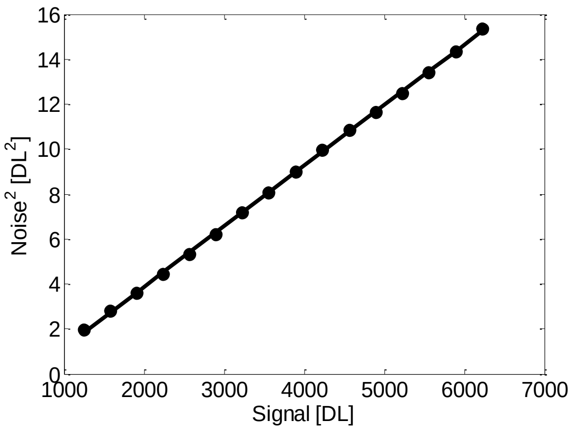
2. ROIC

Since 2002 SCD has been manufacturing ROICs with analog to digital (A/D) conversion at the focal plane [6, 7]. This feature is operated successfully in several detectors such as Hercules, Pelican D, and Sebastian. For Blackbird, SCD has adopted a new approach for increasing the ROIC functionality, autonomy and compatibility with standard system video and serial communication protocols. As a result Blackbird can be integrated easily into a system without any additional electronic boards. The ROIC achieves a 120 Hz frame rate at the full format with a power consumption of less than 400mW. It features several conversion gain options that are implemented at the pixel level. The main integration capacitor is 2.5 Me^- for both integrate-then-read (ITR) and integrate-while-read (IWR) operation modes, with a better noise performance for the ITR mode. Other available effective capacitor sizes are 4.5 Me^-, 0.6 Me^- (ITR only), and a High Gain 0.3 Me^- (see Tab. 2 for details). By enabling different conversion gains at the pixel level, charge capacity can be traded off with readout noise and adapted for different applications and scenarios. The ROIC also enables windowing in the vertical direction and flipping of the horizontal and vertical readout directions. A 2-by-2 pixel binning feature implemented at the ROIC level improves the Signal to Noise Ratio (SNR) and increases the frame rate by a factor of four for an effective pixel size of 20μm. The main features of the ROIC are:

- 3Mpxl, 10μm pitch,
- Multiple in-pixel gain modes,
- Simple interfacing and operation,
- Self-initialization from external E^2PROM,
- Internal frame sequence,
- Glue-less video output,

- Standard serial interface (E^2PROM compatible),
- 120 Hz maximum frame rate,
- Reduced bandwidth & power consumption modes,
- Reset options: software command reset, Hard reset,
- Temperature reading by video output,
- Direct-access temperature diode, available also when the ROIC is off.

The 1920x1536 matrix readout circuit for the 10x10 μm^2 P-on-N InSb photodiode array is designed to operate at around 77K, and is implemented in the advanced 0.18μm CMOS process. For imager applications the main drawback of an advanced process such as 0.18-μm is noise sources such as 1/f, Random Telegraph Signal (RTS), and various leakage mechanisms, which tend to increase at lower temperatures. Special attention was paid to overcome these noise sources in the design of the previous generation 15 μm pitch Hercules and Pelican D ROICs and this issue is addressed further in the Blackbird ROIC, as dictated by the pixel size reduction. Fig 1(a) presents a measurement of the squared noise as a function of the signal in the InSb FPA, for different integration times. A linear dependence is observed which indicates that the detector is shot noise limited. These results represent a fine readout process from the ROIC pixel without the introduction of any additional noise components. Another key parameter of the ROIC is its linearity. A measurement of the Blackbird linearity is presented in Fig. 1(b). The deviation from linearity is less than 0.06% of the full dynamic range from 5% to 90% capacitor well-fill. This result demonstrates the excellent linearity exhibited by Blackbird over almost the full dynamic range.



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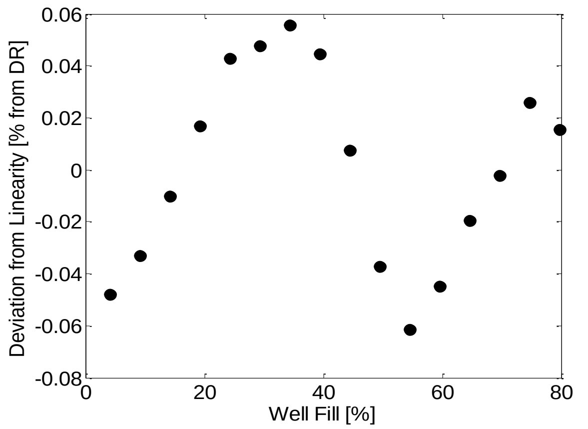
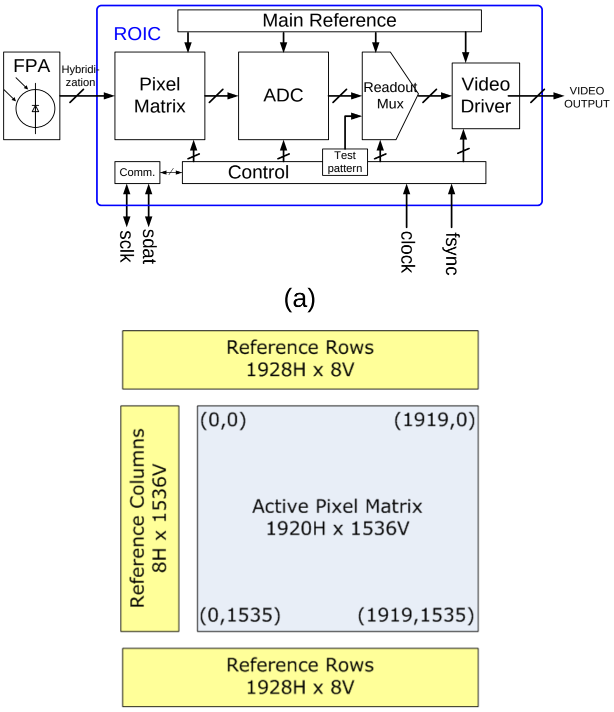


(b)

Figure. 1 (a) *Squared noise as a function of signal in digital levels measured for the Blackbird InSb FPA, for increasing integration times* ***(b)*** *Deviation from linearity, where the well-fill is varied using the integration time.*

A high speed digital video interface is developed to output the required data bandwidth at a reasonable pin count. The dedicated column ADC is a Dual Ramp convertor. It is designed for low noise and low power consumption reaching less than 160 µV Input-Referred Noise and less than 35 µW power consumption per each column ADC, while reaching a 95 kHz sampling rate. The ROIC consists of two rows of 1920 column ADCs integrated on chip at opposite edges of the matrix including an output MUX which multiplexes

1920x2 ADCs to the chip output. This MUX is compact enough not to increase the die size significantly, despite the 10 μm column pitch. Reading the pixel signals simultaneously with the 3840 column ADCs yields a total conversion rate of over 360 Mpxl/sec which enables full frame readout at 120 Hz. To output 1920 x 1536 pixels of 13 bits each, at a frame rate of 120 Hz, a data bandwidth greater than 4.6 Gbps (without taking into account headers and status bits) is required.



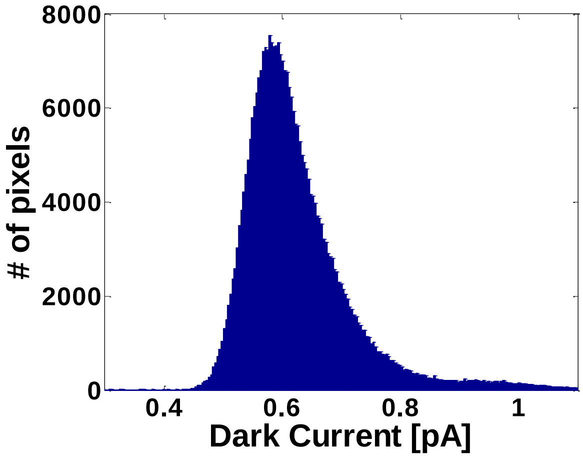
(b)

Figure. 2 *(a) ROIC functional block diagram. (b) A scheme of the pixel matrix structure*

A sub-LVDS based video output was developed where each sub-LVDS pair will output 560 Mbps by utilizing a low-jitter low-power Phase Locked Loop (PLL) to multiply the input clock frequency, and a serializer to send the parallel pixel data over the serial link. The video outputs are arranged in a channel-link manner, each group including four lanes of data and one lane of sampling clock for receiver synchronization. The ROIC is controlled through a standard serial communication protocol, as well as frame-sync. It enables 3 basic modes of frame readout rate which are termed Full-Rate, Half-Rate and Quarter-Rate. These modes enable lower power consumption at lower frame rates, as well as a reduced pixel rate at the video output. The reduction of pixel rate is achieved by operating only a part of the video channels, which means a reduced pin count at the Dewar interface. This allows for system optimization by reducing the size, power and cost of the external electronics required to handle the data bandwidth. Additional functionality in the ROIC includes self-initialization from an external E^2PROM device. The same ROIC I/O pins serve also as an E^2PROM compatible communication port for system control. The Blackbird ROIC's high functionality and autonomy along with its standard communication and video output allows integration to the system without a proximity electronics board. However such a board is present in the current application to act as a buffer to protect the ROIC.

3. InSb DIODE ARRAY

A fundamental building block of the Blackbird detector is the InSb diode array of 10x10 μm^2 InSb pixels based on a matured planar technology developed at SCD over the years [3]. The scale down of the 15μm pixel to a 10μm pixel is not trivial. The increased ratio of surface to volume imposes new design rules to maintain key parameters such as high External Quantum Efficiency (QE) and low Dark Current (I_{dark}). These parameters (and others) are also affected by the thickness of the active layer whose value needs to be controlled fairly precisely in order to achieve low crosstalk between neighboring pixels. The InSb array is integrated with the ROIC using Flip-Chip indium bump technology and these bumps are now smaller than the ones used for the 15μm pitch FPA. All these challenges are addressed and resolved in the Blackbird detector so that a high FPA performance with QE >80% and I_{dark} <1.3pA at 77K have been achieved. In Fig.3 (a) we present a histogram of the dark current values for all the InSb diodes in one of the blackbird FPAs. The narrow distribution (~0.2 pA) indicates a high level of dark current uniformity over the matrix as can also be seen in the dark current image in Fig.3 (b).



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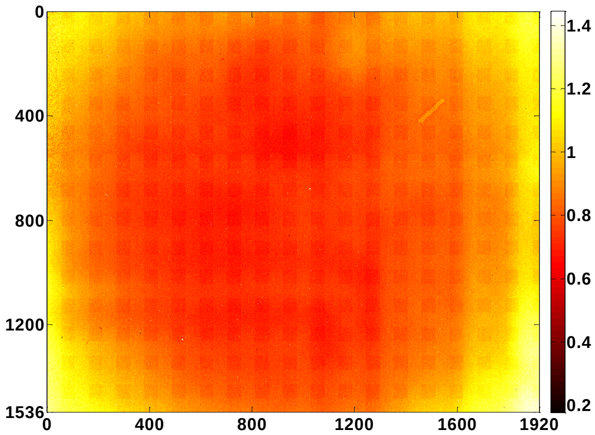

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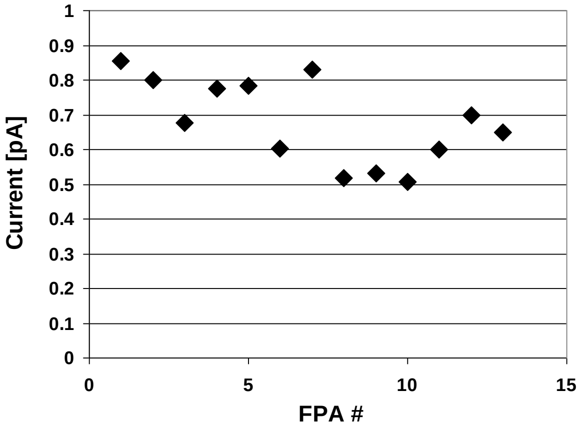


(c)

Figure. 3 *Dark current at 77K plotted as (a) Histogram (b) image and (c) mean values for 13 FPA's.*

Moreover, the stability of the InSb diode fabrication process is demonstrated through the narrow statistical spread of the average dark current values (for all pixels in the FPA) for several FPAs as shown in Fig.3 (c).

An important issue in FPA image quality is the inter-pixel cross talk. This is the fraction of the light signal falling on a given pixel that is detected by one of its neighbors. The Blackbird FPA exhibits low cross talk characteristics where 54% of the total light signal falling on the pixel area is detected in it, 9% are detected at each of the four nearest neighbors and 2 % at each nearest–diagonal neighbor. The rest 2% of the light signal is detected at the next line of nearby pixels. The cross talk is most conveniently quantified by the Point Spread Function (PSF) measurement as presented in Fig. 4 [8]. The Modulation Transfer Function (MTF) is shown in Fig. 5. The MTF is the amplitude of a spatially periodic signal detected by the FPA as a function of the signal's spatial frequency. We calculate the MTF by Fourier transform of the PSF as measured with the use of a gold mask with 400 2.5µ×2.5µ shifted square openings on the back side of the FPA [8].

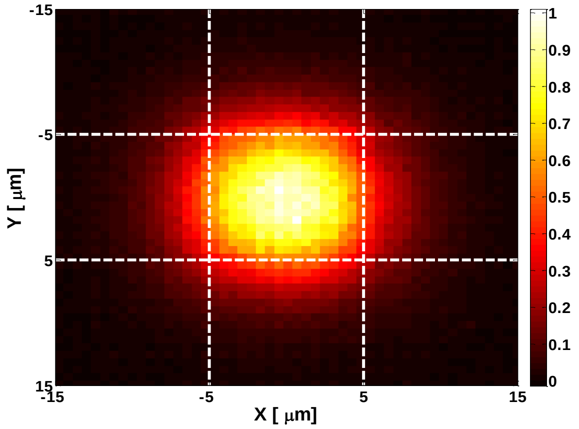


Figure. 4 *PSF image of InSb 10µm pitch, the pixel borders are indicated by white dashed lines.*

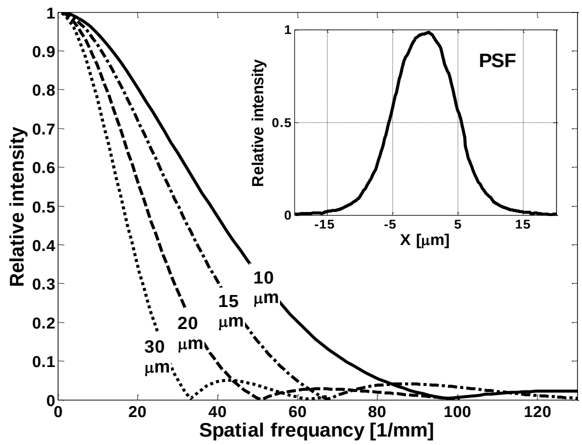


Figure. 5 *MTF curves of InSb FPAs with four different pitches: 30, 20, 15 and 10 µm, corresponding to SCDs Blue Fairy, Sebastian, Pelican and Blackbird FPA's, respectively. Insert: Cross section of the PSF image (Fig. 4) at Y=0.*

4. ELECTRO OPTICAL PERFORMANCE

The performance of an array detector is determined by several key properties characterizing its sensitivity, homogeneity, and linear response. The sensitivity is normally defined by the Noise Equivalent Temperature Difference (NETD). The spatial fixed noise following a Non Uniformity Correction (NUC) procedure defines the Residual Non Uniformity (RNU). Usually the NUC is calculated linearly from two different signal levels. It is thus related to residual deviations from linear response in the FPA.

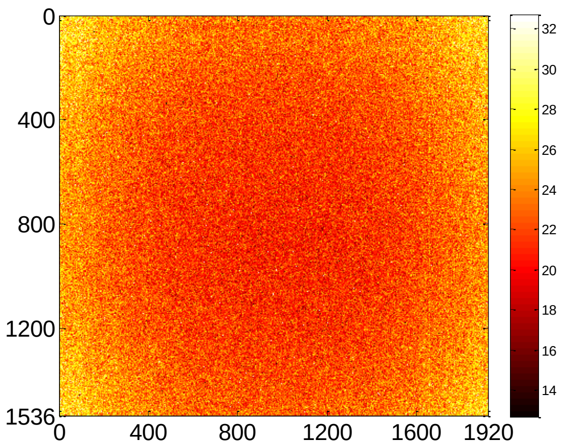
NETD & READOUT NOISE

The NETD is a key parameter in the evaluation of an IR detector. It is a measure of the detector's ability to register a temperature difference which causes a signal larger than the detector's noise. Due to the low readout noise and low dark current the NETD is background limited (BLIP) even at low well fill (low signal). However, at very low signal level the NETD is dominated by the readout noise (floor level noise), which is the measured as the temporal noise of the signal recorded at zero integration time. At null integration time there is no charge from the photodiodes in the integration capacitors, so the readout noise is a property of the ROIC, and is independent of the InSb diode. The readout noise is dominated by Johnson-Nyquist noise of the equivalent readout circuit [9]. Blackbird exhibits very low noise characteristics as can be seen in Tab 1.

Table. 1 *Measured noise characteristics for all readout modes in a typical Blackbird FPAs*

Integration Capacity [Me$^-$]	**Readout Noise [e$^-$]**
4.5	950_{IWR}
2.5	370_{IWR} 260_{ITR}
0.6	90_{ITR}
0.3	60_{ITR}

The NETD is usually calculated at an averaged signal, corresponding to median well fill. In Fig 6 (a), a map of the FPA NETD (per pixel) at 70% well-fill is presented for the 2.5 Me^- integration mode. As can be seen in the image, there are no spatial features in the temporal noise, indicating no additional noise mechanisms aside from the shot noise. In Fig. 6(b) the smooth Gaussian like histogram of the NETD is shown.



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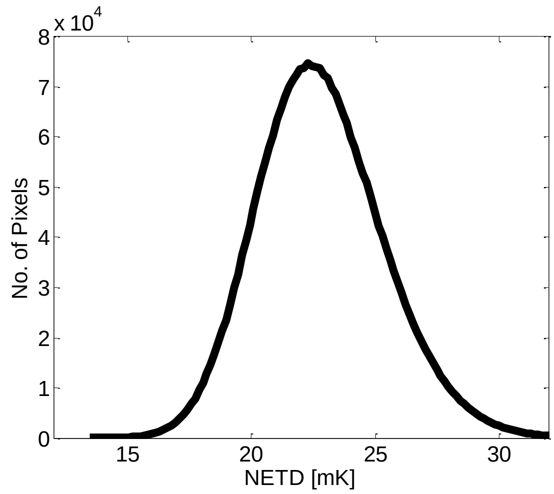


(b)

Figure. 6 *(a) NETD image at F/4, 77 K and 70% well-fill. The color scale is in mK. (b) NETD histogram of the data in Fig 6(a). The average NETD is 22.5 mK and the standard deviation is 2.5 mK.*

SCD is now able to manufacture Blackbird FPA's with good reproducibility and a low number of defective elements that yields operability higher than 99.8%. In Fig.7 it is shown that the NETD is not varying significantly from FPA to FPA, and is in accordance with the results demonstrated above for one sample.

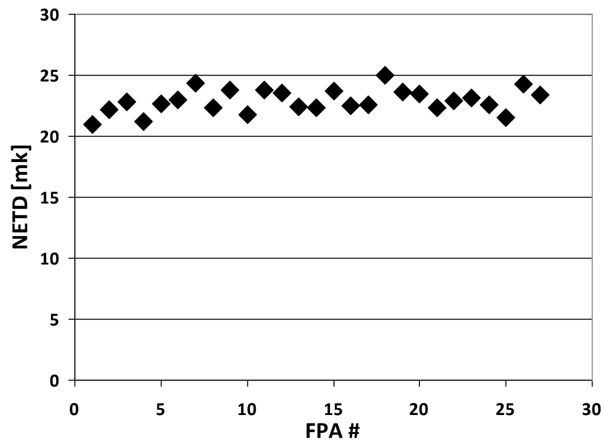
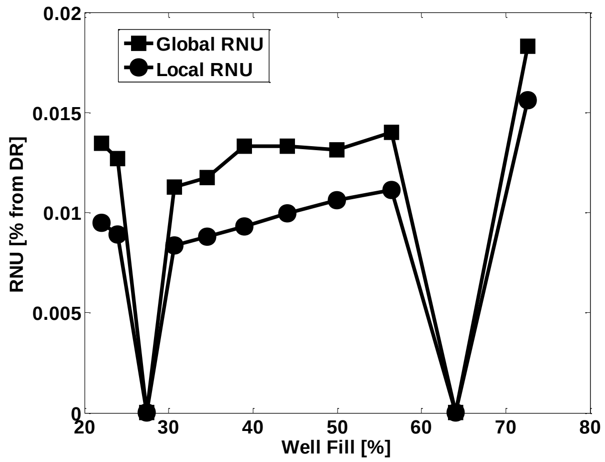


Figure. 7 *Averaged NETD values for 27 FPAs.*

RNU

The second key parameter with respect to the performance of two dimensional arrays is the uniformity of the pixels in the array. The uniformity is evaluated from an analysis of the corrected image after NUC [10]. Here we present the results for a standard linear 2-point NUC. Fig. 1(b) demonstrates the excellent linearity of the ROIC over almost the entire dynamic range (DR) of the detector. Such high pixel linearity and its narrow distribution naturally yield a low RNU as can be seen in Fig. 8. The measurement and analysis procedure for the RNU is as follows. The detector is placed in front of a uniform extended black-body and then a set of signal measurements is recorded for different blackbody temperatures, while the integration time is kept constant. Each signal measurement is an average of 64 consecutive frames in order to reduce the effect of the temporal noise on the spatial correction.



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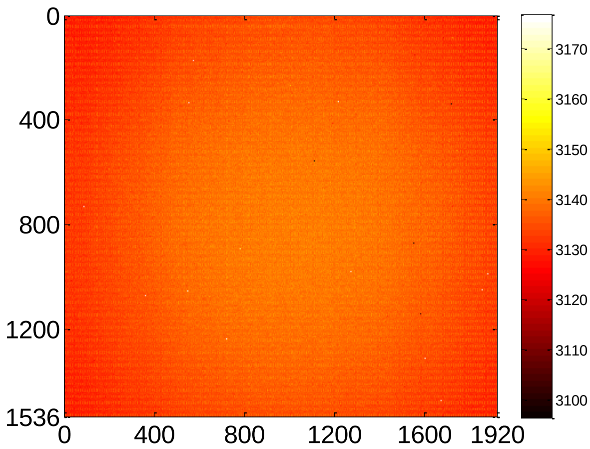

(b)

Figure. 8 *(a) RNU at F/4, 77 K as a function of well-fill. The signal is varied by changing the black-body target temperature at constant integration time. (b) An image of a uniform target at 50% well-fill. The color scale is in digital levels. No Bad Pixel Replacement (BPR) routine was applied.*

The measurements at about 25% and 65% well-fill capacity are used to calculate the linear 2-point NUC coefficients. These coefficients are then used to correct all the other measurements. The quality of the correction is determined by the spatial standard deviation of all non-defective pixels in the FPA after the correction is applied, and is termed the RNU (at the correction points the RNU is zero by definition). When calculated for all pixels in the array the RNU is termed "Global RNU" and is affected by both low and high spatial pattern frequencies in the recorded image. High frequency patterns usually originate from spatial inhomogeneity across the FPA pixels. They are related to variance in the parameters of the individual pixels in both the ROIC and InSb arrays and can be traced back to the fabrication processes of the two. This type of non-uniformity has white noise characteristics, is local in nature and determines the ability of the detector to distinguish targets from their close environment. It is therefore useful to discriminate the high frequency spatial patterns from the low frequency patterns. To that aim we define the local RNU as the standard deviation (STD) calculated over the 15×15 neighbors around a given pixel in the corrected image and averaged for all pixels. As can be seen in Fig. 8 it is lower than the global RNU since low frequency patterns are filtered out. The RNU is plotted in Fig. 8(a). The global (local) RNU of the Blackbird FPA is less than 0.02% (0.01%) StD/full span for a range of signals between 20-75% well fill capacity (the full capacity is 2.5 Me-), indicating the high quality of the array. In Fig. 8(b) an image of a uniform target is presented after non-uniformity correction. As can be seen, there is a dominant low spatial frequency residual non-uniformity, which is related to a residual illumination effect. Another important parameter of image quality is related to the stability of the RNU (and so the validity of the NUC tables) over time and from one operation to another. In order to test this, we have used a standard F/3 Blackbird IDCA to obtain a few sets of measurements in the same manner as presented above. The second set was measured four hours after the first while the detector remained cooled and powered, while the third set was measured two hours later in this case after the ROIC power supply had been turned off and on again. The last set was measured one day later during which time the FPA temperature reached room temperature before being cooled back down to 77K prior to the measurement. The RNU of all the sets is calculated as described above from the Gain and Offset tables of the "original" first set. The results are presented in Fig. 9. It is evident that the RNU is very stable during an operation cycle (constant temperature and power) and after an On/Off procedure while it degrades moderately after a cooling cycle.

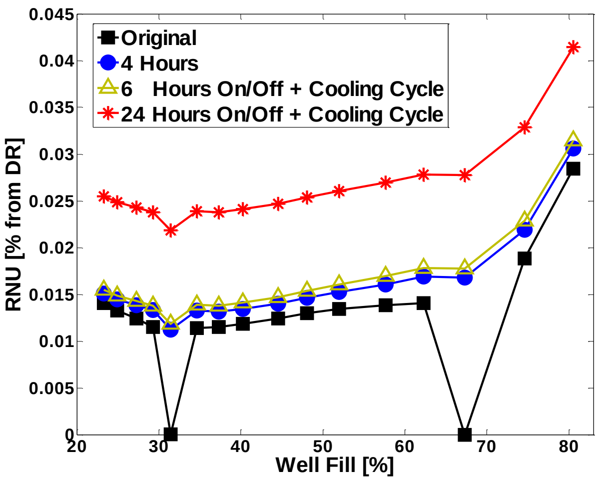

Figure. 9 *RNU at F/3 as a function of well-fill measured at different times but corrected with the same initial table of NUC coefficients.*

5. IDCA CONFIGURAION

When packaged in a Dewar which is integrated with a cryo-cooler and an electronic proximity board the FPA is ready to operate. This Integrated Detector Cooler Assembly (IDCA) makes a compact MWIR detector that generates 13 Bit, 3M pixel images at a frame rate of up to 120 Hz with a total power consumption of less than 30 Watt at 71C. Despite the large format of the FPA, Blackbird has been designed to be integrated into a standard compact "Hercules" package. SCD has adapted its well established rigid Dewar technology from Blackbird's predecessors to fit the current detector. It is based on a rugged Dewar envelope with supporting strings which are connected to the cold finger.

Table 2. *Blackbird IDCA characteristics*

Parameter	Typical value
Format	1920x1536
Pixel Size	10x10 μm^2
Output	Digital 13 bit
Well Fill Capacity And Readout Noise	$0.3Me^-$ / $60e^-$ $0.6Me^-$ / $90e^-$ $2.5Me^-$ / $370e^-$ ($260e^-$ ITR) $4.5Me^-$ / $950e^-$
Integration modes	ITR, IWR
Frame cycle control	Free running, System control
Maximum Frame rate	120 Hz (4 video ports) 60 Hz (2 video ports) 30 Hz (1 video ports)
FPA power consumption	400 mW (@ 120Hz) 230 mW (@ 60Hz) 150 mW (@ 30Hz)
Binning mode	2x2 (450Hz)
Cooler power steady state @ 23C	20 W
Weight	700 gr
RNU	0.07 STD/full span
NETD	< 24 mK
Operability	>99.5%

The structure and the geometry were optimized to give a high natural frequency. This results in a sub pixel lateral movement of the FPA when subjected to rough vibrations in the frequency range of 5-2000Hz. The resultant heat loads of the Dewar (and cold finger) at an ambient temperature of 71 ºC together with the power consumption of the ROIC at maximum frame rate give a total heat load of ~0.9 Watt. This load is well handled by an "off the shelf" standard 1W cryo-cooler such as the K543 cooler manufactured by Ricor. The electronics proximity board that was designed for the Blackbird detector is based on the same concept as for the Hercules detector with a single power supply and a standard video output that enables a fast and easy integration of the detector into any system. However since the ROIC of the Blackbird detector is more autonomous than that of the Hercules detector, and since its video output has the Sub-LVDS standard, the proximity board is simpler and has fewer functions to perform compared to the proximity boards in privies SCD generation of digital detectors. The proximity board includes an FPGA, a local oscillator, power supplies and Flash memory components (see Fig. 10). A single supply of 5V±10% is supplied to the proximity board with a noise level up to 10 mV RMS. The board power consumption is 3 Watt. The core of the proximity board is an FPGA which serves as a buffer between the ROIC and the system. The FPGA samples the digital data which comes out of the ROIC and performs a simple conversion of the data from sub into normal serial LVDS, resulting in a standard channel link interface to the system, which supports a video data rate of up to 2 Gbit/sec. The system controls the detector with a serial communication command through a standard I^2C protocol. The ROIC self-initiates from a preprogramed set of parameters saved to the proximity board E^2PROM memory. Tab. 2 summarizes the Blackbird detector main specifications and Fig. 11 presents a picture of the complete IDCA with its proximity electronics.

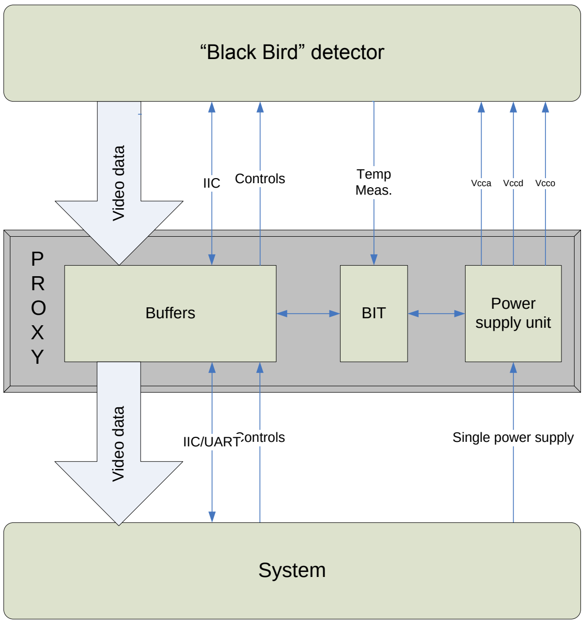

Figure. 10 *Scheme of the proximity electronics.*

Figure. 11 *The Blackbird detector.*

6. SUMMARY

In this paper we have presented the new Blackbird detector, a unique InSb cooled detector with a 10μm pitch and 1920X1536 pixels, designed for the MWIR spectral range. The development of the new ROIC and InSb diode array is a milestone in SCD's roadmap of cooled MWIR detectors with the aim of meeting the market trend of increased format and pixel shrinkage. The Blackbird detector electro-optical performance makes it a high-end IR detector. Moreover, the detector has relatively small Size, Weight and Power characteristics for such a large array. Fig. 12 shows an image from the new detector.

7. ACKNOWLEDGMENT

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Figure. 12 *Image from the Blackbird detector at F/3, 2km away.*

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