SCD solutions for Missile Warning System Applications

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ABSTRACT

SCD has developed a series of Infra Red (IR) detectors based on the well established technologies of InSb diodes and the most advanced analogue and digital signal processors. These detectors exhibit great advantages for Missile Warning System (MWS). Their special modes of operation combined with a high level of performance enable efficient optimization for MWS applications. These high-end applications require special features including large dynamic range, high frame rate, high sensitivity at low signal and dual-color detection. The first detector that was developed for MWS applications is the “Blue Fairy” detector which has 320x256 elements. After the “Blue Fairy” a new generation of digital detectors was developed, starting with “Sebastian”. Sebastian is based on a novel digital Focal Plane Processor (FPP) with formats of 640x512 and 480x384 elements. A detector based on two Sebastian Focal Plane Arrays (FPAs) assembled on a single substrate with a high degree of registration provides a good dual-color solution for MWS systems. In this paper the special features and the performance of all these detectors are presented showing their advantages for MWS applications.

Keywords: Digital Detector, Sebastian, 480x384 element detector, 640x512 element detector, Focal Plane Array, Digital Focal Plane Processor, MWS, IR detector, InSb, Dual color detector.

INTRODUCTION

Over the past few years there has been a growing demand for applications related to Missile Warning Systems (MWS) and Muzzle Flash Detection Systems (MFDS), for both air and ground platforms. MWS's have been in use for many years in military aircraft. Some of these systems are based on Radar, Ultra Violet (UV) or Infra Red (IR). Among them, there is an increasing trend of adapting IR systems for use in MWS's. Two of the main challenges in MWS systems of today are to reduce the False Alarm Rate (FAR) to a minimum and to be able to identify a large variety of threats. To be able to distinguish between the real target and the surrounding clutter, which can include sun glints and radiant objects with a similar signature to the real target, is one of the most difficult problems in a MWS system. However, due to great progress in the development of third generation 2D IR detector arrays during the past five years which has resulted in higher resolution, higher sensitivity, smart signal processors and dual color detection, these detectors are now very attractive candidates for MWS applications.

The main requirements from IR detectors for MWS applications are\(^1,2,3\):

- Large dynamic range for identifying a large variety of threats
- High frame rate for identifying targets with a high speed or a short duration
- High Non Uniformity Correction (NUC) stability to keep the sensitivity high for all of the operation period
- Uniform performance over all the Field Of View (FOV)
- High level of linearity for the algorithm of the system
- Large simultaneous range of linearity and Residual Non Uniformity
- Flexible windowing with the ability to increase the frame rate.
- High level of sensitivity at low level of well fill due to the short integration time at the high frame rate and the low level of photocurrent as a result of the narrow bandwidth of the optical filter
- Smooth transition of modes from frame to frame, especially recovery from saturation
- Dual/Multi-color detection is needed to distinguish between the real threat and other signals from the clutter
The challenge in optimizing IR detectors for MWS applications is to make all these features exist together and function simultaneously. Considering all these requirements a few years ago SCD started to develop a series of single color detectors with all of the required features except dual/multi color and lately a dual-color device was developed specially for MWS use.

At SCD, special care was taken in the design of the signal processor for our 2D InSb arrays to achieve all of the above mentioned features in our detectors. First, a high performance 320×256 element detector was developed for the mid-format, which is called "Blue Fairy". This detector has high linearity and low Residual Non Uniformity (RNU) over a large dynamic range combined with high functionality, including a combined mode for large dynamic range. Blue Fairy has been produced for more than six years and is operating in a large variety of systems including Hand-Held cameras, missile seekers and MWS applications.

Following Blue Fairy, SCD developed a family of new generation InSb IR digital detectors ("Sebastian") which are based on a novel signal processor in which the analog to digital converter is on the Focal Plane Array (FPA) itself. The main advantage of the "Sebastian" digital detector is that it gives the ability to achieve the same level of performance on the system level as is measured on the FPA alone, without any degradation. This is possible because the digital FPA is well shielded inside the Dewar and thus the signal is not sensitive to external noise and ambient temperature conditions. The first product of the Sebastian family was developed with a large format of 640×512 elements. The main characteristics of the Sebastian detector include: high linearity with low RNU over a wide range, a low level of temporal noise, long term stability of the RNU and a simple interface to the system such as a camera-link which enables fast and easy integration of the detector into the system. Special integration modes unique to the Sebastian detector provide a simple way to optimize applications which require high dynamic range with high sensitivity or high frame rate. The Sebastian detector has already been integrated into several systems, where it has demonstrated excellent performance similar to that achieved with the detector in the laboratory.

Next, for the mid format a digital detector with 480×384 elements was developed, based on the same concept as the large format Sebastian detector but with some additional functionality. The format of the 480×384 element with a 20µm pitch was chosen in order to maintain the same active area as in a standard format 320×256 element with the 30µm pitch of today, but with improved resolution. As a direct consequence, the detection range of a typical thermal imager is increased by 22-35%, depending on the target type, when using this detector instead of the conventional 320×256 element detector. The 480×384 element detector is in use in many kinds of applications such as Hand-Held cameras, missile seekers and MWS applications.

In this paper we introduce the main and unique features of the SCD detector family which give a great advantage when using them in MWS applications. First, we describe the main features of the three detectors, Blue Fairy and Sebastian family. Next, we show the unique integration modes of our detectors including demonstrations of their operation in MWS applications. Finally, we show the new dual-color detector which was developed lately especially for MWS use. It is based on two Sebastian Focal Plane Arrays (FPAs) mounted in the same Dewar.

MAIN FEATURES OF THE DETECTORS

In general, the three above mentioned detectors are similar in their basic signal processor design, except that the Sebastian detector includes A/D conversion inside the signal processor. In the Sebastian the conversion resolution is controlled externally and can be changed continuously from 12-15 bits. There is a trade off between the conversion resolution and the maximum frame rate, such that a higher frame rate can be achieved with lower resolution. An anti-blooming circuit was implemented at the input stage of the signal processor to avoid a very strong light source from disrupting its operation. All the detectors contain a Correlated Double Sampling (CDS) mechanism inside the signal processor, where the CDS data is read outside and is subtracted from the video data. The use of CDS during operation was found to be very useful for low frequency noise reduction and for NUC stability enlargement. In the following table there is a comparison between the main features of the three detectors:
### Table 1: The main features of the Blue Fairy and Sebastian detectors

<table>
<thead>
<tr>
<th>Feature</th>
<th>Blue Fairy</th>
<th>Sebastian 480</th>
<th>Sebastian 640</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
<td>320×256</td>
<td>480×384</td>
<td>640×512</td>
</tr>
<tr>
<td>Pixel capacity Me-</td>
<td>17Me-@IWR</td>
<td>7Me-@IWR</td>
<td>7Me-@IWR</td>
</tr>
<tr>
<td></td>
<td>30Me-@ITR</td>
<td>14Me-@ITR</td>
<td>14Me-@ITR</td>
</tr>
<tr>
<td>Frame rate@full frame</td>
<td>&gt;450Hz</td>
<td>&gt;160Hz@15bit</td>
<td>&gt;120Hz@15bit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;240Hz@13bit</td>
<td>&gt;160Hz@13bit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;280Hz@12bit</td>
<td>&gt;180Hz@12bit</td>
</tr>
<tr>
<td>Main Integration modes</td>
<td>ITR/IWR/Combined</td>
<td>ITR/IWR/Combined/</td>
<td>Multistep/Multiple</td>
</tr>
<tr>
<td>Readout dilution</td>
<td>----</td>
<td>Every 2nd and 6th row</td>
<td>Every 2nd row</td>
</tr>
<tr>
<td>Pixel merging</td>
<td>----</td>
<td>1×2, 2×1, 2×2</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>&lt;0.05%%@2-90%WF</td>
<td>&lt;0.02% over all dynamic range</td>
<td></td>
</tr>
<tr>
<td>RNU std/dr</td>
<td>&lt;0.025%%@2-90%WF</td>
<td>&lt;0.02% over all dynamic range</td>
<td></td>
</tr>
<tr>
<td>InSb bias operating point</td>
<td>500pA-1µA</td>
<td>70pA-100nA</td>
<td>70pA-100nA</td>
</tr>
<tr>
<td>Windowing</td>
<td>Every 2 rows/16 columns</td>
<td>Every 2 rows</td>
<td>Every 4 rows</td>
</tr>
</tbody>
</table>

The pixel merging mode is a connection of every two or four adjacent pixels together, which is done inside the signal processor. This feature enables operation with an effective pixel area of twice or four times that of the original area of the pixel. This mode is very useful when trying to detect a sub pixel target where the image is smeared over four pixels (due to the diffraction limitation of the optics) and the signal is very weak. By applying the four pixels merging function the signal to noise improves significantly, compared to the case where an external addition of the data is done at the digital level of the image processing.

### HIGH DYNAMIC RANGE MODES

In the following section three integration modes which are very useful for MWS applications, will be presented.

1. **Combined Integrate Mode – High dynamic range with high sensitivity.**

This Mode was first implemented in the Blue Fairy detector and later in the Sebastian detector. The combined mode enables wide dynamic range operation for the system together with high sensitivity, by using two integration pulses: a long one and a short one, which change consequently from frame to frame. For high dynamic applications, simultaneity between the two integration pulses can be achieved by splitting the long integration pulse into two halves and inserting the short one in between them. This feature is unique to SCD detectors.

By using the appropriate algorithm, the user can choose the best frame out of the two, or fuse the two frames with the corresponding weight for each one, in order to get an optimal image containing both high and low radiant objects together. A second important aspect of our detectors in respect to this mode is high linearity starting at very low well-fill capacities (see details below). This means that while using the combined mode the short integration period can be very short without any degradation in the image uniformity. Hence, one could easily achieve an effective dynamic range (proportional to the long integration to short integration ratio multiplied by the pixel capacitance) of 140Me- in this mode.

Figure 1 presents a panoramic set of images captured during evaluation flights of Elisra's PAWS system mounted onboard a helicopter. The PAWS is an IR MWS system developed by Elisra and comprises Elisra's signal processor and four sensors developed by ElOp. Every sensor contains a Blue Fairy detector operating in the combined mode. One can see very clearly the big advantage of the combined mode which enables the sensing of a wide range of objects in the same image, from sun to sea water.
2. Multi-step integration mode – high dynamic range with high frame rate.

The multi-step integration mode enables dynamic optimization of the detector operation in a single frame. In this mode a wide dynamic range is achieved in one frame, thus allowing higher frame rate operation compared to the combined mode. This mode was first implemented in Sebastian detectors. In this mode the pixel saturation level is changed according to the level of the photocurrent, together with the use of multiple integration pulses in the same frame. Such a mode with two integrations per frame, each with a long pulse and a short pulse is demonstrated in figure 2. Before each integration starts, the saturation level parameter is changed (by the communication channel) as shown in the timing diagram. A low Saturation level is set before the long integration pulse, and a high saturation level is set before the short integration pulse.

For a low irradiated pixel, the accumulated signal will be proportional to the total integration time. For a highly irradiated pixel the signal level will be the sum of the low saturation level and the signal accumulated during the short integration with the high saturation level. Thus two ranges are used in the same frame: one with the low saturation level for the low radiant pixels and the second between the low and the high saturation levels for the high radiant pixels. For example: for the first range with the low saturation level, a background temperature up to 150°C can be detected with a typical NETD of 20mK, whereas for the second range a background temperature from 150°C to 800°C can be detected with NETD of 1-2 K. Using this mode the dynamic range is increased, as demonstrated in figure 2, with high frame rate. This method can be extended to more than two integration pulses per frame together with the use of the multiple saturation levels available.
3. **Multiple integration mode – high rate image sampling**

A high rate of image sampling is required in MWS applications due to high speed targets and/or the need to detect short lived events. A major limitation of the frame rate is the maximum readout rate, which is limited by the FPA signal processor and the conducting bonds inside the Dewar. In the multiple integration mode the detector can operate with several integration pulses within one readout cycle. The timing diagram of such a mode is depicted schematically in figure 3. In this mode we overcome the limitation of the maximum readout rate of the detector. The integration pulse is divided into many integration pulses according to the required frequency (for example: 1 KHz), where the total number of electrons which are collected in the integration capacitor can be controlled by the ratio between the single integration pulse and the non integrating period (duty cycle). Using this integration mode the system can have high rate sampling of the background with the ability to detect events with short time duration, and to track targets with high speed.

**LINEARITY AND RNU**

As mentioned above, many of the algorithms in the systems are based on the assumption that the detector is highly linear, especially the Non Uniformity Correction (NUC). A special care in the design was implemented in the signal processors in order to achieve high linearity over a large dynamic range. In figure 4, we present the results of the
measured linearity of a Sebastian detector. The graph shows the measured signal as a function of integration time with a constant black body temperature of 50 °C, a gain of 7 Me− and a conversion resolution of 15bit. The two characteristics that define the quality of a detector for the aspect of linearity are the span of the linear regime (especially towards the low level) and the deviation from linearity in that regime. As shown in Fig. 4, the linearity of the Digital detector is of an extended high quality. Its deviation from linearity is below 5 Digital Levels (DL) (0.02% maximum deviation/full range) over a regime starting at almost empty well fill and up to 100% well-fill capacity. This value can be compared to typical analog detectors which have a linearity of about 0.1% maximum deviation/full range. Fig. 5 shows the measured RNU of the Sebastian detector after a two point correction. One can see that the low level of the RNU is maintained from a very low well fill up to almost 100% well fill of the capacitor with only one set of gain and offset tables correction. This large simultaneous range of RNU indicates the excellent linearity of the detector over the full dynamic range.

Fig. 4- The linearity of the Sebastian detector. (A) Shows the average signal of the array as a function of the Well fill capacitor (B) presents the deviation of the signal from its linear fit

Fig. 5- Residual Non Uniformity as a function of well fill capacity
1. Introduction

The use of dual color MWIR detectors for MWS is expected to improve the performance of the systems especially with regard to FAR. The main problem of the system is the ability to distinguish the missile signature from the clutter background such as sun reflections and other blinking objects. Since the missile plume has its own spectral signature, the way to handle it is to use a two color detector with two spectral bands; above and below the CO$_2$ Absorption band at 4.2µm (red and blue bands). The ratio of intensities between the blue and the red bands in the case of missiles is very high compared to the background and enables the system to discriminate easily between the missile plume and the background. However, the current solutions today which are based on monolithic structures with technologies such as MCT, QWIP and antimonide based superlattices, suffer from some disadvantages that tend to counteract the improvements that can be achieved relative to single band detectors with a high level of performance. The main problems with the monolithic structures are:

- The dual color monolithic pixel structure can suffer from a relatively small fill factor due to the extra metal pads that are required and this leads to a lower sensitivity for the detector.
- In these detectors the amount of data is double that in single band detectors, thus the frame rate reduces by half due to the readout rate limitation of the signal processor.
- The dual color pixel monolithic structure also suffers from optical crosstalk between the two bands.
- Implementation of two input stages in one pixel area results in smaller integration capacitors, at least by half. The direct consequence of this is lower dynamic range and lower sensitivity.
- In order to keep the level of sensitivity as in a single color detector the pixel area should be increased significantly, so that the resolution of the detector will be adversely affected.
- Focusing problems can arise in the case of different focusing depths for the two bands.

A straight forward solution to all these problems is to use two completely separate detectors/cameras, one for each band. However, besides the problems of size, weight and cost, the requirement for a high level of registration between the two detectors/cameras cannot possibly be fulfilled in this arrangement over any significant length of time.

A recent performance study of MWIR systems for MWS applications shows that in fact the performance level of systems based on a single 3rd generation one band detector (such as Sebastian) is quite comparable to that available from a current monolithic dual color detector. However, this study also shows that by combining the high performance level of a 3rd generation single band detector with dual color detection ability will result in a great improvement of the system FAR, by a few orders of magnitude. Therefore, we have developed a new approach to achieving such a device which avoids the problems associated with two separate cameras. It incorporates two separate FPAs mounted on a single substrate with a very high degree of registration. In the following section this new detector which was specially developed at SCD for MWS applications will be described.

2. Detector description

The concept of the new dual-color detector based on high accuracy butting of two FPAs on a single ceramic substrate is demonstrated in figure 6. Each FPA consists of a Sebastian 480×384 signal processor bonded to an InSb array. Above each FPA a cold shield is mounted and on top of each cold shield a cold spectral filter is installed as demonstrated in figure 7. Each cold filter has its own spectral band. The detector was designed such that each FPA is connected through the feed-through unit to its own proximity electronics board. Having two separate electronics channels allows the operation of the detector with full frame rate and simultaneous integration of the two bands which is necessary for target identification. Optically, the physical separation between the two bands enables the handling of each optical path separately in the case of different focusing depths for the two bands. Figure 8 shows the image of the whole detector after assembling with the cooler attached to it. Figure 9 shows two images captured by the dual color detector; the left image belongs to the "red" spectral band of the detector while the right image belongs to the "blue" spectral band of the detector. One can see the differences of the images between the two bands, especially the transmittance through the glass window of the car can be observed. This concept of the detector gains all the advantages of maximum frame rate, high level of sensitivity, high resolution and high level of registration between the two FPAs.
Figure 6: the ceramic substrate and the two Sebastian FPAs mounted on

Figure 7: the assembled Dewar with the two cold shield and their spectral filter
SUMMARY

For the past five years SCD has been developing and producing detectors with features, modes and performance that give great advantages for systems which deal with MWS applications. These abilities are based on SCDs sophisticated Signal Processors and on SCDs highly mature technology of InSb 2D array detectors. This maturity is based on more than 10 years of experience in manufacturing InSb detectors and on a high production capability of over 7,000 IR detectors per year. These signal processors can also be bonded to epitaxially grown InAlSb based arrays which enable detector operation at temperatures as high as 100 K, or even beyond. MWS applications require high end performance of the IR detector with the ability to have many features/modes functioning simultaneously. The main requirements include: high dynamic range, high frame rate, high linearity at wide dynamic range, on-line mode transition and dual-color detection.
Three detectors were designed at SCD for MWS applications. Blue Fairy with a format of 320×256 elements has been in production for over six years. A few hundred detectors have been already integrated into many systems successfully operating for several years at the field. Blue Fairy detectors were integrated into Elisra's PAWS missile warning system using sensors provided by ElOp, and successfully demonstrated its performance, especially using the combined mode. High linearity with very low RNU over a large dynamic range was achieved in the detector. After Blue Fairy, a new family of detectors with a revolutionary digital signal processor was introduced, starting with "Sebastian". These detectors combine all the features of the Blue Fairy detector with additional functionality and A/D conversion inside the FPA. The main advantage of the Digital detectors is expressed at the system level due to their immunity to external noise and environmental conditions. First, for the large format based applications, a detector with 640×512 elements was developed. Next, a mid format digital detector with a format of 480×384 and a 20µm pitch was introduced, which has the same active area as the 320×256 detector but a higher resolution. These detectors were integrated into some systems and demonstrated the same high performance at the system level as was measured in the laboratory.

Based on two Sebastian FPAs SCD has developed a dual-color detector which combines all the abilities of the single Sebastian detector with the additional feature of dual-color detection. An excellent registration between the two FPAs was achieved due to the fact that both of them are mounted on the same ceramic substrate. Each FPA has its own proximity electronics which enables operation at full frame rate. Combining all these features together in one detector should give great advantages in MWS applications especially with regard to FAR reduction.

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