Uncooled Detectors Optimized for Unattended Applications

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ABSTRACT

SCD has recently presented an uncooled detector product line based on the high-end VOx bolometer technology. The first FPA launched, named BIRD – short for Bolometer Infra Red Detector, is a 384x288 (or 320x240) configurable format with 25µm pitch. Typical NETD values for these FPAs range at 50mK with an F/1 aperture and 60 Hz frame rate. These detectors also exhibit a relatively fast thermal time constant of approximately 10 msec, as reported previously\(^1\).

In this paper, the special features of BIRD optimized for unattended sensor applications are presented and discussed. Unattended surveillance using sensors on unattended aerial vehicles (UAV's) or micro air vehicles (MAV's), unattended ground vehicles (UGV's) or unattended ground sensor (UGS) are growing applications for uncooled detectors\(^2,3\). This is due to their low power consumption, low weight, negligible acoustic noise and reduced price. On the other hand, uncooled detectors are vulnerable to ambient drift. Even minor temperature fluctuations are manifested as fixed pattern noise (FPN). As a result, frequent shutter operation must be applied, with the risk of blocking the scenery in critical time frames and loosing information for various scenarios.

In order to increase the time span between shutter operations, SCD has incorporated various features within the FPA and supporting algorithms. This paper will discuss these features and present some illustrative examples. Minimum power consumption is another critical issue for unattended applications. SCD has addressed this topic by introducing the "Power Save" concept\(^4\). For very low power applications or for TEC-less (Thermo-Electric–Cooler) applications, the flexible dilution architecture enables the system to operate the detector at a number of formats. This, together with a smooth frame rate and format transition capability turns SCD's uncooled detector to be well suited for unattended applications. These issues will be described in detail as well.

Keywords: uncooled FPA, VOx technology, unattended applications, "Power Save" mode, UAV, MAV, UGV, UGS

1. INTRODUCTION AND BACKGROUND

The evolvement of uncooled infrared detectors, featuring a considerable reduction in cost, size and operating power compared to cooled IRFPA's have opened the route for the development of unattended system applications which were not considered in the past for cooled detectors.

The detector specifications for these applications include reduced size and weight – usually achieved by the majority of uncooled detector producers.

The RNU (Residual Non Uniformity) is maintained using offset correction against a uniform background – usually an internal shutter, at some predetermined time intervals. Drift mechanisms may include correlated ambient drift , and uncorrelated 1/f noise. Small changes in ambient temperature are reflected as RNU deterioration leading to reduced performance. This implies the use of frequent shutter operations, which may block the scenery in a critical time. In order to optimize the shutter control and maintain a better performance for longer time periods, BIRD provides two complementing mechanisms: A real-time (frame-by-frame) ambient drift compensation accompanied by an RNU prediction mechanism. This feature is described in detail in section 2.

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The performance of uncooled arrays might be limited in general by the 1/f noise and row correlated line bounce as described by Hanson. BIRD exhibits very low 1/f noise indicating the quality of the material technology. BIRD's architecture enables a pre-delivery calibration for row drift. These characteristics reduce FPN and enable the use of BIRD for extended time periods without invoking the shutter for offset calibration.

High performance detectors demand tight (down to 0.01 °C) FPA temperature stabilization using a TEC (Thermo-Electric–Cooler). However, under extreme environmental conditions the TEC will consume excessive power. The "Power Save" concept, described in section 3, in which the die temperature can be stabilized to the instantaneous ambient temperature, reduces the power consumption with minimal performance degradation.

For many UGS applications it is important to maintain work with very little power for very long periods, this with tradeoff in terms of reduced performance. This mode of work is intended for "Target detection". When a potential target is detected, the system can automatically invoke a full performance mode at normal power consumption, in order to perform target recognition tasks. BIRD enables the system to swiftly switch between operation modes of the detector using a simple communication protocol. Some of these operational modes are described and discussed in section 4.

2. OVERCOMING SIGNAL DRIFT IN BIRD

RNU Prediction and Compensation

Uncooled arrays are extremely sensitive to ambient variations. The detector package is mounted and interfaced to a heat-sink within the camera, which in turn closely follows the ambient temperature. For F/1 system applications for example, the interior parts of the camera can contribute as much as four times the scene (target) flux. During routine system operation the ambient temperature may drift. Temperatures can change by even 20 degrees in a matter of hours. It can be either a slow and gradual drift (e.g. UGS for surveillance systems) or much sharper (e.g. UAV's sensors). In practice, each pixel of the array has a different FOV (Field of View) of the camera body, thus experiencing a different flux. This is added to the inherent process induced non-uniformity. As the temperature drifts, each pixel drifts slightly differently, destroying the low RNU (Residual Non Uniformity) achieved during the two point correction.

The compensation of this effect is one of the most challenging problems facing uncooled system designers. It is especially difficult during the initial stabilization period. The common practice is to perform frequent offset corrections with an optical shutter.

However, this method suffers from few major drawbacks: The shutter might block the scenery in a critical time frame for various applications. Secondly, the image deteriorates between subsequent shutter operations. In addition, the shutter – being the only moving part of the camera – limits the system reliability and MTBF.

In order to circumvent these difficulties and facilitate system-level solutions, SCD has introduced a real-time frame-by-frame non-uniformity prediction & correction mechanisms. The scheme utilizes special auxiliary data that is streamed as an integral part of the video line. It is than incorporated (on a frame-to-frame basis) in the standard NUC block, without any additional temporal or spatial manipulations.

Figures 1a & 1b exhibit the RNU prediction mechanism: The system calculates the standard deviation of the special RNU prediction columns and activates the shutter when a pre-determined threshold is reached. Evidently, there is a tight correlation between the predicted and actual array RNU. Due to the existence of an ambient drift compensation mechanism, even with a variable ambient the shutter is activated only a few times during eight hour duration. When the module is put in a stabilized environmental chamber, the shutter is not activated for more than 5 hours (!). This demonstrates once again the high temporal stability of SCD's VOx technology.
Figure 1: RNU Prediction (*) vs. Array RNU (+) for a variable ambient temperature (a), and a stable ambient temperature (b). Shutter is invoked at predicted RNU of 125 mK.

Next, we move to the ambient compensation mechanism. Figure 2 shows images captured roughly 90 minutes after a two point correction with no shutter activation. During that period the ambient drifted spontaneously about 5 °C. In the left-hand image, only the original correction is applied. There is a perceptible non-uniformity pattern especially in the periphery. This is due to the fact that the edges are affected the most by the ambient variation. In the right-hand image the real-time auxiliary mechanism was applied and the image is considerably sharper.

Figure 2: BIRD imagery (50mm lens) illustrating the real-time ambient compensation (right image) after 5.25°C drift during 90 minutes with no shutter activation.

In order to obtain a more quantitative perspective, we have repeated the entire experiment against a uniform black-body source. The measurement proceeded for almost 5 hours with 4 °C drift. The results, shown in Figure 3, exhibit more than an order of magnitude reduction in RNU (from 2K to 100mK) when utilizing the compensation mechanism. It should be noted that the RNU curve closely follows the ambient drift, indicating that this is indeed the dominant contributor to the spatial noise (rather than the 1/f pixel noise).
The combined RNU prediction and compensation mechanism is a very powerful tool, especially so for unattended sensor applications\(^8\), where the idle time (due to shutter activations) should be drastically minimized.

![Figure 3: RNU vs. \(\Delta T_{\text{ambient}}\) following a two point correction (left-hand graph) and the additional auxiliary correction mechanism (right-hand graph). Time span is roughly 300 minutes.](image)

**Minimizing Correlated row fixed pattern**

Correlated row fixed pattern is one of the sources degrading the detector performance. This pattern may appear during time because of variations in the ambient temperature. The row pattern is introduced because of the detector architecture and operation mode: Usually each row is activated alone in order to reduce operating power and prevent over heating of the pixels. The detector is designed with “blind” pixels for each of the 288 rows. These “blind” pixels are common to each line and any drift will show itself as correlated row pattern. A special mechanism in BIRD allows the optimization per row for best performance and uniformity. Special pre-delivery calibration is applied for deselecting those “blind” pixels which may produce correlated row pattern.

**1/f noise in BIRD pixels**

As was previously mentioned, the 1/f noise is regarded as one of the main sources of FPN. The physical origin and explanation of this phenomenon is outside the scope of this article. However, experimental results shown before and in the next figures demonstrate the quality of BIRD in terms of long period signal stability.

A BIRD detector was put in a temperature stabilized environment. The detector signal was measured and averaged every two minutes for one hour. The signal change with time of selected typical 1000 pixels is shown in Figure 4. Although measures were taken in order to assure temperature equilibrium, some correlated drift can be seen presumably from immeasurable temperature drift of the mechanical setup (15mV drift is equivalent to about 300mK drift in the setup during one hour).
1/f experiment for one hour: Offset corrected signal (typical results for 1000 selected pixels)

Figure 4: Signal drift of typical 1000 pixels during one hour in a temperature stabilized environment.

PSD analysis was done in order to characterize the 1/f noise behavior of each pixel. The Nyquist frequency (fn) in this experiment was 4.2 mHz.
As can be seen from PSD curves in figure 5, the typical \( f_{\text{knee}} \) is under 1.5 mHz. This result has been measured on several samples. This confirms the imaging results shown previously where no calibration was actually needed during operation of the detector for several hours.

PSD measurement for one hour: typical PSD for 1000 pixels

Figure 5: PSD of typical 1000 pixels (fn = 4.2 mHz) in a temperature stabilized environment.

3. THE "POWER-SAVE" CONCEPT

Power Dissipation

The "Power Save" concept was introduced a few months ago\(^1\). We have also detailed its advantages over the "TEC-less" architecture. In this section we elaborate further with a special emphasis on the reduced power consumption and the "mission readiness".

While optimized for a 25\(^{\circ}\)C FPA temperature, the detector was designed to withstand a large tolerance in the bolometer resistance, dynamic heating, and TCR. The temporal NETD is below 60mK for the entire region (-35\(^{\circ}\)C to +65\(^{\circ}\)C) as
depicted in Figure 6. Special provisions and on-chip gain selection reduce the coarse non-uniformity range after compensation below 300mV (equivalent to about 7K) throughout, while still maintaining 100K intra-scene dynamic range. Regular offset correction gives RNU figures of less than 30mK.

The Detector's cumulative power dissipation is contributed by several sources: the FPA (ROIC and pixels), the TEC and external system electronics. The full array (EUR format: 288X384) contributes roughly 200mW. A 50% check board dilution (e.g. only corner neighboring pixels) will reduce it to about 130mW. By applying also row dilution, an additional reduction of about 15mW can be achieved. The detector transits "smoothly" between full and diluted images with only offset (shutter) correction. Hence, in a typical surveillance application, the system can reduce the power consumption operating in the dilution mode and upon initial target detection merge to the full format.

Figure 6: Temporal NETD vs. FPA temperature within the "Power-Save" mode

Figure 7 presents the excess TEC dissipation under the "Power Save" scenario, where the FPA is stabilized exactly to the ambient temperature. As expected, the excess dissipation rises in the low temperature regime but is still below 150mW for the whole operation range. This can be compared to a regular operation were the power dissipation of a stabilized TEC at 25℃ can consume well above 1W of power at extreme conditions.

Combining this information with the dilution data we can conclude the following:

a. Detector Power dissipation at Full format with "Power Save" is lower than 350mW
b. With check board dilution and "Power Save" < 280mW
c. With full dilution and "Power Save" < 265mW.
Mission Readiness

In the previous section we elaborated on the power reduction advantages of the "Power-Save" mode. Here we describe another merit which is the so-called "mission readiness". When operating an uncooled detector at a constant FPA temperature (e.g. 25°C), then under extreme ambient conditions it might need several minutes to stabilize after power-on. During this period the detector is virtually inactive.

In contrast, when using the "Power-Save" mode this period is much shorter since the FPA stabilizes to the instantaneous ambient temperature or its vicinity. Further more, even during this short transition period the detector will supply a reasonable image.

In order to verify this point, we have performed a smooth "Power-Save" transition varying the FPA temperature between 25°C and 40°C. The FPA was corrected (compensation & one-point NUC) at 25°C and then heated gradually to 40°C with a ~ 2.5°C/minute ramp. The 25°C compensation & gain correction arrays were used throughout. The shutter was activated once every minute. The same procedure was repeated between 25°C and 10°C.

Figure 8 shows representative images captured (8 frames per image) during this interval. The instantaneous FPA temperature is added for reference on each image.

Figure 8: Representative images captured during "Power-Save" Transition
Our conclusions are as follows:
1. With a proper TEC controller and several shutter activations (10 frames per activation) the detector can be tuned smoothly up to \(\pm 15^\circ C\) while still maintaining reasonable image quality.
2. The compensation array may be valid for a \(\pm 15^\circ C\) FPA temperature variation (although we recommend a new table every \(~10\) degrees in order to maintain the full target dynamic range).
3. The gain correction array varies slowly and smoothly with the FPA temperature.

Finally, It should be noted again that all the above provisions make our detector also fit for "TEC-Less" operation mode. However, the "Power-Save" concept (especially when used with discrete points) reduces the spatial noise, computational complexity and the demands for on-chip voltage regulation.

Reducing power for low-power applications

When using the detector for UGS applications, low power UAV or MAV, it is inevitable to consider ways of reducing the overall power dissipation during the mission. As was described previously, using the Power-Save operation mode will reduce the detector total power to below 350 mW for the entire operational range (-35°C to 65°C). When considering a partial operating range, e.g. -10°C to 65°C the total power can be reduced to less than 220 mW without any payment in performance.

Further optimization of TEC temperature to some temperature above the current ambient temperature should decrease TEC power under **20mW for the whole temperature range.** The next figure and data table represents experimental results of optimizing TEC power of a detector operated in a thermal chamber. In this experiment the FPA temperature was varied and stabilized at various temperatures by the TEC. The ambient temperature was kept at -25°C. The result show that the TEC can be optimized to work with virtually no power at T_{FPA} = -15°C.

![Figure 9: TEC power optimization for Tambient = -25°C: Voltage in Volts, Current in Ampere and Power in Watt are shown on same scale.](image)

**Figure 9:** TEC power optimization for Tambient = -25°C: Voltage in Volts, Current in Ampere and Power in Watt are shown on same scale.
Table 1 – TEC power optimization data for Tambient = -25°C

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A power rating of 220mW is well under the typical detector power dissipation budget of a UGS or UAV system.

BIRD power can also be reduced with some performance tradeoff as will be described herein. BIRD can be operated at even lower power with reduced frame rate, gain and resolution (dilution). Some system performance calculations were made, in order to get estimation about range performance degradation due to reduced spatial resolution by dilution. For a typical compact system configuration, with focal length of 42mm, a field of view of about 13°x10° and system NEDT of 90mK, detection range (at probability of 90%) and recognition range (at probability of 50%) were calculated by TRM3.

The next two tables present calculated ranges for a human target and a standard NATO target- 2.3m x 2.3m.

Table 2 – System detection and recognition ranges for man target using TRM3 model

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<th>Detection range with Pd=90%</th>
<th>Recognition range with Pd=50%</th>
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<tr>
<td>Diluted format - 144X192</td>
<td>370m</td>
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<tr>
<td>Full format - 288X384</td>
<td>650m</td>
</tr>
<tr>
<td>Performance Degradation (Diluted vs. Full format)</td>
<td>44%</td>
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390m
Table 3 – System detection and recognition ranges for a standard NATO target (2.3mx2.3m) using TRM3 model

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<th>Format Type</th>
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<td>860m</td>
<td>500m</td>
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<tr>
<td>Full format - 288X384</td>
<td>1400m</td>
<td>870m</td>
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<tr>
<td>Performance Degradation (Diluted vs. Full format)</td>
<td>38%</td>
<td>42%</td>
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The calculated results indicate that, for example, working at a frame rate of 12.5 Hz at 144X192 diluted format, will enable a similar detection range compared to a full format mode recognition range.

Power as a function of frame rate for several operation modes is shown in figure 10. Several and most common, operational modes are shown. BIRD is designed to support other modes of operation including random access row selection and 16 column group selection enabling the system engineer to tailor the detector format and resolution to the application needs.

Figure 10: BIRD ROIC power (TEC power is not included) as a function of frame rate at various operation modes. Looking at figure 10, it is clear that the system performance indicated in tables 2 and 3 for target detection can be achieved with under 60mW ROIC power consumption (144x192 check board dilution at 12.5Hz frame rate). Working
in Power Save mode and optimizing TEC power in this configuration can reduce the detector total power to under 80mW. Working with slower frame rate can reduce power even further.

5. SUMMARY AND CONCLUSIONS

Maintaining performance for a very long period is important in unattended applications. We have shown experimental results which verify the ability of BIRD to automatically keep the performance without any operator intervention. This is done by frame to frame internal ambient drift correction and RNU prediction features. BIRD detector has been operating for hours in a changing ambient temperature environment without any shutter operation. The power consumption of BIRD in the Power Save mode is less than 350mW including the TEC for the full operation temperature range (with no TEC power optimization). TEC power can be optimized for specific ambient temperature. An additional power reduction can be achieved with some performance tradeoff by selecting various operational modes – slower frame rates or diluted formats. These modes may be used to operate the detector for target detection and prolonged operational mission time. Once a target has been detected, the detector can easily change to target recognition mode by a simple communication protocol. This can be done with no degradation in target detection and recognition unattended system performance.

BIRD can be easily integrated into an unattended platform thus creating "high-end" benefits for the system: 25μ pitch with mid-format up to 288X384, VOx technology with virtually no 1/f noise, 5 or 10 mSec (by customer request) thermal time constant pixels. These, together with a flexible architecture design and internal drift compensation capabilities provide a real advantage for unattended applications.

ACKNOWLEDGMENTS

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