Temperature dependence of spatial noise in InSb focal plane arrays

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ABSTRACT
Performance of InSb focal plane array (FPA) detectors depends to a great extent on both the absolute temperature and the temperature fluctuations of the detector. The residual spatial noise, which can be achieved and maintained after a two-point non-uniformity correction (NUC), increases when the FPA temperature changes relative to that at which the NUC procedure was performed.

A model is described, which allows prediction of the InSb FPA residual non-uniformity (RNU) as a function of the FPA temperature fluctuations for a given set of the FPA, cold shield and background radiation parameters. The calculated values are confirmed by experimental data. It is demonstrated that, as predicted, RNU degradation is primarily caused by signal offset changes corresponding to the InSb dark current variations, which are induced by the FPA temperature instability.

The influence of the FPA temperature variation on NUC can be effectively compensated by a one-point offset correction. When this procedure is impractical, the dark current compensation method is proposed, which allows for a real-time, continuous compensation of the FPA temperature variations, resulting in a low residual non-uniformity.

Keywords: Focal Plane Array, FPA, Non-uniformity, NUC, InSb detector, Spatial noise.

1. INTRODUCTION
Signal non-uniformity among elements of two-dimensional staring array detectors gives rise to a spatial noise. Under typical operating conditions, considering also aperture effects on the illumination non-uniformity, this noise is larger than the temporal noise by about two orders of magnitude. Consequently, a non-uniformity correction (NUC) procedure must be applied in order to bring the spatial noise to or below the temporal noise level. The ability of the NUC algorithm to effectively reduce the spatial noise is critical to achieving of optimum detector performance.

Common NUC procedure is a two-point calibration algorithm, which assumes linear dependence of the output signal on the incoming radiation flux. This algorithm, when applied to InSb focal plane array (FPA) detectors, gives excellent results and is sufficient for most applications. However, it is sensitive to changes in FPA operating conditions, such as integration time, ambient temperature and FPA temperature. In InSb detectors the effects of FPA temperature variations are more pronounced, because there is a strong dependence of the detector dark current on the FPA temperature. Thus, in certain applications where the FPA temperature cannot be sufficiently well stabilized, FPA temperature fluctuations induce offset changes to the signal, which may result in a significant increase of the residual non-uniformity (RNU).

In this paper, two methods of recovery from the RNU degradation are presented. The first is a well-known one-point correction. Although extremely effective in compensating for any offset changes, its automatic implementation requires an optical hardware provision, and it is limited to those applications, which can tolerate off-line calibration procedure, during which the background and target image is interrupted. The second is the dark current compensation method, introduced here. It is based on understanding of the dark current mechanism in InSb detectors and its temperature dependence. Using this knowledge, additional non-uniformity calibration data can be provided for each FPA in order to allow for a real-time, continuous compensation of the temperature instability effects.

Although this work was performed on a 320×256 InSb detector array flip-chip bonded to an SCD CMOS readout integrated circuit, a similar technique can be applied to any InSb detector. In fact, the concept of the dark current compensation can be applied to other detectors as well, provided that the dark current dependence on the FPA temperature is known. In those cases where the temperature drifts may cause change in the quantum efficiency of the detector as well, a more elaborate numerical technique could be contemplated whereby both offset and gain dependence on the FPA temperature would be corrected.
2. NON-UNIFORMITY CORRECTION - REVIEW

By far the most popular method of improving the non-uniformity noise in two-dimensional FPA detectors is through the standard two-point correction procedure. Assuming a linear response to the incident flux and to the integration time, the output signal, S, coming out of any array element, (i,j), can be described as

\[ S_{i,j} = \left[ \eta_{i,j} \Phi(T_{bb}) + kI_{ex} \right] T_{int}, \]

where \( \Phi(T_{bb}) \) is the blackbody irradiance at a temperature \( T_{bb} \) in a specified spectral range, \( \eta_{i,j} \) is the quantum efficiency of each detector element corrected for aperture effects, \( T_{int} \) is the integration time, and \( k \) is a constant. The excess current, \( I_{ex} \), is the detector current offset, which consists of the intrinsic detector dark current, \( I_d \), and of all other offset current contributions, such as the stray light current, \( I_s \) (Equation [2]). It is the former component, originating in the reverse-biased InSb photodiode saturation (leakage) current, which strongly depends on the FPA temperature \( T_{FPA} \).

\[ I_{ex} = I_d(T_{FPA}) + I_s + ... \]

Equation [1] can be also written as:

\[ S_{i,j} = a_{i,j} \Phi + b_{i,j} \]

The goal of the two-point NUC is to transform the output signals of different array elements to a single value, as specified in Equation [4]. The gain (G) and offset (O) correction matrices, required to perform the NUC operation, are obtained by recording the signal of each pixel at two different temperatures of a uniform radiator, such as an extended blackbody. \( G_{i,j} \) and \( O_{i,j} \) can be expressed by \( a_{i,j} \) and \( b_{i,j} \) so that the resultant corrected signal

\[ S'_{i,j} = G_{i,j}S_{i,j} + O_{i,j}, \]

is uniform.

The image of a uniform extended blackbody produced by a 320×256 InSb FPA is shown in Figure 1. Both raw and two-point corrected images are presented using the same gray scale level. Two dominant spatial noise sources are observable in the raw image: the high-frequency pattern due to the readout circuitry column-wise gain non-uniformity, and the low-frequency concentric pattern created by the cold shield aperture \( \cos^4 \theta \) illumination non-uniformity. None of these fixed patterns is discernible in the two-point corrected image.

![Figure 1](image_url)

**Figure 1:** (a) - a raw image of an extended blackbody; (b) - the same image after a two-point correction.

Array non-uniformity is defined as the standard deviation (std) of the signal generated by a uniform target in all pixels, divided by the mean signal of the pixels (std/mean). The raw non-uniformity is typically in the range of 3÷7%, depending on the FPA size and cold shield height. The two-point NUC procedure usually brings the RNU below 0.1%.
3. RESIDUAL NON-UNIFORMITY DEPENDENCE ON FPA TEMPERATURE

From Equations [1] and [2] it is clear that fluctuations in the FPA temperature result in changes of the offset coefficient matrix, \((O)\), in Equation [4]. Therefore RNU may degrade when the FPA temperature significantly deviates from its value during the NUC procedure. Figure 2 shows the RNU obtained by a two-point NUC method at \(T_{FPA} = 78.5K\), and a dramatic RNU deterioration, when the original NUC coefficients \((G)\) and \((O)\) were also used to perform NUC at \(T_{FPA} = 85.5K, 88.5K\) and \(91K\). At \(T_{FPA} = 78.5K\) the RNU is at the level of 0.05% std/mean, and it increases to ~1% for a 10K temperature drift.

\[
\begin{align*}
S^*_{i,j} &= G_{i,j} \left(S_{i,j} + \Delta S\right) + O_{i,j} \\
&= G_{i,j} S_{i,j} + O_{i,j} + G_{i,j} \Delta S
\end{align*}
\]

\(G_{i,j} \Delta S\) is not uniform because \(G\) is not uniform (both the readout and illumination-induced fixed patterns contribute mainly to the gain non-uniformity). Moreover, if the offset change were different for each pixel, then the resultant non-uniformity would be worse, and given by the following expression:

\[
RNU = \frac{1}{\left\langle S^*_{i,j}\right\rangle} \Delta \left(G_{i,j} \Delta S_{i,j}\right) = \frac{1}{\left\langle S^*_{i,j}\right\rangle} \sqrt{\left(\Delta \left(G_{i,j}\right) \Delta S_{i,j}\right)^2 + \left(G_{i,j} \Delta \left(S_{i,j}\right)\right)^2} = \\
= \sqrt{\left(\frac{\Delta \left(G_{i,j}\right)}{\left\langle S^*_{i,j}\right\rangle}\right)^2 + \left(\frac{\Delta \left(S_{i,j}\right)}{\left\langle S^*_{i,j}\right\rangle}\right)^2}
\]

where \(\left\langle S^*_{i,j}\right\rangle\) is the mean corrected signal.

**Figure 2:** Residual non-uniformity deterioration after deviation of the FPA temperature from the NUC conditions.
For a common offset to all the pixels, $\Delta S_{ij} = \Delta S$, the average deviation of $\Delta S$ is zero and the non-uniformity becomes:

\[
NU = \frac{\Delta(G_{i,j})}{\langle G_{i,j} \rangle} \approx \frac{\langle G_{i,j} \rangle (\Delta S)_{ij}}{\langle G_{i,j} \rangle (S_{ij}^*)} = \frac{\Delta(G_{i,j})}{\langle G_{i,j} \rangle} \cdot \frac{\langle S_{ij}^* \rangle}{\langle S_{ij} \rangle}.
\]

[7]

If during the two-point NUC the response of all pixels is brought to the array mean value, then it is reasonable to assume $\langle G \rangle \approx 1$ because $G$ is a transformation matrix, which calibrates the specific responsivity of each pixel to the array mean responsivity. Since approximately half of the pixels have responsivity above the average value and another half - below, the average of all gain coefficients is approximately unity. Thus, if the responsivity distribution of 5% std/mean is assumed, the gain correction coefficient distribution, $\Delta G / \langle G \rangle$, is also about 5%. A similar derivation can be done for a gain variation after NUC, but it is beyond the scope of this paper.

As discussed earlier, the FPA temperature variation may cause significant offset changes in InSb FPAs. For the sake of simplicity it is assumed that the temperature change, $\Delta T_{FPA}$, is uniform across the detector array. It will be demonstrated later, that this assumption provides satisfactory results even for unrealistically wide span of temperature drift, and therefore should be sufficient for most practical cases. Furthermore, this assumption is mandatory for a relatively simple implementation of the real-time, numerical offset compensation method, suggested in Section 5.

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In InSb FPA detectors the offset change, $\Delta S$, due to FPA temperature drift is generated by the dark current variation. Figure 4 shows the offset (excess) current measured at different FPA temperatures. A very good fit to the equation:

\[
I_d(T_{FPA}) = I_0 e^{-E_g / 2kT_{FPA}},
\]

is also demonstrated (Eg is the InSb bandgap energy, k is Boltzmann’s constant, and $I_0$ - an empirical constant). In principle, both $E_g$ and $I_0$ are FPA-temperature dependent, but this dependence is relatively very weak and can be neglected. These results confirm a well-known fact, namely, that in cryogenic temperatures the main mechanism of the dark current the InSb photodiodes is generation-recombination in the depletion zone. This means that the dark current is proportional to the intrinsic carrier concentration, and therefore given by Equation [8].
Figure 4: Excess current as a function of the FPA temperature. Squares – measured data, dashed line – fit to Equation [8].

Understanding of the dark current mechanism enables an accurate prediction of the detector offset current variation with FPA temperature and, consequently, a good estimation of $\Delta S_{i,j}$ in InSb arrays. Table 1 summarizes RNU calculations based on Equations [7] and [8] for different FPA temperatures, using gain and offset coefficients from the two-point NUC at 78.5K. All calculations refer to measurements of an extended blackbody at 30 °C, which are shown as the data point with the lowest well fill at each $T_{FPA}$ in Figure 2. There is a good agreement between the RNU estimations in the table and the measured data shown in Figure 2.

This model can be used, for example, in order to specify cooler stability needed to achieve the required RNU for a specific configuration of an InSb FPA. In Section 5 we shall demonstrate that this model can be useful for a numerical compensation of the temperature-induced offset fluctuations, thereby allowing for a real-time preservation of the two-point NUC performance regardless of cooler instabilities, which may occur under varying ambient conditions.

Table 1: Calculated residual non-uniformity due to FPA temperature drift from 78.5K.

<table>
<thead>
<tr>
<th>FPA Temperature [K]</th>
<th>$I_d(T_{FPA})/I_d(78.5K)$</th>
<th>Average signal (S) [% saturation]</th>
<th>$\langle \Delta S \rangle / \langle S \rangle$</th>
<th>RNU [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.5</td>
<td>1.0</td>
<td>29</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>85.5</td>
<td>4.3</td>
<td>32</td>
<td>0.14</td>
<td>0.7</td>
</tr>
<tr>
<td>88.5</td>
<td>7.6</td>
<td>36</td>
<td>0.23</td>
<td>1.2</td>
</tr>
<tr>
<td>91.0</td>
<td>11.8</td>
<td>42</td>
<td>0.32</td>
<td>1.6</td>
</tr>
</tbody>
</table>

4. SOLUTION I: ONE-POINT OFFSET CORRECTION METHOD

In this paper two methods of dealing with the RNU degradation due to changes of FPA temperature are presented. This section deals with a well-known one-point offset correction method. It involves a measurement of a uniform target whenever the FPA temperature is changed, in order to update the offset coefficients ($O_{i,j}$). In the notation used here the original two-point NUC procedure involves image recording of a uniform target at two signal levels, $S_1$ and $S_2$, while the later, one-point offset correction is performed with a uniform target at an arbitrary signal level, $S_3$. This additional calibration image produces a matrix of offset coefficients, $O'$, so that $[G S_3 + O + O']$ is uniform.
Since, by definition, the corrected $S_3^*$ has to be uniform despite the offset $G\Delta S_3$ due to the FPA temperature drift, the measured offset correction term is given by: $O' = -G\Delta S_3$. The indices $i,j$ were left out for convenience. This method does not depend on the signal level, $S$, because:

\[
S_3^* = G(S_3 + \Delta S_3) + O + O' = GS_3 + O + G\Delta S_3 + O' = GS + O + G\Delta S - G\Delta S_3 = GS + O
\]

provided that $\Delta S$ does not depend on flux but only on the FPA temperature, and therefore $G\Delta S = G\Delta S_3$.

Figure 5 contains the same data as in Figure 2, but with updated offset correction coefficients. By using the one-point offset correction method, the original uniformity, as achieved with the two-point NUC, was restored.

5. SOLUTION II: DARK CURRENT COMPENSATION METHOD

The drawback of the one-point offset correction method is that it cannot be applied in real-time. When a temperature change occurs, the detector has to be calibrated against a uniform target, which means that the imaging of real scenery has to be interrupted, until the offset correction is updated. Naturally, this procedure is not always possible. Another method, introduced here, is the dark current compensation method. It uses prior knowledge of the offset dependence on the FPA temperature, as discussed earlier. It can numerically update the offset coefficients to compensate for the FPA temperature drift. Since this offset correction is purely computational, it can be performed without losing sight of the observed scenery, and, in principle, even on a continuous basis, if needed for highly demanding applications. The idea of compensating for the dark current change is probably general, but the behavior is typical for each detector.
As mentioned before, in InSb photovoltaic detectors the main mechanism of the dark current is generation-recombination in the depletion zone. Equation [8] can also be written in a general form:

\[ I_d(T_{\text{FPA}}) = I_0 e^{-\alpha T_{\text{FPA}}} \]

where \( \alpha \) and \( I_0 \) are constants which can be found empirically. We have found that for most practical purposes \( \alpha \) can be assumed constant not only for all the pixels in a given array, but even for different InSb FPAs as well. However, \( I_0 \) has a different value for each pixel, \((I_0)_{i,j}\). The matrix \( I_0 \) has to be measured and supplied by SCD with each specific FPA. For the best RNU results, this parameter should be optimized for every application, considering system requirements for both the FPA temperature span and the RNU level.

The results of this algorithm, as applied to data on Figure 2, are demonstrated in Figure 6. For large FPA temperature variations shown here, the results are not as good as the offset method, because the calculations are limited to the accuracy of the FPA temperature measurements. The FPA temperature accuracy is crucial to the validity of the algorithm, due to the exponential dependence of the dark current on temperature. Nevertheless, the improvement of the uniformity is dramatic. The range of the temperature drift presented here is extremely large. In most application the FPA temperature fluctuations are much smaller. In such cases the method yields very good results.

![Figure 6: Data from Figure 2 after applying the dark current compensation method.](image)

6. SUMMARY

In this paper the standard two-point correction algorithm was applied to an InSb 2-D FPA detector. It yields excellent results over a wide range of detector and background temperatures, which are sufficient for a vast majority of applications. However, in certain application, where the FPA temperature cannot be sufficiently well stabilized, residual non-uniformity can degrade to an unacceptable level. This problem relates to InSb detectors, because of the strong dependence of the InSb photodiode dark current on the FPA temperature. The problem is visually depicted in Figure 7, which presents images of a uniform target after: (a) - standard two-point NUC at \( T_{\text{FPA}} = 78.5 \text{K} \), and (b) - after a dramatic 12.5K change of the FPA temperature to 91K, while still using the original sets of gain and offset correction coefficients.

Two methods of dealing with this problem were described in this paper: the one-point offset correction and the dark current compensation model. The one-point offset method yields excellent results over a wide range of temperatures, as shown in image (c) in Figure 7. This method can be as effectively applied to any kind of offset changes, such as those induced by varying integration time, ambient temperature, or a signal dc offset, as well as to any combination thereof. However, it requires hardware provision in the optical path in order to generate a uniform scene at a temperature close to the background temperature. In addition, it cannot be applied simultaneously with the normal imaging operation, a limitation that may be unacceptable for some applications.
The dark current compensation method is a through real-time, numerical method, which can be applied continuously without image perturbation. It gives very good results over a reasonable span of FPA temperature fluctuations. This method does not require any optical hardware, such as uniform target or image defocusing, but it needs more computational resources, such as a digital signal processor (DSP) and extra memory to accommodate for additional correction tables, which should be supplied by the detector manufacturer.

Finally, the algorithm presented here is probably applicable to other detectors as well, provided that the behavior of the dark current is modeled. Such a model can both predict the effect of the temperature drift on offset, and compensate for it.

Figure 7: (a) - an extended blackbody image after NUC at 78.5K; (b) –the FPA temperature is raised to 91K; (c) – image (b) after applying of the one-point offset correction method, and (d) - image (b) after applying of the dark current compensation method.