Scene-Based Nonuniformity Correction Method Using Constant-Range: Performance and Analysis

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ABSTRACT
This paper discusses the performance and analysis of a recently published scene-based statistical technique for nonuniformity correction (NUC) of infrared focal plane arrays (FPA). In particular, the method is improved by reducing the number of parameters computing in real-time from three (gain, offset and the standard deviation of the temporal noise) to two (gain and offset). A simple statistical technique to estimate the so-called Constant-Range from the noisy sequences of infrared frames has been developed. A recursive version of the Constant-Range NUC method per pixel and per frame using the $L_1$ norm has been also developed. The Constant-Range method can not estimate the gain of a few individual pixels in which the read-out is constant in the sequence. A technique to estimate the gain of such pixels has been also derived. The performance of the proposed modifications for the constant-range NUC method and its ability to compensate for nonuniformity noise is demonstrated using sequences of infrared imagery with both real and simulated nonuniformity.

Keywords: Focal-plane array detectors, nonuniformity correction, infrared sensors.

1. INTRODUCTION
The performance of charge-coupled device (CCD) infrared focal-plane arrays (FPAs) is known to be affected by the random spatial and temporal nonuniformity in the detectors' photoresponse. Spatial nonuniformity is due to the fact that each individual detector in the FPA has different characteristic from neighboring detectors. What is meant by temporal nonuniformity is the slow temporal variation (with respect to the frame time) in the characteristic of each detector. Normally, the FPA is calibrated periodically using unless two sources of uniform radiation (black-body radiation). The radiation source could be costly, bulky, heavy, and it requires the FPA to steer away from the target and point to the radiation source during the calibration. Calibration is therefore a burden in many applications such satellite imaging and aerial reconnaissance. These considerations support the need for developing algorithms that correct spatial and temporal pixel nonuniformities in real time (Scene-based NUC). Several Scene-based NUC methods have been published in the literature. Statistical Scene-based NUC methods have been developed by Narendra et al. [1, 2], Harris and Chiang [3, 4], and Hayat and Torres [5, 6, 7, 8, 9]. These algorithms continually compensate for spatial and temporal noise. In this paper, we analysis and improve the scene-based statistical method reported in [5, 6, 7, 8, 9]. The performance of the method is improved by reducing the number of parameters computing in real-time from three (gain, offset and the standard deviation of the temporal noise) to two (gain and offset). It is shown using sequences of infrared data with both real and simulated temporal noise, that the constant-range method is able to compensate for nonuniformity without the estimation of the read-out noise. A key assumption in the Constant-Range NUC method is that within each sequence of frames, all detectors are exposed to approximately the same range of irradiance. A simple statistical technique to estimate the Constant-Range from the noisy sequences of infrared frames has been developed. It is shown using real infrared data and such technique that the frames compensated by the Constant-Range method has also been developed. This recursive version is applied to sequences of infrared frames with both real and simulated nonuniformity. The performance parameter $Rho$ [5, 6, 7, 9] is computed to determine the minimum number of frames needed to reach good NUC and to evaluate the dependence
on the level of nonuniformity. The number of operations per pixel and per frame is also calculated. Sometimes, with real infrared data, the Constant-Range method can not estimate the gain of a few individual pixels in which the read-out is constant in the sequence. A technique to estimate the gain of such pixels has been also developed and applied to a sequences of real infrared data with targets in motion and background with many pixels with constant read-out during the sequences. This paper is organized as follows. In Section 2 we improved the constant-range NUC method eliminating the real-time estimation of the temporal noise. In Section 3 we develop a statistical technique to estimate the Constant-Range from the noisy sequences of infrared frames. Section 4 contains a recursive version of the Constant-Range NUC method per pixel and per frame using the $L_1$ norm and Section 5 considers a technique to estimate the gain of pixels in which the read-out is constant in the sequence. Section 6 presents the conclusions.

## 2. TEMPORAL NOISE

In this section, we study the effect of eliminating the temporal noise from the linear detector model used by the constant-range NUC method. The constant-range NUC method considers for the $(i, j)_t$th detector in the FPA, and at time $n$, that the read-out signal $Y_{ij}(n)$ is approximately given by the relation $[5, 6, 7, 9]$

$$Y_{ij}(n) = A_{ij}(n) \cdot X_{ij}(n) + B_{ij}(n) + V_{ij}(n), \quad (1)$$

where $A_{ij}(n)$ and $B_{ij}(n)$ are the gain and the offset associated with the $(i, j)_t$th detector at time $n$, respectively, and $X_{ij}(n)$ is the irradiance collected by the detector during the detection integration time. The term $V_{ij}(n)$ represents the additive read-out noise associated with the $(i, j)_t$th detector at time $n$. Then, the constant-range NUC method has to estimate in real time three parameters: the gain, the offset and the standard deviation of the temporal noise $[5, 6, 7, 9]$. It is known that scene-based NUC methods are limited by the trade-off between the time required to collect calibration infrared data and the drift in the detectors response which occurs on a time-scale near to the compensation time. In this paper, we modify the constant-range method in such a way that it adaptively performs NUC, using the scene data to estimate in real time only the gain and the offset of each pixel on the FPA.

From now on, the subscripts $ij$ will be omitted from all the variables with the understanding that all operations are performed on a detector-by-detector basis. After simple operations, it can be shown that the gain and the offset of each detector on the FPA are given by

$$A^2 = \frac{\sigma_Y^2 - \sigma_X^2}{\sigma_X^2}, \quad (2)$$
$$B = E[Y] - A \cdot E[X], \quad (3)$$

where $\sigma_Y^2$ and $E[Y]$ are the variance and the mean of the read-out data respectively. The collected irradiance $X$ is assumed a uniformly-distribute random variable in a fixed range common to all detectors. Then, $\sigma_X^2$ and $E[X]$ are variance and the mean of the infrared irradiance (see Section 3).

First, we study the dependence of the method on the temporal noise applying it to a set of terrestrial infrared data. The data set was collected using a 128×128 InSb FPA camera (Amber Model AE-4128) operating in the $3 \sim 5 \mu m$ range and with a rate of 30 frames per second. We estimate the gain and the offset considering and no considering the temporal noise. The nonuniformity compensation is performed by simple subtracting the estimated offset from the data and dividing the outcome by the estimated gain. The NUC capability is measured by means of the softness parameter Rho. Rho is defined for any image $f$ by $[5, 6, 7, 9]$

$$Rho(f) \triangleq \frac{||h \ast f||_1 + ||h^T \ast f||_1}{||f||_1}, \quad (4)$$

where $h$ is a horizontal mask $[1, -1]$, $||f||_1$ is the $L_1$ norm of $f$, and $\ast$ represents discrete convolution. Note that, Rho is zero for a uniform image and it increases with the detector-to-detector variation in the image. Moreover, Rho can be used as a measure of NUC in real infrared data as well as simulated data.

Figures (1), (2) and (3) show a frame with real nonuniformity, the corrected frame considering the temporal noise, and the corrected frame without considering the temporal noise respectively. The parameters Rho compute for the raw frame and corrected frames, demonstrate a reduction in the nonuniformity by a factor of 3. Notably, the parameter Rho computed for the frame compensate without considering the temporal noise is smaller than the one computed considering the temporal noise.

Now, we study the dependence of the method on the temporal noise applying it to a set of infrared data corrupted by simulated temporal noise. The parameter Rho is calculated for each trial of the simulation-based analysis and averaged over the total trials. The mean of the gain is assumed to be one and the mean value of the offset as well as the mean value of the temporal noise is taken as zero. As an example, Figure (4) show an infrared image corrupted with a simulated temporal noise with a standard deviation equal to 10. Figure (5) depicts the parameter Rho computed on the corrected frame. The compensation of nonuniformity is implemented considering and without considering the temporal noise. Note that the parameter Rho is a little greater when the temporal noise is considered. This is explained since Rho is sensible to the dynamic range of the images. The images compensated considering the temporal noise have a greater dynamic range than those compensated without considering the temporal noise and than the raw frames (see Figures (1), (2) and (3)). Note also that Rho is independent of the level of temporal...
noise added to the images. Finally, Figure (6) shows the parameter Rho computed on the uncorrected frame versus the standard deviation of the temporal noise.

3. CONSTANT RANGE

The key assumption in the constant-range method is that within each sequence of frames, all detectors are exposed to approximately the same range of irradiance \([X_{\text{min}}, X_{\text{max}}]\), a condition which can be met, for example in the presence of motion. It is important to note that the constant-range \([X_{\text{min}}, X_{\text{max}}]\) is an input for the method and it could be in theory any pair of numbers; for example previous papers have used \([X_{\text{min}} = 18, X_{\text{max}} = 30]\) and \([X_{\text{min}} = 0, X_{\text{max}} = 255]\) [5, 6, 7, 9]. Compensation does not depend of the constant-range chosen for the input infrared irradiance. What depend of the constant range chosen is the post-processing image operations on corrected frames. In this section, we present a simple method to estimate this constant-range from the raw data. The method is quite simple and it contains the following steps: 1) Normalize the raw data to the gray scale, 2) Look for the minimum values of the normalized read-out data through the infrared sequence for each pixel on the FPA, 3) Look for the maximum values of the normalized read-out data through the infrared sequence for each pixel on the FPA, 4) Take the medium value of the minimum and the maximum read-outs and used them as \([X_{\text{min}}, X_{\text{max}}]\) respectively.

Figures (7) and (8) show a histogram of the minimum and the maximum read-outs over all the pixels and over 3000 real infrared frames respectively. The medium values of the minimum and the maximum read-outs are 34 and 255 respectively. Therefore, the constant-range irradiance is taken equal to \([X_{\text{min}} = 34, X_{\text{max}} = 255]\). Figures (3) and (9) show a frame corrected with \([X_{\text{min}} = 34, X_{\text{max}} = 255]\) and the corrected frame considering \([X_{\text{min}} = 0, X_{\text{max}} = 255]\) respectively. Note that, using the estimate constant-range, the dynamic range of the corrected image is very close to the dynamic range of the raw frame.
4. RECURSIVE VERSION OF THE CONSTANT-RANGE METHOD

In this Section, we present a recursive version of the constant range method per pixel and per frame based in the job published by Harris [3, 4]. The equations (5) and (6) are used to estimate the mean and the standard deviation of the read-out data per pixel and per frame. The gain is estimate dividing the estimate standard deviation of the read-out noise by the standard deviation of input infrared irradiance. The offset is estimate subtracting from estimate mean of the read-out data the product between the estimate gain and the mean of the input irradiance.

Figures (10), (11) and (12) show a frame corrected considering 10 frames, a frame corrected considering 100 frames, and the parameter Rho calculated on the corrected frame versus the number of frames used in the correction.

\[
E[Y(n)] = \frac{Y(n) + (n - 1) \cdot E[Y(n - 1)]}{n}, \quad (5)
\]

\[
\sigma_Y(n) = \frac{|Y(n) - E[Y(n)]| + (n - 1)\sigma_Y(n - 1)}{n}, \quad (6)
\]

5. PIXELS WITH CONSTANT READ-OUT

The constant-range method can not estimate the gain of pixels in which the read-out lecture is constant during the infrared sequence. In this section, we show a technique to resolve that situation. The technique is also quite simple and it consists of replacing the variance over the read-out data of such pixels for the variance of the closest non-zero variance pixel.

Figures (13) and (14) show the corrected first and the corrected last frame of a sequence of real infrared data with a target in motion and several pixels with constant read-out data respectively. The pixels with constant read-out values are situated out of the trajectory of the target.
6. CONCLUSIONS

In this paper, we analyzed and improved the constant-range scene base NUC method. The method is improved reducing the number of parameters estimating in real-time from three (gain, offset and the standard deviation of the temporal noise) to two (gain and offset). It is shown using real infrared data and simulations that the constant-range method is able to compensate for nonuniformity without the estimation of the temporal noise. In fact, using the performance parameter Rho and simulations; it is shown that a good and similar compensation is reached for any level of temporal noise. The method is also improved by incorporating a simple statistical technique to estimate the constant-range from the noisy sequences of infrared frames. It is shown using real infrared data that with such technique the contrast of the corrected frames is almost the same as the contrast of the raw frames. Using the recursive version of the constant-range NUC method per pixel and per frame presented; it is shown that good nonuniformity is reached with approximated 100 frames. Finally, using a technique to estimate the gain of pixels with constant read-out lectures. It is shown in a sequence of real infrared data with a target in motion that such situation can occurs and its solution is simple.

7. ACKNOWLEDGMENTS

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8. REFERENCES


Figure 13: The first frame of a sequence of images of a target with constant background.

Figure 14: The last frame (frame 1200) of a sequence of images of a target with constant background.