New approach to thermal drift correction and gain determination in microbolometer thermal cameras

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Abstract

The authors proposed a novel approach to non-uniformity correction (NUC) of microbolometer focal plane arrays in microbolometer thermal cameras. This approach includes thermal drift correction without interrupting the thermal observation. For this purpose a translucent shutter is used instead of an opaque one. The authors provide detailed description of the proposed thermal drift correction approach. Another proposed technique enables verification if gain coefficients of microbolometers remain stable – this requires an IR emitter to be built into the camera. In this paper the latest advances on the proposed NUC approach are presented.

1. Introduction

This paper deals with the problem of non-uniformity correction of microbolometer focal plane arrays (FPA), which are commonly used in thermal cameras. Each microbolometer, as an element of this array, may be considered as a pixel detector of the thermal radiation, and thermal cameras contain typically from 384×288 to 1024×768 single microbolometers. The infrared radiation is focused through the camera lens and heats up the microbolometer matrix. The microbolometers' temperature value changes are few hundred times lower than the changes of scene temperature values. Therefore the readout circuit (ROIC) integrated with the microbolometer matrix has to be very sensitive. Unfortunately this condition alone is insufficient to provide clear thermal image from the focal plane array - in practice it turns out that raw thermograms are extremely noisy and therefore unusable. An example is shown in fig. 1a. This noise results from the fact, that each single microbolometer has a different response to the same infrared excitation. It may be taken for the sake of simplicity, that this response is linear, with different (often random) gain and offset values. This randomization, caused by the technological spread, is referred to as non-uniformity and must be subjected to correction to enable acquisition of usable thermograms. If the correction addresses only offset values, it is called one-point NUC (non-uniformity correction). Although qualitative improvement it introduces is clearly visible (fig. 1b), it is advised to rely on two-point NUC, which also takes into account gain values - thermogram after two-point NUC is shown in Fig. 1c.

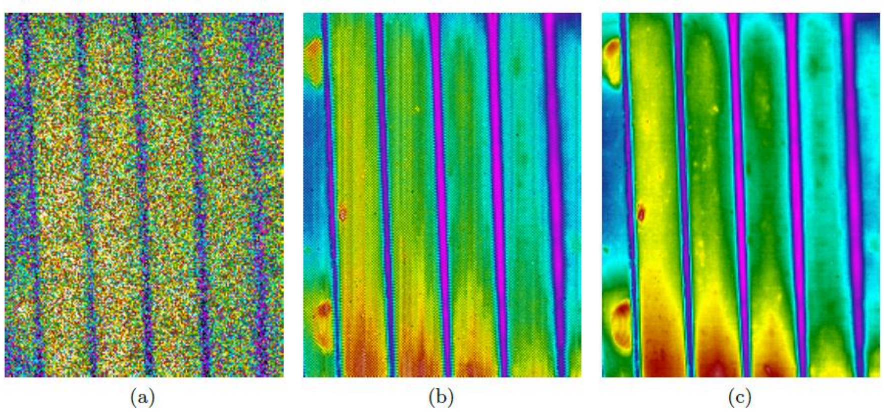


Fig. 1. (a) Exemplary thermogram before non-uniformity correction, (b) after one-point or (c) two-point non-uniformity correction.

2. Current approaches to thermal drift correction

The main problem to be addressed is the thermal drift (influence of microbolometer detector housing temperature variations resulting in the appearance of false temperature gradients in thermograms). This phenomenon causes improper temperature measurement and thermogram nonuniformity. Due to the presence of thermal drift, the values of offset factors change unevenly with time. Hence it is required to constantly perform thermal drift correction and periodically update the array of correction factor values. Without this correction, the error of temperature measurement could increase by about 0.7 °C every minute (in average). Locally (for some pixels) this value, however, might even exceed 1 °C per minute.

The most commonly used approach is shutter-based. It means that an opaque shutter is built into the thermal camera (fig. 2a) and it is automatically and periodically introduced between the lens and the FPA (fig. 2b). It enables updating of offset correction factors. The drawback of this method is that every minute this shutter disturbs the thermal observation resulting in periodically “frozen” image for one to two seconds. What is more, this approach assumes that all microbolometers have gain values corrected at the factory, and there is no need to repeat this correction.

To perform the two-point nonuniformity correction with well-known shutter approach, it is necessary to record a sequence of consecutive frames showing the shutter surface. In theory one frame would be enough, but in practice it is advised to average in time domain at least 20 consecutive frames to reduce the noise and effects of microbolometers’ time constants. Offset correction factors *o* for each single microbolometer at position i,j in the array may be calculated with eq. (1):

$$o_{ij} = \overline{Y}\,(T_{ref}) - g_{ij} Y_{ij}(T_{ref}) \tag{1}$$

where:

$\overline{Y}(T_{ref})$ – averaged response of microbolometers to the thermal excitation T_{ref} (shutter reference temperature value),
g_{ij} – value of gain correction factor for microbolometer at the position i,j in the array
$Y_{ij}(T_{ref})$ – response of microbolometer at the position i,j to the thermal excitation T_{ref} (shutter reference temperature value).

Of course this method assumes that shutter temperature value is known (measured with an additional sensor) and also gain correction factors were pre-determined at the stage of thermal camera production. Then it is possible to apply eq. (2) to determine response of each single microbolometer to scene temperature *T* after two-point non-uniformity correction.

$$Y^{2p}{}_{ij}\,(T) = g_{ij} Y_{ij}(T) + o_{ij} \tag{2}$$

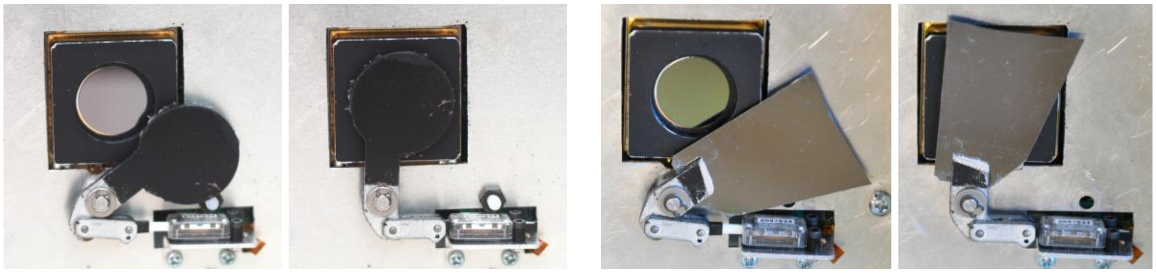
Taking into account the assumption about the pre-determined gain correction factor values, and the fact that nowadays the operation of the vast majority of thermal cameras rely on this assumption, the authors proposed a method to verify if microbolometers’ gain values remain unchanged. In case of detection that gain values changed, it is possible to compensate for observed differences [1,2].

Another and more important improvement proposed by the authors is to replace the shutter which is opaque for infrared radiation (fig. 2a) with a shutter that is translucent for IR (fig. 2c) [3,4]. This translucent shutter has to be periodically introduced in front of the detector (fig. 2d) similarly as an opaque shutter in traditional solution (fig. 2b). The aim of the proposed method is to preserve the advantages of shutter-based method and eliminate its main disadvantage – periodical image “freezing”. This method is described in the next chapter.

It is worth noting that there is another group of currently known and widely used shutterless non-uniformity correction methods [5] referred to as SBNUC (Scene Based Non-Uniformity Correction). The idea behind these methods is to determine offset correction factor values basing on statistical analysis of scene movement. Hence these methods are applied in observation cameras only, because measurement cameras are often used in stationary conditions. In addition, SBNUC methods generally are unable to correlate signal levels with temperature values, because there is no reference such as shutter temperature value measured with other sensor.

3. Thermal drift correction with the proposed method

The proposed method for the thermal drift (offset non-uniformity) correction uses a shutter translucent for IR, which is periodically introduced in front of the detector (similarly as a shutter in traditional NUC solutions) – fig.2. Knowing the transmittance of the translucent shutter for infrared radiation, it is possible to calculate the microbolometer matrix offset map, and use it to perform offset correction. During the instantaneous translucent shutter usage it is possible to compensate for its transmission to deliver the live thermal image to the camera screen (displayed temperature values have to be increased by a factor equal to the transmission loss introduced by the translucent shutter). The method relies on the fact, that the translucent shutter with an uniform transmittance factor is an additional source of infrared radiation for the FPA.



a) ***opaque*** *shutter open and closed* **b)** ***translucent*** *shutter open and closed*

Fig. 2. *Images of a) opaque and b) translucent shutter mounted inside the thermal camera*

The principle of operation requires the translucent shutter to be periodically inserted by the camera mechanism in front of the FPA for about one second. During this time reference thermograms are recorded. If the shutter transmittance is 0%, we have a particular case, which is well known shutter-based approach. If the transmittance was 100%, the proposed method wouldn't work – there would be no difference from normal observation.

It is required to acquire two series of thermograms (with the shortest possible time delay) – before introduction of the translucent shutter, and directly after inserting it in front of the FPA. During those acquisitions the movement of scene objects is allowed as long as there is thermally uniform scene background or the camera is stationary – this is the limitation of this method. The translucent shutter temperature has to be measured using contact method by the camera for the correction purposes. This may be done with e.g. with a thermocouple.

Let us assume that the camera acquires raw thermograms (without any correction). In t_0 time instant there was a mirror placed instead of the shutter and camera recorded thermogram $Y_{ij}^{ref}(\emptyset_m)$ showing reflections of microbolometer FPA. In order to perform non-uniformity correction in time instant t_1, it is required to acquire image $Y_{ij}(\emptyset)$ without the shutter. Next, without any delay the translucent shutter should be introduced and thermogram $Y_{ij}^{prz}(\emptyset,\emptyset_p,\emptyset_m)$ acquired. This image, basing on Kirchhoff's law, may be written with eq. (3) assuming known values of translucent shutter's transmission τ, emissivity ε and reflectance ρ. In addition it is necessary to temporarily assume that the scene was stationary.

$$Y_{ij}^{prz}(\phi,\phi_p,\phi_m) = \tau Y_{ij}(\phi) + \varepsilon Y_{ij}^{ref}(\phi_p) + \rho Y_{ij}^{ref}(\phi_m) \tag{3}$$

Hence the thermogram $Y_{ij}^{ref}(\emptyset_p)$ of the translucent shutter surface may be described with eq. (4). This thermogram is independent on scene radiation $(\emptyset)$ and reflections of FPA $(\emptyset_m)$ in the surface of the translucent shutter.

$$Y_{ij}^{ref}(\phi_p) = \frac{Y_{ij}^{prz}(\phi,\phi_p,\phi_m) - \tau Y_{ij} - \rho Y_{ij}^{ref}(\phi_m)}{\varepsilon} \tag{4}$$

Next, similarly as in traditional approach, it is necessary to determine the mean image value $\overline{Y_{ij}^{ref}(\emptyset_p)}$. It enables determination of values of offset correction factors valid for t_1 time instant – eq. (5):

$$o_{ij} = \overline{Y^{ref}(\phi_p)} - Y_{ij}^{ref}(\phi_p) \tag{5}$$

This equation is valid under the assumption that the temperature of the translucent shutter is uniform. It is also necessary to assume constant FPA structure temperature (thanks to Peltier cell), what ensures the stability of thermogram $Y_{ij}^{ref}(\emptyset_m)$.

To perform two-point non-uniformity correction with the proposed method one may use eq. (6), which is equivalent to eq (5) but with added gain correction factors g_{ij}. These factors must be known, but it is easy to determine it with two blackbodies at the stage of camera production or calibration.

$$o_{ij} = \overline{Y^{ref}(\phi_p)} - g_{ij} Y_{ij}^{ref}(\phi_p) \tag{6}$$

The last step is to use eq. (7) to determine the thermogram after two-point non-uniformity correction with the proposed method.

$$Y_{ij}^{2p}(\phi) = g_{ij} Y_{ij}(\phi) + o_{ij} = g_{ij}\left(Y_{ij}(\phi) - Y_{ij}^{ref}(\phi_p)\right) + \overline{Y^{ref}(\phi_p)} \tag{7}$$

4. Thermal drift correction results

The proposed method of thermal drift correction was tested for blackbody model. To estimate its efficiency, RNU (residual non-uniformity) values were calculated with eq. (9) both for uncorrected and corrected thermograms acquired during 15 minute test session. Results are shown in fig. 3.

$$s_Y = \sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(Y_{ij} - \overline{Y}\right)^2} \tag{8}$$

$$\mathrm{RNU} = \frac{s_Y}{\overline{Y}} \cdot 100\% \tag{9}$$

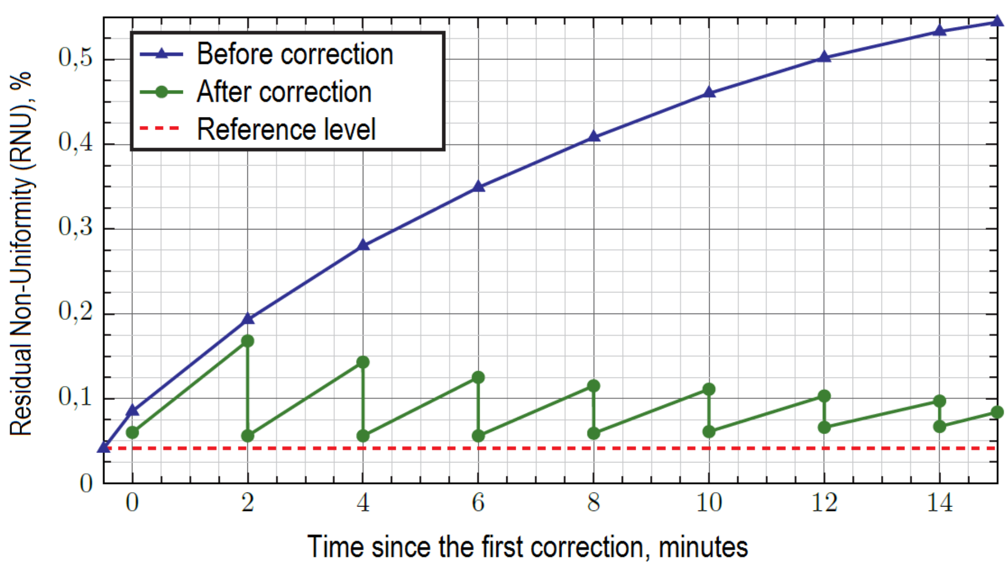
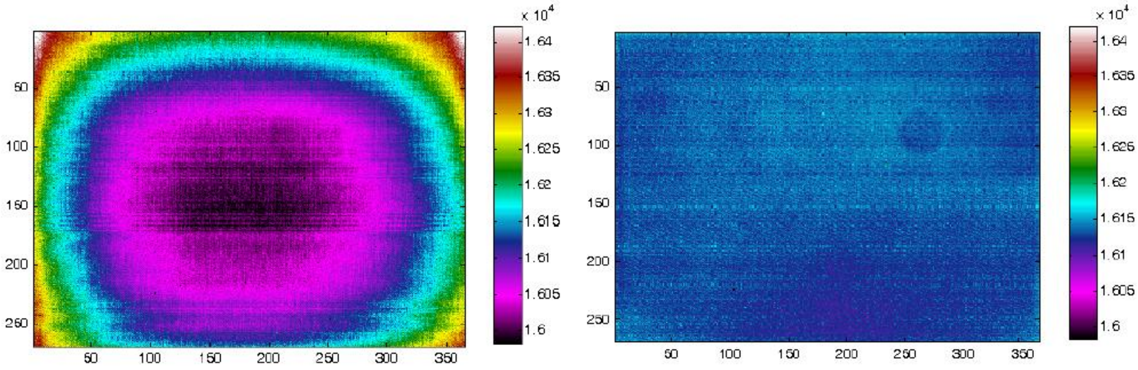


Fig. 3. *Efficiency of the proposed method of thermal drift correction tested with blackbody model*

Fig. 3 proves that the proposed method is very efficient. In this particular case the update of offset correction factors is done every two minutes and just after the updates the RNU values are very close to the reference level. In addition, in fig. 4a and 4b there is an exemplary comparison of raw and corrected thermograms (both with the same scale).



(a) $Y_{ij}(\phi)$ (b) $Y_{ij}^{2p}(\phi)$

Fig. 4. *a) Raw thermogram, b) thermogram a) corrected with the proposed method*

As presented above, it is possible to obtain high non-uniformity correction efficiency with the proposed method, but under two strictly defined conditions:

- it is required to know very precisely the values of translucent shutter emissivity value ε, transmission τ and reflectance ρ factor. Otherwise the temperature measurement error may rise rapidly, as shown in simulation - fig. 5. This simulation was performed for different pairs of τ and ε values of translucent shutter. The lowest value of mean scene temperature measurement error is obtained when user knows and uses for calculations exact value of τ.

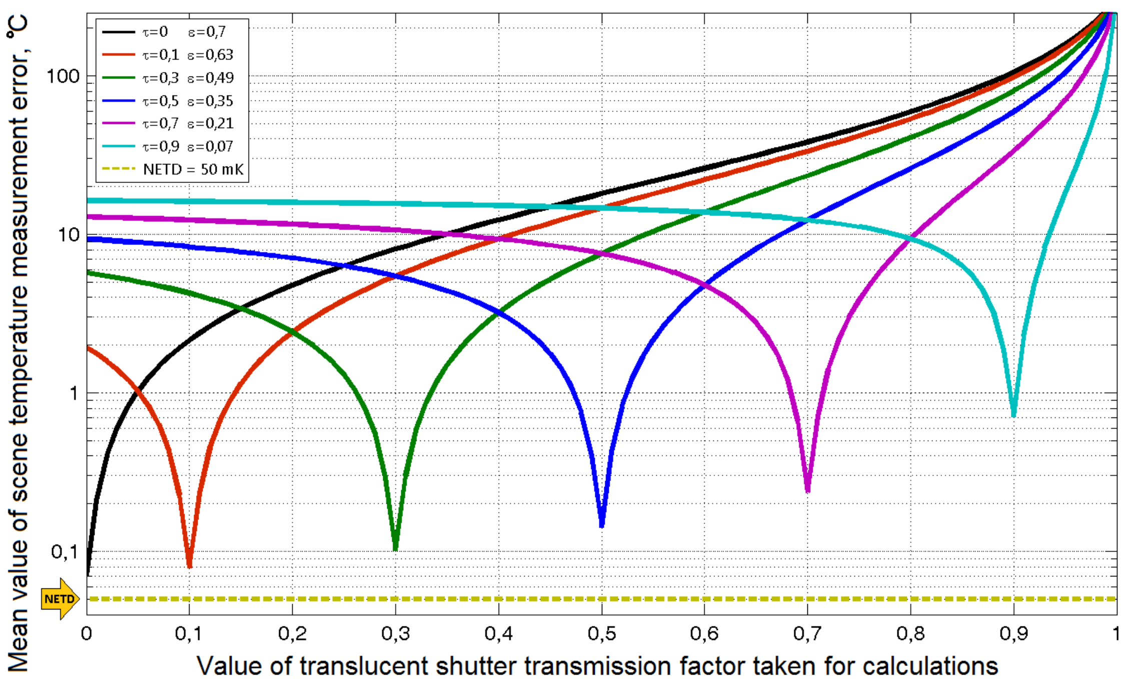


Fig. 5. Simulation of mean value of scene temperature measurement error versus the value of translucent shutter transmission factor taken by the user for calculations

- acquisition of thermograms with and without translucent shutter for the correction purposes is not limited to single frames – it is advised to perform averaging in time domain from at least 20 frames to reduce noise. It is clearly visible in simulation (fig. 6) that without averaging the histogram of corrected thermogram is much wider compared to the reference one (fig. 6a) than with averaging from 20 frames (fig. 6b). Note that different horizontal scales in both cases (signal level and temperature) do not influence above mentioned observations.

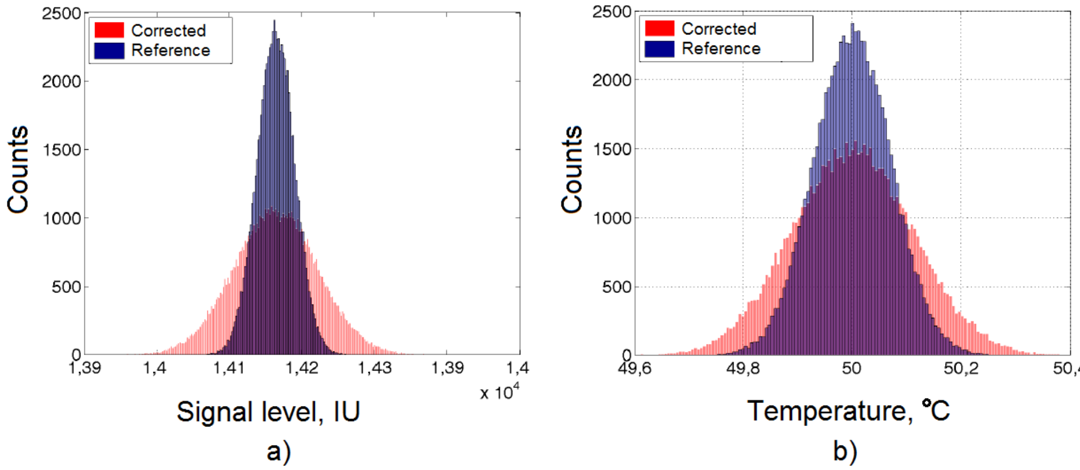


Fig. 6. Simulated exemplary histograms of corrected and reference thermograms for a) correction without frame averaging, b) 20 frames averaged in time domain

There are differences between corrected and reference histograms in both fig. 6a and 6b, and it is unfortunately the disadvantage of the proposed thermal drift correction method. This difference is dependent on the τ value of translucent shutter – the higher is τ, the higher is this difference. On the other hand, the higher is τ, the less noise is introduced to the live image during translucent shutter usage. The optimal value of translucent shutter transmission factor proposed by the authors is about 0.82, because with 20 frames averaging in time domain it is possible to obtain the mean error of temperature measurement at the level of 0.09 °C directly after the thermal drift correction with the proposed method.

5. Conclusions

Thermal drift correction with the proposed method is less efficient than classic opaque-shutter-based approach, but it enables two-point nonuniformity correction without interruption of the thermal observation – it was not possible in the case of traditional shutter-based method. Knowing the transmittance of the translucent shutter, camera may compensate for it when displaying thermogram, so that its introduction may be invisible for the user. Proposed method was proven to be useful and efficient for applications such as shutterless measurement thermal cameras. It is planned to replace the translucent shutter with tunable one, to simplify the construction and remove mechanical motor otherwise necessary for removing and inserting the shutter.

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