NON-UNIFORMITY CORRECTION IN MICROBOLOMETER ARRAY WITH TEMPERATURE INFLUENCE COMPENSATION

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Abstract

In the article a non-uniformity correction method is presented which allows to compensate for the influence of detector's temperature drift. For this purpose, dependency between output signal value and the temperature of the detector array was investigated. Additionally the influence of the temperature on the Offset and Gain coefficients was measured. Presented method utilizes estimated dependency between output signal of detectors and their temperature. In the presented method, the shutter is used for establishing signal reference. Thermoelectric cooler is used for changing the temperature of the detector array.

Keywords: microbolometer, non-uniformity correction.

1. Introduction

A microbolometer belongs to the group of thermal detectors and consist of temperature sensitive resistor which is exposed to measured radiation flux. A bolometer array employs a pixel structure prepared in silicon micromachining technology (MEMS). The detecting area is defined by the size of a thin membrane, usually made of amorphous silicon (aSi) or vanadium oxide (VOx). The detecting area is coated with material having high absorption coefficient. A resistive bolometer changes its electrical resistance with temperature due to absorption of electromagnetic radiation [1]. The trend of resistance change depends on material on the active area. If the resistance increases with increasing temperature (metal) the bolometer is said to have a positive temperature coefficient, otherwise it is said to have a negative temperature coefficient (semiconductors). The resistance of a bolometer is measured by an electronic readout circuit and converted to the output voltage signal.
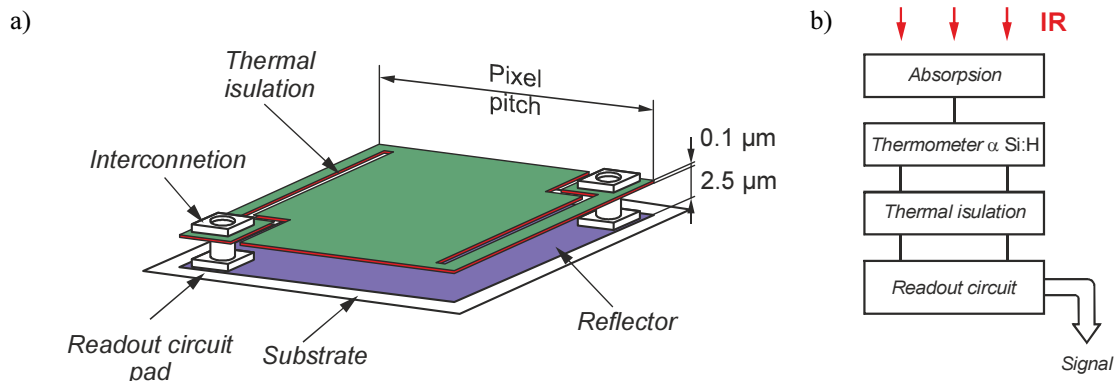

Fig. 1. A single microbolometer (a) and the principle of its operation (b).

Fig. 1 presents structure of a single microbolometer detector and its principle of operation. Focal Plane Arrays (FPAs) are made of a multitude of detector elements (for example 640 × 480), where each individual detector has a different responsiveness and offset due to the detector-to-detector spread in the FPA fabrication process [2]. Additionally, it can change with the sensor operating temperature, biasing voltage variation or temperature of the observed scene [11]. The difference in a responsiveness and offset among detectors (which is called non-uniformity), together with their high sensitivity, produces a fixed pattern noise (FPN) on the produced image. The FPN degrades parameters of infrared cameras, like sensitivity or NEDT. Additionally, it degrades the image quality, radiometric accuracy and temperature resolution.

2. Procedure of a non-uniformity correction

A non-uniformity correction (NUC) is a digital process of removing the FPN from the image using digital signal processing techniques on the detector output signal. The FPN removal process requires knowledge of correction coefficients for every detector in the array [3].

The calibration-based technique is the simplest, most accurate and most common NUC method used to correct non-uniformities [10]. Calibration-based methods include a single point correction (SPC), a two point correction (TPC), a multiple point correction (also known as a piecewise linear correction), and an improved two point correction algorithm. In these methods, the gain and offset parameters are estimated by exposing the FPA to different uniform blackbody temperatures depending on the algorithm adopted [5]. In a multiple point correction the detector is exposed to several black bodies at different temperatures to divide nonlinear characteristic to piece–wise linear sections. This approach requires a significant increase in the capability of the NUC electronics and a precise calibration source [3, 5].

The next group of the NUC is a group of scene-based algorithms. The scene-based algorithms are divided into two types [7]:
- statistical methods,
- registration-based methods.

The constraint for the statistical methods is the temporal statistics being only roughly constant for each pixel. The constant statistics method assumes that the temporal means and variances are identical for all pixels [6]. This constraint assumes that the detector array is actually periodically moving and that the average statistics of each pixel image should be constant when averaged over a very long time. In pathological situations where humans or machines are forced to stare at a single static scene for a long time, this assumption is violated. Additionally, this method requires a large number of frames for calculation of the NUC coefficients. The accuracy of the correction strongly depends on the number of analysed images.

The second one is a registration-based group of methods. This type of algorithms do not use or require any statistical assumptions about the scene and could estimate the non-uniformity in a much smaller number of image frames. These methods consider that each detector should have the identical response when observing the same scene point [8, 9]. Therefore, registration-based methods require accurate estimation of the motion between frames.

All scene-based non-uniformity correction algorithms require that the objects in the image do not remain stationary for too long. This can be accomplished by either periodically moving the camera or else requiring objects in the scene to move [7]. If an object in the image violates this assumption and remains stationary for a large number of iterations, the object will blend

into the background. If this stationary object eventually moves from the field of view, it will leave a reverse ghost image in the scene.

The first group of scene-based algorithms requires a large number of frames. In the second one there is a high risk of a ghosting effect. The benefit of using scene-based algorithms is avoiding the necessity of calibration during manufacturing. It allows for correcting the gain and the offset errors without using special calibration images and procedures. In practice, a shutter is not used in the camera.

In comparison to scene-based algorithms the calibration-based technique is more dependable, simplest and most accurate. There is no ghost effect or another risk, like algorithm faults. One of its disadvantages is the calibration with use of a reference target which is indispensable. Additionally, those methods need an adequate amount of memory space for storing the table of correction coefficients depending on the number of calibration points. For this reasons the most commonly used algorithm is a two point correction method. This method allows to correct both the responsiveness variation and offset spread, and is described by the equation:

$$U_{ij}^{*}(\Phi) = G_{ij}U_{ij}(\Phi) + O_{ij},$$

(1)

where $U_{ij}(\Phi)$ is the response of a i,j detector before correction, $U_{ij}^{*}(\Phi)$ is the response after correction, G_{ij} i O_{ij} are the GAIN and OFFSET correction coefficients of the detector characteristics. The correction coefficients GAIN and OFFSET are described by:

$$G_{ij} = \frac{U(\Phi_2) - U(\Phi_1)}{U_{ij}(\Phi_2) - U_{ij}(\Phi_1)},$$

(2)

$$O_{ij} = U(\Phi_1) - G_{ij}U_{ij}(\Phi_1),$$

(3)

where $U_{ij}(\Phi_1)$ i $U_{ij}(\Phi_2)$ are the responses of a single i,j detector to the radiation flux coming from a black body at a temperature of T_1 and T_2, $U(\Phi_1)$ i $U(\Phi_2)$ are the mean values of the detector response calculated by the formula:

$$U(\Phi) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}U_{ij}(\Phi),$$

(4)

where $U_{ij}(\Phi)$ represents the response of a i,j detector to the radiation flux Φ from a black body, M is the number of rows, and N is the number of columns in the detector array. The idea of the NUC is presented in Fig. 2.

Fig. 2a. presents a spread of the microbolometer characteristics before the NUC. The second image illustrates characteristics after the one point correction. In this case only a shift of the characteristics is corrected. In practice, this correction is executed inside the camera by use of a mechanical part called a shutter. The last image presents microbolometer characteristics during the two point correction with use of two reference black bodies. In this case the shift and the slope of the characteristics are corrected. Most often the GAIN table coefficients are calculated at a laboratory test bench. After calculation, the detector coefficients are stored in a non-volatile memory in the camera and the process of correcting the output signal is performed by the camera in real time.
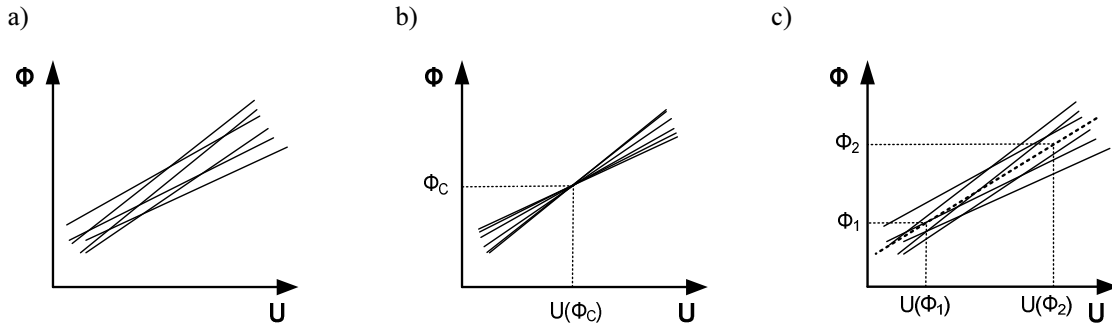
a)

b)

c)

Fig. 2. The characteristics of detectors: before the NUC correction (a),
after the one point correction (b), during the two point correction (c).

3. Influence of microbolometer array temperature on infrared image

The temperature of a detector array has an important impact on the values of the output signal and its parameters, like NETD [3]. Therefore, even an insignificant change of the detector temperature has a crucial influence on the NUC process quality.
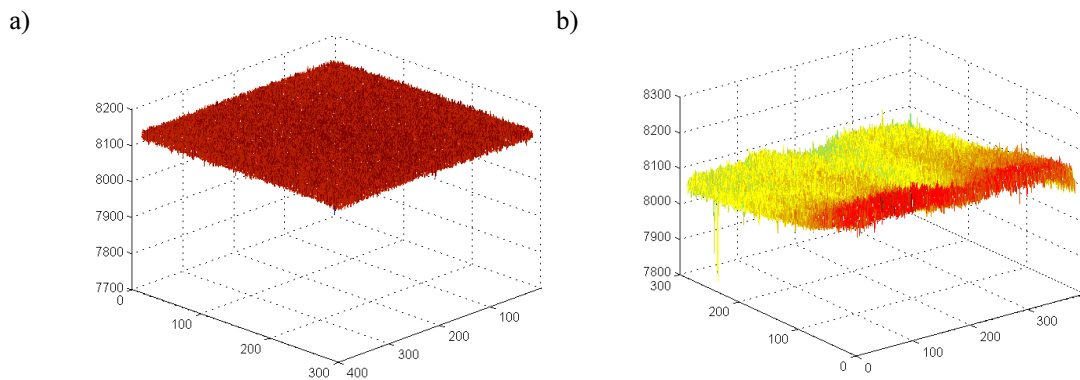
a)

b)

Fig. 3. The detector array signal after the NUC at the detector temperature equal to T_{fpa}=29°C (a),
and after the temperature drift of a detector by 3°C with the same NUC coefficients (b).

Fig. 3a. presents an image after the two point correction for the array detector temperature equal to 29°C. Non-uniformity of this image is 2.7°mV. The detector temperature change of 3°C causes deterioration of the NUC process and results in four times larger FPN (Fig. 3b).

Because of a significant impact of the microbolometer array temperature on the infrared image quality, it is necessary to compensate the influence of the temperature on the NUC process. In the most common applications two approaches are used. The first of them is stabilization of the microbolometer array temperature by a thermoelectric cooler with a special controller. The second is updating offset coefficients by using a shutter. Both of them have disadvantages. The first case needs a considerable amount of energy. The second one needs a reference target and a mechanical procedure to place the target at the front of the detector. Additionally, during calibration the reference target is blocking radiation from the scene, thus interrupting measurements with the thermal camera.
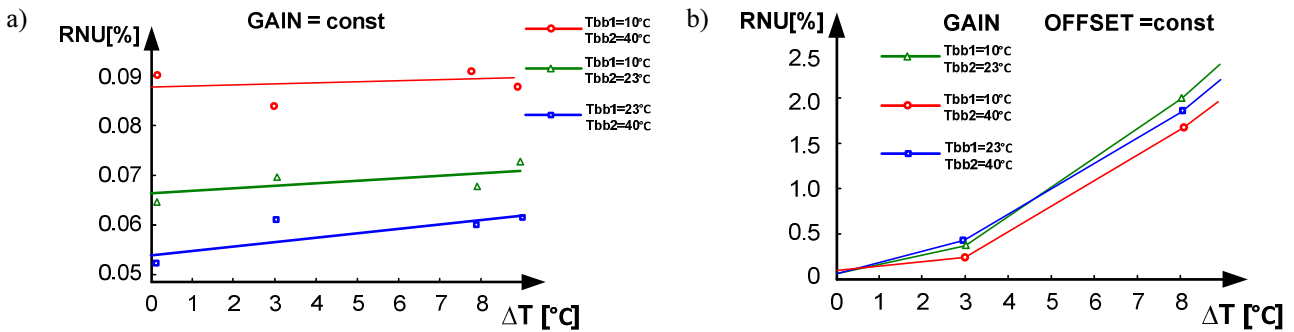
Fig. 4. The GAIN (a) and OFFSET (b) influence on the image non-uniformity
as a function of the detector array temperature.

The NUC coefficients are calculated for a specified temperature of a detector. Therefore, it is very important to find out a relationship between the NUC coefficients and non-uniformity of the corrected image. The impact of the detector array temperature on the correction quality was specified on the basis of a registration prepared at a laboratory test bench with an infrared camera and a black body. The temperature of the microbolometer detector was set and stabilized by a thermoelectric cooler. The registration was performed for three temperatures of the black body and four temperatures of the infrared detector. It allowed to estimate changes in Residual Non-Uniformity (RNU) (5) as a function of the detector array temperature.

$$RNU = \frac{S_k}{Y} \cdot 100\% , \tag{5}$$

$$S_k = \sqrt{\frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[Y - X_{ij} \right]^2} , \tag{6}$$

where S_k – the standard deviation of the image defined by the equation (6), Y – the mean value of the image, X_{ij} - the output signal value for the i,j bolometer.

The research shows that differences between the subsequent values of the RNU are rather inconsistent, for the constant GAIN table (Fig. 4a). Additionally, the values of calibration points used to calculate GAIN coefficients have a bigger impact on the RNU values than the temperature drift of a detector. The same test was performed for the OFFSET table coefficients (Fig. 4b). It can be seen that changes in the detector temperature have a much bigger influence on the RNU when the OFFSET coefficients are constant. This result allows to conclude that the detector temperature has a more significant impact on the OFFSET coefficients than the GAIN ones.

4. NUC with temperature drift compensation

In the proposed method a compensation of influence of the microbolometer array temperature on the image non-uniformity, based on calculation of additional coefficients which allows to compensate the output signal after the NUC procedure, is presented. This algorithm refers to the method presented in [4]. The difference lies in the way the correction factor is calculated. The authors of [4] register responses of a detector to the radiation flux coming from black bodies at the temperatures T1 and T2. The detector array temperature is changed by 15°C at each one measurement. In the next step they interpolate the nearest response of the detector to the environment temperature. The measured data are used to calculate the OFFSET and GAIN tables. The actual coefficient tables are determined every

time the temperature of the detector changes by 0.2°C. The OFFSET table is calculated from two neighbouring tables and the detector response to shutter radiation. The authors made the measurements in a climatic chamber.

In the proposed method one needs to determine three coefficient tables: GAIN, OFFSET and drift compensation coefficients of the detector array. The GAIN coefficients are determined at a test stand and are stored in the camera memory. Only the OFFSET table and compensation coefficients are calculated in the camera.
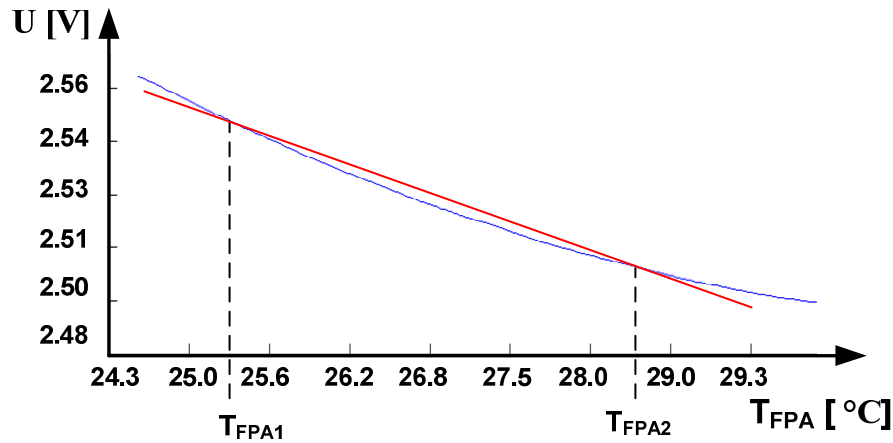

Fig. 5. The dependency of the detector signal on the detector array temperature.

The OFFSET table is calculated basing on the radiation flux coming from a reference body, called a shutter, installed in the camera and temporarily blocking radiation from the scene. The idea of the temperature drift compensation bases on calculation of the signal error caused by temperature changes. The characteristics of the output signal as a function of the detector temperature is presented in Fig. 5. It is assumed that the characteristics of the signal change as a function of the detector temperature can be approximated by a linear function in the range of 3°C -5°C around the detector temperature.

The slope of the linear function is the last compensation coefficient calculated for every single detector by the formula (9). To determine compensation factors one have to register images with a closed shutter for two temperatures of the bolometer array:

$$T_{FPA1} = T_A - \Delta T/2, \ \ T_{FPA2} = T_A + \Delta T/2, \qquad (7)$$

where T_{FPA1} and T_{FPA2} - the calibration points of the detector temperature, T_A - the ambient temperature, ΔT - the temperature range. The compensation factors are determined at two different temperatures owing to temperature regulation by a thermoelectric cooler.

The idea of the proposed method is to use the thermoelectric cooler when the camera is being turned on. The calculated compensation table is used in the next step when the camera is running. From that time on the thermoelectric cooler is turned off and the shutter is opened.

The algorithm of determining the compensation coefficient table is presented in Fig. 6. Knowing the actual temperature of the detector and the detector temperature when the OFFSET table was calculated, it is possible to estimate the signal change caused by the temperature drift. Additionally, to calculate the signal error, it has to be known the slope of the linear estimation of the output signal as a function of the detector temperature.

Compensation of influence of the temperature drift on the output signal is described by the formula:

$$\widetilde{U}_{ij}(\Phi) = U_{ij}^{*}(\Phi) + \widetilde{G}_{ij} \cdot \left(T_{NUC} - T_{C}\right), \tag{8}$$

where: $\widetilde{U}_{ij}(\Phi)$ - the output signal of the bolometer *i,j* after compensation, $U_{ij}^{*}(\Phi)$ - the value of the output signal before compensation, T_{NUC} - the detector array temperature during OFFSET calculation, T_{C}- the actual detector array temperature, $\widetilde{G}_{ij}$ - the compensation coefficient calculated by the formula:

$$\widetilde{G}_{ij} = \frac{U_{ij}\left(T_{FPA2}\right) - U_{ij}\left(T_{FPA1}\right)}{T_{FPA2} - T_{FPA1}}, \tag{9}$$

where: $U_{ij}(T_{FPA1})$, $U_{ij}(T_{FPA1})$ - the *i,j* detector response to the constant reference radiation for temperatures of the detector array set to T_{FPA1} and T_{FPA2}.
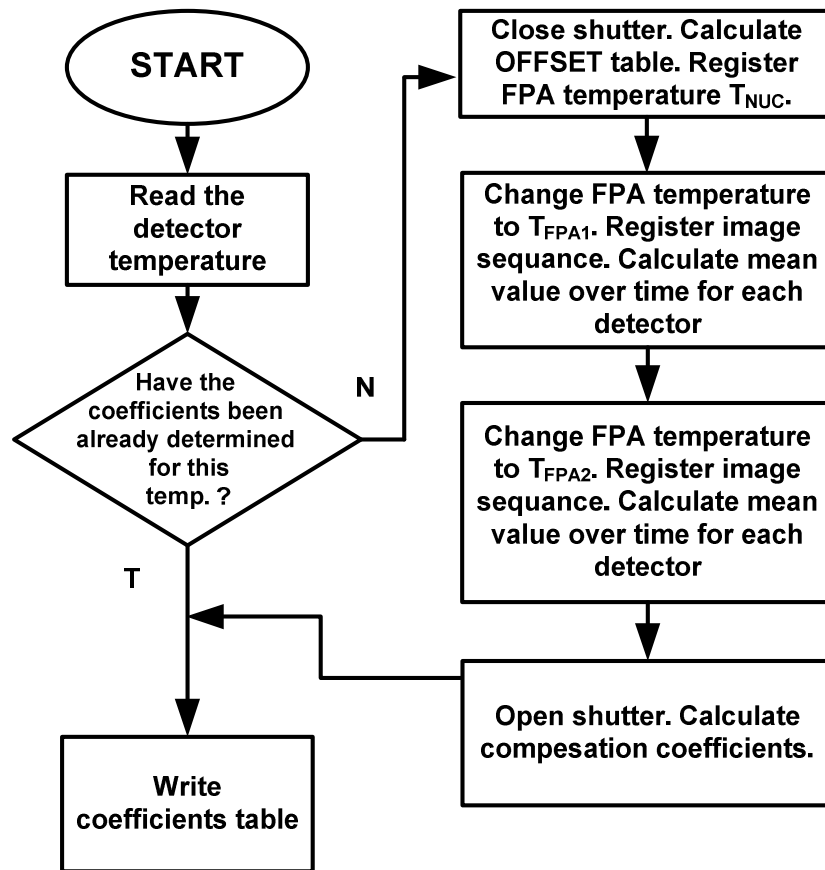

Fig. 6. The algorithm of NUC with the temperature drift compensation.

Introduction of the parameter T_{NUC} gives a possibility to estimate changes of the detector output signal as a function of the detector array temperature by comparison with the temperature of the microbolometer during OFFSET updating. The larger the difference between T_{NUC} and T_C, the larger the value of the error signal. If the uniformity of an image is deteriorated, it is possible to close the shutter and update the OFFSET table. In this case the temperature T_{NUC} must be also updated. The table of coefficients is recalculated every time the temperature of the detector array T_C exceeds the following range:

$$T_{FPA1} - \Delta T/2 < T_C < T_{FPA2} + \Delta T/2. \tag{10}$$

4. Measurement results

The presented method was tested in a laboratory environment with the use of an infrared camera, three black bodies, a data acquisition card and a computer (Fig. 7).
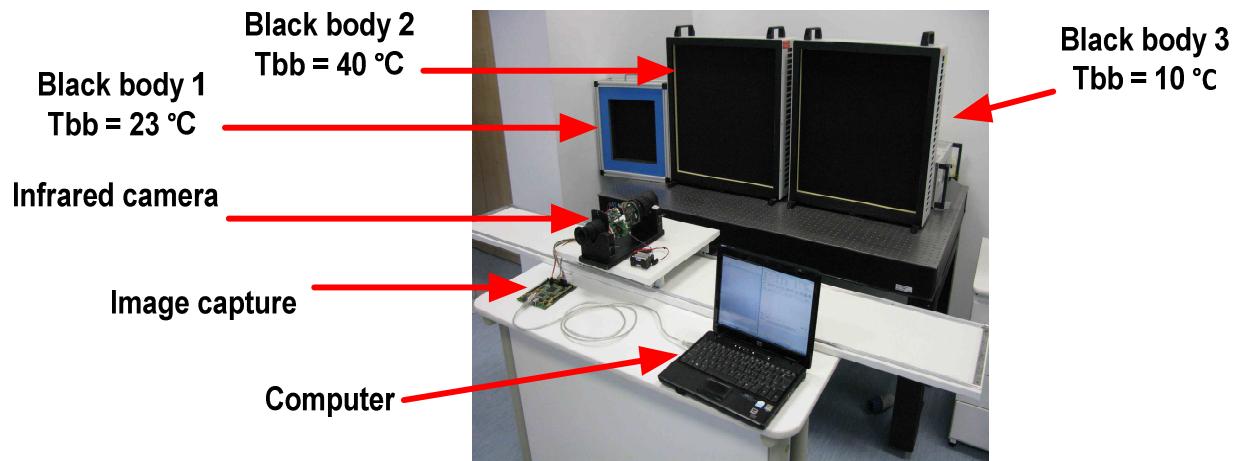

Fig. 7. The test stand for verifying the proposed method.

Black bodies are used to determine GAIN and OFFSET coefficients and for the method evaluation purposes. The temperature of the detector array was set by a thermoelectric module placed inside the microbolometer array package. Owing to the built-in temperature sensor the tested detector was capable of reading measurement data together with the temperature of the detector array. All images were captured through Orange-Tree evaluation board with a special application designed by our team [4]. Improvement of the uniformity quality by the proposed algorithm was measured using the standard deviation (6).
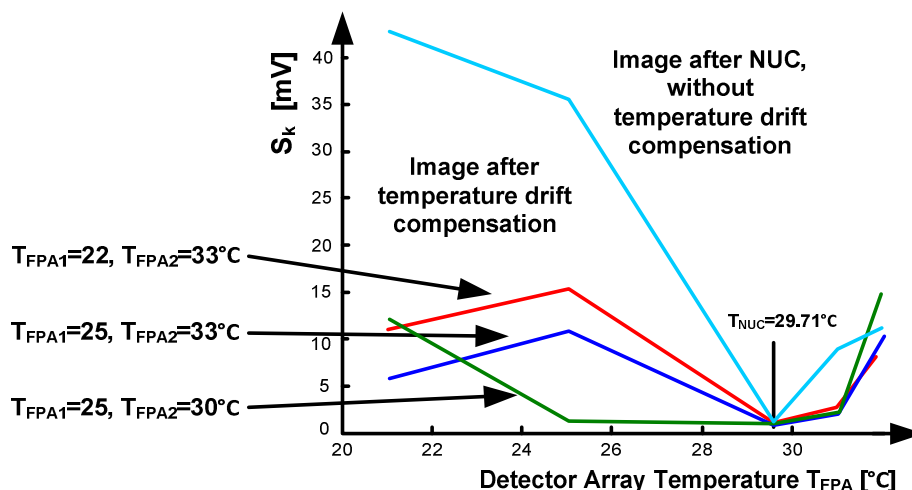
Fig. 8. The RNU value of an image as a function of the detector array temperature.

The GAIN table was calculated for temperatures of the black body set to $Tbb_1=10°C$ and $Tbb_2=40°C$, when the temperature of the detector array was equal to $T_{NUC}=29.71°C$. The OFFSET coefficient table was calculated at the same temperature of the detector array. In Fig.8 it is demonstrated that the non-uniformity of an uncompensated image is the lowest for the detector temperature equal to T_{NUC}. If the temperature of the detector changes, the non-uniformity of the image rises. The compensation coefficient table was calculated for three ranges of the detector temperatures which allows to research its influence on the compensation quality. The narrower the range of the detector temperature, the smaller the value of the non-uniformity in the compensated image. This is due to nonlinearity of the detector signal as a function of the detector temperature.

Conclusion

In the paper a non-uniformity correction (NUC) method is presented, which allows to compensate the influence of the detector temperature drift. For this purpose, the relationship between the output signal value and the temperature of the detector array was investigated. Additionally, the influence of the temperature on the OFFSET and GAIN coefficients was measured. The research allows to conclude that the detector temperature has a greater impact on the OFFSET coefficients than on the GAIN ones. The presented method utilizes estimated relationship between the output signal of detectors and their temperature. In the presented method, the shutter is used for establishing the signal reference. A thermoelectric cooler is used for changing the temperature of the detector array. The results of the performed measurements indicate that the proposed algorithm works correctly in a narrow range of temperature changes.

References

[1]   Kruse, P. W. (2002). *Uncooled Thermal Imagining. The Society of Photo+Optical Instrumentation Engineers*.

[2]   Milton, A. F., Barone, F. B., Kruer, M. R. (1985). Influence of nonuniformity on infrared focal plane array performance, Optical Engineering, 24(5), 855−862.

[3]   Krupiński, M., Bareła, J., Firmanty, K., Kastek, M., (2013). Test stand for non-uniformity correction of microbolometer focal plane arrays used in thermal cameras, Proc. SPIE, 8896, Electro-Optical and Infrared Systems.

[4] Minassian, C., Tissot, J. L., Vilain, M., Legras, O., Tinnes, S., Fieque, B., Chiappa, J. M., Robert, P. (2008). Uncooled amorphous silicon Tec-less ¼ VGA IRFPA with 25µm pixel-pitch for high volume applications Infrared Technology and Applications XXXIV, proc. of SPIE, 6940.

[5] Mudau, A. E., Willers, C. J., Griffith, D., Roux, F. P. J. L. (2011). Non-Uniformity Correction and Bad Pixel Replacement on LWIR and MWIR Images Defense, IEEE.

[6] Harris, J., Chiang, Y., (1999). Nonuniformity correction of infrared image sequences using the constant statistics constraint, IEEE TIP 8, 1148–1151.

[7] Chao, Z., Qian, C., Guohua, G., Xiubao, S., Weixian, Q. (2011). Scene-based nonuniformity correction method using multiscale constant statistics, SPIE Optical Engineering, 50(8).

[8] Hardie, R. C., Hayat, M. M., Armstrong, E., Yasuda, B. (2000). Scene-based non-uniformity correction with video sequences and registration, Appl. Opt. 39, 1241– 1250.

[9] Chao, Z. , Qian, C., Guohua, G., Xiubao, S., Jianle, R. (2012). Improved interframe registration based nonuniformity correction for focal plane arrays, Infrared Physics & Technology 55, 263–269.

[10] Hayat, M. M. Ratliff, B. M., Tyo, J. S., Agi, K. (2004). Generalized Algebraic Algorithm for Scene-based Nonuniformity Correction, proc. of Spie, 5556, 122−136.

[11] Bieszczad, G., Kastek, M. (2011). Measurement of thermal behavior of detector array surface with the use of microscopic thermal camera, *Metrology and Measurement Systems*, 18(4), 679−690.