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Temperature drift compensation in metrological microbolometer camera using multi sensor approach

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Abstract

The paper presents a new concept of bolometer detector's signal correction for metrological infrared camera. The specially designed camera's hardware with multiple temperature sensors along whole optical path is described. Developed nonlinear, multidimensional computational methods allow to update the correction coefficients of focal plane array detectors online. The results of the work reduces the periodic use of mechanical shutter. This enables the continuous registration of the object temperature during the measurement in Non Destructive Testing and medical application.

1. Introduction

The significant popularity rise of thermal cameras use can be observed in recent years. The main reason is the price drop of these systems, which leads to theirs higher availability to end users. This is an effect of the technological progress in the production of microbolometer detectors focal plane arrays (FPA). What is more, Infrared (IR) cameras available today on the market have larger and larger image resolutions. At the same time, IR focal plane arrays characterize with better parameters. The most significant parameter Noise-Equivalent Temperature Differance (NETD), that describes thermal sensitivity of the camera, reaches the values of 20 mK. Such low NETD was available few years ago only in photon cameras. Nowadays, this high sensitivity of uncooled thermal cameras allows to use them in the applications where recently only expensive cooled cameras were suitable. However, technological advances did not solved the problem of temperature drift which is the main disadvantage of microbolometer detectors.

The main reason of using the IR uncooled cameras in many applications is the necessity of contactless temperature measurement. These exemplary applications are building inspections, industrial system and process monitoring, medical applications especially massive fever screening, scientific research and others. Nowadays, in all constructions of microbolometer, metrological infrared cameras, the temperature drift compensation is performed by using a mechanical shutter, which is located between the detector array and the lens [1-3]. The drift correction is based on a periodic shutter activation. During such correction, the observed scene is 'frozen', which leads to the loss of few frames of images sequence. In some applications like scientific research, active thermography, massive fever screening or monitoring, the continuous image acquisition is crucial and cannot be interrupted. In such applications, uncooled cameras cannot be used there due to the mechanical shutter. There are documented attempts to develop methods for carrying out the correction with limited use of the shutter, or without the shutter. Some of these methods focus only on the non-uniformity correction and without considering the temperature measurement. Other methods require large amount of memory and computational power. In result, there is no shutterless measurement uncooled infrared camera available on the market today. There are only observation cameras available that have shutterless correction algorithms. None uncooled camera enables an uninterrupted temperature measurement for tens of minutes.

This paper presents a concept of the novel signal correction method for the measurement uncooled IR camera. The concept assumes the calculation of thermal drift using nonlinear, multidimensional approximation of the non-uniformity. The correction value is calculated for each pixel as a function of the pixel's position in the FPA. The correction polynomial formula is same for the whole matrix. However, the coefficients of the polynomial can vary for some subregions of the FPA. These coefficients are calculated using data from multiple temperature and radiation sensors that are placed in the camera. The preliminary results of Residual Non-Uniformity (RNU) correction with described methodology are presented.

2. Temperature drift

For the construction of uncooled infrared cameras, a microbolometer Focal Plane Array is used [1]. Almost every modern metrological application of infrared cameras, require high temperature measurement accuracy and uniform response from the detectors' matrix when the same incident power of infrared radiation is absorbed by the detector. In practice, it strongly dependes on the effectiveness of the signal correction method [2]. Manufacturers of metrological infrared cameras use a two-point Non-Uniformity Correction (NUC) method, defined as Two-Point Correction [3]. This correction assumes the linear transfer characteristics of the detectors. For each detector of the array, two coefficients are calculated for this linear approximation: gain and offset. Calculated coefficients are stored in the memory of the camera. However, the change of the offset coefficient must be updated inside the camera because of the thermal drift effect. This

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drift is the result in a change of the detectors own temperature (not caused by the incident radiation from the object). Furthermore, this phenomenon is an uneven, which means that each of the microbolometers in the matrix change its temperature by the different value.

Other methods of the non-uniformity correction are statistical methods. However, they are used only in observation cameras, the principles of their operation is described in detail in many publications [4-6].

Known correction algorithms

Nowadays, in all constructions of microbolometer, metrological infrared cameras, the temperature drift compensation is performed by using a mechanical shutter, which is located between the detector array and the lens. The drift correction is based on a periodic shutter activation, with the frequency dependent on the level of temperature change inside the camera. During this operation, the acquisition of shutter image is performed as the reference data corresponding to the uniform temperature. For each detector in the matrix, an offset coefficients of drift correction are calculated. These coefficients are stored in the memory of the camera and allow camera operator to obtain the corrected thermal images. For a moment of making the correction, temperature of shutter is also measured. Together with the average, digital value (Isothermal Unit –IU) of shutter image, it allows conversion of IU to the temperature of the observed object. Currently, it is the only correction method used by the manufacturers of metrological cameras. Unfortunately, it involves interruptions during image acquisition carried out with the bolometer camera.

There are documented attempts to develop methods for carrying out the correction with the lengthen time between the successive shutter operations. There are also the first solutions without the shutters at all.

The is a developed system with the semi-permeable shutter for infrared radiation which partly solves the problem of interrupting the acquisition of the observed scene [7]. However, this solution suffers from the lower quality of the detector array non-uniformity correction than the traditional method.

In another paper, it is assumed that the temperature of the shutter is the same as the temperature inside the device [8]. This temperature is measured using a contact sensor attached to the mechanical elements between the detector matrix and the lens. This method assumes that it is possible to correlate the temperature change in a camera with the change of the detectors response, similarly to the shutter activation at this temperature. On this basis, it is possible to estimate the drift correction factors for each pixel without the use of the shutter and perform linear correction of the signal taking into account the temperature changes inside the camera only. In this cited patent of 2008, there are no quantitative measurements presented, describing the correctness of the proposed correction, and at the moment there is no camera from FLUKE Company on the market that uses described method.

Next approach uses sensors that monitor the temperature of the die, inside the housing of the detector [9]. For each detector in the array, the values of offset correction coefficient were estimated on the basis of the second degree polynomial. The independent variable of the polynomial is the FPA temperature measured by a single sensor. However, this solution has been tested only in the thermal steady state in a climatic chamber.

There is an approach which involves the use of several temperature sensors located in different places inside the camera [10]. This solution enables the correction of the signal in the thermal transient state of the camera. The authors proposed an estimation of the effect of temperature drift on the signal in the bolometer matrix by means of non-linear functions. Coefficients of these functions were calculated on the basis of thermal time constants of individual sensors, that temperature change was induced with the use of climatic chamber. Described correction method gives promising results in final temperature readout with the small error of ±0.8K. Unfortunately, the calibration process with the described method is time consuming. What is more, the correction formula consists up to 17 coefficients for every pixel in the array. The authors also claim that this correction is only suitable for measurements with ambient temperature changes that affect the infrared camera almost uniformly. Moreover, sensors used in the study (TI LM61) have large reading errors rated as ± 2.0°C.

Manufacturers of the IR detectors also develop technology to correct the temperature drift. One of them proposes to use an additional, so-called "blind" pixels, which are arranged at the edge of two sides of the matrix [11]. The signal of these blind pixels does not depend on the radiation of the observed scene because they are intentionally optically shielded by the detectors housing. Their response vary only to temperature changes of housing, which allows estimating quantitatively the influence of the drift on active pixels in the matrix.

Characterization of the problem

The temperature drift of the bolometer detectors is caused by:

- read-out circuit integrated with the IR sensors, which warms up everything inside the case, including the detectors array,
- detector case, which heats unevenly each detector in the focal plane array by radiation,
- all mechanical elements along the optical path between the focal plane array and the lens
- electronic circuits powering the system and processing data along image transmission path, which dissipate power and heat up the detector as well.

The effect of irradiation by mechanical parts, such as the case and the lens is particularly visible at the edges of the IR image. It is called Residual Non-Uniformity (RNU).

Thus, the problem of correcting temperature drift and signal non-uniformity of the detector array is a complex issue and cannot be solved using one-dimensional approach. In order to solve these problems it is necessary to take into account all the factors that cause these undesirable phenomenon – RNU.

The permanent increase of the integration of the modern digital circuits and computing power enable the use of new, more accurate methods of computations in real-time systems. Now, the in-built system of the camera still uses the simplest mathematical models developed years ago. The correction method with higher computational complexity can be implemented today.

Therefore, the effective signal correction method should take into account:

- temperature of all system components that which radiation affects the detector array,
- direct measurement of radiation camera internal components using independent radiation sensors,
- a multi-dimensional, non-linear estimation of temperature drift correction coefficients that take into account all the above assumptions.

3. Proposed correction concept

The aim of the research was to develop a new algorithm for thermal drift correction for the uncooled, metrological infrared camera. The camera with implemented algorithm should allow to update correction coefficients of the detector array in real time, reducing the use of the shutter and scene "freezing". An important aspect of the research was to take into account all of the previously described reasons of the thermal drift in static and dynamic conditions. It is especially important to shorten the delay time after turning on until the camera is ready for the reliable temperature measurements.

Because of the greatest capabilities to monitor the various parameters of the detector, our method was implemented and tested using the camera with vanadium oxide detector (VOx). These detectors have many built-in solutions and capabilities to measure the temperature of the matrix and other elements of the detectors housing. The temperature of the FPA can be measured by diodes and blind bolometers, that signal is transmitted with every frame. There are the side reference pixels measuring the radiation of the housing of the detector. This type of the detector is also characterized by a very low value of the NETD<35 mK. Moreover, it has built-in Peltier module. It allows to the comparative study the detector signal behavior with and without the thermally stabilized FPA.

The idea of the novel thermal drift correction algorithm is the actualization of initially calculated matrix offset coefficients. These offset coefficients are calculated with the use of the mechanical shutter after powering the camera. After system initialization and initial temperature rise, the standard 2-point non-uniformity correction is performed. This allows to overcome the problem of factory dispersion of the detectors characteristics, which correction coefficients (gain and offset) are rather randomly distributed. The thermal drift affects the pixels gray level offset, mainly because of parasitic radiation and self-heating.

One assumes that the change of signal values depends on two main factors:

- pixel position in the focal plane array as each pixel is differently illuminated with parasitic radiation from the camera elements,
- temperature of the camera’s element that generate the radiation power in the direction to the detector.

For the specified mechanical construction of the camera, the radiation configuration factor for each pixel is constant and the radiation power of the each camera’s element that affects the FPA depends on the temperature of this particular element.

Based on the above assumptions, a novel temperature drift correction algorithm was formulated. The influence of the thermal drift on the pixels of the FPA could be characterized by a nonlinear model. This model is the function of pixel’s position in the detector. The coefficients of the proposed model are temperature depended and estimated in real time using the data from temperature sensors located on the relevant parts of the camera. Moreover, only one set of the coefficients defines the correction values. This approach is totally different from previous ones, where correction coefficients were calculated for every pixel of the FPA. In result, the proposed nonlinear, multidimensional correction method is much less demanding, when the needs of memory and computational power is considered.

The research will be carried on custom designed microbolometer thermal camera presented in figure 1. The camera uses VOx microbolometer detector of 384x288 resolution. The system was equipped with the high accuracy temperature sensors, that allow to monitor precisely the thermal state of the camera.

The new solution assumes also to use multivariate approximation by polynomials of the higher degrees, B-spline curves and neural networks for the model coefficients’ calculation. The developed method can take into account the different environmental conditions in static and dynamic states, in particular the state of the thermal stabilization of the camera after turn-on.

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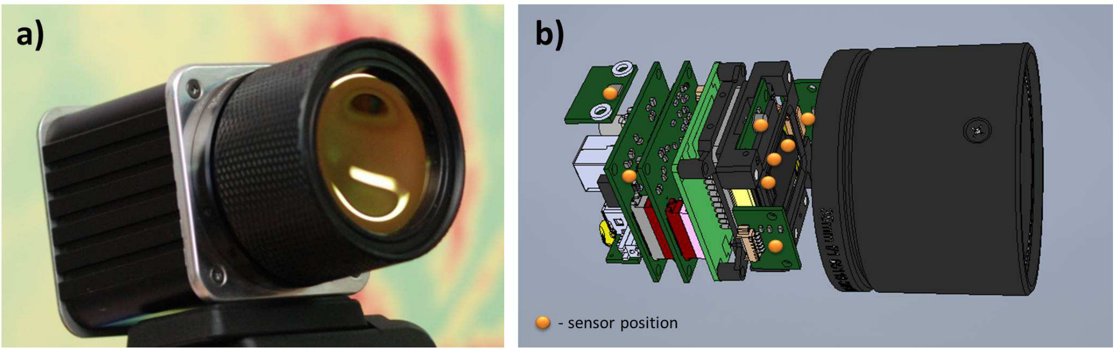

Fig. 1. *The designed infrared camera (a) and its perspective view of interior with marked sensors positions (b)*

4. Preliminary research & results

The laboratory tests in climate chamber were carried out to obtain the working parameters of the described thermographic system. The tests were performed to characterize camera's readout values change due to change of thermal conditions. The climate chamber temperature (camera's environmental temperature) was changed from 2°C to 40°C, while black body temperature was change from above 0°C to 60°C.

RNU correction

The aim of the preliminary research was to characterize the camera's Residual Non-Uniformity and correct it by using the proposed drift correction model. RNU is the non-uniformity of thermal image that remains after standard 2-point drift correction made by the shutter activation. It is caused by the internal parasitic radiation from the mechanical components of the camera. These components are mainly camera and lens housing, that are located in front of the mechanical shutter (towards the lens). Moreover, the temperature of these parts is different for different environmental working conditions of the camera. This affects the intensity of the RNU, easily visible in the thermal image. The RNU deteriorates the image quality more if the lens are bigger and have larger Back Focal Length. This enlarges the surface that emits the radiation to the detector. It also results in temperature readout errors.

In order to characterize the RNU effect, the thermal steady state of the camera was considered. The environmental temperature of climate chamber was stabilized to 5 different temperatures (2°C, 10°C, 20°C, 30°C and 40°C). After 45 minutes of camera stabilization, the image of the black body at 40°C were captured just after performance of 2-point NUC.

As the temperature of the shutter was different in every measurement, the absolute gray level values (IU) of the signal from the detector differs. The reference value IU_{ref} for every measurement was defined. The mean value from the center area of the image 16x16 pixels was selected. The matrix of image error in gray level, due to the RNU effect, was calculated for every environmental temperature by using eqn. (1).

$$RNUcoeffs_{T.ENV}(x,y) = IU(x,y) - IU_{ref.} \quad (1)$$

where *T.ENV* stands for environmental temperature, *x* and *y* for the coordinates of pixels in the FPA, IU_{ref} is a reference, correct readout value. The values obtained by eqn. (1) are offset correction coefficients that should be subtracted from recorded images in order to get the detectors' uniform response for black body radiation.

Analyzing *RNUcoeffs*, it can be noticed that spatial distribution of image error values has the same characteristic for every working temperature of the camera in steady, stabilized state. The distribution of RNU values can be presented as a surface in figure 2. There are results for 3 climatic chamber temperatures. Moreover, the statistical parameters of RNU reach the close values for every temperature of the camera – table 1.

Table 1. *Parameters of RNU for different temperature conditions of working camera*

Environmental temperature [°C] RNU parameters [IU]	**2**	**10**	**20**	**30**	**40**
RNU maximum value	322	280	277	260	318
RNU mean value	87	76	69	64	75
RNU spread	324	282	278	264	318

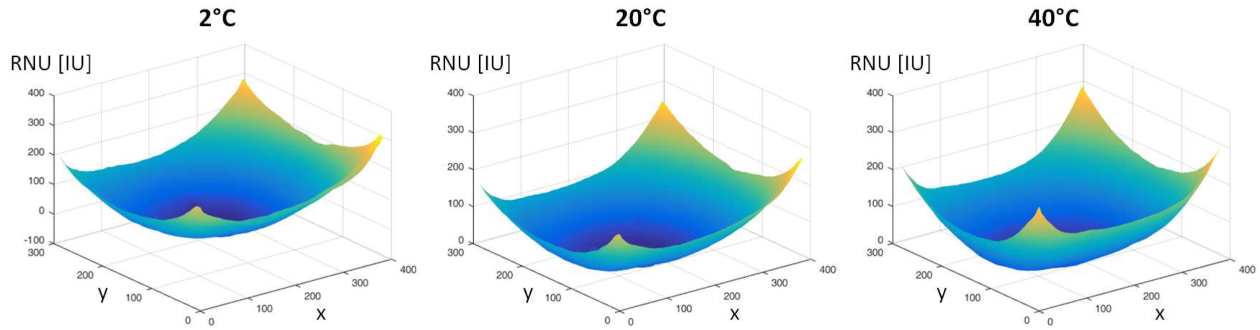

***Fig. 2.** 3D visualisation of RNU characteristics for different temperature conditions of working camera*

According to the proposed correction algorithm, the *RNUcoeffs* matrix values for each pixel could be approximated by a polynomial of the higher order. In the research, 3rd order polynomials were chosen, defined by eqn. (2)

$$RNUcoeffs_{T.ENV}(x,y) = c_1x + c_2y + c_3x^2 + c_4x^2 + c_5x^3 + c_6y^3 \quad (2)$$

where c_1 to c_6 are the coefficients of the polynomial.

Due to the fact that the change of values in *RNUcoeffs* matrix is not symmetrical and the coefficient values in the corners of the matrix are different, the approximation was done with two functions *RNU₁coeffs* and *RNU₂coeffs*. Each of them were fitted to the half of matrix in horizontal direction.

The results of the function fitting to the data in *RNUcoeffs* matrix for every temperature *T.ENV* are presented in table 2. The high values of the coefficient of determination (R^2) presented in table 2 confirm the good approximation of RNU by the proposed polynomial model. Moreover, each parameter of the polynomial changes slightly with the ambient temperature. Therefore, every parameter value can be calculated in function of temperature inside the camera. The example of parameters c_1 and c_2 value change and their approximation as the function of climatic chamber temperature are presented in figure 3.

***Table 2.** Values of calculated coefficients for proposed nonlinear RNU correction function*

Functions	**RNU_1coeffs (columns from 1 to 192)**				
Environmental temperature [°C] / Polynomial parameters:	**2**	**10**	**20**	**30**	**40**
c_1	-5,053E-02	-3,627E-02	1,372E-02	2,239E-02	4,723E-02
c_2	-3,340E-01	-3,624E-01	-2,645E-01	-1,199E-01	-1,544E-01
c_3	6,037E-03	5,294E-03	5,287E-03	5,297E-03	6,651E-03
c_4	-4,737E-03	-5,015E-03	-4,899E-03	-3,609E-03	-4,988E-03
c_5	-7,574E-06	-7,281E-06	-8,737E-06	-9,002E-06	-1,104E-05
c_6	-3,037E-05	-2,871E-05	-2,948E-05	-2,621E-05	-3,655E-05
R^2	0,995	0,996	0,996	0,996	0,995
Functions	**RNU_2coeffs (columns from 1 to 192)**				
Environmental temperature [°C] / Polynomial parameters:	**2**	**10**	**20**	**30**	**40**
c_1	-5,053E-02	-3,627E-02	1,372E-02	2,239E-02	4,723E-02
c_2	-3,340E-01	-3,624E-01	-2,645E-01	-1,199E-01	-1,544E-01
c_3	6,037E-03	5,294E-03	5,287E-03	5,297E-03	6,651E-03
c_4	-4,737E-03	-5,015E-03	-4,899E-03	-3,609E-03	-4,988E-03
c_5	-7,574E-06	-7,281E-06	-8,737E-06	-9,002E-06	-1,104E-05
c_6	-3,037E-05	-2,871E-05	-2,948E-05	-2,621E-05	-3,655E-05
R^2	0,995	0,996	0,996	0,996	0,995

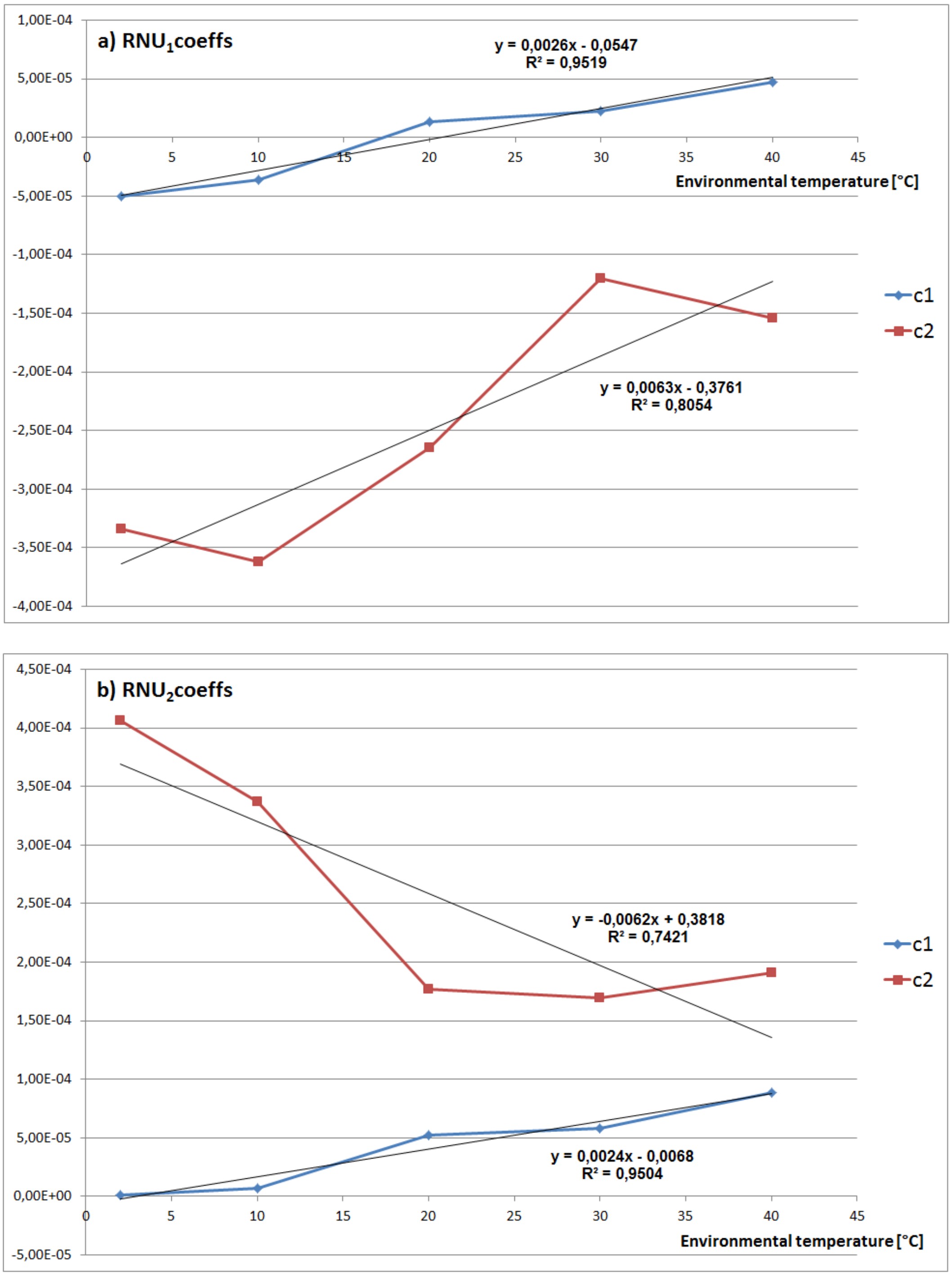

Fig. 3. *Graphs of c1 and c2 coefficient changes in function of the temperature of climatic chamber and their approximation with the linear function*
a) RNU_1coeffs polynomial for columns <1,192> b) RNU_2coeffs polynomial for columns <193,384>

Results

Using the calculated models of RNU, all images of black bodies were corrected. Because of the small differences of polynomials coefficients values for different environment temperature, all tests were corrected with the model calculated for the middle temperature, the camera works in, equal to 20°C. The quantitative improvement of the black body signal uniformity is presented in table 3. The example of qualitative improvement of the black body image uniformity is shown in figure 4. The developed RNU correction was also tested under normal working conditions of the camera, which is presented in figure 5. The false color mapping is equal for all pairs of presented images (before and after correction). All presented results are satisfactory.

Table 3. *Results of the image quality improvement after use of developed RNU correction*

Environmental temperature [°C] / Image parameters [IU]	**2**	**10**	**20**	**30**	**40**
	before RNU correction				
mean value	8733	8827	9029	9072	8954
spread	378	330	294	277	342
standard deviation	61,0	52,1	52,0	48,9	58,7
	after RNU correction				
mean value	8663	8758	8960	900	8885
spread	146	121	88	77	133
standard deviation	12,6	7,8	5,2	6,6	13,0

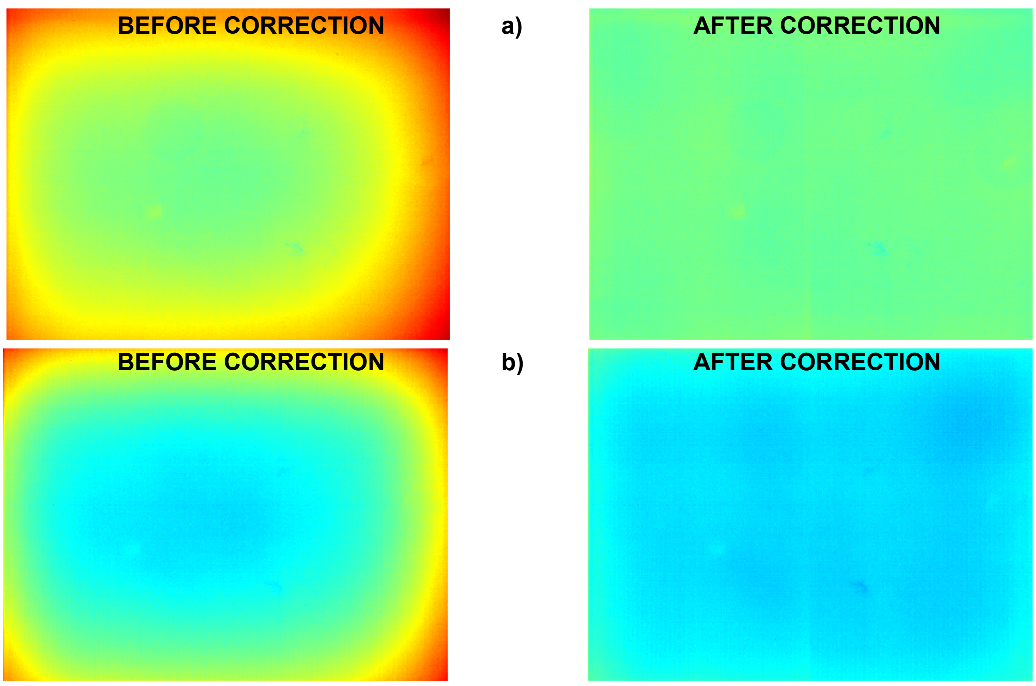

Fig. 4. *False color images of black body (set to 40°C) before and after developed RNU correction for two different temperatures of camera working environment. a)* $T_{ambient}$*=20°C b)* $T_{ambient}$*=40°C*

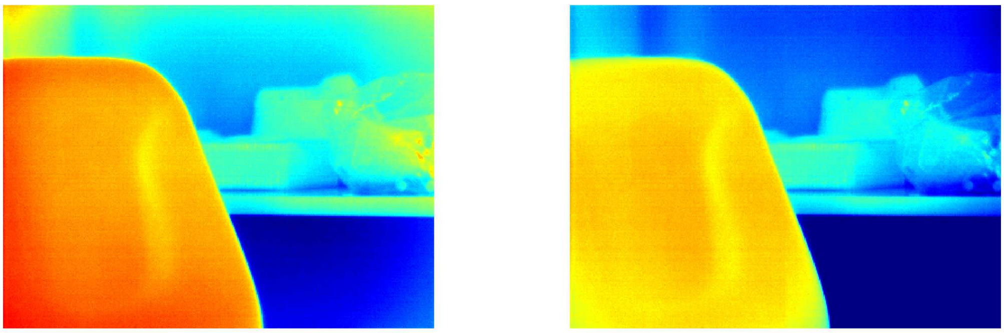

Fig. 5. *. False color images of office interior before and after developed RNU correction*

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5. Conclusion

The novel concept of thermal drift correction for metrological uncooled cameras is presented. The new concept of correction was tested for Residual Non-Uniformity. The possibility of using one, global set of coefficient correlated with camera's working temperature for nonlinear model was shown. The method gives very good and promising results.

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