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CRITICAL REVIEW OF PRESENT-DAY METHODOLOGY OF THERMAL IMAGER NOISE CHARACTERIZATION

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Abstract

This paper presents a review of reasons that create metrological chaos in the field of characterization of noise in thermal imagers. In detail, the paper presents a critical review of myriads of past and present-day definitions/measurement methods of noise parameters of thermal imagers that create this chaos and significantly reduce reproducibility of measurement of noise parameters carried out by different test teams.

Keywords: thermal imager, noise, 3D noise, NETD.

1. Introduction

Noise is a phenomenon that generates unwanted (mostly random) variations in time and space in a video image generated by thermal imagers. It is considered as one of main factors that limits the performance of thermal imagers. In detail, noise parameters determine the limit of ability of thermal imagers to detect large targets of low thermal contrast. Therefore, proper characterization of noise in thermal imagers is of crucial importance for thermal imaging metrology.

Numerous definitions and measurement methods of parameters for characterization of noise of thermal imagers have appeared since the advent of this technology in the 1970s. However, for the last three decades noise has typically been characterized using three parameters: *noise equivalent temperature difference* (NETD) and *fixed pattern noise* (FPN) as well as a set of parameters under the common name of the 3D Noise model.

NETD is a very old parameter that has been used as primary criterion for characterization of noise in thermal imagers since the beginning of the 1970s. In detail, it is typically defined as a measure of temporal noise in thermal imagers. Further on, FPN is another old parameter to characterize noise in thermal imagers. In contrast to NETD, FPN is a measure of spatial noise. Finally, the 3D Noise model is a set of seven independent parameters that combined offer detailed characterization of seven types of noise of thermal imagers. It should be noted that the 3D Noise model is also a relatively old concept (with the origins at the beginning of the 1990s). To summarize, both NETD, FPN and the 3D Noise model can be considered as mature (at least three decades old) concepts for characterization of noise in thermal imagers. However, in spite of maturity of these three parameters, it is a common situation that measurements of NETD, FPN or 3D Noise model components of the same thermal imager carried out by several different test teams (manufacturers, scientific institutes) produce significantly different results with differences of up to 50% or more. The main reasons for this undesired metrological situation are imprecise and changing definitions and differences in measurement methods of NETD, FPN and 3D Noise model components. This situation is especially frustrating for the author, who is

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the CEO of a manufacturer of equipment for testing thermal imagers and sometimes meets a situation when the same test system is considered as pessimistic by one customer and as too optimistic by another.

This paper presents a review of reasons for metrological chaos in field of characterization of noise in thermal imagers. In detail, the paper presents a critical analysis of myriads of past and present-day definitions/measurement methods of noise parameters in thermal imagers that have created this chaos and significantly reduce reproducibility of measurement of noise parameters carried out by different test teams.

2. Literature on characterization of noise

The situation in literature on characterization/measurement of noise parameters in thermal imagers apparently looks very good. There is very numerous literature on NETD in thermal imagers. Only the SPIE library can produce over five hundred results for when keyword NETD is used either in a paper tittle or in an abstract [1]. References [2-5] are examples of scientific papers that present some definition/measurement methods of NETD in thermal imagers. There are also dozens of Internet websites that present definitions and some measurement guidelines for NETD, including big manufacturers of thermal imagers or IR FPA sensors [6-8]. There is also a standard issued by a well-known US organization that regulates the measurement of NETD [9]. Further on, information on the definition and measurement method of NETD can be found on internet websites or educational presentations of manufacturers of equipment for testing thermal imagers [10-13]. There are also books devoted to testing thermal imagers that cover the measurement of NETD [14-15]. However, detailed analysis of this literature reveals a rather pessimistic picture.

Rich literature on the subject of NETD, including the previously mentioned papers, presents a series of slightly different definitions and methods to measure NETD. The same can be said about internet websites. Further on, the standard mentioned above presents obsolete recommendations not valid for testing modern staring thermal imagers that cannot be used practically. None of the books listed presents a review of NETD definition/measurement methods for modern staring imagers and recommendations for optimal solutions.

This thesis about lack of clarity in definitions/measurement methods of NETD is supported by a recently published paper by scientists from an important US electro-optical metrology centre that lists officially four different definitions of the same NETD parameter [16]. In addition, there are papers that indicate the dependence of measurement results of the *Signal Transfer Function* (SiTF), critical parameter needed to calculate NETD), on the type of the test system [17-18].

The literature on FPN is much smaller in comparison with that on NETD. Still, it is quite abundant: only the SPIE Digital library produces at least fifty papers with keyword "Fixed Pattern Noise" in the paper tittle or abstract. It should also be noted that the FPN phenomenon exists not only in thermal imagers, but also in VNIR cameras and SWIR imagers. Therefore, hypothetically, literature on the same phenomenon in VNIR cameras should also be useful. However, a detailed analysis of numerous literature reveals a similar, rather pessimistic perspective for a series of reasons.

First, the community working in the field of evaluation of VNIR cameras claims that FPN is a misnomer, because noise cannot be fixed [19]. Further on, this community has developed their own terminology/methodology to characterize spatial noise of VNIR cameras *i.e.* the EMVA1288 standard.

Second, the IR FPA community uses the term FPN to describe spatial noise generated by IR FPA sensors before uniformity correction is applied; and the term *residual fixed pattern noise* (RFPN) is used to describe spatial noise in output image generated by thermal imagers after uniformity correction is applied [20-21]. This terminological chaos is amplified by the use of two additional terms: Spatial NETD [13, 22] and *inhomogeneity equivalent temperature difference* (IETD) [23-24]) to describe the same phenomenon of fixed pattern noise in images generated by thermal imagers.

Third, the sources listed above propose relatively different methods to measure FPN and these differences reduce reproducibility.

Fourth, there are reports that indicate that FPN varies significantly depending on the time from last non-uniformity correction and this variability creates the fundamental problem of measurement of FPN understood as one number parameter.

Theoretically, a situation with a third way to characterize the noise phenomenon (the 3D Noise model) should be much better. The concept of the 3D Noise model was developed by scientists from the NVESD (Night Vision of Electronics and Sensor Directorate) at the beginning of the 1990s [26-27] and has been continuously updated by them in a series of papers [16, 18, 25, 28, 29, 30]. These later papers by authors from the NVESD that upgrade the original 3D Noise concept are of critical importance to understand the present-day situation in characterization of noise of thermal imagers using this model. In fact, several of these papers are treated by some test teams worldwide as semi-standards.

However, unfortunately for the test teams world-wide, who often look to the NVESD for guidance, these papers do not present detailed official recommendations of this institution on how measurement of 3D Noise is to be carried out, but present only definitions/measurement methods currently used by the authors that vary from paper to paper. In addition, the papers leave important questions related to filtration of raw data, time duration of the captured video sequence, or optimal method of measurement of SiTF unanswered. A good example of such papers, i.e. one presenting unanswered questions of critical importance, is relatively a recent paper from year 2017 [31] in which the authors state "*Finally, decisions should be made by the measurement and modeling community as a whole to decide on what (if any) high pass filters should be applied in the measurement system noise"*. Further on, some NVESD papers deliver analysis of some problems, but avoid indicating any solution to the analysed problem and emphasize that the paper presents no recommendations. Reference [18], which delivers an excellent analysis of the problem how to measure FPN, states "*There are no recommendations based upon this work at this time since this is too preliminary for there to be conclusions"* is a good example of such papers. Therefore, NVESD papers are "a must to be read" by anyone aspiring to understand 3D Noise model, but do not deliver uniform, detailed definition/method for measurement of this model.

The situation described above is especially frustrating for the author, who is a CEO of a company manufacturing systems for testing thermal imagers and is always under pressure from customers to deliver systems measuring parameters of thermal imagers according to non-existing standards or according to recommendations from top world EO metrology centres like the NVESD that do not deliver detail precision recommendations.

In next sections reasons that create this dismal metrological situation when every day noise parameters like NETD, FPN, 3D Noise of thousands of thermal imagers are measured, but at the same time there is no precise guidelines how such measurements should be carried out and different test teams obtain slightly different test results. Such poor situation with characterization of noise of thermal imagers differ totally comparing to characterization of noise parameters of VNIR cameras used in machine vision applications that is carried out typically according to detailed recommendations of the EMVA1288 standard [19].

3. Noise division

According to the classical concept, the noise present in images generated by thermal imagers is generally divided into two groups: temporal noise and spatial noise [14, 15]. Next, each group can be further divided into low- and high-frequency components (Fig. 1).

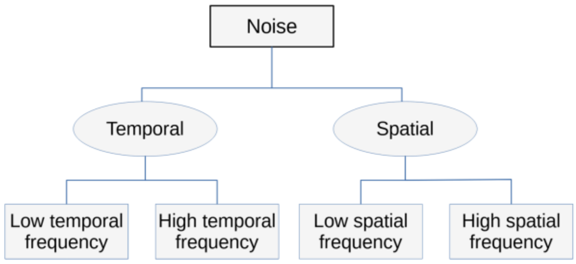

Fig. 1. Classical division of noise.

Temporal noise generates temporal variation of intensity of pixels of the output image even when incoming radiation does not change in time. The spatial noise (FPN) phenomenon generates spatial variations of intensity of pixels of the output image that do not depend on time (fixed pattern) and cannot be eliminated by frame averaging.

High-frequency temporal noise generates fast temporal variations of intensity of camera pixels (Fig. 2a). The intensity varies from frame to frame. Low-frequency temporal noise generates slow temporal variations of intensity of camera pixels (Fig. 2b).

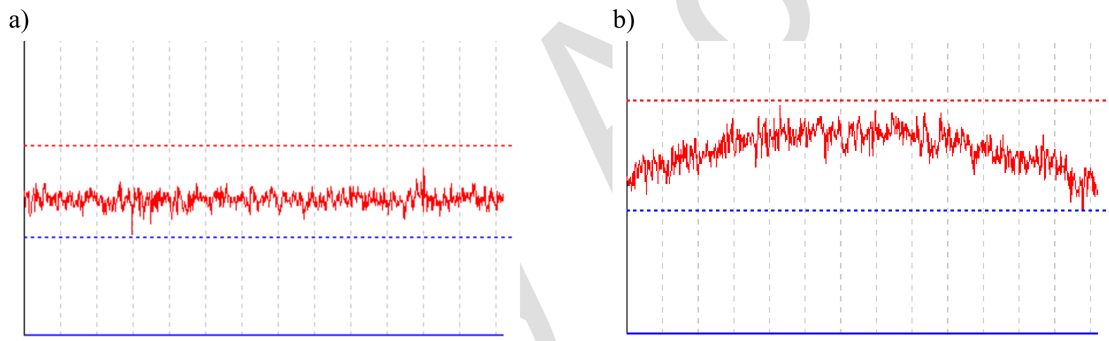

Fig. 2. Temporal variations of signal from a single pixel a) imager generating only high-frequency noise b) imager generating high-frequency noise fixed with low-frequency noise.

High-frequency spatial noise generates fast pixel-to-pixel spatial changes of brightness that are identical for every frame. These changes are noticeable when comparing the brightness of neighbouring pixels (Fig. 3a).

Low-frequency spatial noise generates slow spatial changes of image brightness (Fig. 3b). The changes are noticeable when comparing average brightness of bigger neighbouring groups of pixels.

There is a clear border between temporal noise and spatial noise due to different definitions. However, the borders between low/high-frequency temporal/spatial noise are not standardized. Therefore, low/high-frequency noise components can be calculated in slightly different ways.

It should also be noticed that there is a big difference between temporal frequency that characterizes cyclic changes in time (unit Hz) and spatial frequency that characterizes cyclic changes in space (unit line pair per mrad or mm).

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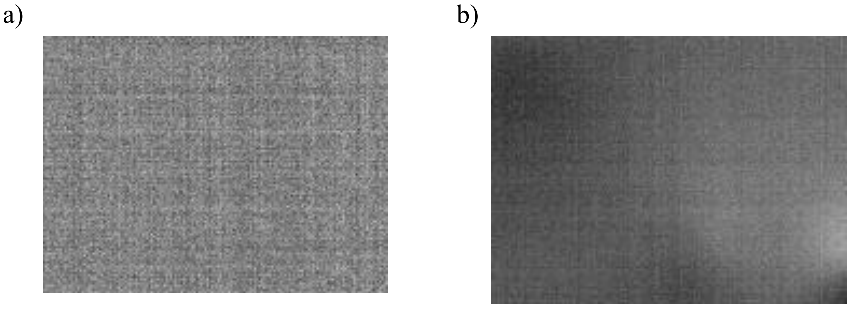

Fig. 3. Mean video frame generated by two hypothetical imagers: a) imager generating image with only high-frequency spatial noise, b) imager generating image with both high- and low-frequency spatial noise.

Low-frequency components are commonly discarded as measurement bias. Therefore, two high-frequency noises are typically used to characterized the noise in thermal imagers:

1. NETD – a measure of high-frequency temporal noise
2. FPN – a measure of high-frequency spatial noise.

This classical noise division does not distinguish between uncorrelated noise (the signal from each pixel at any frame is random) and correlated noise (signals can be correlated depending on the column, row or frame).

Proposed at the beginning of 1990s, the 3D Noise model is a concept of characterization of thermal imager noise (potentially also other types of EO imagers) that takes into account types of noise correlation and proposes to divide imager noise into seven components: 1) random spatio-temporal noise, 2) temporal row noise (streaking), 3) temporal column noise (rain), 4) random spatial noise, 5) fixed row noise, 6) fixed column noise, 7) frame-to-frame noise [27]. Each of these components can be treated as a separate parameter, but usually the term 3D Noise is used to describe the set of these seven parameters. Each of seven 3D Noise components can be further divided to low/high-frequency part.

4. Concept of noise equivalent parameters

NETD, FPN and the 3D Noise model are three most popular noise parameters of thermal imagers. However, it should be emphasized that definitions of all these parameters are based on the same concept of noise equivalent to differential temperature. According to this concept, the noise parameter can be expressed mathematically as (1):

$$Parameter = \Delta T \rightarrow \Delta S = N_{\mathrm{im}}, \tag{1}$$

where ΔS is a differential signal generated by a target of differential temperature ΔT, and N_{im} is rms of a component of specified type of noise generated by the thermal imager.

It is also possible to say that NETD, FPN and the 3D Noise model can be measured using the same four-stage method:

- Measurement of imager responsivity (SiTF) as a ratio of an output differential signal ΔS (typically in digital levels) caused by input differential temperature ΔT (in temperature units), as in (2):

$$SiTF = \frac{\Delta S[digL]}{\Delta T[mK]}, \tag{2}$$

where ΔT must be sufficiently small to keep radiometric input signal it in linear part of imager response function.

- Capturing a short video sequence of a uniform target (area blackbody) of known temperature (preferably over one hundred video frames),

- analysis of the captured video sequence and calculation of rms of specified noise component of thermal imager,
  calculation of the noise parameter as the ratio of rms noise component to imager responsivity SiTF, as in (3):

$$NoiseParameter = \frac{N_{\mathrm{im}}[digL]}{SiTF[digL/mK]}. \tag{3}$$

The difference between measurements of NETD, FPN, and 3D Noise components is only in ways of analysing the captured video sequence (the 3D data cube) generated by the imager looking at a uniform target (area blackbody). Depending on how we define imager noise N_{im}, we will get different noise parameters using the same formula (3).

5. Definitions of main noise parameters

5.1. NETD

NETD is an old parameter of thermal imagers with origins in the 1970s. Therefore, in order to understand the present-day confusing situation with NETD definitions and measurement methods, it is necessary to learn original the historical definition/measurement method.

As can be found in old books, NETD was originally defined as the blackbody temperature difference between a target and its background required to produce a peak-signal-to-rms-noise ratio of unity at a suitable point in the output electrical channel (Fig. 3) [14, 33]. This definition in mathematical form can be presented as (4):

$$NETD = \Delta T \rightarrow \Delta V = V_n, \tag{4}$$

where ΔV is the differential voltage generated by a warm target of differential temperature ΔT, and V_n is the rms of the voltage noise signal.

The presented NETD definition was developed at the time when all thermal imagers were the scanning thermal cameras that generated analogue video images. Although the definition does not state it clearly, NETD was a metric of only high-frequency temporal noise along a single video line (Fig. 4) analysed using an oscilloscope. Low-frequency temporal noise was eliminated using an analogue high-pass electrical filter of the limit at about 150kHz [14]. The low-frequency noise component was treated as a cosmetic defect (DC component of an oscilloscope line).

a) b)

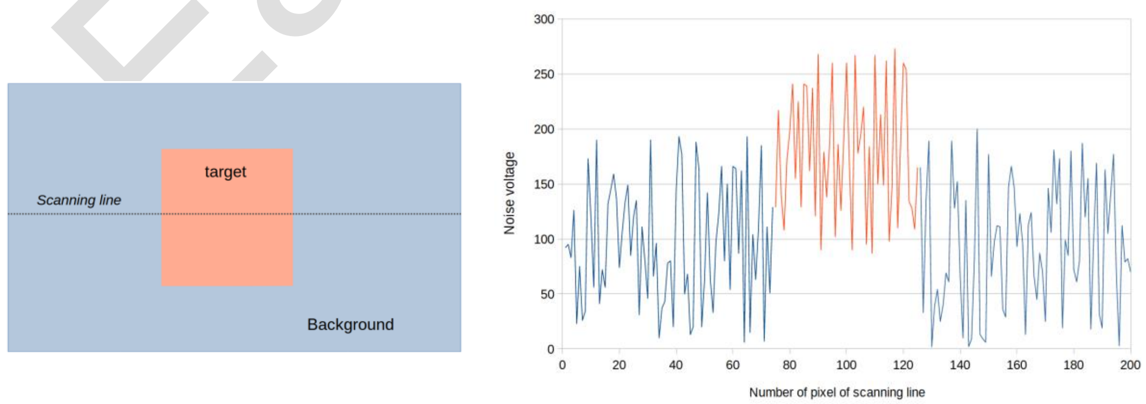

Fig. 4. Concept of NETD measurement of scanning thermal imagers: a) warm target on a cold background, b) noisy voltage signal of a single scanning line for a scenario when the rms noise voltage equals the voltage signal difference caused by a target of relative temperature difference.

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The concept of direct measurement of NETD is based on the idea to regulate the target differential temperature to achieve rms noise voltage being equal to a relative signal difference caused by the target of that differential temperature (Fig. 4). However, this direct method is not convenient as it is difficult and time-consuming to regulate differential temperature to achieve such a situation. It is more convenient to use a higher differential temperature in order to obtain a higher signal to noise ratio (ratio of voltage differential signal ΔV to rms noise V_n) and calculate NETD using following formula (5):

$$NETD = \frac{V_n}{\frac{\Delta V}{\Delta T}} = \frac{V_n[mV]}{SiTF[mV/K]}, \tag{5}$$

where SiTF, also called imager responsivity, is a linear part of the imager response function (Fig. 5).

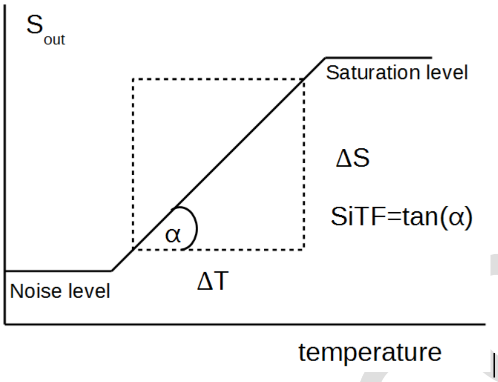

Fig. 5. Graphical concept of SiTF.

It should be also emphasized that NETD defined in the following way:

1. It is a measure of only high-frequency temporal noise of a single video line,
2. The definition gives no information about the spatial noise between different video lines of old scanning imagers.

Nowadays, there is a general consensus that NETD of modern staring thermal imagers is a measure of temporal variations of brightness of all pixels within a certain 2D area (potentially total output image). Output brightness is typically measured in digital levels.

Therefore, after changing analogue voltage V (in Volt units) to more general term, signal S (in digital level units) (5) is converted to a new form (6):

$$NETD = \frac{N_{\mathrm{im}}[digL]}{SiTF[digL/mK]}. \tag{6}$$

There is also an agreement that SiTF is to be measured by capturing the image of a blackbody at two different temperatures. One of these temperatures is typically equal to ambient temperature.

Further on, it appears that there is agreement that reference test conditions are as follows: NETD is to be measured for temperature of the blackbody equal to 300K, and measurement data is corrected to simulate the case of an ideal blackbody and collimator (emissivity of the blackbody is one, transmission of the collimator is one) [34-35]. However, there is no agreement how exactly noise N_{im} is to be defined and measured.

Analysis of earlier-listed websites of manufacturers of thermal imagers [6-7], manufacturers of IR FPA sensors [8], standards [9] and manufacturers of equipment for testing thermal imagers [10-13], popular books on testing thermal imagers [14-15], while searching for a definition of imager noise, can generate a surprising conclusion that there are big differences in definitions of the term “imager noise” that can be met in literature (Table 1).

Table 1. Definitions of imager noise N_{im} for use in NETD calculation according to different literature sources.

No	Type of literature source	Definition of imager noise for the NETD formula
1	Manufacturer of IR FPA sensors [8]	Total electronic noise
2	Manufacturer of thermal imagers [6]	Temporal noise that corresponds to the 2-D mean temporal pixel noise
3	Manufacturer of thermal imagers [7]	Noise signal
4	ASTM standard [9]	RMS noise voltage (measured using an RMS meter)
6	Manufacturer of test systems [10]	Temporal noise
7	Manufacturer of test systems [11]	RMS random noise
8	Manufacturer of test systems [12]	Temporal noise
9	Manufacturer of test systems [13]	1. Signal variations of pixels at a single frame (spatial NETD) 2. Temporal variances for each pixel (temporal NETD) 3. N_{TVH} component (Random 3D noise NETD)
10	Books on testing thermal imagers [14-15]	High-frequency temporal noise
11	Paper by the staff of a manufacturer of test systems [32]	N_{TVH} (component of 3D Noise) reveals RMS noise associated with NETD
12	Paper by scientists from US NVESD in year 1992 [26]	N_{TVH} (the random component of the 3D Noise model) replaces NETD in the FLIR 92 model
13	Paper by scientists from the US NVESD in year 2005 [28]	1. Imager noise should not be interpreted as standard deviation from N_{TVH} (random component of the 3D Noise model), 2. Imager noise is 2D mean pixel temporal noise (for Temporal NETD) 3. There is also Spatial NETD (standard deviation from time averaged 2D frame)
14	Paper by scientists from the US Army, Aviation and Missile Research, Development, and Engineering Center in 2014 [17]	NTVH component of the 3D Noise
15	Paper by scientists from the US NVESD in year 2023 [16]	1. Standard deviation from spatio-temporal variations in the recorded noise array 2. Square root from average variance of temporal variations of pixels of the recorded noise array 3. Average standard deviation of temporal variations of noise of pixels of the recorded noise array. 4. Square root from median of variances of temporal variations of pixels of the recorded noise array

Definitions 1 and 3 are too general for any practical use. The definition 4 is obsolete because the method of measurement indicates that it refers to old scanning imagers. It is not clear what RMS random noise in Definition 7 actually is. Definitions 6, 8, 10 are general but at least indicate that imager noise is to be temporal noise. Only Definitions 2, 9, 11, 12, 13, 14, 15 are precise enough to be used practically to define the type of imager noise needed by the formula to calculate NETD.

The latter definitions combined show that imager noise used in the NETD formula can be defined in at least five different ways (Table 2). This finding can be surprising to some readers who expect one standard definition of NETD. Further on, it should also be noticed that recommendations from the main US institution in the field of EO metrology (NVESD) change with time (compare [16], [26], [28]). In addition, scientists from various US institutions present different conclusions related to the definition of imager noise used in NETD calculations (compare [16] and [17]).

Table 2. Definitions of imager noise used in NETD calculations.

No	Type of imager noise	Short definition
1	Total spatio-temporal noise	Standard deviation from raw spatio-temporal variations in the recorded noise array
2	Average power temporal noise	Square root from average variance of temporal variations of pixels of the recorded noise array
3	Average intensity temporal noise	Average standard deviation of temporal variations of noise of pixels of the recorded noise array.
4	Median power temporal noise	Square root from median of variances of temporal variations of pixels of the recorded noise array
5	Random spatio-temporal noise	Standard deviation from random spatio-temporal variations in the recorded noise array (the raw noise array must be filtered to remove any correlations)

5.2. Fixed Pattern Noise

FPN is a phenomenon that manifests itself in images generated by thermal imagers/IR FPA sensors in the form of a fixed pattern (mesh) that does not change from frame to frame (Fig. 2a). As FPN does not change in time, some scientists claim that it should not be treated as noise, but as non-uniformity [19]. It should also be noted that the FPN phenomenon can be treated as spatial noise (see Section 4).

FPN is a parameter used to characterize earlier defined spatial noise. It can be treated as broadband spatial noise, but practically, it is measured after the removal of low-frequency noise (as high-frequency spatial noise).

The main terminology problem with defining FPN is a fact that often the same term is used to describe fixed-pattern noise of two different video images:

1. raw uncorrected video image generated by an IR FPA sensor (strong fixed pattern is seen),
2. corrected video image at the output of a thermal imager (only minor fixed patterns are noticeable).

Therefore, the same term means a totally different video image for the IR PFA community and for specialists in testing complete thermal imagers. In the latter case, a more proper name is residual fixed pattern noise (RFPN). However, in order to keep with common terminology of thermal imaging, the term FPN is used in this paper to describe residual fixed pattern noise at the output of thermal imagers.

In addition, it should be also noted that parameter defined in this way is sometimes also called Spatial NETD [13, 22] or inhomogeneity equivalent temperature difference (IETD) [23-24].

However, in spite of this terminological chaos, there is a general consensus that the FPN parameter understood a measure of spatial noise of thermal imagers can be calculated as a ratio of high-frequency spatial noise $N_{SP\text{-}HF}$ and imager SiTF:

$$FPN = \frac{N_{SP-HF}[digL]}{SiTF[digL/mK]}. \tag{7}$$

The noise component $N_{SP\text{-}HF}$ is typically defined as the rms value of a 2D noise array obtained from the original 3D raw video sequence generated by the thermal imager looking to a uniform target after two mathematical operations:

1. temporal averaging of all captured video frames,
2. high-pass temporal frequency filtration.

Operation of temporal averaging of pixel signals can be presented in the mathematical form as in (8):

$$S_{i,j} = \frac{1}{T}\sum_{t=1}^{T} S\,[i,j,t], \tag{8}$$

where S[i,j,t] means original the 3D raw video sequence generated by the thermal imager seeing a uniform target. HF filtering is commonly performed by removing from raw-time averaged S[i,j] array its low-frequency component, as in (9):

$$S_{i,j}^{HF} = S_{i,j} - S_{i,j}^{LF}. \tag{9}$$

The problem is that there is no consensus how to calculate this low-frequency time averaged array $S_{i,j}^{HF}$. There are at least two main approaches for low-frequency filtering:

1. approximation of raw-time averaged array $S_{i,j}$ using second-degree polynomials,
2. convolution of raw-time averaged array $S_{i,j}$ with a blur kernel.

Sometimes two stage low-frequency filtering is carried out in order to wipe completely any low-frequency trends [29].

5.3. 3D noise model

Proposed at the beginning of the 1990s, the 3D Noise model is a concept of characterization of the thermal imager (potentially also of other types of EO imagers) noise by precise division of noise into seven components (Table 3) [27].

Table 3. Noise components of the 3-D Noise model.

No	**Mathematical symbol**	**Name**	**Mathematical form**	**Calculations**
1	N_{TVH}	Random spatio-temporal noise	3D array (T x VxH px)	3D array after removal of all correlations
2	N_{TV}	Temporal row noise (streaking)	2D array: T·V px	each row is averaged over *H* pixels
3	N_{TH}	Temporal column noise (rain)	2D array: TxH px	each column is averaged over *V* pixels
4	N_{VH}	Random spatial noise	2D array: V·H px	each pixel is averaged over *T* frames
5	N_V	Fixed row noise	1D array (V px)	each row is averaged over *H* pixels and *T* frames
6	N_H	Fixed column noise	1D array (H px)	each column is averaged over *V* pixels and *T* frames
7	N_T	Frame to frame noise	1D array (T px)	each frame is averaged over *V·H* pixels
8	S	Average cube	single number	each frame is averaged over *V·H* pixels and *T* frames

The 3D Noise model is based on the concept of the D_i directional averaging operators that allow the mathematical derivation of eight noise components from the noise data [27]. The operators average the data in the direction indicated by the subscripts. If a sequence of images generated by the tested imager was captured, the captured data can be presented in the form of

3D array N_{TVH}. The T-dimension represents time or numbers of the framing sequence. The H-dimension and V-dimension give spatial information.

The noise components are calculated by converting the raw 3D array (video sequence) into a series of 3D, 2D or 1D arrays: noise components N_{TVH}, N_{VH}, N_{TV}, N_{TH}, N_H, N_V, N_T, S, as shown in (10-11).

$$N_{TVH} = (1 - D_t) \cdot (1 - D_v) \cdot (1 - D_h) \cdot S_{[t,v,h]}, \tag{10a}$$
$$N_{VH} = D_t \cdot (1 - D_v) \cdot (1 - D_h) \cdot S_{[t,v,h]}, \tag{10b}$$
$$N_{TV} = (1 - D_t) \cdot (1 - D_v) \cdot D_h \cdot S_{[t,v,h]}, \tag{10c}$$
$$N_{TH} = (1 - D_t) \cdot D_v \cdot (1 - D_h) \cdot S_{[t,v,h]}, \tag{10d}$$
$$N_V = D_t \cdot (1 - D_v) \cdot D_h \cdot S_{[t,v,h]}, \tag{10e}$$
$$N_H = D_t \cdot D_v \cdot (1 - D_h) \cdot S_{[t,v,h]}, \tag{10f}$$
$$N_T = (1 - D_t) \cdot D_v \cdot D_h \cdot S_{[t,v,h]}, \tag{10g}$$
$$S = D_t \cdot D_v \cdot D_h \cdot S_{[t,v,h]}, \tag{10h}$$

where D_t, D_v, D_h are averaging operators defined below:

$$D_t = \frac{1}{T}\sum_{t=1}^{T} S_{[t,v,h]},\ D_v = \frac{1}{V}\sum_{v=1}^{V} S_{[t,v,h]},\ D_h = \frac{1}{H}\sum_{h=1}^{H} S_{[t,v,h]}. \tag{11}$$

N_{TVH}, N_{VH}, N_{TV}, N_{TV}, N_H, N_V, N_V, N_T are to be understood in a dual way: 1) 3D/2D/1D arrays obtained from the original raw 3D array by mathematical operation as shown in (10); 2) standard deviation from these arrays.

It should be also emphasized that it is possible to calculate basic components of the traditional model (total temporal noise and total spatial noise) from the components of the 3D Noise model, but inverse solution is not possible. The conversion formulas are as below (12, 13):

$$N_{temp} = \sqrt{N_{TVH}^2 + N_{TV}^2 + N_{TH}^2 + N_T^2}, \tag{12}$$

$$N_{spat} = \sqrt{N_{VH}^2 + N_V^2 + N_H^2}, \tag{13}$$

where N_{temp} is total temporal noise, N_{spat} is total spatial noise.

6. Factors that reduce reproducibility of measurement of noise parameters

It is obvious that definition chaos (five different definitions) in the case of NETD will produce significantly different measurement results when the measurement of NETD is carried out using different definitions. In contrast, accurate stable results should be expected in the case of FPN and 3D Noise parameters that are defined in a uniform way (very precise definition especially for the 3D Noise model).

However, in practice, it is a common situation that measurements of NETD, FPN or 3D Noise model components of the same thermal imager carried out by several different test teams (manufacturers, scientific institutes) produce significantly different results (differences up to 50% or more).

The main reason for such pessimistic metrological situation is lack of precisely determined measurement methods of these parameters. In detail, there are at least five main factors that reduce reliability and accuracy of measurement of noise parameters for NETD, FPN, 3D Noise:

1. length of the video sequence (number of video frames) analysed to calculate imager noise,
2. filters used to remove low-frequency noise components,
3. type of test system to measure responsivity (SiTF) of the thermal imager,
4. moment when tests are carried out,
5. methods to correct raw measurement results.

6.1. Length of the analysed video sequence

The author has not been able to find any literature source that gives direct recommendation on optimal length of video sequence captured and analysed to determine imager noise. However, there are some papers that give indirect recommendations in the form of a number of frames to be captured [6, 17, 32]. Reference [32] presents a general guideline: the more frames, the better because more accurate results are expected. More detailed recommendations can be found in some literature: 100 frames [14, 16] or 128 frames [2, 16]. The rationale behind these recommendations can be found in [32]. It suggests that maximum bias error of calculations of components of the 3D noise model is kept at a modest level of approximately 1.5%, if 100 frames are captured from an imager of typical 640x480 image resolution. These findings suggest that number of frames (length of the video sequence) is not important on condition it is over 100 frames, or even over about 60 frames, if higher potential error at a level of about 2% is accepted. However, practical experiments carried out by the author have shown that measured temporal noise can depend significantly on the number of frames even if it is over 100 frames on condition that a raw noise cube is analysed (Table 4).

Table 4. Imager temporal noise calculated for video sequences for the frame number of the captured video sequences (results normalized for 100 frames).

Imager type/number	**Frame number**			
	50	100	200	2000
Uncooled imager no 1	0.94	1.00	1.24	2.02
Uncooled imager no 2	0.74	1.00	1.13	1.50
Uncooled imager no 3	0.97	1.00	1.01	1.03
Cooled imager no 1	0.99	1.00	1.03	1.11

In the author's opinion, the earlier-presented recommendations on the minimal number of frames are based on three wrong assumptions. First, the noise of thermal imagers can be treated as white noise. In reality, the spectrum of temporal noise of thermal imagers depends strongly on frequency, especially in the low-frequency band. Second, the number of frames determines the length of the captured video sequence. It is not true, as there are on the market imagers of different frame rates: 25FPS, 30FPS, 50FPS, 60FPS or different ones. Third, a modest number of frames (about 100 frames) enables accurate measurements of rms of imager noise. In reality, such a small number of frames is captured in a relatively short time period (from about 2 sec to 4 sec). This short time window works as a high-frequency filter that attenuates low-frequency noise components. The strength of this filtering depends on the frame rate of tested imager.

6.2. Low-frequency filtration

The discussion on filtration of a raw 3D noise array used a source of data when calculating noise parameters has been carried out for decades. NETD and FPN have traditionally been considered as measures of high-frequency noise (NETD – temporal noise, FPN – spatial noise)

[14-15]. However, precise, standardized rules for filtration to separate low-frequency noise and high-frequency noise have not been formulated. The same with components of the 3D Noise model. Analysis of papers by scientists from the NVESD can lead to the conclusion that recommendations vary with authors and time of publication: no filtration [26], approximation using a second-degree polynomial [28], Gaussian filter [16]. Therefore, the high-frequency noise cube is typically calculated using two main ways (14, 15):

$$Noise(h,v,t)_{(HF)} = Noise(h,v,t)_{(raw)} - Approximation(Noise(h,v,t)_{(raw)}), \tag{14}$$

or

$$Noise(h,v,t)_{(HF)} = Noise(h,v,t)_{(raw)} - Noise(h,v,t)_{(raw)} \otimes Gauss(h,v,t). \tag{15}$$

The Gaussian filter is defined as in (16)

$$Gauss(h,v,t) = \exp\left(\frac{-h^2}{2\sigma_h^2}\right) \cdot \exp\left(\frac{-v^2}{2\sigma_v^2}\right) \cdot \exp\left(\frac{-t^2}{2\sigma_t^2}\right), \tag{16}$$

where σ_h, σ_v, σ_t are filter directional standard deviations of typical values equal to eight (pixels or frames). The value of the Gaussian filter parameter σ is not standardized and can vary but typically it equal 8px or 8 frames [16].

It is natural that these different ways of filtering shall generate different results of measurement of high-frequency temporal/spatial noise. As we can see in Table 5, there is a significant influence of the filtering method on some of the noise components of the 3D Noise model. In addition, this influence varies from one imager to another (Table 5).

Table 5. Temporal noise calculated using different filtering methods (normalized to no-filter results).

	Filtering method			
Imager	**No filter**	**Approximation with 2nd-degree polynomial**	**Gaussian filter (Gaussian parameter 8 frames)**	**Two stage filtering**
Uncooled imager no 1	1	0.68	0.55	0.55
Uncooled imager no 2	1	0.85	0.34	0.33
Uncooled imager no 3	1	0.99	0.97	0.97
Cooled imager no 1	1	1	1	1

6.3. Type of systems for measurement of SiTF responsivity

Measurement of imager SiTF responsivity is one of the steps of procedure to measure noise parameters of thermal imagers. This rule is valid for NETD, FPN and the 3D Noise model. There are three types of test systems used for measurement of SiTF of thermal imagers:

1. Collimator test systems,
2. Focus mode systems,
3. Flood mode test systems.

The systems from the first group are built as image projectors based on typically reflective collimators capable to project the image of a reference target (a uniform one or a blackbody) into direction of the thermal imager. Such test systems are typically built as sets of blocks: collimator, rotary wheel, set of targets, small active blackbody, large passive blackbody, frame grabber, PC set, software (Fig. 6a). The collimator is used as an image projector that projects the image of a target located at a collimator focal plane and it simulates such a target at optical infinity. A rotary wheel enables an easy exchange of a target to be simulated. Targets are manufactured as high-emissivity painted metal sheets with holes of different patterns. Large square targets are typically used during SiTF measurement. However, this measurement can be also carried out using no targets at all i.e. the tested imager can directly see the blackbody emitter through a hole in the rotary wheel). It should be noted that these collimator systems are good simulators of real work conditions when the imager sees distant targets that emit near parallel ways of beams that reach imager optics.

Due to the narrow FOV of typical collimators, such systems can project images of targets of relatively narrow angular size (below 3°). Therefore, the projected images typically fill only a fraction of the FOV of the tested imager (Fig. 7). The image of a small target of regulated temperature is sufficient to measure SiTF, but it should be noted that a uniform target of preferably ambient temperature filling the imager's FOV is needed to capture the noise cube (Fig. 8) used later to calculate noise components.

The test systems from the second group are much simpler. They are basically a set of a large active blackbody, frame grabber and PC/laptop. The blackbody is located at the exit of the optics of the tested imager and fully fills the imager's FOV (Fig. 8). The PC controls blackbody temperature and analyses images generated by the tested imager.

The systems from the third group (focused test systems) are similar to the flood-mode systems. The difference is that the blackbody is located at a greater distance (preferably over 20 times of the focal length of the IR objective of the tested imager) when the tested imager can focus on the blackbody and generate its image. Therefore, the blackbody fills only a small part of total FOV due to the significant imager-blackbody distance (image similar to Fig. 7).

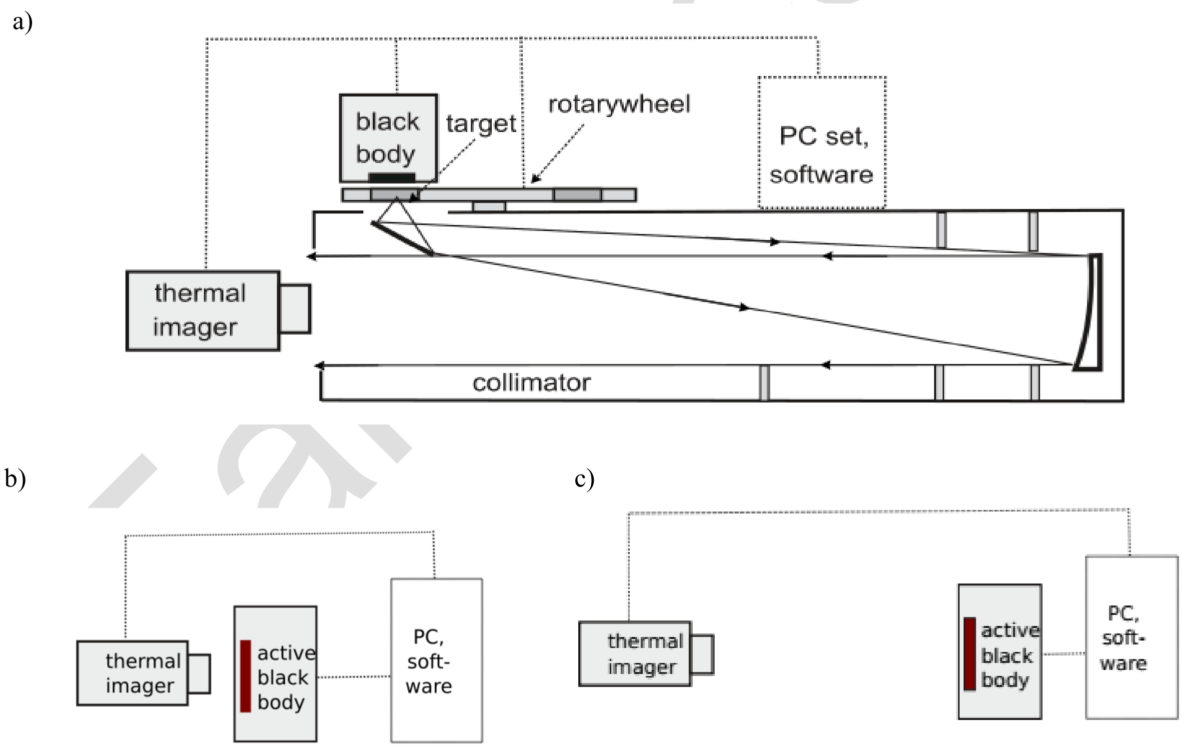

Fig. 6. Block diagrams of three types of test systems a) collimator system, b) flood-mode system, c) focused-mode system.

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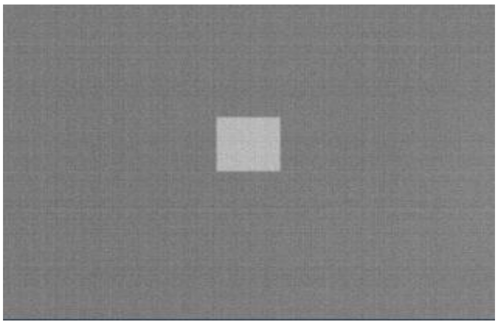

Fig. 7. Image of a square target projected by the collimator.

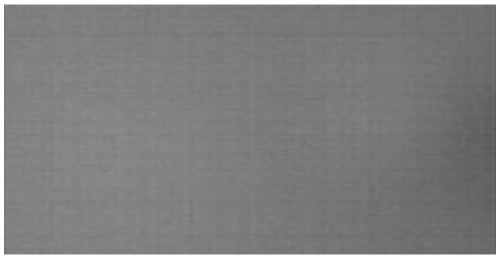

Fig. 8. Image of a large passive blackbody that fully fills the imager's FOV.

Theoretically, all types of test systems should generate the same results for SiTF measurement after losses due to limited transmittance of the collimator are compensated. However, in practice, all three methods generate significantly different results. As reported in [17, 18] the measurement of SiTF using flood-mode test systems generates results that can be up to 50% (typically up to 30%) higher compared to those generated by the collimator test systems. Focus-mode systems generate results somewhere between the collimator systems and the flood-mode systems.

The conclusions from [17, 18] have been confirmed by an experiment carried out by the author (Table 6). This means that type of test systems used during noise measurement is a source of big reproducibility errors when tests are carried out by teams using test systems of different types.

In the author's opinion, the main reason for this is the stray light effect that is amplified when using flood-mode systems. The interior of an IR objective is typically covered w low-reflectivity coatings. However, due to longer wavelengths, the reflectivity of such coatings/paints is still significantly higher comparing to the reflectivity of the interiors of visible range objectives. Therefore, in addition to black coatings, special baffles are often added in IR objectives. These parts of optical objectives (two black rectangles in Fig. 9) are expected to prevent light emitted by targets of interest from reflecting from the objective casing.

In the case of collimator systems that emit parallel beams, the baffles prevent the transmitting beam from reflecting from the IR objective casing. The only radiation that reaches the IR FPA sensor is direct. However, in the case of the flood system, the blackbody emits light in a nearly complete hemisphere. Some of such radiation reaches the IR FPA sensor directly in the same way as in the collimator system. However, there is also other radiation that reaches the IR FPA sensor indirectly by reflecting from the objective casing. In this way, the total signal is higher in the case of the flood system, especially with IR objectives of higher interior reflectivity.

Practically, it means that flood-mode test systems favour poorly designed IR objectives when measuring SiTF of thermal imagers. In such a situation, collimator systems are preferable for SiTF measurements. However, the problem is that flood mode systems, due to their simplicity and low cost, are the preferred choice of manufacturers of thermal imagers. Therefore, the use of such test systems can lead to overoptimistic results of measurement of noise parameters.

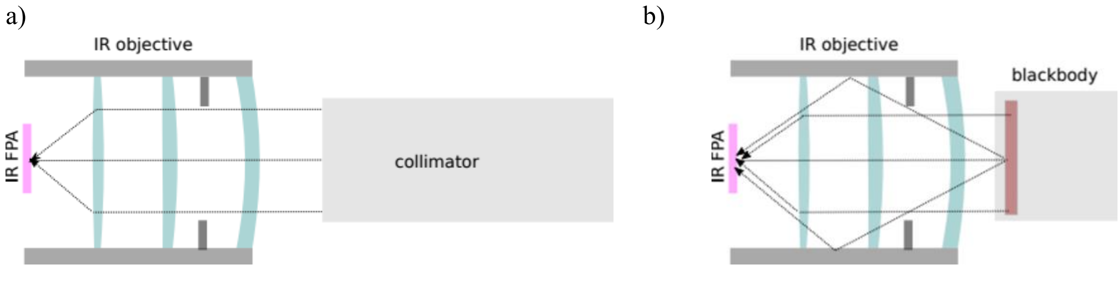

Fig. 9. Simplified concept of work of optical baffles for two types of test systems.

Table 6. Normalized SiTF measured using three different types of test systems (normalization to SiTF measured using the collimator system).

Imager	Collimator system	Focused-mode system	Flood-mode system
Uncooled imager no 1	1.00	1.15	1.50
Uncooled imager no 2	1.00	1.10	1.30
Uncooled imager no 3	1.00	1.03	1.10
Cooled imager no 1	1.00	1.09	1.15

6.4. Temporal moment when tests are carried out

It is commonly known that transient changes of temperature of both the tested imager and the test system can influence measurement results of noise parameters. Therefore, it is commonly accepted that both systems should be in thermal equilibrium before measurements can start. This state can be typically achieved in about 1 hour after powering on the imager and switched on the test system. However, it is often impractical to wait such a long time to achieve thermal equilibrium of every tested thermal imager. Therefore, tests of thermal imagers are carried out using thermal imagers at different stages of achieving thermal equilibrium.

Further on, it is also possible to improve the measured SiTF (and, indirectly, the noise parameter) keeping the imager off for several hours, powering the imager on, and then making a SiTF measurement only after several minutes of waiting. There are reports that using this simple trick it is possible to improve SiTF up to about 3% compared to results obtained in near thermal equilibrium, after one hour of waiting [18]. To summarize, the results of the measurement of SiTF (and, indirectly, the results for noise parameters) depend on the time interval from the moment the imager was switched on.

It has also been reported that, in spite of its name, fixed pattern noise is actually a long-term transient phenomenon. The fixed-pattern noise is at a local minimum immediately after a non-uniformity correction (NUC) operation and monotonically increases with time from this moment [25]. FPN measured one hour after the NUC can be several times higher compared to the minimal FPN immediately after the NUC. The most significant changes occur within the first 10 min following the NUC. Thus, it is logical that the measurement results for spatial noise components including FPN do depend significantly on the time elapsed from the moment the one-point NUC operation was carried out. It should be noted that this rule is fully valid for shutter thermal imagers. It is not clear if this is the case with shutterless thermal imagers as they use numerous image processing methods to reduce spatial noise. One point is certain – there are thermal imagers that generate fixed pattern-noise that significantly depends on the moment when the FPN measurement is carried out. The experiments carried out by the author confirm this thesis (Fig. 10).

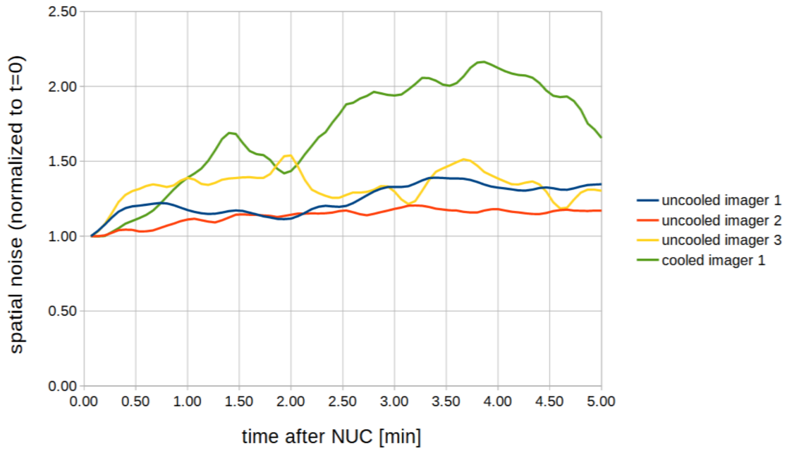

Fig. 10. Dependence of the measured FPN on the time interval from one-point NUC of tested thermal imager.

6.5. Corrections

There are three types of corrections of raw measurement results of noise parameters:

1. Correction due to non-standard ambient reference temperature,
2. Correction due to imperfect test system,
3. Correction due to filtering of raw data.

The problem is that due to lack of standardized regulation these corrections are performed by different teams in different ways. It is customary to measure and specify NETD of IR FPA sensors at 300K temperature [35-36]. However, this is not always the case with NETD of thermal imagers. A measurement of NETD is typically carried out at a typical laboratory temperature of about 22ºC. Due to non-linear relationship between temperature and radiant exitance, NETD depends on reference ambient temperature and measurement results at 22ºC will differ from those for 27º*C* (300K). Therefore, the result obtained for tests carried out at temperatures different from 27ºC should be corrected. The corrections formulas have been known for decades [15]. However, some manufacturers of thermal imagers do not give the information for what temperature NETD is specified.

The second correction is related to imperfections of the collimator and the blackbody: 1) collimator transmission is below one, 2) emissivity of the blackbody is also below one. Therefore, in order to correct these imperfections, raw measurement result must be multiplied by a product of blackbody emissivity and collimator transmission. Most teams remember about these simple corrections but some forget to implement it.

High-pass filtering is carried out to remove the low-frequency component of noise and later calculate NETD, FPN, σ_{TVH}. Typically, no correction is carried out following such removal of low-frequency noise. The latter component is treated typically as a measurement bias. However, a recent paper has claimed that such filtering also removes valuable noise in the form of low-frequency spectrum of imager white noise and, therefore, the results should be corrected [16]. However, very few test teams are aware of the latter recommendation. Anyway, this recommendation can be an additional source of variability of measurement of noise parameters when carried out by different teams.

7. Discussion

Thermal imagers are of critical importance for military/security forces worldwide. They have found a series of civilian applications, too. Noise parameters are important tools to characterize thermal imagers and have been known for decades. Therefore, it is commonly expected that there are some international/national standards (or semi-standards contained in documents issued by top world organizations) that regulate measurement of these parameters. In such a situation the metrological chaos in the form of a series of slightly different definitions/measurement methods presented in the previous sections can be surprising for some readers, but it merely presents everyday reality.

Thermal imaging technology has significantly improved within the last several decades. The performance of modern staring thermal imagers is several times better in comparison with old scanning imagers from two decades ago.

There has also been some progress in the design of systems for testing thermal imagers. Performances of critical modules of such systems (blackbodies) has improved during last decades. Differential blackbodies of temporal stability as low as 1 mK, uncertainty below 10 mK (for low temperature differences) traceable to NIST or EU metrology systems are commonly used in systems for testing thermal imagers. However, there is no progress in field of legal metrology: there are still no international/domestic standards that could properly regulate measurement of noise parameters. In fact, the situation is not much better in the case of other parameters of thermal imagers.

One potential way to develop the needed standard that could regulate defining/measurement of noise parameters of thermal imagers is cooperation of wide international community involved in the thermal imaging technology. The fact that machine vision international community has developed the EMVA1288 standard that regulates the testing of VNIR cameras for machine vision applications proves that such a solution is possible.

A second potential way to solve problem of present-day poor standardization is development of the needed standard by a scientific institution from a country that is one of most important manufacturers and gradual acceptance such local standard by the international community.

A third potential way to develop the needed standard is a product of work international standard organizations like ISO.

Any other way could be acceptable as long as the needed standard could be generated. It should be noted that present-day metrological chaos is a real problem only on the international scale. Locally, it is only a minor technical problem. The reason is that in most technologically advanced countries there is one government-authorized centre that performs the testing of thermal imagers and generates results that are accepted locally. This system enables to keep quite good local reproducibility of measurements of the noise parameter in thermal imagers but it is a bad solution globally.

8. Conclusions

This paper presents a critical review of numerous of past and contemporary slightly different definitions/measurement methods of noise parameters in thermal imagers (NETD, FPN, 3D Noise model) that create a metrological chaos and significantly reduce reproducibility of measurement of noise parameters carried out by different test teams. The paper explains that significant differences between measurement results obtained by different test teams (differences at the level of 50% or more) are not related to limited performance of commercially available test systems, but are caused by the metrological chaos due to poor standardization of characterization/measurement of noise parameters in thermal imagers. Therefore, a significant improvement in field of standardization of defining/measurement of the noise parameters is urgently needed to enable continuous fast growth of the thermal imaging technology.

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