Metrol. Meas. Syst., Vol. 32 (2025), No. 2
DOI: 10.24425/mms.2025.154668

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

CRITICAL REVIEW OF PRESENT DAY METHODOLOGY OF CHARACTERIZATION OF NOISE OF THERMAL IMAGERS

Krzysztof Chrzanowski[1,2]

1) *Military University of Technology, Institute of Optoelectronics, 2 Kaliski Str., 00-908 Warsaw, Poland*
2) *INFRAMET, Bugaj 29a, Koczargi Nowe, 05-082 Stare Babice, Poland* (✉ *kch@inframet.com*)

Abstract

This paper presents a review of reasons that create metrological chaos in field of characterization of noise of 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 variations (mostly random) in time and space in a video image generated by thermal imagers. It is considered as one of main factors that limits performance of thermal imagers. In detail, noise parameters describe the limit of ability of thermal imagers to detect large targets of low thermal contrast. Therefore, proper characterization of noise of 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 been fluctuating since advent of this technology in 1970s. However, for last three decades noise is typically characterized using two parameters, *noise equivalent temperature difference* (NETD) and *fixed pattern noise* (FPN), as well as a set of parameters under common name 3D Noise model.

NETD is a very old parameter that has been used as primary criterion for characterization of noise of thermal imagers since the beginning of 1970s. In detail, it is typically defined as a measure of temporal noise of thermal imagers. Further on, FPN is another old parameter to characterize noise of thermal imagers. In contrast to NETD, FPN is a measure of spatial noise. Finally, 3D Noise model is a set of seven independent parameters that combined together offer detail characterization of seven types of noise of thermal imagers. It should be noted that, 3D Noise model is also a relatively old concept (origin at the beginning of 1990s). To summarize, both NETD, FPN and 3D Noise model can be considered as mature (at least three decades) concepts for characterization of noise of 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 (differences up to 50% or more). The main reasons for such a gloomy metrologic situation are imprecise and fluctuating definitions and differences in measurement methods of NETD, FPN and 3D Noise model components. This situation is especially frustrating for the author, who is CEO of one of

Copyright © 2025. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (CC BY-NC-ND 4.0 http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits use, distribution, and reproduction in any medium, provided that the article is properly cited, the use is non-commercial, and no modifications or adaptations are made.
Article history: received October 7, 2024; revised November 19, 2024; accepted December 9, 2024; available online June 3, 2025.

Early Access

manufacturers of equipment for testing thermal imagers and sometimes meets 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 that create metrological chaos in field of characterization of noise of thermal imagers. In detail, the paper presents a critical analysis of myriads of past and present day definitions/measurement methods of noise parameters of thermal imagers that created this chaos and significantly reduce reproducibility of measurement of noise parameters carried out by different test teams.

2. Literature on characterization of noise

Situation in a field of literature on characterization/measurement of noise parameters of thermal imagers apparently looks very good. There is a very numerous literature on subject of NETD of thermal imagers. Only 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 of thermal imagers. There are also dozens of internet websites that present definitions and some measurement guidelines of 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 measurement of NETD [9]. Further on, information on definition and measurement method of NETD can be found at 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 measurement of NETD [14-15]. However, detailed analysis of this literature can reveal rather gloomy situation.

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

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

Literature on the subject of FPN is much smaller in comparison to literature on the subject of NETD. However, literature on this subject is still quite numerous: only SPIE Digital library can produce (keyword Fixed Pattern Noise in paper tittle or abstract) at least fifty papers. It should also be noted that 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, detailed analysis of numerous literature reveal similar, rather gloomy, situation for a series of reasons.

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

Second, IR FPA community uses the term FPN to describe spatial noise generated by IR FPA sensors before uniformity correction is applied; and the term RFPN (residual fixed pattern noise) is used to describe spatial noise in output image generated by thermal imagers after uniformity correction is applied [20-21]. This terminology chaos is amplified by use of two additional terms (Spatial NETD [13, 22] or 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 slightly different methods to measure FPN and these differences reduce reproducibility.

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

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

However, unfortunately for the test teams world wide, who often look to 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 captured video sequence, or optimal method of measurement of SiTF unanswered. A good example of such papers, that presents unanswered questions of critical importance, is relatively 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 of NVESD papers deliver analysis of some problems, but avoid to indicate any solution to analyzed problem and emphasize that the paper presents no recommendations. Reference [18] delivers 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 "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.

Situation described earlier is especially frustrating for the author, who is CEO of company that manufacture 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 centers like NVESD that do not deliver detail precision recommendations.

In next sections reasons that create this dismal metrologic 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 EMVA1288 standard [19].

Early Access

3. Noise division

According to the classical concept 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).

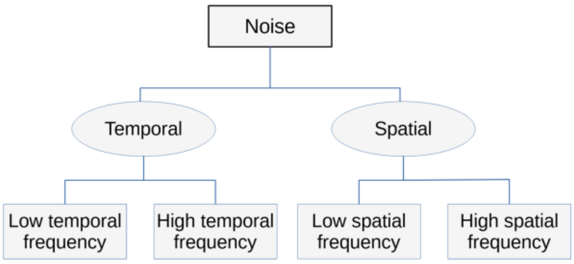


Fig. 1. Classical division of noise.

Temporal noise generates temporal variation of intensity of pixels of output image even when incoming radiation does not change in time. Spatial noise (FPN) phenomenon generates spatial variations of intensity of pixels of 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 the 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).

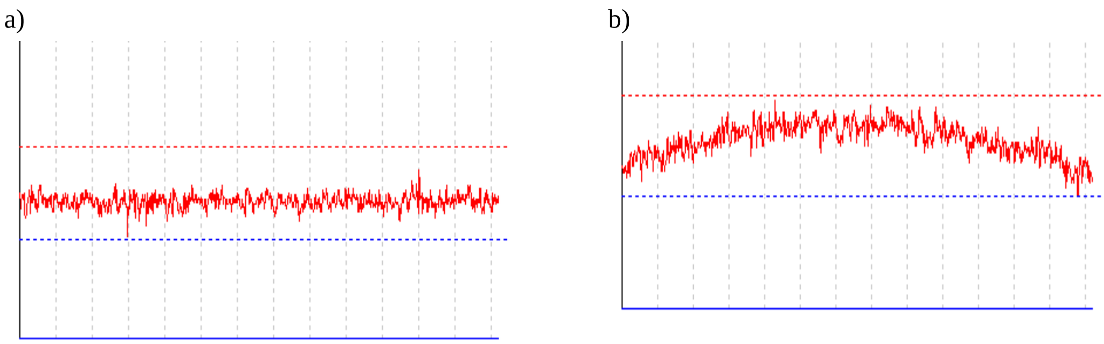


Fig. 2. Temporal variations of signal from a single pixel a) imager generating only high frequency noise b) imager generating high frequency noise fixed with low frequency noise.

High frequency spatial noise generates fast pixel to pixel spatial changes of brightness that are identical for every frame. The changes are noticeable when comparing brightness of neighbour 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 neighbour groups of pixels.

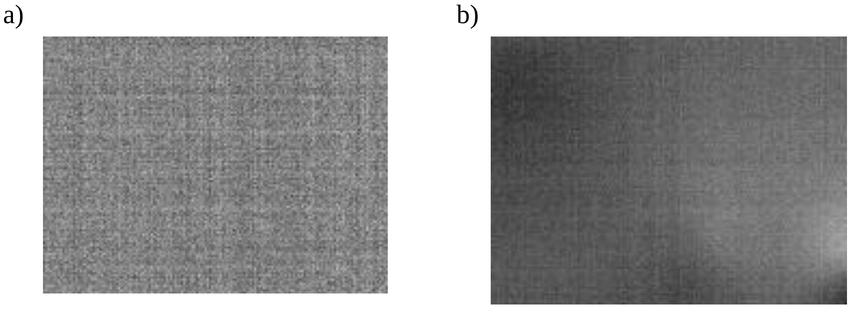


Fig. 3. Mean video frame generated by two hypothetical imagers: a) imager generating image with only high frequency spatial noise, b) imager generating image with both high frequency and low frequency spatial noise.

There is clear border between temporal noise and spatial noise due to different definitions. However, 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 characterize cyclic changes in time (unit Hz) and spatial frequency that characterize cyclic changes in space (unit line pair per mrad or mm).

Low frequency components are commonly discarded as measurement bias. Therefore, two high frequency noises are typically used to characterized noise of 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 (signal from each pixel at any frame is random) and correlated noise (signals can be correlated depending on column, row or frame).

Proposed at the beginning of 1990s 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 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, noise parameter can be expressed mathematically as (1):

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

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

It is also possible to say NETD, FPN and 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 short video sequence of a uniform target (area blackbody) of known temperature (preferable over one hundred video frames),

Analysis of the captured video sequence and calculation of rms of specified noise component of thermal imager,

Calculation of noise parameter as 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, 3D Noise components is only in ways of analysis of captured video sequence (3D data cube) generated by imager looking to 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 of origin in 1970s. Therefore, in order to understand present day confusing situation with NETD definitions and measurement methods, it is necessary to learn original 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 differential voltage generated by a warm target of differential temperature ΔT, and V_n is rms of 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 image. 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 analogue high-pass electrical filter of limit at about 150kHz [14]. The low frequency noise component was treated as a cosmetic defect (DC component of an oscilloscope line).

DOI: 10.24425/mms.2025.154668

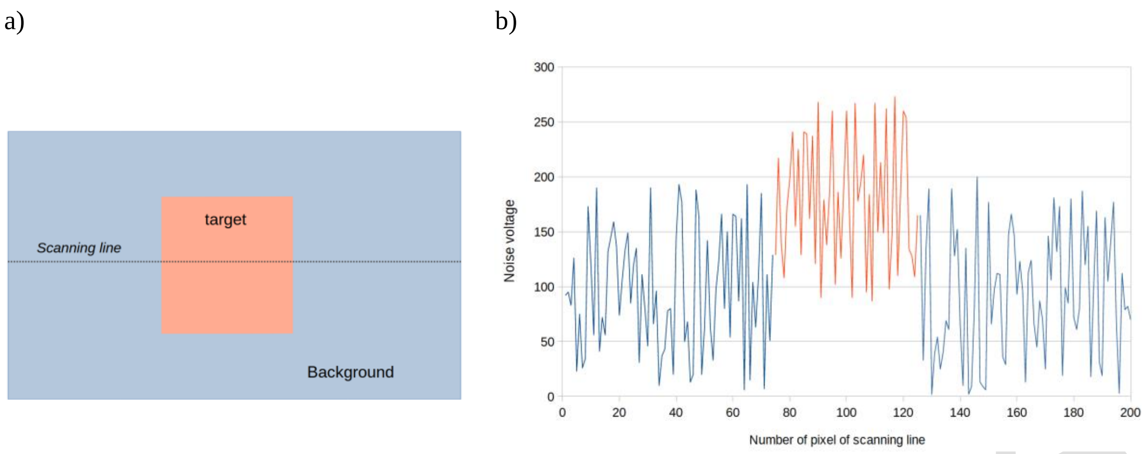


Fig. 4. Concept of NETD measurement of scanning thermal imagers: a) warm target on a cold background, b) noisy voltage signal of a single scanning line for a scenario when rms noise voltage equals to voltage signal difference caused by target of relative temperature difference

Concept of direct measurement of NETD is based on the idea to regulate target differential temperature to achieve situation when rms noise voltage equals to relative signal difference caused by a 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 higher differential temperature in order to obtain 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 imager response function (Fig. 5).

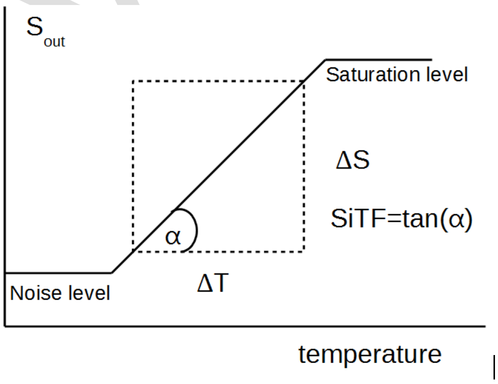


Fig. 5. Graphical concept of SiTF.

It should be also emphasized that NETD defined in this way:

1. 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.

Early Access

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 image of a blackbody at two different temperatures. One of these temperatures is typically equal to ambient temperature.

Further on, it looks that there is agreement that reference test conditions are: NETD to be measured for temperature of the blackbody equal to 300K, and measurement data is corrected to simulate case of 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] searching for 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 of literature source**	**Definition of imager noise for 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 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 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 staff of a manufacturer of test systems [32]	N_{TVH} (component of 3D Noise) reveals RMS noise associated with the NETD
12	Paper by scientists from US NVESD in 1992 year [26]	N_{TVH} (random component of 3D Noise model) replaces NETD in FLIR 92 model
13	Paper by scientists from US NVESD in 2005 year [28]	1. Imager noise should not be interpreted as standard deviation from N_{TVH} (random component of 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 US Army, Aviation and Missile Research, Development, and Engineering Center in 2014 [17]	NTVH component of 3D Noise

DOI: 10.24425/mms.2025.154668

15	Paper by scientists from US NVESD in 2023 year [16]	1. Standard deviation from spatio-temporal variations in recorded noise array 2. Square root from average variance of temporal variations of pixels of recorded noise array 3. Average standard deviation of temporal variations of noise of pixels of recorded noise array. 4. Square root from median of variances of temporal variations of pixels of recorded noise array

The definitions no 1, and no 3 are too general for any practical use. Definition no 4 is obsolete because the way of measurement indicates that it refers to old scanning imagers. It is not clear what is actually RMS random noise in definition 7. The definitions 6, 8, 10 are general but at least indicate that imager noise is to be temporal noise. Only the definitions 2, 9, 11, 12, 13, 14, 15 are precise enough to be used practically to define type of imager noise needed by formula to calculate NETD.

The latter definitions combined together show that imager noise used in NETD formula can be defined in at least five different ways (Table 2). This finding can be be shocking to some readers who expect one standard definition of NETD. Further on, it should also be noticed that recommendations from main US institution in field of EO metrology (NVESD) fluctuates with time (compare [16], [26], [28]). In additions, scientists from different US institutions present different conclusions related to 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 recorded noise array
2	Average power temporal noise	Square root from average variance of temporal variations of pixels of recorded noise array
3	Average intensity temporal noise	Average standard deviation of temporal variations of noise of pixels of recorded noise array.
4	Median power temporal noise	Square root from median of variances of temporal variations of pixels of recorded noise array
5	Random spatio-temporal noise	Standard deviation from random spatio-temporal variations in recorded noise array (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 a form of fixed pattern (mesh) that does not change from frame to frame (Fig. 2a). Because 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 FPN phenomenon can be treated as spatial noise (see Section 4).

FPN is a parameter used to characterize earlier defined spatial noise noise. It can be treated as broadband spatial noise, but practically, it is measured after 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 describes fixed pattern noise of two different video images:

1. raw uncorrected video image generated by IR FPA sensor (strong fixed pattern is seen),

Early Access

2. corrected video image at output of thermal imager (only minor fixed patterns are noticeable).

Therefore, the same term means totally different video image for IR PFA community and specialist in testing complete thermal imagers. In the latter case 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 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 terminology chaos there is a general consensus that 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 rms value of 2D noise noise array obtained from original 3D raw video sequence generated by 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 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 3D raw video sequence generated by thermal imager seeing uniform target. HF filtering is commonly done 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 two 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 1990s 3D Noise model is a concept of characterization of thermal imager (potentially also other types of EO imagers) noise by precision division 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 then, the captured data can be presented in form of 3D array N_{TVH}. The *T*-dimension represents time or numbers of 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 understand in dual way: 1) 3D/2D/1D arrays obtained from original raw 3D array by mathematical operation as shown (10); 2) standard deviation from these arrays.

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

Early Access

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

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

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 case of NETD will produce significantly different measurement results when measurement of NETD is carried out using different definitions. In contrast, accurate stable results should be expected in case of FPN and 3D Noise parameters that are defined in a uniform way (very precise definition especially for 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 gloomy metrologic 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 like NETD, FPN, 3D Noise:

1. time length of 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 thermal imager,
4. temporal moment when tests are carried out,
5. methods to correct raw measurement results.

6.1. Time length of analysed video sequence

The author has not been able to find any literature source that gives direct recommendation on optimal time length of video sequence captured and analyzed to determine imager noise. However, there are some papers that give indirect recommendations in 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 rational behind these recommendations can be found in [32]. It suggests that maximum bias error of calculations of components of 3D noise model is kept at modest level approximately 1.5%, if 100 frames are captured from imager of typical 640x480 image resolution. These findings suggest that number of frames (length of 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 has shown that measured temporal noise can depend significantly on number of frames even if number of frames is over 100 frames on condition when raw noise cube is analyzed (Table 4).

DOI: 10.24425/mms.2025.154668

Table 4. Imager temporal noise calculated for video sequences of frame number of captured video sequence (result normalized for case of 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 author opinion, the earlier presented recommendations on minimal number of frames are based on three wrong assumptions. First, noise of thermal imagers can be treated as white noise. In reality, spectrum of temporal noise of thermal imagers depend strongly on frequency, especially at low frequency band. Second, number of frames determines time length of captured video sequence. It is not true, as there are on market imagers of different frame rate: 25FPS, 30FPS, 50FPS, 60FPS or different ones. Third, modest number of frames (about 100 frames) enables accurate of measurement of rms of imager noise. In reality, such small number of frames is captured in 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. Strength of this filtering depends on the frame rate of tested imager.

6.2. Low frequency filtration

Discussion on filtration of raw 3D noise array used a source of data when calculating noise parameters has been carried out for decades. NETD and FPN has traditionally been considered as measured 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 has not been formulated. The same with components of 3D Noise model. Analysis of papers by scientists from NVESD can deliver conclusion that recommendations vary with authors and time of publication: no filtration [26], approximation using second degree polynomial [28], Gausian filter [16]. Therefore, high frequency noise cube is typically calculated using two main ways (14, 15):

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

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)

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

where σ_h, σ_v, σ_t are filter directional standard deviations of typical values equal to eight (pixels or frames). Value of the Gaussian filter parameter σ is not standardized and can vary but typically equals to 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 significant influence of filtering method on some of noise components of 3D Noise model. In addition, this influence vary from imager to imager (Table 5).

Early Access

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

	Filtering method			
Imager	**No filter**	**Approximation 2-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 responsivity SiTF

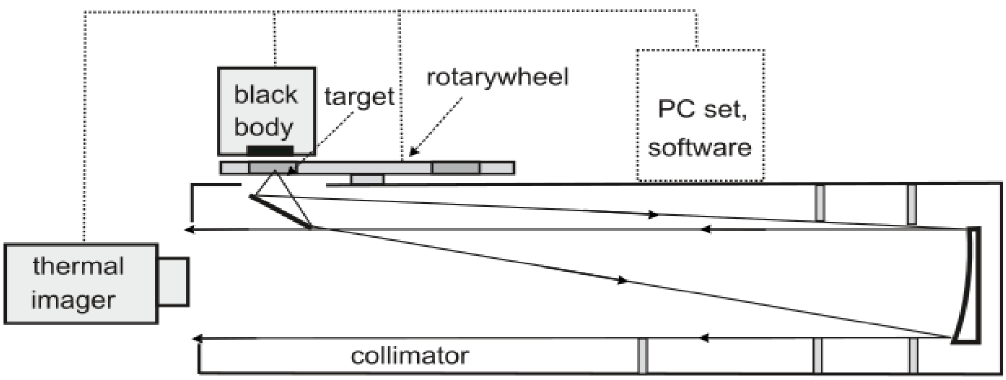
Measurement of imager responsivity SiTF is one of steps of procedure to measure noise parameters of thermal imagers. This rule is valid for NETD, FPN and 3D Noise model. There are three types of test systems used for measurement of SiTF of thermal imagers:

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 image of a reference target (uniform target or blackbody) into direction of tested thermal imager. Such test systems are typically built as a set 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 image projector that projects image of a target located at a collimator focal plane and it simulates such a target at optical infinity. A rotary wheel enables easy exchange of a target to be simulated. Targets are manufactured as high emissivity painted metal sheet 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 (tested imager can see directly blackbody emitter through a hole in rotary wheel). It should be noted that this collimator systems are good simulators of real work conditions when imager sees far away targets that emits near parallel ways of beams that reach imager optics.

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

a)



Metrol. Meas. Syst., Vol. 32 (2025), No. 2
DOI: 10.24425/mms.2025.154668

b) c)

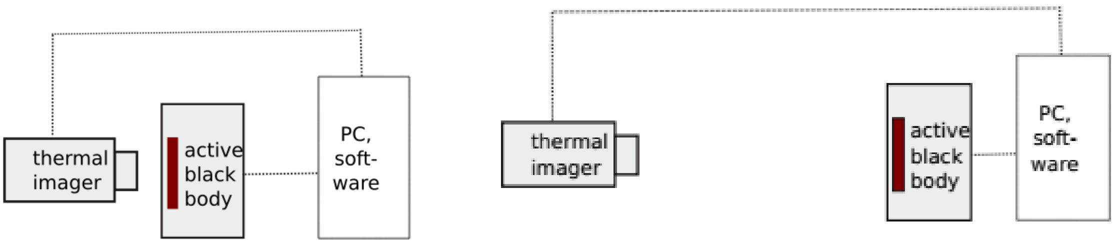


Fig. 6. Block diagrams of three types of test systems a) collimator systems, b) flood mode system, c) focused mode system.

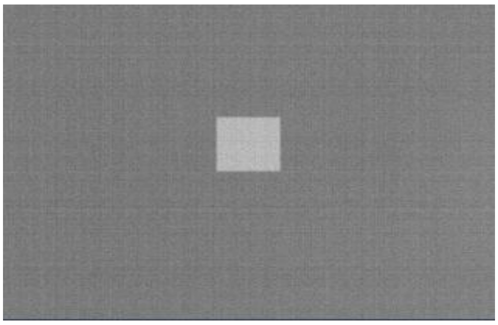


Fig. 7. Image of a square target projected by the collimator.

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

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 optics of the tested imager and fully fills imager FOV (Fig. 8). PC controls blackbody temperature and analyse images generated by the tested imager.

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

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

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

In author opinion, the main reason for such a situation is stray light effect that is amplified when using flood mode systems. Interior of IR objective is typically covered using low reflectivity coatings. However, due to longer wavelengths reflectivity of such coatings/paints is still significantly higher comparing to reflectivity of interior of visible range objectives. Therefore, in addition to black coatings, special baffles are often added in IR objectives. These

Early Access

parts of optical objectives (two black rectangles in Fig. 9) are expected to prevent light emitted by targets of interest from reflecting on objective case.

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

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

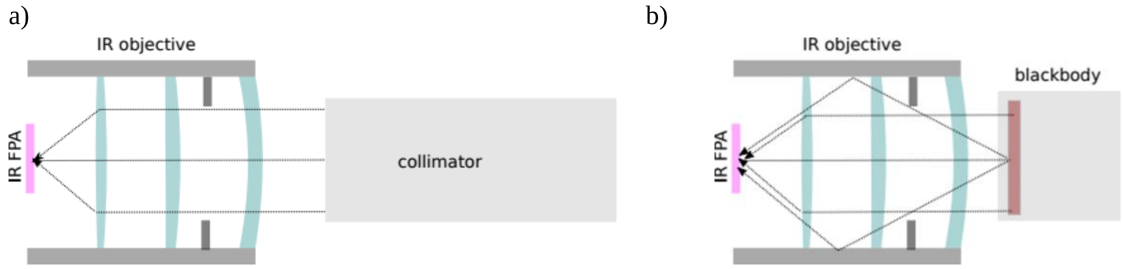


Fig. 9. Simplified concept of work of optical baffles for case of two types of test system.

Table 6. Normalized SiTF measured using three different types of test systems (normalization to SiTF measured using 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 know that transient changes of temperature of both tested imager and 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 after about 1 hour after powering of the imager and test system is switched on. However, it is often impractical to wait such long time to achieve thermal equilibrium of every tested thermal imager. Therefore, tests of thermal imagers are carried out using thermal imagers being at different stages of achieving thermal equilibrium.

Further on, it is also possible to improve measured SiTF (and indirectly noise parameter) keeping the imager off for several hours, powering imager and then making 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, results of measurement of SiTF (and indirectly results of noise parameters) depends on time interval since moment when imager has been switched on.

It is has been also reported that fixed pattern noise in spite of its name is actually a long term transient phenomenon. The fixed pattern noise is at a local minimum immediately after NUC

DOI: 10.24425/mms.2025.154668

operation and monotonically increases with time since this time moment [25]. FPN measured one hour after NUC can be several times higher compared to minimal FPN immediately after NUC. The most most significant changes occur within the first 10 min following the NUC. In such a situation it is logical that measurement results of spatial noise components including FPN do depend significantly on time duration since one point NUC operation has been carried out. It should be noted that this rule is fully valid for shutter thermal imagers. It is not clear what is situation in case of shutterless thermal imagers as they use myriads of different image processing methods to reduce spatial noise. One point is certain – there are thermal imagers that generate fixed pattern noise that significantly depends on temporal moment when FPN measurement is carried out. Experiments carried out by the author confirm this thesis (Fig. 10).

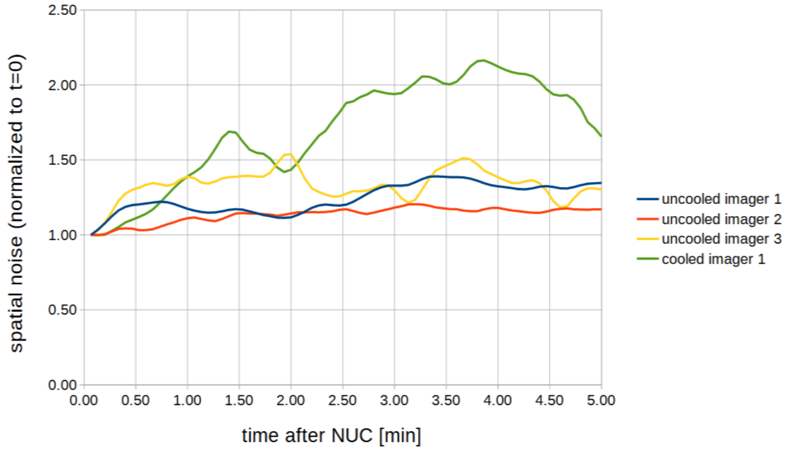


Fig. 10. Dependence of measured FPN on time interval since one point NUC of tested thermal imager.

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 non perfect test system,
3. Correction due to filtering of raw data.

The problem is that due to lack of standardized regulation these correction are done by different teams in different ways. It is customary to measure and specify NETD of IR FPA sensors at 300K temperature [35-36]. Situation with NETD of thermal imagers vary. Measurement of NETD is typically carried out at typical laboratory temperature 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 results carried out at 27º*C* (300K). Therefore, result obtained for tests carried out at temperatures that differ from 27ºC should be corrected. Corrections formulas are known for decades [15]. However, some of of manufacturers of thermal imagers do not give information for what temperature NETD is specified.

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

High pass filtering is carried out to remove low frequency component of noise and later calculate NETD, FPN, σ_{TVH}. Typically no correction is done due to such removal of low frequency noise. The latter components is treated typically as a measurement bias. However, recent paper claims that such filtering removes also valuable noise in form of low frequency spectrum of imager white noise and therefore results should be corrected [16]. However, very few test teams are aware about 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 world wide. They have found a series of civilian applications, too. Noise parameters are important tools to characterize thermal imagers and are known for decades. Therefore, it is commonly expected that there are some international/national standards (or semi-standards documents issued by top world organizations) that regulate measurement of these parameters. In such a situation the metrological chaos in form of series of slightly different definitions/measurement methods presented in previous sections can be shocking for some readers, but it presents everyday reality.

Thermal imaging technology has improved very significantly within last several decades. Performance of modern staring thermal imagers is several times better in comparison to old scanning imagers from two decades ago.

There is also some progress in design of systems for testing thermal imagers. Performance 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 rather not better in case of other parameters of thermal imagers.

One of potential ways to develop needed standard that could regulate defining/measurement of noise parameters of thermal imagers is by cooperation of wide international community involved in thermal imaging technology. Example of machine vision international community that has developed EMVA1288 standard that regulated testing VNIR cameras for machine vision applications is an example that such a solution is possible.

The 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 international community.

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

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

8. Conclusions

This paper presents a critical review of myriads of past and present day slightly different definitions/measurement methods of noise parameters of thermal imagers (NETD, FPN, 3D Noise model) that create 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 level of 50% or more) are not related to limited performance of commercially available test systems, but are caused by metrological chaos due to poor standardization of characterization/measurement of noise parameters of thermal imagers. Therefore, significant improvement in field of standardization of defining/measurement of the noise parameters is urgently needed to enable further fast growth of thermal imaging technology.

References

[1] SPIE Digital Library. https://www.spiedigitallibrary.org

[2] Bell, P. A., Hoover, C. W., Jr, & Pruchnic, S. J., Jr. (1993). Standard NETD test procedure for FLIR systems with video outputs. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. https://doi.org/10.1117/12.154715

[3] Li, Y., Pan, D., Yang, C., & Luo, Y. (2007). NETD test of high-sensitivity infrared camera. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. https://doi.org/10.1117/12.783521

[4] Krupiński, M., Chmielewski, K., Bareła, J., & Kastek, M. (2017). Test stand and procedures for estimating parameters of microbolometer detector. *Measurement Automation Monitoring*, 63(2), 73-75.

[5] Fucu, H., Dongpeng, S., Ye, Z., Chang, L., Zhinan, G., & Yanan, W. (2021b). Development and application of infrared imaging check and evaluation system. *Journal of Physics Conference Series*, 2005(1), 012067. https://doi.org/10.1088/1742-6596/2005/1/012067

[6] FLIR. (2024, December 20). *FLIR Cameras - How is NETD of cooled cameras measured?*. https://flir.custhelp.com/app/answers/detail/a_id/128/related/1

[7] PULSAR. (n.d.). *Thermal Imaging Technologies*. https://www.pulsar-nv.com/glo/support/thermal-imaging-technologies/2232/

[8] Sofradir EC. (2011). *Understanding Infrared Camera Thermal Image Quality*. https://www.lynred-usa.com/media/wp-understanding-tiq-v06-web.pdf

[9] ASTM E1543-00 (2011), Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems, ASTM International, 2011.

[10] HGH Infrared Systems. FAQ: Electro-optical testing, NETD, MRTD, MTF. https://hgh-infrared.com/infrared-testing-faq/

[11] CI Systems – Electro Optical Testing & Measurement. (2012, December 13). *NETD Test | FLIR Testing | CI Systems* [Video]. YouTube. https://www.youtube.com/watch?v=iV83NOL-DzY

[12] Inframet (n.d.). *Thermal imagers*. https://www.inframet.com/thermal_imagers.htm

[13] Santa Barbara Infrared, Inc. (2014, October 17). *Noise Equivalent Temperature Difference (NETD) - Santa Barbara Infrared (SBIR)* [Video]. YouTube. https://www.youtube.com/watch?v=9LGwjsulf2M

[14] Holst, G. C. (1998). *Testing and evaluation of infrared imaging systems* (*2nd ed.*). JCD Pub.

[15] Chrzanowski, K. (2010). *Testing Thermal Imagers: Practical Guidebook*. Military University of Technology.

[16] Haefner, D. P., Burks, S. D., & Preece, B. (2023). Decomposing measured noise cubes: SiTF, 3D noise, uniformity, and drift. *SPIE, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXXIV*. https://doi.org/10.1117/12.2663351

[17] Rogers, R. K., Edwards, W. D., Waddle, C. E., Dobbins, C. L., & Wood, S. B. (2014). Reporting NETD: why measurement techniques matter. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. https://doi.org/10.1117/12.2050559

[18] Burks, S. D., Haefner, D. P., & Burks, T. J. (2015). Signal intensity transfer function determination on thermal systems with stray light or scattering present. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. https://doi.org/10.1117/12.2178150

[19] European Machine Vision Association. (2021). *Standard for Characterization of Image Sensors and Cameras, Release 4.0 General* (EMVA Standard 1288).

Early Access

[20] Dupont, B., Chammings, G., Rapellin, G., Mandier, C., Tchagaspanian, M., Dupont, B., Peizerat, A., & Yon, J. J. (2008). New readout integrated circuit using continuous time fixed pattern noise correction. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE.* https://doi.org/10.1117/12.779279

[21] Nghiem, J., Jaeck, J., Giard, E., Caes, M., Rodriguez, J., Christol, P., Haidar, R., Costard, E., & Ribet-Mohamed, I. (2017). MTF and FPN measurements to evaluate midwave infrared T2SL focal plane arrays. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE.* https://doi.org/10.1117/12.2251160

[22] Tie-li, H., Shi-bang, M., Yu, G., Zhou, X., Si-wei, L., Qi, X., ... & Jun-ning, L. (2014). Spatial NETD measurement of thermal imager. *Journal of Applied Optics, 35*(6), 1094-1098.

[23] North Atlantic Treaty Organisation (2023). *Experimental assessment parameters and procedures for characterisation of advanced thermal imagers* [RTO technical report 75 (II)].

[24] Driggers, R. G., Vollmerhausen, R. H., & Krapels, K. A. (2001). Target identification performance as a function of temporal and fixed pattern noise. *Optical Engineering, 40*(3), 443. https://doi.org/10.1117/1.1346583

[25] Haefner, D. P., & Burks, S. D. (2023, June). Measurements and metrics of fixed pattern noise: a new procedure for thermal camera noise measurement. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXXIV* (Vol. 12533, pp. 276-285). SPIE. https://doi.org/10.1117/12.2663353

[26] Scott, L. B., & D'Agostino, J. A. (1992, September). NVEOD FLIR92 thermal imaging systems performance model. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing III* (Vol. 1689, pp. 194-203). SPIE. https://doi.org/10.1117/12.137950

[27] D'Agostino, J. A., & Webb, C. M. (1991, September). Three-dimensional analysis framework and measurement methodology for imaging system noise. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing II* (Vol. 1488, pp. 110-121). SPIE. https://doi.org/10.1117/12.45794

[28] O'Shea, P., & Sousk, S. (2005, May). Practical issues with 3D noise measurements and application to modern infrared sensors. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XVI* (Vol. 5784, pp. 262-271). SPIE. https://doi.org/10.1117/12.604588

[29] Burks, S. D., & Nguyen, Q. (2012, May). Advanced trend removal in 3D noise calculation. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIII* (Vol. 8355, pp. 60-66). SPIE. https://doi.org/10.1117/12.917726

[30] Haefner, D. P., Preece, B. L., Doe, J. M., & Burks, S. D. (2016, May). Spatially resolved 3D noise. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXVII* (Vol. 9820, pp. 116-125). SPIE. https://doi.org/10.1117/12.2222905

[31] Haefner, D. P. (2017). Power spectral density of 3D noise. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. https://doi.org/10.1117/12.2260885

[32] Bomzon, Z. E. (2010, October). Biases in the estimation of 3D noise in thermal imagers. *In Electro-Optical and Infrared Systems: Technology and Applications VII* (Vol. 7834, pp. 77-85). SPIE. https://doi.org/10.1117/12.864848

[33] LYNRED (2019, September 4). *How to select best infrared detector for your needs*. https://www.lynred.com/blog/how-select-best-infrared-detector-your-needs

[34] LYNRED (n.d.). *Pico640Gen2™ - Infrared Detector*. https://www.lynred-usa.com/products/vga-resolution/pico640gen2-infrared-sensors.html

SAAB (n.d.). *Rugged Camera Module – InfraRed*. https://www.saab.com/globalassets/products/support-and-services/vehicle-electronics-solutions/oflf-1509-1-rcam-ir-product-sheet.pdf

[35] TEMPSENS (n.d.). *High Resolution LWIR Ultra Compact Infrared Camera for Non Contact Temperature Measurement*. https://tempsens.com/thermcam-pro-640-high-resolution-long-wavelength-ultra-compact-infrared-camera.html

DOI: 10.24425/mms.2025.154668

Krzysztof Chrzanowski received his Ph.D., and D.Sc. both in Electronics, from Military University of Technology in Warsaw, Poland. He works currently as Professor in the mentioned above university. His main scientific interests include system analysis, characterization, testing and computer simulation of electro-optical surveillance systems (thermal imagers, night vision devices, VIS-NIR cameras, SWIR imagers, laser range finders, laser designators, fused imagers, multi-sensor surveillance systems). He is an author or co-author of over 150 scientific papers and conference communications. He is also CEO of a high-tech company that manufactures equipment for testing electro-optical imaging and laser systems (Inframet www.inframet.com)

Early Access