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Testing passive surveillance terahertz imagers

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During the last decade there has been a significant interest in THz imaging technology and a series of both passive and active THz imagers have been developed. However, so far the methodology and test apparatus for testing passive THz imagers have been developed. In this paper, it has been proposed to test passive surveillance THz imagers using the test methodology prepared for testing surveillance thermal imagers. A test system developed for testing passive surveillance imagers is presented, too.

Keywords: THz imaging, metrology.

1. Introduction

Terahertz range possesses two very interesting features for imaging applications. First, THz radiation can penetrate some thin screens like clothing, human skin, *etc*. Second, THz frequencies are short enough to provide relatively good quality images in comparison to the images obtained using microwave imagers.

There has been a significant interest in THz imaging technology during the last decade. A series of THz imagers have been developed [1–5].

Terahertz imaging is still an emerging technology at a fast development stage. However, it can be logically forecast that, similar to thermal imagers, THz imagers will develop into two relatively distinct groups: surveillance imagers and measurement imagers.

The main aim of surveillance THz imagers is to develop a high quality image of targets of interest. This aim can be achieved using two types of THz imagers. The first group are passive imagers that use radiation emitted by the targets, employed to create a THz image of such targets. The radiation distribution is proportional to the relative temperature distribution of the targets. The second group are active imagers that use radiation emitted by an artificial source and reflected by the targets, employed to create a THz image of these targets.

Measurement (commercial) THz imagers create the images of targets of interest in a THz range, too. However, in contrast to surveillance imagers, the task of a measurement imager is to create images that are directly related to the absolute amount of THz radiation emitted (or reflected) by the target and to enable measurement of received THz radiation. The task of measurement THz imagers is not only to create a THz image but also to enable measurement of some physical quantities connected with the intensity of THz radiation.

This subtle difference between the surveillance THz imagers and the measurement THz imagers will cause differences in design of THz imagers similar to differences we see nowadays between the surveillance thermal imagers and the measurement thermal imagers.

The main market for surveillance THz imagers is a security/defense sector. The measurement THz imagers are mostly used for commercial applications in industry, science, medicine, *etc*. Sometimes the border between these two groups is blurred as some measurement THz imagers are used for both surveillance and measurement applications. However, in any case both groups of THz imagers should be tested using separate test methodologies because of different application purposes.

In this paper we concentrate on testing passive surveillance THz imagers. It can be expected that this group of THz imagers will dominate the market of THz imagers similarly to the situation in thermal imaging.

It has been noted recently that the metrology infrastructure and the theory in the infrared and optical radiometry sectors are extremely well-developed and comprehensive, and their large portions can be adapted to the millimeter-wave and terahertz frequency range [6]. Therefore the task of this paper is to analyze the possibilities to use the test methodology developed for testing surveillance thermal imagers for surveillance THz imagers.

2. Testing surveillance thermal imagers

Testing surveillance thermal imager is based on a concept of projecting the images of some standard targets onto the direction of a tested thermal imager and measuring the parameters determined using the output distorted images. The thermal imager is then evaluated directly on the basis of measured parameters (MRTD, MDTD, MTF, NETD, FPN, non-uniformity, distortion, FOV, *etc*.) or ranges of detection, recognition and identifications of standard targets that are calculated on the basis of measured MRTD values.

The task of a test system for testing thermal imagers is to generate the images of some standard static targets of precisely known shapes, dimensions and temperature [7]. These images can be projected onto the tested thermal imager by the test system or viewed directly by the tested imager (Fig. 1). In both cases, the tested imager generates distorted copies of the original targets images. Next, the images generated by the tested imager are evaluated and important characteristics of the tested imagers are determined.

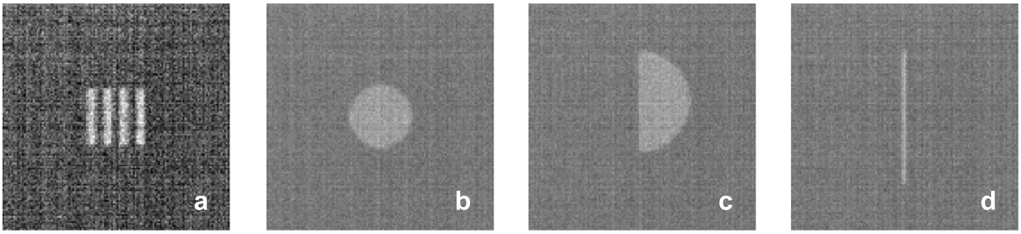

Fig. 1. Images of standard targets used during testing thermal imagers: 4-bar target (**a**), pinhole target (**b**), edge target (**c**), and slit target (**d**).

Technically, a system designed to test thermal imagers must satisfy four basic requirements:

– Ability to simulate targets of different geometrical shapes (needed to measure different parameters of thermal imagers);

– Ability to regulate precisely the angular size of simulated targets (in order to simulate changes in the distance at real conditions);

– Ability to regulate precisely the temperature difference of the simulated target in comparison to background temperature (needed in order to simulate variable contrast of thermal targets at real observation conditions);

– Ability to simulate targets located at a distance bigger than the minimal focus distance of the tested imager (typical work conditions).

The most popular type of test systems is a variable target image projector that projects the images of targets fixed to a rotary wheel using a reflective collimator as an image projector (Fig. 2). The tested thermal imager is located at the output of IR collimator and the target is located at the collimator input (the focal plane). The distance between the target and the tested imagers is very short. The distance is typically no more than about 4 m if the optical ray way is analyzed; and the distance is usually not within the focusing range of typical surveillance thermal imagers. However, because the collimator is used as an image projector, the imager “sees”

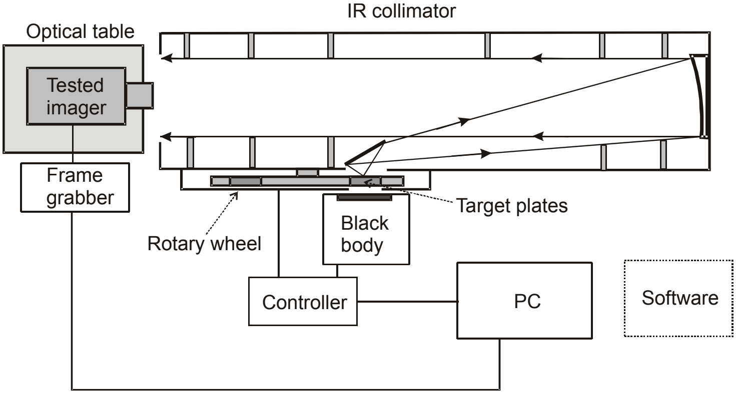

Fig. 2. Diagram of the variable target test system (image projector).

the target as a very long distance object that is within the imager focusing range. Next, a series of targets are fixed to a rotary wheel. By rotating the wheel, it is possible to exchange targets quickly. By changing target dimensions, the changes in the distance are simulated.

Images generated by tested thermal imagers are analyzed subjectively by human observers (measurement of MRTD and MDTD) or by software (semi-automatic measurement of MTF, SiTF, NETD, FPN, non-uniformity, distortion, FOV, *etc*.).

3. Concept of testing surveillance THz imagers

Nowadays, surveillance THz imagers are typically bulky devices used in indoor conditions for short range security surveillance in contrast to small, portable thermal imagers that can be used at any conditions. However, the task of surveillance THz imagers is the same as the task of surveillance thermal imagers: to detect, recognize and identify targets of interest. At the same time, passive THz imagers use the same principle to create the image of observed scenery: differences in the power of thermal radiation emitted or reflected by the targets of interest in comparison to the power of thermal radiation emitted by the background.

Such a situation creates a theoretical possibility to use the complete typical methodology of testing thermal imagers for testing THz imagers. It looks that there are no logical obstacles to use such parameters like MRTD, MDTD, MTF, noise parameters (NETD, FPN, non-uniformity), distortion, FOV, *etc*., for testing passive surveillance THz imagers.

As it was shown earlier testing of thermal imagers is based on the use of image projectors built as a set combing reflective collimators, rotary wheels, targets and area blackbodies.

Reflective collimators built of metal-coated mirrors work well both in infrared and THz regions, particularly well in the case of gold-coated mirrors. Next, the general concept of manufacturing targets by cutting precision holes in metal sheets is valid both in IR region and THz region.

There are however several serious technical challenges to convert typical infrared test systems into a system for testing THz imagers.

First, typical differential blackbodies used in the systems for testing thermal imagers offered by several manufacturers [8–12] poorly perform when testing THz imagers due to too low emissivity of the differential area IR blackbodies in THz region. The reason is that typical high emissivity paints used in design of differential area infrared blackbodies become partially translucent in THz region. In this way, the reflectance of typical metal emitters coated with Nextel 811 (typical coating) rises over the level of 0.05 (effective emissivity below about 0.95) at wavelengths over about 70 μm. A special coating developed for the THz range by DuPont Coatings GmbH, Germany (the Herberts 1356H) performs significantly better but still its reflectance is over 0.05 level at wavelengths higher than about 180 μm [13]. Another commercial coating (Sensoterm) performs poorly in the whole THz region as its reflectance is over 0.1 [13].

Second, there are the same problems with the test targets manufactured as metal sheets coated with the same paints as with the blackbodies.

Third, typical IR collimators used in THz region would be more vulnerable to stray radiation due to higher reflectivity of their internal coatings. Next, it is necessary to use big targets and big blackbodies due to low resolution of THz imagers. This means that potential THz collimators should be characterized by much bigger field of view than FOV of typical IR collimators and this situation would generate bigger aberrations. However, the problem with the collimator can be solved easily because this module is not strictly needed for testing surveillance THz imagers.

A great majority of surveillance thermal imagers was designed to enable observation of long distance targets (at least hundred of meters). Therefore collimators are needed to simulate targets at long distance conditions (optical infinity).

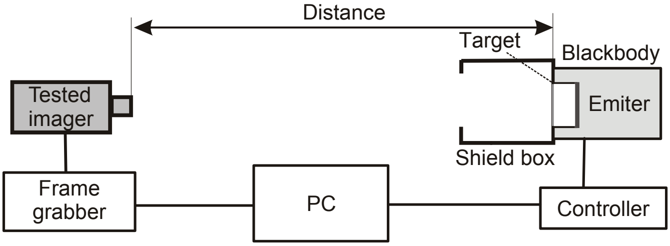

Fig. 3. Diagram of the variable distance test system.

THz imagers due to high absorbance of atmosphere will be probably mostly used for short distance surveillance (not more than a dozen meters). Therefore a test system understood as a large blackbody integrated with a target seen directly by tested THz imagers can be used for testing these imagers (Fig. 3). If a distance imager–target is varied, then spatial frequency of 4-bar target is regulated and different distances of imager–real targets can be simulated. Practically this is a copy of a concept of the so-called variable distance test system used sometimes in testing thermal imagers.

To summarize, it is possible to use almost directly the methodology of testing thermal imagers for testing THz imagers if proper THz blackbodies and THz targets are developed.

4. Requirements on blackbodies for testing surveillance THz imagers

Let us now formulate requirements on a blackbody for the testing THz imagers system.

First, emissivity of IR blackbodies used in testing thermal imagers is typically at the level of 0.97±0.01. However, popular STANAG 4349 that presents requirements on the equipment for testing thermal imagers requires the usage of the blackbodies of emissivity equal or higher than 0.95 [14]. Let us adopt the same requirements for the emissivity of THz blackbodies.

Second, blackbodies used in the variable distance test systems for testing thermal imagers are typically large, with the active area not smaller than 150×150 mm. Due to low resolution of THz it should be logically expected that the same size blackbodies or larger ones will be needed.

Third, differential blackbodies capable to generate both the positive contrast images and the negative ones are needed in testing thermal imagers. If the methodology of testing thermal imagers in testing THz imagers is to be used, then the differential blackbodies of a differential temperature range at least ±20 K relative to ambient temperature are needed.

Fourth, in long terms it can be expected that NETD of passive THz imagers can be similar to NETD of non-cooled thermal imagers (range from about 50–150 mK). Therefore, the temperature resolution of THz blackbodies should not be worse than 10 mK (preferably 1 mK). Roughly the same can be said about temporal stability.

Fifth, the measurement of most parameters of thermal imagers requires the blackbody to be stabilized at a set of different temperature levels. Therefore, the blackbody speed (time needed to change and stabilize blackbody temperature) a crucial parameter if we want to avoid spending hours to measure a single parameter of a single thermal imager. The same conclusion is valid in the case of THz imagers, too. Typical settling time at 10 K temperature step is below 60 s in the case of typical differential IR blackbodies. Let us reduce here the requirements on the speed of THz blackbodies and assume that the settling time of THz blackbodies should be lower than 120 s.

The development of only one potentially interesting THz blackbody has been reported lately: aqueous blackbody calibration source [6]. This blackbody looks potentially very promising: high emissivity (> 98.5% over the operating band), large area (200×200 mm), wide temperature range from about 0 to about 100 °C (if cooling/heating systems are used), and good temperature stability (20 mK). However, the developed aqueous THz blackbody is a bulky blackbody of big thermal and temporal inertia (21 liters of water). It is not clearly stated what is this blackbody speed but it can be estimated that time needed to stabilize the temperature below say 20 mK at 10 K step should be not lower than about 15–30 minutes. This is a big decrease in the blackbody speed in comparison to fast and convenient differential IR blackbodies used in the systems for testing thermal imagers of settling time close to 1 minute. Anyone having experience in testing thermal imagers will agree that blackbody speed is an important factor. At the same time, due to mechanical constraints, there could be problems to use aqueous blackbodies in the systems where the blackbody is to cooperate with a rotary wheel with targets or directly with targets. Finally, the aqueous blackbody discussed here was developed for scientific projects not as commercial products that could be easily reproduced and manufactured.

5. Design of differential area THz blackbody

On the basis of arguments presented in previous section it can be concluded that the aqueous blackbody presented in [6] is not well suited for systems for testing surveillance THz imagers. Therefore the ways to adapt the design of a typical differential area of IR blackbodies used in systems for testing thermal imagers [8–12] should be analyzed. Drawing of an exemplary typical differential area of IR blackbody is shown in Fig. 4. If this drawing is analyzed then it can be found that the blackbody of such a design can be directly used for testing THz imagers if only one basic technical problem is solved: too low emissivity of emitters in the typical differential area blackbodies. The emitters are typically built as metal plates manufactured from metals of high thermal conductivity (copper and its alloys) coated using special black matte paints (Nextel 811, *etc*.). The paints becomes semitransparent in THz range and emitter emissivity can drop even below 0.5 at longer wavelengths.

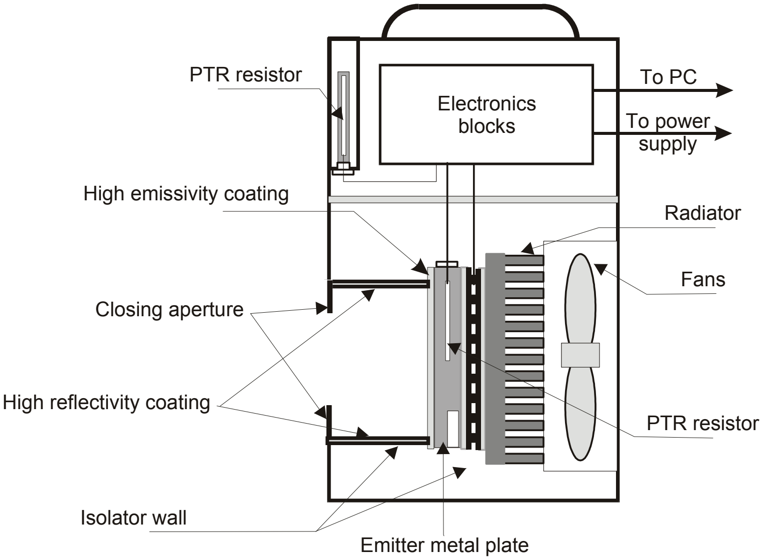

Fig. 4. Block diagram of exemplary differential area IR blackbody.

The simplest potential solution to design a blackbody emitter for THz range would be to manufacture this emitter not from metal plate but from materials that work as good THz absorbers. High absorbance means high emissivity and then the problem of low emissivity of blackbody emitter is solved.

There are commercially available microwave absorbers that absorb well also THz radiation [15–18]. These commercial microwave/THz absorbers are manufactured using a set of different technologies. However, all these commercial THz absorbers are practically useless for designers of THz blackbodies because of their low thermal conductivity. The latter parameter is not given by manufacturers as being not important for typical applications. However, practical experiments carried out by the author showed that the thermal conductivity of these absorbers roughly vary from about 0.02 $Wm^{-1}K^{-1}$ in the case of carbon loaded foam laminate sheets to about 0.4 $Wm^{-1}K^{-1}$ in the case of absorbers based on rigid urethane. If the latter values are compared with thermal conductivity of copper (common material for emitters of IR blackbodies) close to level of 400 $Wm^{-1}K^{-1}$ then it can be concluded that thermal conductivity of commercial THz absorbing materials is very low. The consequences are very serious. External surface would be much cooler comparing to internal surface heated by Peltier element. Temperature sensor inserted in the center of the emitter plate would sense an average temperature. Therefore, it is not possible to predict accurately the intensity of THz radiation on the basis of temperature sensor indication if the emitter plate is made from typical THz absorbing materials.

To conclude, it is not possible to design accurate differential area THz blackbodies using typical commercial THz absorbers. New materials characterized by at least medium thermal conductivity, and high absorbance of THz radiation are needed.

A long series of experiments with different materials within last several years was performed by the author. The preliminary results showed that it is not possible to design proper THz blackbody emitter using only one-component material. When high absorbance was achieved then thermal conductivity was too low, and *vice versa*. Therefore, the work was concentrated on finding a technology of processing a mixture of different components that would produce a rigid plate of both high THz absorbance and medium/high thermal conductivity. There are dozens of potential technologies and hundreds of combinations of mixing the potentially interesting components.

The author of this paper is not a material engineering specialist. Next, the funds for experiments were very limited. Therefore the experiments were carried out on a try and check basis with low accuracy control of material processing. Great majority of experiments failed to produce any useful results but several of them produced more promising results.

Processing at a high temperature of mixture of graphite powder, alumina powder, diamond powder, ferrite powder subjected to high pressure is an example of a technique that produces quasi-rigid material of quite high emissivity in THz range and a good thermal conductivity. Experiments showed that it is possible to produce rigid plates of width of about 15 mm and thermal conductivity of about 14 $Wm^{-1}K^{-1}$. This conductivity is almost 30 times lower than thermal conductivity of copper but it is almost sufficient for emitter in differential blackbodies where the temperature difference relative to ambient temperature is rather small (typically not bigger than 20 K) and losses due to radiant transfer are not big. Next, the emitter plate was molded to achieve triangular wave shape as shown in Fig. 5**a**. Measurement results of spectral normal reflectance in THz range shown in Fig. 5**b** confirm that normal reflectance of the blackbody emitter is lower than 0.05 in spectral range up to 2 mm wavelength.

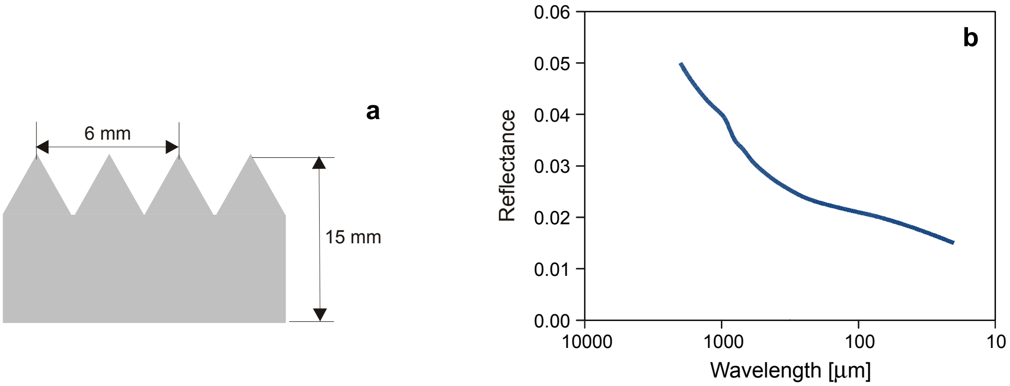

Fig. 5. Properties of emitter plate of the differential THz blackbody: dimensions (**a**), spectral reflectance (**b**).

Such results suggest that emissivity of the blackbody emitter is higher than 0.95 in this THz band.

Measurement results of reflectance of tested emitter plate are significantly higher than reflectance of commercial THz absorbers [15–18]. Thermal conductivity of this emitter plate is barely medium level. Further on, the manufactured plate is brittle. There are also other disadvantages of briefly described earlier manufacturing method. These disadvantages open perspectives for future improvements of manufacturing emitters for THz blackbodies.

6. Design of THz test system

As it was mentioned in Section 3 the concept of the variable distance test system can be directly used for testing passive surveillance THz imagers (Fig. 3). The tested imager sees directly differential blackbody through holes (typically four bar pattern) in a large target of ambient temperature. By regulation of the blackbody emitter temperature of we regulate the differential temperature relative to the target temperature. Regulation of spatial frequency of 4-bar target can be achieved by regulation of the imager–target distance.

Targets used for testing the thermal imagers are typically the emissive type targets. This means that the target manufactured from a metal sheet is coated using high emissivity coating and the target emits IR radiation depending on its temperature. For reasons discussed earlier targets for testers of THz imagers cannot be manufactured from metal sheets. These targets could be manufactured from the same material as the earlier discussed blackbody emitter that works as a good THz absorber. The problem is that this material is rather brittle and it is difficult to make required holes with a high accuracy. Therefore, it was proposed to use the reflective type targets as shown Fig. 6. The target is manufactured from a polished metal sheet of high reflectivity over

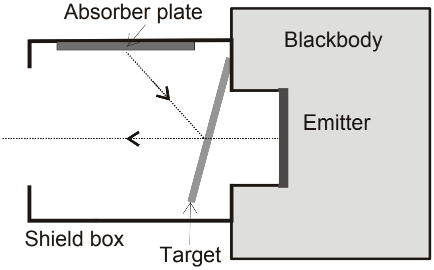

Fig. 6. Diagram of THz test system built using a reflective target.

0.99 in THz region. Holes (typically 4-bar shapes) are precisely cut in the target sheet. The tested imager will see the blackbody emitting via holes in the target. Next, the target is tilted by an angle of about 20 deg and the THz imager will see the blackbody emitter through holes in the target and the absorber plate reflected by target plate.

Two temperature sensing probes are used by the blackbody: one in the emitter plate, second in the absorber plate. In this way the differential temperature of target simulated by the test system is precisely known and can be regulated by changing the temperature of the emitter. Generation of images of different target shapes and target dimensions can be achieved by manual exchange of the reflective targets.

Fig. 7. Photo of the test system for testing passive surveillance THz imagers.

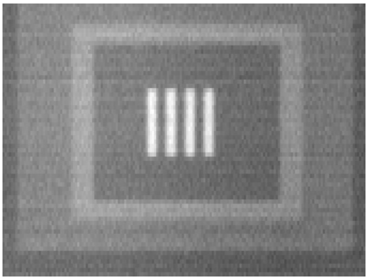

Fig. 8. Image of the THP test system generated by the tested THz imager during MRTD measurements (tests of a scanning 64-element imager).

Table 1. Parameter of THz test system.

Parameter	Value
Modules	blackbody, shield box, absorber plate, set of targets, frame grabber, portable PC
Blackbody	
Blackbody aperture	150×150 mm
Absolute temperature range	From 5 °C to 65 °C at 25 °C ambient temperature
Differential temperature range	From –20 °C to 40 °C
Emissivity	≥ 0.95 at spectral band up to 2 mm wavelength
Set point and resolution	1 mK
Temperature uniformity	< 0.06°C
Settling time	< 120 s at $\Delta T = 10$ °C
Regulation stability	±4 mK at $\Delta T = 10$ °C
Set of targets	
Dimension of the target	200×200 mm
Target number	Set of eight 4-bar targets (for MRTD measurement), set of eight pinhole targets (for MDTD measurement), one edge target (for MTF measurement), one square target (for noise parameters measurement)
Bar width of 4-bar targets	16 mm, 10 mm, 8 mm, 6 mm, 4 mm, 3 mm, 2 mm, 1.5 mm
Target reflectivity	> 0.99
Absorber plate	
Dimensions	350×250 mm
Emissivity	≥ 0.97 at spectral band up to 2 mm wavelength
Test capabilities	
List of measured parameters	MRTD, MDTD, MTF, NETD, FPN, non-uniformity, FOV Option: 3D Noise model, NPSD

Photo of the test system designed using the concept discussed earlier is shown in Fig. 7 and the parameters of this test system in Tab. 1. If the parameters presented in the latter table are analyzed then it can be concluded that the test capabilities of this THz tester are almost identical as capabilities of similar test systems designed for testing thermal imagers. Therefore it should be expected that the developed test system should be a useful tool in testing and evaluation of passive surveillance imagers.

The developed test systems has already passed preliminary tests with a prototype THz imager built using 64-element linear detector (spectral band from 0.05 to 1 mm) and optical scanning system. The imager generated images of different targets as it was expected theoretically (Fig. 8). More tests are expected when the development of this THz imager is finished.

7. Conclusions

A methodology of testing passive surveillance THz imagers understood as test methods and test apparatus was proposed in this paper. The proposed methodology can be treated as a modification of a well established methodology used for testing thermal imagers. It should be expected that proposed test methods and test system will find wide applications in testing passive surveillance THz imagers.

The proposed methodology was initially verified by testing a prototype THz imager but practical validation of the developed test system using a series of different THz imagers is needed. Next, further research on improvements of the developed test system should be carried out. Bigger blackbodies and bigger targets are needed when testing THz imagers of lower resolution or from longer distance. Improvement of technology of manufacturing the emitters for THz blackbodies are needed to improve emitter emissivity, thermal conductivity and mechanical properties. Further on, methods to evaluate passive surveillance THz imagers on the basis of measured parameters should be developed.

To summarize, the THz imaging technology is at the preliminary phase of development and the same can be said about the THz test methodology. The paper should be treated as a starting point on a way to establish a metrological infrastructure for testing earlier mentioned new type of surveillance systems.

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