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Analysis of a blackbody irradiance method of measurement of solar blind UV cameras' sensitivity

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ABSTRACT

This paper presents a critical analysis of a current typical method to measure sensitivity of solar blind ultraviolet cameras using a high temperature blackbody as a calibrated source of ultraviolet light. It has been shown that measurement of sensitivity of solar-blind ultraviolet (SBUV) cameras defined as minimal detectable blackbody irradiance at optics plane of the tested SBUV camera generates inflated, misleading and prone to measurement errors' results that should not be used for evaluation of SBUV cameras' performance.

1. Introduction

Solar-blind ultraviolet (SBUV) cameras are electronic cameras sensitive only to ultraviolet (UV) light below about 280 nm, where due to absorption of Earth atmosphere ozone layer there is almost no Sun light [1,2]. SBUV cameras enable detection of the corona discharges from high-voltage lines and equipment that are indicative of possible faults at both day and night conditions. Therefore, SBUV cameras have found a series of applications that survey and detection of power lines for potential problems, such as cracks on insulators which can eventually lead to costly power outages, can be considered as the most important one.

SBUV cameras are typically manufactured as bispectral cameras operating at two spectral bands: solar blind UV-C band and visible band. They generate output images as a fusion of UV and visible image. SBUV cameras present complex opto-electric (OE) device. A high sensitivity UV image intensifier, solar blind filter, visible image sensors, image processing electronics, advanced software and know how to combine all these blocks are needed to manufacture professional SBUV cameras. It should be also noted that SBUV imaging is a relatively modern technology developed mostly during the last two decades and that market of SBUV cameras is dominated by a small group of companies [3–8].

Sensitivity is a crucial parameter of SBUV cameras. If we are to make a review of data sheets of SBUV cameras offered by a group of top manufacturers [1–6], then we can conclude that value of sensitivity of SBUV camera vary in a relatively narrow range from 2×10^{-18} to 3×10^{-18} W/cm^2. Such situation suggests that SBUV cameras of similar sensitivity are offered on market and that the cameras are tested using the same standardized method. In addition, such data suggest that SBUV enable detection of UV sources of an extremely low light intensity (detection of single photons emitted by an area of 1 cm^2 in period of 1 s). However, the real situation is totally different.

There is no international/national standard that regulates testing solar blind cameras. In addition, there is no other scientific paper that proposes detail methods for testing these cameras. More important, there are very serious doubts about the logic of method to measure sensitivity of SBUV cameras used commonly by their manufacturers. Typical sensitivity values presented in data sheets are much inflated and are misleading because real SBUV cameras cannot detect the image of UV sources of such low light intensity. Finally, practical experience of the author shows that real sensitivity of two SBUV cameras having identical data sheets can differ significantly.

This paper presents a critical analysis of a typical method to measure sensitivity of SBUV cameras using high temperature blackbody as a calibrated source of UV light. Reasons why measurements of sensitivity of SBUV cameras defined as minimal detectable blackbody irradiance at camera optics plane generate highly inflated and misleading results are presented.

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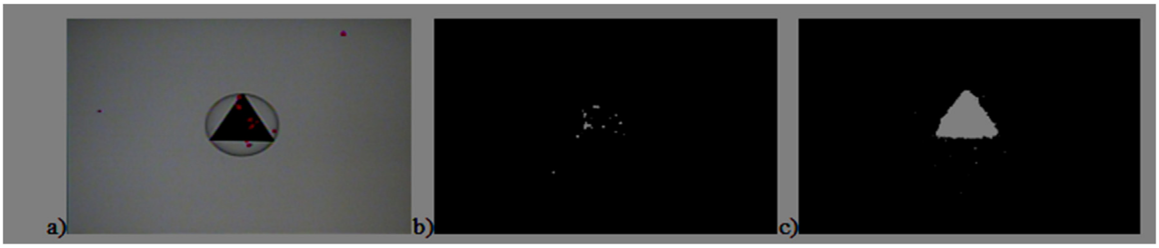


Fig. 1. Exemplary images generated by an SBUV camera: a) fused image of a low light triangle target, b) UV image of a triangle target emitting low intensity UV light, c) UV image of a triangle target emitting high intensity UV light.

Table 1
Sensitivity of popular models of SBUV cameras.

Manufacturer	Model	Sensitivity [W/cm^2]
Uvirco Technologies	CoroCAM 6D	2.05×10^{-18}
OFIL Systems	UVollé-SX	2.6×10^{-18}
Zhejiang ULIRVISION Technology Co	Corona Camera UVSee TD100	3×10^{-18}
OLIP Systems	Olip CR-720	3×10^{-18}
Sonel	UV-260	3×10^{-18}
Infrared Cameras International (ICI)	Corona Camera	2.2×10^{-18}

2. Special features of SBUV cameras

SBUV cameras generate video images of the scenery of interest like other types of electro-optical imaging systems: color visible (VIS) cameras, monochrome visible and near infra-red (VIS-NIR) cameras, short-wave infrared (SWIR) cameras, thermal imagers. However, there are two special features that make them different from other EO imaging systems:

1 fusion of images of the scenery recorded in SBUV band with an image of the scenery recorded in VIS band [Fig. 1a)],
2 ability of SBUV imaging channel to work at single photon detection mode [Fig. 1b)].

The first feature means that typical images generated by SBUV cameras are actually a fusion of typical color image of scenery of interest with SBUV image of the same scenery where color blobs indicate places where SBUV light is detected.

The second feature means that if a camera works in high gain mode and looks on low intensity light source, then an image in form of several blinking white spots on black background is generated [Fig. 1b)]. These blinking spots are random in both time and space. If a camera works in low gain mode (or in best case scenario in no gain mode) and looks at high intensity light source, then a camera generates an image that resembles target shape [Fig. 1c)].

SBUV cameras are rarely used to generate images of high intensity UV sources and even in such cases perfect image quality of these sources is not important. The main task of SBUV cameras is to detect UV sources in camera field of view (FOV), and this task can be achieved even if an image is slightly blurred or distorted. Therefore, typical parameters that characterize image quality of electro optical imaging systems like modulation transfer function (MTF), resolution, distortion are of low importance. However, it is still necessary to remember that SBUV cameras are a type of EO imaging systems. Therefore, part of methodology developed to testing EO imaging systems still applies to SBUV cameras.

3. Blackbody irradiance method to measure sensitivity

All manufacturers of SBUV cameras present information on sensitivity of these cameras in data sheets [3–8]. Exemplary data, shown in Table 1, suggests that SBUV cameras enable detection of UV sources of extremely low light intensity. The second conclusion is that all models available on the market seem to have similar performance. However, there are doubts on such conclusions.

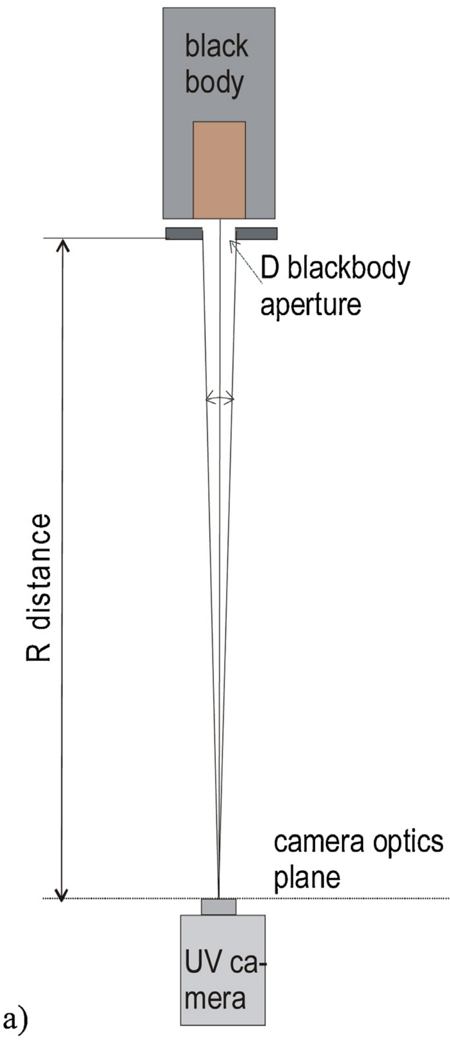
Table 2
Average numbers of photon counts by two SBUV cameras generated by two light conditions: a) no light, b) blackbody 960 °C at camera central part of FOV.

	Camera 1 Output signal [number of counts/second]	Camera 2 Output signal [number of counts /second]
No light	0.79	4.04
Blackbody 960 °C	1.8	5.05

Despite the fact that sensitivity is potentially the most important parameter and is present in each data sheet, it is surprisingly difficult to find how actually manufacturers of SBUV cameras measure their sensitivity. Some available scientific papers only acknowledge, without details, calibration method used by manufacturers called Planckian source method [9]. Next, there are only two easily accessible literature sources (leaflet from one of leading manufacturers and M.Sc thesis on testing of SBUV cameras) that present only very basic measurement concept of sensitivity based on use of a high temperature blackbody [10,11]. In addition, the author has been able also to get copies of two test certificates issued by manufacturers of SBUV cameras with sensitivity measurement results and detail test conditions that make possible to conclude how sensitivity is measured [12,13]. Finally, there is a paper published by a distributor of one of main manufacturers that presents quite detailed description of equipment and method used to measure sensitivity of SBUV cameras [14].

The earlier mentioned documents [11–14] show that sensitivity of SBUV cameras is defined as a minimal detectable irradiance in SBUV band at camera optics plane generated by a high temperature blackbody used as a calibrated source of SBUV light. The minimal detectable irradiance is defined as irradiance that generates video image of temporal density of registered photon counts equal to one photon count per second [12–14].

The measurement of sensitivity is done using a test system based on a high temperature cvity blackbody of drawing shown in Fig. 2a). Exemplary results of such sensitivity measurements for a series of blackbody temperatures are shown in Fig. 2b). This system drawing and this part of a test report present basic measurement concept of sensitivity of SBUV cameras.



a)

b)

BB Temp °C	Irradiance* W/cm²	UV Cnts/s
950	2.73E-18	0
960	3.87E-18	1
970	5.46E-18	3
980	7.66E-18	6
990	1.07E-17	10
1000	1.48E-17	16
1010	2.05E-17	[redacted]
1020	2.82E-17	[redacted]
1030	3.85E-17	[redacted]
1040	5.25E-17	[redacted]
1050	7.10E-17	75
1060	9.59E-17	[redacted]
1070	1.29E-16	[redacted]
1080	1.72E-16	[redacted]
1090	2.30E-16	[redacted]
1100	3.04E-16	316
1110	4.02E-16	[redacted]
1120	5.29E-16	[redacted]
1130	6.94E-16	[redacted]
1140	9.06E-16	[redacted]
1150	1.18E-15	1175
1160	1.53E-15	[redacted]
1170	1.97E-15	[redacted]
1180	2.54E-15	2541
1190	3.26E-15	[redacted]
1200	4.17E-15	4175

*2 m with Black Body aperture = 22 mm
Camera Gain @ 85%

Fig. 2. Method of measurement of sensitivity: a) graphical concept, b) part of test report [12].

In detail, the sensitivity of SBUV cameras is determined in three steps:

1 Measurement of temperature of the blackbody when a user can see on camera screen shots of UV photons originated from blackbody light detected by a tested camera at speed one photon count per second.
2 Calculation of blackbody effective radiant exitance M_{bb} at this minimal temperature:

$$M_{bb}(T) = \varepsilon \cdot \int s(\lambda) M(T, \lambda) d\lambda \approx \varepsilon \cdot \int_{\lambda 1}^{\lambda 2} M(T, \lambda) d\lambda, \quad (1)$$

where ε is the blackbody emissivity, $s(\lambda)$ is the relative spectral sensitivity function of the camera, and λ_1 and λ_2 are the wavelengths that determine approximate rectangular spectral band of the tested SBUV camera and blackbody spectral radiant exitance $M(T, \lambda)$ at temperature T (in Kelvins) and wavelength λ (in μm) is equal to:

$$M(T, \lambda) = \frac{c_{(1)}}{\lambda^5 (e^{(c_2/\lambda T)} - 1)}. \quad (2)$$

The c_1 and c_2 are the constants of following values c_1 = 3.741832 × 10^4 [W cm^{-2} μ m^4] and c_2 = 14387.86 μm K.

3 Calculation of irradiance E (in W/cm^2) generated by blackbody of aperture D at camera optics plane located at distance R (values in exemplary test certificate: R = 2 m and D = 22 mm) as:

$$E(T) = \frac{A \cdot M_{bb}}{\pi R^2} = \frac{D^2 \cdot M_{bb}}{4R^2}, \quad (3)$$

where A is the area of blackbody emitter, R is the distance between blackbody aperture and camera optics (in mm) and D is the diameter of blackbody aperture (in mm).

If we assume following data typical SBUV band (λ_1 = 240 nm, λ_2 = 280.2 nm), high emissivity cavity blackbody (ε = 0.999), and blackbody emitter and distance to tested camera as in test report in Fig. 2 (R = 2 m, D = 22 mm), then results of calculation of irradiance E using Eqs. (1)–(2) fits well (difference at level below 1 %) to irradiance data shown in Fig. 2b). However, it should be noted that different values of test conditions (D, R) can be found in different test certificates. Next, test certificates rarely presents detail data on dependence of irradiance on blackbody temperature as in shown in Fig. 2b).

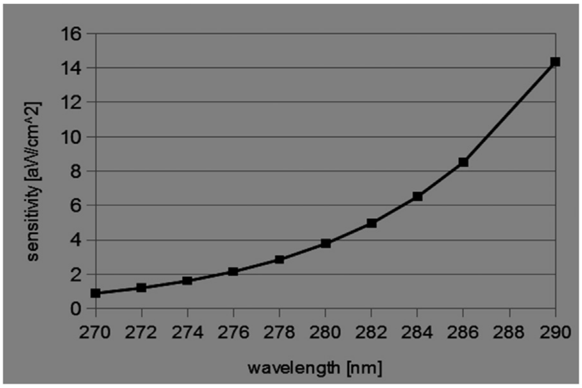


Fig. 3. Sensitivity calculated using Eqs. (1)–(3) for blackbody temperature of 960 °C, blackbody aperture of 2.2 cm, distance blackbody optics of 200 cm [as in certificate in Fig.2b)] but for different assumed location of a long-wave limit of spectral sensitivity band of tested SBUV camera.

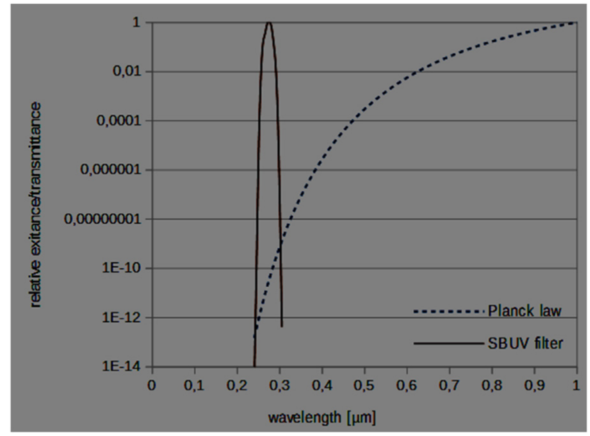


Fig. 4. Relative spectral exitance of blackbody at 960 °C temperature and approximate relative transmittance of exemplary SBUV filter [16].

4. Analysis of blackbody irradiance method for sensitivity measurement

The concept of using high temperature blackbodies as calibrated SBUV light sources for measurement sensitivity of SBUV cameras looks apparently sound. Simplicity and relative low cost of a test system are main advantages of this concept. Commonly available high temperature blackbody can be easily acquired on the market at price below 9k USD. In addition to blackbody, what is only needed is a PC for simple mathematical calculations based on Planck law and radiometry rules. Moreover, there are many accredited laboratories capable to do calibration of high temperature blackbodies.

One of high temperature blackbodies available on the market (HTB-25D-1000 from Inframet [16]) has been used to built a test system as in Fig. 1a).Next, there have been carried out sensitivity tests of a series of SBUV cameras using the blackbody irradiance method described in the previous section. The cameras for tests have been obtained mostly from their final users who could deliver only data sheets and sometimes test certificates. The data sheets of all tested cameras stated sensitivity values of about 3×10^{-18} W/cm^2 and the test certificates had confirmed these claims.

The test results have shown that minimal temperature of the blackbody [in test conditions as in test certificate as in Fig. 3b)] required to detect light capable to generate one photon counts per second in image generated by tested SBUV camera varies from about 940 °C to about 1020 °C. This high dispersion of minimal temperature suggests significant dispersion of sensitivity of tested cameras in contrast to equal performance claims shown in data sheets. However, this hypothesis has not been verified because spectral sensitivity band of tested cameras was not known and accurate calculation of sensitivity according to Eqs. (1)–(2) was not possible. It should be noted that it is commonly known that spectral sensitivity band of SBUV cameras is from about 240 nm to about 280 nm but detail spectral sensitivity data is considered secret and is not published in data sheets or test certificates. In detail, only a long-wave limit of spectral sensitivity band is needed because influence of a shortwave limit on calculated sensitivity is negligible.

The situation described earlier illustrates a big limitation of the blackbody sensitivity method that precise measurements of sensitivity of SBUV cameras by non-manufacturers which do not know spectral sensitivity band are practically impossible. In addition the experiments and detail analysis have shown that the blackbody sensitivity method is based on a set of assumptions that are not fulfilled, and consequences can be seriously negative.

These assumptions are:

Spectral sensitivity function of tested SBUV camera is known with high accuracy.

1 Minimal detectable irradiance at camera optics plane generated by an UV source of interest is a proper radiometric quantity to characterize camera ability to detect this light source.
2 Output signal at level of one photon counts per second in video image generated by the camera is a good criterion for detection of UV source.
3 Sensitivity as defined in way as in Section 3 is enough to characterize camera total performance.

First, it should be noted that users of SBUV cameras typically can only estimate position of a longwave limit of spectral sensitivity in the range from about 270 nm to about 290 nm. In addition, manufacturers of SBUV cameras typically get SBUV filters from subcontractors who manufacture these filters with limited repeatability. Bandpass UV filters are typically manufactured with ±2 nm tolerance for central wavelength and ±2 nm tolerance for transmission width [15]. Practically, it means ±4 nm tolerance on position of a longwave limit of spectral sensitivity band of SBUV cameras is quite acceptable. However, sensitivity calculated using blackbody irradiance method [Eqs. (1)–(3)] is extremely sensitive to position of a longwave limit of spectral sensitivity band of tested SBUV camera (Fig. 3). It means that on the basis of the same measurement results of blackbody minimal detectable temperature it is possible to calculate a totally different sensitivity of tested camera depending on assumed spectral sensitivity. It clearly shows that test certificates without information on spectral band are of limited value because it is easy to manipulate the measurement results.

The reason for this extreme dependence of sensitivity results on spectral position of SBUV spectral filter is spectrum properties of light emitted by high temperature blackbody in SBUV spectral band. As can be seen in Fig. 4 spectral intensity of SBUV light emitted by a typical high temperature blackbody varies very quickly with wavelength. Intensity of light at a longwave limit is over hundred times higher than intensity of light at a shortwave limit of the spectral band of SBUV camera. Such situation suggests that blackbodies of temperature about 1000 °C typically used for tests of SBUV cameras are not optimal to be used as a calibrated SBUV source.

There is a tempting solution to solve the problem of an unknown spectral sensitivity curve of tested SBUV camera by assuming typical values of limits of the SBUV filter (240–280 nm) like in Fig. 3b) but it leads to big errors if real spectral sensitivity curve differs from the assumed one. Data in Fig. 3 clearly shows that if we assume that a longwave limit of spectral band is of 280 nm, when a real longwave limit is of 284 nm (only 4 nm difference), then we will get a sensitivity of 1.7 times lower comparing to true value.

On the basis of arguments presented so far it can be concluded that the first assumption of blackbody irradiance method is clearly not fulfilled and even small errors in determination of spectral sensitivity function of tested SBUV camera generates significant error in calculation of sensitivity of such camera.

It can be argued that manufacturers of SBUV cameras are allowed to use any radiometric quantity to characterize their products. Therefore, the second assumption about irradiance at camera optics plane as the radiometric quantity used in measurement of sensitivity looks as justified. However, such a solution is against typical rules used in metrology of imaging systems.

Sensitivity of imaging cameras (thermal imagers, SWIR imagers, VIS-NIR cameras) is measured as a minimal detectable value of absolute/relative radiometric/photometric quantity that characterize target of interest. The quantities that characterize input stimulus can differ (temperature, radiance/irradiance, luminance/illuminance), but always characterize directly target (light source) under surveillance using the imaging camera. In addition, the target is typically located at some distance from the camera within its focusing range. Sometimes the target (light source) is located very close to the optics of tested camera but then the target fills total FOV of tested camera. Disregarding these rules brings several negative consequences.

Firstly, use of irradiance measured at a camera optics plane as the radiometric quantity to characterize light source in measurement of sensitivity generates highly inflated results compared to a situation when the same source is characterized by radiant exitance measured at the source plane. Both radiant exitance and irradiance are presented using the same units: W/cm^2. However, in case of the test conditions mentioned in the test report in Fig. 3b) (distance blackbody-optics of 200 cm, blackbody aperture of 22 mm) irradiance at optics plane is 33,057 times smaller than exitance at blackbody plane. Therefore, sensitivity shown in data sheets at a level of about 3×10^{-18} W/cm^2 creates illusion that SBUV cameras are capable of seeing a light source of radiant exitance at 3×10^{-18} W/cm^2 level, when it is totally impossible.

It is not logical to expect SBUV cameras to detect targets of exitance at 3×10^{-18} W/cm^2 level when these cameras are built using image intensifiers of Equivalent Background Input (EBI) at much higher level: 1×10^{-15} W/cm^2 [17]. It should be noted that due to losses on optics, fiber optics and filter the sensitivity of real SBUV camera must be many times worse than EBI of the image intensifier used as a block of the camera.

The second negative consequence of using irradiance measured at camera optics plane as the radiometric quantity to characterize light source in measurement of sensitivity is that such situation creates illusion that camera ability to detect and locate an UV light source is directly proportional to irradiance at camera optics generated by the light source. In practice, with two targets of different angular sizes with the same irradiance the smaller target is easier to detect than the larger target with camera.

This effect is very clear in case of high intensity light sources when camera is working in low gain (no gain) mode. The explanation of this situation is that if both targets are to generate the same irradiance at optics plane the target radiant exitance (related to brightness) of the smaller target is higher than radiant exitance of the large target. In detail ration of the exitances is equal to inverted ratios of targets areas. The same effect, though much smaller, can be observed in case of low light sources that create blinking photon images. As can be seen in Fig. 3 smaller target generates more photon counts and they are more concentrated. Therefore, image of a smaller target is easier to detected from background of noise counts compared to image of a larger target that generates the same irradiance at optics plane.

The third assumption on the criterion that determines a minimal output signal that can be detected looks apparently sound. Number of recorded photons counts in output camera image is directly proportional to a total flux of the UV light source at least in some ranges of light intensity. All SBUV cameras offer counting of recorded photon events. Therefore, output signal at a level of one photon counts per second in video image generated by the camera looks apparently as a good criterion for detection of UV source. However, practically situation is not so easy, because SBUV cameras are not noise free imaging systems.

Typical reader looking at the test certificate shown in Fig. 3b) can imagine that when camera is working in UV mode looking on a blackbody of temperature 960 °C (temperature at detection level) then there is a single white spot blinking with 1 Hz frequency. The reality is much different. All SBUV cameras offered on the market generate noisy images (unless gain is set to near zero). SBUV cameras always generate dozens of fake photon counts due to internal noise of the image intensifier block.

The problem with the analyzed criterion of photon counts is that it does not takes into account number of fake photon counts generated by camera noise. Practically it means that the analyzed criterion does not make difference between two SBUV cameras of the same responsivity to UV light measured in photon counts per radiometric unit but having different level of internal noise (number of fake photon counts per time unit).

Figure error: Reference source not found shows exemplary profiles of recorded photon counts vs. time for two SBUV cameras working in a high gain mode. Difference between average numbers of photon counts is the same for both cameras. It means that both cameras are characterized by the same responsivity to UV light and sensitivity of both cameras is the same. However, visually it is easy to notice light emitted from the blackbody in UV image generated by the camera no 1 and very difficult to notice this light in UV image generated by camera no 2. In practical terms it means that analyzed criterion that determines sensitivity of SBUV cameras cannot distinguish near perfect low noise camera from poor noisy camera.

The discussed situation is a reason why sensitivity of all EO systems to detect low intensity radiation sources is defined using noise related parameters: noise equivalent temperature (NETD) for testing thermal imagers, noise equivalent illuminance/irradiance (NEI) for testing visible/near infrared cameras. These parameters are generally defined as minimal value of radiometric quantity of target of interest that generates input stimulus that is equivalent to internal noise of the imager. Practically, it means that sensitivity of SBUV cameras should be defined not as minimal value of radiometric quantity of target of interest that generates one photon counts per second in video image but as a quantity that generates average number of photon event counts equal to number of noise event counts. In the latter solution if camera is more noisy then higher number of photon counts is required to be considered that target is detected (Figs. 5 and 6).

The assumption number fourth creates illusion that sensitivity as a single parameter can be considered as figure of merit of SBUV cameras. This conclusion is totally not true for two main reasons. First, the concept of measurement of sensitivity is based on a series of wrong assumptions as it was clearly shown earlier. Second, SBUV cameras are sophisticated electro-optical systems that cannot be characterized by a single parameter.

SBUV cameras represent probably a type of EO imaging systems that is the most difficult for in depth understanding. Other types of EO imaging systems are basically simple linear systems that generate image of brightness proportional to input radiometric stimulus. It is also relatively easy to predict and potentially correct influence environment conditions in a generated image. In case of SBUV imaging everything is much more complicated.

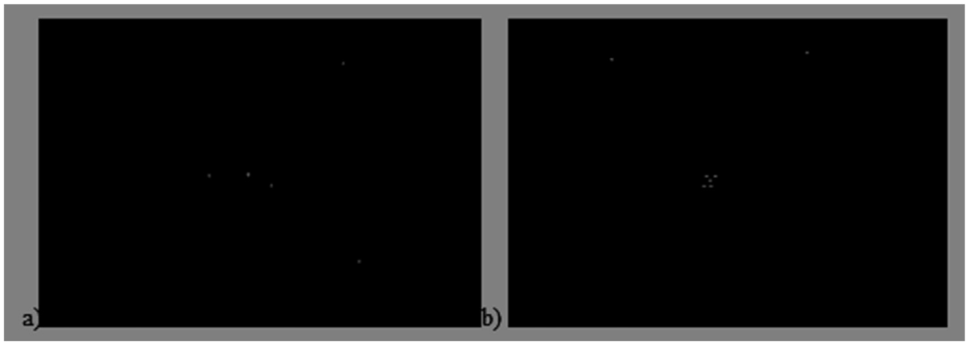


Fig. 5. Images of two low intensity light sources that generate the same irradiance level equal to 3.6×10^{-17} W/cm^2 at camera optics plane located at a distance of 2 m from UV light source captured using long integration mode a) image of light source of diameter of 24 mm and exitance of 1×10^{-12} W/cm^2 b) image of a light source of 3 mm diameter of exitance of 36×10^{-12}W/cm^2.

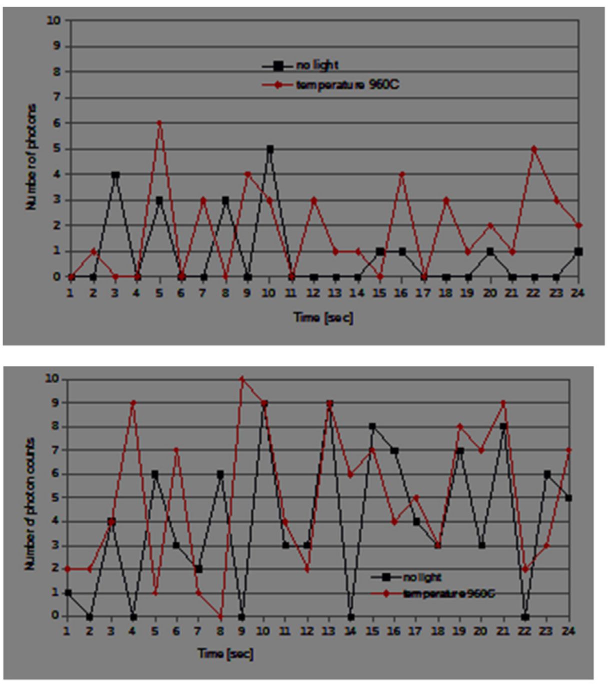


Fig. 6. Camera counts vs. time recorded by two tested SBUV cameras of the same responsivity but of different noise when seeing two targets (1-black target that emits no light, 2-blackbody of 960 °C temperature): a) counts of camera no 1 (Table 2), b) counts of camera 2 (Table 2).

Relationship between input radiometric stimulus and output signal measured in a number of photon counts or image brightness is non linear and dependent on camera settings. Next, solar light can significantly reduce ability of SBUV cameras to detect low intensity UV light sources at a degree difficult to predict. Therefore, it is clear that sensitivity alone is not enough to characterize SBUV cameras at the level needed for using them as reliable measuring tools that could enable determination of corona power loss on basis of images recorded by SBUV cameras. A long series of scientific papers devoted to determination of this relationship show that a set of parameters that could describe precisely performance of SBUV cameras is badly needed [18–22].

5. Conclusions

The analysis carried out in the previous section has clearly shown that currently used blackbody irradiance method to measure sensitivity of SBUV cameras uses wrong criterion of a minimal detectable level of input stimulus, wrong radiometric quantity to characterize this input stimulus, and wrong type of radiation source. The consequences of such situation are very serious:

1 Values of sensitivity of SBUV cameras presented in data sheets are misleading for potential readers of data sheets (create impression that SBUV cameras can detect UV light sources emitting light at level thousand times lower comparing to real light intensity of UV source that can be detected),
2 Users of SBUV cameras have no chance to verify data on sensitivity due to necessity of knowing value of a specific design parameter (longwave sensitivity limit) that is not published by manufacturers,
3 Sensitivity measured using blackbody irradiance method is inherently very vulnerable to variations of parameters of tested camera (longwave sensitivity limit) that can be considered to be within acceptable tolerances,
4 Two SBUV cameras of the same sensitivity in data sheets can differ significantly in their ability to detect weak sources of SBUV light,
5 Two SBUV cameras of the same sensitivity in data sheets can perform totally different when exposed to solar light,
6 The definition and measurement method of sensitivity of SBUV cameras is based on a totally different logic comparing to definitions of sensitivity of other types of electro optical imaging systems.

The final conclusion is that a new definition and measurement method is needed to characterize ability of SBUV cameras to detect low intensity UV light sources. It can be also predicted that a set of new parameters and measurement methods is needed to precisely characterize total performance of SBUV cameras and enable understanding of complex physical phenomenon that makes possible solar blind UV imaging. This understanding is much needed to reach a holy grail of SBUV technology: accurate prediction of corona power loss on the basis of images generated by SBUV cameras.

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