Characterizing the temperature response of a Hg-Cd-Te camera for field applications

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ABSTRACT

Hg-Cd-Te (MCT) cameras can be used to analyze the thermal emission or the infrared reflective response of physical systems. However, measurements performed with this instrument need to be corrected for the thermal emission from the environment surrounding the camera. In this work we analyzed this effect under conditions typically met in field applications, when environmental temperature variations are common. The dark current signal on a Xeva MCT 320 CL TE4 camera was studied as a function of ambient temperature and the integration time used for image acquisition. The MCT sensor at the focal plane was kept at a constant nominal temperature of 210 K by a thermoelectric cooler unit throughout the experiment. Integration times for data acquisition varied between 2.0 to 12.0 ms. The camera body temperature was monitored within ±0.2 °C, ranging from about 17.0 °C to 27.0 °C. The camera unit was allowed to reach thermal stabilization in a controlled-temperature lab before each measurement session. Both the integration time, and temperature range intervals were chosen to represent typical field deployment conditions. The average dark current signal showed a clear linear dependence with integration time, for a constant environmental temperature setting. The slope of this linear relation increased with the ambient temperature, whereas the intercept was insensitive to temperature changes. The standard deviation of the dark current signal was a function of integration time, but independent of the ambient temperature setting. These results allowed modeling the dark current signal as a function of the integration time and the camera body temperature. To minimize the dark current for a given integration time setting, measurements should be performed under the coldest possible conditions, in opposition to manufacturer recommendations. As a direct consequence of these results, the useful dynamic range for science applications with this MCT camera is reduced with increasing integration times and ambient temperatures. For instance, when acquiring images with 5 ms integration time, at 22 °C ambient temperature, the resulting dark current signal reduces the maximum useful dynamic range in about 20%. The results shown here can be promptly adapted to other applications with MCT cameras, especially in situations with a non-controlled thermal environment, or when analyzing the reflective properties of cold targets.

1. Introduction

Hg-Cd-Te (MCT) thermal cameras have been used in many applications to characterize the temperature response of physical systems (e.g. Bieszczad and Kastek, 2011; Biju et al., 2009; Breiter et al., 2016; Deppermann and Kneer, 2015; Lang et al., 2015). This type of device relies on the material properties of the MCT alloy (Lei et al., 2015; Norton, 2002), a semiconductor with a bandgap ranging from ~0 to ~1 eV, making it suitable for detectors that can respond in many parts of the infrared spectrum (Goldberg et al., 2003). An MCT image sensing device consists of a typically rectangular array of radiation-sensing pixels at the focal plane of a lens system, the focal plane array (FPA). An image is generated by scanning the scene across the pixel elements. At standard video frame rates, the radiation reaching each pixel during a short integration time induces charges across the MCT bandgap, which are subsequently readout from the detector matrix (Rogalski, 2012) and converted to physical units.

Using an MCT camera to assess accurate radiometric results requires the proper subtraction of the “dark current” signal from acquired raw images. This signal manifests itself as a positive intensity (as pixel counts) in acquired images, even when the lens is capped and therefore no net radiation from the target reaches the sensor. The dark current signal

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originate from a variety of physical processes at the MCT sensor (e.g. Hu et al., 2009), with a final effect largely dependent on the camera body temperature, sensor temperature, image integration time and intrinsic sensor electronic characteristics. Many references in the literature have characterized the dark current of a MCT sensor (e.g. Beletic et al., 2008; Breiter et al., 2016; Goldberg et al., 2003; Hanna et al., 2016; Hu et al., 2009; Knowles et al., 2011). Hanna et al. (2016), for instance, show that for one specific type of MCT detector the dark current surface density increases four orders of magnitude, from about 10⁴ to 10⁹ pA/μm² as its temperature changes from about 46 to 87 K. For this reason all commercial and/or scientific MCT cameras ship with a cooling module, to keep the FPA at a stable temperature (e.g. ~210 K or colder) during its regular operation.

Applications using MCT cameras are usually designed to carry out measurements under stringent environmental conditions, to derive quantities such as brightness temperature, thermodynamic temperature, or infrared emissivity on a surface target, under the assumption the target follows Planck’s spectral density function for its emitted infrared radiation. Experiments set under laboratory conditions can therefore maintain a near constant level of dark current signal during operation. This dark current signal is subsequently subtracted during data analysis of acquired images.

The MCT sensor and its controlling electronics may be affected by the emitted thermal radiation of the camera body and its surroundings. The blackbody radiative emission at ambient temperatures can be partly detected by the camera spectral response. Figure 1 shows a typical MCT sensor spectral response (solid blue line), with the sensitivity increasing almost linearly from wavelengths of 0.8 μm up to about 2.4 μm, then sharply decreasing to a minimum above ~2.7 μm. The position of this upper wavelength cutoff limit can vary depending on the specific stoichiometry used when building the MCT alloy. Superimposed on the same graph we show Planck’s blackbody emission spectral density function at 25.0°C (dashed red line), a typical temperature level for lab conditions. The convolution of Planck’s distribution function over the spectral region where the MCT sensor is responsive will be positive. The net effect will depend on the position of the upper cutoff wavelength. Figure 1 thus suggests the camera body, or more generally, the environmental blackbody emission can in principle influence the effective acquired signal or the dark current response.

MCT cameras can also be deployed in field measurements (Correia and Catandi, 2016; Martins et al., 2011), when thermal environmental conditions can vary substantially during operation. In this type of field application the sensor FPA itself is kept at nearly constant temperature, but the camera body and electronics in general are not subject to rigorous temperature control. Therefore, the dark current signal due to thermal environmental variations can in principle change over time, and thus needs to be modeled or recorded in order to be properly accounted for during data analysis.

In particular, measuring reflective properties of “cold” targets (e.g. clouds) in the field requires adequate knowledge about how the dark current in MCT cameras responds to environmental temperature changes. Under these conditions, the measured intensity of infrared radiation is not due to blackbody or graybody emission from the targets, but to their reflective properties when illuminated by the Sun. Martins et al. (2011) used an MCT camera to measure the solar radiance field reflected by clouds at wavelength channels centered around 2.10 and 2.25 μm, to derive cloud thermodynamic phase and droplet size (Nakajima and King, 1990). The cloud reflected solar infrared radiation is much smaller than the emission signal from a hot target, hence the subtraction of the proper dark current is even more critical when analyzing reflective properties of cold targets, especially considering possible environmental temperature fluctuations.

The goal in this work is to characterize the thermal response of a MCT camera in the context of its deployment for field measurements. The results shown here can be used in any applications using MCT cameras, but are particularly relevant in cases when this instrument is used in a non-controlled thermal environment, where the sensor response to ambient temperature fluctuations can be significant, and for the assessment of radiometric properties of cold targets. Section 2 presents the experimental setup and the methodology used to characterize the MCT sensor. Section 3 shows how the MCT dark current signal responds to environmental temperature variations, under conditions typically met in the field. Section 4 presents a discussion of the main findings, and derives a model to express the dark current as a function of temperature and the integration time used during image acquisition.

2. Materials and methods

Figure 2 shows the core instrumentation used in this study featuring a Xenics Xeva 320 MCT CL TE4 camera. This instrument acquired 14-bit images with its full resolution of 320 × 256 pixels, transferring the data to a computer via mini-USB cable. The manufacturer’s instructions¹

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¹ https://bit.ly/3akmMCT accessed on Jun 20th 2018 14:00 UTC.
advise to keep the camera body at a constant room temperature of approximately 20°C to optimize the signal quality, and explain that for temperatures above or below this ideal room temperature, additional cooling or heating could be necessary. However, the manual offers no description on how exactly the signal quality can be affected by ambient temperature variations, or how to apply a thermal bias to the ensemble. During this study the camera thermal response was assessed while ambient temperature was set in the range 15.0°C–30.0°C, within the recommended operating range from 0°C to 50°C. Adjustments of internal camera electronics, instrument control, and data acquisition were performed with the proprietary Xenics software that ships with the instrument.

In the camera the MCT sensor is connected to three main modules: a cooling interface, a sensor voltage regulator, and an Analog-to-Digital Controller (ADC) to read out the sensor matrix voltage and convert it to pixel counts. The thermoelectric cooler module was operated at a fixed setting throughout the study, keeping a stable sensor temperature of 210 K. The sensor voltage regulator allows the user to set the “Sensor Vin” and “Sensor Vref” voltages, which control how the MCT sensor responds to an input infrared signal. The ADC allows the user to set the “ADC Vin” and “ADC Vref” voltages, that how the ADC unit converts analog voltages to discrete pixel counts. Note the voltage settings at the sensor and at the ADC unit are crucial to determine the output signal recorded by the camera. Both the sensor regulator and the ADC interface were operated at their default settings. Table 1 shows the default settings for the camera unit used in this study.

The suite was used in a configuration deployed for field measurements of cloud reflectance (Correia and Catandi, 2016), including an adapted objective lens Nikon AF Nikkor 20 mm f/2.8D, and a 8-position FLI filter wheel used to select wavelength channels around 2.10 and 2.25 μm (cf. Figure 2). A dual-channel Minipa MT-241 thermocouple probe was adapted on the camera body to measure its temperature and also the ambient room temperature. The uncertainty for temperature measurements was estimated to be about 0.2°C. The thermocouple probe was fixed on one side of the camera body, as close as possible to the sensor FPA, and in the center of the optical path. The camera case was not open since the focus of this study was to simulate the thermal environment and measurement conditions usually met in the field.

Figure 2. The Xenics Xeva 320 MCT CL TE4 camera with an adapted filter wheel, objective lens and a dual channel Minipa thermocouple used to characterize the camera body temperature and ambient temperature. Data acquisition was performed by a laptop computer connected to the camera (not shown).

Table 1. Default voltage settings used for the MCT camera.

| Camera setting | Voltage (V) |
|----------------|-------------|
| Sensor Vin     | 2.097       |
| Sensor Vref    | 2.097       |
| ADC Vin        | 1.756       |
| ADC Vref       | 1.693       |

2 Minipa MT-241 thermocouple probe technical specifications: http://www.minipa.com.br/images/Manual/MT-241-1102-BR-EN.pdf accessed on Jun 20th 2019 14:30 UTC.

2.1. Sensor linearity test

Initially a sensor linearity test was performed to characterize the camera response as a function of the acquisition (integration) time, τ. The method consisted in collecting and analyzing the mean intensity (in counts) of 48 “dark images”, with varying integration time spans, at constant room temperature of 27.1 ± 0.2°C, and constant nominal FPA temperature set by the controlling software at 210 K. “Dark images” were generated by acquiring data with the camera lens capped, so they represent the final result of the dark current effect. Since the FPA temperature was constant, the acquired dark current images represent the sensor response as a function only of the variations in integration time. The span of variation in τ went from 0.5 to 20 ms, slightly above the maximum of 18 ms recommended by the manufacturer. For the sake of randomizing any possible residual temperature effect, the acquisition of dark images followed an alternate order of integration times.

2.2. Analysis of the camera body temperature influence on the sensor response

Once the linearity check was completed, the experimental setup was used to acquire several dark current images at different integration times and room temperature settings. The experimental suite was initially acclimatized in a temperature-controlled lab room over a period of about 12 h at a constant temperature of 15.0°C. This initial temperature setting was chosen to simulate typical conditions the camera faces in the field for our specific application (Correia and Catandi, 2016). In order to avoid condensation on the instrumentation, the atmospheric relative humidity was continuously monitored in the lab, and the instrumental suite was never moved out of the thermally controlled environment abruptly. After the camera was thermally stabilized, we acquired dark images using different integration times, varying from 2 to 12 ms. The range of integration time settings was determined so as to ensure enough counts in the resulting dark images, but avoiding having more than ~1% saturated pixels, while still representing typical values selected during active (non-dark) measurements. During all acquisition sessions, the uncertainty of the temperature measurement was based on the temperature fluctuations indicated by the thermocouple when the room temperature was settled. After the first batch of images was acquired the room temperature setting was increased by about 2.0°C and the system temperature was allowed to re-stabilize. A new batch of dark images was acquired with the same set of integration times previously chosen, following the same protocol to ensure the camera body temperature remained constant, then starting a new temperature change cycle. During this whole process the camera body temperature varied between ~17.0°C to 27.0°C. This range of temperatures was defined for being representative of actual conditions observed in field deployments.

3. Results

3.1. Sensor linearity results

Figure 3 shows an example of a dark image acquired by the camera system. The intensity counts in each pixel is mapped on the color bar. Notice in Figure 3 the presence of inhomogeneities like vertical stripes, dark or bright regions, and “hot” pixels, i.e. pixels that appear “white” or saturated independently of the integration time used for the acquisition.
Figure 3 also shows the corresponding histogram of pixel intensity values. The distribution of intensity counts in the histogram is defined from the voltage applied to the MCT sensor and the ADC module, shown in Table 1. Different voltage settings modify the histogram mean position and its width, i.e., the standard deviation of acquired data. The histogram maximum in Figure 3 is necessarily capped at the value 16383, due to the 14-bit limit of the ADC controller. The local peak at this maximum value shown in Figure 3 is due to the occurrence of hot pixels.

For the sensor linearity test the lab temperature was kept at 27.1 ± 0.2°C while 48 dark images were taken with different integration times. The mean intensity and the standard deviation of intensities in the dark current images are shown in Figure 4 as a function of integration time.

The linear fit shown in Figure 4 is:

\[ D(\tau, T_o) = (-248 \pm 18) + (0.589 \pm 0.006) \cdot \tau \]  

where \( D(\tau, T_o) \) is the average dark current intensity in counts, at temperature \( T_o = 27.1 \)°C, and \( \tau \) is the integration time in μs. This linear fit resulted in a reduced \( \chi^2 \) statistic of ~2.4, leading to the conclusion that one cannot reject the null hypothesis that the MCT sensor responds linearly relative to the integration time, under fixed conditions of sensor, room, and camera body temperatures. Notice also Figure 4 shows the standard deviation of intensities increases with \( \tau \), due to the stochastic nature of dark current readout noise.

While the linear response can be assessed with this result, it represents just one specific thermal configuration for the environment in the lab, when the camera body temperature is kept constant within 0.2°C. Next we assess how changes in the camera body temperature modify the intensity response.

### 3.2. Temperature response results

The relationship between temperature and the dark signal response for the camera was investigated by allowing the ambient room temperature to vary in steps of 2.0°C, as described in section 2.2. Figure 5 shows the average intensity of dark images as a function of the integration time, for given camera body temperature conditions. As shown in Figure 5, the sensor linear response depends on the camera body temperature, with the slope increasing with temperature.

In order to better characterize the camera temperature response, the slope and intercept of each linear fit in Figure 5 were analyzed separately.
as a function of camera body temperature, as shown in Figures 6 and 7, respectively.

Figure 6 shows, to a first-order approach, the slope of the sensor linear response function can be itself modeled with a linear dependence on the camera body temperature. One can notice residuals fluctuate about the linear fit in Figure 6 with an apparent regular structure (i.e. above and below the adjusted function), but we opted to keep a linear fit to describe the general trend for simplicity. The slope can be thus determined by:

$$\alpha(T) = \left( -0.01 \pm 0.05 \right) + \left( 0.0266 \pm 0.0023 \right) \cdot \frac{1}{C} \cdot T$$

where $\alpha(T)$ is the slope in units of $\mu s^{-1}$, and $T$ is the camera body temperature in °C. The intercept value of $-0.01 \pm 0.05 \mu s^{-1}$ in Eq. (2) is compatible with zero and can be disregarded if one wishes to keep a simpler model.

In Figure 7 one notices the intercept of the sensor linear response function can be considered nearly independent of the temperature. The average intercept was determined as:

$$\beta = \left( -206 \pm 48 \right)$$

where $\beta$ is the intercept in arbitrary units (counts). The intercept corresponds to the (dark) signal in the camera when the integration time tends to zero, and thus represents the minimum level of intensity the electronics can convert to digital counts. A null integration time will naturally lead to an expected small or null thermal influence, which is consistent with the result shown in Figure 7.

This set of Eqs. (2) and (3) define a linear model that can be used to predict what will be the dark signal for a given camera body temperature, so it can be adequately accounted for when assessing radiometric properties in a measurement session. The dark current signal can thus be estimated as:

$$D(\tau; T) = \beta + \alpha(T) \cdot \tau$$

where $\alpha(T)$ itself is a linear function of the camera body temperature given by Eq. (2). The fact the camera body temperature acts linearly on
the slope can be interpreted as a “gain factor” that affects the recorded intensity count, at least in the temperature range used in this study.

The overall data quality in camera acquired images also depends on the distribution of intensities around a mean value, i.e., the standard deviation of intensities. As explained previously, this distribution depends on the voltages applied on the MCT sensor and the ADC unit (cf. Table 1), but in general these settings are kept fixed during the regular camera operation. In Figure 4 one notices the standard deviation, represented by the vertical error bars, increases with integration time. In order to characterize how the ambient temperature may affect data quality, the standard deviation of intensities in dark current images was investigated for different camera body temperatures, as shown in Figure 8 for given integration time settings.

From the results shown in Figure 8 one notices the standard deviation of intensities is nearly independent of camera body temperature, and is determined by the integration time. This is in contrast with the information presented in the camera manual, where it is stated the noise is due both to the integration time and the ambient temperature. Statistically, the slope in each linear fit shown in Figure 8 is compatible with zero. This is also relevant to the analysis of active (non-dark) images. The results in Figure 8 show that a change in camera body temperature does not impact the precision of the measurements, at least within the temperature range that was used in the tests.

4. Discussion and final remarks

The deployment of MCT sensor cameras in field experiments usually is performed under fixed calibration parameters, for instance keeping stable sensor temperature and voltage settings. However, the camera body and electronics in general are not subject to rigorous temperature control or monitoring. Our results show (cf. Figures 5 and 6) how variations in the environmental temperature affecting the camera body can influence the measurements performed by a MCT camera, even though...
the sensor itself is kept at constant temperature by a thermo electric cooler module.

When the dark signal needs to be subtracted from acquired images, it is thus advisable to keep the camera in a constant temperature environment. If that is not possible, e.g. when the camera is deployed in field measurements, comparisons of the net signal acquired in different thermal backgrounds need to account for the changes in temperature experienced by the suite. Ideally this can be accomplished by acquiring dark images every few raw images, so the net signal can be computed a posteriori for the same general environmental conditions. In some situations, however, the camera needs to be operated continuously, e.g. when no filter wheel is available to ensure measuring dark images along the measuring session.

In this situation, a general methodology to adequately subtract the dark signal from acquired raw images, based on our results, would be: a) record the camera body temperature while the camera is operated; b) for a given camera body temperature, determine the dark signal linear model from Eqs. (2) and (3); c) apply the proper linear model to correct the intensity recorded in a reference dark image; d) use the corrected dark image matrix to subtract from the corresponding raw image signal. This procedure can be successful since, as we have shown, the standard deviation of intensities is nearly independent of camera body temperature variations (cf. Figure 8).

In general, the net signal matrix, \( N_\tau(t) \), that one seeks to obtain for the i-th image acquired is:

\[
N_\tau(t) = R_\tau(t, T) - D_\tau(t, T)
\]

where \( \tau \) is the integration time, \( T \) is the camera body temperature, and \( R_\tau \) and \( D_\tau \) are the raw signal and dark current matrices, respectively. The average dark signal depends both on the temperature and the integration time for the acquisition, as shown in Figure 5. The net signal should depend only on the integration time, since the camera body temperature bias is removed by applying a modeled dark signal matrix, mimicking the dark signal for the environmental conditions when \( R_\tau \) was acquired.

The issue under discussion here is how to get \( D_\tau \) from the linear model derived in this study, while still representing the uncertainty, or standard deviation for a particular integration time during the acquisition of raw images. First we build a \( D_\tau \) reference matrix that has the same standard deviation as the raw data:

\[
D_\tau = (R_\tau - J R_\tau)
\]

where the bar sign indicates the average intensity of the raw image matrix \( R_\tau \) and \( J \) is an all-ones matrix with the same dimensions as \( R_\tau \). In this way the matrix \( D_\tau \) has a null average, and keeps the standard deviation associated with the integration time \( \tau \), used when acquiring the raw image \( R_\tau \). The dark current matrix is obtained by adding to the matrix \( D_\tau \) the proper numerical offset from Eqs. (2) and (3):

\[
D_\tau = D_\tau + J(0.0266 T \tau - 0.01 \tau - 206)
\]

where \( D_\tau \) is the dark current matrix we seek to derive; \( T \) and \( \tau \) refer to the camera body temperature, and the integration time used during the acquisition of \( R_\tau \), respectively. Combining Eqs. (5), (6), and (7) we get the final equation for the net signal:

\[
N_\tau = J(R_\tau - 0.0266 T \tau + 0.01 \tau + 206)
\]

From Eq. (8) we see the net signal for an acquired image can be calculated from the average intensity of the raw signal, from which we subtract a modeled dark current signal, that accounts for different camera body temperatures (in °C) and image acquisition times (in μs), while still keeping the standard deviation of the original raw image. This model can be considered valid for a temperature range between about 15.0 °C to 30.0 °C (the approximate range used in this study), and should be used with caution in extrapolations.

### 4.1. Some considerations on the effective dynamic range

For this particular camera, the full dynamic range represents 16384 levels of intensity (14-bit) that can be recorded for each raw image acquired by the instrumentation. However, in general one seeks to use only about 80% of the full dynamic range (“useful range”) to avoid the occurrence of saturated pixels, that cannot be used for science applications.

Eq. (8) indicates the net signal depends on the original raw signal and a dark current bias that decreases its intensity. The resulting net signal is decreased with increasing temperature and integration time. This effectively reduces the available dynamic range for measurements, and so Eq. (8) can be used to model the “available” or effective dynamic range for a particular application. Considering, for instance, a typical integration time of 5000 μs, and the camera body temperature of 22.0 °C, the negative bias due to the dark current amounts to 2681 intensity counts, which represents about 20% of the useful dynamic range. In an extreme case of \( \tau = 10000 \mu s \) and \( T = 30.0 \) °C, the dark current would reduce the useful range in about 59%, with only ~5400 intensity counts left for scientific applications. The conclusion is that for this MCT camera it is recommended to keep the integration time and the camera body temperature as low as possible. This will ensure there is dynamic range available to assess variations of radiometric properties for the target. Notice the manufacturer recommends, on the contrary, to apply external heating to the camera unit if the environmental temperature is below 20.0 °C, which is not supported by our results.

The method described in this work can be useful in similar cases. In science applications where the signal is relatively small, e.g. measuring the reflected infrared signal in cold targets, the subtraction of the dark current effect is essential for accurate quantification. The method shown here addresses this issue, especially when environmental temperature conditions can vary during acquisition.

### Declarations

#### Author contribution statement

Christian Lang Ostermayer: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Alexandre L. Correia: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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#### Competing interest statement

The authors declare no conflict of interest.

#### Additional information

No additional information is available for this paper.

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#### References

Beletic, J.W., Blank, R., Gullbransen, D., Lee, D., Loose, M., Piouette, E.C., Spraße, T., Tennant, W.E., Zandian, M., Zini, J., 2008. Teledyne Imaging
Sensors: infrared imaging technologies for astronomy and civil space. In: Proc. SPIE 7021, High Energy, Optical, and Infrared Detectors for Astronomy III, p. 70210H.

Bieszczad, G., Kastek, M., 2011. Measurement of thermal behavior of detector array surface with the use of microscopic thermal camera. Metrol. Meas. Syst. XVIII, 679–690.

Biju, N., Ganesan, N., Krishnamurthy, C.V., Balasubramaniam, K., 2009. Frequency optimization for eddy current thermography. NDT E Int. 42, 415–420.

Breiter, R., Benecke, M., Eich, D., Figgemeier, H., Weber, A., Wendler, J., Sieck, A., 2016. MCT SWIR modules for passive and active imaging applications. In: Proc. SPIE 9819, Infrared Technology and Applications XLII, p. 98190K.

Correia, A.L., Catandi, P.B., 2016. Deriving cloud microphysics from radiometric measurements in the Amazon Basin. Atmos. Sci. Lett. 17 (11), 596–602.

Deppermann, M., Kneer, R., 2015. Determination of the heat flux to the workpiece during dry turning by inverse methods. J. Inst. Eng. Prod. 9, 465–471.

Goldberg, A.C., Kennerly, S.W., Little, J.W., Shafer, T.A., Mear, C.L., Schaeke, H.F., Winn, M., Taylor, M., Uppal, P.N., 2003. Comparison of HgCdTe and quantum-well infrared photodetector dual-band focal plane arrays. Opt. Eng. 42 (1).

Hanna, S., Eich, D., Mahlein, K.-M., Fick, W., Schirmacher, W., Thot, R., Wendler, J., Figgemeier, H., 2016. MCT-based LWIR and VLWIR 2D focal plane detector arrays for low dark current applications at AIM. J. Electron. Mater. 45 (9).

Hu, W.D., Chen, X.S., Quan, Z.J., Ye, Z.H., Hu, X.N., Li, Z.F., Luc, W., 2009. Analysis of temperature dependence of dark current mechanisms for long-wavelength HgCdTe photovoltaic infrared detectors. J. Appl. Phys. 105, 104502.

Knowles, P., Hipwood, L., Pillans, L., Ash, R., Abbott, P., 2011. MCT FPAs at high operating temperatures. In: Proc. SPIE 8185, Electro-Optical and Infrared Systems: Technology and Applications VIII, p. 818505.

Lang, W., Gardner, A.D., Mariappan, S., Klein, C., Raffel, M., 2015. Boundary-layer transition on a rotor blade measured by temperature-sensitive paint, thermal imaging and image derotation. Exp. Fluids 56, 118.

Lei, W., Antoszewski, J., Faraone, L., 2015. Progress, challenges, and opportunities for HgCdTe infrared materials and detectors. Appl. Phys. Rev. 2 (4), 41303.

Martins, J.V., Marshak, A., Remer, L.A., Rosenfeld, D., Kaufman, Y.J., Fernandez-Borda, R., Koren, I., Correia, A.L., Zubko, V., Artaxo, P., 2011. Remote sensing the vertical profile of cloud droplet effective radius, thermodynamic phase, and temperature. Atmos. Chem. Phys. 11, 9485–9501.

Nakajima, T., King, M., 1990. Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: theory. J. Atmos. Sci. 42, 1878–1893.

Norton, P., 2002. HgCdTe infrared detectors. Opto-Electron. Rev. 10 (3), 159–174.

Rogalski, A., 2012. History of infrared detectors. Opto Electron. Rev. 20 (3).