New Thermal Infrared Hyperspectral Imagers

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ABSTRACT

The aim for this paper is to present designs and performance characteristics of the new push-broom hyperspectral imagers in thermal wavelength region. The guiding motive for this work has been to design high performance instruments with good image quality, compact size and easy operation for different application requirements. The studies involve imaging systems based on both MCT and microbolometer detector. All the systems base on push-broom imaging spectrograph with transmission grating and on-axis optics.
Two instruments have been developed for LWIR wavelength range, 8 – 12 µm. The airborne remote sensing imager utilizes MCT detector combined with BMC-technique (background monitoring on-chip), background suppression and temperature stabilization. This instrument provides high performance suitable for airborne and on-the-field remote sensing applications. The performance of the imager with 84 spectral bands and 384 spatial samples has been studied and NESR of 18 mW/(m^2srμm) at 10 μm wavelength for 300 K target has been achieved. This leads to SNR of 580. These results are based on a simulation models.
Realizing these goals without considerable cooling of the whole instrument is a challenging task. The key issue in the design is to control the instrument radiation falling on the detector from all the surfaces of the instrument itself. Consequences of the instrument radiation are raising background level and reduction in dynamic range. This challenge is particularly prominent in hyperspectral instruments, where the optical power from the target is spread spectrally over tens of pixels, but the instrument radiation is not dispersed. Without suppression, the instrument radiation may exceed the radiation incident from the target by several orders of magnitude. The same principles applied to the LWIR hyperspectral imager, are applicable in the case of MWIR, 3 – 5 µm, wavelength region.
The second design of the imager base on uncooled microbolometer detector technology and ambient temperature optics. This design aims at laboratory, research and industrial applications where illumination of the target with high temperature heaters with ellipsoidal reflectors is possible. An example of applications is mineralogical analysis of drill cores. Performance characteristics for the microbolometer version have been experimentally verified and found to comply with simulations and calculations well.
Keywords: Hyperspectral imaging, LWIR, infrared, thermal, spectral camera, pushbroom

1. INTRODUCTION

Hyperspectral imaging in the LWIR (7 to 14 um) region is still in an early stage. This is true in airborne remote sensing, but also in industrial process or quality control and laboratory studies. There are very few instruments available which can provide both feasible performance and usability. SEBASS and AHI instruments are most widely used push-broom imagers in LWIR airborne experiments.[1, 2] They are bulky and require intensive care and maintenance during operation. Fourier Transform (FT) imaging spectrometers and chromotomographic imaging spectrometers are being developed for imaging applications in the field and laboratory.[3] The longest commercial history in LWIR spectral imaging is in microscopic imaging solutions for laboratory analysis.
SPECIM is developing a family of LWIR and MWIR hyperspectral cameras for various industrial, laboratory and remote sensing applications. The first of the hyperspectral cameras, LWIR HS with an

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15. SUBJECT TERMS

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uncooled microbolometer detector, has already been manufactured and tested. It is aimed at industrial and laboratory use with illumination. It can also be used in laboratory verification measurements for airborne data interpretation. For airborne remote sensing SPECIM is developing a cooled MCT-detector based high performance hyperspectral camera, which will be the sensor of AisaOWL airborne remote sensing system. A spectral camera with the same basic structure will be available for demanding industrial and laboratory applications. MCT detector is at least 10 times more sensitive than a microbolometer. Thus the detector type largely determines the performance of the hyperspectral camera, and to which applications it can be used. The MWIR hyperspectral camera will be based on the same principles as AisaOWL and the same technological principles apply for that.
The most common performance parameter with thermal IR instruments is traditionally NETD (noise equivalent temperature difference). However, this figure of merit is not well applicable to spectral instruments, because it also depends on temperature, emissivity and spectral features of the target. The well describing figure of merit for a hyperspectral camera is NESR (noise equivalent spectral radiance). It does not depend on the target properties, but is unique to the instrument, and allows immediate estimation of the SNR once the spectral radiance of the target is known. [4, 5]

2. OVERVIEW OF THE IMAGERS AND AIRBORNE SYSTEM

The LWIR imagers presented here are push-broom type hyperspectral imagers. Push-broom hyperspectral camera consists of two functional opto-electronic parts: imaging spectrograph with fore lens and a 2D-detector unit with camera electronics. Cooling and temperature stabilization of the system is included in the AisaOWL sensor. The flexibility in all of the instruments is ensured by features like fore-optics, which can be changed and integration time, which is independent of frame rate.
A push-broom hyperspectral camera acquires a line image on the target at a time. The imaging spectrograph in the camera diffracts the line image to its spectral components (bands), and the 2D detector behind the spectrograph records the line image at all of the contiguous spectral bands exactly simultaneously. Thus a push-broom imager is an ideal solution for any application where either the camera moves (or is scanned) or the target moves.

Figure 1: The measurement system and main functional parts of the AISA airborne remote sensing system. Position data is captured using GPS/INS unit and position data is synchronized with signal and background measurement data from sensor head. Fodis-sensor may be included in visible-near-infrared (AisaEAGLE) and short-wave-infraed (AisaHAWK) systems.

The measurement system structure and information flow of an AISA system is shown in figure 1. The sensor head records the data, which is then synchronized with position data. The synchronized data is collected to data acquisition unit and stored on a hard disk. Processing is performed afterwards in one or several steps.

The resolution in the image line is 384 pixels in both LWIR cameras, as seen in Table 1, which summarizes the main specification of the instruments. AisaOWL is a design for high spectral resolution, and has 84 contiguous spectral bands. LWIR HS has broader spectral bands in order to collect more energy per spectral pixels, and compensate for the lower sensitivity of the microbolometer.

Table 1: The main specifications of AisaOWL and LWIR HS.

	AisaOWL	**LWIR HS**
F#	2.0	1.0
Wavelength range	8.0 – 12.0 µm	7.8 – 12.0 (13.0)
Number of spectral pixels	84	22 (30)
Number of spatial pixels	384	384
Spectral resolution	100 nm	400 nm
Detector type	MCT	Microbolometer
Spectral sampling	48 nm	200 nm (mean)
Instrument temperature	300 K	300 K
Instrument temperature	Stabilized	None
Camera dimensions	220x200x220 (mm)	55x130x125 (mm)
Camera weight	8.5 kg	2.5 kg

AisaOWL - Temperature stabilized optics with MCT detector

High sensitivity and excellent stability have been the driving design targets with the AisaOWL sensor. The temperature and temperature variation of the opto-mechanical part is an important factor affecting the performance of instrument. The camera structure is divided to separate compartments. Parts generating heat are insulated and radiation is shielded from opto-mechanics to avoid additional heat load from them. Spectrograph is temperature stabilized to minimize fluctuation in the instrument radiation from the opto-mechanics onto the detector. The detector array is cryogenically cooled below 70K, and a special cold filter is used to suppress background radiation. Remaining variation in instrument radiation is eliminated with the background-monitoring-on-chip (BMC) calibration described in chapter 3. In spite of the means for temperature control, the size and weight of the sensor camera will be very compact. The dimensions can be seen in Table 1. AisaOWL sensor is shown in figure 2.

Figure 2: AisaOWL sensor head. The longest dimension of the sensor is 285 mm. Fore-optics is protected against direct heat flow with a removable cover.

LWIR HS – Reflection measurement of illuminated targets with uncooled optics and microbolometer detector

The LWIR HS spectral camera consists of an imaging spectrograph with a fore-optics and uncooled microbolometer camera. Temperature control of the instrument is less critical with the microbolometer. Each pixel in the microbolometer acts like a thermometer, and does not saturate from higher background radiation as a photon detector could do. A higher background signal does not either cause any significant deterioration of the SNR in a microbolometer

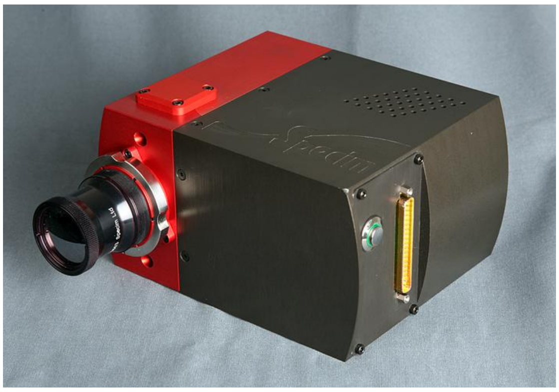


Figure 3: Hyperspectral LWIR HS camera. The longest dimension of the camera is 185 mm.

The background level from the instrument radiation changes with instrument temperature, but this is compensated by using the BMC calibration method.

Being able to leave out means for temperature control and cooling, keeps the structure of the LWIR HS camera very simple and compact. The weight is only 2.5 kg.

3. PRINCIPAL PERFORMANCE FACTORS

Three main factors rule the performance of the thermal wavelength region instruments. The first is instrument radiation, which is thermal radiation at the same wavelengths as radiation originating from the target. Second factor is the quality of radiometric calibration and third is the quality of spectral calibration. The first, instrument radiation, is characteristic specifically to optical thermal range instruments. The two latter are basic calibration routines that are familiar also from other wavelength ranges.

The difference between instrument radiation and radiation from the target is that instrument radiation is broad band radiation whereas the radiation from the target is being split to narrow bands. The consequence of instrument radiation is that background level of the data rises. Photon detectors are collecting charge generated by photons within integration time. High background will lead to very small dynamic range for signal because charge capacity would be filled by background if background is not suppressed in any way. This would result a very low signal-to-noise ratio.

There are means available to reduce the instrument radiation. The most common technique is to cool down the opto-mechanics. It is a straightforward, but bulky way, and it generates need for a sealed compartment in order to prevent water condensation, and need for special design of the opto-mechanics for very large temperature differences. Also, depending on the cooling technique, it may result in troubles either with liquid nitrogen or high power consumption and space requirement.

Another means is to integrate a specific optical cold filter in the detector to block out unwanted part of the spectrum and/or suppress the broadband background.

In a microbolometer, the pixels settle down to heat transfer equilibrium with target and surroundings. The pixel temperature is then read via a temperature dependent resistance. This means that there is not such a saturation effect as in a photon detector and microbolometer do not need cooling and they also do not suffer from instrument radiation to the same extent as MCT. However, the high and varying background level needs to be compensated in microbolometer data too, to assure the quality of the data in long data sets.

Several means exist to deal with background signal generated by the instrument radiation. It can be subtracted from data if background is monitored between measurements. A typical way is to perform a two point temperature calibration between measurements by acquiring image signal from blackbodies at two different temperatures and making a radiometric calibration with them. Second way is to record an image of a cold reference target to be subtracted from the data.

Another approach is to monitor the instrument radiation in real time during image acquisition, and then to subtract the variations form the data in image processing. In this approach the instrument needs to be radiometric calibrated beforehand in laboratory, but the need for calibrated sources during operation of the instrument is avoided. A substantial benefit is gained, because there is no need to break a continuous measurement mission.

In the studied hyperspectral LWIR instruments this monitoring is realized by BMC technique. It uses a part of the FPA to monitor the instrument radiation in real time. The correlation between the variations in monitoring signal and background variations in the actual image area of the FPA due to variations in the instrument radiation is determined (calibrated) in laboratory. This calibration allows subtraction of the instrument radiation from the image data by each image frame. Some verification test results for stability for noise in data and for instrument temperature changes are shown in this paper.

The second and third key performance verification factors, radiometric and spectral calibration, are realized in similar routines as for other wavelength ranges (visible and short wave infrared). Spectral lamps or similar absolute spectral peak sources are not available in LWIR range. That is the reason why absorption references or narrow band interference filters with a high temperature blackbody source. The absorption references may be solid films like plastic sheets, or gas filled couvettes. The radiometric calibration is done with a calibrated temperature controlled blackbody source. It has to be supplemented with the BMC-calibration to allow proper background subtraction during data processing.

4. PERFORMANCE OF SENSOR WITH COOLED MCT-DETECTOR

A photon detecting MCT detector is used in AisaOWL sensor. It is divided to 84 pixels in spectral direction and data is averaged over two pixels resulting 42 averaged pixels (software binning by 2 pixels) and its sensitivity ranges from 8 μm to 12 μm.

The performance in terms of signal to noise ratio (SNR) and noise equivalent spectral radiance (NESR) of the AisaOWL sensor design has been estimated using simulation models. They take into account the detailed spectral properties of the optics, detector, instrument radiation, and target. In the results shown, instrument radiation is taken into account as a worst case simplified model, as radiation from a blackbody source with emissivity of 1.0 and solid angle defined by cold stop of the detector dewar. The instrument radiation is suppressed by a special cold filter, which is included in the simulation model.

The signal to noise ratio (SNR) depends, in addition to the optical and electrical properties of the optics and detector with its electronics, on the temperature of both the target and instrument itself. Only these temperatures can significantly affect to SNR once the instrument is built and calibrated.

The target is a blackbody radiator at 300 K. Special background suppression technique is used in the sensor to reduce the instrument radiation falling to the detector and for parameters with uncertainty safe values are used. Table 1 summarises the main performance characteristics of the sensor at three wavelengths.[6]

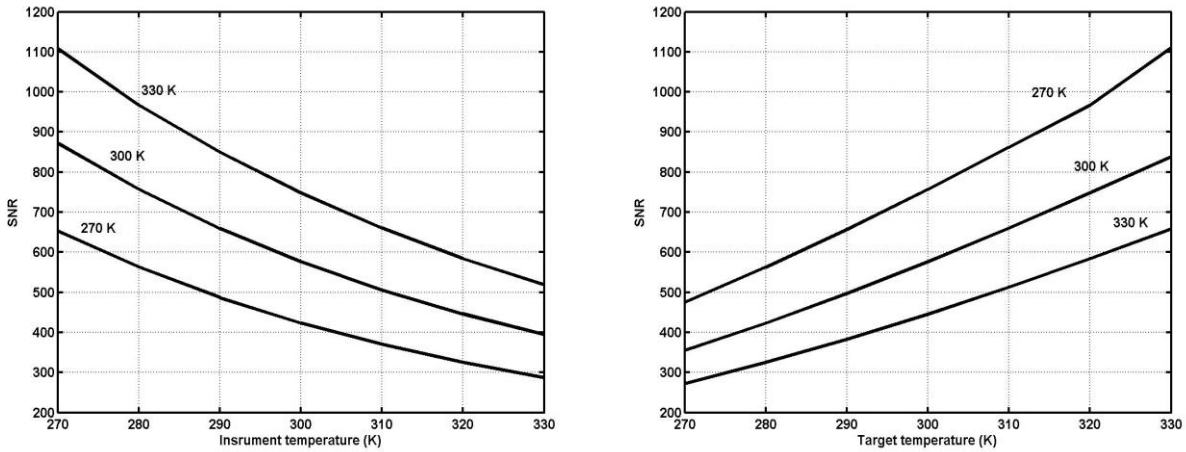
Table 1: The main performance properties of AisaOWL sensor. Both instrument and target are at 300K temperature.

	SNR	NESR (mW/m²srµm)	NETD (K)
8 µm	450	21	0.13
10 µm	580	18	0.12
12 µm	215	43	0.37

The NESR describes a spectral imaging systems performance best with SNR. NETD and NESR are not independent figures, but the relation between them is

$$NESR = \frac{\Delta L_\lambda}{\Delta T} \cdot NETD$$

where ΔL_λ is change in spectral radiance and ΔT is corresponding temperature difference.



a) **b)**

Figure 4: The SNR of the instrument at 10 µm wavelength as a function of instrument temperature (left, panel a) and target temperature (right, panel b). In left panel the three curves represent the SNR for three different target temperatures. In Right panel they are for three instrument temperatures.[6]

The design goal for the AisaOWL working condition is 300 K for both the instrument and typical target temperature. The simulation results in Table 2 show the performance properties in these conditions. If either of the temperatures changes it results a change in the performance. Figure 4 illustrates this effect with fixed target temperature, but instrument temperature changing (panel a), and with fixed instrument temperature, but target temperature changing (panel b).[6]

Background subtraction reliability in thermal hyperspectral sensors

The high performance of the instrument cannot be achieved if background subtraction is not properly done. This includes a good stability of background monitoring using BMC method and validity of BMC method calibration. This has been tested in a data set using an MCT 256x256 LWIR detector. The spectral range of it does not cover the full 8 – 12 µm, but the results are prominent for the validity of the method. The temperature of the target was 200˚C and there is not any instrument radiation suppression involved. About 15% well fill was used.

The data set consists of four data cubes with 300 frames each. All of the cubes were acquired from the same target, but temperature of the opto-mechanics of the instrument was 29˚C, 31˚C, 33˚C and 35˚C. Instrument temperature does not affect on the temperature of the focal plane array, which is in constant

temperature.
The stability of BMC monitoring value was ascertained by following its behaviour with time within a data set. The BMC values vary within one quantization unit from mean value (dynamic range of the camera is 14 bits). This means that monitoring of instrument radiation is stable.
The stability of the background subtraction against disturbances from noise of the original signal was verified by observing the signal level at about 9.5 µm wavelength through a data set of 300 frames. The result shows a similar noise characteristic in the background subtracted signal as in the original signal. The standard deviation of the original signal is 2.39. It is slightly bigger than for background subtracted signal, 2.21, which means that subtracting background does not add noise to the data.
The reliability of the BMC method can be considered as reproducibility of the results when instrument temperature changes. This means that the same signal from the same target has to be acquired independent of the instrument temperature. The results show that differences in signal are 0.6% or less of the raw signal when the temperature of the instrument changes.

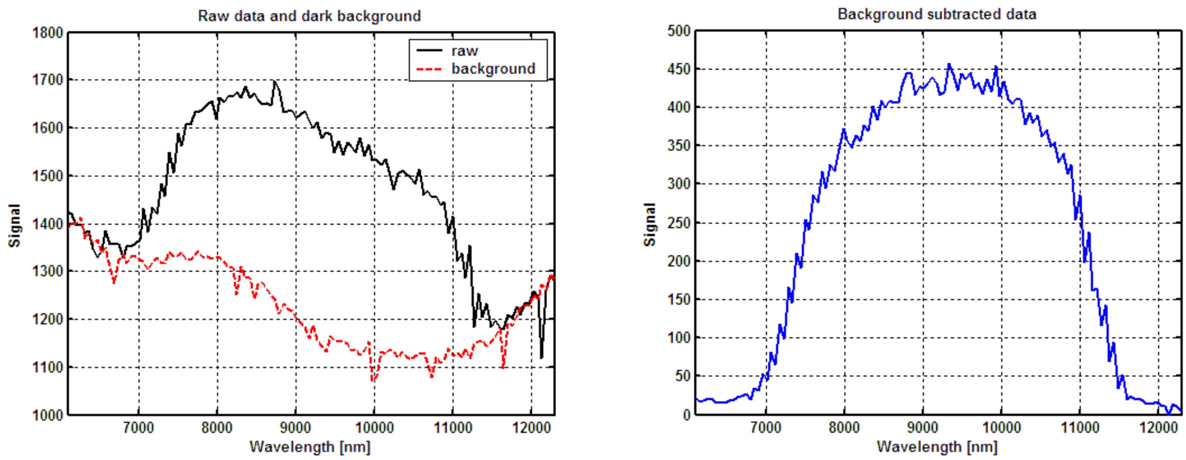


Figure 5: Raw signal, BMC-calibrated background and background subtracted signal of the 200˚C blackbody target with an instrument at 31˚C temperature. The saw-tooth-like behaviour of the signal is not real. It comes from the properties of the test camera.

An example of a raw signal, calculated background and background subtracted signal are shown in figure 5. The final result represents the spectrum of the target. In this case the target was a blackbody radiator at 200˚C.

5. PERFORMANCE OF SENSOR WITH UNCOOLED MICROBOLOMETER DETECTOR

The performance of LWIR HS has been experimentally verified in terms of SNR in the previous study[6]. The target in the tests was a calibrated blackbody radiator with adjustable temperature. Used target temperatures are seen in table. Corresponding radiances where calculated from Planck’s radiation law and signal relative to 0 K target was derived. 100 frames were recorded for each target temperature. The SNR for each target temperature at 8 µm wavelength is shown in table 2.
The results show, that LWIR HS is not well applicable for measuring room temperature targets. For warmer targets or illuminated targets performance is reasonable. It is obvious from these characteristics that main uses for this sensor are laboratory testing and industrial use. The SNR has been calculated from properties of the detector and optics. The differences between experimental and simulated results are 3 % at maximum. This is a well acceptable difference.

Table 2: SNR in LWIR HS camera at 8 µm with the blackbody target at different temperatures. Data is for one pixel and no averaging or binning is performed. Simulated values base on properties of the optics of the sensor and noise characteristics of the detector.

Target temperature (K)	Experimental SNR	Simulated SNR
296	36	37
323	63	61
373	133	130
423	237	231
473	370	365
523	538	531
573	748	724

An example of an application is shown in figure 6. The measurement was done using a linear scanner with illumination. The targets were geological samples and they were illuminated by quartz heaters. Illumination geometry is diffuse reflection at 45 degrees angle between illumination source and line of sight of measuring instrument. The measurements have been treated as normal reflection data, using a diffuse mirror reflection from heater rod as a “white” reference and a room temperature plate as “dark” reference. The data has then been normalized between these values at each wavelength.

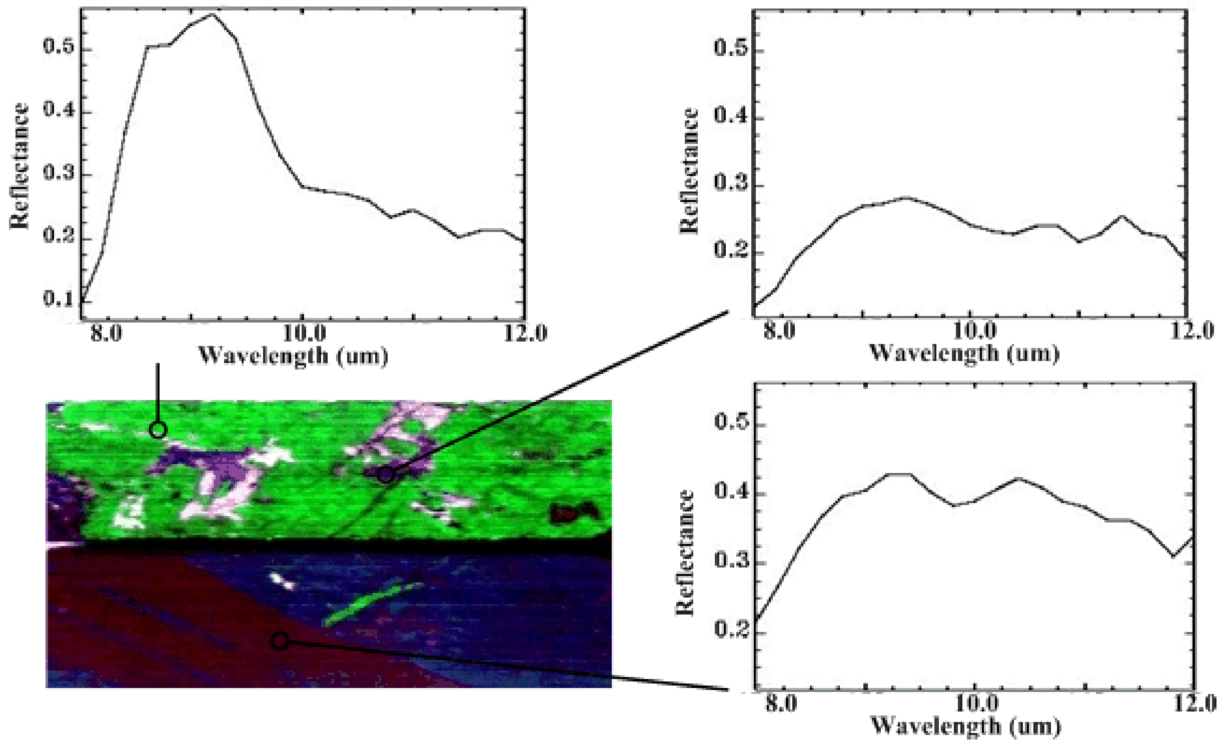


Figure 6: Two mineral samples scanned with LWIR HS. A quartz rod illumination was used in the measurement and examples of reflection spectra are shown. (r,g,b)-channels are (8.6 ,9.0, 10.1) µm. The index 130 is about 7.6 µm and index 150 about 11.8 µm on the horizontal axis. Reflectivity of the target is on the vertical axis. The green colour (curve on the left) represents quartz.

6. CONCLUSIONS

Hyperspectral imaging sensors AisaOWL and LWIR HS are introduced and their main performance characteristics described in this study. Both instruments base on room temperature optics. The optics is temperature stabilized in AisaOWL.

AisaOWL sensor is based on cooled MCT-detector and has highest performance with a peak SNR of 580 at 10 µm for a room temperature target. The performance in terms of signal to noise ratio (SNR) and noise equivalent spectral radiance (NESR) has been simulated. Simulations have been verified in experimental tests for LWIR HS and they agreement is good.

In radiometric measurements the quality of radiometric calibration and reliability of the results rely on proper background subtraction. The background is highly variable in thermal range optical instruments due to the instrument radiation. The stability and accuracy of background subtraction is tested and the results show that subtraction by BMC-method (background monitoring on chip) does not add significant noise to the data. The calculated background levels are stable and reproducible.

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