Advanced pushbroom hyperspectral LWIR imagers

Hannu Holma, Timo Hyvärinen, Jarmo Lehtomaa, Harri Karjalainen and Risto Jaskari
Specim, Spectral Imaging Ltd., POB 110, FIN-90571 Oulu, Finland

ABSTRACT

Performance studies and instrument designs for hyperspectral pushbroom imagers in thermal wavelength region are introduced. The studies involve imaging systems based on both MCT and microbolometer detector. All the systems employ pushbroom imaging spectrograph with transmission grating and on-axis optics. The aim of the work was to design high performance instruments with good image quality and compact size for various application requirements.

A big challenge in realizing these goals without considerable cooling of the whole instrument is to control the instrument radiation from all the surfaces of the instrument itself. This challenge is even bigger 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 any suppression, the instrument radiation can overwhelm the radiation from the target by 1000 times.

In the first imager design, BMC-technique (background monitoring on-chip), background suppression and temperature stabilization have been combined with cryo-cooled MCT-detector. The performance of a very compact hyperspectral 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 model.

The second version of the imager with an uncooled microbolometer detector and optics in ambient temperature aims at imaging targets at higher temperatures or with illumination. Heater rods with ellipsoidal reflectors can be used to illuminate the swath line of the hyperspectral imager on a target or sample, like drill core in mineralogical analysis. Performance characteristics for microbolometer version have been experimentally verified.

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. 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] Both instruments are bulky and require a lot of maintenance. There are other techniques, like Fourier Transform (FT) imaging spectrometers and chromotomographic imaging spectrometers being developed for imaging applications in the field and laboratory.[3] Longest commercial history in LWIR spectral imaging is in microscopic imaging solutions for laboratory analysis. They employ FT imaging spectrometers with array detectors of moderate resolution from 16x16 pixels to 128x128 pixels.

SPECIM is designing a family of LWIR and MWIR hyperspectral cameras for various industrial and remote sensing applications. The first LWIR spectral camera, LWIR HS, has been manufactured and tested and the first performance results are presented here. The second, higher performance camera, LWIR C, has been carefully studied and the main parts designed, and performance simulation results are presented for it. LWIR C is based on the most advanced, cooled MCT detector technique whereas LWIR HS on an uncooled microbolometer detector. The MCT detector is 10 times or even 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.

LWIR C provides the highest performance with high spectral resolution and high signal to noise ratio. It is aimed at the most demanding airborne and groundborne remote sensing applications without compromising any properties. The microbolometer camera LWIR HS is a lower cost alternative for applications, where SNR requirement is not so critical or target temperature is higher. The target may also be illuminated with a high temperature radiation source, and the image acquired in reflection mode. This approach works well in many industrial and laboratory chemical imaging applications. Also another spectral camera version, LWIR HR, with a microbolometer detector is being designed. The width of the spectral bands in HR will be 70 nm instead of 200 nm in HS. It will make HR capable of measuring narrower spectral features of solids, like minerals, plastics and many other industrial samples.

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 LWIR IMAGERS

The LWIR imagers presented here are push-broom type hyperspectral imagers. Push-broom hyperspectral camera consist of two or three functional parts: imaging spectrograph with fore lens, 2D-detector unit with camera electronics, and in the LWIR C camera, cooling and temperature stabilization system. The fore-optics can be changed.

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 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.

The resolution in the image line is 384 pixels in both cameras, as seen in Table 1, which summarizes the main specification of the cameras. LWIR C is 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 microbolometers.

Table 1. The main specifications of the LWIR C and LWIR HS cameras.

	LWIR C	LWIR HS
F#	2.0	1.0
Wavelength range	8.0 – 12.0 µm	7.8 – 12.0 (13.0) µm
Number of spectral pixels (bands)	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 control	Stabilized	None
Camera dimensions	220x200x220 (mm)	55x130x125 (mm)
Camera weight	8.5 kg	2.5 kg

2.1. LWIR C - Temperature stabilized optics with MCT detector

High sensitivity and excellent stability have been the driving design targets with the LWIR C camera. The temperature of the opto-mechanical parts 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 LWIR C camera will be very compact, as seen from Table 1.

2.2. LWIR HS - Uncooled optics with microbolometer detector

The LWIR HS spectral camera consists of an imaging spectrograph and uncooled microbolometer camera. Temperature control of the instrument is less critical with the microbolometer. Each pixel in the microbolometer basically acts as 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

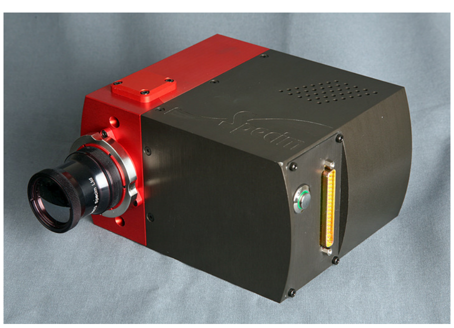


Figure1. Hyperspectral LWIR HS camera.

The background level from the instrument radiation changes with instrument temperature, but this is compensated by using the BMC calibration method. All the experimental results in this study relate to HS-version.

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. CONTROLLING INSTRUMENT RADIATION

Optical instruments working in the LWIR range suffer from a phenomenon called instrument radiation. It is radiation in the same spectral range as the radiation to be measured from the target. It is falling onto the same pixels on the focal plane array as the signal from the target. The difference is that instrument radiation is broad band radiation whereas the radiation from the target is being split to narrow bands. Thus the instrument radiation has a strong effect of raising the background level of the data. In a hyperspectral instrument operating in 300 K temperature, the instrument radiation entering the detector is typically two or three orders of magnitude more intense than the spectrally split signal from target, if the instrument radiation is not suppressed in any way. If the target is in higher temperature, this effect is smaller, but up to target temperatures of several hundreds of degrees it is significant.

The instrument radiation could result in a very small dynamic range to be available for the signal. It would limit the SNR which could be achieved in photon detectors, which are collecting charges generated by photons within the integration time (exposure time). MCT is a photon detector, whereas a microbolometer is not. 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, like MCT and microbolometers do not need cooling and they also do not suffer from instrument radiation to the same extent as MCT.

There are means available to reduce the instrument radiation. The most common techniques 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.

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 radiometrically 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.

4. CALIBRATION PROCEDURES

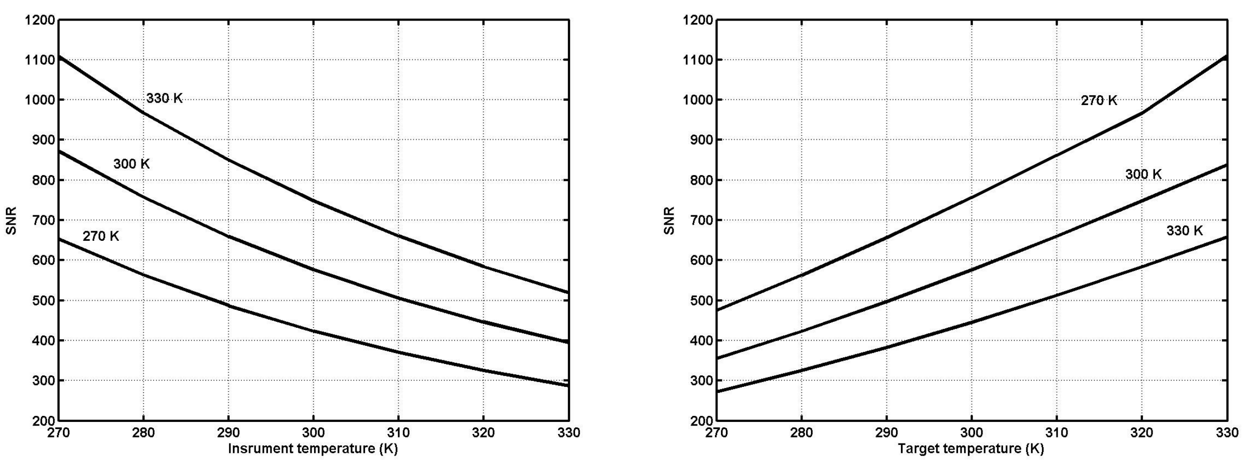
In addition to BMC calibration, there is a need in LWIR spectral imagers for similar calibration routines as for instruments in other wavelength ranges, i.e. VNIR and SWIR. These routines include wavelength calibration and radiometric calibration.

Spectral lamps or other spectral peak sources are not available in LWIR range. This arouses a need for using 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 cuvettes. 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.

5. PERFORMANCE EVALUATION OF LWIR C

The performance of the LWIR C design has been estimated using Specim's spectral camera simulation models. The models 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.



a) b)

Figure 2. 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.

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

Table 2. The main performance properties of LWIR C spectral camera. Both instrument and target are at 300K temperature.

	SNR	NESR (mW/m^{2}srµm)	NETD (K)
8 µm	450	21	0.13
10 µm	580	18	0.12
12 µm	215	43	0.37

6. PERFORMANCE TESTS OF LWIR HS

Three different experiments have been performed to illustrate and verify the properties of the LWIR HS camera. In the first experiment the blackbody target measurements were done with several target temperatures between room temperature and 573 K. This data has been used to characterize the sensitivity and SNR of the instrument.

The second and third experiments were different scanning experiments. They were performed to show the capabilities of the instrument in two special application cases: One was scanning measurement of a scene at close to room temperature, and the other was imaging an illuminated geological sample in reflection mode, with illumination at the table scanner.

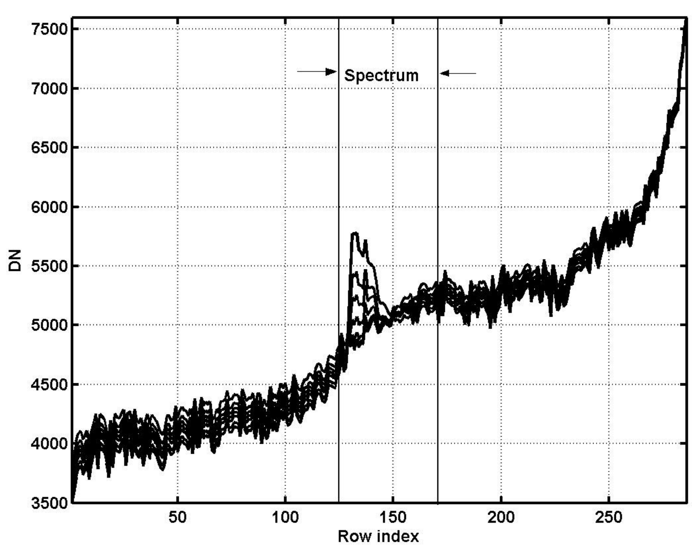


Figure 3. The raw data is plotted along the column at the middle of field of view is plotted. A set of curves from the blackbody at different temperatures between 296 K and 573 K are show without separation.

6.1. Blackbody measurements

The data that is used in this section was acquired from a calibrated blackbody radiator. The measurements were done with fore-optics of the spectral camera close to the blackbody so, that the whole field of view was filled. A series of images was taken from the blackbody at different temperatures. The starting temperature was room temperature 296 K and measurements were done at every 25 K up to 573 K. 100 frames were acquired at each temperature. Also a set of BMC-calibration images from a cold reference target was taken.

The raw data of the measurement results are illustrated in the figure 3. The data of a column at the center of the image are plotted to show the total signal variation along spectral direction of the image. Curves from all of the different temperatures are plotted and this total signal includes the signal from the target as well as the contribution from instrument (background).

The target signal is the bump in the curves at the middle of the figure ("spectrum"). The height of this actual target signal feature is smaller than variation of the total signal along the column. Also the variation from pixel to another is high. This results that the actual signal is hardly visible in the raw data image before background subtraction.

The signal comes apparent when background subtraction is done. The subtraction was performed using BMC technique. Subtraction removes the pixel to pixel variation almost fully and sets the base level of all the curves to the same. Now the zero signal level is the radiation level of the 0 K temperature target. The results are shown in the figure 4. The only operations done are the averaging of the 100 frames for each temperature and background subtraction using BMC technique.

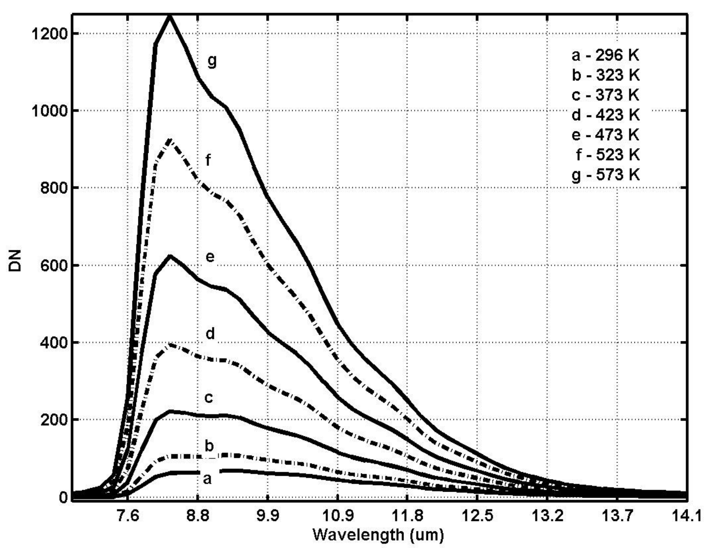


Figure 4. The background subtracted data as a function of wavelength. Each profile is one column at the center of the spectral image, and only the data from rows (rows 125 to170) which correspond to the calibrated spectral range is plotted.

The frame to frame noise (noise of one pixel data between the frames) is determined in order to make possible to find the signal to noise characteristics of the instrument. The noise is presented in Figure 5 for two detector rows. Row 30 lies well outside the image area and does not get a signal from the target. The row 130 is about the row of the maximum signal. The standard deviation of the data values is taken as noise here and it is plotted for each of the pixels of these two rows. There is not any difference depending on the signal level. This also means that if signal doubles, also SNR doubles. It can be seen in Figure 6. It shows the SNR with the same blackbody target at various temperature. Table 3 summarizes the SNR at different target temperatures at 8 µm wavelength.

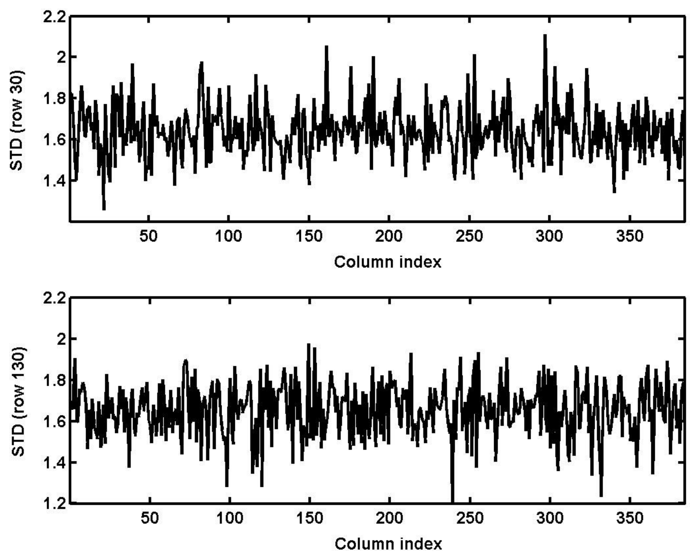


Figure 5. The frame to frame noise of each pixel in two different lines of the detector is shown. The noise is the standard deviation of the signal of a single pixel in 100 frames acquired during measurement of 473 K blackbody target. Upper panel shows the standard deviation of the pixels of row 30 and lower panel in row 130. These rows correspond to no-signal and maximum signal conditions.

Table 3. 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.

Target temperature (K)	SNR
296	36
323	62
473	130
423	230
473	365
523	540
573	730

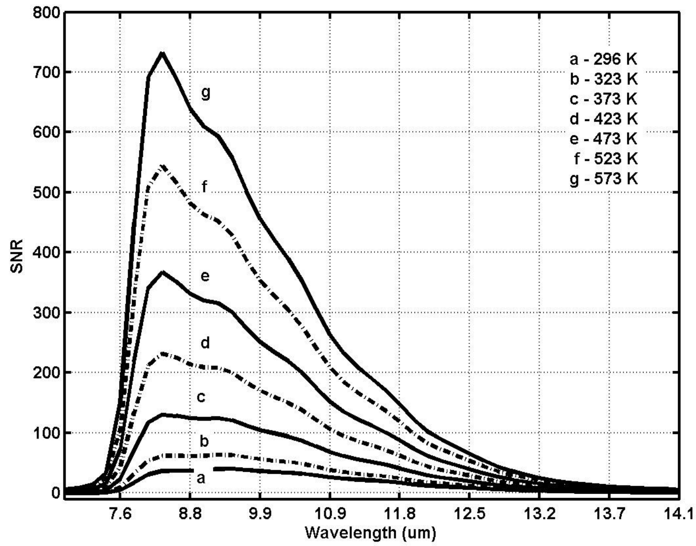
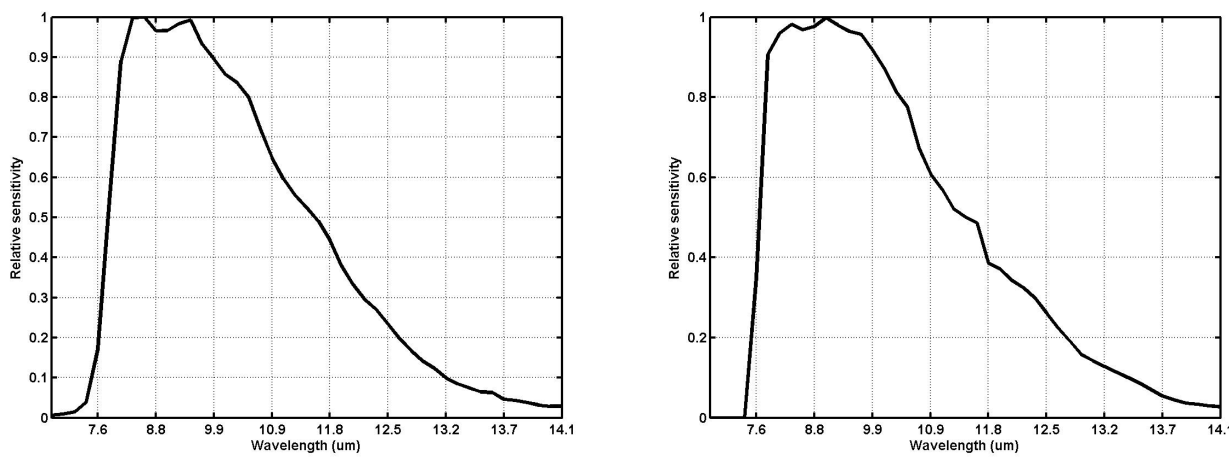


Figure 6. SNR in LWIR HS with the blackbody target in different temperatures.



a) b)

Figure 7. The relative spectral sensitivity of the LWIR HS instrument. Curve at the panel *a)* has been calculated from the data of the figure 6. The curve at the panel *b)* has been simulated from the instrument characteristics. Both curves have been normalized to the maximum value of each sensitivity curve.

The measured sensitivity curve in Figure 7 has been derived from the data by dividing the background subtracted and 0K – referenced data (Figure 4) by blackbody radiance. The data from the blackbody at 573 K target has been used in the calculation. The simulated curve on the right hand side panel was derived from the simulation model by using detailed characteristics of the detector, optics and target as input. The measured data is in a reasonably good agreement with the simulation.

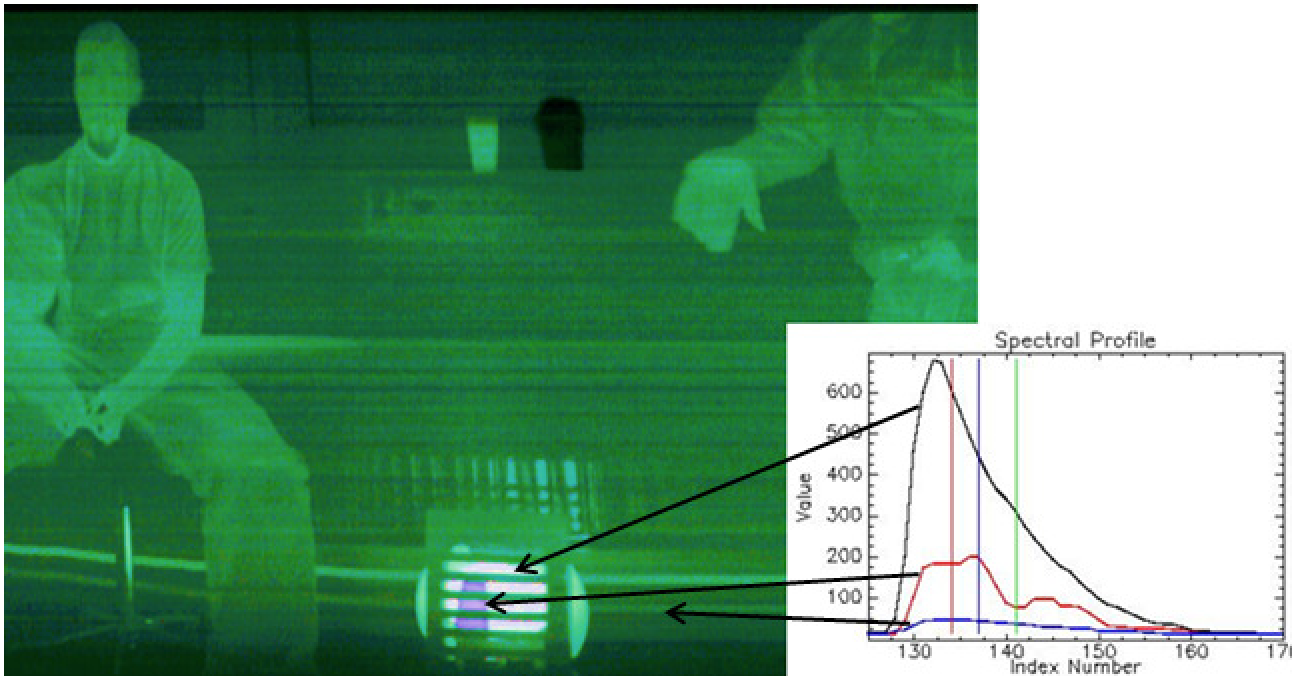


Figure 8. A view in the laboratory room scanned with LWIR HS. The spectrum of the mug is seen in the curves plot. Black curve is from the hot plate, red curve from the plastic mug and blue curve is the background on the side of the plate. Only cold image subtraction has been performed to the data. (r,g,b)-channels are seen in plot. The index 130 is about 7.6 µm and index 150 about 11.8 µm on the horizontal axis. Signal of emission is on the vertical axis. (r,g,b)-channels are (143,136,131). 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.

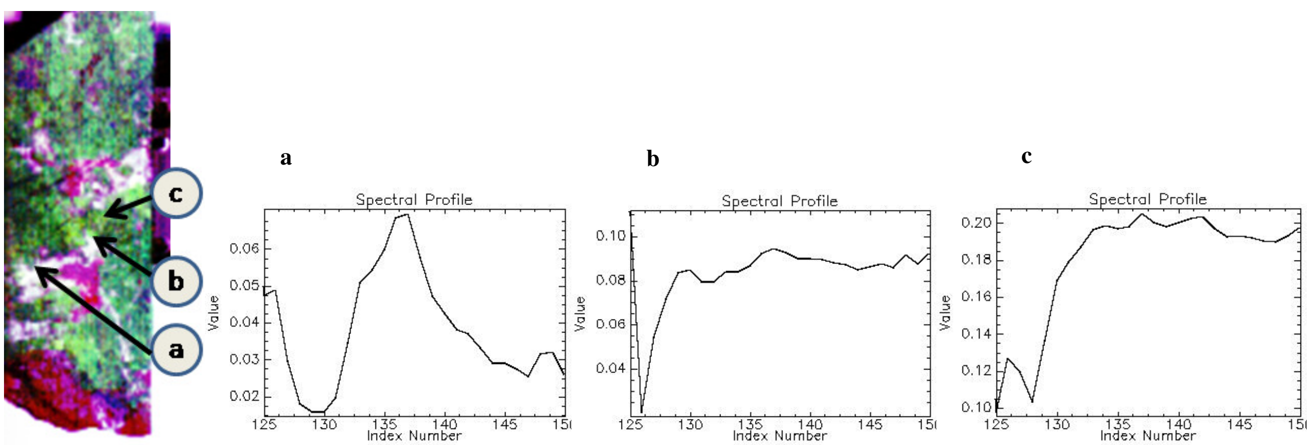


Figure 9. A mineral sample scanned with LWIR HS. A quartz rod illumination was used in the measurement and examples of reflection spectra are shown. (r,g,b)-channels are (143,136,131). The index 130 is about 7.6 µm and index 150 about 11.8 µm on the horizontal axis. Reflectivity of the target is on the vertical axis.

6.2. Scanning experiments

Figures 8 and 9 show two images scanned with the LWIR HS camera. The image in Figure 8 is scanned on a tripod by rotating the spectral camera manually during data acquisition. A cold reference target (snow) image has been subtracted from the data. The processed image shows then difference to the radiance of snow and any areas with smaller radiance than that would be seen as negative intensity (negative data numbers) in the image. The image has not been further processed.

There are a lot of details visible even in this very draft data: The frame of the windows has a slight temperature difference to the window blinds and to the wall. The electrical sockets can be resolved under the window and several reflections from the hot plate via the target grid are seen on the radiator. The upper edge of the radiator as well as pipes leading warm water in are seen as brighter horizontal stripes. The pipe is under the radiator near the floor and the upper edge is seen to the right of the man's waist. Radiator has just started to heat up and only an arrow-like feature is seen at the part where heat comes in.

The measurement in Figure 9 was done using a linear scanner with illumination. The sample was a geological sample and it was illuminated by quartz heaters. Illumination geometry is direct reflection to achieve maximum intensity with one heater only. The measurements have been treated as normal reflection data, using a 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. The illuminator was a very preliminary one, and the SNR can be significantly improved by optimizing the illumination.

7. CONCLUSIONS

Two push-broom hyperspectral LWIR imagers have been presented and characterized in this study. LWIR HS is based on a microbolometer camera, and is a completed instrument. Its performance was evaluated in a series of laboratory tests. LWIR C employs a cooled MCT detector, and it is in final design stage. Simulated evaluation results are shown for LWIR C.

Along the laboratory tests of the LWIR HS system, it was approved that the simulation model for the LWIR spectral cameras provides reliable results. The HS camera behaves very closely as predicted. Noise in the camera is very low, only about 1.7 DN. In order to achieve high quality data however requires precise correction of the large pixel to pixel variations in the microbolometer detector, which is a very dominating feature in the raw image. Precise correction requires a careful background subtraction.

Several means can be used for subtraction:

1) Two point calibration between measurements using two different temperature blackbody references. A linear fit between signal and reference radiances is done and applied to the data. This is a typical calibration procedure for thermal imagers.
2) Acquiring a cold blackbody reference, that is subtracted from the data as a dark reference. If the reference is not colder with spectral radiance smaller than features in the target, negative signals appear in the data.
3) Applying the developed background-monitoring-on-chip (BMC) technique for monitoring the instrument radiation level at the detector and then performing the background subtraction using that.

The BMC technique is the only means to compensate instrument temperature variations during the measurement. With it the shift of the background level due to the changes in the instrument temperature are suppressed very well. BMC technique can also be used with the other two subtraction methods to improve the data quality.

Though the LWIR HS camera provides feasible performance with room temperature targets, it is best suited to imaging targets in higher temperatures and for applications where the sample is illuminated and imaged in reflection.

The simulated performance of LWIR C is very good and meets the design goals. Its performance in terms of NESR and SNR will be 10 times or more better than that of the uncooled LWIR HS camera, and will meet the requirements for outdoor remote sensing in the field and from the air. Still the instrument construction will be very compact and require low maintenance only.

REFERENCES

[1] Kirkland, L. E., K. C. Herr, E. R. Keim, P. M. Adams, J. W. Salisbury, J. A. Hackwell, A. Treiman, First Use of an Airborne Thermal Infrared Hyperspectral Scanner for Compositional Mapping, *Remote Sens. Environ. 80*, 447–459, (2002).
[2] Mares, A.G., Olsen, R.C., and Lucey, P.G., LWIR Spectral measurements of volcanic sulfur dioxide plumes, Proceedings of the SPIE, Volume 5425, pp. 266-272 (2004).
[3] Chamberland,M., Belzile, C., Farley, V., Legault, J-F., and Schwantes, K., Advancements in field-portable imaging radiometric spectrometer technology for chemical detection, Proc. SPIE, Vol. 5416, 63 (2004).
[4] Dereniak,E.L. and Boreman, G.D., Infrared Detectors and Systems, John Wiley & Sons, (1996).
[5] Kruse, P.W., Uncooled Thermal Imaging, SPIE Tutorial Texts in Optical Engineering Vol. TT51, (2001).