New Compact High Performance Cooled and Uncooled LWIR Hyperspectral Sensors

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Abstract

Several chemical compounds, like many minerals, have their strongest spectral signatures in the thermal region (3 to 12 µm), and this information is often not available in the visible and shortwave infrared hyperspectral images. Two compact LWIR (8-12 µm) push-broom spectral cameras have been developed in order to make thermal hyperspectral imaging available for industrial, outdoor and airborne applications. The first imager employs state of the art cooled MCT detector array with innovative means to minimize and handle instrument radiation without deeply cooling the optics. The imager provides high sensitivity and spectral resolution (NESR better than 25 mW/(m^2·sr·µm) with 84 spectral bands in the 8-12 µm region) in a very compact instrument (22x18x28 cm, 13.5 kg).

The second imager is based on an uncooled microbolometer array and it provides a low cost solution for industrial applications where the thermal signal can be increased by illuminating the target and

measuring the image in reflection mode. Both hyperspectral cameras have been demonstrated to produce valuable information in mineralogical mapping of geological samples. The cooled camera has proven its potential in gas leak detection on ground and from airborne platforms.

Keywords: Hyperspectral imaging, hyperspectral sensor, LWIR, infrared, thermal, spectral camera, pushbroom, airborne, chemical imaging, gas leak, methane

1. Introduction

The performance of hyperspectral cameras in VIS (380-800 nm), VNIR (380-1000 nm) and SWIR (1000-2500 nm) regions has developed significantly in the last years, and at the same time their reliability, compactness and cost has become affordable for a growing number of industrial, biomedical, chemical and remote sensing applications. Thermal spectral region can provide information which is not available in the VIS to SWIR region, because several materials (chemical compounds) have their most distinctive and strongest spectral feature in the MWIR (3-5 μm) and/or LWIR (8-12 μm) spectral range. By using thermal hyperspectral imagers, a broader range of chemical compounds could be detected, identified, mapped and sorted. It is known from spectroscopy that many molecules have their strongest primary absorption feature in the LWIR and accordingly higher detection accuracy and sensitivity can be obtain there than by using corresponding overtone absorption bands in the VNIR and SWIR regions.

With the increasing military and civilian interest in thermal spectral imaging, instrument suppliers are now developing Fourier Transform (FT) and chromotomographic imaging spectrometers. They both are 2-dimensional imagers which collect the hyperspectral datacube in a period of time, typically in 0.1 to

10 seconds.[1,2] The use of these instruments is limited to imaging a stationary target from a stationary platform. Imaging moving targets (like an industrial process line), live outdoor scenes and airborne remote sensing applications require a push-broom type spectral imager which collects all the spectral data simultaneously. The compact thermal push-broom hyperspectral imagers which can provide good performance and usability have been missing from the market. The SEBASS instrument (Spatially Enhanced Broadband Array Spectrograph System) has practically been the only high performance push-broom LWIR hyperspectral imager, and has become a 'golden standard' in airborne and other remote sensing spectral imaging experiments in the LWIR.[3,4,5] Although of high performance, SEBASS is far from an easily manageable commercial instrument as it requires special expertise in its operation and maintenance, and is bulky and expensive. Second push-broom thermal hyperspectral imager currently available is TASI (Thermal Airborne Spectral Imager), which also is very bulky and substantially falls behind SEBASS in terms of sensitivity, signal-to-noise ratio and spectral resolution.[6]

SPECIM, Spectral Imaging Ltd., has designed and implemented a family of compact MWIR and LWIR push-broom hyperspectral cameras for various industrial and remote sensing applications. This paper gives an overview of the LWIR imagers and their performance, and presents results from application experiments.

The detector type largely determines the performance of a thermal hyperspectral camera and the applications where it can be used. SPECIM has developed and launched to the market two LWIR hyperspectral cameras based on a low cost uncooled microbolometer focal plane array (FPA) and on a most advanced deeply cooled Mercury Cadmium Telluride (MCT) FPA. The MCT FPA is more than 10 times sensitive than the microbolometer. The cooled camera is designed for most demanding airborne and ground remote sensing applications, like gas leaks detection and mineralogical mapping. The microbolometer based uncooled camera is a lower cost alternative for applications, where target/background temperature difference (emission signal) is higher, or the target can be illuminated with a high temperature radiation source, and the image acquired in reflection mode. The latter approach works well in many industrial and laboratory chemical imaging applications.

The most common performance parameter with thermal IR cameras is traditionally NETD (Noise Equivalent Temperature Difference). However, this figure of merit is not well applicable to spectral instruments, because the signal depends on both the temperature and spectral emissivity of the target. The most appropriate figure of merit for a thermal 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 SNR (Signal-to-Noise Ratio) once the spectral radiance of the target is known.[7,8]

This paper first addresses the issue of radiation emitted by the instrument itself (instrument radiation) and how it is handled in the two LWIR hyperspectral camera designs presented, the camera based on a high sensitive cooled photon detector and the camera employing a low cost uncooled microbolometer array. The camera designs and constructions as well as results from performance measurements in the laboratory are presented. Finally results from application demonstrations in mineral identification and mapping and in gas leak detection are shown and the industrial applicability is discussed.

2. Instrument radiation – a challenge for a thermal hyperspectral imager

Electro-optical instruments working in the thermal region suffer from a phenomenon called instrument radiation. It is radiation emitted by the instrument itself in the same spectral range as the radiation 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 split by the spectrometer to narrow spectral bands. In a hyperspectral instrument operating in 300 K temperature, the instrument radiation entering the detector pixels is typically two or three orders of magnitude higher than the spectrally split signal from the target, if the instrument radiation is not suppressed in any way. If the target is in a higher temperature, the relative effect is smaller, but up to target temperatures of several hundreds of degrees Celsius, the instrument radiation is significant.

The instrument radiation is particularly harmful to any photon detector, like an MCT detector array, because it will saturate the pixel well capacity and leave no dynamic range for the target signal. A microbolometer has a different operational principle and does not suffer from instrument radiation as severely as a photon detector. In a microbolometer, the pixels settle down to heat transfer equilibrium with the target and surroundings. The pixel temperature is then read from the changes in the pixel's temperature dependent resistance. This means that there is not such a saturation effect as in a photon detector.

The instrument radiation must be reduced by some means in a photon detector instrument. The most common technique is to cool down the opto-mechanics. It is basically a straightforward approach, but makes the instrument opto-mechanical design challenging, the instrument structure bulky and increases maintenance requirements. SPECIM has taken a totally different approach where a specific optical cold filter is integrated in the detector dewar. First, the filter blocks out practically all the background radiation outside the instruments active spectral region and secondly it also suppresses majority (approximately 95%) of the broadband instrument radiation within the active spectral region. This approach, together with precise stabilization of the instrument optics to a temperature close to the typical operational ambient temperature (like 22° C), is applied in the MCT photon detector imager presented in this work. This kind of temperature stabilization is much easier to implement in a compact and maintenance-free construction than in a deeply cooled optics.

3. Compact push-broom LWIR hyperspectral imagers

The major requirements for LWIR hyperspectral imagers depend on the user market and application:

1. Military and security applications, either surface or airborne, require the highest sensitivity because the emitted signals are low from targets in normal ambient temperature and high SNR is required for reliable target, change or chemical detection.

2. Industrial applications are cost sensitive and a lower sensitivity camera can be applied as the targets are hotter in many industrial processes, or the measured signal can be made higher by illuminating the sample with a high temperature source.

In all these application areas either the target (like an industrial process line) or the camera platform (like an aircraft) is in continuous movement. Only a push-broom type hyperspectral imager is able to produce spectrally and spatially pure data in these conditions. The LWIR hyperspectral imagers presented here are push-broom type imagers and they consist of three functional parts: a fore objective lens, imaging spectrograph, and 2-dimensional FPA with camera electronics. The imaging spectrograph in both imagers employs SPECIM's proprietary design, which is schematically shown in Figure 1. The design combines both reflective and refractive optics in a way that their best properties are optimally utilized to achieve superior optical performance in a compact device. The push-broom camera acquires a spatial line image at a time. The imaging spectrograph diffracts the line image to its spectral components (bands) and the 2-dimensional FPA behind the spectrograph records the line image at all the contiguous spectral bands simultaneously. Thus the spectral data from a push-broom imager is insensitive to camera and target movement.

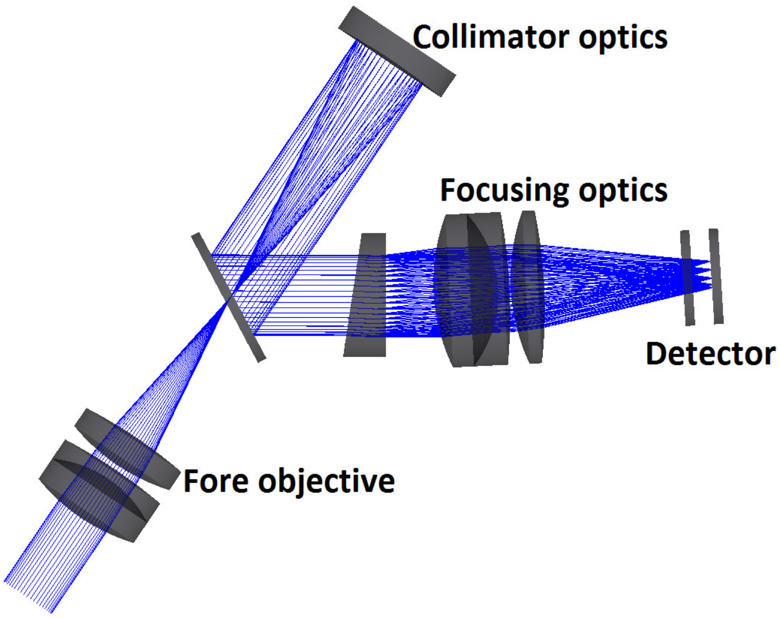


Figure 1. Schematic optical design of the imaging spectrograph in SPECIM's LWIR hyperspectral cameras. The diffracting element is before the focusing optics.

Figure 2. The cooled spectral camera LWIR C (a), and uncooled spectral camera LWIR HS (b).

	LWIR C	**LWIR HS**
Field of view	24°	30°
F#	2.0	1.0
Wavelength range	8.0 – 12.0 µm	7.8 – 12.0 µm
Number of spectral pixels (bands)	84	22
Number of spatial pixels	384	384
Spectral resolution	100 nm	400 nm
Spectral sampling	48 nm	200 nm (mean)
NESR @10µm	15 mW/(m^{2}srµm)	160 mW/(m^{2}srµm)
Detector type	MCT	Microbolometer
Spectral sampling	48 nm	200 nm (mean)
Instrument temperature	300 K (stabilized)	300 K
Detector temperature control	57 K (cryo-cooled)	300 K
Camera dimensions	220x175x280 (mm)	55x130x125 (mm)
Power consumption	< 200 W	< 4 W
Operational temperature range	+5 - 40°C	+5 - 40°C

Table 1. The main specifications of the cooled (LWIR C) and uncooled (LWIR HS) hyperspectral cameras.

The main specifications of the two thermal hyperspectral cameras presented in this paper are summarized in Table 1 and pictures of the cameras are shown in Figure 2. The block diagram of the cooled LWIR hyperspectral camera is presented in Figure 3. The imager employs the most advanced custom made MCT detector array, which operates at 55 K, and provides outstanding sensitivity across the broad spectral range of 7.6 to 12.5 μm with high pixel well capacity (>10 Me^-) and extraordinary low dark current. Dark current is approximately 0.2 Me^-/ms (4 times lower than in a traditional very long wave infrared MCT material), meaning that dark current only fills less than 5% of the pixel's dynamic range with typical operational exposure times. A special custom cold filter is integrated in the detector dewar to suppress the instrument radiation to a small fraction. The temperature in the imaging spectrometer is precisely stabilized, by using a thermo-electric solution, to +22 C to minimize variation in the instrument radiation. The camera includes a shutter, and an automatic pixel-to-pixel offset correction is done before each data acquisition session. This design eliminates the need to deeply cool down the optics temperature, as the cold filter suppresses the instrument radiation to a level which corresponds to radiation signal emitted by an instrument at ca. 183 K (-90 C) temperature. This approach has made it possible to build the first highly sensitive compact thermal spectral imager of dimensions 285x200x175 mm and weight of 13.5 kg only. It is compact enough for easy use in the field and installation in various aircraft, including mini-size UAVs. Still its performance in terms of NESR and spectral resolution is close to that of the SEBASS instrument, which has deeply cooled optics.

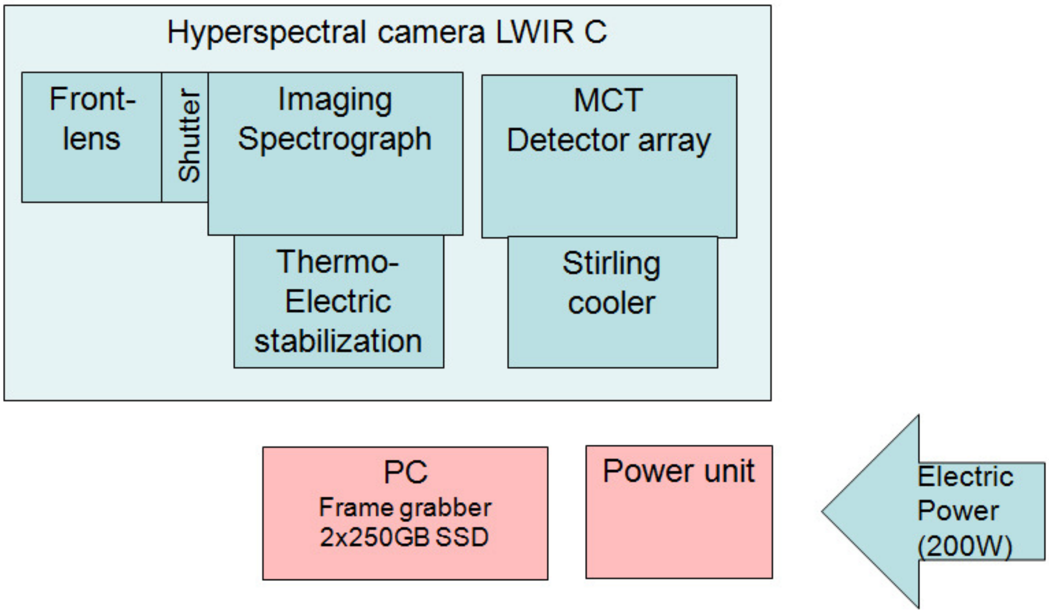
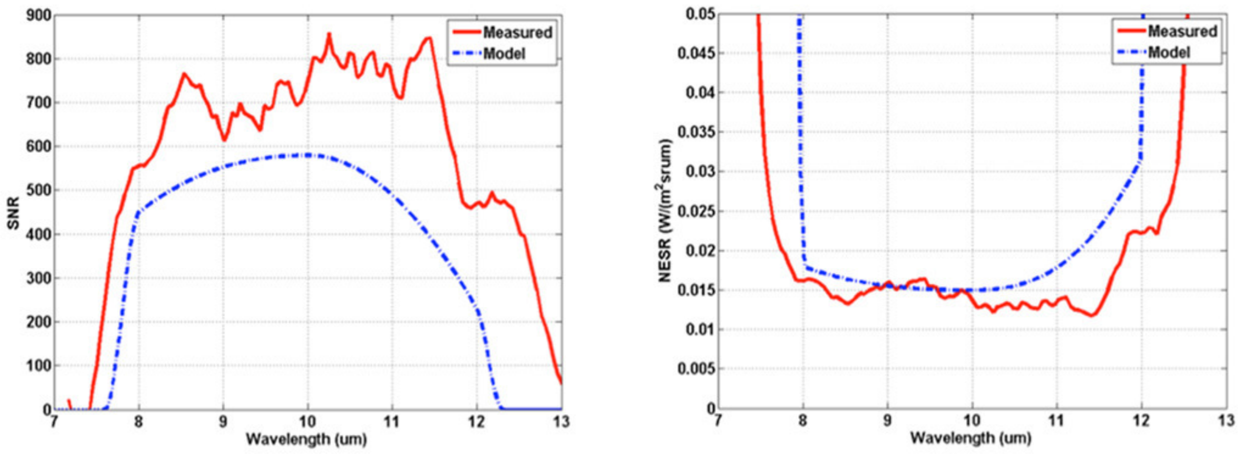


Figure 3. Block diagram of the cooled LWIR hyperspectral camera.

The performance of the cooled imager has been thoroughly characterized. The spectral SNR and NESR, with the peak signal filling 90% of the well capacity, is shown in Figure 4 together with the simulated values. Both figures of merit are excellent over a broad spectral region from 7.6 to 12.5 um. The NESR is at the level of 15 mW/(m^2·sr·µm) from 8 µm to 11.5 µm and below 25 mW/(m^2·sr·µm) through the whole design wavelength range of 8 µm to 12 µm. These NESR values correspond to spectral noise equivalent temperature difference (NETD) of 0.13, 0.11 and 0.25 K at 8, 10 and 12 µm, respectively.



a) **b)**

Figure 4. SNR (a) and NESR (b) in the cooled spectral camera LWIR C at the middle of the field of view as a function of wavelength. Both the simulated and measured curves are shown. The data has been averaged by two spectral pixels.

The main design target for the second thermal spectral camera has been low cost with sufficient performance for high temperature emission measurements as well as laboratory and industrial applications in reflectance mode (by illuminating the target). The camera employs an uncooled microbolometer detector array with an imaging spectrograph where the numerical aperture is matched to that of the microbolometer detector (F/1.0) in order to maximize the radiation collection efficiency and sensitivity of the camera. Compared to the cooled camera, the spectrograph in the uncooled camera is designed to provide broader spectral band per pixel in order to collect more energy per pixel. Still the lower sensitivity is the most significant performance trade-off with the microbolometer array. Temperature control of the instrument is less critical in a microbolometer instrument, because the detector does not saturate. Nor does the instrument radiation deteriorate the SNR in a microbolometer instrument. Still variations in instrument temperature influence the background signal level, and these changes are corrected in data processing. As both the optics and detector are uncooled, it keeps the camera structure extremely compact and power consumption low, as presented in Table 1. The spectral SNR in the uncooled camera with various blackbody target temperatures is presented in Figure 5. For the SNR determination 100 images from a blackbody source were acquired with each black body temperature shown in Figure 5. Standard deviation in the pixel signals over the 100 images was calculated and SNR was determined as the ratio of the standard deviation to the mean signal with each source temperature, respectively.

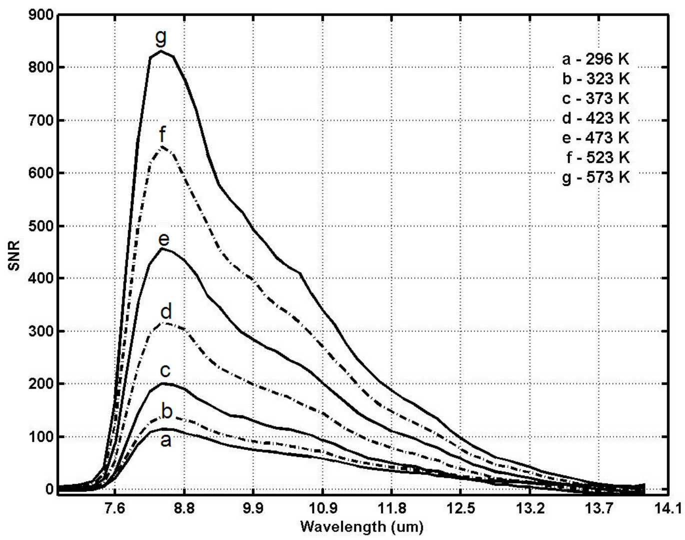


Figure 5. SNR in the uncooled spectral camera LWIR HS with different blackbody target temperatures (a to g). Zero signal level refers to 0 K target.

4. Mineral mapping using LWIR spectral imaging

In industrial and laboratory applications the thermal signal can be made higher by illuminating the sample from a high temperature thermal light (heat) source, and measuring the reflected signal. Figure 6 presents an experimental installation which consists of a linearly moving sample table, two thermal light sources and the cooled LWIR hyperspectral camera. A quartz heater bar with a cylindrical gold coated reflector is used to form a line light source. Two line light sources are installed to illuminate the sample from both sides of the imaging field of view. The measurements are treated as normal reflection data, using heater rod reflection from a diffuse metal surface as a “bright” reference and unilluminated stainless steel plate in room temperature as a “dark” reference. The sample data is then normalized between these reference values at each wavelength.

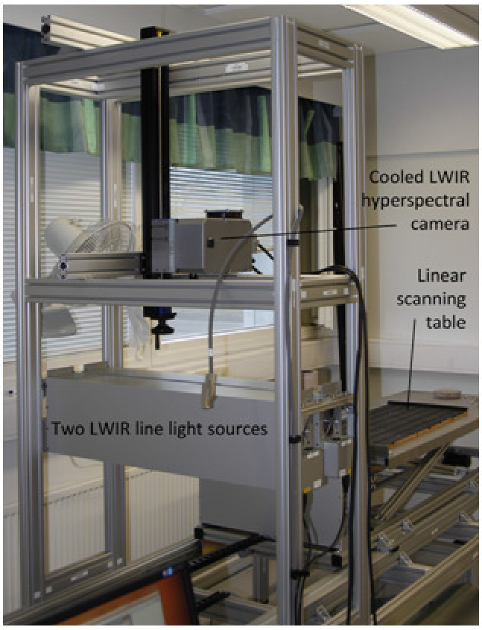


Figure 6. LWIR scanning setup for imaging experiments in reflectance mode

Several industrial applications have been studied, including the following:

- Mineral identification and mapping of geological samples, like drill cores and rock pieces. They can be rapidly mapped for nearly all minerals of commercial interest with the fusion of SWIR and LWIR spectral imaging. LWIR is mandatory for the detection of minerals in feldspar, silica, calcite, garnet and olivine groups.
- Applications where strong infrared spectral absorption signatures make it possible to inspect surfaces for minute impurities, like oil residual on steel surface, surface oxidation and uniformity of thin coating layers.

Various drill core and other geological samples have been scanned with both the cooled and uncooled LWIR camera in the setup. Figure 7 shows a subset of a drill core image acquired with the cooled camera in reflection mode. The colors in the image show various classes based on identified spectral end members in the LWIR data. The data was acquired in the spectral region of 8 to 12 µm with 48 nm spectral sampling. Spatial sampling on the drill core was ca 0.4 mm, and linear scanning speed 40 mm/s. This experimental setup demonstrates an excellent SNR around 350 in the spectral data which provides reliable mineral identification and mapping.

Figure 8 shows an example where pieces of rock were scanned both with the uncooled (LWIR HS) and cooled (LWIR-C) camera in reflection mode with the same spatial resolution. Even the uncooled camera provides a reasonable SNR in the range of 30 to 100, and is capable of providing valuable information about mineral groups which may not have spectral signature in the SWIR. The higher spectral resolution and signal dynamics throughout the full spectral range of 7.6 to 12.5 µm in the cooled camera is clearly shown in the quartz and feldspar spectrum, which can easily be distinguished from each other. Based on preliminary studies, the cooled camera may even be able to separate placioglase feldspars based on the composition. It can have significant value in mineral exploration and in optimizing commercial mining operations.

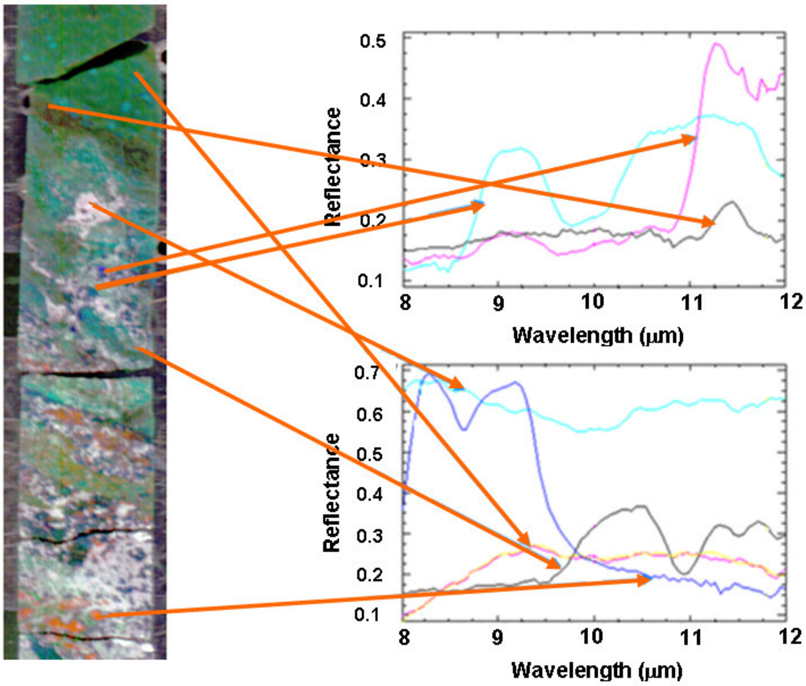


Figure 7. A piece of a classified drill core image which was scanned with the cooled LWIR spectral camera with 0.4 mm spatial resolution. Spectra on the top, cyan: clinopyroxene, black: carbonate, magenta: unknown mineral. Spectra at the bottom, cyan: sulphite, black: garnet, yellow: phylosilicate (most likely), blue: quartz.

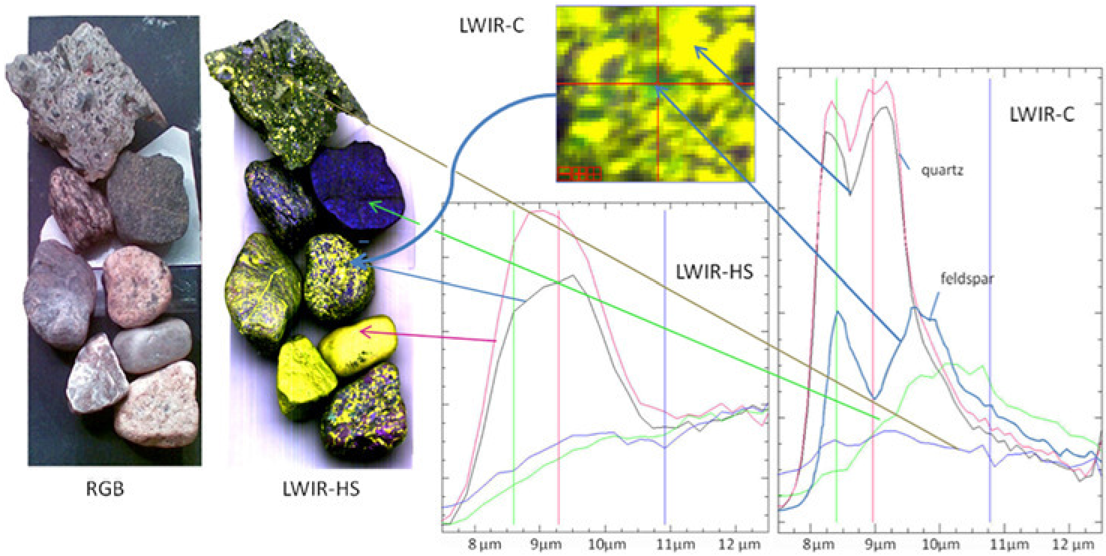


Figure 8. A set of stones were scanned with the uncooled LWI-HS and cooled LWIR-C spectral camera in reflection mode. The LWIR-C produces higher spectral resolution, leading to much more accurate mineral identification. In the zoomed LWIR-C image, the quartz and feldspar spectra are clearly recognizable.

Figure 9 presents a system (SPECIM SisuROCK) which is specifically designed for rapid high throughput mineral mapping in full size drill core boxes with spatial resolution of 2 mm. The sample tray is capable of taking a box of 150 cm long and 64 cm wide. The camera and illumination compartment can include two hyperspectral imaging setups, like SWIR and LWIR for simultaneous scanning in both regions. A full drill core box is scanned in 15 to 30 seconds, providing extremely high data collection capacity of 500 to 1000 m of core per work shift. The system is also capable of working in a very high spatial resolution mode for analyzing single core with 0.2 mm spatial resolution.

Figure 9. An industrial hyperspectral imaging scanner, SisuROCK, for rapid mineral mapping in drill cores and other geological samples.

5. Detection of gas leaks using LWIR hyperspectral imaging

Gas leaks from industrial plants and the worldwide natural gas distribution infrastructure pose threads to the environment and population security. Thermal hyperspectral imaging provides a rapid, cost-efficient remote sensing technique to monitor industrial sites and the large scale natural gas distribution network.

Figure 10. The cooled LWIR-C camera installed on a rotary stand for outdoor scanning.

The high spectral and spatial resolution, high image rate and compact size of the cooled LWIR camera presented in this paper provide unique capability to detect and monitor methane, ammonium and several other gases on the ground and from various airborne platforms. Several gas detection experiments have been carried out using a scanning setup where the cooled camera was installed on a rotary stand, as shown in Figure 10.

Figure 11 shows an experiment where the image was acquired in clear sky conditions with an outdoor temperature of ca -10° Celsius. Data was acquired with 48 nm sampling and 100 Hz image rate, and was processed to radiance (W/m^2 sr µm) based on the radiometric calibration done for the camera in the laboratory. The image is an RGB visualization in wavelengths of 8.75 µm, 9.07 µm and 8.40 µm. The person on the left holds a clean air spray bottle in his hand, and releases a plume which spreads to the right. In addition to clean air, the plume also includes propellant gas, 1,1,1-2-tetrafluoroethane, which has a distinctive spectral signature in the LWIR with absorption bands at 7.69, 8.40, 9.07 and 10.29 µm. Against a warm background, the person on the right, the propellant gas is detected based on its absorption peaks in the radiance spectra (cyan spectrum in the spectral plot). Against a cold background, the building and particularly the sky, the gas plume is warmer, and the propellant gas is detected based on its emission peaks (magenta spectrum in the spectral plot).

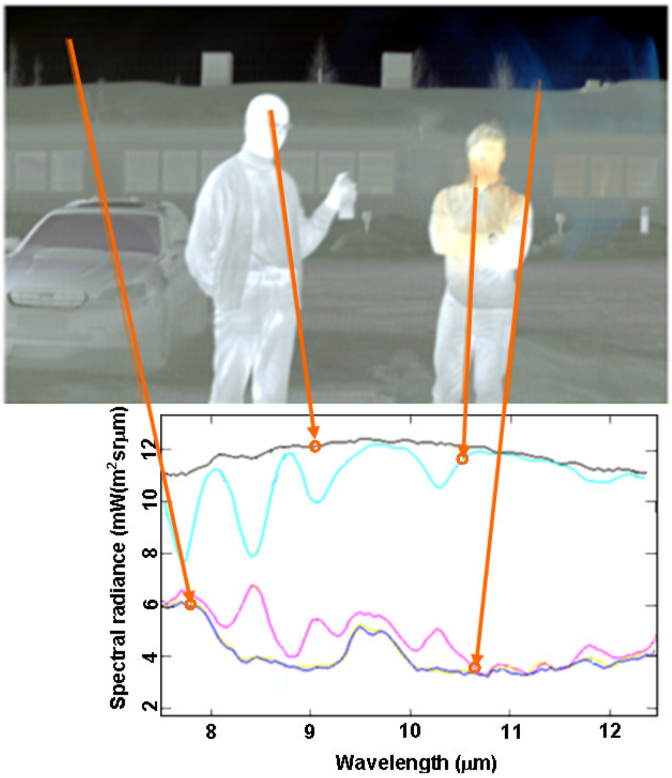


Figure 11. Outdoor gas measurement experiment with the cooled spectral camera LWIR-C in ambient temperature of -15 C. Propellant gas (1,1,1-2 tetrafluoroethane) is detected based both on its emission (magenta spectral plot) and absorption (cyan spectral plot).

Figure 12 shows another experiment where methane gas is released at the rate of 20 liters per minute. At this low flow rate the plume temperature quickly balances to the ambient temperature. The operator holds the gas nozzle in his hand in front of a black body source and the wind turns the gas flow towards the operator. The methane absorption band at around 7.7 µm is clearly seen against the black body source (black spectrum in the spectral plot) and also against the warm trousers of the operator (magenta and yellow spectrum). The image is an RGB visualization of bands at 8.25 µm, 7.70 µm and 7.65 µm, which reveals the methane flow in a reddish color. The experiment demonstrates the capability of the cooled LWIR camera to detect a fairly low methane leak of 20 l/min. By applying advanced detection algorithms, like matched spectral filter, lower detection limit can most likely be achieved.

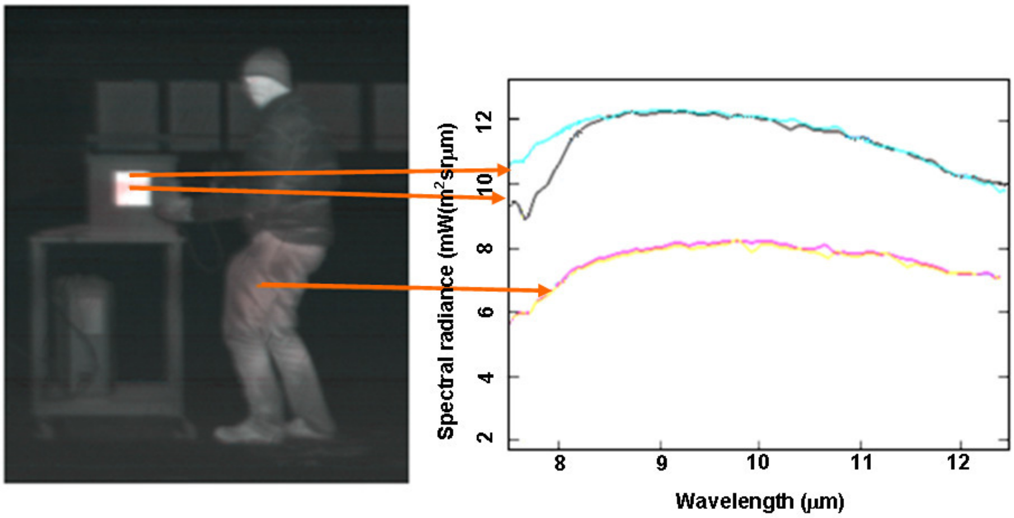


Figure 12. Outdoor methane gas detection experiment with methane flow rate of 20 l/min. Methane flow is visualized in reddish color in the scanned image. Methane absorption around 7.7 µm is clearly seen in the radiance spectrum (black spectral plot) against the blackbody surface (cyan spectral plot).

A LWIR hyperspectral airborne system, AisaOWL, has been implemented by integrating the cooled camera with a GPS/INS (Inertial Navigation System) and high capacity data acquisition computer. The system has been installed in a small fixed wing aircraft by SpecTIR LLC in the USA, and it has proved to produce high quality, geo-referenced spectral radiance data in airborne conditions.[9] A flying platform can be an efficient solution for large scale pipeline leakage monitoring. The application will require pretty high ground sampling distance, like 20 cm, which can be achieved by operating the AisaOWL system with an image acquisition rate of 100 Hz in a platform moving 20 m/s at the altitude of 180 m. A helicopter will be an optimal platform for this flying speed and altitude, and can make it possible to monitor 72 km of pipeline per hour.

Conclusions

It is shown that a highly sensitive compact LWIR hyperspectral imager can be fabricated and it does not require sofisticated maintenance and operational skills. The system can be easily used outdoors and installed in various aircraft. It is demonstrated that a more compact and low cost uncooled LWIR hyperspectral imager based on microbolometer can be fabricated and it can provide, in reflection mode, valuable information in industrial applications.

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Biographies

Timo Hyvärinen was born in Kalajoki, Finland, on April 2nd, 1957. He received the MSc and Lic.Tech. degree in optical measurement technology from the University of Oulu in 1981 and 1988, respectively. He worked for the Technical Research Centre of Finland (VTT) from 1981 till 1995, first as a scientist and then as a group leader in Optical Measuring Technologies. Timo Hyvärinen is a co-founder of SPECIM, Spectral Imaging Ltd, and worked as the Managing Director of the company since its start in 1995 till 2010, when moved to act as the Chairman, and focused his responsibility back to R&D in hyperspectral imaging.

Hannu Holma has worked in the fields of optics, spectroscopy, and instrument development for 20 years. His background is in space physics and auroral research. For the last eight years he has been responsible for SPECIM's LWIR and MWIR hyperspectral imager development.