

Thermal Infrared Multispectral Imaging of Minerals

For years, scientists have used thermal broadband cameras to perform target characterization in the longwave (LWIR, 8-12 μm) and midwave (MWIR, 3-5 μm) infrared. The analysis of broadband imaging sequences typically provides energy, morphological and/or spatiotemporal information. However, there is very little information about the chemical nature of the investigated targets when using such systems due to the lack of spectral content in the images. In order to improve the outcomes of these studies, Telops has developed dynamic multispectral imaging systems which allow synchronized acquisition on 8 channels, at a high frame rate, using a motorized filter wheel. An overview of the technology is presented in this work as well as results from measurements carried out on minerals. Time-resolved multispectral imaging carried out with the Telops system illustrates the benefits of spectral information obtained in a short period of time. Comparison of the results obtained using the information from the different acquisition channels with the corresponding broadband infrared images illustrates the selectivity provided by multispectral imaging for characterization of minerals.

Introduction

Thermal infrared (8-12 μm) imaging has been used for many years for the characterization of solid targets and gas clouds. Self-emission under ambient conditions makes thermal infrared very attractive over other spectral ranges as information can be obtained in various illumination conditions. Spatial contrasts in thermal infrared images result from temperature or emissivity differences between neighboring objects. In the case of solid targets such as minerals, contrast is typically defined relative their surroundings. The sensitivity and accuracy of modern thermal infrared systems allows measurement of very small thermal contrast, at high spatial resolution, fast frame rate and on a wide dynamic range (Figure 1). In order to retrieve the most out of imaging sequences, different image processing strategies are used. Pattern recognition within a scene commonly carried out by matching shapes/energy with thermal signature of known objects such as flares, decoys and ship plumes. Despite all these efforts, broadband thermal infrared systems bring limited information about the chemical nature of the targets. For such systems, the response of each pixel results from the sum, over a fixed spectral range, of all contributions, from all objects in a scene, regardless of their chemical nature. It is well known that most chemicals selectively absorb/emit infrared radiation at

discrete energies, i.e. very narrow spectral ranges. Consequently, the minor contributions of gas/solid targets to the overall signal recorded by an infrared detector translate into very small thermal contrasts. The reflectivity pattern of solids as a function of wavelengths (or wavenumbers) is referred to as its infrared spectral signature. For solid targets like polymers, minerals and organic and inorganic salts, both self-emission and reflection occur at wavelengths which depend on their chemical nature. Selectivity concerns rapidly arise when dealing with simultaneous detection of targets of different chemical nature. Therefore, it is very challenging to infer the nature of a target based on broadband imaging, especially when chemicals have similar spectral features. Information on the spectral dimension is typically required to achieve efficient and selective detection of targets from infrared imaging sequences. In some situation, this information should be obtained in a short period of time.



Figure 1 Telops high performance cooled infrared camera.

In order to acquire spectral information using thermal infrared cameras, tuning of the detectors' spectral response is typically achieved using spectral filters. Band-pass (BP), long-pass (LP) and high-pass (HP) spectral filters are commercially available and can readily be added in the cameras' optical path. For cooled infrared cameras, narrowband imaging can be achieved by installing a BP filter directly in the detector assembly. Cold filters provide high sensitivity, but are typically designed to address very specific applications since they cannot easily be changed (permanent) in most cases. In order to get more flexibility, interchangeable filters, at ambient temperature, can be added in the cameras' optical path. Whether the filter is cold or at ambient temperature, its spectral range must be selected with great care since no filter change can be made without stopping the acquisition and/or redoing a radiometric calibration. For this reason, filter wheel systems have gained popularity since they allow to store a selection of spectral filters readily available for acquisition. Multispectral imaging consists in acquiring multiple images of the same scene using the different spectral filters and this represents a great compromise between broadband imaging and hyperspectral imaging.¹ Spectral information can be obtained from the response of individual spectral filters, ratios, subtractions and/or combinations of multiple filters. In general, a greater number of spectral bands provide more flexibility to face challenging situations. Despite the obvious advantages of thermal infrared multispectral imaging, the low acquisition rate, i.e. spectral band rate, of most commercially available systems make their use less appealing than conventional imaging systems. In most of these systems, the filter wheel does not rotate during image acquisition. The selection and/or spectral filter change must be made between each acquisition sequence. Such operation mode is time consuming. In addition, the limited number of available spectral filters (typically 4) provides low spectral resolution, thus low selectivity.

The Telops MS-IR infrared camera series performs dynamic multispectral imaging, at a high frame rate, on 8 channels using a fast-rotating filter wheel. In order to

perform time-resolved multispectral imaging, both the filter wheel rotation and the FPA clocking are synchronized such that a single frame is recorded at each filter position. Sequences are then calibrated using in-band photon radiance (IBR) format, frame by frame, according to their respective spectral filter dataset. In order to illustrate the capabilities of this system, time-resolved multispectral imaging of various minerals was carried out using a combination of 7 spectral filters and 1 neutral density filter with the MS-IR VLW camera (very longwave 7.7-11.8 μm). The results illustrate how thermal contrast can be enhanced by selecting spectral filters which match the absorption bands of a target of interest. Multispectral imaging of a hematite (Fe_2O_3) drill core containing quartz (SiO_2) veins, iron pyrite (FeS_2) and amethyst was carried out at a frame rate of 30 Hz/channel. Within a second, spectral information about the investigated targets was obtained providing spectral information to discriminate the different targets. The rapidity at which this information was obtained clearly illustrated the efficiency of the MS-IR system developed by Telops over more conventional stationary filter wheel systems. The IBR profile correlation was applied to the multispectral imaging sequences to enhance thermal contrast based on spectral information. In each case, comparison with corresponding broadband images illustrates the selectivity enabled by dynamic multispectral imaging.

Experimental Information

Telops MS-IR Infrared Cameras Series

Telops MS-IR imaging systems (Figure 2) are high performance cooled multispectral infrared cameras available in different models covering the complete mid-infrared spectral range. The MS-IR MW (midwave, 3.0-4.9 μm) and MS-IR VLW (very longwave 7.7-11.8 μm) use 640x512 pixels InSb and 320x256 pixels MCT (Mercury-Cadmium-Telluride) focal plane array (FPA) detectors respectively.

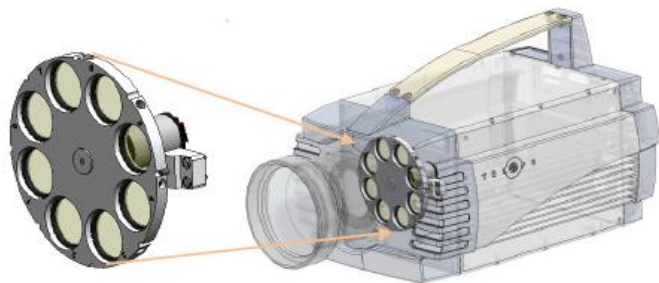


Figure 2 Telops MS-IR infrared camera

The MS-IR-HD is the midwave version which uses a high-definition 1280×1024 pixels FPA detector. The MS-IR-FAST is a fast 320×256 pixels FPA detector which allows image acquisition at the highest frame rate available. The MS-IR infrared cameras allow splitting of the scene radiance into eight different spectral bands rather than only one broadband image hereby providing spectral information about the investigated targets. The filter wheel is a fast rotating mechanism designed to maximize the camera's frame rate and can be used either in fixed or rotating mode. The filter wheel is capable of reaching up to 6000 rpm (revolutions per minute), leading to a maximum effective frame rate of 800 Hz, i.e. 100 Hz per channel. All cameras from the MS-IR series benefit from the real-time radiometric and non-uniformity correction features using Telops patented blackbody free correction method.²

Experimental Setup

In order to provide spectral information, 8 different filters were used. Channel #1 was occupied by a neutral density filter and the associated frames are representative of broadband images. Acquisitions were carried out using the full FPA frame, i.e. 320×256 pixels, using integration times ranging from 195 to 400 μ s depending on the spectral filter. The filter wheel rotation speed was set to 1800 rpm leading to an effective frame rate of 30 Hz/filter. A circular 50 mm Janos Varia lens was used for all experiments. The camera was installed at a distance of 2 m from the targets leading to a spatial resolution of 4 mm²/pixel. A hematite (Fe₂O₃) drill core contaminated with quartz (SiO₂) veins, iron pyrite (FeS₂) and amethyst minerals

were placed in oven set to 150 °C for few minutes. The minerals were then placed on a table (Figure 3) and multispectral sequences were readily recorded.



Figure 3 Visible image of a hematite drill core contaminated with quartz veins (left), iron pyrite (center) and amethyst (right).

Image Processing

Spectral filters typically transmit radiance over relatively wide spectral ranges. Radiometric calibration of multispectral cameras consists in characterizing the detector and its optical components responses against known radiance values. Therefore, the IBR procedure mostly consists in integrating the Planck curve equation over a finite spectral range, i.e. the one corresponding to each filter. The IBR of a selected target can be estimated for each filter according to its spectral emissivity for defined concentration and thermal contrast conditions. Thermal contrast can then be enhanced, for a selected target, by correlating its estimated IBR profile with measured IBR profiles of individual pixels in a scene.

Results and Discussion

Selective Absorption/Emission of IR Radiation

Multispectral imaging of minerals was carried out to illustrate how spectral information can benefit the characterization of solid targets for which the emissivity varies as a function of wavelength. As seen in the visible image shown in Figure 3, the hematite drill core appears fairly homogeneous except for a few obvious quartz veins. Hematite has no appreciable spectral features in the LWIR. Therefore, it is expected to behave like a grey body. Amethyst is a quartz variety doped with iron (Fe) molecules and its spectral emissivity pattern is similar to quartz. It should be noted that the exposed surface of the amethyst mineral in the experiment is essentially a group of «pure» quartz

crystals. The emissivity spectrum of quartz is represented in Figure 4 as well as the transmittance curves of each spectral filter convolved with the FPA detectors' spectral response.

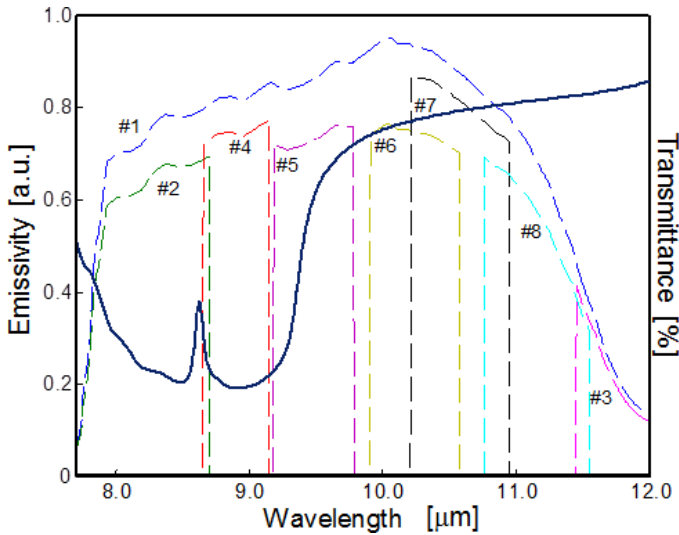


Figure 4 LWIR spectral emissivity of quartz (dark blue curve). The transmittance curves of each spectral filter used for the experiment are shown for evaluation purposes.

As seen in Figure 4, the emissivity of quartz is lower within the 7.7 – 9.6 μm spectral range, a spectral feature associated with the Si-O stretch vibration mode of quartz. For minerals (and solid targets in general), lower emissivity translates into higher reflection. In this case, irradiance, i.e. the total incident power from a hemisphere on the mineral, corresponds to self-emission from the colder walls and ceiling of the room. Therefore, quartz should appear as «colder» in this spectral range. In the 9.6 – 12 μm range, quartz is expected to behave like a blackbody source and its self-emission will be function of its temperature as expressed by the Planck equation. From Figure 4, it can be assumed that the most potent spectral bands for quartz characterization correspond to filters #2, #4 and #5. The individual response of each acquisition channel is shown in Figure 5 on a normalized scale. In order to compare the response of each individual filter with one another, each IBR was normalized with the corresponding IBR of a blackbody source set to an arbitrary temperature of 90 °C. This normalization procedure allows to evaluate, on a mutual basis, the

potential of each spectral filter to characterize a specific target.

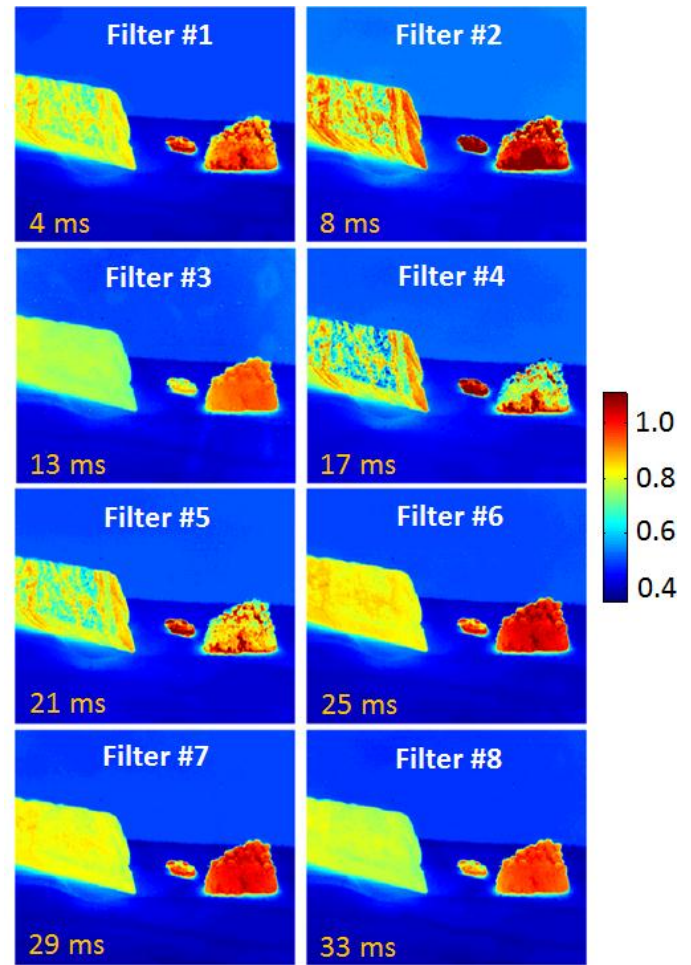


Figure 5 Normalized responses (blackbody source of 90 °C) of each acquisition channel for multispectral imaging experiment on minerals.

As seen in Figure 4, similar responses through all spectral filters were obtained for the background wall and the table. This suggests that both objects behave like grey bodies, i.e. have a constant emissivity value in the investigated spectral range. The emissivity dependency of quartz as a function of wavelength can be readily seen in Figure 4 as thermal contrast associated with quartz minerals is different in all acquisition channels. As expected, contrasts on the hematite surface can mostly be seen through filters #2, #4 and #5 as a result of the presence of quartz. From the infrared images, quartz appears to be sparsely dispersed throughout the whole hematite drill core and much more than the visible image suggests. A similar

spectral filter response trend is observed for the amethyst mineral with the exception of filter #2 where the signal is higher than expected. Evaluation of the different spectral bands through a normalization procedure is subject to contrast variations which depend on the normalization factor. As seen in Figure 7, there is a significant temperature difference between the hematite drill core and the amethyst mineral.

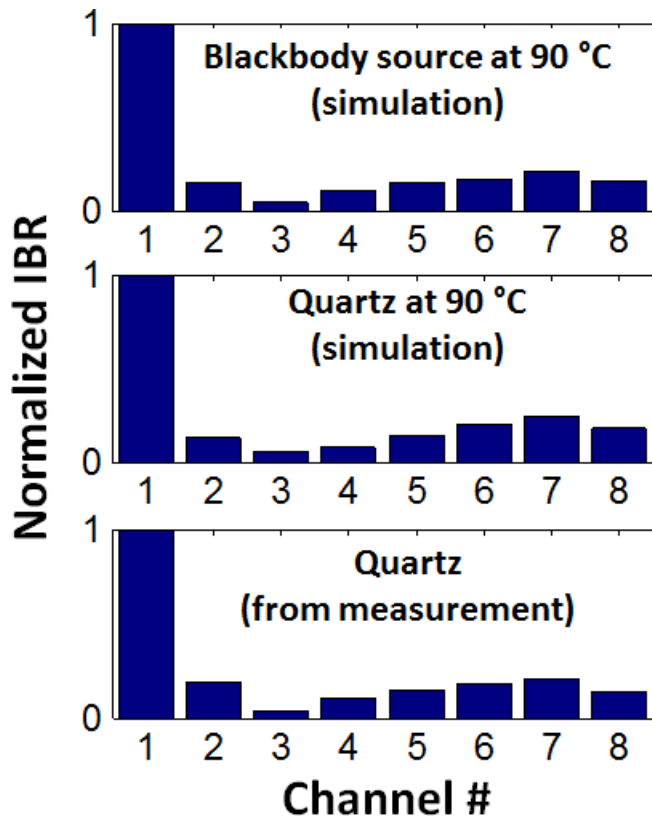


Figure 6 In-band radiance (IBR) profiles estimated for a blackbody source (top) and a warm quartz mineral (middle) both at 90 °C as well as the measured IBR profile of selected pixels associated with quartz mineral (bottom).

In-band Photon Radiance

From broadband infrared imaging, it is difficult to obtain information about the chemical nature of targets in a scene due to the lack of spectral information. As seen in Figure 5, the raw spectral information provided by the thermal contrast measured in the different channels brings some additional information about chemical nature of a target. However, one must not solely rely on the presence/absence of thermal contrast in a specific spectral channel to identify a target in a scene. The

detector response in a single channel is function of many parameters and is also subject to interfering agents. In order to enhance contrast in a scene relative to a target of interest, image correlation of its IBR profile is carried out. To illustrate this procedure, the IBR profile of a blackbody source and quartz mineral at 90 °C were estimated, according to their spectral emissivity features, and the results are shown in Figure 6. The measured IBR profile of pixels associated with quartz mineral is also shown in Figure 6. Although the differences between IBR profiles are slight, dissimilarities can be easily enhanced using a correlation algorithm.

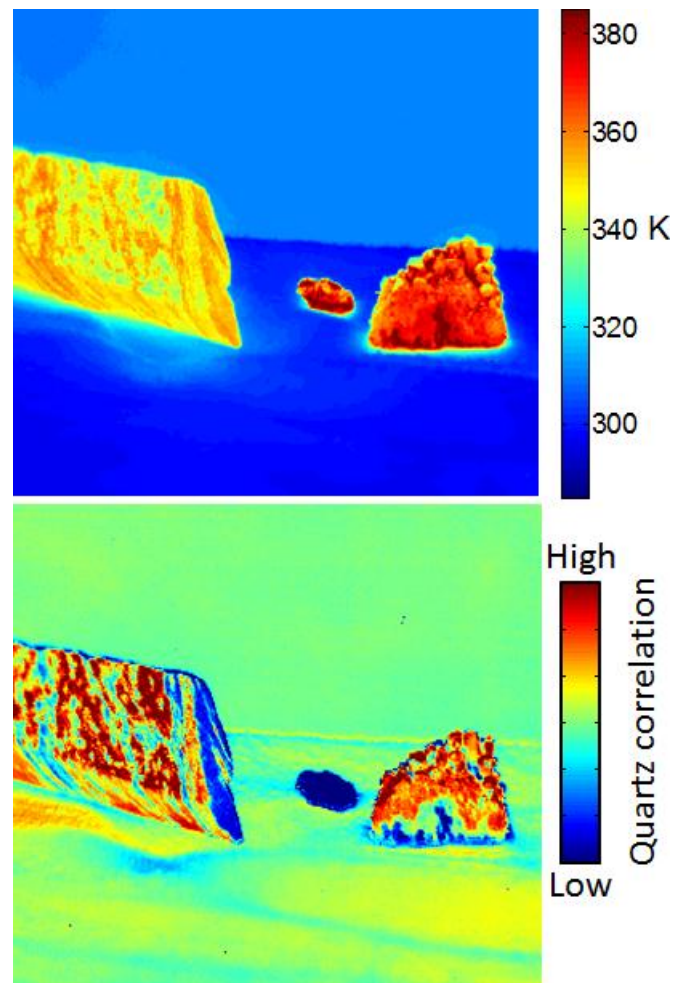


Figure 7 Radiometric temperature image (top) of the experimental setup on minerals and the corresponding correlation images (bottom) obtained from the IBR profile of quartz.

The correlation image calculated from the IBR profile of quartz is also shown in Figure 7. The contrasts in the

image are highly representative of the spatial distribution of quartz through the minerals. Multiple quartz veins can be seen on the surface of the hematite drill core. As expected, the amethyst crystals at the surface of the mineral strongly correlate with quartz IBR profile. The lower correlation obtained for the iron pyrite mineral illustrates the selectivity provided by multispectral imaging over broadband imaging. The correlation procedure also has the advantage of being much less sensitive to temperature differences between similar targets (as seen in Figure 5) for target characterization. Both the hematite drill core and amethyst minerals have the same spectral features associated with quartz, but are at very different temperatures.

The spectral information provided by multispectral imaging allows contrast enhancements based on spectral emissivity and not only self-emission. Comparison of the correlation image with the temperature image (Figure 7) clearly highlights this point.

Conclusion

Time-resolved multispectral imaging allows efficient characterization of solid targets such as minerals in a very short period of time. IBR profiles drawn from 8 acquisition channels provide good information for image contrast enhancement. The additional information brought by dynamic multispectral imaging over conventional thermal cameras brings new possibilities for infrared signature measurements.

References

¹ Pierre Tremblay *et al.*, "Standoff Gas Identification and Quantification from Turbulent Stack Plumes with an Imaging Fourier-transformed Spectrometer," *Proc. of SPIE* **2010**, 7673, 76730H.

² Pierre Tremblay *et al.*, "Pixel-wise real-time advanced calibration method for thermal infrared cameras," *Proc. of SPIE* **2010**, 7662, 766212-1.

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