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# Gas leaks detection using passive thermal infrared hyperspectral imaging

**Abstract**

There are many types of natural gas fields including shale formations which are common especially in the St-Lawrence Valley (Canada). Since methane ($CH_4$), the major component of shale gas, is odorless, colorless and highly flammable, in addition of being a greenhouse gas, methane emanations and/or leaks are important to consider for both safety and environmental reasons. On this regard, passive remote sensing represents an interesting approach since it allows characterization of large areas from a safe location. In order to illustrate the potential of passive thermal infrared hyperspectral imaging for research on natural gas, imaging was carried out on a shale gas leak that unexpectedly happened during a geological survey near Hospital Enfant-Jesus (Québec City, Canada) in December 2016. Quantitative methane imaging was carried out based on its unique infrared spectral signature. The results show how this novel technique could be used for advanced research on shale gases.

**Keywords**: Methane, Imaging, Infrared, Hyperspectral, Shale gas.

## 1. Introduction

Natural gas is an energy resource in great demand worldwide. Regardless of its origin, methane ($CH_4$) is the major component of natural gas. Shale gas represents an important source of natural gas. There are many types of gas fields including shale formations, which are especially common in the St-Lawrence Valley (Canada) [1]. Dealing with methane emanations and/or leaks is an important and challenging task from both a safety and environmental perspective. Methane gas is colorless, odorless and highly flammable. For this reason, natural gas leaks can lead to hazardous situations. Methane is also a major greenhouse gas contributing significantly to global warming [2]. Its high global warming potential comes from the fact that methane is a highly infrared-active molecule. For this reason, thermal infrared imaging remote sensing represents one of the best approaches for investigating methane gas clouds, over large areas, and from a safe location.

Passive infrared hyperspectral imaging was previously shown successful for carrying out gas imaging on large distances [3]. By fitting the spectral radiance measured at sensor level with a set of unique spectral signatures associated with each gas target, selective chemical imaging can be achieved. However, chemical imaging of methane gas represents a particular case since it is already omnipresent in the atmosphere. Therefore, discriminating atmospheric methane from methane emanating from a leak source requires a more sophisticated approach. As the amplitude of the signal scales with distance, an efficient atmospheric radiative transfer model is required in order to measure leaks on large distances. In addition, there is a strong overlap between the spectral features of water vapor and methane, making this task even more challenging. Therefore, in order to successfully image methane gas clouds over large distances, high spectral resolution is required. Recent progress in hardware development and signal processing allowed both spectroscopic confirmation and methane quantification, down to ambient level, for all pixels simultaneously, and over relatively large distances [4].

In order to illustrate the potential of passive thermal infrared hyperspectral imaging for research on natural gas, the same imaging system was brought out near a shale gas leaks that unexpectedly happened during a geological survey near Hospital Enfant-Jesus (Québec City, Canada) in December 2016 (see Fig. 1). Methane was selectively identified in the gas from its unique infrared spectral signature. Preliminary quantification results are also presented. The results show how this novel technique could be used for imaging natural gas leaks.


Fig. 1. Visible image of the shale gas leaks site as seen from the sensor location

## 2. Experimental Information

### 2.1. Standoff infrared hyperspectral imaging

The Telops Hyper-Cam is a lightweight and compact hyperspectral imaging instrument that uses Fourier Transform Infrared (FTIR) technology. It features a closed striling cycle cooled mercury-cadmium-telluride (MCT) focal plane array (FPA) detector, which contains 320×256 pixels over a basic 6.4°×5.1° field of view (FOV). The spectral resolution is user-selectable up to 0.25 $cm^{-1}$ over the entire spectral range of the instrument. The Hyper-Cam-Methane was specifically designed for methane investigation. Its optics and detector are specifically tuned on the methane spectral features, 7.4 to 8.2 μm (1230 – 1350 $cm^{-1}$), in the thermal infrared spectral ranges. A wide-angle de-magnifying 0.25× telescope was used for the measurements leading to a FOV of 25.6°×20.4° [5]. The sensor was located at approximately 50 m from the core drilling location leading to an effective pixel size of about 49 $cm^2$/pixel. The instrument's FOV was narrowed down to 128×256 pixels and the spectral resolution set to 2 $cm^{-1}$ (84 spectral bands). Outside temperature and relative humidity during the acquisitions were −15°C and 50% respectively.

### 2.2. Radiative Transfer model

The broadband image associated with each hyperspectral cube was obtained by summing, for each pixel, the radiance measured at each wavenumber over the whole FPA detector spectral range. Column density results, expressed in units of ppm×m, were obtained by solving Eq. 1, where L is the measured radiance at sensor, $L_{bkg}$ the radiance at the back of the gas plume, $\varepsilon_{bkg}$ the spectral emissivity associated with the background, $D_w$ the downwelling radiance, $\tau_{plume}$ the gas plume transmittance, $L_{plume}$ the self-emission radiance associated with the gas plume, and $L_{atm}$ and $\tau_{atm}$ the self-emission radiance and transmittance associated with the atmosphere respectively [6, 7].

$$L = \left[\left(L_{bkg}\varepsilon_{bkg} + \left(1-\varepsilon_{bkg}\right)Dw\right)\tau_{plume} + L_{plume}\left(1-\tau_{plume}\right)\right]\tau_{atm} + L_{atm}\left(1-\tau_{atm}\right) \quad (1)$$

Self-emission is function of the surface thermodynamic temperature while transmittance is function of gas concentration (expressed in ppm), path length $l$ (expressed in meters) and the gas molar absorptivity $\kappa$ (with units of $m^{-1} \cdot ppm^{-1}$) as expressed in Eq. 2. Only gas contributions with relative fitting error lower than 30% were considered positive detections.

$$\tau\_plume = \exp\left(-\sum [\![ \kappa l[gas] ]\right) \qquad (2)$$

## 3. Results and Discussion

### 3.1. Hyperspectral Imaging

Many materials encountered in outdoor environments behave like infrared grey bodies, i.e. are featureless across all wavelengths. Unlike many common materials, gases like methane ($CH_4$) and water vapor ($H_2O$) behave like selective absorbers/emitters of infrared radiation. Their absorption/emission pattern is function of wavelength (or wavenumbers).


Fig. 2. Example of data registered by HyperCam LWIR

Therefore, their presence can be easily detected when looking at high spectral resolution infrared data. Hyperspectral imaging allows recording of such spectra for each pixel. In order to illustrate the great variety of infrared-active material within a scene, typical spectra associated with selected pixels are shown in Fig. 2. Three point presented in Fig. 2: A – region of shales gas, B – region of the roof which represent of grey body, C – region of the sky. That three regions will be analysed helped detect region where the methane is.

The infrared spectrum associated with a grey body surface should be a straight curve. However, because of the presence of atmospheric gases in the path located between the infrared sensor and the target, the measured spectrum is highly structured. They are mostly associated with ground-level atmospheric component like water vapor, $CH_4$ and nitrous oxide ($N_2O$) (Fig. 3). The radiance recorded by HyperCam and according the Planck's law the temperature was recalculated. This temperature is named the brightness temperature is a result measurement of the radiance of the radiation traveling from the target throw the atmosphere to the sensor, expressed in units of the temperature of an equivalent black body. The brightness temperature is the fundamental parameter measured by passive spectral radiometers.

Since the atmospheric water content is typically a few orders of magnitude higher than the other components, water spectral features are dominant. The high-resolution infrared spectra corresponding to a pixel close to the drill is quite different and shares many similarities with the methane reference absorption spectrum. In the Fig. 3a is presented infrared spectra associated with a single pixel representative of shale gas (A), the roof from the rear house (B) and sky radiance (C). Fig. 3b presents the reference absorption spectra of water vapor and methane are shown for comparison purposes. The spectra are plotted on a brightness temperature scale for clarity purposes.

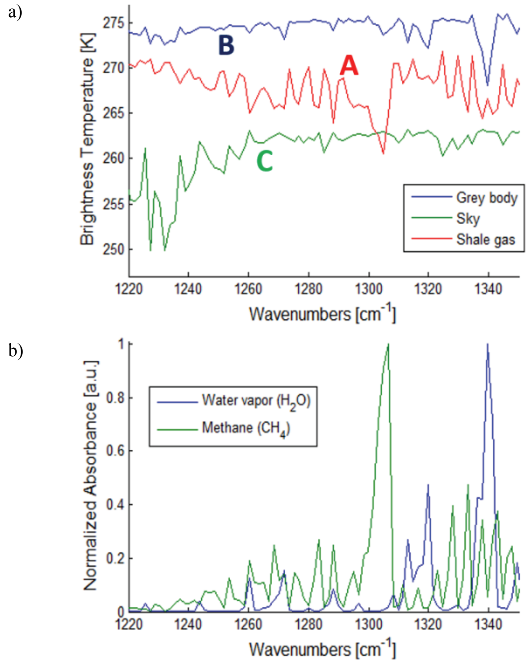


Fig. 3. a) Infrared spectra associated with a single pixel representative of sky radiance, the roof from the rear house, and shale gas, b) The spectra are plotted on a brightness temperature scale for clarity purposes. The reference absorption spectra of water vapor and methane are shown for comparison purposes

### 3.2. Methane column density maps

The image contrast obtained using conventional infrared broadband and narrowband imaging is essentially qualitative. As expressed in Eq. 1 and Eq. 2, the amplitude of the signal obtained for each pixel is function of numerous parameters like the thermal contrast (spectral radiance) between the gas and its background, the gas concentration and the path length.

It cannot be easily translated to any quantitative gas concentration values. The signal measured by the hyperspectral camera used in this work has some physical meaning as it is expressed in terms of spectral radiance units ($W/sr \cdot m^2 \cdot cm^{-1}$). Quantification can then be handled by fitting Eq. 1 with a non-linear optimization routine [6, 8] in order to estimate the relative contribution of each parameter within the measurement. According to the distance estimated with atmospheric components like water vapor and nitrous oxide ($N_2O$), the atmospheric methane content was subtracted from the total amount estimated in the line-of-sight of each pixel. The "excess" of methane contribution was attributed to the shale gas leaks, and the results are shown in Fig. 4.

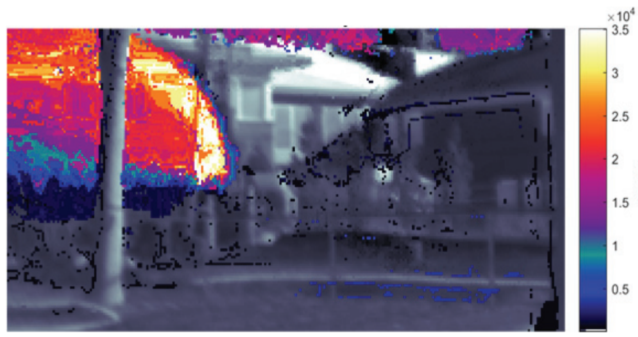


Fig. 4. Column density map of methane

As expected, a greater gas concentration (column density) is observed near the drill where the gas leaks originate. Due to the wind and the high gas pressure of the shale reservoir, methane gas is being spread all over the place, which explains why some positive quantification results can be observed away from the leak source. Sky radiance is usually considered a very good background source. It creates a very high thermal contrast for gas detection since it allows detection at lower concentration values. For this reason, positive methane detections are obtained in the sky area.

The estimated gas column density near the leak source was on the order of 35 000 ppm·m. Assuming a cylindrical symmetry of the gas plume in the center portion, the radius and depth are on the order of 1 m. Therefore, it can be estimated that the methane content in the shale gas is on the order of (3-4)%, which is in good agreement with previous geological surveys carried out on the shale composition of this area [1]. Such leaks represent a life-threatening situation because this methane concentration lies within the flammable concentration bounds. The mixture could indeed be ignited be the firefighters on site during the installation of a rescue-flaring unit.

## 4. Conclusion

An accidental shale gas leaks resulting from geological activities could be successfully visualized using passive thermal infrared hyperspectral imaging. The incident could be investigated from a safe location without the need of any additional means such as an illumination source or an invasive sampling analysis. Methane could be selectively identified in the mixture from its unique infrared spectral signature. Here, the methane content was estimated at (3-4)%, which is within the flammable concentration bounds. This emphasizes the need for remote sensing technologies when dealing with natural gas leaks.

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