Remote Detection and Quantification of Methane Emissions Based on Hyperspectral Data Analysis

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Abstract: Measurement of methane emissions from leaks occurring on the territorially extensive network of transmission gas grid is a topical issue and highly desirable from the point of view of safety and reducing methane emissions into the atmosphere. Remote detection of methane is a problem whose technical solution is based on several types of optoelectronic devices, e.g. thermal imaging cameras with sets of optical filters, spectroradiometers, laser systems of the DIAL (DiFferential Absorption Lidar) type. On the other hand, the quantification of emission magnitudes is in most cases realized by spectroradiometric systems. This paper will present a method for analyzing hyperspectral data from an imaging Fourier infrared spectroradiometer. Measurements will be made on a purpose-built bench simulating methane emissions from a transmission network. Data obtained from ground level under different atmospheric conditions will be presented, together with the results of their analysis for different methane emissions.

Keywords: hyperspectral detection, methane detection, infrared imagine methane detection

1. Introduction

As part of the iDiaGaSys research and development project co-funded by the NCBR, the Gas Transmission Operator GAZ-SYSTEM S.A. and industrial partners, a measurement system was developed for periodic monitoring of leakage and ambient conditions of transmission pipelines. The iDiaGaSys system consists of: the measurement subsystem – a manned helicopter with a mounted imaging Fourier infrared spectroradiometer, and the data analysis subsystem – database infrastructure and diagnostic software with implemented methods of hyperspectral data analysis that enable detection of the presence of methane and prohibited objects in the gas pipeline environment [1].

The Fourier imaging infrared spectroradiometer miniHyperCam Airborne, was mounted on a Robinson R44 helicopter using stabilised platform suspended from a GSS R44 MOUNT (Fig. 1). Paper presents a method for detecting methane emissions using components of a system developed within the iDiaGaSys project and used on a test bench for ground-based measurements.
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 Stirling cycle cooled InAs/InAsSb (SLS) focal plane array (FPA) detector, which contains 320 × 256 pixels over a basic 13.5° × 10.9° field of view (FOV). The spectral resolution is user-selectable from 0.25 cm⁻¹ up to 64 cm⁻¹ over the entire spectral range of the instrument. The miniHyperCam Airborne was specifically designed for methane investigation. Its optics and detector are specifically tuned on the methane spectral features, 1230–1350 cm⁻¹ (7.4–8.2 µm), in the thermal infrared spectral ranges [1].

A method for the detection and quantification of methane emissions based on hyperspectral data from an imaging Fourier infrared spectroradiometer was developed for the project. As part of the project tasks, measurements were carried out under near-real conditions with controlled methane emissions simulating leaks occurring in real conditions on a transmission gas grid. The measurement system was placed at a distance of 50 m from the emission point, for research purposes additionally a blackbody was placed in the field of view of the spectroradiometer, a weather station for monitoring weather conditions and a wind speed variation system. Figure 2 shows photographs of the measurements carried out.

Measurements were carried out for different methane emission volumes, at a constant pressure, which corresponds to the pressure in the transmission pipelines. During the measurements, atmospheric conditions affecting methane detection were monitored: air temperature (22–28 °C), wind speed (0.7–5.7 m/s), atmospheric pressure (998–999 hPa) and relative humidity (51–56 %), emission of the methane on surface. Table 1 provides a summary of the conditions under which the test measurements were carried out.

### Table 1. Test conditions for the detection of methane emissions

<table>
<thead>
<tr>
<th>No</th>
<th>Number of measurements</th>
<th>Pressure of methane (bar)</th>
<th>Emission volumes (l/min)</th>
<th>Wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>20.2</td>
<td>5</td>
<td>0.7–4.6</td>
</tr>
<tr>
<td>2</td>
<td>141</td>
<td>20.2</td>
<td>7</td>
<td>0.7–4.7</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>20.2</td>
<td>10</td>
<td>0.7–5.6</td>
</tr>
<tr>
<td>4</td>
<td>61</td>
<td>20.2</td>
<td>15</td>
<td>0.7–5.6</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>20.2</td>
<td>30</td>
<td>0.2–5.7</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>20.2</td>
<td>40</td>
<td>0.3–5.4</td>
</tr>
</tbody>
</table>

2.2. Radiative transfer model

It is important to understand that there are many paths that photons can take to arrive at a sensor pointed at the ground. There are photons emitted by materials at their respective temperatures, and transmissions through gases, as well as absorptions and reflections by opaque objects. Though there are many paths to consider, there are only a few that significantly contribute to the signal measured at the sensor in LWIR measurements. Only those important paths will be considered in this development, which is drawn mainly from the literature focusing on the detection problem, but also from some work done on artificial plume insertion [2–4].

Firstly, a model will be developed for paths that arrive at a sensor which is pointed at the ground, but not viewing any gaseous plumes in the atmosphere. The main contributing paths to the signal in this situation are atmospheric upwelling (L_u), background (ground) radiance (L_g), and noise (L_n). Atmospheric upwelling is radiance that comes from the atmosphere’s thermal emission at its temperature. The ground radiance is described as a combination of the thermal emission of an object at the ground’s temperature scaled by the emissivity of the material emitting (ε_g), and atmospheric downwelling. The noise term encompasses a few effects including the noise on the focal plane and the thermal emission of the sensor itself onto its focal plane. The combination measured at the sensor can be stated as:

\[
L_{\text{meas}}(\lambda) = L_g(\lambda) + L_u(\lambda) \tau_{\text{atm}}(\lambda) + L_n(\lambda)
\]

which describes the attenuation of the ground radiance by the transmissivity of the atmosphere, \(\tau_{\text{atm}}\). This also denotes the wavelength (\(\lambda\)) dependence of all these terms. The background radiance must be further broken up into constituent terms:

\[
L_g(\lambda) = B(\lambda, T_g) \varepsilon_g(\lambda) + L_n(\lambda) \left[1 - \varepsilon_g(\lambda)\right]
\]

The background material is held to be at some temperature \(T_g\) and it is assumed to be radiating as a perfect blackbody.
does. The $B(A, T)$ function represents the Planck function for radiating blackbodies. This radiation is scaled by the emissivity of the material, $\varepsilon$. The other significant contribution to the background radiation term is the reflected atmospheric downwelling. The atmosphere, as previously mentioned, radiates upwards towards the sensor, but some of that energy will be radiated towards the ground and consequently reflected back towards the sensor. This radiation will not be perfectly reflected, as some will be absorbed by the material. However, for simplicity’s sake, it is assumed that the particles absorbing this downwelled radiance are in local thermodynamic equilibrium [5, 6].

Including the effects of a plume in scene can be done in a few short steps. The paths that govern this model are slightly more complicated than before. The atmospheric upwelling radiance remains a significant contributor to the signal, but the downwelling radiance that is reflected to the sensor now passes through the plume. The plume has a similar effect on the background thermal radiance. The resultant effect on these signals (reflected downwelling and background thermal radiance) is further attenuation based on the transmission of the plume ($\tau_p$). The radiance of the plume material itself also contributes to the signal model. This radiance ($L_p$) occurs at the temperature of the plume material, and must pass through (and thus be attenuated by) the intervening atmosphere to reach the sensor. The atmospheric attenuation is assumed applied to the plume at the same strength it is applied to the background thermal radiance path. This is because the plume is assumed to be close to the ground, rather than much closer to the sensor. The result of these effects can be written as:

$$L_{\text{trans}}(\lambda) = L_p(\lambda) + L_b(\lambda) \tau_p(\lambda) + L_b(\lambda) \tau_p(\lambda) + L_b(\lambda)$$

(3)

This statement describes many of the important paths and their terms, but what is desired is to express this model with a signal term (and an associated strength) and an additive noise term. The signal term should also be a function of the signature of the chemical being detected, $b(\lambda)$. The linear expression from this model that explicitly involves $b(\lambda)$. The transmission of the plume can be expressed as follows:

$$\tau_p(\lambda) = \exp\left(-c b(\lambda)\right) = 1 - c b(\lambda).$$

(4)

where $c$ is the column density of the gas plume as a measure of the amount of intervening matter between an sensor and the background observed, and the chemical signature of the gas is $b(\lambda)$ [10]. This transmissivity is approximately linearized using the assumption that $c b(\lambda)$ is small. The assumption of a small $c b(\lambda)$ must be kept true, otherwise the linear model will be unfaithful to the physical process.

2.3. Method for the detection and quantification of methane emissions

The developed method for detection and quantification methane emissions was based on hyperspectral data analysis using various techniques including spectral unmixing, gas detection algorithms and statistics method. Developed method is doing the analysis hyperspectral data following steps:

- Collected hyperspectral data: Hyperspectral data can be collected using miniHyperCam Airborne. The data were collected in special stand with full control emission.
- Preprocessing: Preprocessing involves removing noise, atmospheric corrections, data normalization and data calibration. Atmospheric corrections is very important for methane detection since the presence of methane can affect the atmospheric transmission in the far-infrared region. In the method was used one of the atmospheric correction methods, such as the atmospheric radiative transfer (ART) model.
- Methane emission detection: Gas detection algorithm is used to identify the presence of methane in hyperspectral data. The algorithm is used spectral signatures of methane to identify methane absorption bands based on adaptive matched filter (AMF), which identifies the methane absorption feature. In the method was used a combination of clutter matched filter CMF and SAM, with appropriate thresholding and spatial filtering, to detect. The PNNL infrared database is used as a reference library for spectral characteristic of the methane [4, 7-9].

In addition, a module has been implemented to convert the concentration of a gas expressed in (ppm-m) to (g/s). Derived from the equation of state of a perfect gas (Clapeyron’s equation) is the equation of state describing the relationship between temperature, pressure and volume of a perfect gas, which can be expressed by the formula:

$$pV = nRT,$$

(5)

where $p$ is the pressure of the gas (in Pa), $V$ is the volume occupied by the gas (in m$^3$), $T$ is the temperature of the gas (in Kelvin, K), $R$ is the gas constant (equal to 8.314462618 J K$^{-1}$ mol$^{-1}$), $n$ is the number of moles of particles in the gas.

The molar volume is the volume occupied by one mole of a substance and is given by the formula:

$$V_m = \frac{V}{n} = \frac{M}{\rho} = \frac{M-V}{\mu},$$

(6)

where: $V_m$ – molar volume (unit: m$^3$/mol), $V$ – volume of $n$ moles of substance, $M$ – molar mass (unit: kg/mol), $\mu$ – mass of substance (unit: kg), $\rho$ – density (unit: kg/m$^3$).

From equation (5), the molar volume can be determined according to the formula:

$$V_m = \frac{V}{n} = \frac{RT}{p},$$

(7)

Knowing the volume of the mixture $V$, the molar volume $V_m$ of the substance and its concentration value $S_{\text{ppm}}$ given in ppm, the number of moles of the substance can be determined using the formula:

$$n = \frac{S_{\text{ppm}} \times 10^{-6} \cdot V}{V_m}.$$  

(8)

Based on formulae (6) and (8), the formula for the mass of the substance can be derived:

$$m = \frac{S_{\text{ppm}} \cdot V \cdot M}{V_m} \times 10^{-6}.$$  

(9)
Inserting into equation (9) the molar volume determined according to equation (7), we obtain:

\[ m = \frac{S \cdot V \cdot M \cdot p}{RT} \times 10^{-6}. \] (10)

When the concentration value of the substance \( S_{\text{ppm-m}} \) is given in ppm-m, and knowing the areas of the mixture \( A \), formula (10) for the mass of the substance can be written in the form:

\[ m = \frac{S_{\text{ppm-m}} \cdot A \cdot M \cdot p}{RT} \times 10^{-6}. \] (11)

A concentration map, which is the instantaneous state of the gas cloud, is then calculated through a gas flow rate conversion module that calculates the amount of gas transported by the wind in one second. Its shape and concentration depend on the flow rate and wind speed. Assuming that the wind direction will be orthogonal to the spectroradiometer’s direction of view, the flow rate can be calculated as the product of the wind speed and a 1 m ‘slice’ of the methane cloud.

\[ f = m_{\text{ppm-m}} \cdot s_{\text{wind}} \] (12)

where: – emission \([g/s]\), \( m_{\text{ppm-m}} \) – mass of gas in a 1 m wide cloud; \( s_{\text{wind}} \) – wind speed (unit m/sec) in the direction perpendicular to the direction of spectroradiometer observation.

The various computational modules were implemented in the MATLAB environment and used to analyze hyperspectral data for the detection and quantification of methane emissions during the ongoing test studies.
Table 2. Data prepared for analysis after detection of methane emissions  
Tabela 2. Wyniki otrzymane po przeprowadzonych analizach emisji metanu

<table>
<thead>
<tr>
<th>File name</th>
<th>Total measured methane emission</th>
<th>Wind speed</th>
<th>Wind speed correction</th>
<th>Total methane emission from pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test_16_20220810_114800_694.sc</td>
<td>3.308</td>
<td>3.6</td>
<td>11.907</td>
<td>15</td>
</tr>
<tr>
<td>Test_16_20220810_114801_827.sc</td>
<td>3.593</td>
<td>3.6</td>
<td>12.934</td>
<td>15</td>
</tr>
<tr>
<td>Test_12_20220810_112654_167.sc</td>
<td>2.48</td>
<td>3.9</td>
<td>9.69</td>
<td>10</td>
</tr>
<tr>
<td>Test_12_20220810_112655_300.sc</td>
<td>1.65</td>
<td>3.9</td>
<td>6.44</td>
<td>10</td>
</tr>
<tr>
<td>Test_7_20220810_111343_156.sc</td>
<td>2.238</td>
<td>3.8</td>
<td>8.505</td>
<td>7</td>
</tr>
<tr>
<td>Test_7_20220810_111344_295.sc</td>
<td>1.711</td>
<td>3.8</td>
<td>6.502</td>
<td>7</td>
</tr>
<tr>
<td>Test_1_20220810_104516_950.sc</td>
<td>1.478</td>
<td>1.9</td>
<td>2.809</td>
<td>5</td>
</tr>
<tr>
<td>Test_1_20220810_104518_085.sc</td>
<td>2.912</td>
<td>1.9</td>
<td>5.533</td>
<td>5</td>
</tr>
</tbody>
</table>

3. Results of the test studies  
3.1. Hyperspectral data and analysis results  
Many materials encountered in outdoor environments behave like infrared grey bodies, i.e. are featureless across all wave- 
lengths. Unlike many common materials, gases like methane (CH₄) and water vapor (H₂O) behave like selective absorbers/ 
emitters of infrared radiation. Their absorption/emission pat- 
tern is function of wavelength (or wavenumbers).

The recorded measurement data at the measuring station according to the measurement plan (part 2.1) were analysed, and an analysis of the results obtained is presented below. 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. 3.
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, CH4 and nitrous oxide (N2O) (Fig. 4). 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.

3.2. Methane column density maps

Based on the recorded data for the different measurement conditions (Table 1), the hyperspectral data were processed and recalculated according to the adopted method. As results, maps of the distribution of detected methane were obtained, which for visualisation purposes were presented as a fusion of a thermogram (broadband image) and a pixel map with detected methane. Example results are presented in the images for different emissions in Fig. 5.

The results data for each of the files corresponding to the measurement of methane emissions was then performed to assess the effectiveness of the method for detecting and quantifying methane emissions. Example data for analysis are shown in Table 2.

### Table 2: Validation of the detection method for methane emissions in the sensitivity range

<table>
<thead>
<tr>
<th>Emissions analysed (l/min)</th>
<th>Number of measurements</th>
<th>Number of measurements with methane detection</th>
<th>Sensitivity of the method - probability of detecting emissions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>150</td>
<td>91</td>
<td>60.7</td>
</tr>
<tr>
<td>7.0</td>
<td>141</td>
<td>135</td>
<td>95.7</td>
</tr>
<tr>
<td>10.0</td>
<td>110</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>15.0</td>
<td>61</td>
<td>61</td>
<td>100</td>
</tr>
<tr>
<td>30.0</td>
<td>31</td>
<td>31</td>
<td>100</td>
</tr>
<tr>
<td>40.0</td>
<td>35</td>
<td>35</td>
<td>100</td>
</tr>
</tbody>
</table>

The last of the validated parameters of the qualitative method for detecting methane emissions was accuracy. In quantitative methods, this is the parameter that combines the sensitivity and specificity of the method:

\[
AC = \frac{SP + SN}{N_+ + N_-} \times 100\%
\]  

(13)

where \( SP/N_+ \) is a sensitivity and \( SN/N_- \) is a specificity, where SP – a number of positive tests assessed as positive, SN – a number of negative tests assessed as negative, \( N_+ \) – the total number of positive tests performed and \( N_- \) – is the total number of negative tests performed.

Taking into account the field nature of the method and formula (13) with the acceptance criteria for sensitivity (above 50 %) and specificity of the method (above 90 %), the acceptable accuracy of the method was assumed to be 70 %. This means that 7 out of 10 results obtained with the validated method will be evaluated correctly with respect to the true value. The field results obtained indicate 100 % specificity of the method and therefore the determined accuracy of the method will be the same as its sensitivity. Based on the results collected in Table 2, it can be concluded that the validated method has acceptable accuracy for methane emissions above 7.0 l/min.
4. Conclusion

The development of a remote system for detecting and measuring methane emissions from the transmission gas grid is a major challenge due to the size of the area to be monitored, the range of methane emissions and changing weather conditions during the measurements. The measurement subsystem developed as part of the iDiaGaSys project is designed to detect and measure methane emissions from the transmission gas grid using the FTIR technique. The Fourier imaging infrared spectroradiometer mini-HyperCam Airborne selected for this purpose together with the developed computational algorithms successfully passed initial tests in the field of detecting methane fugitive emissions greater than 5 l/min. Due to the method of conducting the initial tests (stationary tests from the ground), in order to fully assess the suitability of the developed measurement subsystem, it is required to perform tests in real measurement conditions.

Acknowledgements

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Inne źródła

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Bibliografia


Zdalne wykrywanie i kwantyfikacja emisji metanu na podstawie analizy danych hiperspektralnych

Streszczenie: Pomiar emisji metanu z wycieków występujących na rozległej terytorialnie sieci gazociągów przesyłowych jest zagadnieniem aktualnym i wysoce pożądany z punktu widzenia bezpieczeństwa i ograniczenia emisji metanu do atmosfery. Zdalna detekcja metanu jest problemem, którego rozwiązanie techniczne opiera się na kilku typach urządzeń optoelektronicznych, np. kamery termowizyjnych z zestawami filtrów optycznych kamery termowizyjne z zestawami filtrów optycznych, spekroradiometry, systemy laserowe DIAL (Differential Absorption Lidar). Z drugiej strony, kwantyfikacja wielkości emisji jest w większości przypadków realizowana przez systemy spekktoradiometryczne. W niniejszym artykule zostanie przedstawiona metod analizy danych hiperspektralnych z obrazującego fourierowskiego spektoradiometru podczerwieni. Pomiary zostały wykonane na specjalnie zbudowanym stanowisku symulującym emisję metanu z sieci przesyłowej. Dane uzyskane z poziomu gruntu w różnych warunkach atmosferycznych, wraz z wynikami ich analizy dla różnych emisji metanu.

Słowa kluczowe: hiperspektralna detekcja w podczerwieni, detekcja metanu, obrazowa detekcja metanu w podczerwieni
Remote Detection and Quantification of Methane Emissions Based on Hyperspectral Data Analysis

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