Passive infrared imaging sensor for standoff detection of methane leaks

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Passive infrared imaging sensor for standoff detection of methane leaks

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ABSTRACT

Physical Sciences Inc. (PSI) has developed an imaging sensor for remote detection of natural gas (methane) leaks. The sensor is comprised of an IR focal plane array-based camera which views the far field through a rapidly tunable Fabry-Perot interferometer. The interferometer functions as a wavelength-variable bandpass filter which selects the wavelength illuminating the focal plane array. The sensor generates 128 pixel x 128 pixel ‘methane images’ with a spatial resolution of 1 m (>100 x 100 pixel field-of-view). The methane column density at each pixel in the image is calculated in real time using an algorithm which estimates and compensates for line-of-sight atmospheric transmission. The compensation algorithm incorporates range-to-target as well as local air temperature and humidity. System tests conducted at 200 m standoff from sensor to leak location indicate probability of detection >90% for methane column densities >1000 ppmv-m and >2K thermal contrast between the air and the background. The probability of false alarm is <0.2% under these detection conditions.

Keywords: methane leaks, remote sensing, infrared imaging

1. INTRODUCTION

This paper describes the development and testing results of the new imaging sensor for remote detection of methane leaks fielded by Physical Sciences Inc. (PSI). The instrument is based on our proven AIRIS (Adaptive InfraRed Imaging Spectroradiometer, U.S. Patent 5,461,477) technology using a Fabry-Perot interferometer operating as a tunable IR bandpass filter with an infrared focal plane array detector [1,2].

Passive sensing of chemical vapor plumes requires exploitation of both the spectral signatures of the target species as well as the radiance contrast between the vapor and the background scene. The tunable etalon provides the spectral resolution necessary to resolve the structured absorption from the molecular vapors. The principle of operation is based on a two-band measurement, on and off a methane absorption band, in order to determine the differential radiance due to the presence of the methane plume. The methane column density is calculated in real time based on an algorithm that compensates for the atmospheric transmission, which is determined based on the range to target and the local ambient temperature and humidity readings. The system incorporates a wide field-of-view for wide area coverage with an automated geo-location of leak sources.

The Methane Leak Detection System has two modes of operation: one-wave and two-wave modes. One Wave Mode is designed to allow the operator to identify a methane leak and its position. During One Wave operation, the system continuously tunes to the methane absorption band at 1304 cm⁻¹, while displaying both the IR and visible scenes. The geolocation data is also displayed along with temperature, humidity, and range values. The IR scene allows the operator to locate the methane plume. Once this is established, the operator can proceed with Two Wave Mode operation which provides real-time determination of the methane column density.

The performance of the methane detection system has been evaluated by ground-level testing, as well as laboratory testing. This paper describes in detail the findings of these experiments.

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2. INSTRUMENT

The basic optical configuration of the sensor is shown in Figure 1. The concept is based on the insertion of a tunable Fabry-Perot interferometer (etalon) into the field-of-view of an infrared focal plane array (FPA). The IR FPA views the far field through the piezoelectric-actuated etalon placed in an afocal region of the optical train. The tunable etalon is operated in low order (mirror spacing comparable to the wavelength of the light transmitted) and functions as an interference filter which selects the wavelength viewed by the FPA. The optical configuration depicted in Figure 1 affords a wide field of view, high optical throughput, and broad wavelength coverage at high spectral resolution. A bandpass filter is placed in front of the FPA to limit its response to a single etalon transmission order. The spacing and alignment of the etalon mirrors are controlled via a closed-loop control system. The etalon can be tuned between resolution elements in 20 to 30 ms while maintaining wavelength positioning accuracy of ~1 cm⁻¹. The system computer is an Intel Pentium-based PC with Windows NT 4.0 as the operating system.

Table 1 lists the salient characteristics of the system's camera and optical train. The Optical Head consists of the main optical train, which includes the IR camera, etalon and focusing lens. The CCD visible camera used as co-reference with the IR imagery, range finder, and compass are also located in the optical head. All of these components are shown in Figure 2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>1000 ppmv-m (5:1 SNR, ΔT=2°C)</td>
</tr>
<tr>
<td>Range</td>
<td>Up to 500 m</td>
</tr>
<tr>
<td>Imaging</td>
<td>128 X 128 pixels</td>
</tr>
<tr>
<td>Response Time</td>
<td>&lt; 50 ms</td>
</tr>
<tr>
<td>Framing Rate</td>
<td>20 frames per second</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1 m at 500 m</td>
</tr>
</tbody>
</table>

3. DATA ACQUISITION AND ANALYSIS

The data acquisition approach is based on two methods of operation. A single wavelength operation is used for the detection of the methane cloud by continuously tuning the etalon to 1304 cm⁻¹ where methane displays a strong absorption (Q branch transition). Once the cloud is located using the operator’s knowledge based on the IR imagery, the two-band analysis is employed for tracking and calculation of the methane column density.

The two band measurement at 1304 cm⁻¹ and 1325 cm⁻¹ is implemented to obtain both methane and background estimations. The first wavelength, 1304 cm⁻¹, is located at the methane absorption band, and by tuning to the second wavelength, 1325 cm⁻¹ (off the methane absorption band), the background radiance can be estimated. Both wavelengths are corrected for the atmospheric transmission using a temperature/humidity model. The overall transmission attenuation is a function of range based on the water content. MODTRAN simulations are used in order to obtain the atmospheric attenuation per meter (k) as a function of the water vapor pressure (VP). Therefore, for a given relative humidity, temperature, range, and wavelength, k is calculated based on a best fit such that the atmospheric transmission at each wavelength is derived:
The atmospheric methane content is included in the correction as a result of the MODTRAN simulations. The algorithm then solves for the cloud transmission at each wavelength based on the following equations for overall radiance at each wavelength:

\[ \tau_{A1} = e^{-k_1 \times \text{Range}} \]
\[ \tau_{A2} = e^{-k_2 \times \text{Range}} \]  

(1)

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1304 cm\(^{-1}\):  
\[ N_1 = (N_B \varepsilon_{B1} \tau_{C1} \tau_{A1}) + N_C (1 - \tau_{C1}) \tau_{A1} + N_A (1 - \tau_{A1}) \]  

(2)

\( N_B, N_C, N_A \) = Background, Methane Cloud, and Atmospheric Radiance  
\( \varepsilon_{B1} \) = Background emissivity  
\( \tau_{C1} \) = Cloud transmission at wavelength “1”  
\( \tau_{A1} \) = Atmospheric transmission at wavelength “1”

1325 cm\(^{-1}\):

\[ N_2 = (N_B \varepsilon_{B2} \tau_{C2} \tau_{A2}) + N_C (1 - \tau_{C2}) \tau_{A2} + N_A (1 - \tau_{A2}) \]  

(3)

and assuming that the methane cloud and the atmosphere are in equilibrium, and also that there is no wavelength dependence on the emissivity of the background, such that:

\[ N_A = N_C \quad \varepsilon_{B1} = \varepsilon_{B2} \]  

(4)

From these equations, the methane cloud transmission is calculated from the following expression:

\[ \left( \begin{array}{c} \tau_{C1} \\ \tau_{C2} \end{array} \right) = \frac{\tau_{A2} (N_1 - N_A)}{\tau_{A1} (N_2 - N_A)} \]  

(5)

The methane column density is then derived based on the methane band model which also accounts for the case in which optical thickness is achieved.

The algorithm has been tested for methane detection ability under the various conditions presented in the next section. For each case, the methane detection threshold is adjusted, and the probability of detection and false alarm are calculated as a function of the threshold. Two approaches are used for false alarm reduction. The algorithm determines that no methane detection is present if the corrected radiance differences are within sensor noise levels. Another situation where no detection is determined is if the background radiance on any pixel has a fixed temperature difference from air radiance for unit emissivity blackbody (minimum \( \Delta T \)).

4. EXPERIMENTAL TESTS RESULTS

The Methane Leak Detection System has been tested for performance in both laboratory and outdoor environments. The open air release testing is meant to determine the system’s ability to perform under realistic conditions of varying backgrounds, temperature, humidity, and range. These conditions are designed to test the system’s ability to measure methane column densities, as well as the ability to reduce false alarms. Each data set taken under these changing conditions has 20 or more measurements of the methane release plume. In most cases the plume swirls with changes in the wind direction, possibly resulting in some detection failures due in part to changes in the wind direction during acquisition. The outdoor tests include ranges from 45 to 310 meters, with temperatures varying from 18 to 32 degrees C, and humidity values from 26% to as high as 52%. A number of tests were performed at an altitude of 16 meters, and in certain cases the wind velocity approached 1.4 m/s. The methane release rate was maintained at a constant value of
1 g/s. Results from some of the experimental measurements are described below. For each data set, the detection probability is investigated as a function of the column density detection threshold free parameter (ppmv-m), which can be adjusted by the user.

**Data set 911_1** was acquired at a range of 50 meters, with an ambient temperature of 32.6 degrees C, and a humidity of 26%, from an altitude of 16 meters. The background was comprised asphalt and cars in a parking lot. The view is looking down at the asphalt from the roof of a building. Figure 3 shows the online (1304 cm\(^{-1}\)) IR image along with the offline (1325 cm\(^{-1}\)) image and the analysis image as produced by the detection algorithm, indicating the pixels identified as containing methane.

The analysis of data set 911_1 indicates good detection probability, which is independent of the threshold setting. The detection probability is approximately 96%. Another observation is that the number of plume pixels detected decreases slightly with threshold. The false alarms are individual uncorrelated noisy pixels. The false alarm rate decreases slightly with increased threshold. The alarm rate is very low, less than 0.05% for this view down to pavement, as shown in Figure 4.

**Data set 909_2** was acquired at a range of 45 meters, with an ambient temperature of 21.5 degrees C, and a humidity of 38%. The background was comprised of asphalt with a temperature of approximately 32 degrees C. Figure 5 shows the online (1304 cm\(^{-1}\)) IR image along with the offline (1325 cm\(^{-1}\)) image and the analysis image as produced by the detection algorithm, indicating the pixels identified as containing methane.

The analysis of data set 909_2 indicates excellent detection probability, which is independent of the threshold setting. The detection probability is 100%, methane being detected in all 27 measurements. An important observation is that the number of plume pixels detected decreases significantly with threshold, as shown in Figure 7. The false alarms are individual uncorrelated noisy pixels, which are randomly distributed in the image. The false alarm rate is on the order of 0.10% and decreases slightly with higher threshold levels as indicated in Figure 6.

**Data set 910_2** was acquired at a range of 171 meters, with an ambient temperature of 23.5 degrees C, and a humidity of 43%. The background was comprised of a car positioned in front of trees, equilibrated at the ambient temperature, as well as asphalt. Figure 8 shows the online (1304 cm\(^{-1}\)) IR image along with the offline (1325 cm\(^{-1}\)) image and the analysis image as produced by the detection algorithm, indicating the pixels identified as containing methane.
The analysis of data set 910_2 indicates good detection probability, which is independent of the threshold setting. The detection probability is approximately 90%. The number of plume pixels detected decreases slightly with threshold. The false alarms are individual uncorrelated noisy pixels, where grass/trees background move during image acquisition. Since more of the field of view is covered by areas where the radiance approaches atmospheric radiance levels and the range has increased to 171 m, thus increasing the atmospheric attenuation, more false alarms are encountered. However, increasing the detection threshold to 5000 ppmv-m, decreases the probability of false alarm from 0.25% to 0.20%, as shown in Figure 9.

A series of open air tests similar to the few described above have been carried out in constantly changing atmospheric conditions and varying backgrounds. Our results lead us to conclude that the Methane Leak Sensor has a probability of detection of better than 90% and a probability of false alarm of less than 0.20% from a distance of approximately 200 m away from the methane leak source.

The laboratory testing is designed to measure the system’s accuracy in detecting a given column density of methane by controlling the amount of methane in a certain measurement. The laboratory testing equipment is based on an absorption cell, which has a path length of 7 cm. The cell is filled with a given mix ratio of methane/nitrogen, such that the following methane column densities are achieved: 5000, 4000, 3000, 2000, and 1000 ppmv-m. The laboratory data was taken at an ambient temperature of 22.7 degrees and a humidity of 38.1%. A blackbody at a temperature of 10 degrees C higher than the ambient was placed behind the absorption cell, and served as the background for the methane measurement. Figure 10 shows the online (1304 cm\(^{-1}\)) IR image along with the offline (1325 cm\(^{-1}\)) image and the analysis image as produced by the detection algorithm, indicating the pixels identified as containing methane. For illustration purposes, only the 4000 ppmv-m data set is shown.

The analysis of the laboratory tests indicates that methane is detected in all 5 cases of varying methane column density. One can refer to the detection probability as the percentage of pixels detected to have a column density greater than 1000 ppmv-m inside the cell. Since the methane column density is uniformly distributed inside the cell, as a result of a constant flow of methane and nitrogen, the total number of pixels is defined as the total number of pixels inside the cell. At 100% detection probability all pixels inside the cell should be identified as containing methane. The detection probability is plotted as a function of the actual methane column density inside the cell. This relationship is shown in Figure 11.

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Since the laboratory tests had the ability to control the methane column density in the cell through the use of a flow controller, they could also provide information about the accuracy of the measurement, relating the calculated average methane column density to the actual methane column density present in the cell. The calculated methane column density is averaged over all detected pixels inside the cell, as well as averaged over all data measurements. The relationship between the calculated methane column density and the actual methane column density in the absorption cell is illustrated in Figure 12. The percent error is as high as 28% when the actual column density is 5000 ppmv-m, primarily due to loss of differential signal as a result of optical thickness in the methane band, but decreases considerably to less than 10% when the column density is 4000 ppmv-m and 3000 ppmv-m. However, as the column density is decreased even further, the percent error once again increases to around 30%, as a result of decreased sensitivity.

The successful development and testing of the PSI Methane Leak Imaging Detector culminated with an on-site demonstration at the Tokyo Gas Research and Development Facility in Tsurumi, Japan. A methane leak was simulated and the sensor was positioned approximately 80 m away from the leak source. Figure 13 demonstrates the successful implementation of the sensor and the positive detection of methane cloud.
5. CONCLUSIONS

We have demonstrated that PSI’s LWIR imaging Fabry-Perot spectrometer functions effectively as a sensor for the remote detection of methane leaks. The system has a wide field-of-view for wide area coverage with an automated geolocation of leak sources. The range is provided by a laser range finder, which along with temperature and humidity values from a temperature/humidity sensor is used in the calculation of the atmospheric attenuation of the radiance signal. The system has identification and detection capabilities in changing atmospheric conditions with a probability of detection of better than 90% and a probability of false alarm of less than 0.2% from a distance of approximately 200 meters away from the methane source.

System can detect column densities as low as 1000 ppmv-m depending on the temperature differential between background and atmosphere.

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