CHEMICAL POLLUTANT DETECTION AND IDENTIFICATION BY PASSIVE LWIR HYPERSPECTRAL IMAGING

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ABSTRACT

Uncontrolled releases of chemical pollutants represent a major threat for public health and security. Their detection, identification and release point localization constitute a real challenge to health, security and first responder's communities. One promising detection method is based on imaging passive standoff detection and identification of chemical vapors. To investigate this method, Defense Research and Development Canada (DRDC) – Valcartier developed and tested passive Long Wave Infrared (LWIR) hyperspectral imaging (HSI) sensors for standoff detection. The initial effort was focused to address the standoff detection and identification of toxic industrial chemicals (TICs) and precursors. Sensors such as the Improved Compact ATmospheric Sounding Interferometer (iCATSI) were developed for this application.

This paper describes the sensor developments and presents results of standoff detection and identification of chemical pollutants. The standoff sensor is based on differential Fourier-transform infrared (FTIR) radiometric technology and is able to detect, spectrally resolve and identify small plumes at kilometer's ranges. Results from a series of field trials in several typical scenarios will be presented. These results will serve to establish the potential of the method for standoff detection of pollutants and surrogates.

Keywords: CATSI, passive standoff detection, remote sensing, area surveillance, chemical pollutant.

INTRODUCTION

Accidental release of gaseous chemical pollutants constitutes a potential risk and important consequences for population heath and the environment. In the last decades, development of passive standoff detection demonstrates high potential for long range detection and identification (D&Id) for surveillance of chemical pollutant released in the environment.

To perform this surveillance mission, Defence Research and Development Canada (DRDC) has been developing and validating very longwave infrared (LWIR) Fourier transform spectrometer (FTS) systems for passive standoff detection of chemical pollutants. These systems are referred to as the Compact ATmospheric Sounding Interferometer (CATSI) family and are based on a symmetrical double input beam FTS which was designed for real

time optical subtraction of the background radiance. The CATSI systems and the associated software were described elsewhere [1-8].
In the last ten years, new development of sensitive Mercury-Cadmium-Telluride (MCT) multi-element or focal plane array (FPA) detectors pave the way of research in the direction of imaging D&Id of chemical pollutants. These technological advances provide detection capability of smaller plumes with a better FOV coverage. DRDC Valcartier is currently developing optical subtraction imaging FTS like iCATSI (improved Compact ATmospheric sounding Interferometer) for the detection and identification of chemical pollutants.
The purpose of this paper is to summarize the main results obtained in the last year for the application of passive differential standoff detection of surrogates. First, a brief description of the passive standoff detection principle together with the sensor hardware attributes for open-air measurements are presented. This is followed by a description of the setup used to demonstrate the detection and identification of chemical pollutants. Finally, characteristics and results obtained with the newly developed sensors referred to as iCATSI FPA are presented. The overall analysis emphasizes the attributes of differential FTIR radiometry for passive standoff detection of chemical pollutants.

PASSIVE STANDOFF DETECTION THEORY

Figure 1 illustrates the principle of passive standoff detection by optical differential FTIR radiometry. A chemical cloud in the atmosphere can be detected when a thermal contrast between the air (target cloud) and the background is observed in the thermal infrared region. In our method the background scene probed (input-2) and optically subtracted from the target scene (input-1) in real-time yielding a cloud spectral signature minimally perturbed by the background radiance.

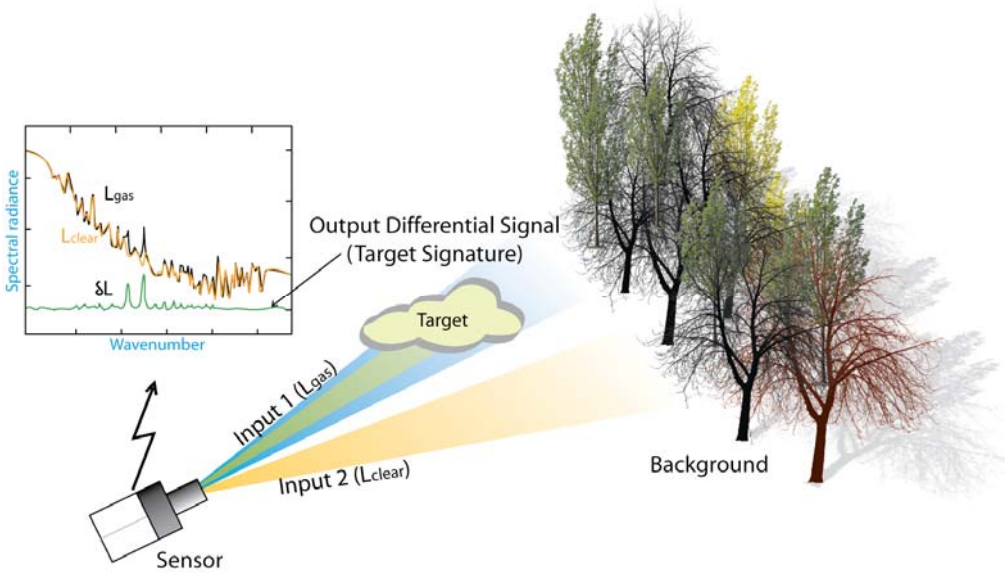

Figure 1: *Schematic of a typical detection scenario with the iCATSI sensor*

Figure 2 is a diagram of the 3-layer model that describes the differential detection method using a double-beam interferometer such as CATSI. The differential detection mode works by subtracting the background radiance (F_{far}) and atmospheric radiance (N_{near}) components from the total input radiance. The resulting differential radiance is given by Eq. (1) [4] where L_{gas}, B_{gaz} and τ_{gas} are respectively the total path radiance, the Planck radiance and the transmittance associated with the target gas layer while L_{clear} and τ_{clear} corresponds to the total path radiance and the near field transmittance of the clear atmosphere.

$$\delta L_{calc} \equiv L_{gas} - L_{clear} = \left(1 - \tau_{gas}\right)\left[B_{gas}\tau_{near} + N_{near} - L_{clear}\right] \quad (1)$$

Equation 1 describes an ideal scenario where the background is assumed to be constant over the two fields of view of the instrument. In cases where there is a background mismatch between the two observed scenes, and in addition if the chemical cloud occupies a fraction, f, of the sensor field-of-view (FOV) it can be shown that, the differential radiance can be calculated by [8]

$$\delta L_{calc} \equiv L_{gas} - L_{clear} = \Delta L_{clear} + f\left(1 - \tau_{gas}\right)\left[B_{gas}\tau_{near} + N_{near} - L_{clear} - \Delta L_{clear}\right] \quad (2)$$

where τ_{gas} is the transmittance associated with the integrated path concentration (CL),

$$\tau_{gas} = exp^{(-\alpha,CL)} \quad (3)$$

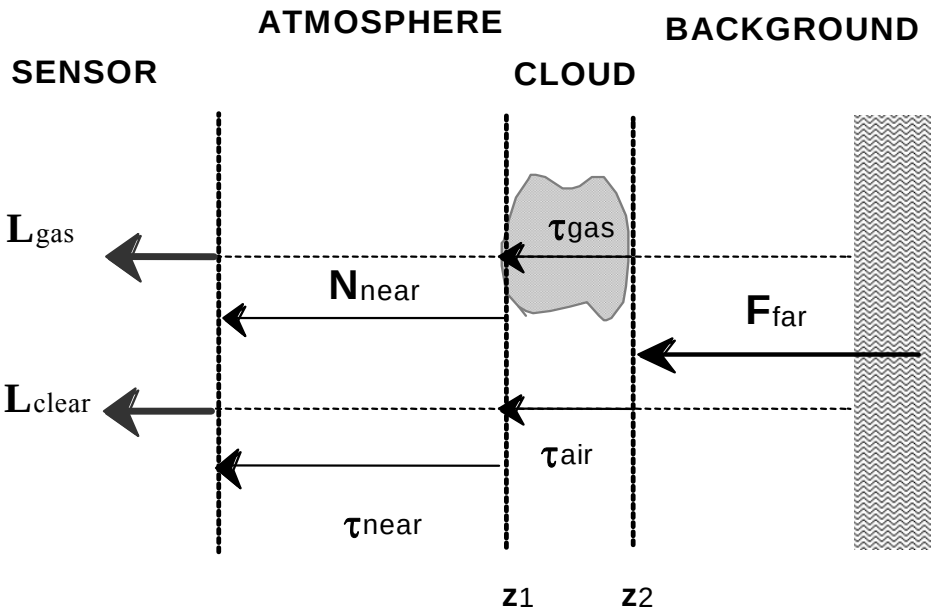

Figure 2: *Diagram of the 3-layer model for the differential detection of chemical cloud*

and $\square_v$ is the absorption coefficient as a function of frequency (in 1/ppm m), C is the volumic concentration in ppm and L is the path length of the target gas in meters. The parameter of interest is the column density (*CL)* expressed in ppm-m.
For more details on the detection method and other scenarios, see references [4, 8, 9-10].

SENSOR DESCRIPTION

iCATSI INTERFEROMETER

The iCATSI (Figure 3) is a dual input - dual output optical subtraction adaptation of the ABB MR*i* imaging spectro-radiometer [11-13]. It is a complete modular and configurable instrument where the input optics and the two detector modules (one per output) can be easily exchanged. The iCATSI interferometer output ports are both configured to focus the beam onto their respective detectors. Stirling-cycle coolers cool both detectors. The signals from the detectors are amplified and digitalized by electronics placed close to the detectors. The digital signals are then sent through the control electronics in the remote computer.
There is a single telescope common to both input ports. At the output of the telescope, a prism splits the FOV in two parts. Each part feeds one input port of the interferometer. The angular separation between both input ports is set to two degrees. The interferometer of the iCATSI is a dual pendulum cube-corner interferometer based on the proven Bomem MR series. Both corner cubes are mounted on a V-shaped scan arm that partly rotates around a ZnSe beamsplitter. The motion of the scan arm is monitored in real time by measuring the interference pattern of a He-Ne laser that travels in the interferometer. The optical path difference of the interferometer is longer than 1 cm. Boxcar-apodized spectral resolution (FWHM) is about 0.8 cm^{-1} at 8 μm and 1.0 cm^{-1} at 3 μm.
The instrument is field deployable and can be considered as weatherproof. Thermal load, heat evacuation and protection against the direct Sun and light rain are implemented.

iCATSI DETECTOR MODULES

Because of the modularity, the iCATSI platform permits the testing of several approaches with the same basic optics (telescope and interferometer). The first output port is populated with a linear array made of 16 independent MCT photodiode detectors disposed along the vertical direction. Each pixel has a field-of-view of 1 mrad. An innovative telescope design including a scanning mechanism allows the system to image the scene with the linear array detector. The scanning mechanism, electronically coupled with the interferometer, could generate hyperspectral image of 16 by 24 mrad with a rate of 2.8 images per second at a resolution of 16 wavenumber. The second output port of the spectrometer has been populated with a single pixel detector. The single pixel detector that populates the second output port has a circular field-of-view with a diameter of 10 mrad. That second detector is appropriate for large extended (with lower concentration) targets or fast moving scenes.

iCATSI FPA

The same modularity of the system gives the opportunity to easily interchange the detector modules and swap the type of detector. The third option of the iCATSI sensor is to change the detector module from a linear array to a high spatial resolution very longwave infrared (VLWIR) MCT focal plane array (FPA). The new MCT FPA provides an image of 256 by 256 pixels with 15µm pitch. The effective full field-of-view (FOV) is 17 meter at 1 kilometer with an instantaneous FOV (iFOV) of 6.6 cm (66 µrad). The HSI sensor provides a cube rate of 2.74 images/sec of the full scene with 256x256 pixels and 18 images/sec with a window of 64x64 pixels at 16 wavenumber.

Figure 3: *Picture of the iCATSI sensor with both mono (left) and multi-pixel (right) detector and the scanning telescope*

FIELD TEST RESULTS

The performance of the sensor has been validated by real time detection and identification (D&Id) of chemical gases released in a real environment. Preliminary tests were performed with iCATSI on 500 meters range. Preliminary test were performed with Freon type refrigerant (F-152a) released from a laboratory fume hood. Figure 4 shows some screen shots of the real time D&Id screen taken with iCATSI during the acquisition of a gas plume release. Six images are shown at various times over a period of one minute. Fifty litres of gas were released during that time. The screen shot shows the differential mode FOV overlays on the visible image. The system at this time provides the same algorithm output for both FOV. This can result in a priori ambiguity on the location of the gas plume. Nevertheless, if necessary, a second level of algorithm can be applied to determine the target input port by measuring the thermal contrast. Even with a low spatial resolution (1 mrad/pixel), the evolution and the release origin of the plume is easily identified. The color code goes as lite blue to red where red shows the higher detection ratio.

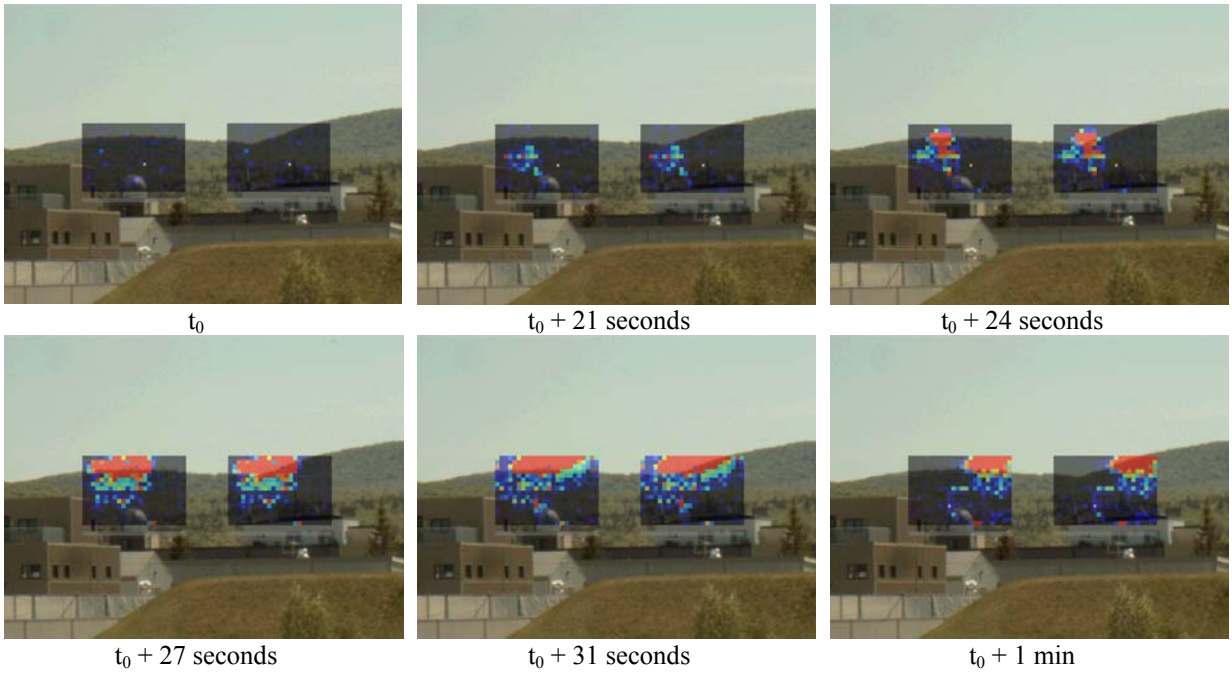

Figure 4: *Evolution of a Freon gas plume over a period of one minute measured with iCATSI*

Figure 5 shows a series of screen shots taken during a release of Acetone under a fume hood. For this experiment, the Acetone was poured in a glass container under a fume hood and left to evaporate at a continuous rate. Each picture shows the output results of the real time D&Id algorithm overlay over the visible image screen taken with iCATSI during the release. Six images are shown at various times over a period of 40 seconds. The darker the pixels are, the lower the probability of detection, and more the color is bright or red, the higher is the detection ratio. At this time, the system provided the same algorithm output for both FOV. Figure 5 shows first detection only a few seconds after the release started (frame 12) and the evolution with time. The figure also shows that the release is very unstable over time (frame 18 vs frame 22). Those fluctuations can be attributed to a non-continuous flow rate du to fluctuation in the fume hood output or the non-uniformity in the Acetone evaporation.

Figure 6 shows the first results obtained with the iCATSI FPA detector over an industrial site scene. This figure shows a series of screen shots taken of three major stacks that release combustion products. The colors over the thermal image show a detection of Carbon Dioxide at 1.5 kilometer. The detector used for this figure is a single band ratio (Equation 4) of CO_2 (735-760 cm^{-1}) over background (800-900 cm^{-1}). The detection band ratio can be specified as:

$$SC_{calc} = \int_{735\ cm^{-1}}^{760\ cm^{-1}} CO_2 \Big/ \int_{800\ cm^{-1}}^{900\ cm^{-1}} Bgd \qquad (4)$$

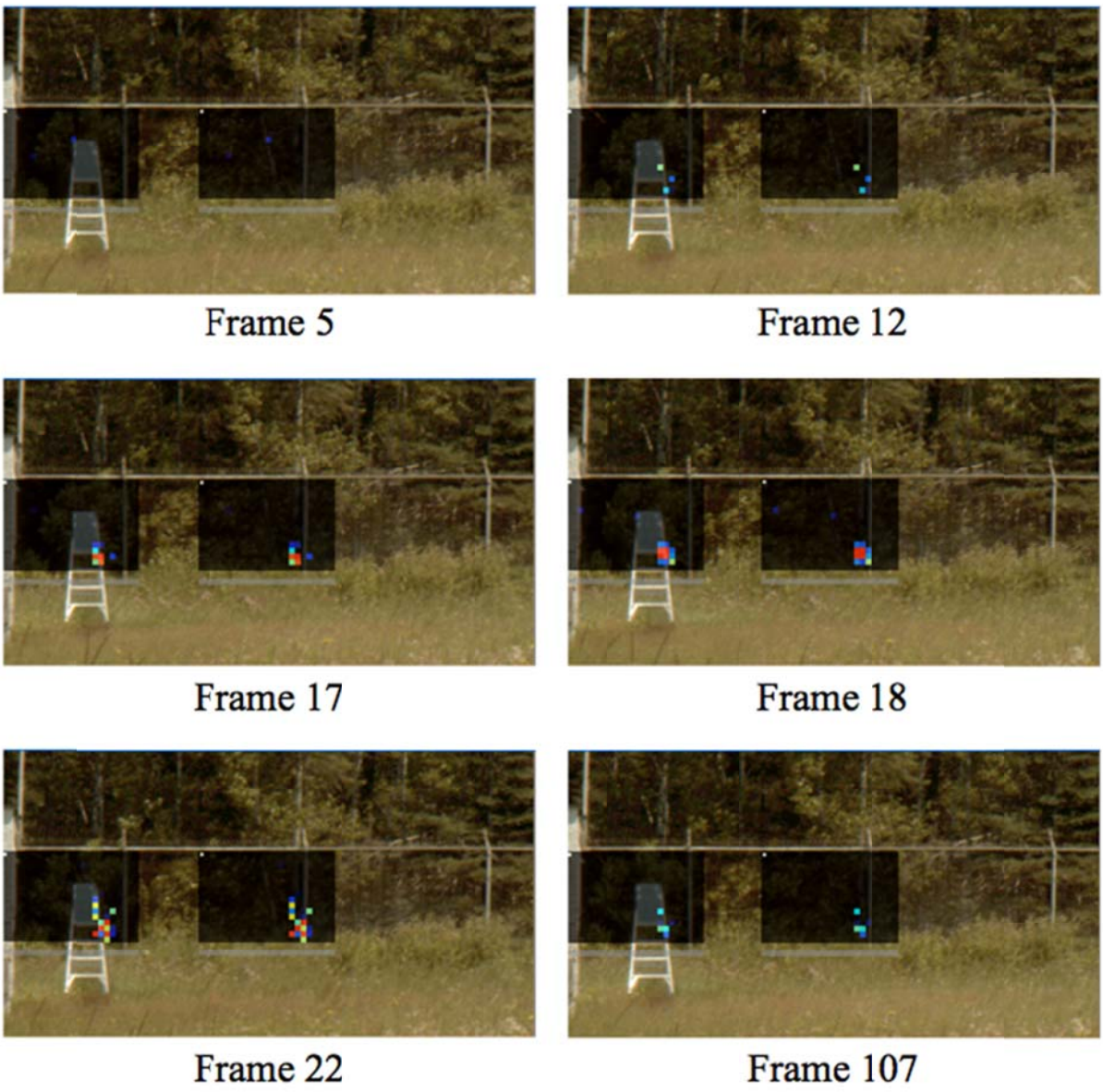

Figure 5: *Evolution of an Acetone gas plume over a period of 40 seconds measured with iCATSI*

The detection plume overlaid on the thermal image shows a Carbon Dioxide plume evolution with time. The color of the detection plume is a function of the threshold. The color purple shows the highest detection of CO_2 (higher radiative signal) and this demonstrates either that the thermal contrast is higher close to the stack or the gas column density is more concentrated. Unfortunately, it is probably a mixture of both mechanisms that give this result. The lowest threshold used to consider detection (in green) was specified as 1.15. In this

measure, the plume temperature was always higher than the background temperature and the Carbon Dioxide contribution from the plume was in emission.

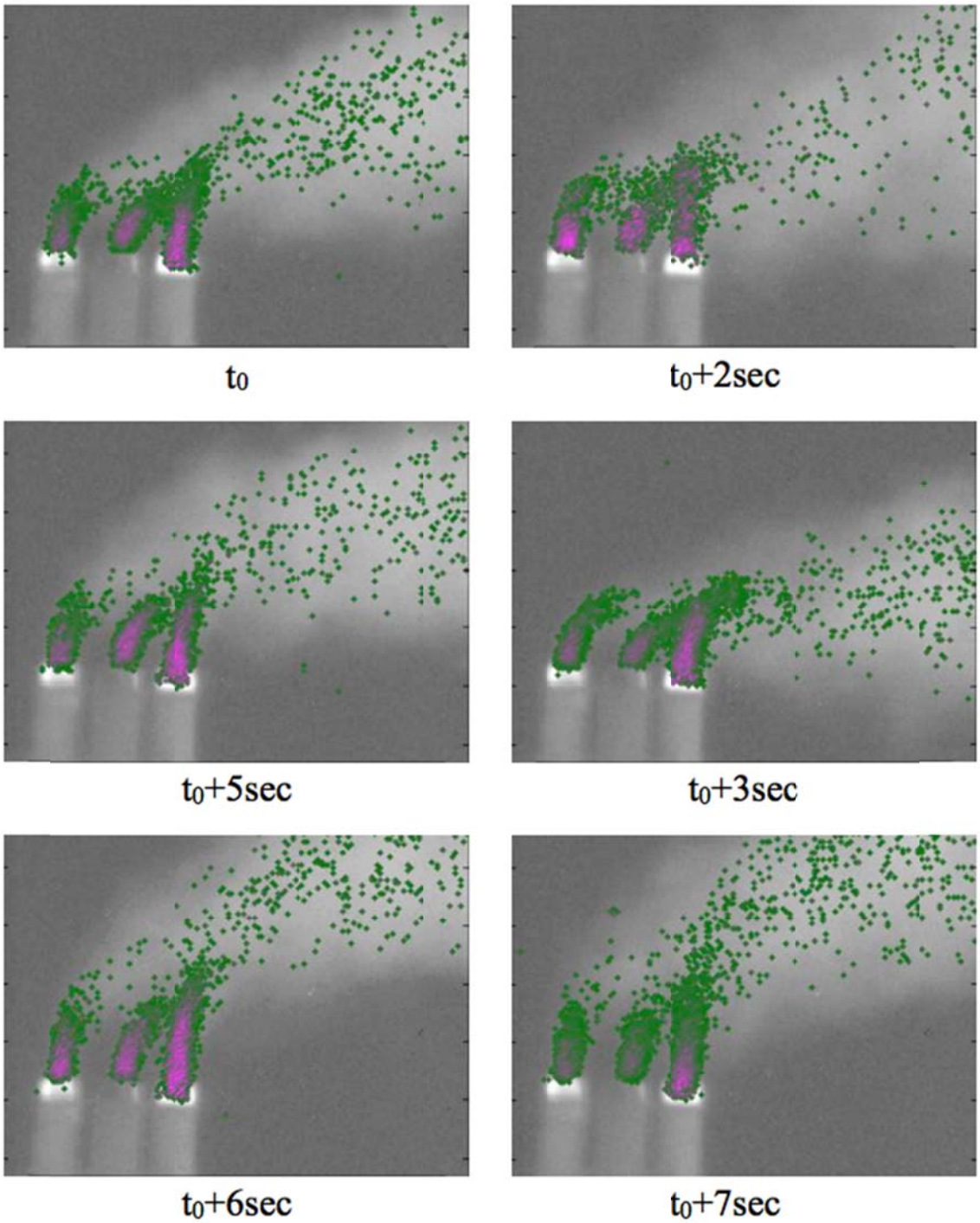

Figure 6: *Evolution of a carbone dioxide plume over a period of 7 seconds measured with iCATSI FPA*

CONCLUSION

This paper presents results obtained with newly developed hyperspectral imaging sensors. The analyses of the results have showed potential of these capabilities for the passive standoff detection, identification and monitoring of small-volume chemical pollutant industrial gas leaks. Development of high spectral sensitivity and high spatial resolution sensors is a key to providing new capabilities for health protection against industrial and accidental leaks.

The modularity of iCATSI provides a good platform to test several kind of LWIR detector (up to 14 μm) with good sensitivity against several types of scenarios. The combination of imaging spectroradiometry with high data cube rate enables very fine temporal and spatial observations of gas cloud evolution. In this study, the detection, identification and monitoring of surrogates and evaporated solvents were demonstrated in a real type scenario at standoff distance of up to 500 meters. The industrial site measurement provides a good understanding of the capability to control air quality and monitor for environmental disasters. These results demonstrate that HSI sensors can reach the sensitivity required to detect and monitor small-volume chemical leaks.

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