Airborne Thermal Hyperspectral Imaging of Gases using Mapping and Targeting Acquisition Modes

Characterization of freely dispersing gas clouds is a challenging task. The large area covered and uneven distribution of these fast moving entities makes conventional ground-based techniques inappropriate in some cases. The Fourier transform technology used in the Telops Hyper-Cam-LW (longwave, 7.7-11.8 μm) airborne platform allows recording of airborne hyperspectral data using two distinct acquisition modes: mapping and targeting. In order to illustrate the benefits of these two acquisition modes for gas imaging, airborne measurements were carried out on smokestacks and a ground-based ethylene (C_2H_4) gas release experiment. Quantitative airborne chemical images of ethylene gas clouds were obtained. The targeting acquisition mode, a unique feature of the Telops Hyper-Cam airborne platform, provides valuable time-dependent information on gas cloud dispersion such as the origin of the gas leak, the gas cloud direction and its velocity.

Introduction

Gas leak surveys and environmental monitoring are typical situations in which the characterization of gas clouds is involved. In some cases, flammable and/or toxic chemicals are involved which makes this task even more difficult. In crisis situations such as massive gas leaks, critical questions must be answered to help decision making: what is the chemical nature of the gas cloud, where does the gas leak originate (leak source), what is the gas concentration, where is the gas cloud heading (direction) and at what speed (velocity)? Many factors influence gas dispersion. In addition to the large areas typically covered by dispersing gas clouds, their concentration distribution is relatively uneven due to diffusion and convection transport mechanisms. Unsteady wind speed also contributes to gas cloud dispersion. The unpredictable dynamic associated with freely dispersing gas clouds in open air situations can make ground-based characterization impracticable.

Traditional gas sampling techniques (e.g. using pressurized canisters and bags) provide results which are subject to sampling issues and are time consuming since the samples need to be taken to a lab. In situ gas concentration measurements carried out using electrochemical cell sensors (gas sniffers) typically provide sensitive and accurate real-time results. Despite the great sensitivity of conventional gas measurement techniques, the later approaches provide single point results which are difficult to correlate with fast moving entities like dispersing gas clouds. Safety issued can be faced when attempting gas leak surveys on explosive gases.

Figure 1 Typical aircraft used for airborne surveys.

The great diversity of chemicals that may be encountered also reinforces the need for a versatile technique. Since many gases are infrared-active, i.e. absorb/emit infrared radiation in a very unique fashion, broadband infrared imaging represents an interesting approach since spatial-temporal information can be retrieved from safe distances. Selectivity issues as well as the lack of quantitative information about the gas cloud are known limitations of this technique. Ground-based thermal infrared hyperspectral imaging, based on Fourier transform spectroscopy (FTS), provides both selective and quantitative information and was proven successful in many field campaigns involving remote gas release detection, identification and quantification.[1-4] The same technology can now be used in airborne sensors (Figure 1), allowing coverage of large areas in addition of providing quantitative results and selectivity for gas and solid detection.

Airborne surveys are traditionally limited to single acquisitions over successive ground areas of interest. Recent progress in the development of thermal infrared hyperspectral sensors now allows FTS imaging using two different acquisition modes; mapping and targeting. In order to illustrate the benefits of the targeting acquisition mode over traditional mapping for gas cloud characterization, airborne measurements were carried out above an operating waste incinerator and a simulated ground-based gas release. Quantitative chemical imaging of an ethylene (C_2H_4) gas cloud was successfully achieved using the targeting acquisition mode. This illustrates how unique dynamic information on gas cloud dispersion can be obtained using airborne hyperspectral FTS-based imaging sensors.

Experimental Information

Telops Hyper-Cam

The Telops Hyper-Cam is a lightweight and compact hyperspectral imaging instrument which uses Fourier transform infrared (FTIR) technology. It provides a unique combination of spatial, spectral and temporal resolution for a complete characterization of the substances being monitored. Its high performance and efficiency for ground-based characterization of gas clouds has been proven through numerous field campaigns. The Hyper-Cam features a 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 3.0 to 5.0 or 7.7 to 11.8 µm spectral range for the Hyper-Cam MW (midwave) and Hyper-Cam LW (longwave) respectively.

The Telops Hyper-Cam Airborne Platform

The capabilities of the ground-based Telops Hyper-Cam, whether it is the MW or LW model,[5-6] can be extended for airborne applications using the Telops Hyper-Cam airborne platform (Figure 2). The very same Hyper-Cam sensor used for ground-based applications can be readily installed on a stabilization platform equipped with a global positioning system (GPS) and inertial motion unit (IMU) for georeferencing and tracking of the aircraft movements in flight. In the case of FTS imaging, data acquisition time for a single datacube can last up to a few seconds depending on acquisition parameters. Therefore, the airborne module is equipped with an image motion compensation (IMC) mirror which uses the GPS/IMU data to compensate efficiently for the aircraft movements during in flight data acquisition. The viewing angle change during data recording is typically less than 2°. All data include the relevant information for orthorectification and stitching. The airborne platform is also equipped with a high-resolution boresight camera which is used to record visible images at the same time as infrared data is collected. Chemical imaging is then carried out using a radiative transfer model developed by Telops.

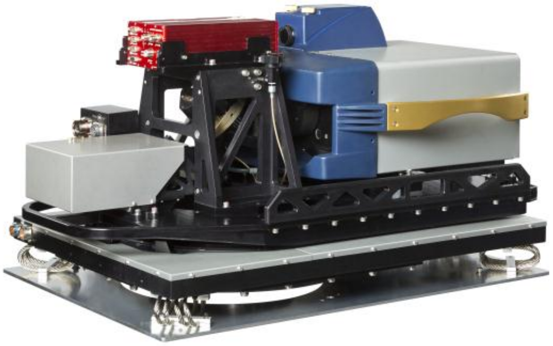

Figure 2 The Telops Hyper-Cam airborne platform.

Flight Conditions

All flights were carried out using a Hyper-Cam LW sensor. A wide angle telescope (0.25×, FOV of 25.6°×20.4°) was used for the measurements carried out over the waste incinerator. Measurements over the waste incinerator using the mapping acquisition mode were carried out at a spectral resolution of 4 cm^{-1} (i.e., 135 bands) and an altitude of 2130 meters leading to a ground pixel size of 9 m^2/pixel. Measurements over the waste incinerator using the targeting acquisition mode were carried out at a spectral resolution of 8 cm^{-1} (i.e., 68 bands) and an altitude of 915 meters leading to a ground pixel size of 1.65 m^2/pixel. Ambient temperature and relative humidity, at ground level, was 11 °C and 49 % respectively. Airborne measurements on the ethylene gas release, using the targeting acquisition mode, were carried out at a spectral resolution of 6 cm^{-1} (i.e., 90 bands) and an altitude of 685 meters leading to a ground pixel size of 0.057 m^2/pixel. Ambient temperature and relative humidity at ground level were 21 °C and 37 % respectively. Pure ethylene gas was released from a pressurized cylinder, connected to few meters of tubes, through a 6 mm nozzle at a constant flow rate of approximately 20 L/min.

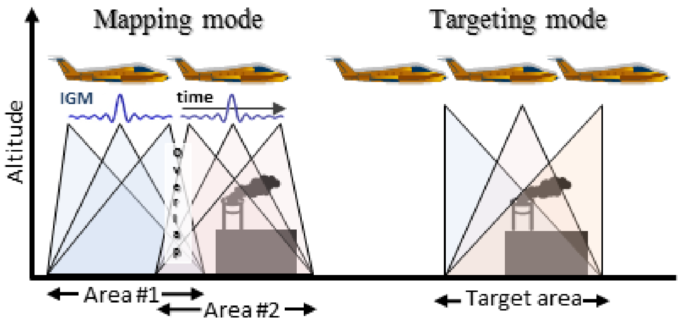

Figure 3 Mapping (left) and targeting (right) hyperspectral imaging acquisition modes of the Telops Hyper-Cam airborne platform. The viewing angle change occurring during each time-dependent measurement was greatly amplified for illustration purposes. The interferogram (IGM) display was omitted in the targeting illustration for clarity purposes.

Mapping vs Targeting Acquisition Mode

Airborne hyperspectral imaging can be carried out in two distinct acquisition modes as illustrated in Figure 3. The mapping acquisition mode is representative of most airborne sensors where individual images or datacubes, (in the case of hyperspectral sensors) are continuously recorded as the aircraft flies above its area of interest (AOI). The targeting acquisition mode takes full advantage of the IMC mirror component as it can be used to record successive hyperspectral datacubes of the same AOI, named the target area in this case. Data acquisition is typically optimized to record, depending on ground speed and altitude, as many datacubes as possible while the aircraft approaches, flies above, and beyond the target area.

Results and Discussion

Airborne FTS Imaging

The FTS infrared technology used in the Telops Hyper-Cam airborne platform allows data acquisition at relatively high spectral resolution. The FTS infrared technology used in the Telops Hyper-Cam airborne system provides much higher spectral resolution than conventional push broom airborne sensors, working in the thermal infrared spectral range, that are typically limited to ~32 spectral bands. Such an advantage over other available airborne systems on the market brings higher selectivity for remote detection and identification purposes. In addition, high spectral resolution also benefits airborne image analysis since common signal processing algorithms like atmospheric correction and temperature-emissivity separation rely on accurate compensation of water vapor and ozone contributions. Typical results obtained with the Telops Hyper-Cam airborne platform are shown in Figure 4 and illustrate, at the same time, the great variability of targets encountered in airborne surveys.

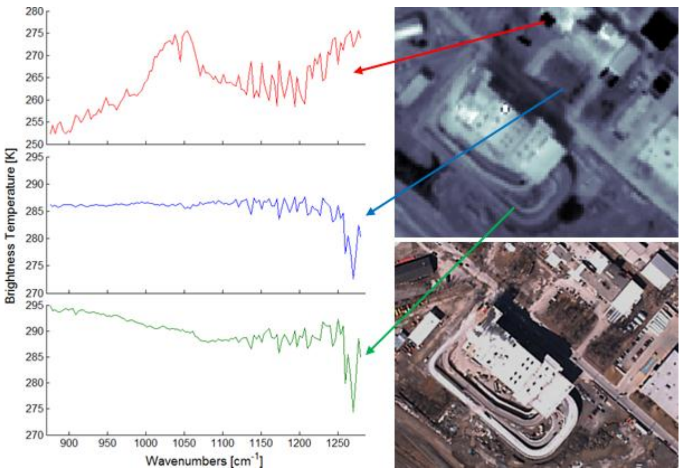

Figure 4 Thermal infrared hyperspectral datacube (top right) and its corresponding visible image (bottom right) recorded with the Telops airborne platform. The infrared spectra of selected pixels corresponding to a reflective metallic surface (red curve, top left), grass (blue curve, middle left) and a concrete road (green curve, bottom left) are also represented.

In the thermal infrared spectral range, both reflection and self-emission occur concurrently. Therefore, low-emissivity surfaces can be acknowledged from recognition of spectral features associated with the sky (ozone and water emission bands). The red curve in Figure 4 is highly representative of the thermal infrared spectrum of a clear sky. Close inspection of the associated visible image reveals that the associated pixel corresponds to a metallic roof surface, thus reflecting, the sky. The infrared spectrum represented by the blue curve in Figure 4 corresponds to a pixel associated with grass. Vegetation mostly behaves like a grey body (no spectral features) in the longwave infrared spectral range. Therefore, the series of sharp absorption bands observed in the infrared spectrum are associated with atmospheric water vapor. The infrared spectrum represented by the green curve in Figure 4 corresponds to a pixel associated with a concrete road. The sand used in concrete preparation, which mostly contains quartz (SiO_2) mineral, has well known absorption bands in the 1075-1225 cm^{-1} spectral range. A broad absorption signal associated with the quartz spectral features can be seen in the infrared spectrum along with the omnipresent absorption bands associated with atmospheric water vapor.

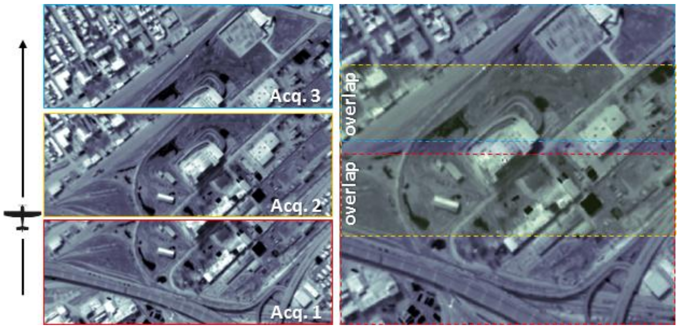

Figure 5 Individual airborne FTS infrared acquisitions from an area containing an operating waste incinerator using the mapping acquisition mode (left). The associated hyperspectral map (mosaic datacube), resulting from stitching and orthorectification of individual acquisitions, is shown on the right.

Waste Incinerator: Mapping Acquisition Mode

An airborne survey was carried out on an area containing an operating waste incinerator. Individual datacube acquisitions from this survey, recorded using the mapping acquisition mode, are illustrated in Figure 5.

Broadband infrared images, resulting from radiance integration over the whole FPA detector spectral range, are displayed instead of an arbitrary slice in the hyperspectral datacube. In order to generate a suitable hyperspectral map from individual acquisitions of a smaller size, sufficient overlap, from neighbouring ground areas, must be included in each acquisition. This greatly facilitates the stitching procedure to produce a single datacube of the whole AOI. The hyperspectral map of the whole AOI, resulting from orthorectification and stitching of three (3) individual acquisitions is shown in Figure 5.

Waste Incinerator: Targeting Acquisition Mode

The information contained in each hypercube acquisition is representative of a snapshot at the moment of the recording. For moving entities like gas clouds, the information retrieved from a single measurement is very limited. In order to illustrate how time-dependent information can be obtained using a hyperspectral airborne sensor, measurements were carried out over the same AOI using the targeting acquisition mode. The target area contained an operating waste incinerator as illustrated in Figure 6. A total of 6 successive hyperspectral datacubes were recorded as the aircraft surveys the installations.

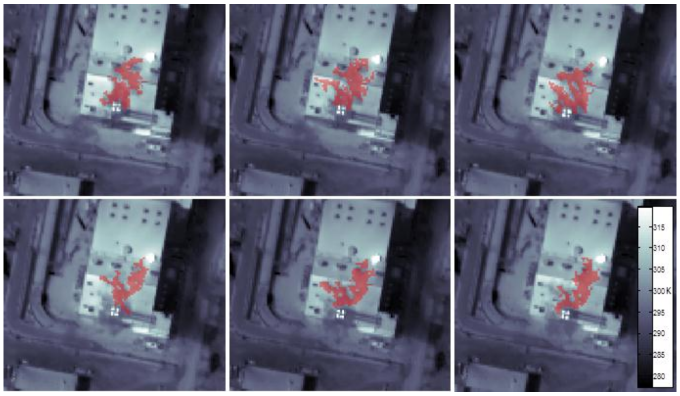

Figure 6 Successive airborne acquisitions of an operating waste incinerator using the airborne FTS infrared targeting acquisition mode. The red clouds correspond to the gases emitted from the main smokestack.

As expected, the hottest spot in the image corresponds to the smokestack output. Chemical imaging of the combustion gases was carried out in each image of Figure 6 (red cloud) to highlight the dynamic associated with gas cloud dispersion as a function of time. Although the conclusion is somewhat obvious for a smokestack, the gas cloud source point can be deduced when comparing the different images. This type of result is unique to the Telops Hyper-Cam airborne system and cannot be obtained using other conventional push broom airborne systems.

Ethylene Gas Release: Targeting Acquisition Mode

Airborne thermal infrared hyperspectral measurements were carried out on a test site where pure ethylene gas was released. Ethylene is a flammable gas massively used worldwide in the production of many polymer materials. During this experiment, ethylene gas was being released prior and during the airborne survey of the target area. The visible image recorded during the gas release experiment is shown in Figure 7 as well as the associated infrared image of the target area. The infrared image was obtained by taking the average spectral radiance value, recorded over the complete detector spectral range, expressed on a brightness temperature scale.

Figure 7 Airborne visible image of the gas release area (left) and infrared broadband image of the target area of interest (right). Areas corresponding to the asphalt pavement and a location near the gas release point are labeled by α and β respectively.

The ethylene gas is expected to be colder than the background asphalt pavement since the gas is released from a pressurized cylinder (Joule-Thomson effect). Even though gas is being released during the datacube acquisition, no contrast associated with the presence of cold infrared-active gas can be seen on the image. This can be explained by the sharp and highly localized infrared spectral features of ethylene which do not contribute significantly to the overall signal once averaged.

The gas release point is located near the β label in Figure 7 while the α label is representative of the background asphalt pavement. The infrared spectra of these two distinct areas are represented in Figure 8, on a brightness temperature scale, as well as relevant reference absorption spectra.

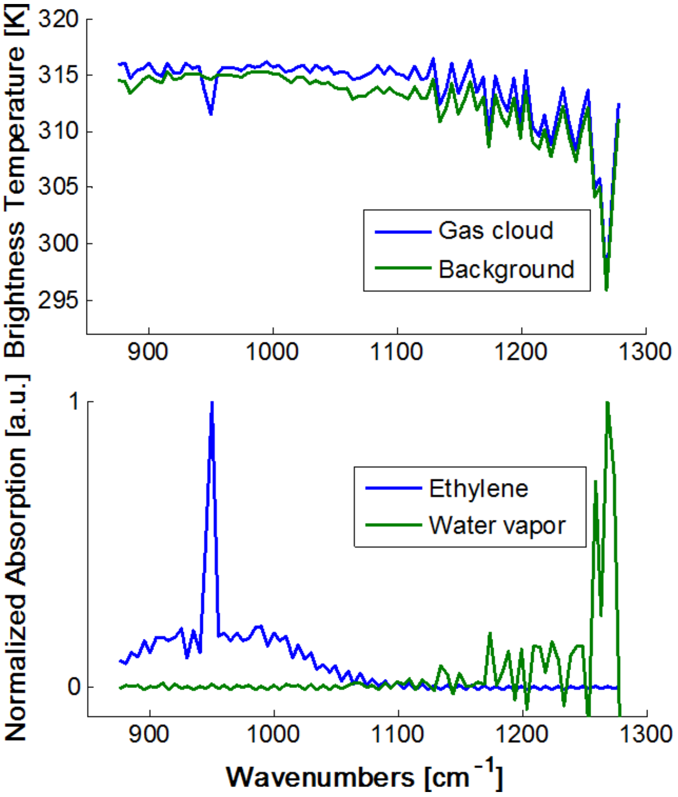

Figure 8 Longwave infrared spectra of representative pixels located in the gas cloud and on a background area (top). Reference absorption spectra of ethylene and water vapor are displayed at the instrument's spectral resolution for comparison purposes (bottom).

The series of sharp absorption bands in the 1100–1300 cm^{-1} are associated with atmospheric water vapor while the distinctive sharp absorption band at 950 cm^{-1} is a spectral feature highly characteristic of ethylene gas.

Quantitative chemical imaging was carried out on two successive acquisitions recorded on the target area of interest and the results are shown in Figure 9. The complete gas cloud spreads over a relatively large area which easily reaches tens of square meters. The gas cloud is being pushed away by the dominant West-East (up-down in the images) wind. Due to unsteady wind conditions near buildings, the gas cloud appears as split into two portions, one being located near the release point and one in the lower part of the field-of-view. As expected, a relatively uneven concentration distribution is observed in both images. A higher column density is estimated in the central portion of the gas cloud than around its edges; a likely consequence of diffusion. From successive airborne measurements on a freely dispersing gas cloud, it is also possible to locate, with greater precision, where the gas leaks originate. In this case, both chemical images point toward the same origin which matches precisely the gas release location.

Estimation of the gas cloud velocity was achieved by analyzing the differences between the two chemical maps presented in Figure 9. The central portion of the gas cloud, where the column density was estimated the highest in both images, moved by about 20 pixels, i.e. 4.8 meters, during an acquisition period of time which lasted 1.15 s. This translates into a linear velocity of about 15 km/h, a value that closely matches the reported wind speed and orientation at the time of the gas release experiment.

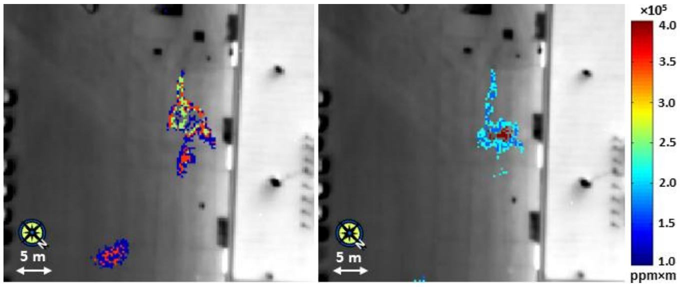

Figure 9 Quantitative airborne chemical imaging carried out on two successive measurements of an ethylene gas cloud using hyperspectral targeting acquisition mode.

Conclusion

The selectivity provided by the high spectral resolution of airborne infrared FTS hyperspectral imaging allows quantitative chemical imaging of gas clouds with good accuracy. The targeting acquisition mode, a unique feature of the Telops Hyper-Cam airborne system, brings valuable time-dependent information for characterization of gas cloud dispersion such as the origin of a gas leak and the direction and velocity of a gas cloud. The good correlation with the expected results illustrates the potential of airborne thermal infrared hyperspectral imaging for characterization of gas cloud dispersion.

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] M. Chamberland et al., High-Performance Field-Portable Imaging Radiometric Spectrometer Technology For Hyperspectral Imaging Applications, *Proc. of SPIE* **2005**, *5994*, 59940N-1.

[3] K. Gross et al., Remote Identification and Quantification of Industrial Smokestack Effluents via Imaging Fourier-Transform Spectroscopy, *Environ. Sci. Technol.* **2010,** *44*, 9390–9397.

[4] Remote Quantification of Greenhouse Gas Emissions from a Power Plant, *Application Note*, Telops.

[5] Airborne Midwave Infrared Mapping for Environmental Monitoring Applications, *Application Note*, Telops.

[6] E. Puckrin et al., Airborne Measurements in the Infrared Using FTIR-based Imaging Hyperspectral Sensors, *Proc. of SPIE* **2009**, *7624*, 73240R-1.

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