Airborne Midwave Infrared Mapping for Environmental Monitoring Applications

Gas emissions from industrial plants located near residential areas can seriously impact the quality of life in these neighbourhoods. Airborne infrared hyperspectral imaging, in the midwave spectral range (3-5 μm), was carried out over different operating plants in order to characterize the gas plume coverage as well as the chemical nature of emission constituents. Water vapor (H_2O) was discriminated from an aerosol cloud formed upon condensation of the water vapor in the gas emissions coming from a waste incinerator and a paper mill. Quantitative chemical imaging of carbon monoxide (CO) and carbonyl sulfide (OCS) gas, emitted from an aluminum smelter plant, was successfully carried out illustrating the versatility of this technique for environmental monitoring applications.

Introduction

Gas emissions from industrial plants located near residential areas is a worldwide problematic that affects public health in many ways (Figure 1). People living near industrial areas can be bothered, when the wind direction changes in an unfavorable way, by strong odors likely associated with gaseous emission from a nearby plant. In the worst case, they can even be exposed to toxic chemicals. Since the gas plume may cover a large area, it can be hard to get a clear picture of the whole situation.

Figure 1 A chemical plant located near a residential neighbourhood.

The chemical nature of gases found in gas emissions from industrial plants is highly associated with the plant's manufacturing process. Consequently, a great variety of gases can be expected reinforcing the need of a versatile tool to address this problematic. Carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl) and water vapors (H_2O) are among the most commonly encountered chemicals found in gas emissions from industrial plants. Since all of them are infrared-active molecules, airborne infrared remote sensing provides a valuable approach to characterize the extent of the gas plume, its direction and how it spreads over an area of interest. In order to get reliable results, the use of infrared hyperspectral imaging presents the best approach as chemical imaging is carried out using the unique infrared spectral features of each target.

In order to illustrate the benefits of airborne midwave infrared (3-5 μm) hyperspectral imaging for measuring gas emissions from industrial plants, mapping of urban areas composed of different industrial plants was carried out using the Telops Hyper-Cam airborne platform. Quantitative chemical imaging of CO, sulfide carbonyl (OCS) was successfully carried out over an aluminum smelter. Airborne measurements carried out above a waste incinerator and a paper mill demonstrate how water vapor can be distinguished from aerosol clouds formed by condensed water. The measurements agree with the expected results from various situations, illustrating the versatility of the airborne Hyper-Cam sensor to characterize industrial areas for environmental applications.

Experimental Information

The Telops Hyper-Cam Airborne Platform

The Telops Hyper-Cam is a lightweight and compact hyperspectral imaging instrument which uses Fourier Transfer 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 as a standoff chemical agent detector has been proven through numerous field campaigns. The Hyper-Cam MW (mid-wave) features a Focal Plane Array (FPA) detector which contains 320×256 pixels over a basic 6.4°×5.1° field of view. The spectral resolution is user-selectable up to 0.25 cm^{-1} over the 3.0 to 5.0 µm spectral range.

The capabilities of the ground-based Telops Hyper-Cam can be extended for airborne applications using the Telops airborne platform (Figure 2). The very same Hyper-Cam sensor used for ground 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 (Figure 2). An image motion compensation (IMC) mirror uses the GPS/IMU data to compensate efficiently for the aircraft movements during data acquisition. The data includes all the relevant information for orthorectification and stitching. Chemical imaging is then carried out using a radiative transfer model developed by Telops.

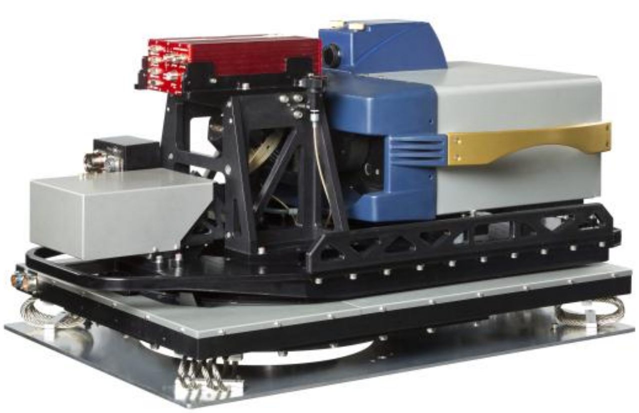

Figure 2 The Telops Hyper-Cam Airborne Platform

Flight Conditions

All flights were carried out at an altitude of 3000 meters and a speed of 110 knots, leading to a ground pixel size of 1 m^2/pixel. A spectral resolution of 9 cm^{-1} was used which gives a total of 110 spectral bands over the whole range covered by the FPA detector. Outside temperature and relative humidity at ground level were 2 °C and 68 % respectively.

Results & Discussion

Atmospheric Transmittance in the Mid-Wave Infrared Spectral Range

The atmosphere contains several constituents which are infrared-active in the 3-5 µm spectral range. Among them are H_2O, CO_2, nitrous oxide (N_2O) and methane (CH_4). In a model environment, the ground surface behaves like a blackbody source and its radiance can be approximated by a Planck curve L_{bkg} at ground temperature. By multiplying this quantity by the atmospheric transmittance (τ_{atm}), we obtained the fraction of the energy which was not absorbed by the infrared-active atmospheric components. The self-emission corresponding to the absorbed energy is expressed by the term $L_{atm}(1-\tau_{atm})$ in Equation 1.

Equation 1 $$L_{tot} = L_{bkg}\tau_{atm} + L_{atm}(1-\tau_{atm})$$

Since the temperature of the atmospheric component is significantly lower than the ground temperature, their self-emission is largely overwhelmed by absorption of the background radiance. Consequently, the total spectral radiance (L_{tot}) measured by a mid-wave infrared airborne sensor will be lower than L_{bkg} at wavenumbers associated with molecular absorption/emission bands of H_2O, N_2O, CO_2 and CH_4 as illustrated in Figure 3.

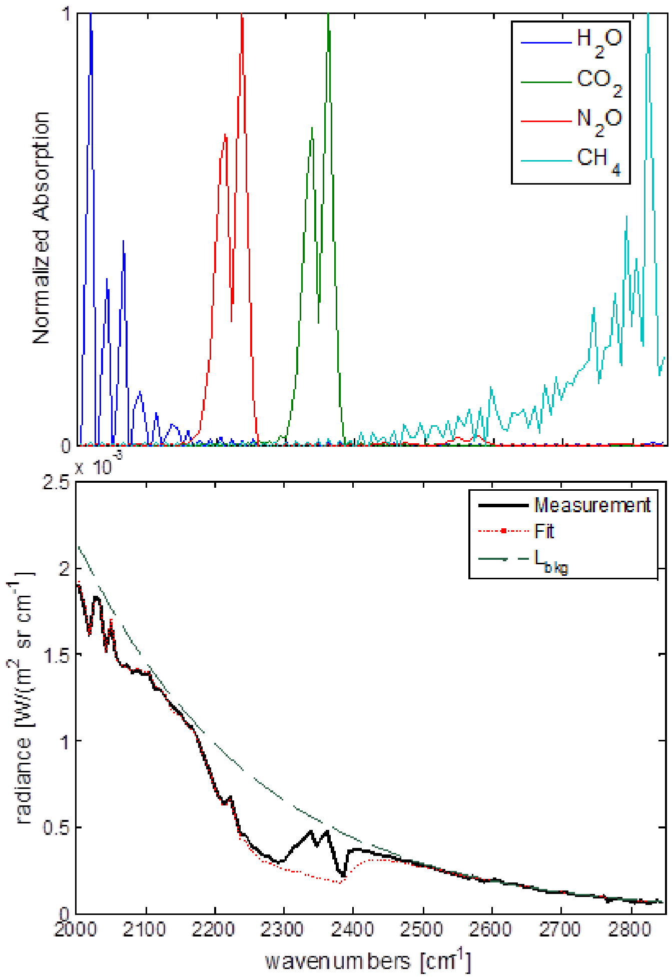

Figure 3 Absorption spectra of the main infrared-active atmospheric components (top) and a typical midwave infrared spectrum (black curve) recorded at a 3000 m altitude (bottom). The best fit of Equation 1 is represented by the red curve and a Planck curve, corresponding to the green spectrum for clarity purposes.

A typical pixel from a midwave infrared hyperspectral datacube, recorded at a 3000 meters altitude, is represented in Figure 3 as well as the non-linear regression of Equation 1. The simulation agrees well with the measurement. The dip between 2300 – 2400 cm^{-1} is a radiometric calibration artifact caused by CO_2 and was omitted in the fits.

Aluminium Smelter

Airborne measurements were carried out over an operating aluminum smelter which is known for emitting CO gas as expressed in Equation 3. Carbon monoxide is among the main reaction product from the reduction of aluminum oxide (Al_2O_3) into metallic aluminum ($Al_{(s)}$).

Equation 2 $$Al_2O_3 + 3C_{(s)} \rightarrow 2Al_{(s)} + 3CO_{(g)}$$

The phenomenology associated with the observation of a gas plume from an airborne sensor is illustrated in Figure 4.

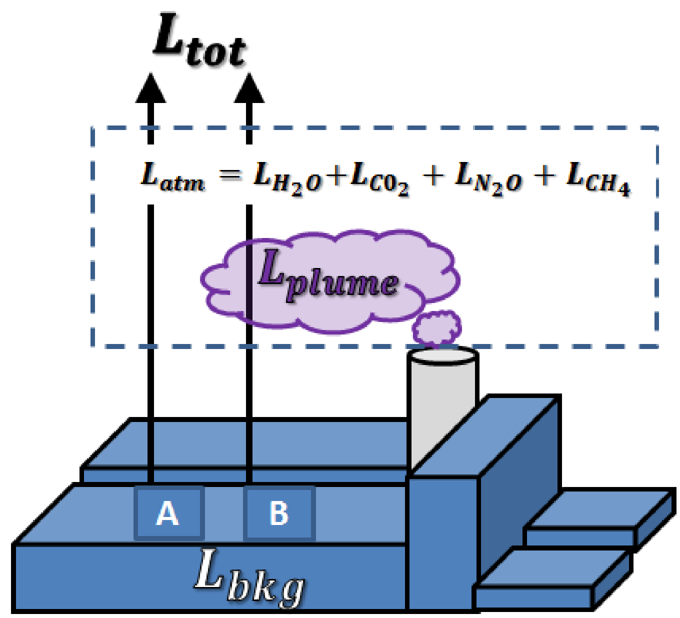

Figure 4 Phenomenology associated with airborne infrared hyperspectral imaging of a gas plume from a ground smokestack. Situation A is representative of a background area while situation B is representative of a gas plume.

In this situation, the gas plume from the smokestack will only transmit (τ_{plume}) part of the background radiance, i.e. L_{bkg}, as a result of the infrared-active components in the emission gases. The infrared self-emission from these gases is expressed by the term $L_{plume}(1 - \tau_{plume})$. In most cases, the gas emissions resulting from the manufacturing process are significantly hotter than their environment and the surrounding ground. Therefore, the self-emission contribution to the measured radiance will dominate and the overall spectral radiance (L_{tot}) will be higher than L_{bkg} at wavenumbers associated with molecular absorption/emission bands corresponding to infrared-active component in the gas plume. The resulting in radiative transfer equation is summarized in Equation 3.

Equation 3 $$L_{tot} = [L_{bkg}\tau_{plume} + L_{plume}(1 - \tau_{plume})]\tau_{atm} + L_{atm}(1 - \tau_{atm})$$

A typical infrared spectrum corresponding to a pixel located near one of the smokestacks is represented in Figure 5. Both carbon monoxide (CO) and carbonyl sulfide (OCS) could be successfully identified and quantified in the gas plume. The presence of OCS can be explained by anode consumption during aluminum electrolysis.[1]

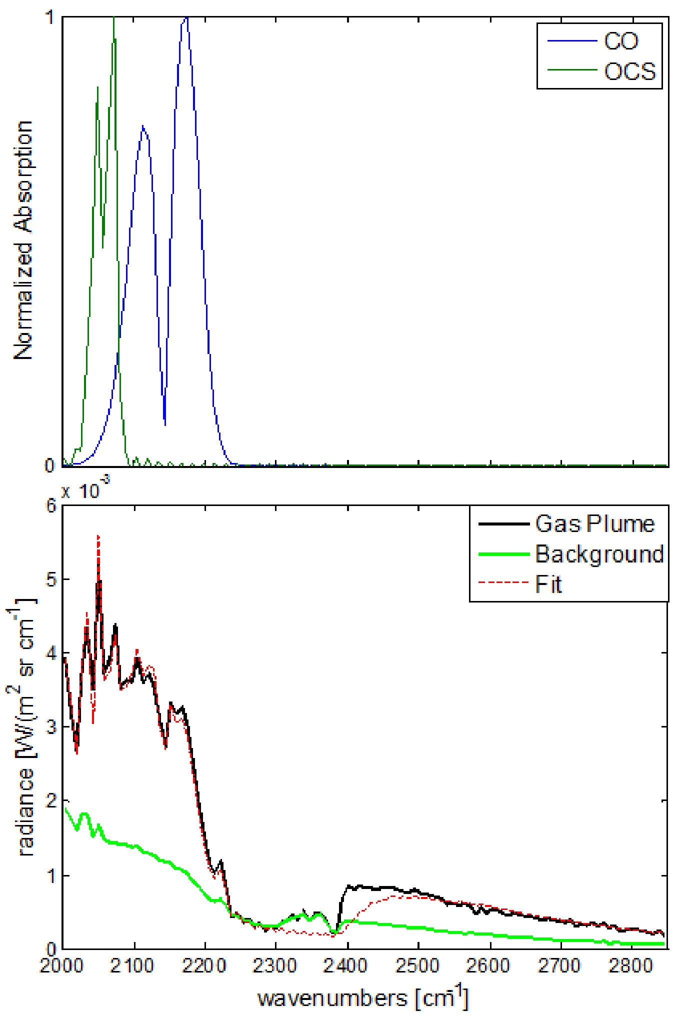

Figure 5 Airborne midwave infrared spectra of pixels corresponding to the gas plume of the aluminum smelter (black curve) and a typical background area (green curve). The best fit for Equation 3 is represented by the red curve (top). The absorption spectra of CO and OCS are shown for comparison purposes (bottom).

The transmittance value (τ) is proportional to the infrared spectral response (ε), the path length (l) and the concentration (c) as expressed in Equation 4. Therefore, quantitative information can be retrieved from the estimated transmittance results using a proper radiative transfer model. Since the extent of the gas plume, i.e. l, cannot be estimated from a 2D-image, quantification results are typically expressed in terms of column density values with units of ppm×m. Quantitative airborne chemical imaging of CO and OCS was successfully carried out and the results are shown in Figure 6.

Equation 4 $$\tau = e^{-(\varepsilon l c)}$$

The CO and OCS column density, results estimated for pixels located near the smokestack exit, were 120 000 ±1200 and 150 ±50 ppm×m respectively.

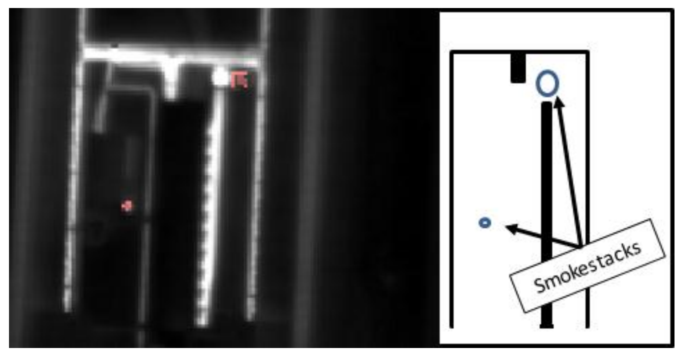

Figure 6 Quantitative chemical imaging of carbon monoxide (CO, red cloud) and carbonyl sulfide (OCS, yellow cloud) from an operating aluminum smelter (Left). A schematic view of the main structures of the aluminum smelter is shown on the right.

Waste Incinerator and Paper Mill

Airborne measurements over a waste incinerator and a paper mill were carried out to address situations where large amounts of water vapor are present in the emission gases. Water and carbon dioxide are the main combustion products from organic material while pulp and paper mills use a lot of steam in the production process. However, the ambient temperature (2 °C) was near water's freezing point at the time of the measurement. Consequently, water vapors readily condense and form aerosol clouds. Water droplets (aerosol) behave differently than gas-phase water as they have the property of scattering and reflecting infrared radiation. Consequently, spectral features associated with sun reflection, passing through the Earth atmosphere, allow to readily distinguish condensed water vapor, i.e. aerosol cloud, from gas-phase water.

Chemical imaging of water vapor and aerosol clouds from the waste incinerator and the paper mill is shown in Figure 7 and Figure 8. As expected, water molecules are completely in the gas phase at their exit from the smokestacks and condensate further as their temperature drops below the condensation point.

Due to the low atmospheric transmittance in the spectral range associated with CO_2, ground sources of CO_2, as in the case of the waste incinerator, are difficult to measure from a large distance as in the case of an airborne mid-wave infrared sensor.

Figure 7 Chemical imaging of water vapor (H_2O, yellow cloud) and water aerosol cloud (red cloud) from a waste incinerator (top). Visible image (bottom) is shown for comparison purposes.

The airborne infrared hyperspectral data allowed successful identification of different chemicals from various industrial plants. Quantitative chemical imaging of the individual components was carried out with a good accuracy.

The results illustrate the potential of airborne mid-wave infrared hyperspectral imaging for efficient characterization of gas plumes over large areas.

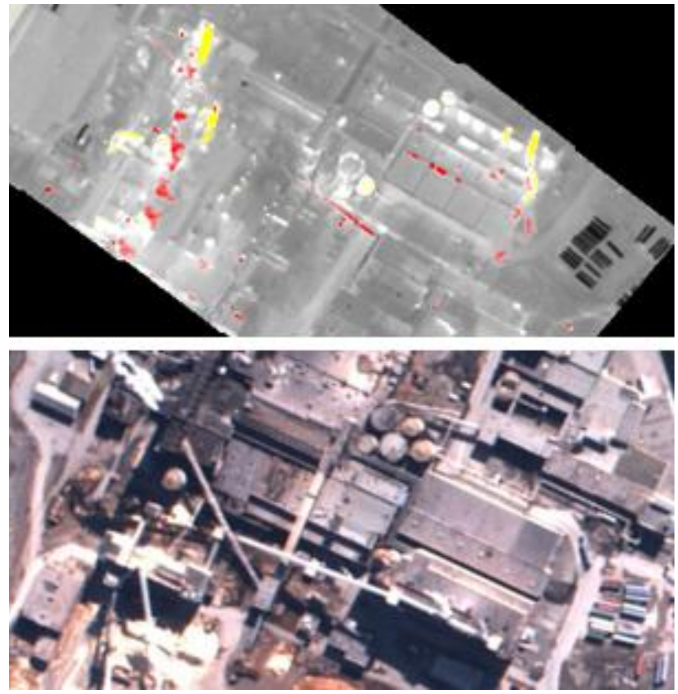

Figure 8 Chemical imaging of water vapor (H_2O, yellow cloud) and water aerosol cloud (red cloud) from a paper mill top). Visible image (bottom) is shown for comparison purposes.

Conclusion

The airborne infrared hyperspectral data allowed successful identification of different chemicals from various industrial plants. Quantitative chemical imaging of the individual components was carried out with a good accuracy. The results illustrate the potential of airborne mid-wave infrared hyperspectral imaging for efficient characterization of gas plumes over large areas.

References

[1] S. J. Hay, The Formation and Fate of Carbonyl Sulfide (COS) gas in aluminum smelting, Ph.D. Thesis, The University of Auckland, New Zealand, 2002.

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