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# Gas imaging by infrared gas-correlation spectrometry

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We describe a new method for visualization of gas flows based on infrared absorption and gas-correlation techniques. This result is a gray-scale or false color-coded image showing the distribution of a specific gas in the area studied. A sequence of images showing the workplace test setup with a turbulent flowing gas is presented. © 1996 Optical Society of America

In many applications there is an interest in finding and visualizing gas plumes in real time. Images of gas concentration distributions are needed in several environmental studies. Global mapping of greenhouse gases from spacecraft-based systems is important.<sup>1-3</sup> Two industrial applications are hydrocarbon emission monitoring from petrochemical installations and leakage detection along pipelines. Indoor monitoring of the working environment and surveillance of hazardous gases are other fields for which imaging is useful. Nitrous oxide leaking from anesthetic masks in operating theaters has been studied with an IR camera with absorption of the gas throughout the spectral region of the camera.<sup>4</sup> The gas can be confined by turbulent flow around the breathing zone of the anesthetist, and ventilation aspects are studied with this method. An active method that uses a carbon dioxide laser that scans the detector field of view is one way to detect gas leaks in industrial environments.<sup>5</sup> Another method uses IR emitters and a retroreflector screen to visualize gas absorption.<sup>6</sup> Gas-correlation spectrometry<sup>7</sup> is a particularly simple and powerful technique that uses an absorption spectrum in a measuring system that is compared with the spectrum of incoming light, and a signal proportional to the number of absorbing molecules of a specific kind is generated. Gas-correlation spectrometry was employed previously in passive point monitoring<sup>8</sup> and in laser radar.<sup>9</sup>

We describe a new method that makes it possible to visualize gases and estimate their concentrations in a two-dimensional image based on IR absorption and gas-correlation techniques. First we recapitulate the point monitoring principle (Fig. 1). The incoming light is sent through a cell containing the gas to be studied at such high concentration that little or no light can pass at the absorption wavelength and then through a variable neutral-density filter. With no external gas present the variable filter is adjusted so that equal intensities are obtained in the spectral region cut out by a bandpass filter. Now, if an external pollution plume is present the signal in the gas cell arm is not affected (except for a minor broadening of the absorption lines) because no more than full absorption can be obtained. The incoming light in the other arm is reduced because of absorption lines in the plume. The imbalance introduced into the two arms is a measure of the gas

concentration in the plume. Note that the presence of interfering gases does not affect the concentration measurement.

In our experiments two images of the flowing gases are formed at the same time on an IR-sensitive camera with a compact Cassegrainian split-mirror telescope.<sup>10</sup> A bandpass filter is used to isolate a small spectral region containing absorption features of the gas to be studied. In front of one part of the telescope a short CaF<sub>2</sub> cell filled with a high concentration of the gas is mounted. The other part of the telescope gives a direct image. The images are correlated in a computer to eliminate differences in background illumination as well as the interference by other gases and particles. The correlation or image processing consists of mainly two steps, in which the first step is to

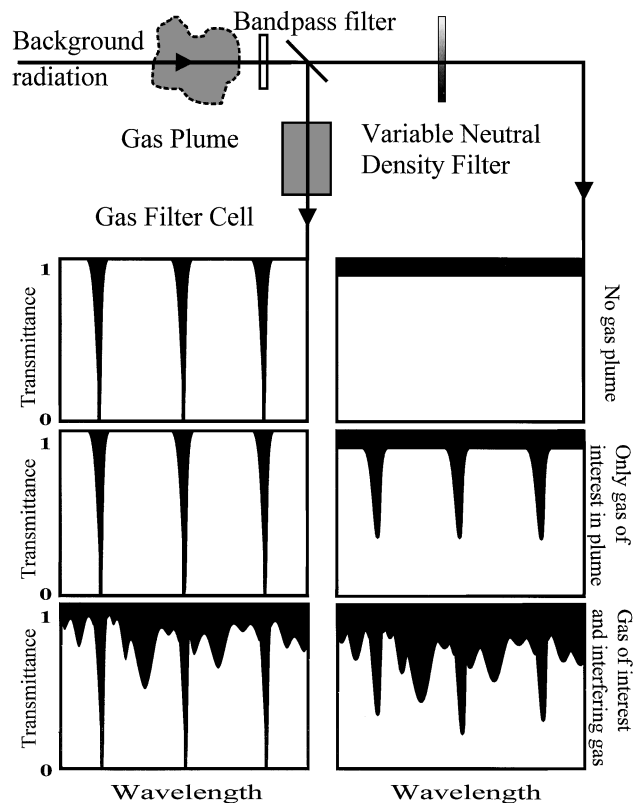


Fig. 1. Point monitoring principle of a gas-correlation spectrometer.

choose a region of interest in the direct image. The direct image is then divided with the gas-filtered image. To divide the images without losing intensity dynamics we multiply the gas-filtered image by a factor. The other step is to optimize the overlap between the images by minimizing the standard deviation of the divided images, which cancels the background and interfering gases. The result is a gray-scale or false color-coded picture showing only the distribution of the specific gas. Flow and concentration in two dimensions can be presented in nearly real time.

Experiments have been performed on flows of methane, nitrous oxide, and carbon dioxide at a workplace test setup as shown in Fig. 2. An Agema Thermovision 900 SW system was employed, and the images were converted from an industrial file format to standard file formats and processed with Concept V.i software on a LabView platform. The camera detector (InSb) was cooled to 77 K, and its sensitivity to IR radiation in the region 2–5.6  $\mu\text{m}$  was restricted by use of either of two bandpass filters, with center wavelengths at 3.35 and 4.54  $\mu\text{m}$  and full half-widths of 0.16 and 0.27  $\mu\text{m}$ , respectively. We chose the filters by using the HITRAN database<sup>11</sup> for the detection of methane and nitrous oxide, but carbon dioxide and water also absorb in these regions. An IR heater was used to illuminate the background. We created a turbulent flow from the nozzle by letting the gases pass through a water lock. In our experiments we mixed the gases by using pressure regulators and in that way controlled the composition of the gas flow. Figure 3 shows the spectral region cut out by the bandpass filter with a center wavelength of 4.54  $\mu\text{m}$ . As can be seen,  $\text{CO}_2$  and  $\text{N}_2\text{O}$  do not interfere in this region, but the simultaneous capture of the direct and the gas-filtered images has the advantage of ensuring that background radiation variation and motion do not affect the resulting image.

Correlation spectrometry enhances the signal-to-noise ratio in the small spectral region cut out by the bandpass filters by turning the gas of interest into its own spectral filter, thereby specifically selecting the gas. In Fig. 4, as an example, the absorption lines of  $\text{C}_2\text{H}_6$  (solid curves) are seen to interfere with the absorption lines of  $\text{CH}_4$ , but it is possible to discriminate  $\text{C}_2\text{H}_6$  from  $\text{CH}_4$  with the gas-correlation approach. Several interesting and environmentally important gases, such as hydrocarbons, sulfur compounds, and nitrous compounds, have vibration-rotation absorption in the IR region. The absorption strength of the gases that we examined increases with the wavelength in the region 2–5.6  $\mu\text{m}$ , but the detector sensitivity falls off with increasing wavelength. This trade-off forced us to choose spectral regions within 3–4.5  $\mu\text{m}$ . Another trade-off is the fact that more energy hits the detector with broad bandpass filters but the specificity of the gas as a spectral filter, with respect to signal-to-noise, is worse with broad bandpass filters. Careful design of the bandpass filters and estimates of the total gas absorption strengths are needed. Water absorbs over broad spectral regions, with strong absorption in some cases, and we take this into account by positioning the bandpass

filters in spectral windows where water absorption is weak.

The resulting images in a sequence of four with 1 s between successive images are shown in Fig. 5. In image 1 a person is approaching the workplace setup with turbulent flowing gases from the water lock. The gas that is seen is nitrous dioxide in a mixture of carbon dioxide and water. In image 2 the person starts to move against the nozzle and thereby disturbs the flow. Image 3 shows the person in profile holding his breath. Image 4 shows a movement with the left arm. The sequence continues with six more images and can be shown as a movie. One of the more important aspects of these photographs, besides the fact that a specific gas can be visualized, is the effect that such a movie

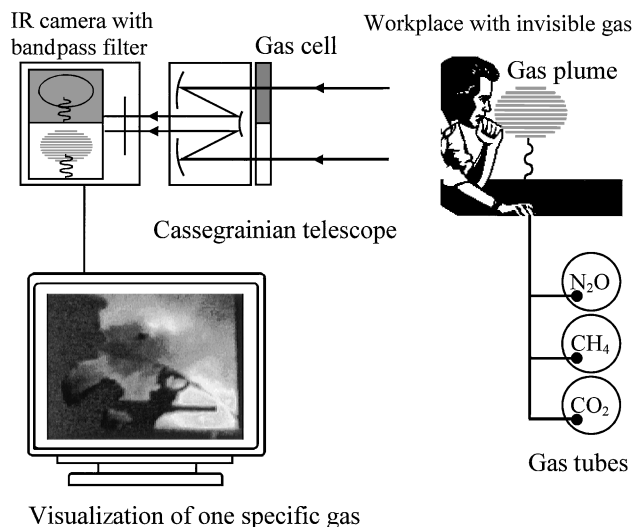


Fig. 2. Schematic diagram of the experimental arrangement.

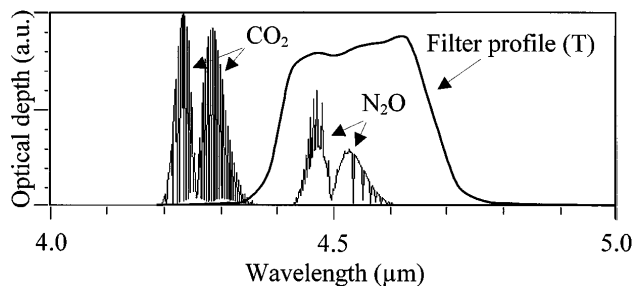


Fig. 3. Spectral features of  $\text{CO}_2$  and  $\text{N}_2\text{O}$ . The transmission of the bandpass filter used is also indicated ( $T_{\text{max}} = 85\%$ ).

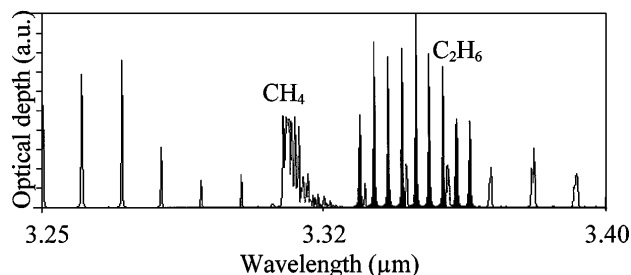


Fig. 4. Interfering spectral features of  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$ .

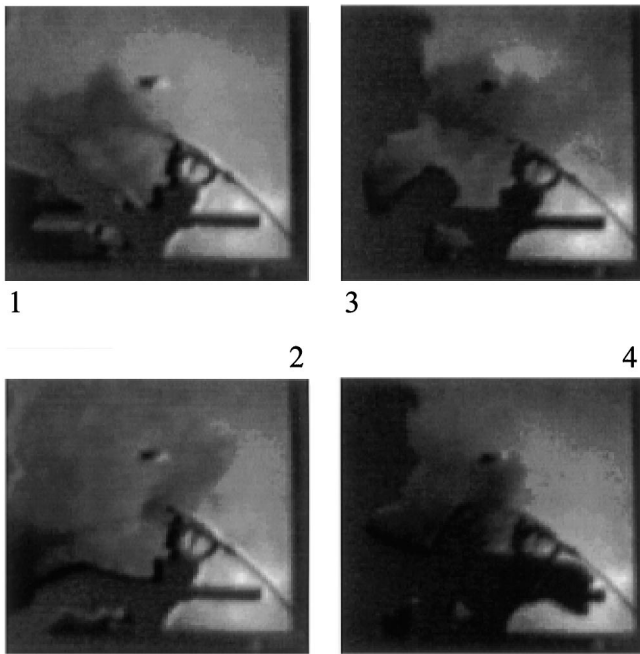


Fig. 5. Gas-correlated images in sequence (without gray-scale manipulation). The visualized gas was  $N_2O$  in a mixture of water vapor and  $CO_2$ . The time between successive pictures was 1 s.

has on workers in real working environments.<sup>12</sup> The power of showing his or her exposure to a worker makes it possible for him or her to avoid certain dangerous work steps, and the ability to use the movie as a tool for creative discussions between employee and employer is useful in designing protection and avoiding hazardous gas. For qualitative purposes the images in Fig. 5 can be enhanced with a gray-scale equalization.

To estimate the concentration of a specific gas one can calibrate the instrument against a group of cells with known gas partial pressures. Various mixtures of air and the gas of interest can be used in standard cells. A nonlinear model is suited to curve-fit data to the standard cells.<sup>13</sup> In the present setup the optical system gives some parallax and vignetting errors, which it should be possible to mitigate with another design of the Cassegrainian telescope. The vignetting is most easily seen in image 1 of Fig. 5 as a dark area in the lower left-hand corner and as a light area in the lower right-hand corner. The parallax results from the finite separation of the two openings of the telescope, through which the workplace setup was observed at a rather short distance. The background was illuminated by an IR lamp because the camera was not sensitive enough for the detection of passive thermal radiation with the available standard bandpass filters. However, better bandpass filters tuned to regions where the absorption lines are stronger and more sensitive cameras [e.g., an Agema Thermovision 1000

system using a Stirling cooled MCT signal-processing-in-the-element (SPRITE) detector, in the region of 8–12  $\mu m$ , with  $798 \times 400$  pixels/image] are available, making practical gas-correlation imaging using thermal background light fully feasible.

In conclusion, we have visualized environmentally important gases with a simple and straightforward technique, using the IR spectral features of the gas as its own spectral filter. Our system is capable of separating interfering gases, and it is insensitive to background and motion variations because of simultaneous capture of the direct and the gas-filtered images. The capture rate is two images/s. Methane, nitrous oxide, and carbon dioxide were gas correlated to give images in nearly real time of the flowing gas at a workplace test setup.

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