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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.\(^1\)\(^-\)\(^3\) 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.\(^4\) 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.\(^5\) Another method uses IR emitters and a retroreflector screen to visualize gas absorption.\(^6\) Gas-correlation spectrometry\(^7\) 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\(^8\) and in laser radar.\(^9\)

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.\(^10\) 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\(_2\) 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...
choose a region of interest in the direct image. The
direct image is then divided with the gas-filtered im-
age. To divide the images without losing intensity
dynamics we multiply the gas-filtered image by a fac-
tor. 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 dimen-
sions 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 μm was restricted
by use of either of two bandpass filters, with center
wavelengths at 3.35 and 4.54 μm and full half-widths
of 0.16 and 0.27 μm, respectively. We chose the
filters by using the HITRAN database11 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 μm. As can
be seen, CO₂ and N₂O 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 inter-
est into its own spectral filter, thereby specifically
selecting the gas. In Fig. 4, as an example, the
absorption lines of C₂H₆ (solid curves) are seen to
interfere with the absorption lines of CH₄, but it is
possible to discriminate C₂H₆ from CH₄ with the
gas-correlation approach. Several interesting and en-
vironmentally important gases, such as hydrocarbons,
sulfur compounds, and nitrous compounds, have vi-
bration–rotation absorption in the IR region. The
absorption strength of the gases that we examined in-
creases with the wavelength in the region 2–5.6 μm,
but the detector sensitivity falls off with increasing
wavelength. This trade-off forced us to choose spec-
tral regions within 3–4.5 μm. Another trade-off is
the fact that more energy hits the detector with broad
bandpass filters but the specificity of the gas as a spec-
tral filter, with respect to signal-to-noise, is worse with
broad bandpass filters. Careful design of the band-
pass filters and estimates of the total gas absorption
strengths are needed. Water absorbs over broad spec-
tral 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 arrange-
ment.](image)

- IR camera with bandpass filter
- Workplace with invisible gas
- Gas cell
- Cassegrainian telescope
- Gas plume
- Gas tubes

![Fig. 3. Spectral features of CO₂ and N₂O. The trans-
mission of the bandpass filter used is also indicated
(Tₘₐₓ = 85%).](image)

- Optical depth (a.u.)
- Wavelength (μm)
- CO₂
- N₂O

![Fig. 4. Interfering spectral features of CH₄ and C₂H₆.](image)

- Optical depth (a.u.)
- Wavelength (μm)
- CH₄
- C₂H₆
has on workers in real working environments. 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. 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 μm, with 798 × 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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