IR/02/158

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Remote detection of gaseous pollutants

Rapid Mapping Technologies

Internal Report IR/02/158

IR/02/158

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/02/158

Remote detection of gaseous pollutants

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Key words

Report; key; words.

Front cover

Cover picture details, delete if no cover picture.

Bibliographical reference

NAME, A, NAME, B, ... 2001. A geological background and planning for any area. *British Geological Survey Internal Report*, XX/00/00. 1pp.

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Keyworth, Nottingham British Geological Survey 2002

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) into the possibility of detecting gaseous pollution via the use of remote sensing tools. The report summaries remote sensing techniques currently used to detect pollution, their relevance to the detection of Carbon Dioxide and Methane emissions from landfill sites in particular is then looked at.

Contents

Summary

The polluting species of Carbon Dioxide and Methane have many sources including leaks from landfill sites and seeps from oil wells. Monitoring of this pollution is necessary to identify their sources, with the eventual aim of reducing their emission. Several techniques have been used to monitor these species in a variety of circumstances. Passive infrared absorption methods are suitable for the monitoring of volcanic plumes (Fourier Transform InfraRed (FTIR), Differential Optical Absorption Spectroscopy (DOAS) and Correlation Spectroscopy (COSPEC)). Vehicle emissions are measured using DOAS, While COSPEC is used to image small gas leaks from short distances. Although these methods can be used to identify the gases of interest, they suffer from resolution and background problems, which would probably render them unsuitable for airborne remote sensing. It is possible to extract images of CO_2 and CH_4 from hyperspectral imagery. However, due to the sensors design to measure surface reflected radiation, images of gaseous attenuation are relatively poor. Differential Absorption Lidar (DIAL) is a promising system for the remote sensing of gases, overcoming both the resolution and background problems. The ability to locate the gas in range measurements is important, and high-powered pulsed lasers mean airborne remote sensing of gaseous pollutants will soon be a reality.

1 Introduction

Many gases, including the pollutants Methane and Carbon Dioxide are invisible to the human eye. Leaks of these gases, from landfill sites, oil wells and other industrial sources, lead to an increased level of the pollutant in the atmosphere. In the case of both Methane and Carbon Dioxide this can lead to warming of the atmosphere due to their role as greenhouse gases, and hence contribute to the phenomena of global warming. Several other impacts are more localised but equally important.

Methane seepage from buried landfills offers a considerable risk to nearby residents; a build up of the gas can cause suffocation and even explosions. This poses a considerable risk when it is considered that one tonne of landfill typically produces 5,000,000 cubic-meters of methane (East, 1998).

Gas leaks are a lost resource that cost the relevant body a substantial amount of money. Gas boards and those responsible for the safe delivery of fuel to homes and businesses, loose millions every year due to leaks. Knowing the location and size of the leak would allow costs to be cut, but it would be costly and time consuming to walk the miles of pipeline throughout the country with a traditional measuring/monitoring device hoping to find a leak. It would be far easier if an instrument could be developed that was capable of detecting leaks remotely in a fast and accurate manner. For example, if a device could be flown over an area to detect the leaks, then efficient monitoring of substantial areas could be realised. In order to accomplish this, the system would need a fine spatial and spectral resolution, and ideally be able to accurately detect the location of areas showing higher than average gas concentrations.

2 Basic Principles

Optical techniques for the remote detection of pollution rely on spectroscopic detection; different species of pollution (i.e. different molecular species) absorb different amounts of electromagnetic energy in different regions of the spectrum. The infrared region of the spectrum is especially suited to the detection of gases since it is within this region that these gases have a strong interaction with incident energy (De Natale et al 2001).

Atmospheric molecules are usually in their ground state. However they have a fair number of unoccupied excited rotational and vibrational states that may be occupied by electrons if the molecule absorbs a discrete amount of energy. In the case of the atmospheric molecules, this amount of energy relates to the photon energies found in the infrared part of the spectrum (IRF, 2001). Therefore, as the source light passes through the atmosphere, each molecular species absorbs a specific part of the light, leaving a characteristic fingerprint of absorption lines in the recorded solar spectrum.

The choice of the correct wavelength is not entirely reliant on the gas species to be 'imaged'. Consideration should also be given to atmospheric transmission and the background radiation flux (Sandsten et al, 2000).

The characteristics of the phenomenon to be sensed, combined with typical constraints of operational surveying, can be used to define the requirements for a suitable sensor:

- Portable.
- Cheap.
- Capable of operating at a distance from the pollutant source.
- Tunable to different gas absorption lines.
- High spectral resolution to distinguish molecular species.
- Adequate spatial resolution to enable identification of leaks.
- Efficient, low power consumption.
- Low noise.

3 Techniques for the remote detection of gaseous pollutants

Given the requirements identified above, several methods exist that may be suitable for the detection of gaseous pollutants:

- Differential Optical Absorption Spectroscopy (DOAS)
- Correlation spectroscopy (COSPEC)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Differential Absorption Infrared Lidar (DIAL)
- Hyperspectral Imaging

3.1 DIFFERENTIAL OPTICAL ABSORPTION SPECTROSCOPY

DOAS maybe active or passive and is capable of detecting the radiation emitted or absorbed by a molecule. The absorption of light by a molecular species is measured; if a species is present then electromagnetic energy of that wavelength will be absorbed. If a particular species is not present, then no light in the wavelength relating to that species will be absorbed. Two readings are therefore necessary; one in which the species to be detected is thought to be present, and one in which none of the species exists; the latter is used as a reference. The two measurements will have different spectral signatures if the area of interest, contains more or less, of a species than the reference. The spectral location of the absorption features is then used to identify the species. Absorption increases linearly with number of molecules; hence the concentration of pollutants can be gained from the spectral response (ABB Bomem).

The disadvantages of DOAS are:

- It only gives an integrated gas concentration between the radiation source and the detector; i.e. it does not pinpoint the range of the gas.
- Passive measurement restricts useable regions of the electromagnetic spectrum to the visible and ultra-violet regions; since it is here that maximum solar emittance occurs (De Natale et al 2001).
- If active sensors are used, then the gas to be measured needs to be between the sensor and source. Problems therefore arise when the technique is being used to locate the gas, since all possible configurations of sensor and source will be required to ensure that no gas is present.
- Measurements need to be made in the absence of pollutants to establish 'normal' levels for the gases.

Active DOAS has been successfully used by the City of Albuquerque (USA) to monitor vehicle emissions (City of Albuquerque). An infrared beam is 'shone' across the road, and pollutants absorb some of the radiation on its way to a detector on the opposite side. Depending on the level of absorption in certain wavelength regions, it can be found if a vehicle is outside of the emissions controls. This technique has not yet been operated from an airborne platform to the knowledge of the author.

3.2 CORRELATION SPECTROSCOPY

Correlation spectroscopy is very similar to DOAS, but lamps or natural background radiation are used as the source. Two readings are made; one directly records the absorption spectrum of natural thermal background radiation once it has passed through the gas of interest. The other reading is made through a gas absorption cell. This is a filter filled with a sample of the gas to be detected; the density of this is modulated via pressure alterations. Modulation can also be achieved via the movement of the sample into and out of phase with the atmospheric spectrum (Edner et al, 1994). This has the effect of altering the absorption profile in the spectral lines of the gas in the cell. The modulated gas sample acts as an optical filter, selectively picking out the spectral pattern of the absorption lines for that particular gas in the atmosphere. This pattern is correlated with the direct reading of absorption to identify the gas (De Natale et al, 2001). However since the technique relies on natural thermal background radiation, an accurate knowledge of the temperature difference between the gas and the background is needed.

Sandsten et al (2000) successfully used this technique to distinguish between two gases, which absorb in a similar wavelength region (ammonia and ethylene), in order to display one of the gases as a real-time image. An infrared camera was set up 20m from the leak; a Cassegrainian telescope was placed in front of this, to split the image in two. One telescope aperture is unfiltered, while the other has a filter made up of the gas of interest. The two images can be used to remove the effects of thermal background radiation, resulting in a pure gas image. This is then overlaid on an image of the area acquired simultaneously by a CCD camera. This technique offers several advantages. It is a remote technique; the tests of Sandsten et al (2000) have shown its capability up to 20m from the target. Since two images are captured simultaneously there is the possibility of accounting for motion. Combined with an increase in resolution, this could lead to operation from helicopters. Images of the gas are produced against a photographic backdrop allowing accurate and fast location of any leaks.

Correlation spectrometers have also been successfully used to quantify the SO_2 flux in volcanic plumes (Wardell et al, 2001). Another successful application is the use of these sensors onboard NASA's Terra satellite to monitor CO_2 and CH_4 levels in the Troposphere (MOPITT). This has proved successful, but the resolution is limited to 22km^2 per measurement.

3.3 FOURIER TRANSFORM INFRARED SPECTROSCOPY

This is usually a passive technique using the sun, moon or volcanically heated rock as a background, so cloud-free conditions are therefore required. Alternatively, the technique can be active, with an artificial infrared source behind the target. With most other measuring techniques, spectral intensity is measured as a function of wavelength, providing spectra showing the degree of the absorption at different wavelengths. In the case of FTIR however, intensity is measured via an interferogram (IRF, 2001). Incoming light is reflected to the detector via a movable mirror. Upon movement of the mirror, the light passes through a variable path difference and so a variable intensity is recorded. From the resulting interferogram, the spectrum as a function of wavelength is calculated by the application of a Fourier Transform (Goff et al, 2001).

Advantages of this approach are:

- Uses the infrared region of absorption for most polluting gas species.
- Choice of active or passive sensing.
- Capable of monitoring complete infrared absorption spectra with a fine spectral resolution (ABB Bomem) and can therefore be used to look at many pollutants at one time.

There are also several disadvantages:

- If active sensing is chosen then the infrared source needs to be placed behind the pollution. This is difficult when the location of the pollution is not known, or sensing is from an airborne platform.
- If passive sensing is chosen, then quantification of the natural pollutant levels is required. Therefore a clear sky measurement must be taken, with the same path length as the first measurement.

3.4 DIFFERENTIAL ABSORPTION LIDAR (DIAL)

DIAL is an active technique whereby pulsed lasers (ultra-violet to infrared) are emitted by the instrument. Detectors then collect the laser signals, after backscattering by gases in the atmosphere. In a similar manner to the operation of radar, the range and direction from the sensor to the gas can be found, having important implications for locating the gas (Edner et al, 1994). Two wavelengths are emitted; one is on a resonance line of the species of interest, while the other is off resonance. A ratio of the two, removes background effects (De Natale et al, 2001). The nature of the backscatter provides information on the scattering elements i.e. the gases.

Advantages are that:

- It is possible to find the range from the sensor to the pollution, possibly helping to locate the source of the leak.
- Background effects are compensated for.

Disadvantages include the fact that:

- Complex models are required to account for the complex backscattering due to many factors.
- Complex optical set up requires specialised personnel.

The suitability of these sensors for monitoring leaks is shown by the Chimera Geophysical Corporation, who plan to use a ground based DIAL system to identify microseeps from hydrocarbon production (Geosat). They believe that the instrument could be flown on an aircraft with few modifications.

3.5 HYPERSPECTRAL SENSORS

These sensors have many spectral bands throughout the visible and infrared regions of the spectrum. The UK Environment Agency has successfully imaged CO_2 and CH_4 from near-infrared Hymap data (personnel communication, 2002). However, due to the fact that these sensors are designed to image surface reflections, rather than gaseous attenuations at these wavelengths in the atmosphere above it, the results are relatively poor. This has led the Environment Agency to investigate airborne DIAL type sensors and low cost infrared digital cameras with interference filters, much like that of Sandsten et al (2000).

4 Indirect Measurement

It is also possible to measure the effect that the pollutant escaping as a gas has on other materials. Two of these are considered here; vegetation stress and surface water bodies.

4.1 VEGETATION STRESS

Although not a direct method, vegetation stress can be useful for the identification of gas seepage. Vegetation in close proximity to leaks of CO_2 is affected by the increased level of the gas in the surrounding atmosphere. If CO_2 levels are too high the vegetation is poisoned and hence dies. This CO_2 induced vegetation stress is easily identifiable in hyperspectral data, owing to the change in reflection properties of the plant in the near infrared region of the spectrum. It may also be detectable in broader band super or multispectral imagery.

Such a technique has been successfully used in the Mammoth Mountain region of California (Pickles, 2001). Mammoth is an active volcano, and as such releases CO_2, which has degassed from the underlying magma. The CO_2 levels are strong enough to kill large areas of trees surrounding the mountain. This area can be identified on HyMap images, and the area delimited by this method agrees well with that of ground surveys, HyMap data has even improved existing measurements via gap filling (Pickles, 2001). The BGS is currently involved in an EC Framework 5 project that will assess this technique for detecting leaks from gas pipelines (PRESENSE).

4.2 CHANGES IN WATERCOLOUR

Alteration of remotely detectable spectral properties of water can arise through gas passing through the water column. For instance, under conditions of hypoxia or anoxia, the meters-deep layer of diatom ooze found along the south western coast of Africa is capable of producing large amounts of hydrogen sulphide (Weeks et al, 2002). As the gas rises, sulphide ions are oxidised in the near-surface oxygenated waters, thus precipitating highly reflective microgranules of sulphur. On a quasi-true colour SeaWIFS image, these microgranules give the water a milky turquoise appearance, enabling clear identification of the extent of the gas (Weeks et al, 2002).

5 Uses for leak detection

It can be seen that the above techniques are all capable of identifying gaseous pollutants via their spectral response in the infrared region of the spectrum. However the issue of their suitability for locating and identifying leaks of gaseous pollutants, in particular CO_2 and CH_4 from landfill sites and oil wells, still remains to be proven.

The techniques outlined here, are not designed for the specific applications of interest to BGS, and several problems are envisaged. One of the greatest problems arises from the need for a source of radiation; DOAS, COSPEC and FTIR are in effect, all passive methods – the radiation source must be behind the target area, with the radiation passing through the target, being spectrally altered and then reaching the sensor. However if a leak is to be located, then its location is unknown, and hence an artificial source cannot be placed behind it. The only remaining option is to use natural background radiation. This is possible when solar radiation can be used. However, if sensing is from an aircraft, the background is the earth's surface. This presents problems due to the varying reflectance and emissivity of different land cover types and hence their differing spectra, all of which would need to be quantified as the background before any gas measurements could take place. Sandsten et al (2000) found that their method worked with a concrete wall as background. However, this will have a fairly uniform emissivity and hence could be modelled/separated. Another limiting factor to the FTIR and DOAS systems is the need for a clear sky reading as a reference, raising the issue of the difficulty of orienting an airborne sensor in a suitable configuration once again.

Even if the earth's reflectance and emissivity could be accurately quantified, these passive techniques face another stumbling block; for any passive remote sensing method to work, enough radiation must reach the sensor. Since the earth has a relatively low reflectance and emittance in the infrared, the area imaged for each measurement needs to be large enough to supply this radiation. It is possible that airborne sensors would therefore require much coarser spatial resolution than is ideal for locating leaks, particularly from pipelines.

Differential Absorption Lidar offers the most realistic means of monitoring gaseous pollutants on such a scale, since it overcomes the above constraints due to its active nature. The radiation source is 'fired' at the target, rather than being placed behind it. There is therefore no need to know where within the atmospheric column, the target is. Also, any leaks can be located accurately in range, via the range and Doppler shift of their measurement. DIAL also overcomes the need for clear sky measurements as a reference, due to the use of a slightly different wavelength for this purpose. It would therefore seem that the DIAL sensors are suitable for the detection of gases on the scale required. They also have the capability to sense a one mile path length (Geosat), and are background independent. However one important consideration needs to be recognised: measurements are made along the whole of the path between the sensor and the gas, so whilst it is possible to locate the gas via the range measurements, a lot of redundant data would be collected. One disadvantage of this method, is the need for accurate atmospheric measurements, in order to interpret the results (Geosat).

It has been shown (Pickles, 2001) that indirect CO_2 leak detection can be accomplished through the effects that this gas has on vegetation. Hyperspectral data, such as that of HyMap can be used to identify areas of increased vegetation growth relating to local increases in CO_2. Although possible, the technique has several drawbacks; the area must be vegetated year round if continual monitoring is sought, and seasonal/phenological changes must be well quantified. The analyst must be sure that the vegetation stress is due to an increase in CO_2 and not some other factor, such as drought, and this may require ground truth.

6 Conclusions

Several methods have been successful in detecting gaseous pollutants from the ground. However, the potential difference in conditions for airborne acquisition, may render an otherwise useful technique unsuitable for remote sensing purposes.

Active data collected from a DIAL type sensor could be of use for the detection of gaseous pollutants, and their source, from a significant distance commensurate with airborne acquisition. In contrast, the passive techniques, although suitable for certain tasks like ground based volcanic plume monitoring, close range leak detection and estimates of pollution in large areas of the atmosphere, are not suitable for relatively small leak detection from considerable distances. Passive sensors suffer from two main problems: the need for a large measurement cell to gather enough radiation, giving low resolution; and changeable reflectance and emissivity when the earth’s surface is used as a background.

Dedicated technologies for the remote detection of gaseous pollution are still in their infancy. Systems are currently being purpose built for the job, due to poor results gained from existing tools such as hyperspectral sensors, which were not designed for the job. In the short term, indirect measurement of vegetation stress is the best way to get at the phenomenon of interest. In the longer term, dedicated DIAL sensors designed for this purpose, will become operational, and are likely to make direct measurements a practical option.

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