

# Infrared Remote Sensing of Hazardous Vapours: Surveillance of Public Areas during the FIFA Football World Cup 2006

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## ABSTRACT

The German ministry of the interior, represented by the civil defence agency BBK, established analytical task forces for the analysis of released chemicals in the case of fires, chemical accidents, terrorist attacks, or war. One of the first assignments of the task forces was the provision of analytical services during the football world cup 2006. One part of the equipment of these emergency response forces is a remote sensing system that allows identification and visualisation of hazardous clouds from long distances, the scanning infrared gas imaging system SIGIS 2. The system is based on an interferometer with a single detector element in combination with a telescope and a synchronised scanning mirror. The system allows 360° surveillance. The system is equipped with a video camera and the results of the analyses of the spectra are displayed by an overlay of a false colour image on the video image. This allows a simple evaluation of the position and the size of a cloud. The system was deployed for surveillance of stadiums and public viewing areas, where large crowds watched the games. Although no intentional or accidental releases of hazardous gases occurred in the stadiums and in the public viewing areas, the systems identified and located various foreign gases in the air.

**Keywords:** hyperspectral, surveillance, remote sensing, FTIR; passive; imaging spectrometry, emergency response

## 1. INTRODUCTION

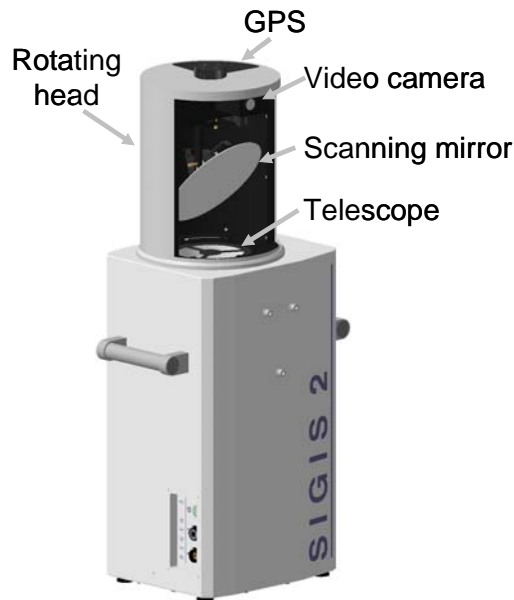
The German ministry of the interior, represented by the civil defence agency BBK, has established analytical task forces for the analysis of released chemicals in the case of fires, chemical accidents, terrorist attacks, or war. In these cases, information about the released compounds is required immediately in order to take appropriate measures to protect workers, residents, emergency response personnel at the site of the release, and the environment.

The analytical task forces are equipped with mobile systems that apply analytical methods such as gas chromatography/mass spectrometry<sup>1</sup> (GC/MS), ion mobility spectrometry, and sensors like photoionisation detectors. Moreover, the task forces are equipped with a hand-held system containing a combination of sensors, the portable gas detector array<sup>2</sup> (GDA 2). The system is comprised of an ion mobility spectrometer, a photoionisation detector, an electrochemical cell, and semiconductor gas sensors. However, all these methods require the collection of a sample, which may be dangerous, time-consuming, and difficult for example in case of a terrorist attack in a stadium or a crowded public place. In contrast, remote sensing by infrared spectrometry allows instant identification of hazardous clouds from a distance. The analytical task forces, based in the four German cities Berlin, Hamburg, Magdeburg, and Mannheim were equipped with Scanning Infrared Gas Imaging Systems (SIGIS<sup>3</sup>) in 2006. During the FIFA world cup 2006 these systems were used for surveillance of stadiums and public viewing areas, where large crowds watched the games.

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## 2. SCANNING INFRARED GAS IMAGING SYSTEM SIGIS 2

SIGIS 2 is a scanning imaging remote sensing system based on the combination of an interferometer with a single detector element and a scanning mirror. The system comprises the interferometer OPAG 33 (Bruker Daltonics, Leipzig, Germany), a telescope, a rotating head containing an azimuth-elevation-scanning mirror actuated by stepper motors, a video camera, a GPS system, and a notebook PC for control, data analysis, and display of the results (Fig. 1).



**Fig. 1:** CAD-drawing of SIGIS 2.

The interferometer is a modified Michelson interferometer with cube-corner mirrors. The interferometer block is mounted on an aluminium base plate. A metal casing protects the interferometer and keeps the inner nitrogen gas atmosphere of the instrument. The maximum optical path difference of the interferometer configuration used in the SIGIS 2 system is 1.8 cm, resulting in a spectral resolution of approximately  $0.5 \text{ cm}^{-1}$ . For identification and visualisation of toxic vapour clouds, a spectral resolution of  $4 \text{ cm}^{-1}$  is used. The choice of resolution is a trade-off between the goals of a low limit of detection and a short measurement time, and the goal of high selectivity. The signal-to-noise ratio improves with decreasing spectral resolution for constant measurement time<sup>4</sup>. On the other hand, higher resolution yields higher selectivity. At  $4 \text{ cm}^{-1}$ , 16 two-sided interferograms per second are measured.

In order to align the field of view and to scan the field of regard, the system is equipped with a rotating head containing an azimuth-elevation scanning mirror. For coarse orientation of the field of regard, the cylindrical head is rotated (Fig. 1). The measurement scene is recorded by a video camera and displayed on the PC. The video image and the interferograms measured by the interferometer are transferred to the PC via Ethernet.

For the visualisation of gas clouds, the rotating head is kept at a fixed position and the scanning mirror is sequentially set to all positions within the field of regard. The size and the direction of the field of regard and the spatial resolution (i.e. the angle between adjacent fields of view) are variable. The operator may define the field of view interactively using the displayed video image and the mouse. Each interferogram measured by the interferometer is transferred to the PC. After the Fourier-transformation, the spectrum is analysed and the results are visualised by the video image, overlaid by false colour images. This direct display of the cloud image in the video image allows simple assessment of the position and the size of the cloud. The combination of a rotating head with a scanning mirror allows  $360^\circ$ -observation and imaging using the described overlay with a real-time video of the scene.



**Fig. 2:** SIGIS 2 mounted in a vehicle of the fire brigade of Hamburg (Photo: T. Lübke-Horn).

**Table 1:** Specifications of the scanning imaging remote sensing system SIGIS 2.

Interferometer	Bruker OPAG 33
Spectral range	680 – 1500 $\text{cm}^{-1}$ (600 - 6000 $\text{cm}^{-1}$ max.)
Maximum spectral resolution (max. optical path difference $D$ )	0.5 $\text{cm}^{-1}$ ( $D = 1.8$ cm)
Spectral resolution (this work)	4 $\text{cm}^{-1}$ ( $D = 0.225$ cm)
Field of view	10 mrad
Field of regard	360°×60°
Maximum spectral rate	16 spectra/s ( $\Delta\sigma = 4$ $\text{cm}^{-1}$ , two-sided interferograms)
NEAT per scan (triangular apodisation, 1000 $\text{cm}^{-1}$ , $\Delta\sigma = 4$ $\text{cm}^{-1}$ )	20 mK (measurement time $t = 44$ ms)
Mass	75 kg
Power (without PC)	100 W

### 3. DATA PROCESSING: IDENTIFICATION AND QUANTIFICATION ALGORITHMS

The identification method is based on the approximation of a measured spectrum with reference spectra. First, the spectrum of the brightness temperature  $T_{br}(\sigma)$  is calculated. The spectrum is analysed sequentially for a variable number of target compounds - which are contained in a spectral library - with different reference matrices. Each matrix contains spectral data of one target compound, atmospheric gases (e.g. H<sub>2</sub>O), and it may contain the signatures of potential interferences. Moreover, it contains functions for the approximation of the baseline. The frequency dependence of the brightness temperature of the background and thermal effects inside the spectrometer<sup>5,6</sup> may cause baseline shifts that exceed the signal of the target compound. The identification is performed in three steps. In the first step, the mean brightness temperature is subtracted and the signatures contained in the matrix are fitted to the resulting spectrum. In the next step, the contributions of all fitted signatures (i.e. interferences, atmospheric species, and baseline) except the signature of the target compound are subtracted from the measured spectrum.

In order to decide if the target compound is present, the coefficient of correlation  $R$  between the corrected spectrum, i.e. the result of the subtraction, and a reference spectrum is calculated in a compound specific number of spectral windows. Moreover, the coefficient of correlation between the fitted spectrum and the measured spectrum is calculated. The signal-to-noise ratio is calculated by division of the maximum brightness temperature difference caused by the target compound (determined by the least squares fitting procedure) by the noise equivalent temperature difference of the spectrum. If all coefficients of correlation and the signal-to-noise ratio are greater than compound specific threshold values, the target compound is identified. In addition to the yes/no decision of the algorithm, which should cause a minimal probability of false identifications, a target compound is regarded as "suspect" if the coefficient of correlation in the spectral range of the strongest absorption signature is above the identification threshold and signal-to-noise ratio is greater than 4. Moreover, the result of the algorithm is classified as "high correlation" if a lower, compound specific threshold is exceeded.

The calculation is performed for three different column densities of the target compound. The reference spectra with different column densities are calculated by convolution of high-resolution transmittance spectra (e.g. calculated with absorption cross sections computed using Hitran<sup>7</sup>) with an instrument line shape function that is given by the convolution of the ideal instrument line shape function of a Fourier-transform spectrometer with a function that describes the distortions in a real instrument<sup>8</sup>.

Optionally, the difference between two spectra, a background spectrum and the last measured spectrum, can be analysed in addition to the direct analysis of brightness temperature spectra.

Two methods for quantification of the column density have been developed. For spectra with high transmission  $\tau$  of the target compound (optically thin clouds), a method based on the assumption that the cloud temperature is equal to the ambient temperature is applied preferably. The temperature of the cloud is estimated by analysis of signatures of CO<sub>2</sub> and water. Using this information, the radiative transfer model<sup>3</sup> may be solved for the column density of the gas. For clouds with a lower minimum transmission this method may result in inaccurate column densities due to an erroneous estimation of the temperature. Thus, a method that is not based on the assumption of thermal equilibrium is applied in the case of optically thick clouds. The quantification of the column density is performed by minimisation of the difference between the measured spectrum and a spectrum calculated using a model. A nonlinear model that contains the column density of the target compound as a parameter is applied<sup>3,8</sup>. The best-fit parameters are determined by the Levenberg-Marquardt method.

The identification and quantification algorithms have been described in references 3 and 9 and the reader is directed to these articles for additional detail.

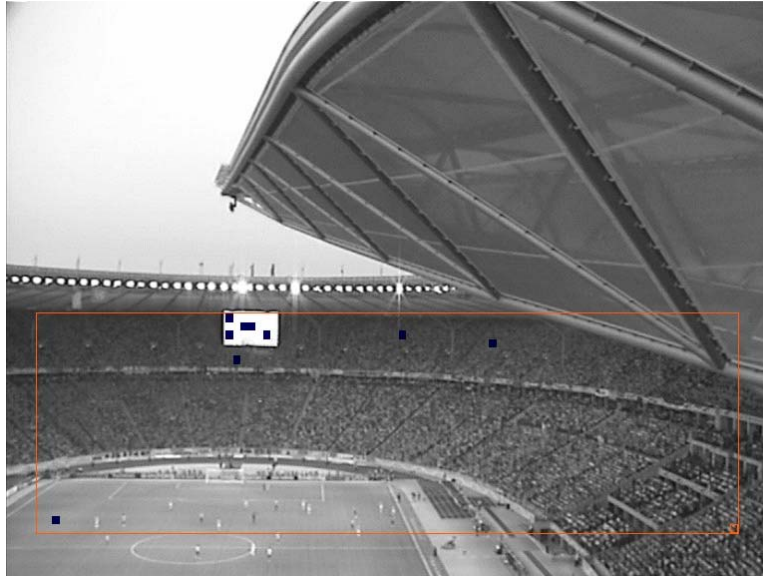
#### 4. RESULTS AND DISCUSSION

During the world cup, five systems were deployed. In addition to the four systems of the task forces, a system operated by TUHH was deployed in Hamburg. In the following paragraphs, selected results are presented and discussed.

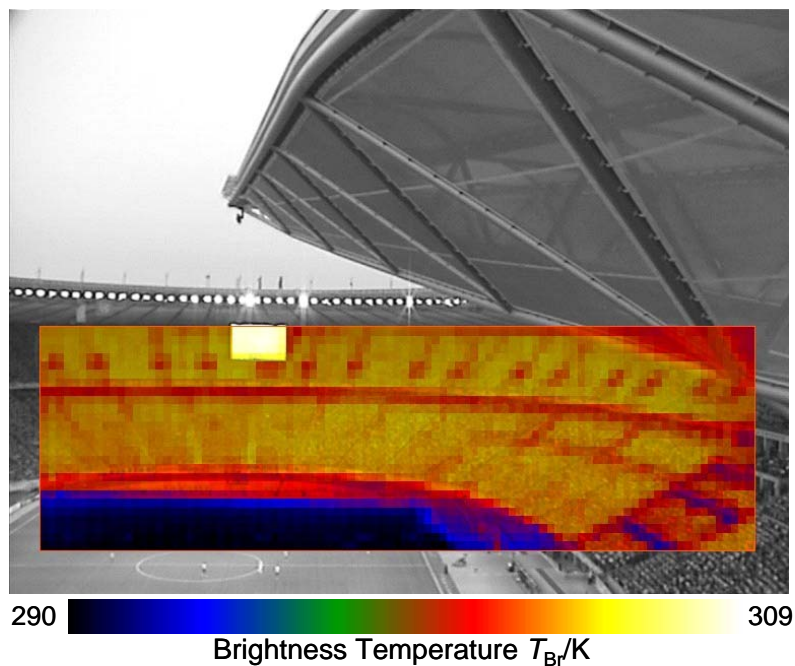
In Berlin, Leipzig, and Hanover, the systems were used for surveillance of the air in the stadiums. The surveillance of the Olympic stadium in Berlin was performed from one of the towers of the Marathon gate of the stadium (Fig. 3). During various games, ammonia was identified. As an example, Fig. 4 shows the result of a scan. In front of the video screen of the stadium many identifications of ammonia occurred. This is due to the high brightness temperature of the screen. A false colour representation of the brightness temperature of the scanned area is depicted in Fig. 5. The signal is proportional to the difference between the temperature of the gas and the brightness temperature of the background. In this case, the screen yielded the highest difference. The signals of ammonia (maximum brightness temperature difference caused by ammonia) were small. The mean concentration (mixing ratio) of ammonia along the optical paths in which the screen was the background was  $(49 \pm 5)$  ppb. The low signals are the reason for the scattered directions in which ammonia was identified. There are different possible sources of ammonia in the stadium. One possible source is the football field, because fertilizers may contain ammonia. In addition to that, human sweat contains ammonia. The temperature of the air was high ( $24\text{ }^{\circ}\text{C}$  at the time of the measurement, the maximum temperature on the 13<sup>th</sup> of June was  $30\text{ }^{\circ}\text{C}$ , outside the stadium) and thus ammonia emitted by the spectators could contribute to the signal. A potential third source is ammonia evaporating from cleaning agents that are used to clean the stadium. In addition to ammonia, ethanol was identified in the stadium during the world cup. Ethanol is evaporating from alcoholic beverages and it is exhaled by spectators which consume alcoholic beverages before or during the game.



**Fig. 3:** Surveillance of the Olympic stadium in Berlin using the SIGIS 2.



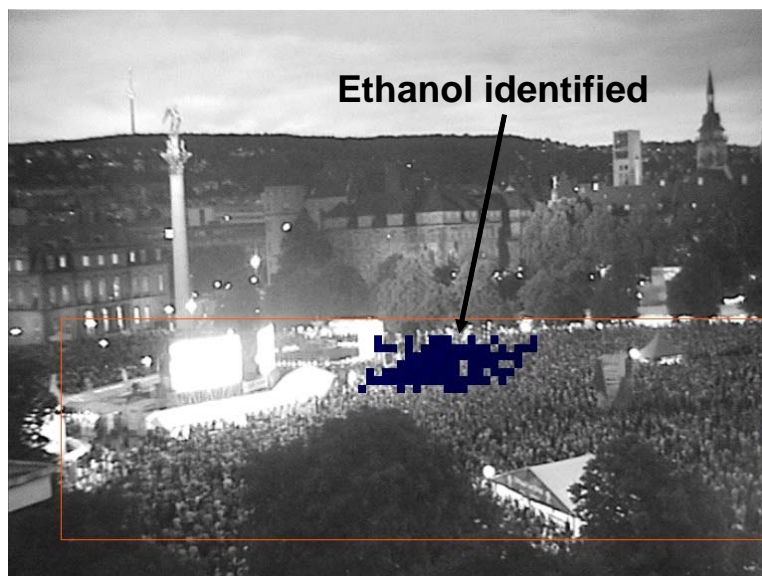
**Fig. 4:** Identification of ammonia in the stadium. The directions in which ammonia was identified are indicated by the overlay of blue squares (■). The signals of ammonia (maximum brightness temperature difference caused by ammonia) were small. This is the reason for the scattered directions in which ammonia was identified. The signal is proportional to the difference between the temperature of the gas and the brightness temperature of the background. In this case, the video screen yielded the highest difference (see Fig. 5).



**Fig. 5:** False colour image of the brightness temperature. The surface of the video screen has the highest brightness temperature.

In Stuttgart, SIGIS was used for surveillance of the public viewing area in the centre of the city. Ethanol was identified in multiple directions (Fig. 6). As in the stadium, alcoholic beverages consumed by the spectators are the source of ethanol.



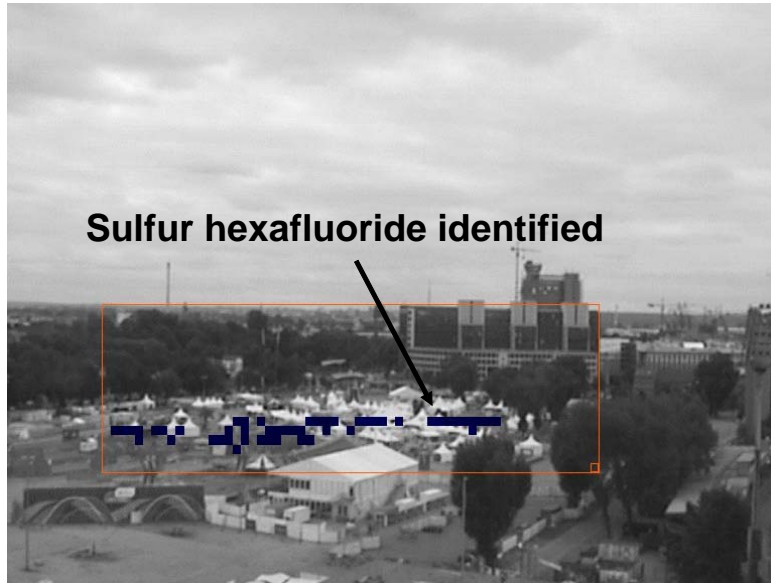


**Fig. 6:** Identification of ethanol in the public viewing area. The directions in which ethanol was identified are indicated by the overlay of blue squares (■).

In Hamburg, two systems were used to monitor the stadium from a building near the stadium and to monitor the public viewing area in the city centre. The public viewing area was monitored on 25 days during the world cup. Sulfur hexafluoride was identified in one measurement. The source of the gas could not be identified definitely. Sulfur hexafluoride is used in electrical equipment and in the past it was also used as a replacement of air in car tires.

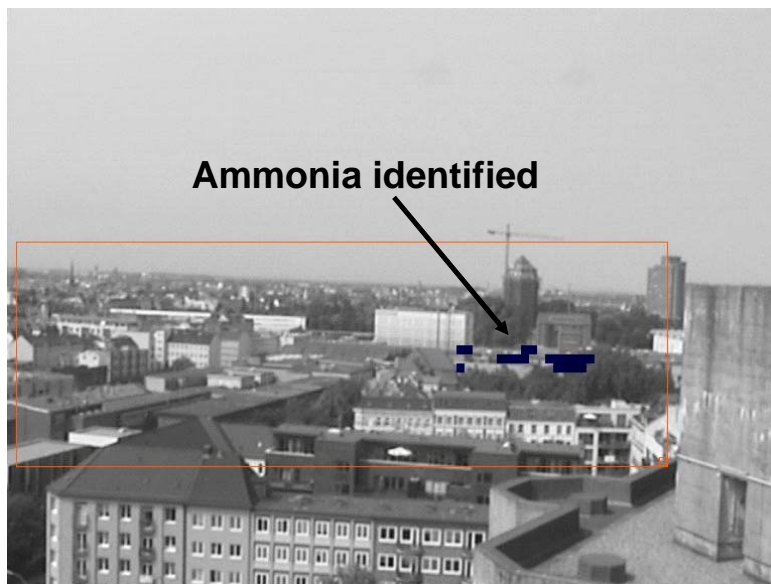


**Fig. 7:** Surveillance of the public viewing area in Hamburg using the SIGIS 2.



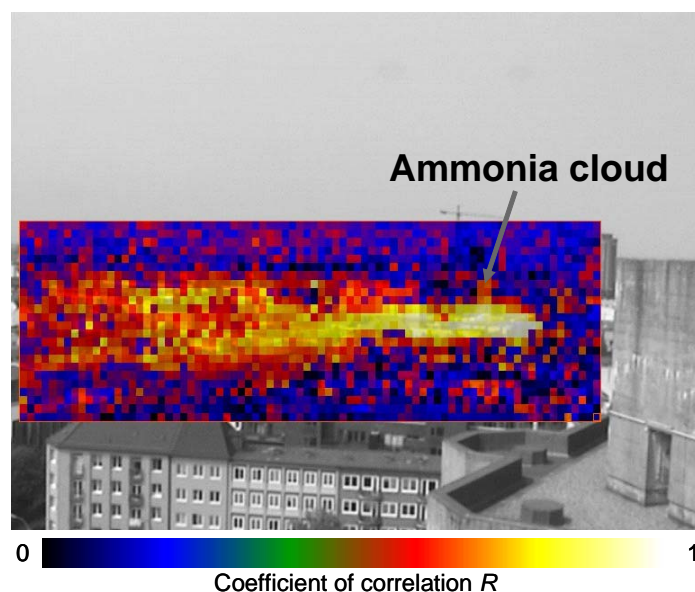
**Fig. 8:** Identification of sulfur hexafluoride in the public viewing area. The directions in which sulfur hexafluoride was identified are indicated by the overlay of blue squares (■).

In addition to the direct surveillance of the public viewing area, the air above the city was monitored with the system. During these measurements, ammonia was identified above a refrigerating storage house. Fig. 10 shows a false colour image of the coefficient of correlation between the measured spectrum after compensation of interferences and a reference spectrum of ammonia. In this representation of the results, the dispersion of the ammonia cloud can be observed. A possible cause for the presence of the ammonia is a leak in the cooling system. In addition, methanol was identified above an incineration plant.



**Fig. 9:** Identification of ammonia above a refrigerating storage house.





**Fig. 10:** Visualisation of trace amounts of ammonia above a refrigerating storage house. The false colours represent the coefficient of correlation between the measured spectrum after compensation of interferents and a reference spectrum of ammonia.

## 5. SUMMARY AND CONCLUSIONS

Five SIGIS 2 systems were deployed for surveillance of public areas during the football world cup 2006. Although no intentional or accidental releases of hazardous gases occurred in the stadiums and in the public viewing areas, the systems proved their effectiveness by identifying and locating various foreign gases in the air.

In Berlin, ammonia and ethanol were identified in the stadium. In Hamburg, sulfur hexafluoride and ammonia were identified and located in and near the public viewing area. In Stuttgart, ethanol was identified in the public viewing area.

## 6. ACKNOWLEDGEMENTS

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