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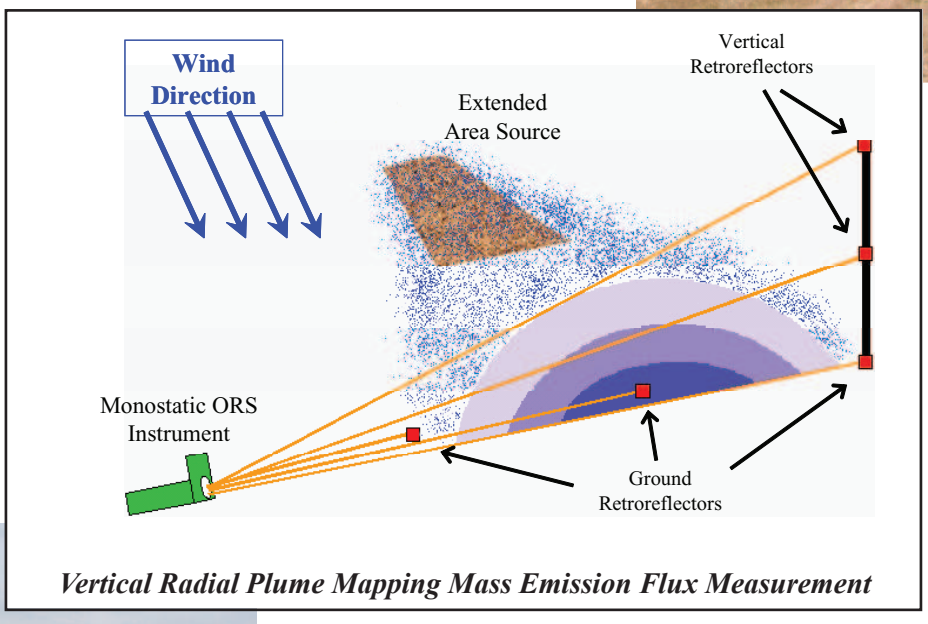
Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology



Vertical Radial Plume Mapping Mass Emission Flux Measurement

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Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability to natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and groundwater; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Abstract

EPA has developed and evaluated a method for characterizing fugitive emissions from large area sources. The method, known as radial plume mapping (RPM), uses multiple-beam, scanning, optical remote sensing (ORS) instrumentation such as open-path Fourier transform infrared spectroscopy, ultraviolet differential absorption spectroscopy, open-path tunable diode spectroscopy, and open-path tunable diode laser absorption spectroscopy in unique radial configurations and optimization algorithms providing essential spatial data for emission calculations. The RPM method can be used for characterizing emissions from a wide range of area sources, including landfills, wastewater treatment plants, and agricultural operations. This report represents a three-year effort conducted to evaluate the feasibility of using ORS instrumentation to measure landfill gas emissions, which include methane, volatile organic compounds, and air toxics.

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1. Introduction

Over the last several years, the Air Pollution Prevention and Control Division (APPCD) of the US EPA's National Risk Management Research Laboratory (NRMRL), and ARCADIS, have developed and evaluated a method for characterizing fugitive emissions from large area sources. The method, known as Radial Plume Mapping (RPM) [Hashmonay et al., 1998; Hashmonay et al., 2001], uses multiple-beam, scanning, Optical Remote Sensing (ORS) instrumentation such as Open-Path Fourier Transform Infrared (OP-FTIR) Spectroscopy, Ultraviolet Differential Absorption Spectroscopy (UV-DOAS), and Open-Path Tunable Diode Laser Absorption Spectroscopy (OP-TDLAS) in unique radial configurations and optimization algorithms, providing essential spatial data for emission calculations. The RPM method can be used for characterizing emissions from a wide range of area sources, including landfills, wastewater treatment plants, and agricultural operations [Shores et al., 2004; Thoma et al., 2005].

Measuring emissions from landfill sites presents unique challenges due to the large source area, spatial and temporal variability of emissions, and the wide variety of target pollutants present in landfill gas. The current project represents a three-year effort conducted to evaluate the feasibility of using ORS instrumentation to measure landfill gas emissions, which include methane, volatile organic compounds (VOC), and air toxics. Landfill gas emissions have been found to be a concern to the environment, as well as human health due to the explosive potential of the gas, emissions of hazardous air pollutants and volatile organic compounds, emissions of methane that contribute to climate change, and odor nuisance associated with landfill gas. The United States Environmental Protection Agency (U.S. EPA) has promulgated regulations under the Clean Air Act to address the public health concerns of landfill gas emissions. The final rule and guidelines are contained in 40 CFR Parts 51, 52, and 60, *Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills*.

The long-term study evaluation is based on several factors including target compounds, minimum detection levels of the instrumentation for the target compounds, resources necessary for deployment of each instrument, and resources needed for data analysis. Some of the site-specific issues affecting this evaluation are the size of the survey area, topography of the site, location of passive vents, and physical barriers at the site such as buildings and other structures. The project consisted of measurement campaigns at a Superfund site in Somersworth, New Hampshire (*Modrak et al., 2004)*, a former landfill site in Fort Collins, Colorado (*Modrak et al., 2005a)*, a formal landfill site in Colorado Springs, Colorado (*Modrak et al., 2005b*), and a measurement campaign and technology demonstration at the Orange County Municipal Landfill in Chapel Hill, North Carolina. Additionally, project members conducted a study to validate the RPM method. This long-term ORS evaluation study was funded by the U.S. EPA Office of Superfund Remediation and Technology Innovation, Technology Integration and Information Branch (TIIB) under its Monitoring and Measurement for the 21st Century (21M^2) initiative. More information on the 21M^2 initiative can be found at on the web at http://www.clu-in.org/programs/21m2.

This report presents a summary of the long-term evaluation of using the ORS instrumentation with the RPM method for conducting measurements in active or former landfill sites. The findings of this report can be used as guidance for selection of the appropriate ORS instrument for use with the RPM method for a particular application.

2. Overview of Optical Remote Sensing with the Radial Plume Mapping Method and Other Traditional Monitoring Approaches

2.1 Background

Open-path optical remote sensing (ORS) technologies have been used for many years as a powerful tool for measuring air emissions. ORS instruments measure path-integrated concentration (PIC) data along a configuration beam path, which is defined as the distance between the instrument detector and the retro-reflecting mirror, or the instrument light source, depending on the type of instrument used. The ORS beam path length typically ranges from 50 to 500 meters, depending on the instrument and application. The major advantage of ORS instrumentation over traditional point monitors is the ability to provide greater spatial information of the monitored area, reducing the chance of missing emissions hot spots.

For several years, researchers have been using ORS data to characterize fugitive emissions using methods such as inverse dispersion modeling, Backward Lagrangian Stochastic (BLS) modeling, and tracer gas releases. A major advancement in the application of ORS instrumentation (for measuring emissions from large area sources) was the advancement of the Radial Plume Mapping (RPM) method, which was developed at the University of Washington in the mid-1990s [Hashmonay and Yost, 1999; Hashmonay et al., 1999]. The method, which can be applied using any scanning ORS instrument, collects path-integrated concentration data along multiple beam paths in the configuration. Multiple retro-reflecting mirrors are deployed in the survey area to define the beam paths used in the survey. The ORS instrument can be scanned in a horizontal plane (Horizontal Radial Plume Mapping) to produce surface concentration contour maps, showing the location of localized surface emissions hot spots. The ORS instrument can also be scanned in a vertical plane deployed downwind of the survey area (Vertical Radial Plume Mapping) to map the emissions plume downwind of the area of interest. By including meteorological data collected concurrently with the ORS measurements, the Vertical Radial Plume Mapping method can be used to calculate the downwind emission flux from the site.

In recent years, work was done by ARCADIS, U.S. EPA, and the U.S. Department of Defense to demonstrate and validate the RPM method in a series of controlled-release experiments. As a result of this work, a protocol for applying the RPM method (*Radial Plume Mapping Method for Emissions Characterization from Non-Point Sources*) was developed and peer reviewed, and the RPM method is now approved as EPA Other Test Method 10 (OTM-10). A copy of OTM-10 can be viewed at http://www.epa.gov/ttn/emc/tmethods.html. OTM-10 is the only documented EPA-approved method for characterizing fugitive emissions from area sources.

2.2 HRPM Method

Horizontal Radial Plume Mapping (HRPM) is a technique that can be used to identify the location of locally higher areas of surface emissions, or hot spots, within the survey area. The technique can be used to perform surveys in areas with dimensions as large as 250 meters. The HRPM method uses one scanning ORS instrument, which is usually deployed in the corner of the survey area. Between four and twelve mirrors are deployed in a radial pattern along the surface of the survey area. The exact deployment location of the mirrors is pre-determined using a computer-based coordinate program. The ORS instrument scans along each path length in the configuration, collecting path-integrated concentration data. This data is input into the HRPM algorithm to produce surface concentration contour maps.

Figure 1 shows a schematic of an example HRPM configuration. In this example, nine mirrors are used in the configuration, and the dimensions of the survey area are approximately 120 meters by 120 meters.

Figure 2 shows an example methane surface concentration contour map generated by the HRPM method in a landfill. Concentrations are shown in ppmv. The red dot indicates the location of the scanning ORS instrument.

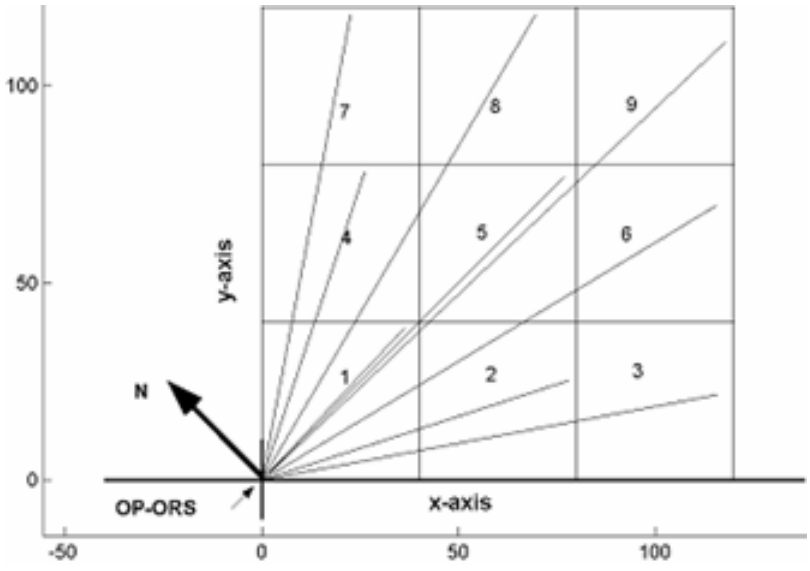

Figure 1. Example HRPM configuration showing the location of the ORS instrument, and the beam paths used for the survey

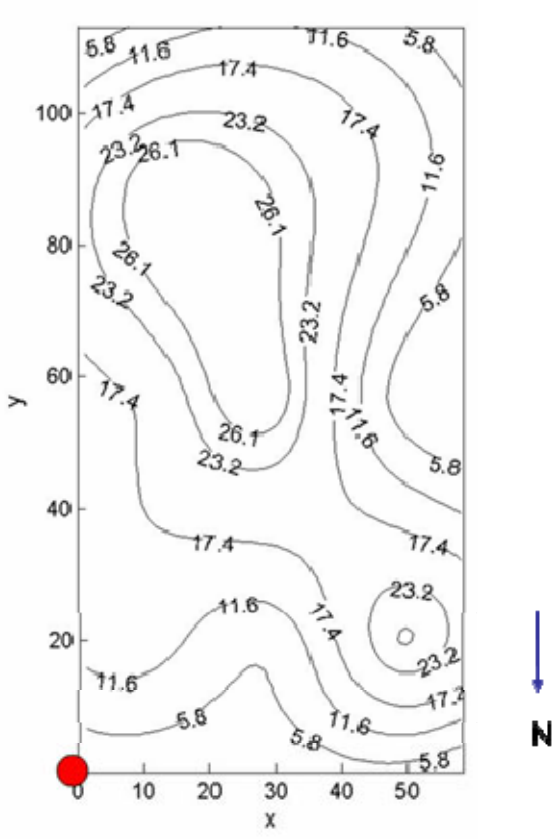

Figure 2. Example surface methane concentration contour map generated using the HRPM method (concentrations shown in ppmv)

The HRPM method is used to provide qualitative information on the location of hot spots in a survey area. This information can be used as guidance in selecting the location of the VRPM configuration, which is discussed in the next section. The data generated with the HRPM method can also be useful to landfill operators, as they can provide information on the general location of surface methane leaks. More information on the HRPM algorithm can be found in Appendix A of this document.

2.3 VRPM Method

Vertical Radial Plume Mapping (VRPM) surveys are performed at a site after completion of the HRPM surveys. When a surface hot spot is located, the VRPM configuration is deployed downwind, with the configuration centered around the detected hot spot (see Figure 3). The VRPM configuration should be deployed so that the prevailing wind direction is as close to perpendicular to the plane of the configuration as possible.

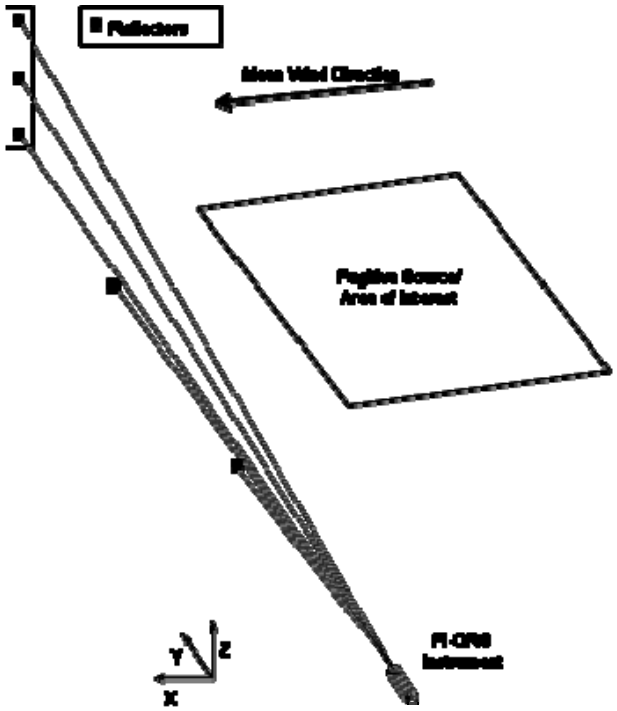

Figure 3. Example of a VRPM configuration deployed downwind of the survey area

The VRPM configuration consists of a scanning ORS instrument, a scissors jack or similar vertical structure (between 5 and 15 meters high) deployed between 50 and 250 meters from the instrument, and multiple mirrors. Typically, three mirrors are deployed along the ground between the ORS instrument and the vertical structure, one mirror is mounted midway up the vertical structure, and one mirror is mounted on top of the vertical structure. Wind speed and wind direction data are collected near the base of the vertical structure, and at the top of the vertical structure. Path-integrated concentration data is collected along each beam path

in the configuration. This data is input into the VRPM algorithm with wind data (collected concurrently) to produce an emissions plume map and downwind emissions flux value. Figure 4 shows an example methane plume map generated using data collected in a landfill. The ORS instrument was located in the lower left corner of the figure, and the location of the vertical structure is indicated by the solid black line. Concentrations are shown in ppmv. The methane flux calculated by the VRPM method was 4.9 grams per second.

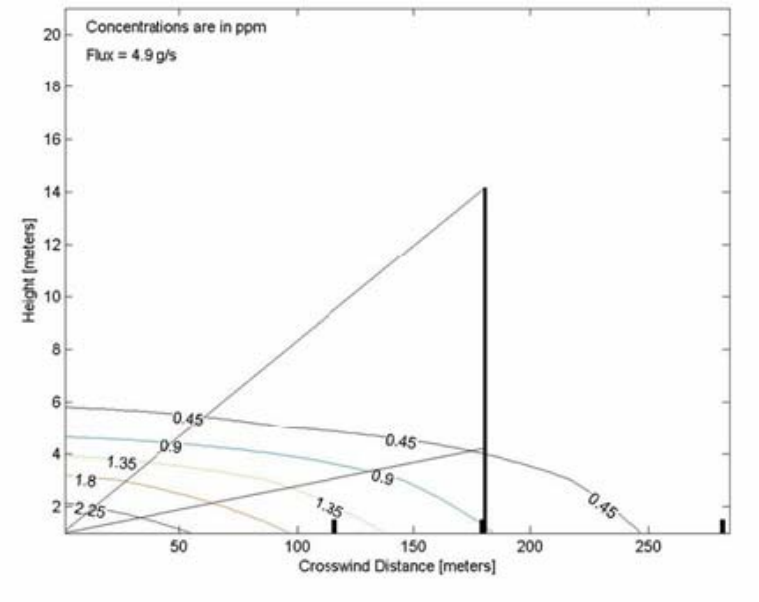

Figure 4. Example plume map generated using the VRPM method (concentrations shown in ppmv). The location of the vertical structure is shown by the solid black vertical line. The scanning ORS instrument is located in the bottom left-hand corner of the figure

Flux data from the VRPM algorithm can be used to estimate an emission factor from the area of interest. The flux values calculated by the VRPM method (in units of mass per unit time) are divided by the surface area of the upwind area contributing to the measured emissions to yield an estimated emission factor from the survey area (in units of mass per unit time per unit area). Thus, the VRPM method can be used to estimate a direct, measurement-based emission factor, without the need for dispersion modeling. More information on the VRPM algorithm can be found in Appendix A of this document.

2.4 Alternative VRPM Approach

The previous section describes the VRPM method, which was utilized for emissions characterization during each of the field campaigns of this long-term project. However, in recent months, an alternative VRPM approach has been developed and applied in other projects. The alternative approach was developed in response to concerns about capturing emission from the slopes of landfill cells (discussed in Section 4.1.2), as well as the reliance on prevailing wind directions during the measurements (discussed in Section 4.1.4).

The alternative approach consists of deploying four VRPM configurations using two vertical structures and two scanning ORS systems. Figure 5 presents an overhead schematic of the configuration.

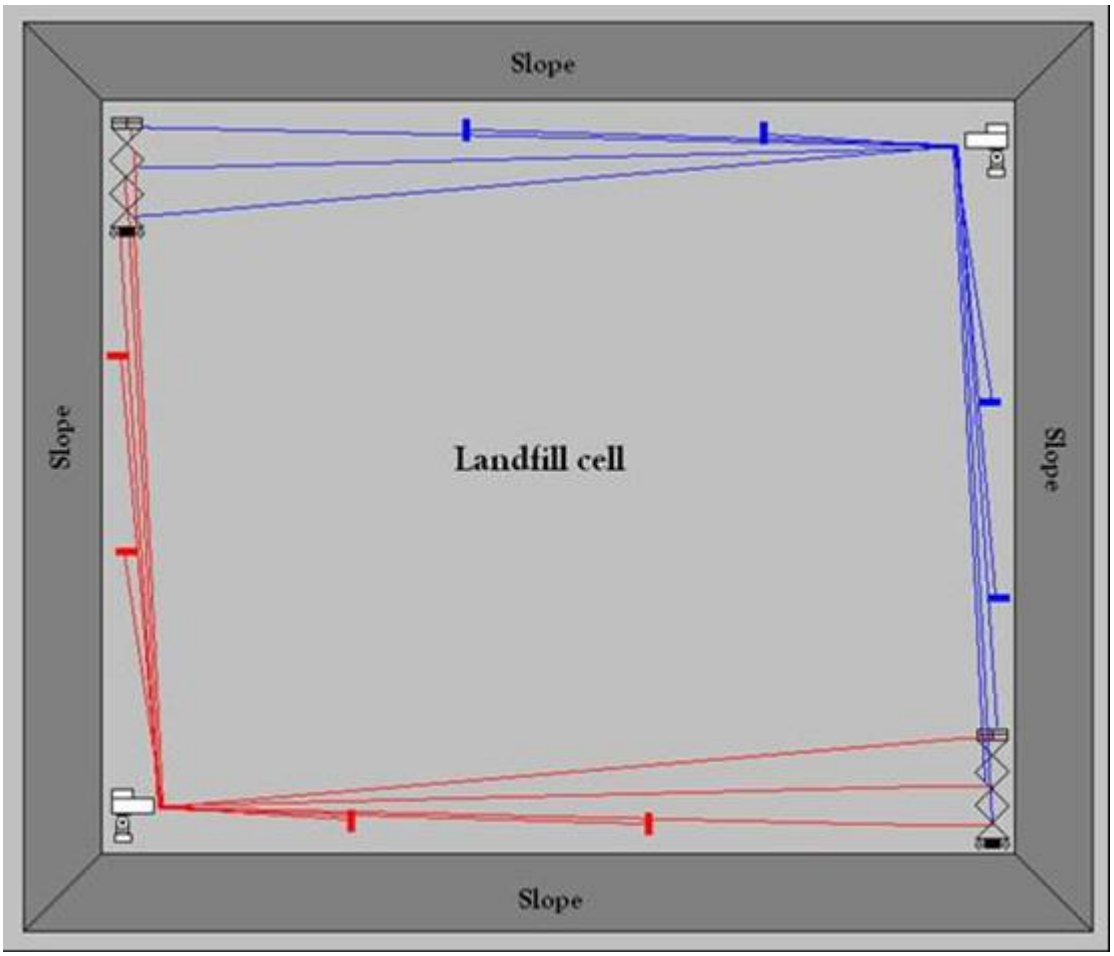

Figure 5. Schematic of the Alternative VRPM Approach

Two scanning ORS instruments are deployed on top of each measurement area, in opposite corners of the landfill cells. Each instrument is scanned to two five-beam VRPM configurations. The data collected along the four VRPM measurement configurations is used to characterize emissions from the slopes of the landfill (or upwind areas), as well as emissions from the actual landfill cell, depending on the direction of the prevailing winds during the time of data collection. The major advantages of this approach are:

1. No reliance on wind direction for VRPM flux calculations. Once the configuration has been deployed, flux measurements can be collected, regardless of wind direction. Since data can be collected during any wind conditions, there is no need to wait for periods of favorable winds, allowing data to be collected in a survey area for a longer period of time. This is especially favorable for projects with limited resources.

2. The ability to more directly characterize emissions from the side slopes.

2.5 Comparison to Other Measurement Approaches

In the past, other measurement approaches have been used to obtain emissions measurements in landfills and other area sources. These include traditional point sampling instrumentation such as PID, PID/FID, Summa canisters, various sorbent methods, and flux boxes. Although these approaches are generally easier to deploy, less costly than ORS-based measurement approaches, and do not rely on prevailing wind direction during the time of measurements, they only provide concentration information from a single point in the survey area, greatly increasing the chances of missing surface emissions hot spots or emissions plumes. Even after collecting data from multiple points in the survey area, the point sampling approaches lack the spatial and temporal data necessary to obtain a complete picture of the emissions from large area sources. Additionally, the flux box approach may not accurately characterize surface emissions from the site, as deployment of the flux box on the surface of the landfill cell may not allow actual emissions to escape from the landfill in the vicinity of the deployment area. Another disadvantage of using the point sampling approaches is that it is necessary to use dispersion modeling to obtain flux data from the site. Table 1 presents a summary of the advantages and disadvantages of the ORS-based, and traditional point monitor approaches.

Table 1. Summary of the advantages and disadvantages of ORS-based and traditional point monitor approaches

Measurement Method	Advantages	Disadvantages
ORS-Based Approach Using Radial Plume Mapping	Measurements collected over a larger area making it less likely to miss major emissions areas Better spatial and temporal resolution Direct, measurement-based emissions calculations	Instrumentation is more costly Requires more time and effort to deploy Relies on prevailing wind direction for emissions measurements
Traditional Point Monitors	Easy to deploy Less costly to deploy No reliance on prevailing wind direction for measurements	Only provides data from a single measurement point Lack of spatial and temporal data Possibility of missing major emissions areas Requires modeling to obtain emissions calculations

Sections 6 and 7 of this document present the results of RPM validation studies done using controlled releases of tracer gases. The studies found that the VRPM method had capture rates as high as 97% of the actual emissions released during the study. An additional RPM validation study using multiple tracer gases also found favorable capture rates when using the VRPM method, as well as favorable results using the HRPM method (Varma et al., 2005).

Table 2 presents a comparison of traditional point monitoring approaches, and ORS-based approaches using RPM. The table includes approximate costs of instrumentation, number of target compounds each approach is capable of detecting simultaneously, minimum detection limits (MDL), spatial resolution of each measurement technique, and number of personnel necessary for deployment. The table does not include labor costs associated with field personnel or data analysis.

Table 2. Summary information on the ORS instrumentation and other traditional monitors

Measurement Approach	Equipment Cost	Number of Target Compounds	MDL (ppb)	Spatial Resolution	Personnel Needed for Deployment
Scanning OP-FTIR with RPM	$125,000[a]	See Table 2	1 to 100	Entire Survey Area	3
Scanning OP-TDLAS with RPM	$75,000[a]	See Table 2	1 to 100	Entire Survey Area	2
Scanning UV-DOAS with RPM	$200,000[a]	See Table 2	1 to 100	Entire Survey Area	2 to 3
ORS/RPM-Based Field Campaign Conducted by Environmental Contractor	$20,000 to $40,000/week[b]	See Table 2	1 to 100	Entire Survey Area	2 to 3
PID	$10,000	Total VOC	1 to 100	Single Point	1
PID/FID	$10,000[c]	Total VOC	1 to 100	Single Point	1
Summa Canister	$350 per sample[d]	Multiple	0.1 to 0.5	Single Point	1
Flux Boxes	$1,000[e]	Multiple	0.1 to 0.5	Single Point	1
Sorbent Methods	Varies	Varies	0.1 to 0.5	Single Point	1

[a]Cost includes ORS instrument, scanner, and retro-reflecting mirrors

[b]Cost includes creation of quality assurance documentation, conducting field campaign, data analysis, and reporting. The cost could vary depending on the size of the site and number of survey areas.

[c]Does not include the cost of hydrogen needed at the site to operate the instrument

[d]Does not include the cost of a gas chromatograph needed to analyze sample

[e]Cost includes materials for constructing box, but does not include the cost of sample analysis, which are typically collected with summa canisters or FID instrumentation

It should be noted that the measurement approaches shown in Table 2 can be performed as a service by an environmental contractor, meaning that an initial capital investment for equipment is not necessary. The approximate costs of hiring an environmental contractor to conduct a five-day field campaign using an ORS/RPM based approach are typically between $20,000 and $40,000, depending on the size of the site, number of survey areas, and target compounds of the study. The cost includes creation of quality assurance documentation, data collection, data analysis, and reporting.

In comparing the costs of an ORS-based measurement approach with traditional point monitoring approaches, an ORS-based approach using the RPM method may be more cost-effective. The ORS-based approach provides much better spatial and temporal resolution of concentration data, allowing for characterization of emissions plumes and direct calculation of emissions fluxes. In order to achieve the same level of temporal and spatial resolution (and speciation of the target analyte) using traditional point monitors, the user would have to deploy a multitude of monitors simultaneously at the site, resulting in substantially increased sampling and analysis costs.

3. Summary of Optical Remote Sensing Technologies

The project team evaluated many different ORS-based instruments as part of this long-term project, including OP-FTIR, OP-TDLAS, and UV-DOAS. Table 3 presents background information on the ORS instrumentation used during the long-term project. The table lists the analytes measured by each instrument, cost of instrumentation, and instrument limitations such as weather and interfering species. Table 4 presents a summary of the instrumentation used for each of the four measurement campaigns.

Table 3. Summary information on the ORS instrumentation used

	OP-FTIR	**OP-TDLAS**	**UV-DOAS**
Wavelength Range	Infrared (2-20 microns)	Near Infrared (approx. 1.5 microns)	Ultraviolet (245-380 nanometers)
Detectable Compounds	Multiple	CO, CO_2, NO_X, NH_3, CH_4, H_2S and others	BTEX, NH_3,, CO, CO_2, mercury, and other VOC
Detection Limits	Parts per billion	Parts per billion	Parts per billion
Limiting Weather Conditions	Heavy rain	Heavy rain, fog	Heavy rain, fog
Interfering Species	Carbon dioxide, water	None	Oxygen, ozone
Instrumentation Cost	$125,000[a]	$75,000[a]	$200,000[a]

[a]Cost includes ORS instrument, scanner, and retro-reflecting mirrors

Table 4. Summary of ORS instrumentation used for each measurement campaign

Somersworth, NH	**Ft. Collins, CO**	**Colorado Springs, CO**	**Orange Co., NC**	**RPM Validation Study**
Unisearch OP-FTIR	Unisearch OP-FTIR	Unisearch OP-FTIR	IMACC OP-FTIR	IMACC OP-FTIR
	IMACC OP-FTIR	IMACC OP-FTIR	Unisearch OP-TDLAS	AIL OP-FTIR
	Unisearch OP-TDLAS	Unisearch OP-TDLAS	Boreal OP-TDLAS	
	OPSIS UV-DOAS	OPSIS UV-DOAS		

The following subsections provide an overview of each of the ORS instruments used during the long-term evaluation. A list of ORS instrument manufacturers and their contact information can be found in Appendix D of this document.

3.1 OP-FTIR

The OP-FTIR Spectrometer is designed for both fence-line monitoring applications, and real-time, on-site, remediation monitoring and source characterization. An infrared light beam, modulated by a Michelson interferometer is transmitted from a single telescope to a retro-reflecting mirror target, which is usually set up at a range of 100 to 500 meters. The returned light signal is received by the single telescope and directed to a detector. The light is absorbed by the molecules in the beam path as the light propagates to the retro-reflecting mirror and again as the light is reflected back to the analyzer. Thus, the round-trip path of the light doubles the chemical absorption signal. One advantage of OP-FTIR monitoring is that the concentrations of a multitude of infrared absorbing gaseous chemicals can be detected and measured simultaneously, with high temporal resolution.

A scanning OP-FTIR instrument manufactured by Unisearch Associates, Inc. was used for the Somersworth, Fort Collins, and Colorado Springs studies. A scanning OP-FTIR manufactured by IMACC, Inc. was used for data collection in the Fort Collins, Colorado Springs, and Chapel Hill studies. Both OP-FTIR instruments contain a Nicolet bench, 12-inch telescope, and can collect data at resolutions of 0.125 cm^{-1}, 0.25 cm^{-1}, 0.5 cm^{-1}, 1 cm^{-1}, 2 cm^{-1}, 4 cm^{-1}, and 8 cm^{-1}. Figures 6 and 7 present pictures of the Unisearch Associates OP-FTIR, and the IMACC OP-FTIR, respectively.

Figure 6. Unisearch Associates OP-FTIR instrument and scanner

Figure 7. IMACC OP-FTIR instrument and scanner

3.2 OP-TDLAS

The OP-TDLAS instrument is a fast, interference free, and sensitive technique, for making continuous concentration measurements of many gases. Concentrations in the range of part per billions are suitable for measurements over an open path up to 1 km, for gases such as CO, CO_2, NO_X, NH_3, and CH_4. The laser emits radiation at a particular wavelength when an electrical current is passed through it. The light wavelength depends on the current and therefore allows scanning over an absorption feature and analyzing for the target gas concentration, using Beer's law. The OP-TDLAS applies a small 4-inch telescope, which launches the laser beam to a retro-reflecting mirror. The laser beam is returned by the mirror to the telescope, which is connected with fiber optics to a control box that houses the laser and a multiple channel detection device. A multiple channel OP-TDLAS instrument (Unisearch Associates, Inc.) was used during the Fort Collins, Colorado Springs, and Chapel Hill field campaigns. This instrument uses multiple telescopes to collect path-integrated methane concentration data along multiple beam paths (up to 8 beams). A single channel OP-TDLAS (Boreal, Inc.) was used during the Chapel Hill field campaign. The instrument is mounted to a scanner, and collects path-integrated concentration data along five beam paths. Figures 8 and 9 show pictures of the Unisearch OP-TDLAS and Boreal OP-TDLAS systems, respectively.

Figure 8. Unisearch OP-TDLAS system

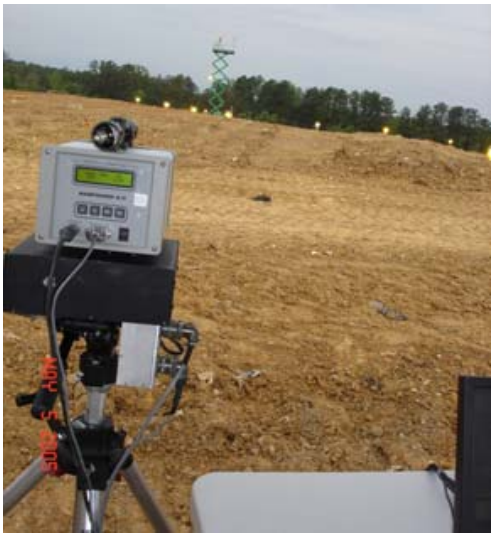

Figure 9. Boreal OP-TDLAS system and scanner

3.3 UV-DOAS

The UV-DOAS instrument (OPSIS, Inc.) has proven to be particularly useful for determination of the concentration of unstable species like free radicals,nitrous acid, and others (*Cowen et al., 2004, Kelly et al., 2003, Myers et al., 2000*). Additionally, many of the aromatic species can be determined at high sensitivity (*Platt, 1994*). UV-DOAS, like all spectroscopic techniques, makes use of the absorption of electromagnetic radiation by matter (Beers law). While the strong, structured UV absorption features of aromatic hydrocarbons have been known for a long time, it only recently became possible to use these properties for the reliable, sensitive, and selective measurement of monocyclic aromatics by UV-DOAS. UV-DOAS measurements of trace gases can be an extremely valuable complement to more traditional techniques like OP-FTIR. It allows the sensitive detection of a series of relevant molecules with good time resolution. The UV-DOAS instrument was used during the Fort Collins and Colorado Springs field campaigns. The instrument was used to measure concentrations of benzene, toluene, and xylene along a single-path configuration. Figure 10 presents a picture of the OPSIS UV-DOAS system.

Figure 10. Opsis UV-DOAS system

The following subsections provide a summary of the evaluation of each ORS instrument used during the long-term evaluation study. The subsections discuss the performance of each instrument, ease of deployment, and advantages and limitations of each instrument. The last subsection presents a comparison of methane data collected with the IMACC OP-FTIR and Unisearch OP-TDLAS instruments during the Fort Collins measurement campaign.

3.3.1 Evaluation of OP-FTIR Instrumentation

Scanning OP-FTIR instruments were used as the primary instrument for each field campaign of the long-term evaluation project. The evaluation included two OP-FTIR instruments (Unisearch, Inc. and IMACC, Inc.). The OP-FTIR instruments were scanned to collect path-integrated methane concentration data over multiple beam paths at the sites. Additionally, the OP-FTIR data was analyzed for the presence of ammonia and VOCs at the sites. The OP-FTIR detected ammonia, methanol, and gasoline (primarily octane) during the Ft. Collins and Colorado Springs field campaigns at ppb concentrations. The major advantage of the OP-FTIR (over the other ORS instruments used in the long-term evaluation project) is the ability to detect multiple compounds from the same data set. In fact, the OP-FTIR is the most cost-effective ORS instrument for applications where it is necessary to measure multiple compounds. Both OP-FTIR instruments were extremely stable and reliable over the course of the four field campaigns, with little or no maintenance required (*Modrak et al., 2005a, Modrak et al., 2005b*).

One of the disadvantages of the OP-FTIR is the effort needed for deployment of the instrument. During the long-term evaluation project, the OP-FTIR was deployed in multiple locations at each site. Although the instrument is mounted on a scanner, it requires at least two technicians to mount the instrument to the scanner cart and deploy the scanner cart to the measurement area. However, the effort needed for deployment of the OP-FTIR would not be an issue for applications where the OP-FTIR instrument is deployed in a single configuration. Once the instrument has been deployed, it must be aligned on each mirror used in the configuration. Alignment of the instrument is done using the scanner joystick control, which makes the alignment process quick and simple.

In recent years, OP-FTIR manufacturers have developed smaller instruments that are substantially lighter than the OP-FTIR instrumentation used in the current project. The disadvantages of these instruments are that the detection limits are generally higher, and the optical range of the instruments is shorter, which would not allow the instrument to scan over beam paths greater than 100 to 200 meters. However, the smaller OP-FTIR instruments may be ideal for certain field applications.

Another disadvantage of the OP-FTIR is the need for liquid nitrogen to cool the instrument detector. During the long-term evaluation project, it was necessary to add liquid nitrogen to the OP-FTIR instruments at the beginning of every day of data collection. For projects requiring 24 hour data collection, it would be necessary to add liquid nitrogen to the instrument approximately every 12 hours. Although filling the

instrument does not require a large amount of effort, it does add some extra cost to the field operations. It should be noted that large liquid nitrogen dewars are commercially available for use with OP-FTIR instrumentation. The dewars can be filled with liquid nitrogen, and are capable of automatically providing liquid nitrogen to the OP-FTIR for long periods of time. Although the large dewars are ideal for projects with permanent deployment locations, the large dewars are not an option for field campaigns with multiple configurations and survey areas.

Post-field analysis of the OP-FTIR data is currently recommended to quantify path-integrated concentrations. However, with the development of quantification software such as Non-Lin and IMACCQuant, this process does not require a Spectroscopist. Recent advancements such as real-time IMACCQuant and ARCADIS Real-Time RPM Software (discussed in Sections 5) have made it possible to quantify real-time concentrations in the field, but the performance of this software is still being evaluated by EPA and ARCADIS. Section 6 of this report presents a comparison of concentration determinations made with real-time and post-field analyses.

3.3.2 Evaluation of OP-TDLAS Instrumentation

The project team used OP-TDLAS instruments during the Fort Collins, Colorado Springs, and Orange Co. measurement campaigns to collect path-integrated methane concentration data. The long-term project evaluated two OP-TDLAS instruments (Unisearch, Inc. and Boreal, Inc.). The Unisearch OP-TDLAS instrument used up to 8 stationary telescopes, each aligned on up to 8 mirrors. The Boreal OP-TDLAS was mounted to a scanner and collected data along 5 beam paths.

The major advantages of the OP-TDLAS instruments are that they are lightweight, can be easily deployed by one person, and operate at ambient, rather than cryogenic, temperatures. The mirrors needed for OP-TDLAS measurements are also smaller and more lightweight than the mirrors traditionally used with OP-FTIR measurements. Another advantage of the OP-TDLAS is that it generates real-time, path-averaged concentration data in the field, without the need for post-field data analysis.

One disadvantage of the Unisearch OP-TDLAS used in the long-term study is that the instrument cannot be mounted to a scanner. The instrument consists of a control box (that houses the laser and a multiple channel detection device) and 8 stationary telescopes. Each telescope must be connected to the control box with fiber optic cables. Depending on the topography and location of physical barriers at the survey area, the distance between the control box and the telescopes may require a large amount of fiber optic cable, which can be difficult to deploy. The Boreal OP-TDLAS instrument used in the long-term study is mounted on a scanner, and was much easier to deploy.

Another disadvantage of the OP-TDLAS instruments is that they are not capable of measuring multiple compounds from the same dataset. Although OP-TDLAS instruments can detect many compounds (such as methane, CO, CO_2, NO_X, and NH_3), it is necessary to employ separate lasers for analysis of multiple gases.

3.3.3 Evaluation of UV-DOAS Instrumentation

A UV-DOAS instrument was used during the Fort Collins and Colorado Springs measurement campaigns to collect path-integrated concentrations of benzene, toluene, and xylenes (BTX). The long-term project evaluated one UV-DOAS instrument (OPSIS, Inc.). The OPSIS UV-DOAS instrument was operated in a bistatic configuration, where the source and detector were deployed at separate ends of a single beam path, along the surface of the survey area.

During the Fort Collins field campaign, a representative of OPSIS, Inc. assisted in deployment of the instrument. Alignment of the instrument was difficult and took a couple of hours to complete, but data was collected. The OPSIS, Inc. representative was not present during the Colorado Springs field campaign. Subsequently, field personnel had difficulty in aligning the instrument, and were unable to make the instrument operational. However, this may have been due to the fact that the field crew did not have previous experience in operating the instrument.

The major advantage of the UV-DOAS instrument is the ability to detect the BTX compounds at low concentrations. The UV-DOAS detected benzene, toluene, and p-xylene during the Fort Collins measurement campaign at levels less than 5 ppb. The OP-TDLAS instrument cannot detect the BTX compounds, and although the OP-FTIR is capable of detecting the BTX compounds, the minimum detection level of the UV-DOAS instrument is much lower than the OP-FTIR. Another advantage of the UV-DOAS instrument is that it does not require liquid nitrogen for operation.

One disadvantage of the UV-DOAS instrument used in the long-term study is that it required post-analysis of the data collected. The data analysis was performed by a representative of OPSIS, Inc. However, a spectral validation of the detected compounds was not provided, which is recommended for any future studies performed using this instrument.

3.3.4 Comparison of Methane Data Collected with the IMACC OP-FTIR and Unisearch OP-TDLAS Instruments

During the Fort Collins measurement campaign, the OP-FTIR and Unisearch OP-TDLAS instruments were deployed to measure path-integrated methane concentrations. The configurations used by the Unisearch OP-TDLAS were often similar to the configurations used with the OP-FTIR instruments. A comparison of the methane measurements from the two instruments was performed (*Modrak et al., 2005a)*. Table 5 presents the average methane concentrations (in ppm) measured with the OP-TDLAS and OP-FTIR along similar beam paths during the measurement campaign. Figure 11 shows a scatter diagram of the same dataset.

Table 5. Comparison of methane concentrations (in ppm) measured with the OP-TDLAS and OP-FTIR instruments

Mirror Number		Area A 9/8/03 Vertical		Area A 9/9/03 Horizontal		Area A 9/9/03 Vertical		Area B		Area D	
		OP-TDLAS	OP-FTIR	OP-TDLAS	OP-FTIR	OP-TDLAS	OP-FTIR	OP-TDLAS	OP-FTIR	OP-TDLAS	OP-FTIR
1	Avg.	1.91	1.92	1.94		1.96	1.74	2.01	1.81	2.03	1.80
	Std. Dev.	0.02	0.03	0.02		0.05	0.04	0.04	0.01	0.12	0.02
2	Avg.	1.99	1.88	1.96	1.78	1.83	1.88	2.03		1.93	1.77
	Std. Dev.	0.08	0.03	0.01	0.01	0.12	0.04	0.05		0.18	0.02
3	Avg.	2.08	1.84	1.98	1.78	2.03	1.86	2.06	1.81	1.90	1.75
	Std. Dev.	0.05	0.02	0.01	0.01	0.05	0.04	0.05	0.02	0.24	0.02
4	Avg.	2.05	1.85	1.95	1.77	2.03	1.88	2.03		1.98	1.75
	Std. Dev.	0.04	0.03	0.02	0.02	0.05	0.05	0.04		0.12	0.02
5	Avg.	2.06	1.84	1.98	1.79	2.03	1.87	1.98	1.82	1.94	1.73
	Std. Dev.	0.05	0.02	0.03	0.02	0.04	0.04	0.03	0.02	0.12	0.02
6	Avg.	2.09		1.99		2.07		2.05		1.95	1.72
	Std. Dev.	0.03		0.02		0.06		0.02		0.15	0.02
7	Avg.	2.09		2.01		2.04		2.02	1.81	1.99	1.73
	Std. Dev.	0.02		0.02		0.05		0.02	0.02	0.13	0.02
8	Avg.	2.06		1.96		2.04		2.07		1.97	1.71
	Std. Dev.	0.02		0.02		0.04		0.02		0.15	0.02

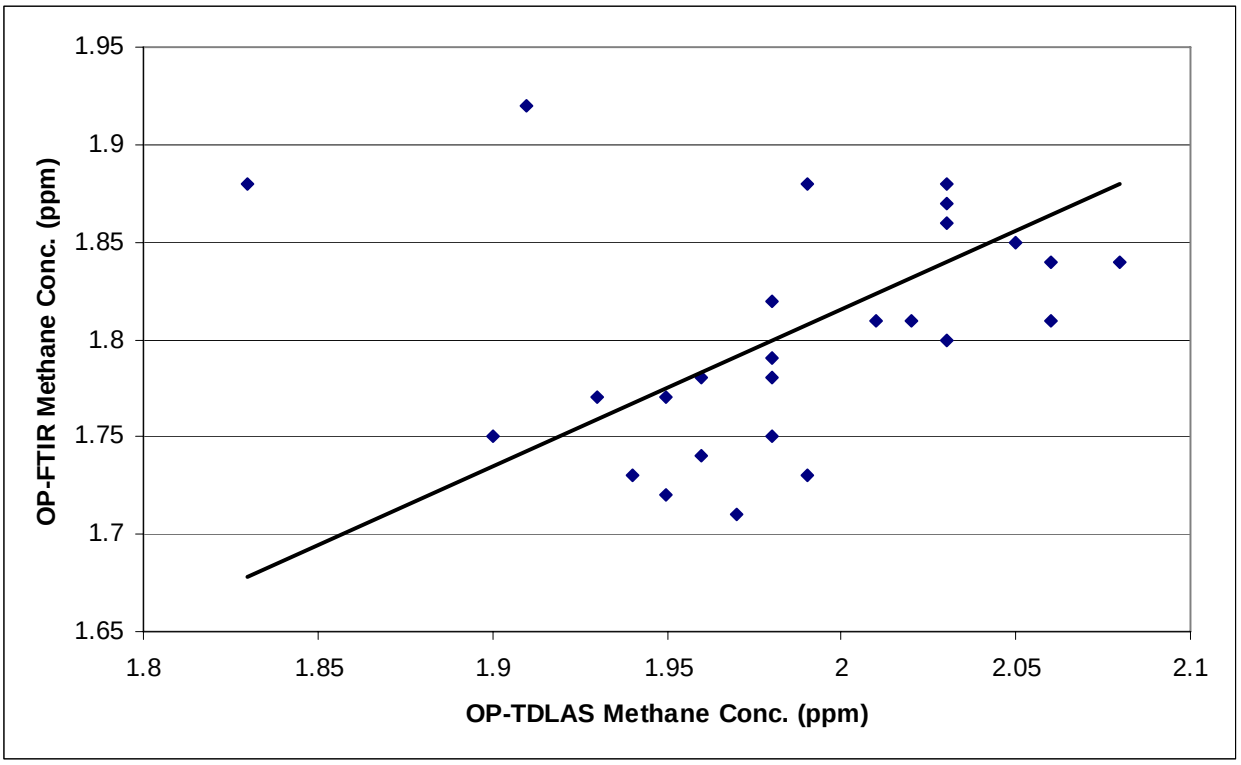

Figure 11. Comparison of methane concentrations measured along similar beam paths during the Fort Collins measurement campaign with the OP-FTIR and OP-TDLAS instruments

The methane concentrations measured by the two instruments were comparable, although the concentrations measured with the OP-TDLAS system were almost always slightly higher than concentrations measured with the OP-FTIR instrument along similar optical paths.

These results are consistent with the results of another experiment conducted (as part of a separate project) to compare methane measurements from the two instruments [Thoma et al., 2005]. During this experiment, the two instruments were deployed side-by-side and aligned to an identical mirror. Methane concentration data were collected with each instrument for a period of 30 minutes. The results of the experiment found that methane concentrations measured with the OP-TDLAS were slightly higher (3%) than concentrations measured with the OP-FTIR instrument.

The results of these comparisons are significant because they show that methane concentration data collected with the two instruments are comparable, and the two instruments can be used interchangeably in RPM configurations.

4. Summary of Project Field Campaigns

As mentioned previously, the long-term evaluation study consisted of four field campaigns. The following subsections present a summary of the findings from the first three field campaigns, as well as difficulties that were encountered (the Orange County field campaign is discussed in Section 5, and Appendix B of this document). It should be noted that the concentration values reported from the Fort Collins and Colorado Springs field campaigns have not been corrected to standard atmospheric conditions.

The Somersworth, NH field campaign was conducted in October 2002 at a Superfund site being considered for re-use as a recreational facility. The study employed OP- FTIR instruments to perform surveys using the HRPM and VRPM methods. Figure 12 shows the surface methane concentration contour map of the entire landfill and located sub areas of high methane emissions (up to 6.5 ppm average methane concentration above the global background). The most intense methane hot spot detected was in the vicinity of a hole dug to install a utility pole which was never installed.

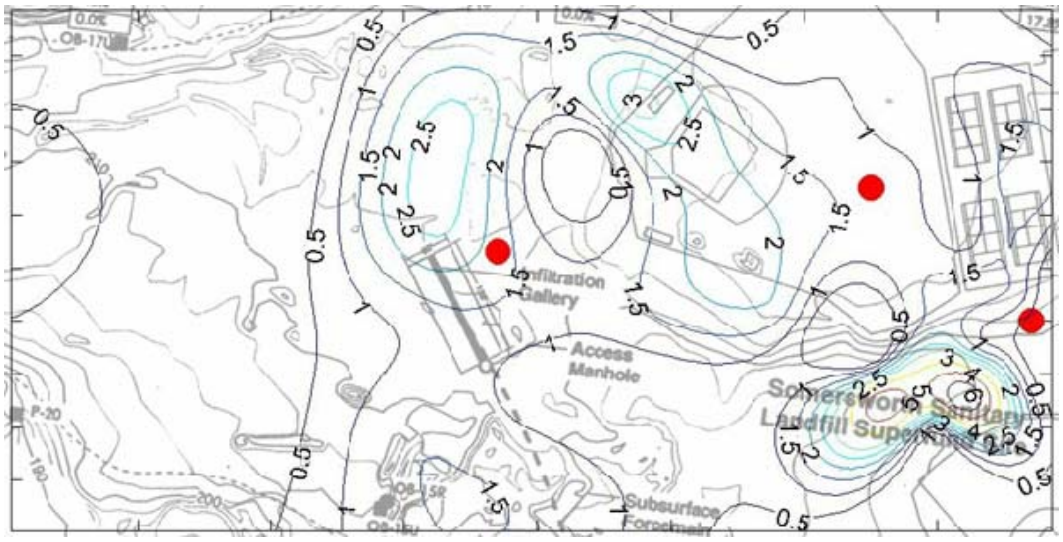

Figure 12. Surface methane concentration contours (in ppmv) overlaid on the map of the Somersworth Superfund Landfill

The VRPM survey found a methane flux of 5.8 grams per second from the site. Figure 13 presents the reconstructed methane plume map from the survey.

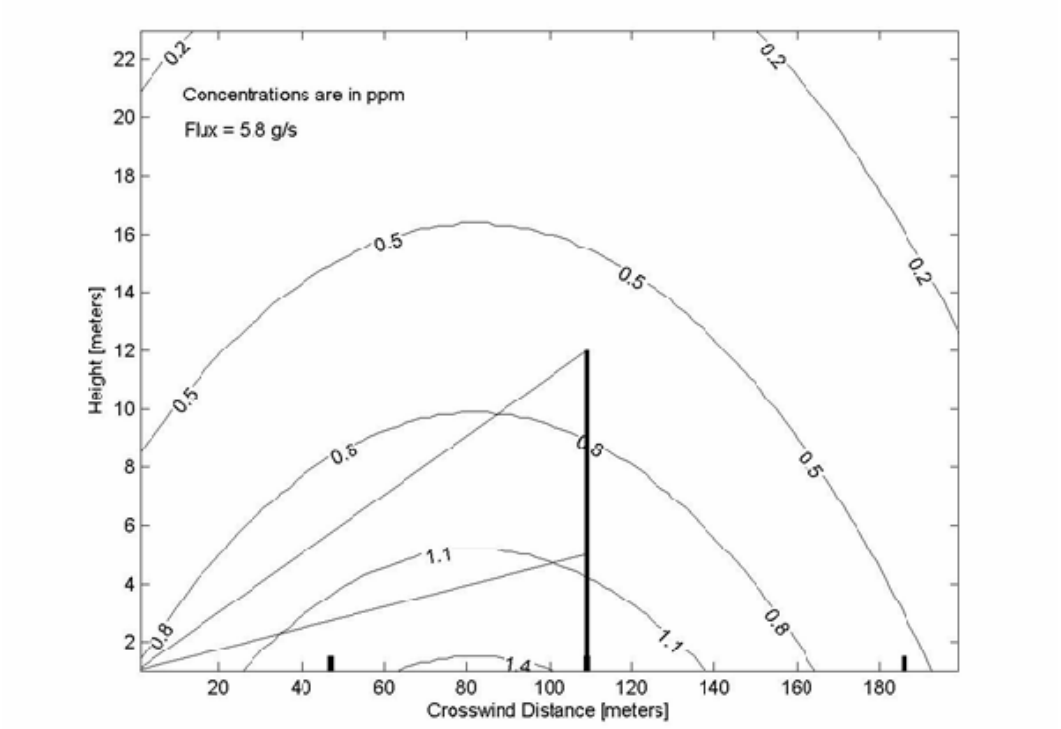

Figure 13. Reconstructed methane plume map from the VRPM survey of the Somersworth site (concentrations shown in ppmv). The location of the vertical structure is shown by the solid black vertical line. The scanning ORS instrument is located in the bottom left-hand corner of the figure

The Fort Collins, CO field campaign was conducted in September 2003 at a former landfill site currently comprised of a commercial area, park, and playgrounds. The city of Fort Collins is interested in developing a larger recreational area at the site, and requested assistance from EPA to perform an assessment of gas emissions at the site. The study used OP-FTIR, OP-TDLAS, and UV-DOAS instruments.

HRPM surveys of the site did not detect the presence of any methane hot spots, and methane surface concentrations at the site were essentially at ambient background levels. However, the HRPM survey detected a gasoline hot spot (average concentration over 81 ppb, maximum concentration about 100 ppb) in the vicinity of a large playground at the site.

A VRPM survey was performed to measure fluxes of fugitive emissions. The survey consisted of two VRPM configurations, located on the upwind and downwind sides of the survey area. The VRPM survey detected methane, ammonia, and gasoline in the downwind configuration, along the fence line of the site. The measured concentrations of methane and ammonia correlated well temporally, suggesting the source of the methane and ammonia emissions may be the same. However, the lack of methane and ammonia concentrations measured during the HRPM survey suggested that the survey area was not a significant source of methane emissions. By looking at data on wind direction, it was concluded that the source of ammonia and methane measured along the downwind VRPM configuration may have been from a source located outside of the site, northeast of the survey area (across the river). Figure 14 shows the surface gasoline concentration contour map generated from the HRPM survey, as well as the suspected source location of the measured methane and ammonia. The identification of the gasoline hot spot is significant because it demonstrates the capability of the ORS instrumentation (with the RPM method) to detect emissions hot spots of compounds (other than methane) from ground-based sources at relatively low concentrations.

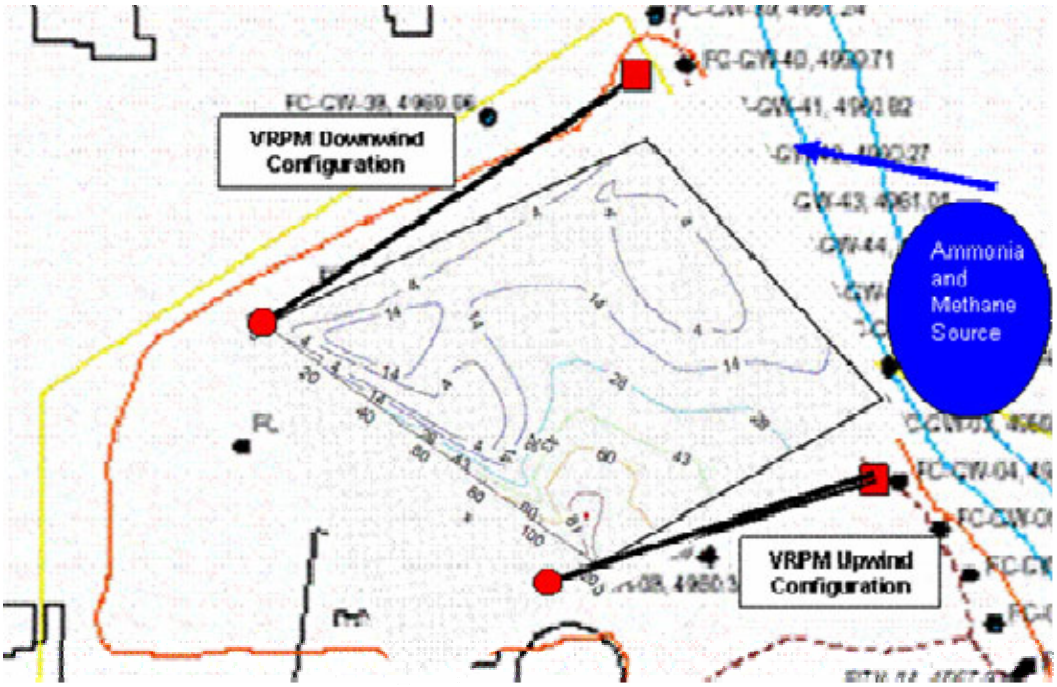

Figure 14. Summary map from the Fort Collins, CO site showing the surface gasoline concentration contour map (concentration shown in ppbv), and suspected source location of the measured methane and ammonia

The UV-DOAS instrument was deployed at the site to collect data concurrently with the OP-FTIR instrument. The UV-DOAS detected the presence benzene, toluene, and p-Xylene. The average measured concentrations of benzene, toluene, and p-Xylene were 2.6 ppb, 21 ppb, and 4.9 ppb, respectively. The concentrations of toluene measured with the UV-DOAS instrument correlated well with gasoline concentrations measured with the OP-FTIR instrument during the same time period indicating that the gasoline plume contains BTX compounds at levels lower than the MDL of the OP-FTIR instrument.

The Colorado Springs, CO field campaign was conducted in September 2003 at a former landfill site as part of an effort to rehabilitate the site for recreational use. The current owners of the landfill and the State of Colorado requested assistance from EPA to perform a site assessment to search for the presence of any fugitive gas emissions from the site. The study used OP-FTIR, OP-TDLAS, and UV-DOAS instruments.

HRPM surveys of the site detected the presence of two methane hot spots located along the eastern side of the site (see Figure 15).

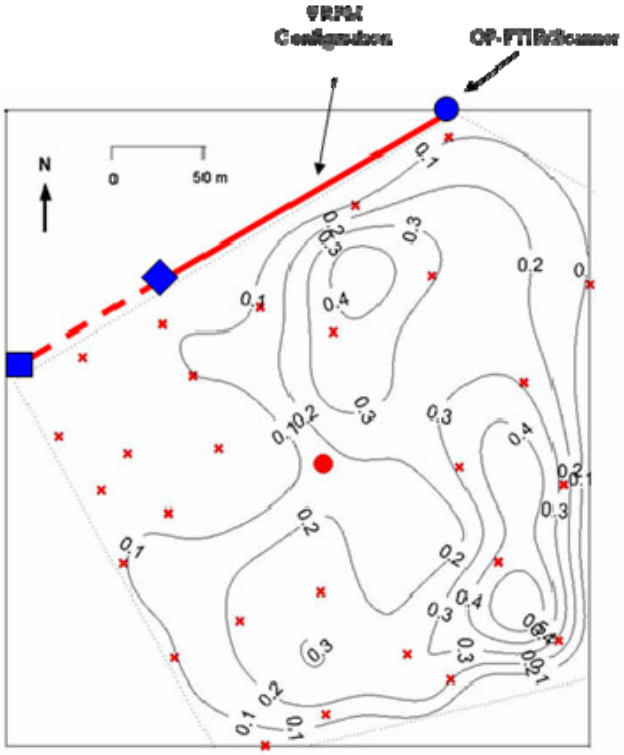

Figure 15. Surface methane concentration contours (in ppmv) overlaid on the map of the Colorado Springs, CO site. The figure shows the location of the VRPM configuration at the site

The first methane hot spot, located in the Northeast quadrant, had concentrations greater than 0.4 ppm above an ambient background concentration of 1.55 ppm. The other hot spot was located in the Southeast quadrant, and had concentrations greater than 0.5 ppm above ambient background levels.

The VRPM configuration was set up along the northern boundary of the site (see Figure 16). The calculated methane flux from the site was 4.9 g/s. The peak of the methane plume measured during the VRPM survey was located close to the location of the OP-FTIR/scanner. This agrees well with the location of the methane hot spots detected during the HRPM survey, indicating that the hot spots may be a major source of the methane plume detected during the VRPM survey. The location of the vertical structure is shown by the solid black vertical line. The scanning ORS instrument is located in the bottom left-hand corner of the figure.

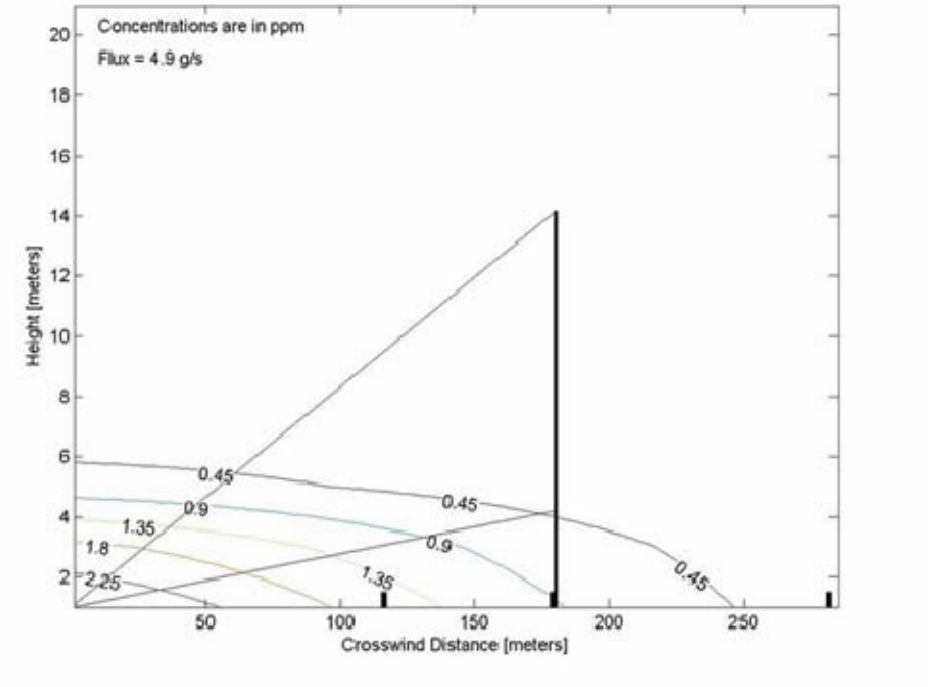

Figure 16. Reconstructed methane plume map from the VRPM survey of the Colorado Springs, CO site (concentrations shown in ppmv). The location of the vertical structure is shown by the solid black vertical line. The scanning ORS instrument is located in the bottom left-hand corner of the figure

The OP-TDLAS system collected information on methane concentrations along the surface of the site and on a slope adjacent to the southern boundary of the site. The survey of the surface found average methane

concentrations between 0.47 ppm and 0.53 ppm above ambient background levels. These values agree fairly well with the methane levels found in hot spots identified during the HRPM surveys.

The survey of the slope along the southern boundary of the site found slightly elevated methane concentrations. The largest average measured methane concentration was 1.34 ppm above ambient background levels.

4.1 Difficulties in the Application of the RPM Method at Landfill Sites

Over the course of the long-term evaluation study, the project encountered some difficulties in applying the RPM methods at the measurement sites. The difficulties were primarily due to the topography and physical barriers of the site,and unfavorable wind directions. The following sections present a discussion of these difficulties, and guidance for addressing them.

4.1.1 Sites with Elevated Passive Vents

The Colorado Springs measurement site had several passive vents installed over the surface of the landfill area. The passive vents were located approximately 2 meters above the surface of the site (see Figure 17). During the HRPM survey of this site, these vents were sealed with plastic because they were suspected methane emissions hot spots, and may have masked other emissions hot spots located along the surface of the site. The seals were removed from the vents for the VRPM survey. However, after reviewing the experimental design for this measurement campaign, this may not have been the best approach for characterizing the surface emissions from this site. The elevated vents are obvious potential surface emissions hot spots. However, the HRPM surveys are used to present a true representation of actual surface emissions from the site, and sealing the vents with plastic during the HRPM surveys may alter the magnitude and spatial representation of actual surface emissions from the site.

Figure 17. Passive vents sealed with plastic at the Colorado Springs site

4.1.2 Measurement of Methane Emissions from Slopes of Sites

The topography of many landfill or former landfill sites consists of a large elevated mound with a flat surface on the top and steep slopes on the sides. The topography of the Colorado Springs site was configured in this manner. The RPM measurements conducted during this measurement campaign were done on the flat surface of the site. Since it was not possible to deploy conventional RPM configurations on the side slopes, the concern is that methane emissions from the slopes were not completely quantified.

As part of the Colorado Springs measurement campaign, the Unisearch OP-TDLAS instrument was deployed along the southern slope of the site. Path-averaged methane concentration data were collected along 8 beam paths. Figure 18 presents a schematic of the configuration. The circles indicate the location of the OP-TDLAS telescopes, the squares indicate the location of the mirrors, and the solid black lines indicate the location of the beam paths.

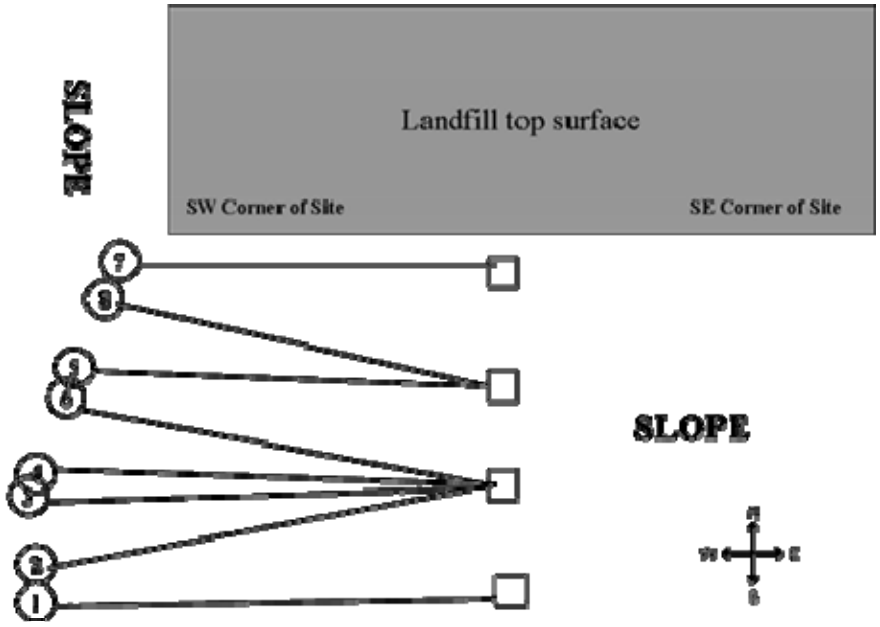

Figure 18. Schematic of the OP-TDLAS configuration deployed along the southern slope of the Colorado Springs site

The survey detected elevated methane along beam path #2 (1.07 ppm above background) and beam path #7 (1.34 ppm above background). Additionally, the study found large standard deviations in the methane concentrations data, suggesting that methane hot spots were present along the slope. However, since a conventional HRPM survey was not conducted along the slope, it was not possible to locate or quantify methane hot spots.

It is recommended that future measurement campaigns at sites with sloped topography include an HRPM survey of the slope areas to locate and quantify methane hot spots. However, HRPM surveys may be difficult to conduct if the site slopes are steep, especially when using the OP-FTIR instrument, because the scanner cart requires a relatively level surface for safe deployment. This may not be possible along the side slopes. The Unisearch OP-TDLAS instrument may be a better instrument to conduct slope surveys because it is lightweight, easier to deploy than the OP-FTIR, and does not require a level surface for deployment.

If sufficient instrumentation and project resources are available, the alternative VRPM approach (described in Section 2.4 of this document) can be applied to directly characterize methane emissions from the slopes of the landfill cell.

4.1.3 Capture of Emissions from Hot Spots Located a Large Distance Upwind of the VRPM Configuration

During some of the measurement campaigns (Somersworth, Colorado Springs), a single VRPM configuration was deployed along one side of the survey area to measure the methane flux from the entire site. As mentioned in Section 2, the VRPM configuration is deployed so that the plane of the configuration is as close to perpendicular to the prevailing wind direction as possible, to ensure that the maximum amount of emissions from the site are captured by the configuration. However, during some of the VRPM surveys, the winds were not exactly perpendicular to the configuration because the prevailing wind direction shifted slightly after the configuration was deployed, or the possible locations for the VRPM configurations were limited due to barriers at the site. The concern is that in cases where the prevailing winds are not close to perpendicular to the VRPM plane, emissions from all of the surface hot spots may not be captured completely by the VRPM configuration, leading to an underestimation of the flux value from the site. This is an even larger concern for hot spots located a large distance upwind of the VRPM configuration.

During the long-term evaluation project, the VRPM configurations were deployed so that the length of the configuration was as long as possible to increase the chances of capturing all of the emissions from the survey area. In fact, whenever possible, the VRPM configuration should be extended beyond the boundaries of the survey area.

The development of the Real-Time RPM software (discussed in Section 5 of this document) is a major advancement in the application of the RPM method. The software is capable of providing real-time surface concentration maps in the field. This is extremely valuable in assuring that emissions from major emissions hot spots are captured by the VRPM configuration, because the VRPM configuration can be setup directly downwind of the hot spot locations, if necessary.

As part of the effort to assess the ability of the VRPM method to capture emissions from hot spots located a large distance upwind of the configuration, ARCADIS and EPA conducted a validation study in June and July 2006 using tracer gas releases. The objective of the study was to provide guidance towards the development of procedures for ensuring the complete capture of emissions by the VRPM method. The results of the study are presented in Section 6 of this document.

4.1.4 Prevailing Wind Direction During the Time of the Measurements

As mentioned in Section 2 of this document, the VRPM method configuration should be set up downwind of the survey area so that the prevailing wind direction is as close to perpendicular to the plane of the configuration as possible This is necessary to ensure that the VRPM configuration is capturing as much of the emissions plume from the survey area as possible. When using the HRPM method, there is no need to consider prevailing wind direction.

During the Colorado Springs field campaign, the project team deployed the VRPM configuration in the morning on the last day of the campaign. The configuration was originally deployed along the eastern boundary of the site, as the forecasted wind direction was from the west. However, after the configuration was deployed, the project team observed that the prevailing winds were from the south. Since this occurred on the last day of the field campaign, the project team decided to re-deploy the VRPM configuration along the northern boundary of the site, in order to capture emissions from the landfill cell.

When applying the VRPM configuration, the project team decides where to deploy the configurations based on forecasted wind directions. However, the actual observed wind direction is not always the same as the forecasted direction. This can be problematic when conducting a project involving multiple configurations with limited project resources. When applying the VRPM configuration, it is recommended to deploy the configuration in one location for the longest time period possible, to account for periods of varying wind conditions.

If sufficient instrumentation and project resources are available, the alternative VRPM approach (described in Section 2.4 of this document) can be applied to characterize emissions from the survey area and slopes, as well as areas upwind of the landfill cell. Because the alternative VRPM approach employs four VRPM measurement planes that totally encompass the survey area, flux measurements can be collected from the area of interest, regardless of the prevailing wind direction during the time of the measurements.

5. Orange County, NC Field Campaign

ARCADIS and EPA conducted a fugitive emissions measurement campaign during May 2005 at the Orange County Municipal Landfill located near Chapel Hill, North Carolina using OP-FTIR and OP-TDLAS instruments. The measurement campaign also served as a demonstration of optical remote sensing technologies and the RPM method. The following section presents background information on the site, the experimental setup used during the campaign, a discussion of how difficulties encountered in previous campaigns were addressed during this campaign, and details on the Real-Time RPM software, which was deployed for the first time during this field campaign. The results of this study can be found in Appendix B of this document.

5.1 Site Information

The project team conducted measurements in the active and closed landfill areas at the site to compare levels of fugitive emissions from different landfill areas. Figure 19 presents an overview of the site.

Figure 19. Site map of the Orange County Municipal Landfill site showing the location of the two landfill areas

The Orange County Municipal Landfill site is located on 200 acres of land. The closed landfill site is located on the northern portion of the site, and has a footprint of 50 acres. The area began accepting waste in 1972, and operated until 1995 when the new Subtitle D Landfill (active site) was ready to accept waste. Approximately 810,000 tons of waste was landfilled during the 23 years that the closed landfill site was in operation. The area accepted municipal solid waste, construction and demolition waste, and yard waste. The Closed Landfill Site was capped with three feet of soil in 1995 and 1996, and 45 elevated, passive gas vents were installed in 1998. Figure 20 shows a picture of the closed landfill site.

Figure 20. Closed landfill site at the Orange County Municipal Landfill

The active landfill Site is a 26-acre Subtitle D landfill that opened on July 1, 1995. Leachate is injected into the waste, and is collected in a lined lagoon at the site. The active landfill site has a capacity of 880,000 tons of waste. As of June 2004, approximately 524,645 tons of waste had been landfilled. Figure 21 shows a picture of the active landfill site.

Figure 21. Active landfill site at the Orange County Municipal Landfill

5.2 Project Objectives

The objectives of the study were as follows:

- Collect OP-FTIR and OP-TDLAS data in order to identify major emissions hot spots by generating surface concentration maps in the horizontal plane using the HRPM method
- Measure emission fluxes of detectable compounds downwind from major hot spots using the VRPM method
- Demonstrate the operation and function of the ORS technologies

5.3 Testing Procedures

The following subsections describe the testing procedures used in the Active and Closed Sites of the landfill facility (refer to Figure 19 for the geographical orientation of each area). The actual survey areas within the two sites were chosen to ensure that the study investigated the maximum amount of surface area at the sites. One factor that affected the location of the survey areas was the topography of each site, and the

location of the work face within the active site. HRPM surveys were performed in each site (using an IMACC OP-FTIR) to produce surface methane concentration maps and to locate any surface hot spots. The project team performed VRPM surveys at both sites to obtain an estimated emission flux rate of methane. VRPM surveys were done in the active site using an IMACC OP-FTIR and Boreal OP-TDLAS. VRPM surveys were done in the closed site using an IMACC OP-FTIR and Unisearch OP-TDLAS.

OP-FTIR data were collected as interferograms. Concentrations were determined in real-time in the field, using the Real-Time RPM software. The software package uses IMACCQuant for concentration determination. The concentration data are then input into the RPM algorithms to produce surface concentration contour maps and downwind plume maps in the field.

In order to evaluate the performance of the IMACCQuant software (used by the Real-Time RPM software), the raw OP-FTIR data (interferograms) were archived to CD-ROM, and a post-field analysis of the data was done using Non-Lin (Spectrosoft) quantification software and the IMACCQuant software. A comparison of the results of the two analysis methods is presented later in this section.

The OP-TDLAS concentration data are provided as a real-time output by the instrumentation. The concentration data from the Boreal OP-TDLAS instrument was input to the Real-Time RPM software to provide downwind plume maps in the field. The concentration data from the Unisearch OP-TDLAS instrument was input to the RPM software after the field campaign to produce downwind plume maps.

Meteorological data including wind direction, wind speed, temperature, relative humidity, and barometric pressure were continuously collected during the measurement campaign. Two RM Young meteorological instruments were deployed in the Active Site, and two Climatronics meteorological instruments were deployed in the closed site. Both models are automated, collect real-time data, and record the data as one-minute averages to the computer used for data collection. Wind direction and speed-sensing heads were used during the VRPM surveys to collect data at two heights, 2 and 10 meters (the 10 meter sensor was placed on top of the scissorsjack).

5.4 Active Site

5.4.1 HRPM Measurements

The project team conducted HRPM surveys in two survey areas within the active site (see Figure 22).

Figure 22. Map of the active site showing the location of the survey areas and prevailing wind direction during the time of the surveys

An HRPM survey was conducted in Survey Area #1 on May 2, 2005 using an IMACC OP-FTIR. The instrument was located in the southwestern corner of the survey area.

HRPM surveys were conducted in Survey Area #2 on May 3-5 using an IMACC OP-FTIR. During each survey, the OP-FTIR instrument was located in the southeastern corner of the survey area. The May 3 HRPM survey consisted of nine optical paths and the May 4-5 surveys consisted of twelve optical paths.

5.4.2 VRPM Measurements

VRPM surveys were not conducted in Survey Area #1 due to the close proximity of the area to the work face of the Active Site. On May 4, two separate VRPM surveys were conducted in Survey Area #2 using the IMACC OP-FTIR and the Boreal OP-TDLAS, respectively. On May 5, one VRPM survey was conducted using the Boreal OP-TDLAS instrument. The prevailing wind direction during the surveys was from the northeast. The VRPM configurations were deployed along the southern boundary of Survey Area #2, and consisted of five retro-reflecting mirrors; two deployed along the surface between the ORS instrument and

the vertical tower, one mounted half-way up the vertical tower, one mounted at the top of the vertical tower, and one along the surface approximately 30 meters beyond the vertical tower. Table 6 presents a summary of the VRPM survey results from the active site.

Table 6. Summary of methane flux values measured during the VRPM surveys in the active site

Date	Instrument Used	Average Methane Flux Value (grams per second)	Range of Methane Flux Values (grams per second)
May 4, 2005	IMACC OP-FTIR	10	4.2 to 17
May 4, 2005	Boreal OP-TDLAS	7.4	2.0 to 16
May 5, 2005	Boreal OP-TDLAS	7.3	1.0 to 24

5.5 Closed Site

5.5.1 HRPM Measurements

The project team conducted HRPM surveys in two survey areas within the closed site (see Figure 23).

An HRPM survey was conducted in Survey Area #1 on May 2 using an IMACC OP-FTIR. The instrument was located in the northeastern corner of the survey area.

HRPM surveys were conducted in Survey Area #2 on May 3 and May 5 using an IMACC OP-FTIR. The May 3 survey used twelve optical paths, and the May 5 survey used nine optical paths. The instrument was located in the northwestern corner of the survey area during both surveys.

5.5.2 VRPM Measurements

VRPM measurements were conducted in the closed site using the IMACC OP-FTIR and Unisearch OP-TDLAS instruments. The locations of the VRPM configurations are shown in Figure 23. The yellow circle indicates the locations of the Unisearch OP-TDLAS instrument, and the red circle indicates the location of the OP-FTIR instrument. The black square denotes the location of the vertical tower during each survey.

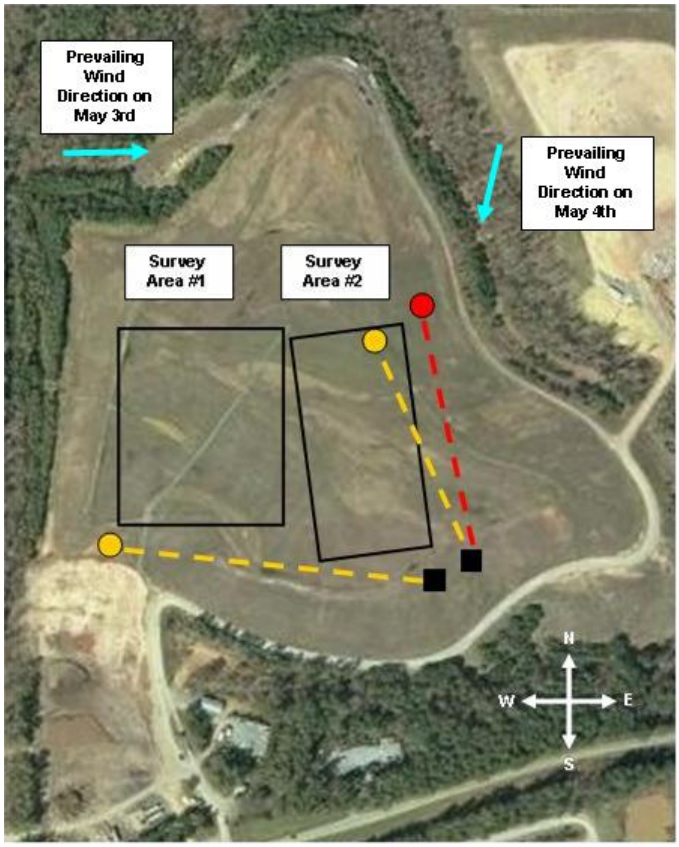

Figure 23. Map of the closed site showing the location of the survey areas and prevailing wind directions during the time of the surveys

On May 3, VRPM surveys were conducted along the eastern side of Survey Area #2 (measuring emissions from both survey areas). During this day, the prevailing wind direction was from the west. The OP-FTIR VRPM configuration consisted of six retro-reflecting mirrors; three deployed along the surface between the ORS instrument and the vertical tower, one mounted half-way up the vertical tower, one mounted at the top of the vertical tower, and one along the surface approximately 25 meters beyond the vertical tower. The OP-TDLAS VRPM configuration consisted of five retro-reflecting mirrors; three deployed along the surface between the ORS instrument and the vertical tower, one mounted half-way up the vertical tower, and one mounted at the top of the vertical tower.

On May 4, a VRPM survey was conducted along the southern side of the closed site (measuring emissions from both survey areas). During this day, the prevailing wind direction was from the northeast. The VRPM

configuration consisted of seven retro-reflecting mirrors; three deployed along the surface between the ORS instrument and the vertical tower, one mounted half-way up the vertical tower, one mounted at the top of the vertical tower, and two along the surface beyond the vertical tower. Table 7 presents a summary of the VRPM survey results from the closed site.

Table 7. Summary of methane flux values measured during the VRPM surveys in the closed site

Date	Instrument Used	Average Methane Flux Value (grams per second)	Range of Methane Flux Values (grams per second)
May 3, 2005	IMACC OP-FTIR	22	5.4 to 58
May 3, 2005	Unisearch OP-TDLAS	10	2.1 to 28
May 4, 2005	Unisearch OP-TDLAS	12	2.0 to 55

5.6 Addressing Potential Difficulties with Applying the RPM Method to the Site

The Orange County Landfill site presented a couple of the same difficulties in applying the RPM method experienced during previous field campaigns (see Section 4). The closed site at the landfill had many elevated passive vents, located approximately 2 meters above the surface of the site. Although it was obvious that the passive vents were probably methane emissions hot spots, the vents were not covered during the HRPM surveys. Although the results of the HRPM surveys (see Figures B8, B9, and B10 of Appendix B) conducted in the closed site found hot spots located in the vicinity of some of the vents, the generated surface concentration contour maps provide a true picture of the surface methane emissions from the area.

Another issue was the concern of capturing emissions from surface hot spots located a large distance upwind of the VRPM configurations. This was not a concern during the VRPM surveys done in the active site, due to the relatively small dimensions of the survey area (approximately 80 meters by 60 meters). However, this issue was a concern during the VRPM surveys of the closed site, due to the large dimensions of the survey area. In response to this concern, the VRPM configurations used in the closed site were extended as far as possible horizontally, given the topography of the site. Each of the VRPM configurations used in the closed site were extended more than 200 meters horizontally, to maximize the chances of capturing emissions from surface hot spots located upwind of the configuration.

5.7 Development of Real-Time Analysis Capabilities

One of the major advancements in the RPM method has been the development of real-time software capabilities. The Orange County Municipal Landfill measurement campaign represents the first time that

Real-Time RPM software has been used in the field. The real-time software package for the OP-FTIR instrumentation uses IMACCQuant for real-time concentration determination of multiple compounds. The concentration data are then input into the RPM algorithms to produce surface concentration contour maps, plume maps, and flux determinations, in real-time, in the field.

The Real-Time RPM software was also used with the Boreal OP-TDLAS instrument. The real-time methane concentration values determined by the instrument are input into the RPM algorithms to create the real-time RPM maps.

The real-time software is particularly useful in the field because it can be used as guidance in selecting the location of the VRPM configurations to ensure the best chance of capturing emissions from major surface emissions hot spots.

Although the real-time concentration software was used during the Orange County Municipal Landfill campaign, Non-Lin quantification software was used to perform a post-field analysis of the OP-FTIR concentration data from the field campaign. This concentration data was then input into the RPM software to produce the OP-FTIR results presented in Appendix B of this report.

6. VRPM Plume Capture Validation Study

6.1 Background Information and Study Objectives

In order to assess the ability of the VRPM method to capture emissions from hot spots located a large distance upwind of the configuration, ARCADIS and EPA conducted a VRPM plume capture validation study during June and July 2006 at the Orange County Municipal Landfill. The study, which used tracer gas releases to determine plume capture by the VRPM method, was conducted in the closed area of the landfill facility (see Figures 18 and 19).

The study used two scanning Open-Path Fourier Transform Infrared (OP-FTIR) spectrometers and was conducted to evaluate the effectiveness of the vertical radial plume mapping (VRPM) method in capturing plumes from tracer gas releases located at different distances upwind of the measurement configuration. The effectiveness of the measurement configuration in capturing plumes (in the horizontal and vertical direction) was evaluated by comparing the actual release rate of tracer gases (deployed at different distances upwind of the configuration) to the flux values recovered by the measurement configurations.

The primary objective of the study was to develop guidance for applying the VRPM method to studies charactering fugitive emissions from area sources. The guidance will include:

- Configuration length necessary for complete plume capture
- Maximum upwind plume source location for which the VRPM method accurately characterizes emission rates

The secondary objective of the study was to characterize emissions of methane from the Closed Area of the landfill. This data was considered non-critical for this study, and was collected to provide further information on methane emissions from landfill sites. The methane flux data (collected along the longest VRPM configuration) from this study can be found in Appendix C of this report.

6.2 Testing Procedures

The experimental setup consisted of two VRPM configurations, co-located in a parallel manner, sharing one vertical structure (scissor lift). The orientation of the configurations was determined for each day based on the forecasted wind direction. The two configurations were oriented so that the prevailing wind direction was as close to perpendicular to the plane of the configurations as possible. The horizontal length of the first configuration was approximately one-third the length of the second configuration. The length of the first configuration was approximately 60 meters, and the length of the second configuration was approximately

200 meters. The configuration lengths deviated from the original project Quality Assurance Project Plan which stated that the length of the two configurations would be 100 and 300 meters, respectively. These lengths were not possible due to the topography of the site.

The first configuration consisted of five retro-reflecting mirrors; two located on the surface between the OP-FTIR instrument and the scissor lift, one at the base of the scissor lift, one mounted at a point half-way up the scissor lift, and one mounted at the top of the scissor lift. The second configuration consisted of five retro-reflecting mirrors; one located on the ground between the OP-FTIR and the scissor lift, one at the base of the scissor lift, one mounted at a point half-way up the scissor lift, one mounted at the top of the scissor lift, and one located along the ground approximately 75 meters beyond the location of the scissor lift. Figure 24 presents a schematic of the two VRPM configurations used for the study.

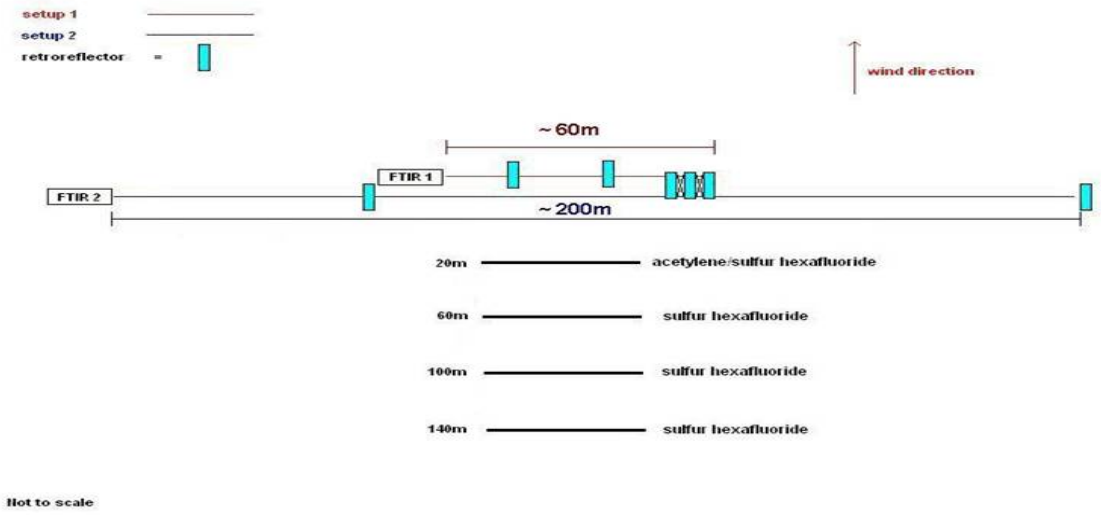

Figure 24. Schematic of the experimental configuration used for the VRPM validation study

The data was collected using two OP-FTIR spectrometers, each mounted on a commercially available scanner manufactured by Orbit, Ltd. The scanner is used to maneuver the instrument in the horizontal and vertical planes, and is typically used for operating equipment used for military applications. Although the QAPP called for collecting data along the first configuration using a IMACC, Inc. OP-FTIR, this was not possible due to an instrument malfunction during the first day of the project. As an alternative, data was collected along the first configuration using a AIL, Inc. OP-FTIR. Data was collected along the second configuration using a second IMACC, Inc. OP-FTIR.

Two tracer gases were released simultaneously during the study, sulfur hexafluoride (SF_6) and acetylene (C_2H_2). The tracer gases were released through soaker hoses which were deployed along the ground upwind of the VRPM configuration. The hoses each had a crosswind dimension of approximately 50 meters long.

The acetylene release was located approximately 20 meters upwind from the VRPM configurations, and remained in this position throughout the measurement campaign, to provide a “ground truth” measurement, or calibration for the sulfur hexafluoride plume capture measurements. The SF_6 was released from four different upwind locations to allow for the evaluation of the vertical plume capture capabilities of the VRPM method. Plumes released a greater distance upwind of the VRPM configuration will be more vertically developed due to atmospheric dispersion, and it was necessary to release a tracer gas at different upwind locations to determine the maximum upwind distance that the VRPM method is able to sufficiently capture the whole plume. The SF_6 release was initially located in the same location as the acetylene, approximately 20 meters upwind from the VRPM configurations. For the second survey, the SF_6 release was moved to a location approximately 100 meters upwind of the VRPM configurations.

After the second survey was completed (with the acetylene located 20 meters upwind of the VRPM configuration and the sulfur hexafluoride located 100 meters upwind), the SF_6 concentrations measured along the two uppermost beam paths ending at the vertical tower (of the longest VRPM configuration) were analyzed. A statistical analysis (a t-test) was performed to compare the average SF_6 concentrations measured along each of the two beams. The t-test was done using a sample size of n=30, with a two-sided 95% confidence interval. This analysis was done to determine the location of the two additional sulfur hexafluoride releases. The ultimate goal was to locate the SF_6 release at upwind locations where the longest VRPM configuration is: (1) easily capturing the SF_6 plume, (2) sufficiently capturing the SF_6 plume, but the release is located at the maximum upwind distance for doing so, and (3) not fully capturing the SF_6 plume. The three possible scenarios were as follows:

1. If there is no statistically significant difference between the average concentrations along each beam (i.e. no vertical concentration gradient), this indicates that the VRPM configuration is not vertically capturing the plume from the 100 meter upwind release point. In this case, two additional SF_6 releases will be performed closer to the plane of the VRPM configurations, at distances of 40 and 70 meters upwind of the VRPM configuration.

2. If the average difference between the average concentrations along each beam is less than 10% (i.e. a slight vertical concentration exists), this indicates that the VRPM configuration is sufficiently vertically capturing the plume from the 100 meter upwind release point, but the release is located close to the maximum upwind distance for doing so. In this case, two additional SF_6 releases will be performed at distances of 60 and 140 meters upwind of the VRPM configurations.

3. If the average difference between the average concentrations along each beam is greater than 10% (i.e. a substantial vertical concentration exists), this indicates that the VRPM configuration is vertically capturing the plume from the 100 meter upwind release point, and the 100 meter upwind location is not close to the maximum upwind location for complete plume capture. In this case, two additional SF_6 releases will be performed at distances of 140 and 180 meters upwind of the VRPM configuration.

The results of the t-test performed during the study after the 100 meter release was completed are presented in Table 8.

The results indicated that when considering the calculated t-value of 3.69 and a sample size of 30, there is a statistically significant difference between the two concentration datasets, at the 95% confidence interval. The results also showed that the average difference between the concentrations measured along each beam was greater than 10% (scenario #3 above). This suggests that two additional SF_6 tracer releases should have been located at distance of 140 and 180 meters upwind of the VRPM configurations. However, due to geographical limitations at the site, the largest possible distance upwind of the VRPM configurations was approximately 140 meters. Due to this limitation, the project team elected to place the two additional SF_6 tracer releases at distances of 60 and 140 meters upwind of the VRPM configurations. These two additional locations allowed the team to collect data from a wide range of distances upwind of the configuration. Also, the 140 and 180 meters distance where predicted with an 300-meter long VRPM configurations for complete horizontal plume capture when wind direction is perpendicular to the plane. The change in the actual long VRPM configuration merited a change in the determined upwind distances of the same size source.

The amount of tracer gas released was regulated using two Environics mass flowmeters, which were calibrated by the EPA Metrology Lab prior to the study. For this study, the mass flowmeter used for the acetylene releases was pre-set to a flow rate of 5600 cubic centimeters per minute, or 0.110 grams per second. The mass flowmeter used for the SF_6 releases was pre-set to a flow rate of 1050 cubic centimeters per minute, or 0.110 grams per second. Additionally, a digital scale was used to provide a secondary method for confirming the release rates of the tracer gases. The digital scale was used to obtain the mass of each gas cylinder before and after each tracer gas release. The release rate (in grams per second), was determined by dividing the total mass of gas released during the tracer release by the total time of the release.

Two meteorological heads were deployed to collect wind speed and wind direction data during the study. One head was deployed at the base of the scissor lift, at a height of approximately 2 meters. The other head was deployed at the top of the scissor lift, at a height of approximately 10 meters. Each survey lasted at least two hours, or until approximately one hour of concentration data was collected during periods that the prevailing winds were within 30 degrees of perpendicular to the longest VRPM configuration and the prevailing wind speeds were between 1 and 8 m/s.

Table 8. Results of the t-test performed using sulfur hexafluoride concentration data collected along beam path 4 and 5 during the 100-meter release

Cycle #	SF_6 Concentrations (in ppm) Measured Along Beam Path #4	SF_6 Concentrations (in pm) Measured Along Beam Path #5
1	0.00238	0.00149
2	0.00265	0.00157
3	0.00284	0.00210
4	0.00176	0.00198
5	0.00196	0.00276
6	0.00169	0.00086
7	0.00212	0.00109
8	0.00204	0.00214
9	0.00291	0.00114
10	0.00206	0.00188
11	0.00145	0.00076
12	0.00436	0.00128
13	0.00350	0.00239
14	0.00261	0.00121
15	0.00151	0.00142
16	0.00149	0.00125
17	0.00198	0.00172
18	0.00278	0.00111
19	0.00431	0.00135
20	0.00213	0.00081
21	0.00129	0.00122
22	0.00119	0.00154
23	0.00165	0.00070
24	0.00288	0.00255
25	0.00235	0.00255
26	0.00267	0.00119
27	0.00254	0.00314
28	0.00216	0.00274
29	0.00421	0.00255
30	0.00299	0.00203
	Mean=0.002415	Mean= 0.001684
t-value=3.69	Variance=0.0000007	Variance=0.0000005

6.3 Procedure for Plume Capture Assessment

The first step in assessing plume capture of the VRPM configurations was to compare the calculated acetylene and sulfur hexafluoride flux values (determined along both VRPM configurations) from the 20 meter upwind release point when both tracer gases were located side-by-side. The calculated flux values were compared to the actual release rates for each tracer gas, yielding the recovery percentage of the VRPM method for each tracer gas. Since the recovery percentage of each tracer gas may differ slightly due to differences in the physical and chemical properties of the gases, it was necessary to eliminate this bias as a variable in the data analysis. In order to eliminate this bias, the recovery percentages of each gas at the 20 meter upwind distance were ratioed along each VRPM configuration. This ratio was then used to calibrate the sulfur hexafluoride measurements made at the additional upwind distances, while the location of the acetylene release remained constant throughout the study.

The acetylene recovery percentages (along both VRPM configurations) calculated from each additional release in the study were used to adjust the corresponding sulfur hexafluoride plume capture percentages from each release point. This was done to confirm that the difference between actual and calculated sulfur hexafluoride rates was due solely to plume capture issues. Table 9 presents a hypothetical data set from the proposed experimental design, and an example of the calculations that were used in the assessment of plume capture.

Table 9. Example dataset from the executed experimental design

Configuration	20-m Acetylene Recovery*	20-m Sulfur Hexafluoride Recovery*	Release #2 (100-m) Sulfur Hexafluoride Recovery*	Release #2 (20-m) Acetylene Recovery*
60-m VRPM	94%	91%	75%	86%
200-m VRPM	97%	95%	80%	90%

* Recovery percentage is defined as the ratio of the flux value calculated by the VRPM method to the actual release rate, multiplied by 100.

In order to assess the plume capture percentage of the VRPM method (along both VRPM configurations) at an upwind distance of 100 meters, the following steps must be taken:

The hypothetical sulfur hexafluoride recovery percentage (the recovery percentage if SF_6 were released at 20 meters during the same time period that it is actually released at 100 meters) is calculated to eliminate factors other than plume capture issues in evaluating the sulfur hexafluoride capture percentage. This is done by proportioning the acetylene to SF_6 recovery percentage found during the side-by-side 20 meter release to the acetylene recovery percentage found during the release coinciding with the 100 meter SF_6 release. The following equation shows how this is done when considering the 60-meter VRPM configuration:

$$\frac{94\%}{91\%} = \frac{86\%}{X}$$

where X = the hypothetical sulfur hexafluoride recover percentage (in this case X = 83%).

The actual sulfur hexafluoride recovery percentage found during the 100 meter gas release (75%) is then ratioed to the value of X calculated above (83%). In this example, (75%/83%*100) is equal to 90%, which is the captured sulfur hexafluoride release percentage that can be attributed to the issue of vertical and horizontal plume captue plume capture. The same calculations are performed for the data collected along the 200 meter VRPM configuration.

6.4 Results and Discussion

The release rate of the tracer gases was determined during the study by using mass flow meters to control the release rate of the gases. The mass flow meters were set to a flow rate of 0.11 grams per second for each gas, for the duration of the study. The original experimental design stated that in addition to the mass flow meters, a digital scale would be used to weigh the gas cylinders before and after each release to confirm the release rate of the gases. However, this was not possible, due to a malfunction in the digital scale after the 20 meter release survey. The malfunction was possibly due to the extremely hot weather during the study, or damage to the scale caused by the weight of the cylinders. The digital scale did not function during the other gas releases performed during the field campaign.

Before this malfunction, the weight of the acetylene cylinder was measured before and after the 20 meter release. According to the measurements, the acetylene cylinder lost 0.75 kilograms of gas over a period of 88 minutes, indicating that the actual release rate was 0.140 grams per second. This may indicate some loses in the fittings before the inlet to the mass flow meter.

6.4.1 20-Meter Releases

The 20-meter tracer gas release survey was completed on June 16. The wind conditions during the duration of the gas releases were light and somewhat variable. Despite the variability of the wind conditions, the initial analysis of the wind data indicate that a sufficient amount of data had been collected during periods of acceptable wind conditions (between the beginning of the release at approximately 10:40 a.m. and 1:00 p.m.). However, during the post-analysis phase of the study, it was revealed that although there were many periods between 10:40 a.m. and 1:00 p.m. when the wind criteria were met, there was not sufficient data during this time period to analyze the plume capture capabilities of the method. Figure 25 shows a time series of sulfur hexafluoride fluxes calculated along the 200 meter VRPM configuration and the prevailing wind direction, from normal to the configuration. The negative flux values depicted in the figure indicate time periods when the prevailing wind was from the side of the configuration opposite to the side where the tracer

gases were deployed. The figure shows that during the time period between approximately 10:40 a.m. and 1:00 p.m., there were periods when the winds were within 30 degrees of perpendicular to the VRPM configuration. However, during this time period, there were only three calculated flux values above 0.10 grams per second. Since the 20-meter SF_6 release was the closest to the VRPM configuration, one would expect a better plume capture, with calculated flux values around 0.11 grams per second (the pre-set mass flow meter release rate). Based on this, and a comparison of the calculated SF_6 fluxes found from the other release points, the data from the 20-meter release was determined to be insufficient due to the very light and variable wind conditions during the time of the releases.

Due to these results, the procedure for plume capture assessment introduced in Section 6.3 of this document could not be utilized for this study. An alternate but similar approach for assessing plume capture capabilities from the results of this study is detailed below in Section 6.5.

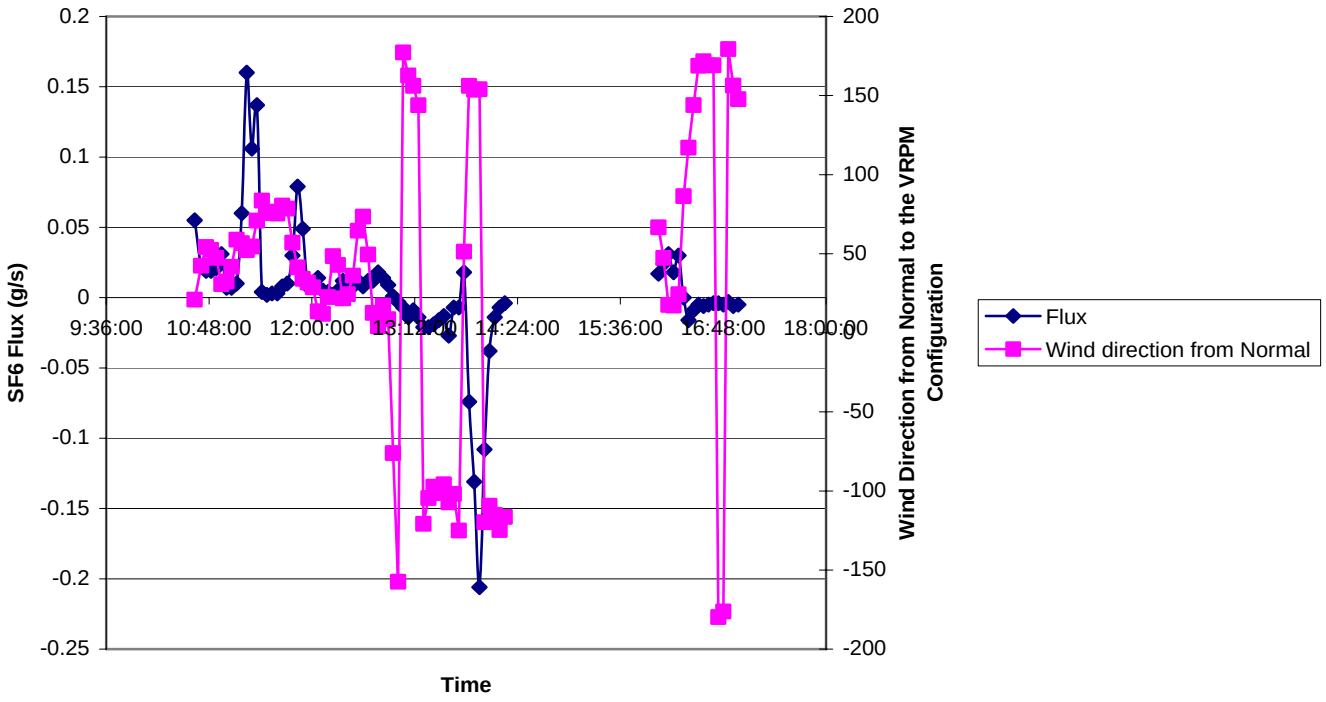

Figure 25. Time series of wind direction and calculated sulfur hexafluoride fluxes from the 20 meter release (as analyzed along the 200 meter VRPM configuration)

6.4.2 60-Meter Releases

The 60-meter tracer gas release study was conducted on July 7. During this survey, the sulfur hexafluoride tracer gas was released from a distance 60 meters upwind of the VRPM configurations, while acetylene was released from a location 20 meters upwind of the configurations. Data was collected for approximately 3 hours. However, the actual data used for the analysis was collected from 2:26 p.m. to 3:25 p.m., during the period of favorable wind conditions. During this period, the prevailing wind directions ranged from 1° to 23° from perpendicular to the longest VRPM configuration.

The average calculated sulfur hexafluoride flux rate along the shortest VRPM configuration was 0.02 ± 0.008 grams per second. The average calculated sulfur hexafluoride flux rate along the longest VRPM configuration was 0.126 ± 0.077 grams per second.

The average calculated acetylene flux rate along the shortest VRPM configuration was 0.10 ± 0.036 grams per second. The average calculated acetylene flux rate along the longest VRPM configuration was 0.140 ± 0.019 grams per second. Figure 26 presents a time series of the calculated flux values of acetylene and sulfur hexafluoride measured along the two configurations.

The figure shows that the lowest flux values for each of the measurements was observed during the first few minutes of the release, as the tracer gas concentrations accumulated, and were eventually carried by the prevailing wind through the configuration. In comparing the calculated flux values of each gas measured on the short and long configurations, it is apparent that greater plume capture was achieved with the longer VRPM configurations.

6.4.3 100-Meter Releases

The 100 meter tracer gas release study was conducted on June 19. During this survey, the sulfur hexafluoride tracer gas was released from a distance 100 meters upwind of the VRPM configurations, while acetylene was released from a location 20 meters upwind of the configurations. Data was collected for approximately 2 hours. However, the actual data used for the analysis was collected from 5:28 to 5:54 p.m., and 6:11 p.m. to 6:43 p.m., during the period of favorable wind conditions. During this period, the prevailing wind directions ranged from 2° to 29° from perpendicular to the longest VRPM configuration.

The average calculated sulfur hexafluoride flux rate along the shortest VRPM configuration was 0.059 ± 0.024 grams per second. The average calculated sulfur hexafluoride flux rate along the longest VRPM configuration was 0.120 ± 0.059 grams per second.

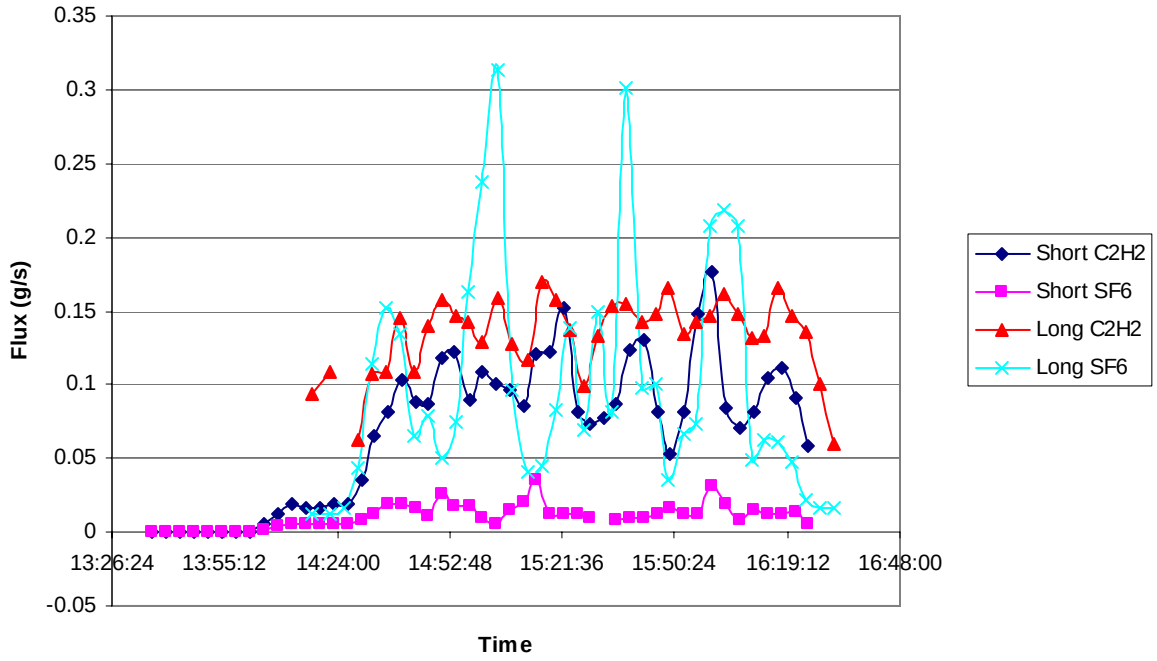

Figure 26. Time series of acetylene and sulfur hexafluoride flux values from the 60 meter release survey

The average calculated acetylene flux rate along the shortest VRPM configuration was 0.067 ± 0.019 grams per second. The average calculated acetylene flux rate along the longest VRPM configuration was 0.166 ± 0.036 grams per second. Figure 27 presents a time series of the calculated flux values of acetylene and sulfur hexafluoride measured along the two configurations.

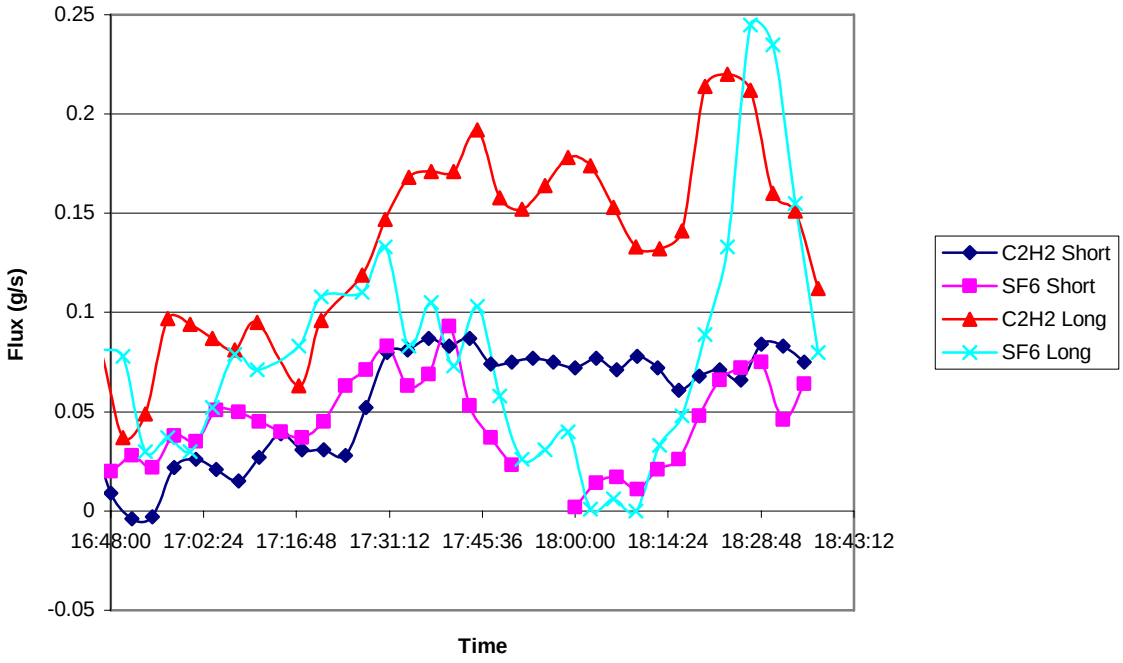

Figure 27. Time series of acetylene and sulfur hexafluoride flux values from the 100 meter release survey

In comparing the calculated flux values of each gas measured on the short and long configurations, it is apparent that greater plume capture was achieved with the longer VRPM configurations. The measurements along the shortest VRPM configuration did not capture the entire plume during most periods of the measurements.

6.4.4 140-Meter Releases

The 140-meter tracer gas release study was conducted on July 5. During this survey, the sulfur hexafluoride tracer gas was released from a distance 140 meters upwind of the VRPM configurations, while acetylene was released from a location 20 meters upwind of the configurations. Measurements were collected for approximately 3 hours. However, the actual data used for the analysis was collected from 1:04 p.m. to 1:30 p.m., 1:53 p.m. to 2:23 p.m., and 2:58 p.m. to 3:19 p.m., during the period of favorable wind conditions. During this period, the prevailing wind directions ranged from 17° to 30° from perpendicular to the longest VRPM configuration.

The average calculated sulfur hexafluoride flux rate along the shortest VRPM configuration was 0.019 ± 0.013 grams per second. The average calculated sulfur hexafluoride flux rate along the longest VRPM configuration was 0.072 ± 0.048 grams per second.

The average calculated acetylene flux rate along the shortest VRPM configuration was 0.055 ± 0.015 grams per second. The average calculated acetylene flux rate along the longest VRPM configuration was 0.118 ± 0.032 grams per second. Figure 28 presents a time series of the calculated flux values of acetylene and sulfur hexafluoride measured along the two configurations.

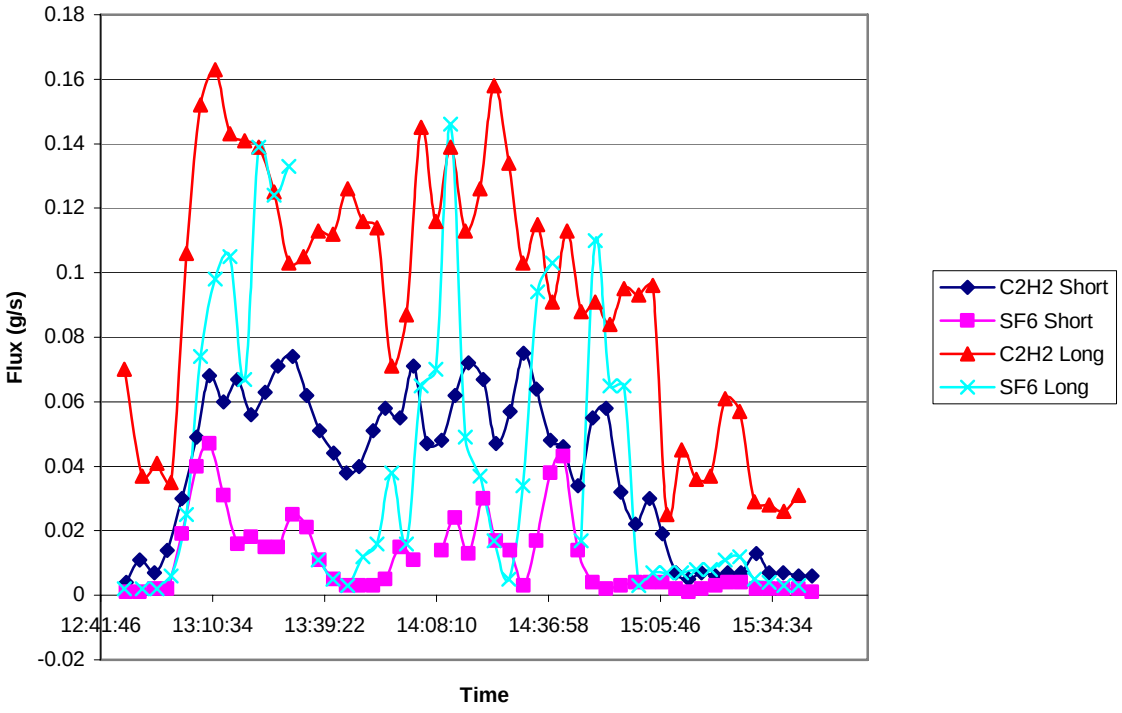

Figure 28. Time series of acetylene and sulfur hexafluoride flux values from the 140 meter release survey

The figure shows that the lowest flux values for each of the measurements was observed during the first few minutes of the release, and again near the end of the release. In comparing the calculated flux values of each gas measured on the short and long configurations, it is apparent that greater plume capture was achieved with the longer VRPM configurations.

6.5 Summary of Release Results

Table 10 presents a summary of the average calculated flux values of each tracer gas from each release of the study.

Table 10. Average calculated flux values from the 60, 100, and 140 meter releases*

Tracer Gas	VRPM Configuration	60-Meter Release Flux Value (g/s)	100-Meter Release Flux Value (g/s)	140-Meter Release Flux Value (g/s)
Sulfur Hexafluoride	Short	0.015	0.059	0.019
Sulfur Hexafluoride	Long	0.126	0.120	0.072
Acetylene	Short	0.099	0.067	0.055
Acetylene	Long	0.140	0.166	0.118

*During each release, the mass flow meters used for each gas were pre-set to a release rate of 0.11 grams per second.

As mentioned previously, the release rate of the tracer gases was determined during the study by using mass flow meters to control the release rate of the gases. The mass flow meters were set to a flow rate of 0.11 grams per second for each gas, for the duration of the study. In addition to the pre-set flow rates, the study used a digital scale to confirm the release rate of the tracer gases. Although the scale malfunctioned early in the study, the scale was used to determine a flow rate of 0.140 grams per second for the acetylene during the 20 meter release study.

An initial analysis of the data presented in Table 10 shows that in general, the flux values measured along the longer VRPM configurations were much closer to the actual release rates, as determined by the mass flow meters. Additionally, the sulfur hexafluoride flux values determined along the longest VRPM configuration during the 60 meter releases indicated a much better plume capture than the flux value determined during the 140 meter and 100 meter release. Also, as expected since the acetylene release was constantly located 20 meters upwind of the VRPM configurations, the acetylene flux values (calculated along both VRPM configurations during each release) consistently indicated a perfect plume capture unlike the corresponding sulfur hexafluoride releases.

Additional analysis was done on the sulfur hexafluoride concentration values measured along the top two beams of the longest VRPM configuration during each release. A t-test was performed to determine if there was a statistically significant difference in the sulfur hexafluoride concentration values (no statistically significant difference would indicate that the VRPM configuration was not fully capturing the sulfur hexafluoride plume in the vertical direction). The results of the t-test indicated that there was a statistically

significant difference for the data from each release, indicating that there were no issues with vertical plume capture during the study.

Section 6.6 of this document presents an additional analysis of the plume capture of the VRPM configurations during this study.

6.6 Assessment of Plume Capture

As discussed in Section 6.4.1, an analysis of the data collected during the 20 meter release indicated that the data was not sufficient for use in the study. Due to these results, the procedure for plume capture assessment introduced in Section 6.3 of this document could not be utilized for this study.

A slightly different approach for plume capture assessment was applied. The approach involves considering the average acetylene and sulfur hexafluoride flux values calculated along the longest VRPM configuration for each release, and expressing them in terms of percent recovery, where percent recovery is equal to the ratio of the calculated flux value of the tracer gas to 0.11 grams per second, which is also the value determined from the mass flow meters. Table 11 presents the results of this calculation.

Table 11. Plume capture percentages determined along the long VRPM configuration from the 60-, 100-, and 140-meter releases

	Acetylene	Sulfur Hexafluoride
60-m Release	127%	115%
100-m Release	151%	109%
140-m Release	107%	65%

As mentioned previously, the recovery percentage of each tracer gas may differ slightly due to differences in the physical and chemical properties of the gases. Additionally, atmospheric conditions could possibly affect the recovery of the tracer gases. In order to eliminate these factors as a variable in the data analysis, the absolute sulfur hexafluoride plume capture percentages from the 60, 100 and 140 meter releases (shown in Table 10), were normalized to the corresponding acetylene plume capture percentages releases to yield a sulfur hexafluoride plume capture percentage (as was proposed in the original approach presented in Section 6.3). Table 12 presents the results of these calculations.

Table 12. Plume capture percentages determined along the long VRPM configuration from the 60-, 100-, and 140-meter releases

Sulfur Hexafluoride Release	Plume Capture
60-m Release	90%
100-m Release	72%
140-m Release	61%

The results in Table 12 show that although the sulfur hexafluoride plume capture percentages are reasonable for the 60 meter, the hexafluoride plume capture percentage gradually decreases with increasing upwind distance to 61% at an upwind release distance of 140 meters.

6.7 Conclusions from the Results of the Study

The results of the study provided valuable information regarding the plume capture capabilities of the VRPM method. The following is a summary of the results of the study:

- The flux values measured along the shorter VRPM configuration were always less than the flux values measured along the longer VRPM configuration for corresponding releases, indicating less plume capture along the shorter configuration (see Table 10). In some cases, the flux values measured along the shorter configuration were more than 50% less than the corresponding flux values measured along the longer configuration.

- The average acetylene flux values calculated along the longest VRPM configuration (0.14, 0.17, and 0.12) were greater than the actual release rate of 0.11 determined with the mass flow meter.

- The acetylene plume capture percentages were consistently higher than the sulfur hexafluoride plume capture percentages. This result is not surprising, since the acetylene was released closer to the configuration, at a fixed upwind distance of 20 meters, indicating a perfect plume capture.

- The sulfur hexafluoride plume capture percentages measured along the longer VRPM configuration (see Table 12) indicated reasonable plume capture during the 60 meter release (90%) However, the plume

capture percentage gradually decreased down to 61% at furthest upwind release distance of 140 meters.

Based on these results, the following recommendations are made for deploying the VRPM method for future studies:

- The length of the VRPM configuration should always be extended as far as possible, considering constraints such as site topography, and instrument signal limitations. The results of the VRPM plume capture study suggest that the longer the length of the VRPM configuration, the better the plume capture percentage.

- The results of the study showed that when using a VRPM configuration with a length of approximately 200 meters, the method achieved reasonable plume capture from a source located 60 meters upwind of the configuration when using a wind criterion of within 30° of perpendicular to the configuration. The results also showed that plume capture percentage decreased nearly linearly as the distance of the upwind source location increased. When considering source locations greater than 60 meters upwind of the VRPM configuration, a tighter wind criterion would probably result in a better plume capture percentage. Another factor that can affect the plume capture percentage is the location of the emissions hot spot with respect to the VRPM configuration. The VRPM configuration should be deployed so that the location of suspected upwind emissions hot spot is approximately near the center point of the VRPM configuration. In order to determine the location of the major emissions hot spots, a Horizontal RPM survey should be conducted before the VRPM survey to provide guidance for deploying the VRPM configuration.

6.8 QA/QC

6.8.1 Equipment Calibration

As stated in the *ECPD Optical Remote Sensing Facility Manual* (USEPA, 2004), all equipment is calibrated annually or cal-checked as part of standard operating procedures. Certificates of calibration are kept on file. Maintenance records are kept for any equipment adjustments or repairs in bound project notebooks that include the data and description of maintenance performed. Instrument calibration procedures and frequency are listed in Table 13 and further described in the text.

6.8.2 Assessment of DQI Goals

The critical measurements associated with this project and the established data quality indicator (DQI) goals in terms of accuracy, precision, and completeness are listed in Table 14. More information on the

procedures used to assess DQI goals can be found in Section 10 of the *ECPD Optical Remote Sensing Facility Manual* (USEPA, 2004).

6.8.3 DQI Check for Analyte PIC Measurement

The precision and accuracy of the analyte PIC measurements was assessed by analyzing the measured nitrous oxide concentrations in the atmosphere. A typical background atmospheric concentration for nitrous oxide is about 315 ppb. This value may fluctuate due to seasonal variations in nitrous oxide concentrations or elevation of the site.

The precision of the analyte PIC measurements was evaluated by calculating the relative standard deviation of each data subset. A subset is defined as the data collected along one particular path length during one particular survey in one survey sub-area. The number of data points in a data subset depends on the number of cycles used in a particular survey.

The accuracy of the analyte PIC measurements was evaluated by comparing the calculated nitrous oxide concentrations from each data subsets to the background value of 315 ppb. The number of calculated nitrous oxide concentrations that failed to meet the DQI accuracy criterion in each data subset was recorded.

Overall, 25 data subsets were analyzed from this field campaign. Based on the DQI criterion set forth for precision of ±10%, all of the data subsets were found to be acceptable, for a completeness of 100%. The range of calculated relative standard deviations for the data subsets from this field campaign was 0.75 to 13.2 ppb, which represents 0.24 to 4.19% RSD.

Each data point (calculated nitrous oxide concentration) in the 25 data subsets was analyzed to assess whether or not it met the DQI criterion for accuracy of ± 25% (315 ± 79 ppb) for path lengths less than 50 meters, ± 15% (315 ± 47 ppb) for path lengths between 50 and 100 meters, and ± 10% (315 ± 32 ppb) for path lengths greater than 100 meters. A total of 1169 data points were analyzed, and 1167 of the points met the DQI criteria for accuracy for a completeness of 99%.

Table 13. Instrumentation calibration frequency and description

Instrument	Measurement	Calibration Date	Calibration Detail
IMACC, Inc. OP-FTIR	Analyte PIC	Pre-deployment and in-field checks	MOP-6802 and 6823 of the ECPB Optical Remote Sensing *Facility Manual*
AIL, Inc. OP-FTIR	Analyte PIC	Pre-deployment and in-field checks	MOP-6802 and 6823 of the ECPB Optical Remote Sensing *Facility Manual*
R.M. Young Meteorological Head	Wind Speed in miles/hour	June 7, 2006	APPCD Metrology Lab Cal. Records on file
R.M. Young Meteorological Head	Wind direction in degrees from North	June 7, 2006	APPCD Metrology Lab Cal. Records on file
Topcon Model GTS-211D Theodolite	Distance Measurement	April 19, 2006	Calibration of distance measurement. Actual distance =19.6 m Measured distance = 19.56 m Measured distance = 19.55 m
Topcon Model GTS-211D Theodolite	Angle Measurement	April 19, 2006	Calibration of angle measurement. Actual angle = 360º Measured angle = 360º28’47” Measured angle = 359º39’24”
Digital Scale	Mass of Tracer Gas Cylinders	January 2006	APPCD Metrology Lab Cal. Records on file
(2) Environics Mass Flowmeters	Flow rate of acetylene and sulfur hexafluoride tracer releases	January 10, 2006 and March 23, 2006	APPCD Metrology Lab Cal. Records on file

Table 14. Data quality indicator goals for the project

Measurement Parameter	Analysis Method	Accuracy	Precision	Detection Limit	Completeness
Analyte PIC	OP-FTIR: Nitrous Oxide Concentrations	± 25%/15%/10% [a]	± 10%	See Table 5-1	90%
Ambient Wind Speed	R.M. Young Met heads post-deployment calibration in EPA Metrology Lab	± 1 m/s	± 1 m/s	N/A	90%
Ambient Wind Direction	R.M. Young Met heads post-deployment calibration in EPA Metrology Lab	± 10º	± 10º	N/A	90%
Distance Measurement	Theodolite- Topcon	± 1 m	± 1m	0.1 m	100%
Tracer Gas Cylinder Mass	Digital Scale	± 0.1 kg	± 0.1 kg	N/A	100%
Prevailing Wind Direction	R.M. Young Met heads	N/A	N/A	N/A	1 hour of data during periods that the wind is within 30° of perpendicular to the VRPM configuration

[a]The accuracy acceptance criterion of ± 25% is for pathlengths of less than 50m, ± 15% is for pathlengths between 50 and 100m, and ±10% is for pathlengths greater than 100m.

6.8.4 DQI Checks for Ambient Wind Speed and Wind Direction Measurements

The meteorological head DQIs are checked annually as part of the routine calibration procedure. The R.M. Young Meteorological heads used in the current study were calibrated by the EPA Metrology Lab on June 7, 2006. The precision and accuracy of the heads is assessed by conducting a post-deployment calibration in the EPA Metrology Lab using the exhaust from a bench top wind tunnel. This calibration procedure differs from the procedure used to perform the annual calibration of the instruments. The results of the post-deployment calibration are pending, as the instrumentation has been deployed for other field campaigns.

Additionally, a couple of reasonableness checks are performed in the field on the measured wind direction data. While data collection is occurring, the field team leader compares wind direction measured with the heads to the forecasted wind direction for that particular day. Another reasonableness check involves manually setting the vane on the meteorological heads to magnetic north (this is done with a hand held compass). The observed wind direction during this test should be very close to 360º.

6.8.5 DQI Checks for the Topcon Theodolite

Calibration checks are not performed before each field campaign. However, the following checks were made on April 19, 2006. The calibration of distance measurement was done at the EPA Facility using a tape measure. The actual distance was 19.6 m., and the measured distances were 19.56 m and 19.55 m. The results indicate accuracy and precision fall well within the DQI goals. The calibration of angle measurement was also performed. The actual angle was 360°, and the measured angles were 360°28'47" and 359°39'24". The results indicate accuracy and precision fall well within the DQI goals.

Additionally, there are several internal checks in the theodolite software that prevent data collection from occurring if the instrument is not properly aligned on the object being measured, or if the instrument has not been balanced correctly. When this occurs, it is necessary to re-initialize the instrument to collect data.

6.8.6 QC Checks of OP-FTIR Instrument Performance

Several diagnostic checks were performed on the OP-FTIR instrumentation prior to deployment to the field, and during the duration of each field campaign. These checks involve assessing the electronic noise of the instrument, the strength of the instrument signal, and features in the collected data spectrum. The results of these tests are used to determine whether or not the instrument is functioning properly. More information on the diagnostic checks that are performed as part of a typical ORS field campaign can be found in MOP 6802 and 6823 of the *ECPD Optical Remote Sensing Facility Manual* (USEPA, 2004).

In addition to the QC checks performed on the OP-FTIR, the quality of the instrument signal (interferogram) was checked constantly during the field campaigns. This was done by ensuring that the intensity of the signal is at least five times the intensity of the stray light signal (the stray light signal is collected as background data prior to actual data collection, and measures internal stray light from the instrument itself). In addition to checking the strength of the signal, checks were done constantly in the field to ensure that the data were being collected and stored to the data collection computer. During the campaign, a member of the field team monitored the data collection computer to make sure these checks were completed.

Prior to instrument deployment, a series of QC checks were performed on the IMACC OP-FTIR to assess the instrument performance. On June 9, 2006, the single beam ratio, baseline stability, noise equivalent absorbance, ZPD stability, saturation, random baseline noise, and stray light diagnostic tests were performed. The results of the tests indicated that the IMACC OP-FTIR was operating within the acceptable criteria range.

Due to a malfunction with one of the IMACC OP-FTIR instruments, it was necessary to use the AIL, Inc. OP-FTIR on the first day of the project. Because of this unexpected change, it was not possible to perform the series of pre-deployment QC checks on the AIL, Inc. OP-FTIR. However, the same series of QC checks

were performed on the same instrument shortly before and after the current study, as part of other projects (on April 27, 2006 and July 16, 2006). The results of these checks indicated that the AIL, Inc. OP-FTIR was operating within the acceptable criteria range.

7. Quality Assurance Methods

Quality Assurance methods are critical to any measurement project. Over the course of this long-term evaluation study, U.S. EPA and ARCADIS have worked on developing and improving the QA/QC procedures used for conducting measurements of fugitive emissions using ORS instrumentation and the RPM method. Many of these improvements were implemented as a result of information gathered from the long-term evaluation study, and review of the Quality Assurance Project Plans submitted for the measurement campaigns. Some of the major QA improvements implemented include:

- A more thorough documentation of the calibration schedule for the ancillary equipment used in the campaigns
- The development of pre-deployment tests to check the precision and accuracy of the meteorological heads
- The development of pre-deployment and in-field checks of the OP-FTIR instruments to detect potential problems that may effect data quality
- A more detailed explanation of checks that should be done on the OP-FTIR during data collection to ensure signal strength and proper mirror alignment
- The establishment of Data Quality Indicators to assess the precision and accuracy of the concentration data collected with the OP-FTIR
- The development of manual checks that can be done to verify the accuracy of the surface concentration contour maps, and the reconstructed plume maps

These points are discussed in greater detail in the U.S. EPA Emissions Characterization and Prevention Branch (ECPB) Optical Remote Sensing *Facility Manual* (U.S. EPA, 2004). Although this document was created as part of a separate project, the development of the document benefited from information and knowledge gathered from the long-term evaluation study.

The following subsections contain details on the quality assurance assessment done for the Orange County Landfill measurement campaign, including an explanation of some of the procedures developed to assess data quality for applying the RPM method using ORS instrumentation. This section also presents the results of a tracer gas release done during the Somersworth, NH campaign to assess the accuracy of the VRPM method, and a comparison of methane concentrations determined using different quantification software packages.

7.1 ORS Instrumentation Calibration

7.1.1 Quality Assurance of the OP-FTIR Instruments

The OP-FTIR instruments are not calibrated in a classical sense, due to the fact that they are open-path instruments, and do not contain a closed sample cell. However, the accuracy and precision of the concentration measurements are analyzed by comparing the measured nitrous oxide concentrations to a known concentration in the atmosphere. A typical background atmospheric concentration for nitrous oxide is about 315 ppb. However, this value may fluctuate due to seasonal variations in nitrous oxide concentrations or elevation of the site.

The precision of the analyte concentration measurements were evaluated by calculating the relative standard deviation of each data subset. A subset is defined as the data collected along one particular path length during one particular survey in one survey sub-area. The number of data points in a data subset depends on the number of cycles used in a particular survey.

The accuracy of the analyte concentration measurements was evaluated by comparing the calculated nitrous oxide concentrations from each data subsets to the background concentration of 315 ppb. The number of calculated nitrous oxide concentrations that failed to meet the accuracy criterion in each data subset was recorded.

Overall, 77 data subsets were analyzed from this field campaign. Based on the criterion set forth for precision of ± 10%, 75 of the 77 data subsets were found to be acceptable for a completeness of 97%. The range of calculated relative standard deviations for the data subsets from this field campaign was 1.13 to 50.5 ppbm, which represents 0.35 to 16% RSD.

Each data point (calculated nitrous oxide concentration) in the 77 data subsets were analyzed to assess whether or not it met the criterion for accuracy of ± 25% (315 ± 79 ppb) for path lengths less than 50 meters, ± 15% (315 ± 47 ppb) for path lengths between 50 and 100 meters, and ± 10% (315 ± 32 ppb) for path lengths greater than 100 meters. A total of 2763 data points were analyzed, and 2709 met the DQI criteria for accuracy for a completeness of 98%. Based on the criterion set forth for accuracy and precision, the OP-FTIR data was found to be acceptable.

In addition to the nitrous oxide concentration check, several QC checks have been developed to assess the performance of the OP-FTIR Instrument. These checks are performed prior to, and during deployment. The QC checks involve assessing instrument noise, the strength of the instrument signal, and features in the collected data spectrum. The results of these tests are used to determine whether or not the instrument is functioning properly.

In addition to the QC checks performed on the OP-FTIR, the strength of the instrument signal (interferogram) is checked constantly during the field campaign. In addition to checking the strength of the signal, checks are performed constantly in the field to ensure that the data is being collected and stored to the data collection computer.

7.1.2 Quality Assurance of Unisearch OP-TDLAS Instrument

The accuracy and precision of the Unisearch OP-TDLAS are checked by the insertion of reference cells, containing gas from the calibrations standards, into the optical path of the instrument. The Unisearch OP-TDLAS response was evaluated prior to performing the VRPM survey on May 4. The response was evaluated by inserting calibration cells into the optical path containing gas at a known concentration. The change in OP-TDLAS response is due to the added gas within the calibration cells. The OP-TDLAS response indicated an average difference of 5.3 percent from the calculated OP-TDLAS concentrations. The OP-TDLAS response and evaluation is limited by the air concentrations existing at the time of the evaluation. Air concentrations changed ~ 2 percent during this response evaluation. Table 15 presents a summary of the calibration of the Unisearch OP-TDLAS instrument. Figure 29 shows a plot of the instrument calibration response. More information on the calibration procedures for the Unisearch OP-TDLAS instrument can be found in the ECPB Optical Remote Sensing *Facility Manual* (U.S. EPA, 2004).

Table 15. Summary of calibration results of the Unisearch OP-TDLAS instrument

Input	Response PAC	PIC	Avg PIC	Diff PIC	QA Value	% Diff
No Cell	3.522359	461.429	417.9451	1.8		
	2.858483	374.4612				
Empty Cell	3.949112	517.3336	496.7141	0	0	0.0
	3.634309	476.0945				
1%, 4/28/05	11.45878	1501.1	1488.926	992.2121	1000	0.8
	11.27292	1476.753				
2.5 %, 11/03/03	21.33168	2794.45	2794.45	2297.736	2500	8.1
2.5%, 04/28/05	22.44113	2939.788	2918.416	2421.701	2500	3.1
	22.11483	2897.043				

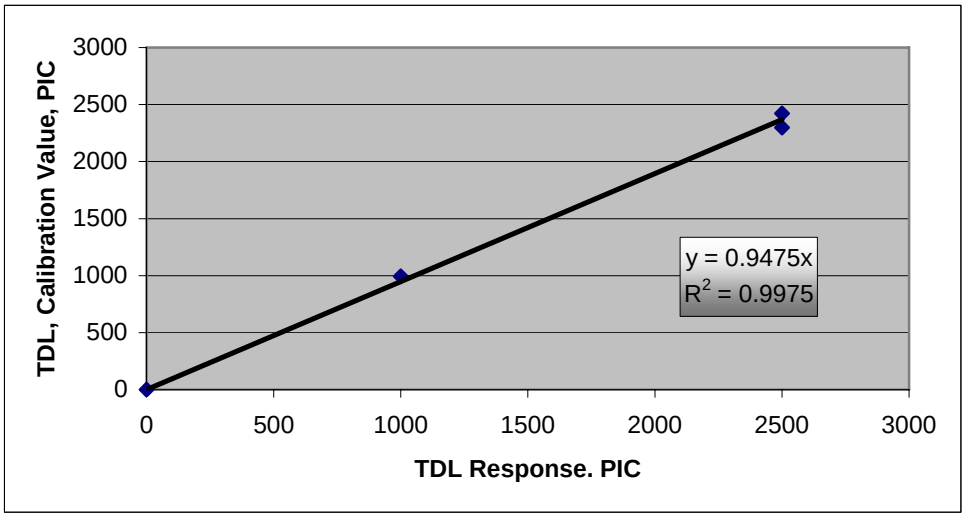

Figure 29. Plot of the Unisearch OP-TDLAS instrument calibration response

At the time of the Orange County measurement campaign, the Boreal OP-TDLAS system had only recently been acquired by ARCADIS. Consequently, standard operating and calibration procedures for the Boreal system are still being developed.

7.1.3 Quality Assurance of the Boreal OP-TDLAS Instrument

The Boreal *GasFinder* 2.0 OP-TDLAS provides an R^2 value for each concentration measurement. The R^2 value is calculated by the internal software of the instrument, and is an indication of the similarity between the waveform of the sample gas and the reference cell gas. When the instrument detector receives the returning laser signal after it has passed through the sample beam path, it converts the signal to the shape of a specific waveform (sample waveform). The instrument also receives a similar laser signal after the laser has passed through the reference cell in the instrument (reference waveform). The two waveforms are then digitized and compared as two numeric arrays. The instrument software then performs a linear least squares regression for each measurement, to evaluate the similarity (R^2) between the sample and reference waveforms.

The instrument provides the R^2 value as an output with every collected measurement. The value is used to assess the accuracy of each concentration measurement. Table 16, taken from the Boreal Laser, Inc. *GasFinder 2.0 Operation Manual,* presents a range of R^2 values, and the corresponding accuracy of the measurement.

Table 16. Accuracy of concentration measurements for different R^2 values

R^2	Measurement Accuracy
> 0.95	± 2%
0.9	± 5%
0.7	± 10%
0.5	± 15%
0.4	± 20%
0.3	± 25%
0.15	± 50%
0.1	± 70%
< 0.05	± 100%

During the Orange County measurement campaign, the R^2 value of each concentration measurement was greater than 0.7, indicating that the accuracy of each measurement was greater than ± 10%.

7.2 Non-ORS Instrumentation Calibration

As stated in the *ECPD Optical Remote Sensing Facility Manual* (U.S. EPA, 2004), all equipment is calibrated annually or cal-checked as part of standard operating procedures. Certificates of calibration are kept on file. Maintenance records are kept for any equipment adjustments or repairs in bound project notebooks that include the data and description of maintenance performed. Instrument calibration procedures and frequency are listed in Table 17.

Table 17. Instrumentation calibration frequency and description

Instrument	Measurement	Calibration Date	Calibration Detail
Climatronics Model 101990-G1 Meteorological Heads	Wind Speed in miles/hour	14 April 2005	APPCD Metrology Lab Cal. Records on file
Climatronics Model 101990-G1 Meteorological Heads	Wind direction in degrees from North	14 April 2005	APPCD Metrology Lab Cal. Records on file
R.M. Young Meteorological Heads	Wind Speed in miles/hour	14 April 2005	APPCD Metrology Lab Cal. Records on file
R.M. Young Meteorological Heads	Wind direction in degrees from North	14 April 2005	APPCD Metrology Lab Cal. Records on file
Topcon Model GTS-211D Theodolite	Distance Measurement	26 May 2004	Calibration of distance measurement. Actual distance = 30 ft. Measured distance = 30.1 ft., and 30.2 ft.
Topcon Model GTS-211D Theodolite	Angle Measurement	26 May 2004	Calibration of angle measurement. Actual angle = 360º Measured angle = 360º28'59", and 360º12' 37"

7.3 VRPM Tracer Release Validation Study

The first field campaign of the long-term evaluation study was conducted at a Superfund site in Somersworth, New Hampshire (*Modrak et al., 2004).* As part of this field campaign, a tracer release study was done to validate the accuracy of the VRPM method.

Ethylene was released through a soaker hose configuration located approximately 30 meters upwind of the VRPM configuration. The wind direction during the time of the release was almost directly perpendicular to the VRPM configuration. The soaker hoses were set up in an "H" configuration to simulate an area source. The approximate dimensions of the "H" configuration were 10 meters wide, and 40 meters long (on each side). The weight of the ethylene cylinder was recorded prior to release of the gas, and immediately after the release was completed, using a digital scale. In addition, the precise starting and ending time of the release

was recorded in order to calculate the average actual flux of ethylene. This flux value was then compared to the ethylene flux calculated from the VRPM survey.

Figure 30 shows a map of the average reconstructed ethylene plume from the release. The contour lines show ethylene concentrations in ppm. The average calculated ethylene flux rate was 0.98 g/s.

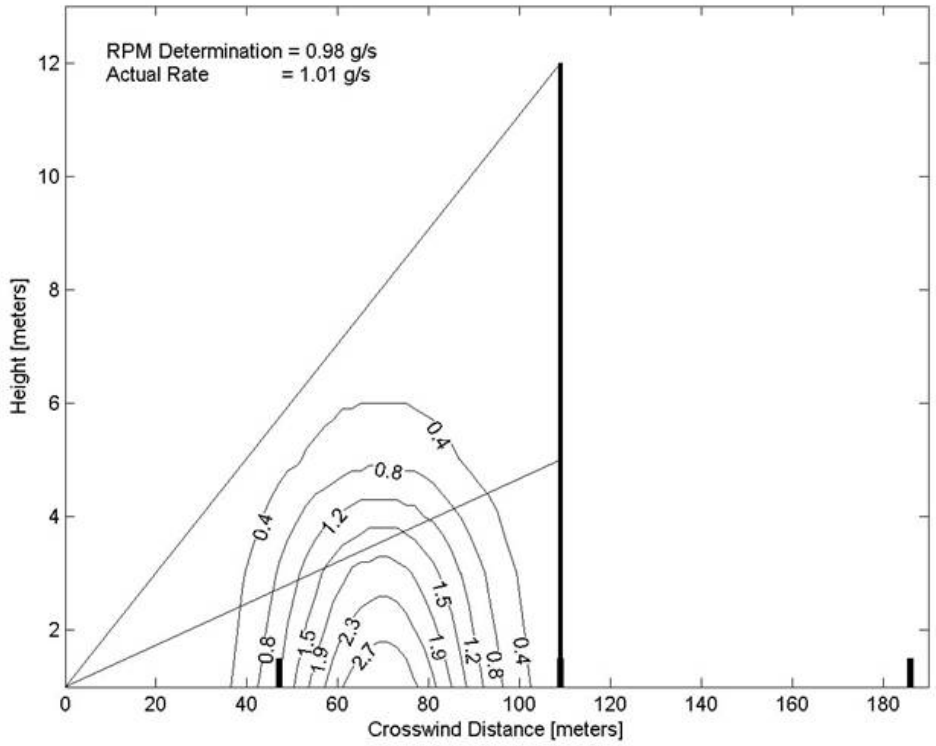

Figure 30. Reconstructed ethylene plume from the VRPM validation study conducted during the Somersworth, NH field campaign (concentrations shown in ppmv). The location of the vertical structure is shown by the solid black vertical line. The scanning ORS instrument is located in the bottom left-hand corner of the figure

The ethylene tracer gas was released for 75 minutes. During this period, the measured mass of the ethylene cylinder was reduced by 4.59 kg. A loss of 4.59 kg over a 75-minute period indicates an average flow rate of 1.01 g/sec. The measured emission rate indicates an ethylene mass recovery by the VRPM method of 97%.

The favorable results found were partly due to the fact that the prevailing winds were nearly perpendicular to the VRPM configuration over the duration of the release. This allowed the configuration to capture a large amount of the ethylene plume from the site. Another factor that contributed to the favorable results found was the small variability in wind direction and speed during the period of the survey that indicates very stable atmospheric conditions. Flux calculations in unstable atmospheric conditions tend to underestimate down to 60% of the actual fluxes (Hashmonay et al., 2001).

7.4 Comparison of Methane Concentration Determination Using the Two Software Packages

As part of the long-term evaluation study, an evaluation of the performance of the two quantification software packages was done by comparing methane concentrations values determined with IMACCQuant to methane concentration values determined with Non-Lin software. The first comparison was done by post-analyzing the same raw data (interferograms) with both software packages. The results of the comparison are presented in Figure 31.

The results of the comparison show that in general, the Non-Lin software quantified higher methane concentrations than the IMACCQuant software. The higher concentrations analyzed with Non-Lin could be a result of an artifact of noise or water vapor interference in the data, which if not filtered out, would yield a higher concentration analysis. Further analysis of the data found that a larger discrepancy between the concentrations determined with the two software packages occurred in data where the IMACCQuant data indicated a larger amount of noise. Unfortunately, the Non-Lin software does not include the ability to assess the amount of noise in the analyzed data. This is unfortunate, as it does not allow the user to perform an assessment of the quality of the data analyzed.

An additional comparison of the methane concentrations analyzed using different methods was done by comparing the concentrations determined in real-time and post-collection, using the IMACCQuant software. The results of the comparison are presented in Figure 32.

The results show that although the results were correlated well, the real-time methane concentration determinations were generally lower than the concentration determinations analyzed post-collection.

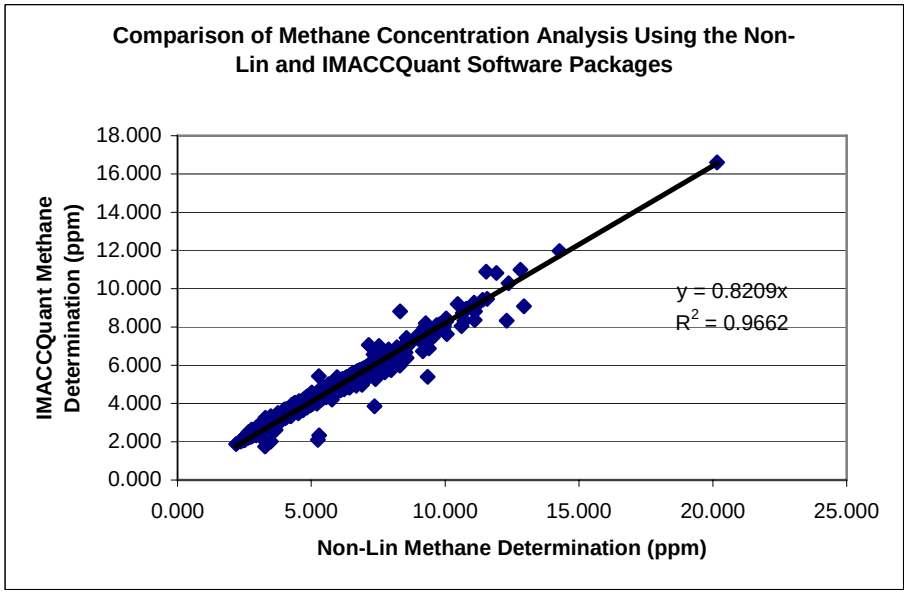

Figure 31. Comparison of methane concentration analysis using the Non-Lin and IMACCQuant software packages

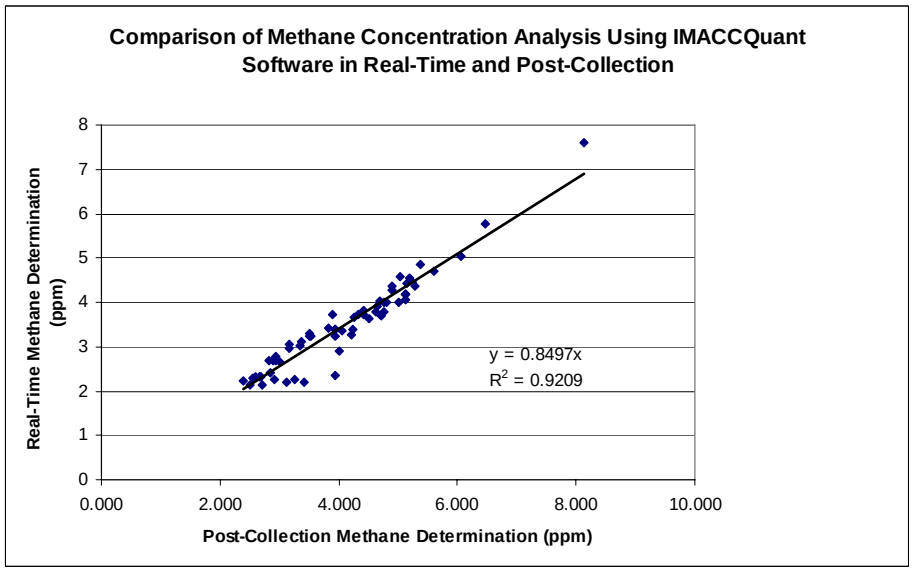

Figure 32. Comparison of real-time and post-collection methane concentration analysis using the IMACCQuant software package

Future of Using Optical Remote Sensing with the Radial Plume Mapping Method for Emissions Measurements

The results of the long-term evaluation study show that ORS instrumentation used with the RPM method is a viable solution for characterizing fugitive emissions from landfill sites, and other large area sources.

In addition to landfill sites, the method has been applied at agricultural sites to measure emissions fluxes from animal houses and lagoons, wastewater treatment plants to measure emissions from lagoons and reactors, and at gas station facilities to evaluate emissions from the gas dispensing areas, underground storage tanks (UST), and UST vents. Additionally, ARCADIS has deployed ORS instrumentation to provide fence line emissions monitoring during a cleanup at an environmental site. ARCADIS has also sold an OP-FTIR –based system to the North Carolina Department of Environment and Natural Resources (NCDENR) for deployment in emergency response situations. Table 18 presents a summary of the advantages and disadvantages of applying the RPM method to the different types of sites, based on the experiences of the project team.

EPA and ARCADIS are currently planning additional measurement campaigns at landfill sites. The campaigns will be done solely to characterize methane emissions at the sites using the HRPM and VRPM methods. Since methane will be the only compound of interest, the campaigns will use only a scanning OP-TDLAS system. This approach will reduce the cost of instrumentation needed for the project, and the number of personnel needed for the measurements (reducing the deployment costs). This measurement approach could be very useful to landfill operators, as a scanning OP-TDLAS system could be permanently deployed at a landfill site to perform periodic surface methane emissions monitoring and emissions flux measurements. The results of this monitoring could improve safety at the sites by identifying surface methane hot spots, and help assure compliance with federal regulations.

The future of the application of ORS instrumentation and the RPM method also includes improving the quality assurance and data collection methods. The creation of the OAQPS protocol and subsequent approval of EPA Other Test Method 10 for characterizing fugitive emissions from area sources (discussed in Section 2 of this document) is a major breakthrough in this effort. Further development will be done to create protocols for applying the RPM method to specific types of area sources such as landfills and industrial facilities. The guidance will address dealing with challenges specific to the different sites, such as topography and obstacles.

Table 18. Summary of the advantages and disadvantages of applying the RPM method to different types of measurement sites

Site	Advantages	Disadvantages
Landfill	Temporal and spatial emissions data Likely to capture all major emissions areas Ability to directly calculate emissions rates Ability to isolate emissions from specific measurement areas	Relies on favorable wind conditions Difficulty in characterizing emissions from side slopes of landfill cell (see Section 4) Due to large survey cells, some uncertainty regarding capture of emissions from sources located a large distance upwind of VRPM configuration (see Section 4)
Agricultural Site	Temporal and spatial emissions data Likely to capture all major emissions areas Ability to directly calculate emissions rates Ability to isolate emissions from specific measurement areas	Relies on favorable wind conditions
Wastewater Treatment Plant	Temporal and spatial emissions data Likely to capture all major emissions areas Ability to directly calculate emissions rates Ability to isolate emissions from specific measurement areas	Relies on favorable wind conditions
Gas Station Facility	Temporal and spatial emissions data Likely to capture all major emissions areas Ability to directly calculate emissions rates Ability to isolate emissions from specific measurement areas	Relies on favorable wind conditions Small source area of the UST vents made it unnecessary to apply the RPM method. A point sampling approach would have been a better option.

Acknowledgements

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APPENDIX A. Radial Plume Mapping Algorithms

Horizontal Radial Plume Mapping (HRPM)

Horizontal Radial Plume Mapping (HRPM) is a technique that provides qualitative localization of the target compounds in a study. HRPM surveys are performed with the ORS beams located as close to the ground as practical. This enhances the ability to detect minor constituents emitted from the ground, since the emitted plumes dilute significantly at higher levels above the ground. The survey area is divided into a Cartesian grid of n times m rectangular cells. A retro-reflecting mirror is located in each of these cells and the ORS instrument scans to each of these mirrors, dwelling on each for a set measurement-time. The system scans to the mirrors in the order of either increasing or decreasing azimuth angle. The path-integrated concentrations measured at each mirror are averaged over several scanning cycles to produce time-averaged concentration maps. Meteorological measurements are made concurrent to the scanning measurements.

The reconstruction algorithm for obtaining surface concentration contour maps consists of two stages. First, an iterative inversion algorithm is used to retrieve average concentration in each of the cells. Then, an interpolation procedure is applied to the concentration values of each cell to calculate concentration in higher spatial resolution. Horizontal Radial Plume Mapping is performed using *Matlab* (MathWorks) software.

For the first stage of reconstructing the average cell concentrations we apply an iterative algebraic deconvolution algorithm. The path-integrated concentration (PIC), as a function of the field of concentration, is given by:

$$PIC_k = \sum_m K_{km} c_m \qquad (1)$$

where K is a Kernel matrix that incorporates the specific beam geometry with the cell dimensions; k is the number index for the beam paths and m is the number index for the cells; and c is the average concentration in the m^{th} cell. Each value in the Kernel matrix K is the length of the k^{th} beam in the m^{th} cell; therefore, the matrix is specific to the beam geometry. To solve for the average concentrations (one for each cell) the Non Negative Least Squares (NNLS) was applied. The NNLS is similar to a classical least square optimization algorithm, but is constrained to provide the best fit of non-negative values. The NNLS algorithm was tested and compared to the relaxation multiplicative algebraic reconstruction technique (MART) program previously developed and used. Both algorithms gave very similar results when reached to the same maximal level of fit between the predicted PIC and the observed PIC but the NNLS was much faster. Therefore, the NNLS algorithm will be applied in this study. This iterative procedure proceeds until the difference of the criteria parameter between sequential steps drops below a very small threshold value (tolerance). The tolerance value depends on many factors, such as the area dimensions, and number of beams used in the survey. A typical value for the tolerance is around 10^{-11}. Multiplying the resulted vertical vector of averaged concentration by the matrix K, yields the end vector of predicted PIC data.

The Concordance Correlation Factor (CCF) is used to represent the level of fit for the reconstruction in the path-integrated domain (predicted vs. observed PIC). CCF calculations are performed using *Matlab* (MathWorks) software. The CCF is similar to the Pearson correlation coefficient, but is adjusted to account

for shifts in location and scale (*Lin, 1989)*. Like the Pearson correlation (correlation coefficient, 'R'), CCF values are bounded between -1 and 1, yet the CCF can never exceed the absolute value of the Pearson correlation factor. For example, the CCF will be equal to the Pearson correlation when the linear regression line intercepts the ordinate at 0, its slope equals 1, and its absolute value will be lower than the Pearson correlation when the above conditions are not met (*Hashmonay et al., 1999, Wu et al., 1999)*.

The second stage of the plume reconstruction is interpolation among the nine points, providing a peak concentration not limited only to the center of the cells. We will use the triangle-based cubic interpolation procedure. To extrapolate data values beyond the peripheral pixel centers and within the rectangle measurement domain, we will assign the concentration of each corner cell to the corresponding corner of the domain.

Vertical Radial Plume Mapping (VRPM)

The VRPM surveys employ at least five mirrors and one vertical structure to provide the crosswind spatial definition downwind of the plume. At least three mirrors are placed between the scanning ORS instrument and the vertical structure, and two mirrors are placed on the vertical structure. The ORS instrument scans in a constant pattern aimed at each mirror (dwelling on each mirror for 10 to 30 seconds), and PIC values are obtained along each mirror to generate a long-term average in each beam path. The flux in each vertical plane is effectively the product of the sum of the vertical plane integrated concentration multiplied by the average wind speed measured during the determinations. The calculated emission flux is then used to yield an estimated total area emission rate.

We use the smooth basis function minimization (SBFM) reconstruction approach with a two-dimensional smooth basis function (bivariate Gaussian) in order to reconstruct the smoothed mass equivalent concentration map. The smoothed mass equivalent concentration map is reconstructed using *Matlab* (MathWorks). In the SBFM approach, a smooth basis function is assumed to describe the distribution of concentrations, and the search is for the unknown parameters of the basis function. Since our interest is in the plane integrated concentration and not the exact map of concentrations in the plane, we fit only one smoothed basis function (one bivariate Gaussian) to reconstruct the smoothed map.

However, this methodology does not assume that the true distribution of concentration in the vertical plane is a bivariate Gaussian. Earlier computational studies showed that one might fit a single bivariate Gaussian function to many kinds of skewed distributions and still retrieve a reasonably good estimate of the plane-integrated concentration (*Hashmonay and Yost, 1999*). The fit of a single bivariate Gaussian function to a multiple mode distribution was also examined and found that the reconstructed plane integrated concentration conserved fairly well the test input plane integrated concentration.

In each iterative step of the SBFM search procedure, the measured PIC values are compared with assumed PIC values, calculated from the new set of parameters. In order to compute the assumed PIC values, the basis function is integrated along the beam path's direction and path-length.

In our beam geometry, it is convenient to express the smooth basis function G in polar coordinates r and θ.

$$G(r,\theta)=\frac{A}{2\pi\sigma_y\sigma_z\sqrt{1-\rho_{12}^2}}\exp\left\{-\frac{1}{2\left(1-\rho_{12}^2\right)}\left[\frac{(r\cdot\cos\theta-m_y)^2}{\sigma_y^2}-\frac{2\rho_{12}\left(r\cdot\cos\theta-m_y\right)\left(r\cdot\sin\theta-m_z\right)}{\sigma_y\sigma_z}+\frac{\left(r\cdot\sin\theta-m_z\right)^2}{\sigma_z^2}\right]\right\} \quad (2)$$

The bivariate Gaussian has six unknown independent parameters:

- *A* - normalizing coefficient which adjusts for the peak value of the bivariate surface
- ρ_{12} - correlation coefficient which defines the direction of the distribution-independent variations in relation to the Cartesian directions *y* and *z* (ρ_{12} = 0 means that the distribution variations overlap the Cartesian coordinates)
- m_y and m_z - peak locations in Cartesian coordinates
- and σ_y and σ_z - standard deviations in Cartesian coordinates. To fit the unknown parameters of the smooth basis function to the PIC data, one has to define an error function for minimization.

The Sum of Squared Errors (SSE) function is defined in our study as:

$$SSE\left(A,\rho_{12},m_y,m_z,\sigma_y,\sigma_z\right)=\sum_i\left(PIC_i-\int_0^{r_i}G\left(r,\theta_i,A,\rho_{12},m_y,m_z,\sigma_y,\sigma_z\right)dr\right)^2 \quad (3)$$

Where *PIC* represents the measured PIC values and the index *i* is for the different beams. The SSE function is minimized using an iterative minimization procedure, such as the Simplex method, to solve for the unknown parameters. These calculations are performed using *MatLab* (MathWorks).

As mentioned earlier, our interest is in the plane-integrated concentration; therefore, we fit one bivariate Gaussian surface to match the volume under the underlying true concentration distribution surface. This volume is highly conserved in the fitting procedure, which emphasizes agreement over the five path integrals. Six independent beam paths are sufficient to determine one bivariate Gaussian that has six independent unknown parameters.

Some reasonable assumptions also may be made when applying the SBFM method to this problem, to reduce the number of unknown parameters to four; (e.g., setting the correlation parameter ρ_{12} equal to zero). This assumes that the reconstructed bivariate Gaussian is limited only to changes in the vertical and crosswind directions. In this case Equation 2 reduces into:

$$G(r,\theta)=\frac{A}{2\pi\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left[\frac{(r\cdot\cos\theta-m_y)^2}{\sigma_y^2}+\frac{\left(r\cdot\sin\theta-m_z\right)^2}{\sigma_z^2}\right]\right\} \quad (4)$$

One also can fix the peak location in the vertical direction to the ground level when ground level emissions are known to exist, as in our field experiment. However, in this methodology, there is no requirement to apply a priori information on the source location and configuration.

Once the parameters of the function were found for a specific run, we calculate the concentration values for every square elementary unit in a vertical domain. Then, we integrate these values, incorporating wind speed data at each height level to compute the flux. In this stage, we convert the concentration values from parts per million by volume to grams per cubic meter, considering the molecular weight of the target gas and ambient temperature. This enables us to directly calculate the flux in grams per second, using wind speed data in meters per second.

Appendix B: Results from the Chapel Hill, NC Field Campaign

The results from the ORS data collected during the field campaign are presented in the following subsections. The methane concentrations presented below represent values above atmospheric background.

Active Site

HRPM Results

An HRPM survey was conducted in Survey Area #1 on May 2, 2006 using nine optical paths. Figure B-1 presents the average reconstructed methane surface concentration contour map. The blue lines show the locations of the optical paths, converging at the location of the OP-FTIR instrument.

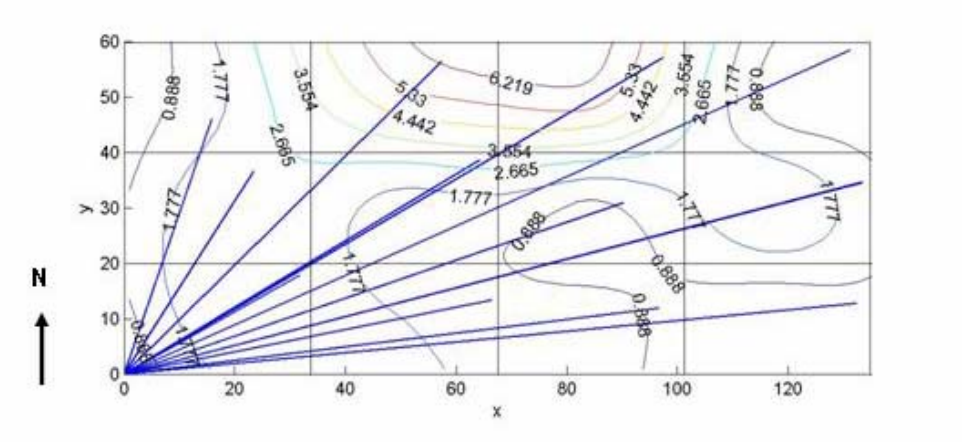

Figure B-1. Average Methane Surface Concentration Contour Map from the May 2, 2006 HRPM Survey of Area #1 (concentrations shown are in ppm above background)

The figure shows the presence of a methane emissions hot spot (having concentrations over 6 ppm above atmospheric background) located in the northern portion of the survey area. This region of the survey area was adjacent to the active work face area at the time of the study.

HRPM surveys were conducted in Survey Area #2 on May 3-5. Figures B-2, B-3, and B-4 show the average reconstructed methane surface concentration contour maps from May 3, May 4, and May 5, respectively. The blue lines show the locations of the optical paths, converging at the location of the OP-FTIR instrument.

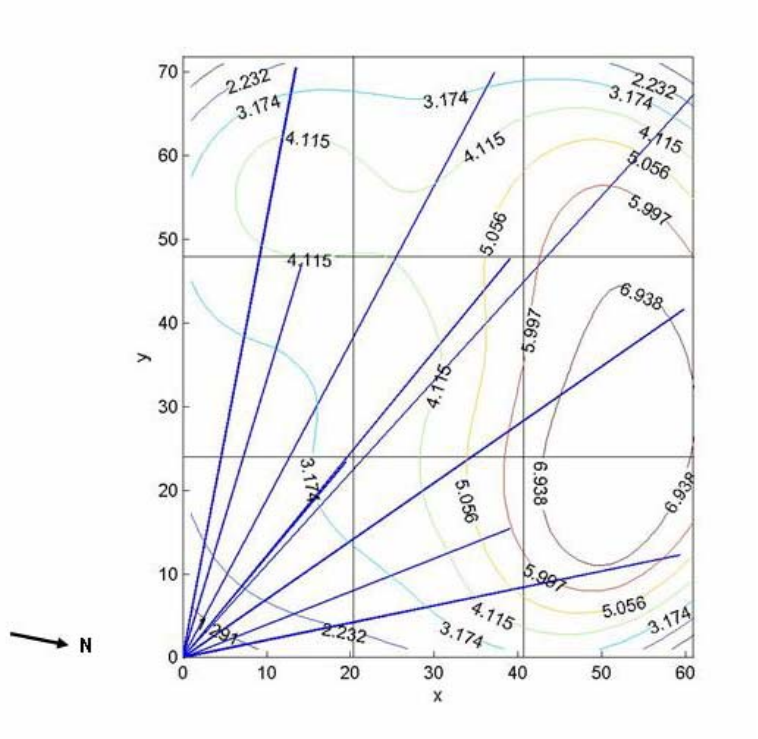

Figure B-2. Average Methane Surface Concentration Contour Map from the May 3 HRPM Survey of Area #2 (concentrations shown are in ppm above background)

The May 3 HRPM survey (see Figure B-2) detected the presence of a methane hot spot located in the northern portion of the survey area having concentrations greater than 6 ppm above atmospheric background levels.

The May 4 HRPM survey (see Figure B-3) detected a hot spot (concentrations greater than 12 ppm above atmospheric background levels) in the same vicinity as the hot spot detected during the May 3 survey. As mentioned previously, the HRPM configuration in Survey Area #2 was extended westward on May 4 and May 5 by adding three additional beam paths to the configuration. An additional methane hot spot having concentrations greater than 12 ppm above atmospheric background levels was detected during the May 4 survey along the western boundary of the survey area.

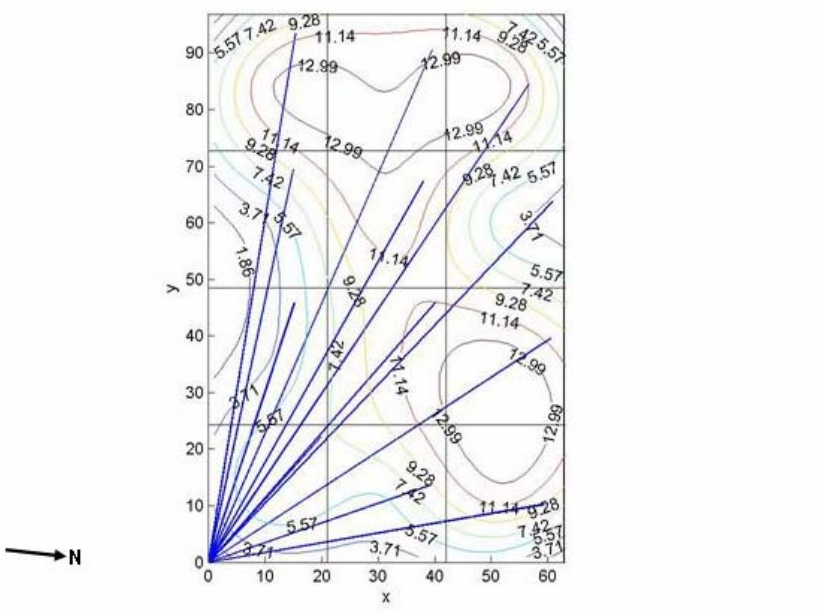

Figure B-3. Average Methane Surface Concentration Contour Map from the May 4 HRPM Survey of Area #2 (concentrations shown are in ppm above background)

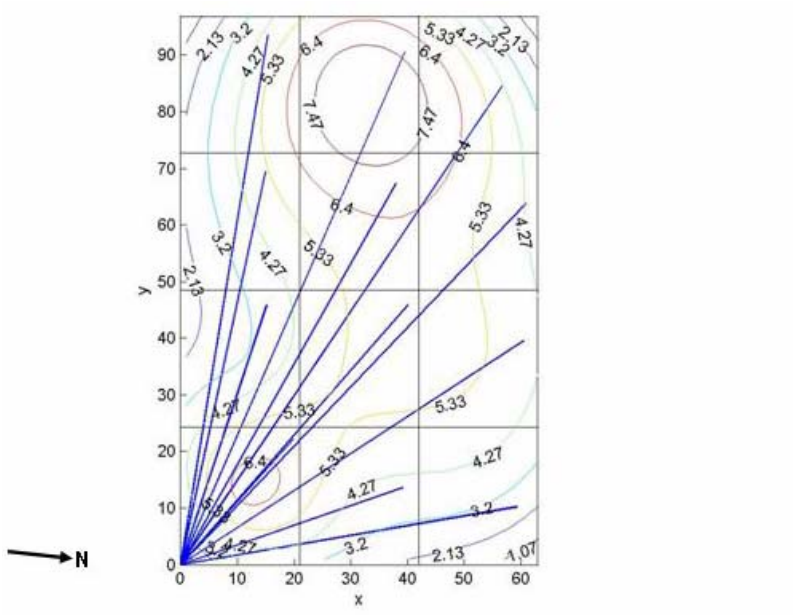

Figure B-4. Average Methane Surface Concentration Contour Map from the May 5 HRPM Survey of Area #2 (concentrations shown are in ppm above background)

The May 5 HRPM survey (see Figure B-4) detected a methane hot spot having concentrations greater than 6 ppm above atmospheric background levels in the southeastern portion of the survey area. The survey detected an additional hot spot along the western boundary of the area (having concentrations greater than 7 ppm above atmospheric background) in the same vicinity as the hot spot detected along the western boundary during the May 4 HRPM survey.

VRPM Results

As mentioned previously, it was not possible to perform a VRPM survey of Survey Area #1 due to the close proximity of the survey area to the active workface. However, two separate VRPM surveys of Survey Area #2 were conducted on May 4 using the IMACC OP-FTIR and the Boreal OP-TDLAS, and on May 5 using the Boreal instrument. Figures B-5 and B-6 present a time series of the calculated downwind methane flux values from the area and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the May 4 IMACC OP-FTIR and Boreal OP-TDLAS surveys, respectively.

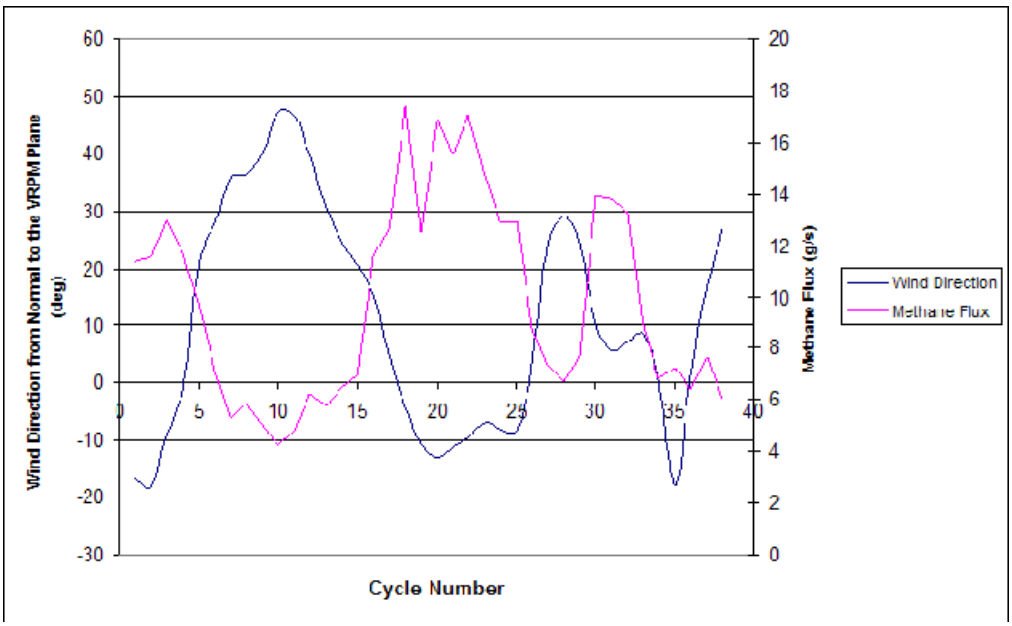

Figure B-5. Time series of wind direction and methane flux values from the May 4 VRPM survey of Survey Area #2 using the IMACC OP-FTIR

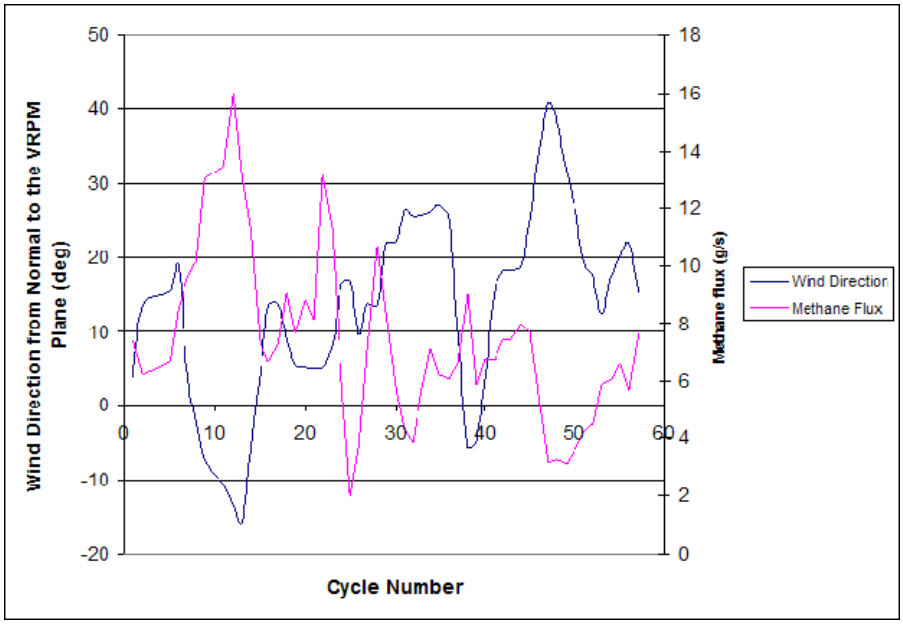

Figure B-6. Time series of wind direction and methane flux values from the May 4 VRPM survey of Survey Area #2 using the Boreal OP-TDLAS

The downwind methane flux values from the IMACC OP-FTIR survey (see Figure B-5) ranged from 5.2 g/s to 17 g/s with an average value of 9.8 g/s. The downwind methane flux values from the Boreal OP-TDLAS survey (see Figure B-6) ranged from 2.1 g/s to 16 g/s with an average of 7.4 g/s. The two surveys yielded a similar range of methane flux values, with the highest flux values occurring when the prevailing wind direction was closest to normal to the plane of the VRPM configuration.

Figure B-7 present a time series of the calculated downwind methane flux values from the area and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the May 5 Boreal OP-TDLAS survey.

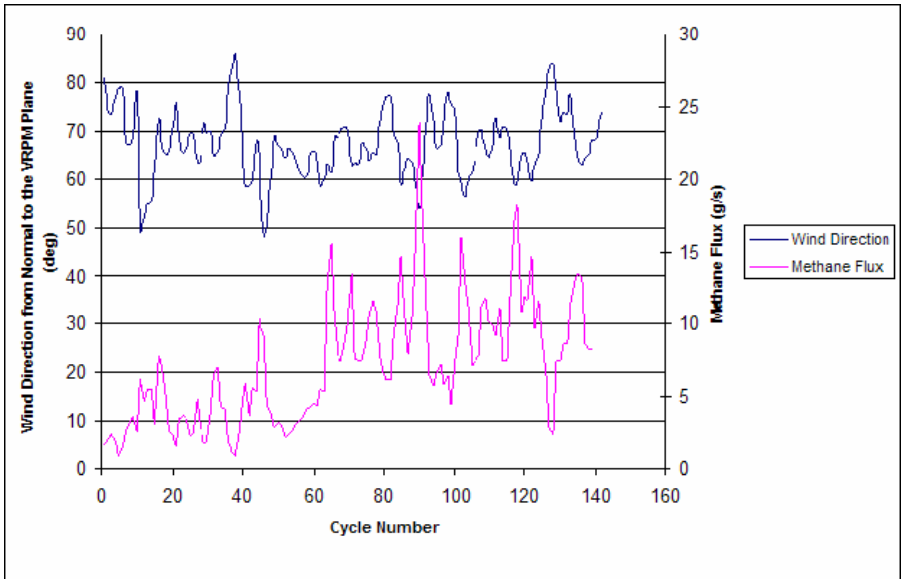

Figure B-7. Time series of wind direction and methane flux values from the May 5 VRPM survey of Survey Area #2 using the Boreal OP-TDLAS

The downwind methane flux values from the survey ranged from .93 g/s to 24 g/s with an average value of 7.3 g/s. At times, the prevailing wind directions during the time of this survey were relatively far from normal to the VRPM plane. However, the average methane flux value from this survey was comparable to the average values from the May 4 VRPM surveys of this area, which were conducted during more favorable wind conditions (prevailing winds were comparatively closer to normal to the VRPM plane).

Closed Site

HRPM Results

An HRPM survey was conducted in Survey Area #1 on May 2, using twelve optical paths. Figure B-8 presents the average reconstructed methane surface concentration contour map. The blue lines show the locations of the optical paths, converging at the location of the OP-FTIR instrument.

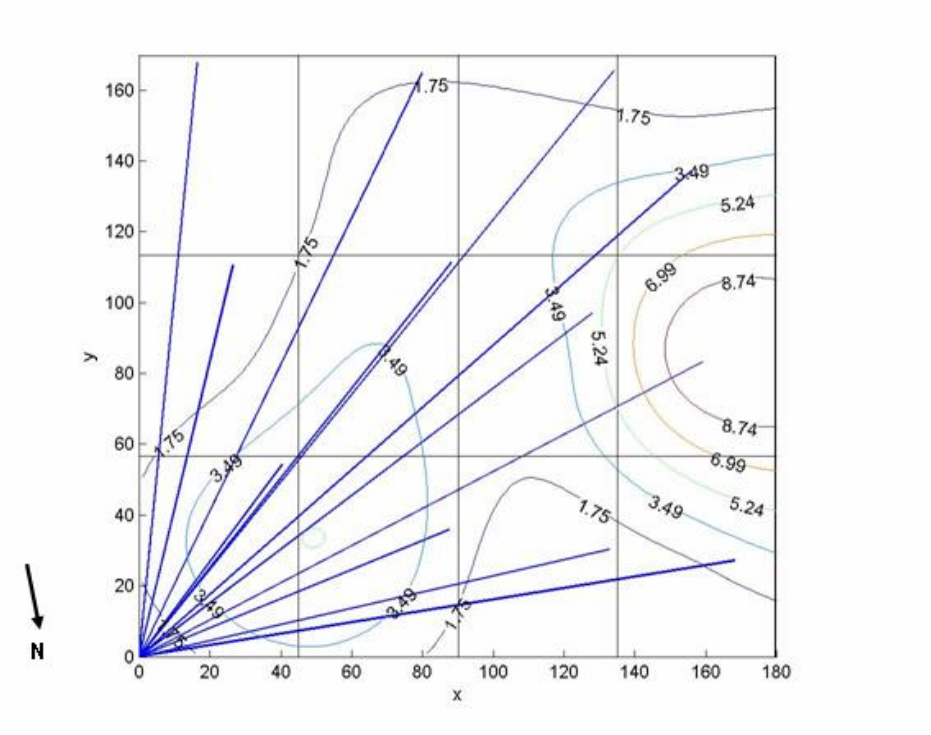

Figure B-8. Average Methane Surface Concentration Contour Map from the May 2 HRPM Survey of Area #1 (concentrations shown are in ppm above background)

The figure shows the presence of a methane emissions hot spot (having concentrations over 8 ppm above atmospheric background levels) located in the western portion of the survey area. The survey detected an additional hot spot in the northeastern portion of the survey area (having concentrations of approximately 4 ppm above atmospheric background).

HRPM surveys were conducted in Survey Area #2 on May 3 and May 5. Figures B-9 and B-10 show the average reconstructed methane surface concentration contour maps from the May 3 and May 5 surveys, respectively. The blue lines show the locations of the optical paths, converging at the location of the OP-FTIR instrument.

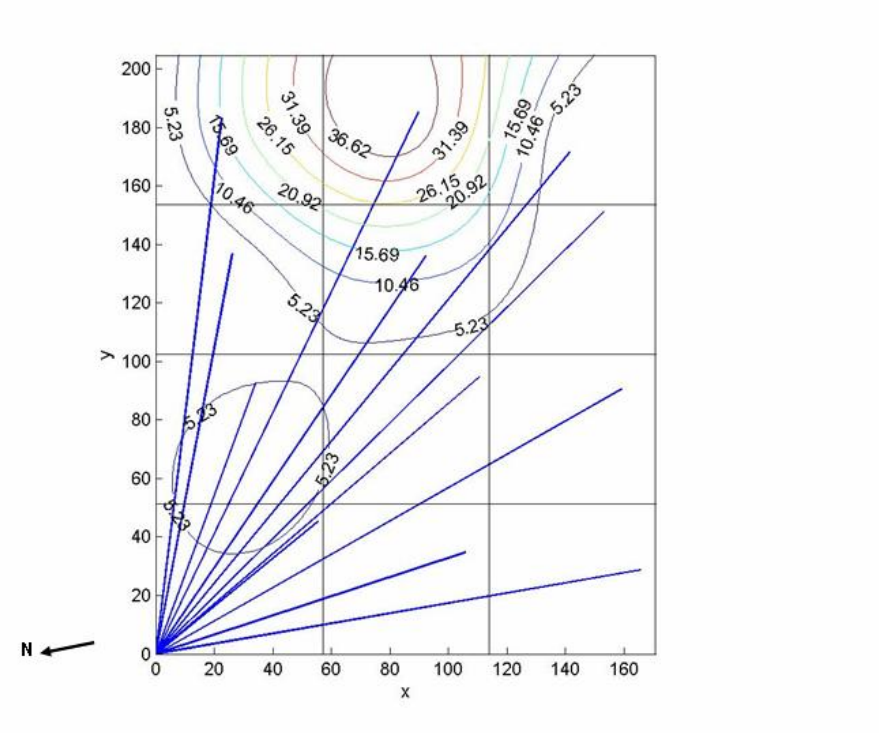

Figure B-9. Average Methane Surface Concentration Contour Map from the May 3 HRPM Survey of Area #2 (concentrations shown are in ppm above background)

The May 3 HRPM survey (see Figure B-9) detected a hot spot (concentrations greater than 36 ppm above atmospheric background levels) in the eastern portion of the survey area. An additional methane hot spot having concentrations greater than 5 ppm above atmospheric background levels was detected near the northwestern corner of the survey area.

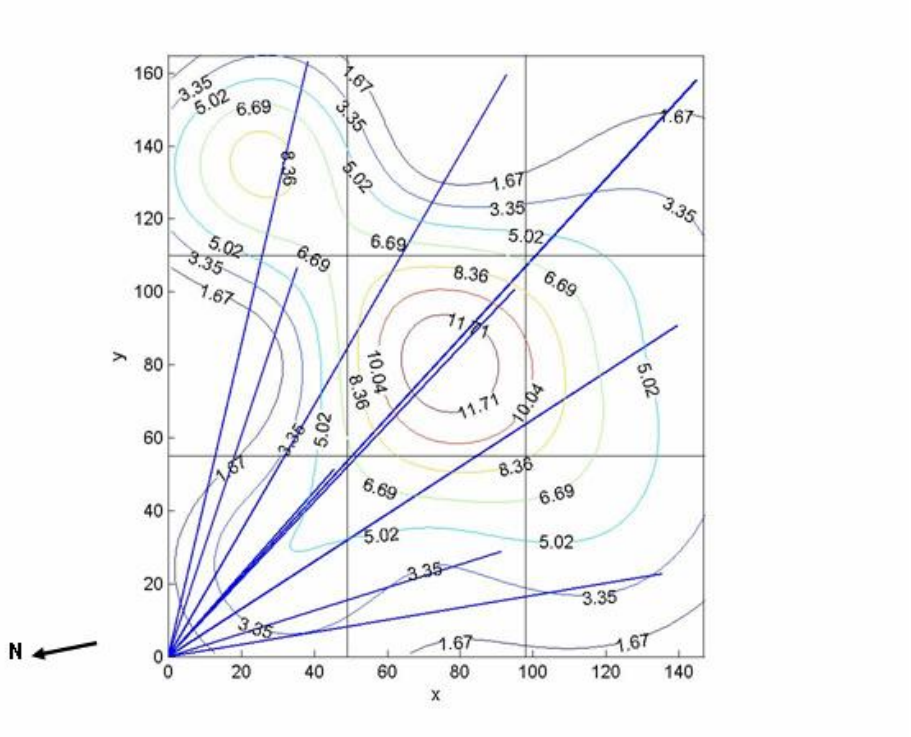

Figure B-10. Average Methane Surface Concentration Contour Map from the May 5 HRPM Survey of Area #2 (concentrations shown are in ppm above background)

The May 5 HRPM survey (see Figure B-10) detected a methane hot spot having concentrations greater than 8 ppm above atmospheric background levels in the northeastern portion of the survey area. The survey detected an additional hot spot near the center of the survey area having concentrations greater than 11 ppm above atmospheric background.

VRPM Results

On May 3, VRPM surveys were conducted along the eastern side of Survey Area #2 (measuring emissions from both survey areas). Two surveys were conducted concurrently, using the IMACC OP-FTIR and the Unisearch OP-TDLAS. Figures B-11 and B-12 present a time series of the calculated downwind methane flux values from the area and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the May 3 IMACC OP-FTIR and Unisearch OP-TDLAS surveys, respectively.

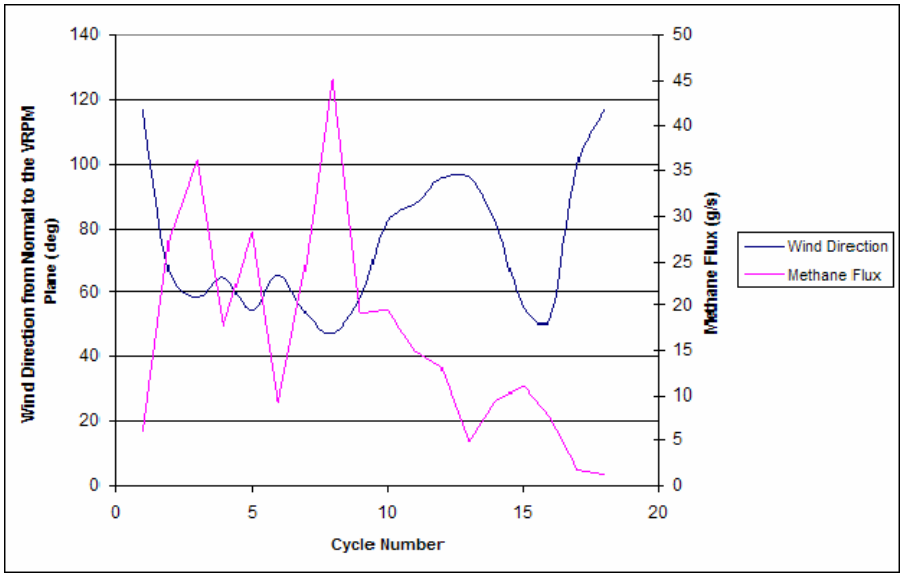

Figure B-11. Time series of wind direction and methane flux values from the May 3 VRPM survey using the IMACC OP-FTIR

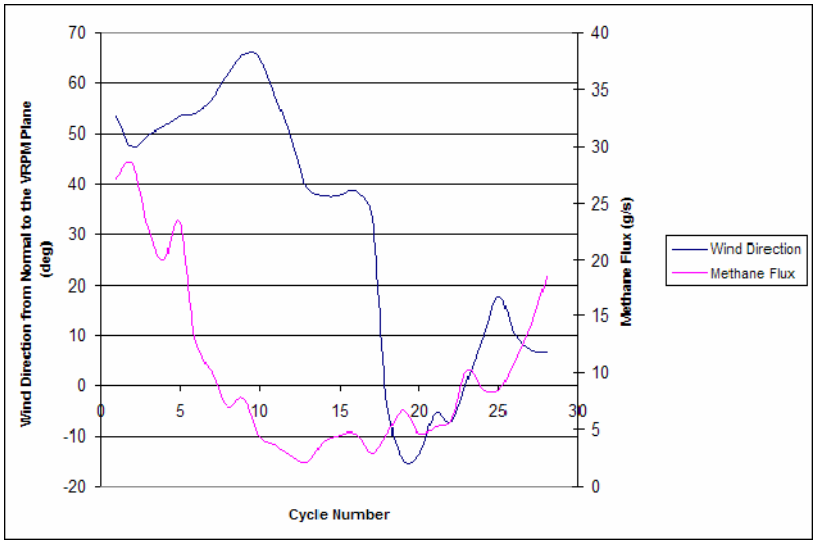

Figure B-12. Time series of wind direction and methane flux values from the May 3 VRPM survey using the Unisearch OP-TDLAS

On May 4, a VRPM survey was conducted along the southern side of the closed site (measuring emissions from both survey areas).

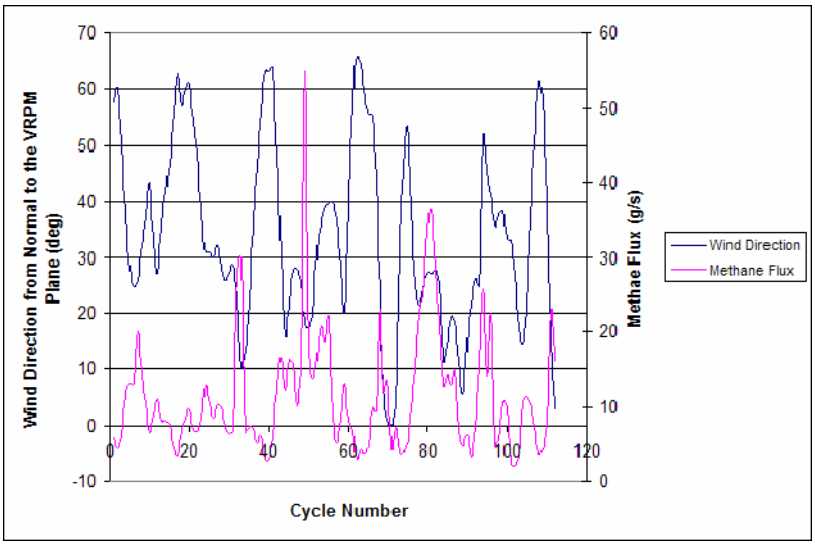

Figure B-13. Time series of wind direction and methane flux values from the May 4 VRPM survey using the Unisearch OP-TDLAS

The downwind methane flux values from the May 4 survey (see Figure B-13) ranged from 3.1 g/s to 55 g/s with an average of 12 g/s. In general, the highest flux values occurred when the prevailing winds were closest to normal to the VRPM plane.

VOC and Ammonia Measurements

All datasets from the HRPM and VRPM surveys from the active and closed site were searched for the presence of VOCs, air toxics, and other pollutants found in landfill gas. The analysis did not detect the presence of any compounds at concentrations above the minimum detection levels (MDL) of the OP-FTIR instruments.

Summary of the Measurement Campaign

ARCADIS and EPA conducted a field campaign in May 2005 at the Orange County Municipal Landfill, located near Chapel Hill, North Carolina. The study used measurements from OP-FTIR and OP-TDLAS instruments and the RPM method to characterize fugitive emissions of methane and VOCs from the active and closed areas at the site.

The HRPM survey conducted on May 2 in Survey Area #1 of the active area detected the presence of a methane hot spot, having concentrations greater than 6 ppm above background, located in the northern portion of the site. The location of the hot spot was close to the active work face area.

HRPM surveys were conducted on May 3-5 in Survey Area #2 of the active area. The May 3 and May 4 surveys detected a methane hot spot in the northern portion of the area having concentrations of 6 ppm above background (May 3 survey), and 12 ppm above background (May 4 survey). The May 4 and May 5 surveys detected a methane hot spot along the western boundary of the area having concentrations of 12 ppm above background (May 4 survey), and 7 ppm above background (May 5 survey).

VRPM surveys were conducted on May 4 and May 5 in Survey Area #2 of the active area. Two VRPM surveys were completed on May 4 using an IMACC OP-FTIR and a Boreal OP-TDLAS. The average methane flux from the May 4 surveys was 9.8 g/s (IMACC OP-FTIR), and 7.4 g/s (Boreal OP-TDLAS). The average methane flux from the May 5 survey was 7.3 g/s.

An HRPM survey was conducted on May 2 in Survey Area #1 of the closed area. The survey detected a methane hot spot having concentrations greater than 8 ppm above background in the western portion of the area. An additional hot spot, having concentrations greater than 4 ppm above background was found in the northeastern corner of the area.

HRPM surveys were conducted on May 3 and May 5 in Survey Area #2 of the closed area. The May 3 survey found methane hot spots in the eastern portion of the area (concentrations greater than 36 ppm above background), and northwestern corner of the area (concentrations greater than 5 ppm above background). The May 5 survey detected a methane hot spot (concentrations greater than 8 ppm above background) in the northeastern corner of the area, and a methane hot spot (concentrations greater than 11 ppm above background) near the center of the survey area.

Two VRPM surveys were conducted on May 3 along the eastern border of the closed area using an IMACC OP-FTIR and Unisearch OP-TDLAS. The surveys found an average methane flux of 22 g/s (IMACC OP-FTIR), and 10 g/s (Unisearch OP-TDLAS). A VRPM survey was conducted on May 4 along the southern boundary of the closed a7rea. The average methane flux from this survey was 12 g/s.

The datasets from the HRPM and VRPM surveys of both areas were searched for the presence of VOCs, air toxics, and other pollutants found in landfill gas. The analysis did not detect the presence of any compounds at concentrations greater than the MDL of the OP-FTIR instruments.

Appendix C: Methane Emissions Results from the VRPM Validation Study Conducted During June and July, 2006

The following sections present data on methane emissions from the Closed Area of the Orange County Municipal Landfill collected during the VRPM Validation Study. The collection of this data was considered non-critical for the study, and was done to provide further information on methane emissions from landfill sites. Methane concentration data was collected during the following days of the study: June 16th during the 20 meter sulfur hexafluoride release, June 19th during the 100 meter sulfur hexafluoride release, July 5th during the 140 meter sulfur hexafluoride release, and July 7th during the 60 meter sulfur hexafluoride release. However, data from June 16th was not analyzed because a post-analysis of the wind data indicated that the prevailing winds during this day were highly variable, and not sufficient to obtain reliable methane flux values through the VRPM configuration. The methane flux values presented were measured along the longest VRPM configuration used in the study.

Methane Flux Values Determined During the June 19 Release

Figure C-1 presents the average reconstructed methane plume map from all of the data collection cycles on June 19. The average calculated methane flux value was 16 grams per second.

Figure C-2 presents a time series of the calculated methane flux values and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the June 19 measurements.

The calculated methane fluxes ranged from 6.1 to 33 grams per second. The highest methane flux values were observed during periods that the prevailing winds were closest to perpendicular to the VRPM configuration.

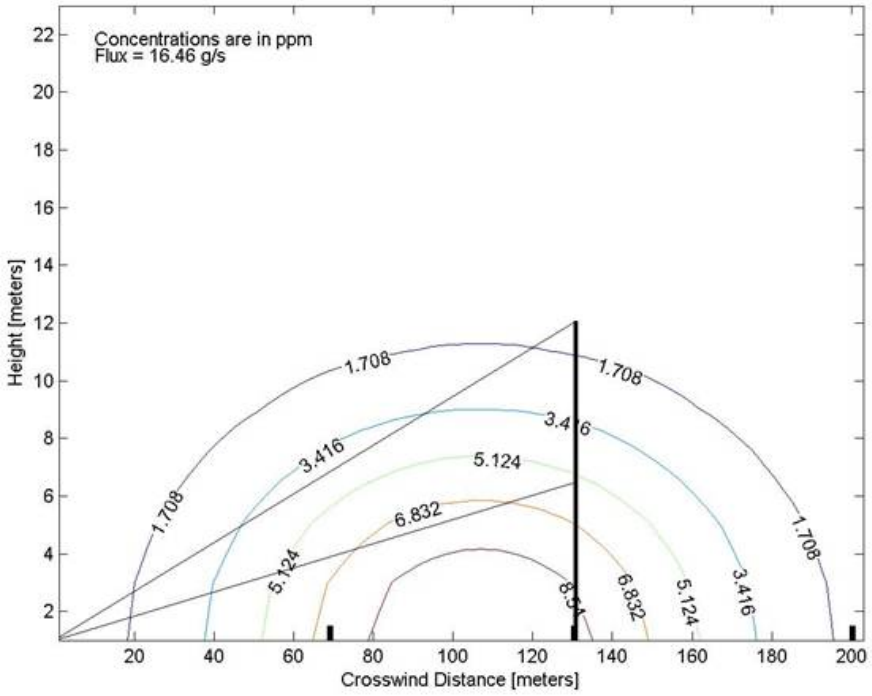

Figure C-1. Reconstructed Methane Plume Map from the June 19 Measurements

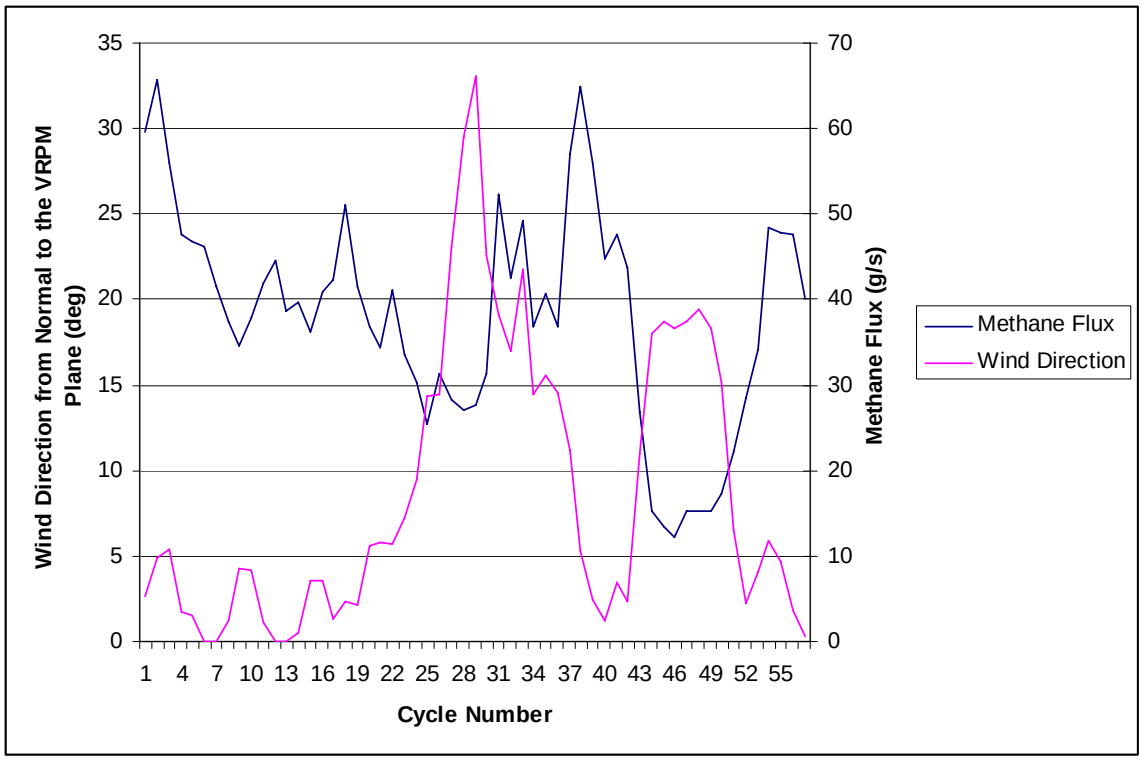

Figure C-2. Time series of wind direction and methane flux values from the June 19 VRPM survey.

Methane Flux Values Determined During the July 5 Release

Figure C-3 presents the average reconstructed methane plume map from all of the data collection cycles on July 5. The average calculated methane flux value was 29 grams per second

Figure C-4 presents a time series of the calculated methane flux values and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the July 5 measurements.

The calculated methane fluxes ranged from 18 to 54 grams per second. In general, there was no observed correlation between methane flux values, and prevailing wind direction during the time of the measurements.

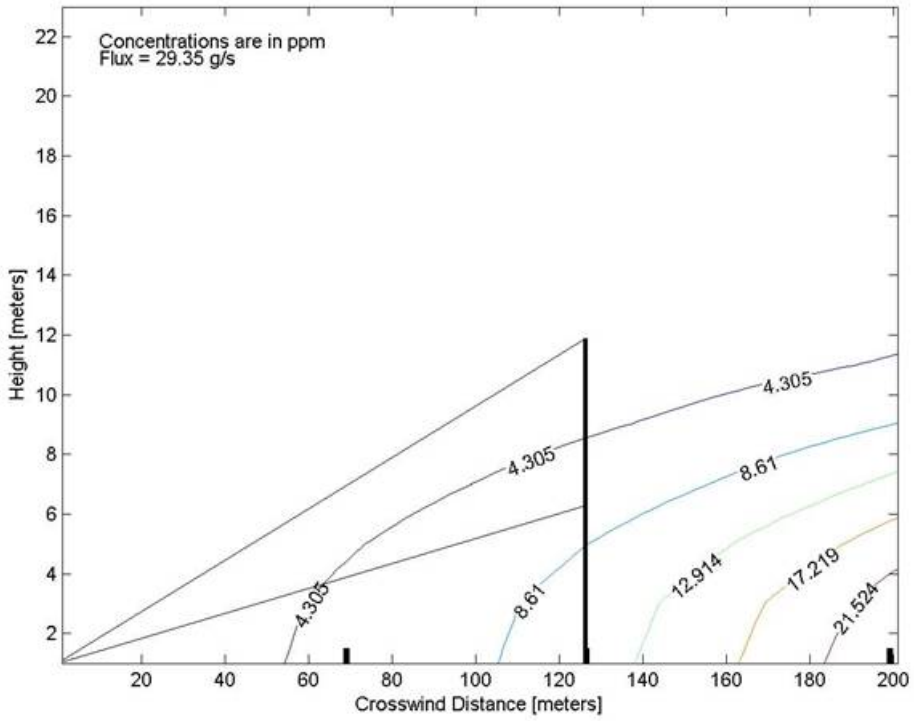

Figure C-3. Reconstructed methane plume map from the July 5 measurements.

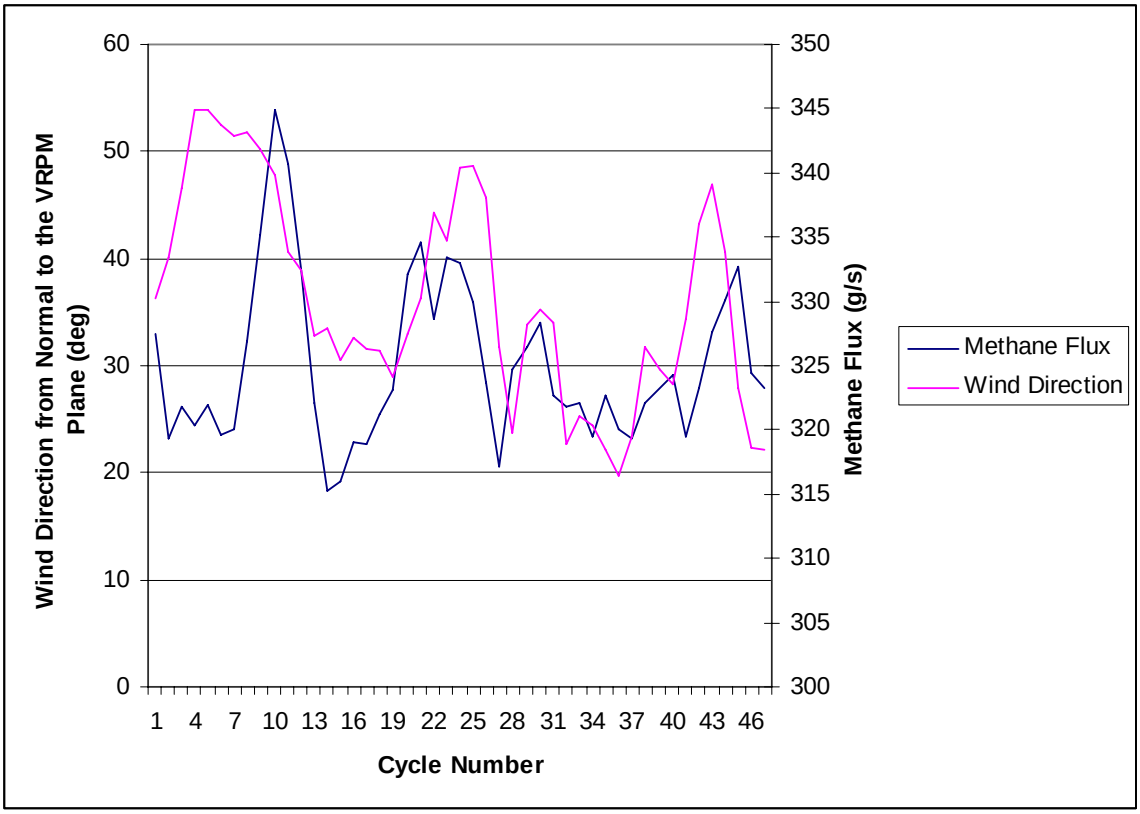

Figure C-4. Time series of wind direction and methane flux values from the July 5 VRPM survey.

Methane Flux Values Determined During the July 7 Release

Figure C-5 presents the average reconstructed methane plume map from all of the data collection cycles on July 7. The average calculated methane flux value was 13 grams per second

Figure C-6 presents a time series of the calculated methane flux values and the prevailing wind direction (from normal to the plane of the VRPM configuration), from the July 7 measurements.

The calculated methane fluxes ranged from 6.3 to 24 grams per second. In general, the highest methane flux values were observed during periods that the prevailing winds were closest to perpendicular to the VRPM configuration.

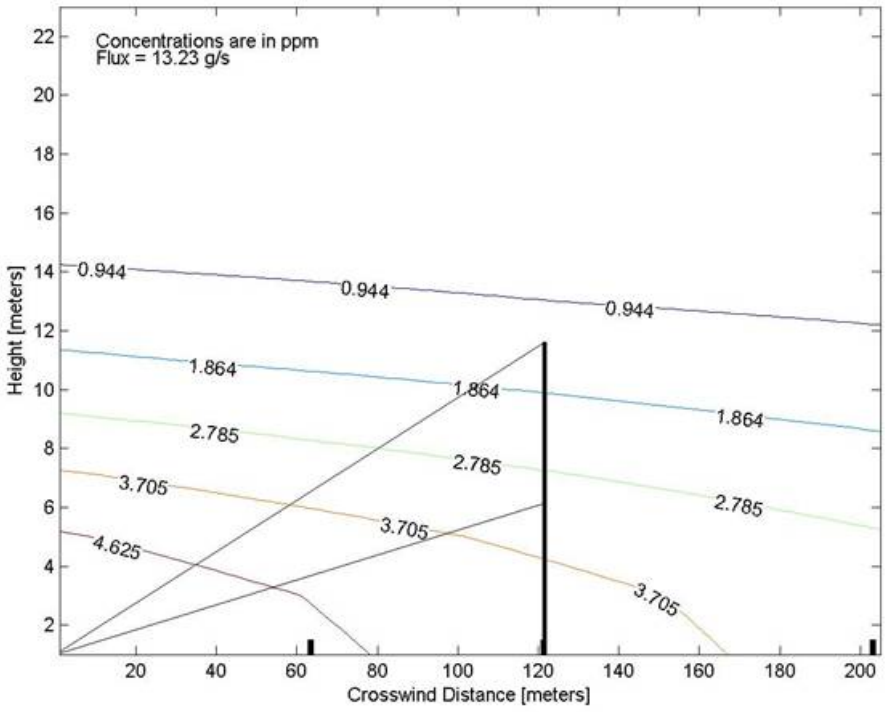

Figure C-5. Reconstructed methane plume map from the July 7 measurements.

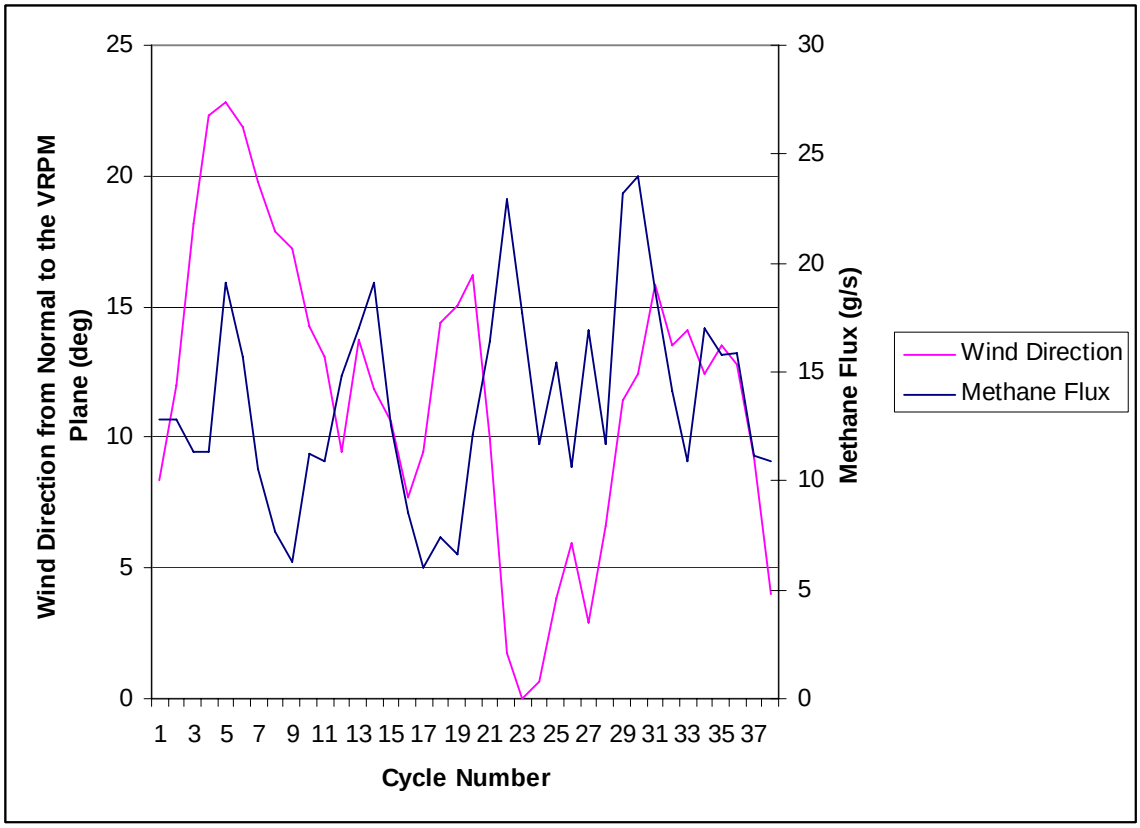

Figure C-6. Time series of wind direction and methane flux values from the July 7 VRPM survey.

Appendix D: ORS Instrument Manufacturers

Company Name	Instrumentation	Address	Telephone
Industrial Monitoring & Control Corporation (IMACC)	OP-FTIR	800 Paloma Dr.Ste 100 Round Rock, TX 78664	(512) 341-8189
Midac Corporation	OP-FTIR	130 McCormick Ave.#111 Costa Mesa, CA 92626	(714) 546-4322
AIL, Inc. c/o Kassay Field Services	OP-FTIR	Not Available	(610) 916-8988
Boreal Laser, Inc.	OP-TDLAS	#13 51127 RR255 Spruce Grove, AB CANADA T7Y1A8	(780) 987-4382
OPSIS, Inc.	UV-DOAS	1165 Linda Vista Dr.,Ste 112 San Marcos, CA 92069	(760) 752-3006
Cerex Scientific	UV-DOAS	1701 Barrett Lakes Blvd.Ste 200 Kennessaw, GA 30144	(678) 819-3766
Unisearch Associates, Inc.	OP-FTIR/ OP-TDLAS	96 Bradwick Drive Concord, Ontario CANADA L4K1k8	(905) 669-3547