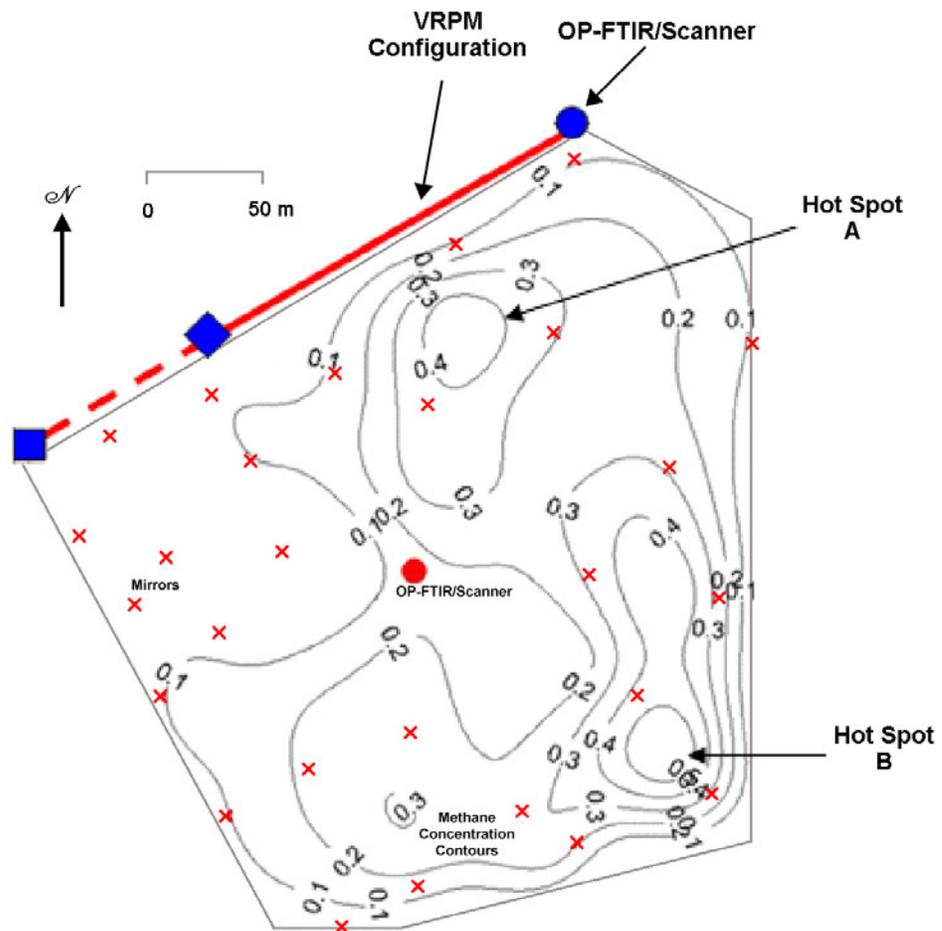


Evaluation of Fugitive Emissions at a Former Landfill Site in Colorado Springs, Colorado Using Ground-Based Optical Remote Sensing Technology



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Evaluation of Fugitive Emissions at a Former Landfill Site in Colorado Springs, Colorado Using Ground-Based Optical Remote Sensing Technology

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Abstract

A former landfill site located in Colorado Springs, Colorado was assessed for landfill gas emissions in support of reuse options for the property. The current owners of the landfill and the State of Colorado requested assistance from the EPA Region 8 Office, and the Office of Superfund Remediation and Technology Innovation, Technology Integration and Information Branch to perform a site assessment to search for the presence of any fugitive gas emissions from the site.

The focus of this study was to evaluate fugitive emissions of methane and volatile organic compounds at the site in support of the reuse objectives, using a scanning open-path Fourier transform infrared spectrometer, open-path tunable diode laser absorption spectroscopy, and an ultra-violet differential optical absorption spectrometer. The study involved a technique developed through research funded by the EPA's National Risk Management Research Laboratory that uses ground-based optical remote sensing technology, known as optical remote sensing-radial plume mapping. The horizontal radial plume mapping (HRPM) method was used to map surface concentrations, and the Vertical Radial Plume Mapping (VRPM) method was used to measure emissions fluxes downwind of the site.

The HRPM surveys detected the presence of a methane hot spot in the Northeast quadrant of the site, and the peak concentration for this hot spot was greater than 0.4 ppm above ambient background levels. Another methane hot spot was detected in the Southeast quadrant of the site, and the peak concentration for this hot spot was greater than 0.5 ppm above ambient background. The VRPM survey measured an average methane flux from the site of 4.9 g/s. The location of the peak of the reconstructed methane plume agrees well with the location of the hot spots detected during the HRPM surveys. This suggests that emissions from the two hot spots are a major source of the methane plume detected during the VRPM survey.

Foreword

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Sally Gutierrez, Acting Director
National Risk Management Research Laboratory

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This study was jointly sponsored by the United States Environmental Protection Agency (EPA) Region 8 Office, and the Office of Superfund Remediation and Technology Innovation, Technology Integration and Information Branch under its Monitoring and Measurement for the 21st Century (21M²) initiative. The 21M² initiative is intended to provide EPA staff with resources to apply new approaches to real site problems.

Executive Summary

Background and Site Information

A former landfill site located in Colorado Springs, Colorado was assessed for landfill gas emissions in support of reuse options for the property. The landfill is approximately 40 acres, and landfill operations took place on the site from about 1957 to 1980. The landfill accepted waste from both commercial and residential operations. Several volatile organic compounds (VOCs) are known to be present in soil gas and groundwater beneath the landfill. The current landfill owners and the State of Colorado requested assistance from EPA to perform a site assessment searching for the presence of any fugitive gas emissions from the site. This assessment was necessary due to the potential adverse health effects associated with exposure to landfill gas. The EPA Region 8 Office requested assistance with this study through the 21M² program to utilize innovative approaches for performing an assessment at the site.

The focus of this study was to evaluate emissions of fugitive gases and VOCs at the site in support of the reuse objectives, using an open-path Fourier transform infrared (OP-FTIR) spectrometer and an open-path tunable diode laser absorption spectroscopy (OP-TDLAS) system. The OP-FTIR instrument provided the critical measurements in the current study. The OP-TDLAS provided non-critical, supplemental data. The study involved a technique developed through research funded by the U.S. EPA's National Risk Management Research Laboratory (NRMRL) that uses ground-based optical remote sensing technology, known as optical remote sensing-radial plume mapping (ORS-RPM) (Hashmonay and Yost, 1999; Hashmonay et al., 1999; Wu et al., 1999; Hashmonay et al., 2001; Hashmonay et al., 2002).

The site assessment consisted of one field campaign performed during September 2003 by ARCADIS and EPA personnel. Figure E1 presents the overall layout of the site, detailing the geographic location of each horizontal radial plume mapping (HRPM) survey area. Figure E2 shows the location of the vertical radial plume mapping (VRPM) configuration that was used to collect data for emission flux calculations.

Testing Procedures

HRPM surveys were done in the NW, SW, NE, and SE quadrants to search for surface emissions of methane, ammonia, and VOCs (see Table 1 of the report for a list of target compounds). A VRPM survey was done along the northern border of the site to measure emissions of methane, ammonia, and VOCs downwind of the site. The OP-TDLAS instrument was deployed along the surface of the site, and on a slope adjacent to the southern boundary of the site to provide additional information on methane concentrations.

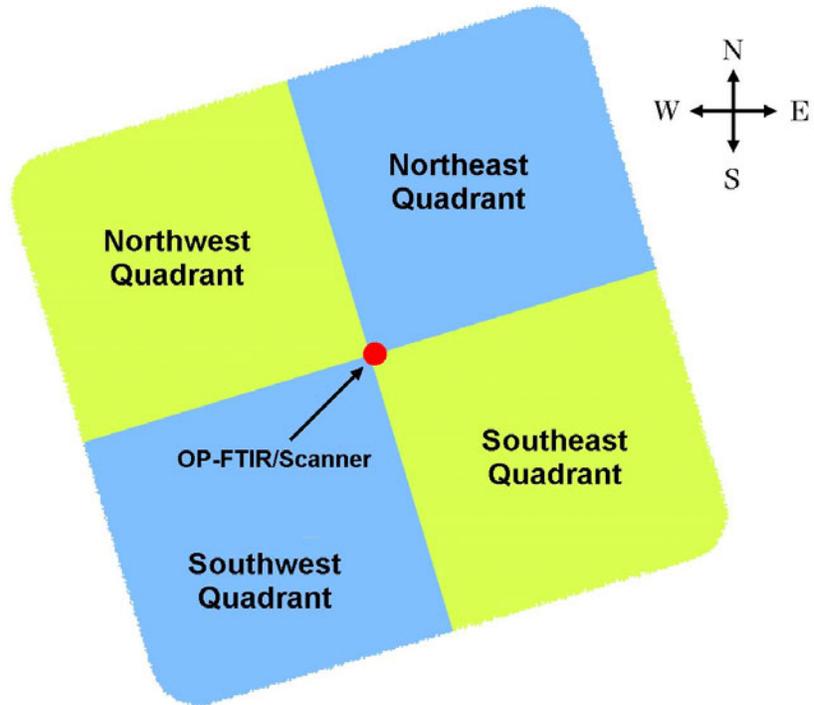


Figure E-1. Map of the Site Detailing the Location of the HRPM Survey Areas.

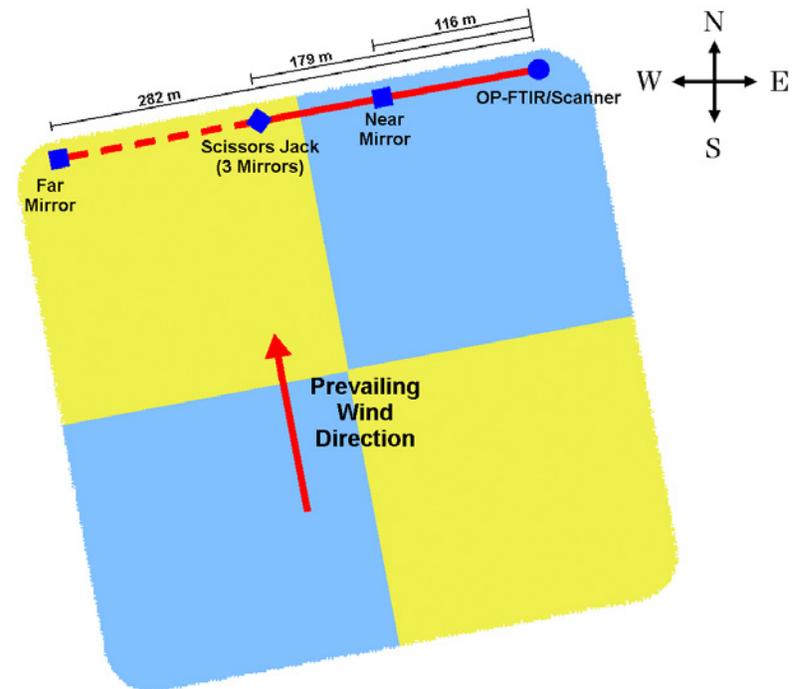


Figure E-2. Map of the Site Detailing the Location of the VRPM Configurations.

Results and Discussion

HRPM Results

The HRPM surveys of the site detected the presence of a methane hot spot in the Northeast quadrant of the site. The peak concentration for this hot spot was greater than 0.4 ppm above the determined ambient background level of 1.55 ppm, which was the lowest methane concentration measured during the field campaign. Another methane hot spot was detected in the Southeast quadrant of the site. The peak concentration for this hot spot was greater than 0.5 ppm above ambient background.

VRPM Results

The VRPM survey measured an average methane flux from the site of 4.9 g/s. The location of the peak of the reconstructed methane plume agrees well with the location of the hot spots detected during the HRPM surveys. This suggests that emissions from the two hot spots are a major source of the methane plume detected during the VRPM survey.

VOC and Ammonia Results

All data sets from the HRPM and VRPM surveys were searched for the presence of VOCs and ammonia. The analysis detected the presence of gasoline (primarily octane) during the HRPM survey of the Northeast quadrant. However, this is attributed to emissions from the gasoline generators used in the field campaign, which were located upwind of the measurement configuration during the HRPM survey of the Northeast quadrant. The measured gasoline concentrations ranged from below the detection limit to 23 ppb. Analysis of the other data sets did not detect VOCs or ammonia at levels higher than the minimum detection levels of the OP-FTIR instruments.

OP-TDLAS Measurements

The OP-TDLAS survey of the surface of the site found average methane concentrations between 0.47 and 0.53 ppm above the ambient background level of 1.55 ppm. The surface methane concentrations measured with the OP-TDLAS system agree fairly well with the methane levels measured during the HRPM surveys.

The survey of the slope along the southern boundary of the site found relatively higher methane concentrations. The largest average methane concentration detected was 1.34 ppm above ambient background. The relatively larger standard deviations found during the slope survey suggest that methane hot spots were present along the slope.

Chapter 1

Project Description and Objectives

1.1 Background

A former landfill site located in Colorado Springs, Colorado was assessed for landfill gas emissions as part of an effort to rehabilitate the site as a recreational facility. The landfill is approximately 40 acres and accepted waste from both commercial and residential sources from about 1957 to 1980. Several volatile organic compounds (VOCs) are known to be present in soil gas and groundwater beneath the landfill. The current owners of the landfill and the State of Colorado requested assistance from the EPA to perform a site assessment to search for the presence of any fugitive gas emissions from the site. This assessment was necessary due to the potential adverse health effects associated with exposure to landfill gas. The EPA Region 8 Office requested assistance with this study through the 21M² program to utilize innovative approaches for performing an assessment at the site. Figure 1-1 shows a picture of the site.

The focus of this study was to evaluate emissions of fugitive gases, such as methane and ammonia, and



Figure 1-1. Colorado Springs, Colorado, Site.

VOCs at the site in support of the reuse objectives, using an open-path Fourier transform infrared (OP-FTIR) spectrometer and an open-path tunable diode laser absorption spectroscopy (OP-TDLAS) system. The OP-FTIR instrument provided the critical measurements in the current study. The OP-TDLAS system provided non-critical, supplemental data on methane concentrations. The study involved a technique developed through research funded by the U.S. EPA's National Risk Management Research Laboratory NRMRL that uses ground-based optical remote sensing technology, known as optical remote sensing-radial plume mapping (ORS-RPM) (Hashmonay and Yost, 1999; Hashmonay et al., 1999; Wu et al., 1999; Hashmonay et al., 2001; Hashmonay et al., 2002). The assessment identified emission hot spots (areas of relatively higher emissions), investigated source homogeneity, and calculated an emission flux rate for each compound detected at the site. This information can be used to identify specific areas at the site in need of better gas control and to assess whether or not better controls should be implemented at the site as a whole. Concentration maps in the horizontal and downwind vertical planes were generated using the horizontal radial plume mapping (HRPM), and vertical plume mapping (VRPM) methods, respectively.

The study consisted of one field campaign performed during September 2003 by ARCADIS and EPA personnel. The Colorado Springs site was divided into four areas. Figure 1-2 presents the overall layout of the site, detailing the geographic location of the HRPM survey areas. The red dot indicates the position of the OP-FTIR instrument during the HRPM surveys. Figure 1-3 shows the location of the VRPM configuration used at the site. The blue dot indicates

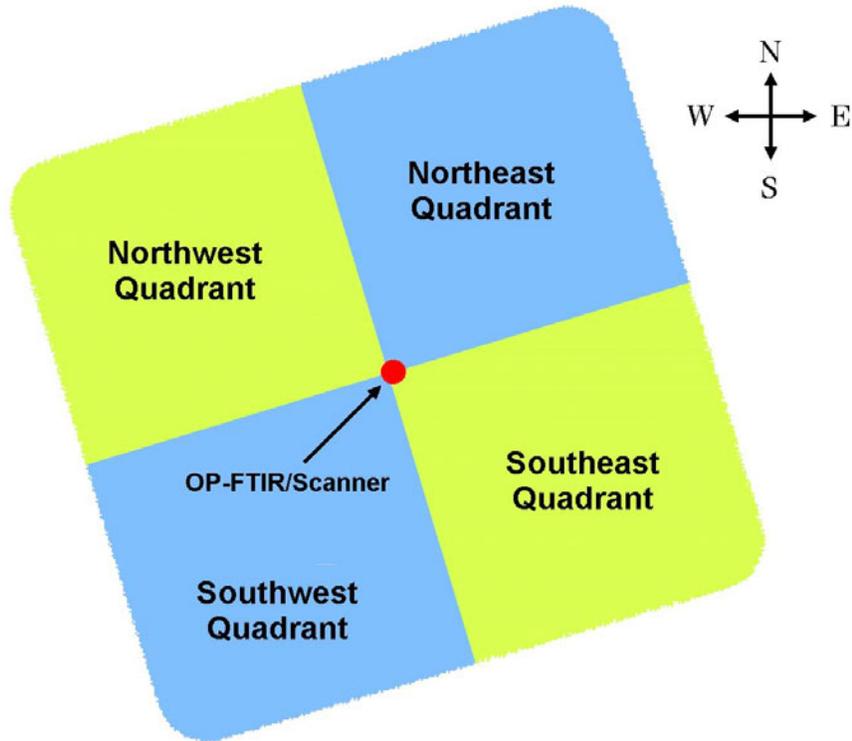


Figure 1-2. Map of Colorado Springs Site Showing the Location of the HRPm Survey Areas.

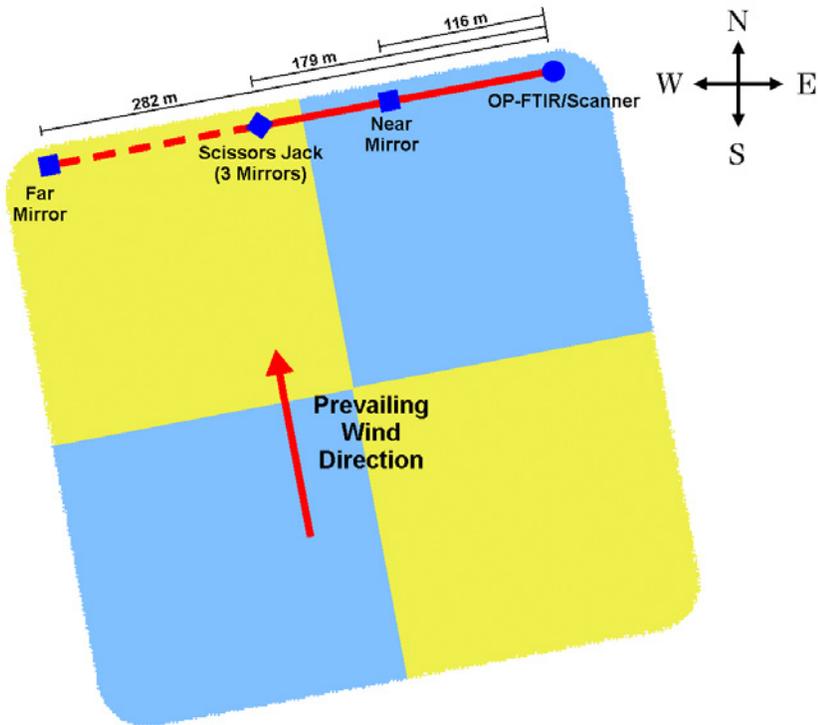


Figure 1-3. Map of the Colorado Springs Site Showing the Location of the VRPM Configuration.

Former Landfill in Colorado Springs, Colorado

the location of the OP-FTIR; the blue diamond indicates the location of a scissors jack (vertical structure) on which were placed three mirrors used in the configuration; and the blue squares indicate the location of the surface mirrors.

1.2 Project Description and Purpose

The objectives of the study were to identify major emissions hot spots by collecting OP-FTIR data and creating surface concentration maps in the horizontal plane, measure emission fluxes of detectable compounds downwind from major hot spots, and demonstrate the operation and function of the optical remote sensing (ORS) technologies.

The ORS techniques used in this study were designed to characterize the emissions of fugitive gases from area sources. Detailed spatial information is obtained from path-integrated ORS measurements by iterative algorithms. The HRPM method involves a configuration of non-overlapping radial beam geometry to map the concentration distributions in a horizontal plane. This method can also be applied to a vertical plane downwind from an area emission source to map the crosswind and vertical profiles of a plume. By incorporating wind information, the flux through the plane is calculated, which leads to an emission rate of the upwind area source. An OP-FTIR sensor was chosen as the primary instrument for the study because of its capability of accurately measuring a large number of chemical species that might occur in a plume.

The OP-FTIR spectrometer combined with the ORS-RPM method is designed for fence-line monitoring; real-time, on-site hot spot detection and source characterization; and emissions flux determination. An infrared light beam modulated by a Michelson interferometer is transmitted from a single telescope to a retroreflector (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 it propagates to the mirror and absorbed further as it is reflected back to the analyzer. One advantage of OP-FTIR monitoring is that the concentrations of a multitude of infrared absorb-

ing gaseous chemicals can be detected and measured simultaneously with high temporal resolution. Figure 1-4 shows a picture of the OP-FTIR instrument/scanner used in the current study.



Figure 1-4. OP-FTIR Instrument/Scanner.

The OP-TDLAS system (Unisearch Associates) is a fast, interference-free technique for making continuous concentration measurements of many gases. The OP-TDLAS used in the current assessment is capable of measuring concentrations in the range of tens of parts per billion over an open path up to 1 km, for gases such as carbon monoxide, carbon dioxide, ammonia, and methane. 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 used in this study is a multiple channel TDL instrument that allows fast scanning electronically (few seconds) among many beam-paths (presently, 8 beams). The OP-TDLAS applies a small 4-inch telescope, which launches the laser beam to a 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. For this particular field campaign, data from the OP-TDLAS were used to provide additional information on methane concentrations at the site. At the time of the field campaign, the OP-TDLAS system had only recently been acquired by EPA. Consequently, standard operating and

calibration procedures were still being developed.

Table 1-1 presents summary information on the ORS instrumentation used in this study. The table lists the compounds measured by each instrument during the current study, and instrument limitations such as weather and interfering species.

Table 1-1. Summary Information on the ORS Instrumentation Used in the Study

Parameter	OP-FTIR	OP_TDLAS
Wavelength range	Infrared (2–20 μm)	Near Infrared (~1.5 μm)
Target analysis	Methane, ammonia, gasoline, other VOCs	Methane
Detection limit	Parts per billion	Parts per billion
Limiting weather conditions	Heavy rain	Heavy rain, fog
Interfering species	carbon dioxide, water	None

Meteorological and survey measurements were also made during the field campaign. A theodolite was used to make the survey measurement of the azimuth and elevation angles and the radial distances to the mirrors relative to the OP-FTIR sensor.

1.2.1 Horizontal RPM

The HRPM provides spatial information to path-integrated measurements acquired in a horizontal plane by an ORS system. This technique yields information on the two-dimensional distribution of the concentrations in the form of chemical-concentration contour maps. This form of output readily identifies the location of higher chemical emissions, or “hot spots.” This method can be of great benefit for performing site surveys before, during, and after site remediation activities. In this particular study, this method is useful for identifying areas where the landfill gas collection control system may not be functioning properly. These areas are the major source of emissions from the site.

HRPM scanning is usually performed with the ORS beams located as close to the ground as is practical. This enhances the ability to detect minor constituents emitted from the ground, since the emitted plumes dilute significantly at higher elevations.

The survey area is typically divided into a Cartesian grid of n times m rectangular cells. In some unique cases, the survey area may not be rectangular due to obstructions, and the shape of the cells may be slightly altered accordingly. A mirror is located in each of these cells, and the ORS sensor scans to each of these mirrors, dwelling on each for a set measurement time (30 seconds in the present assessment). The system scans to the mirrors in the order of either increasing or decreasing azimuth angle. The path-integrated concentrations (PIC) 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.

Figure 1-5 represents a typical HRPM configuration. In this particular case, $n = m = 3$. The solid lines represent the nine optical paths, each terminating at a mirror.

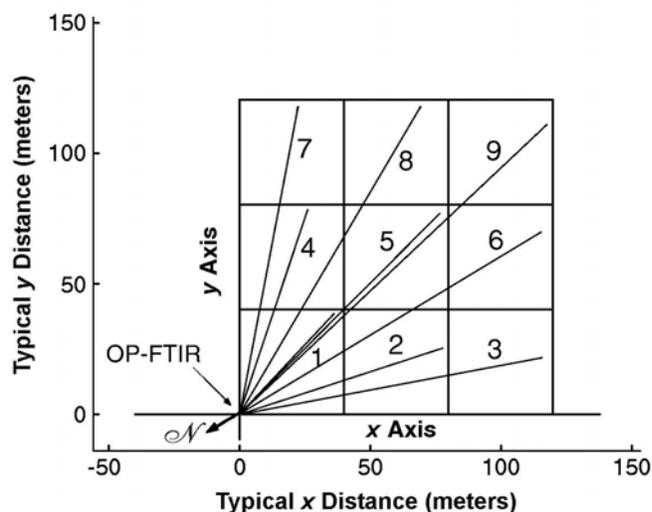


Figure 1-5. Example of a HRPM Configuration.

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One OP-FTIR instrument (manufactured by Uni-search Associates) was used to collect HRPM data during the field campaign.

1.2.2 Vertical RPM

The VRPM method maps the concentrations in the vertical plane by scanning the ORS system in a vertical plane downwind from an area source. One can obtain the plane-integrated concentration from the reconstructed concentration maps. The flux is calculated by multiplying the plane-integrated concentration by the wind speed component perpendicular to the vertical plane. Thus, the VRPM method leads to a direct measurement-based determination of the upwind source emission rate (Hashmonay et al., 1998; Hashmonay and Yost, 1999, Hashmonay et al., 2001).

Figure 1-6 shows a schematic of the experimental setup used for vertical scanning. Several mirrors were placed in various locations on a vertical plane in-line with the scanning OP-FTIR. A vertical platform (scissors jack) was used to place two of the mirrors at a predetermined height above the surface. The location of the vertical plane is selected so that it intersects the mean wind direction as close to perpendicular as practical. One OP-FTIR instrument (manufactured by IMACC, Inc.) was used to complete the VRPM survey.

1.3 Quality Objectives and Criteria

Data quality objectives (DQOs) are qualitative and quantitative statements developed using EPA's DQO Process (U.S. EPA QA/G-4, 2000) that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data.

Quantitative objectives are established for critical measurements using the data quality indicators (DQIs) of accuracy, precision, and completeness. The acceptance criteria for these DQIs are summarized later in Table 5-2 of Section 5 of this report. Accuracy of measurement parameters is determined by

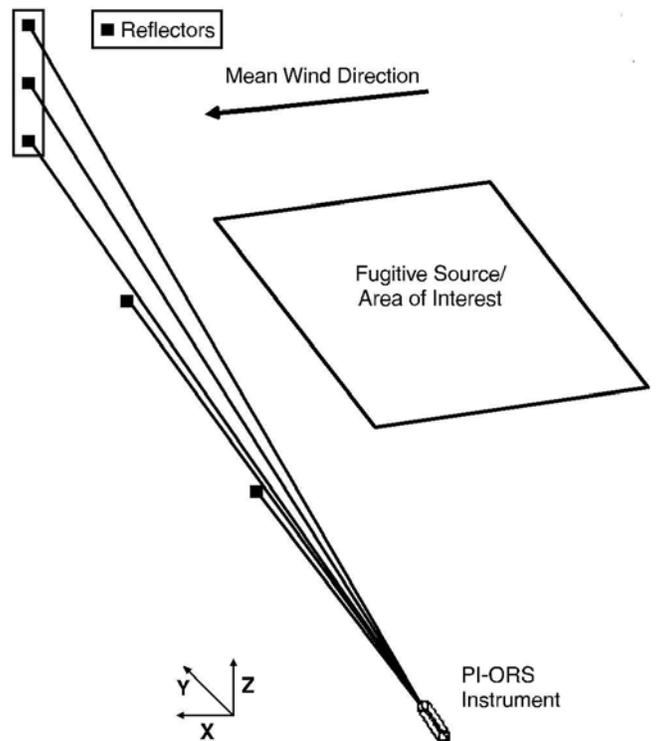


Figure 1-6. Example of a VRPM Configuration.

comparing a measured value to a known standard, assessed in terms of percent bias. Values must be within the listed tolerance to be considered acceptable.

Precision is evaluated by making replicate measurements of the same parameter and assessing the variations of the results. Precision is assessed in terms of relative percent difference (RPD) or relative standard deviation (RSD). Replicate measurements are expected to fall within the tolerances shown later in Table 5-2. Completeness is expressed as a percentage of the number of valid measurements compared to the total number of measurements taken.

Estimated minimum detection limits of the OP-FTIR instrument, by compound, are given in Table 1-2. It is important to note that the values listed in Table 1-2 should be considered first step approximations, as the minimum detection limit is highly variable and depends on many factors including atmospheric conditions. Actual minimum detection levels are

Table 1-2. Detection Limits for Target Compounds.

Compound	OP-FTIR Estimated Detection Limit for Path Length = 100m, 1 min Average (ppmv)	AP-42 Value ratioed to an average methane concentra- tion of 50 ppm ^a (ppmv)
1,4-Dichlorobenzene	0.012	0.000021
2-Propanol	0.0060	0.0050
Acetone	0.024	0.00070
Acrylonitrile	0.010	0.00063
Butane	0.0060	0.00050
Chlorobenzene	0.040	0.000025
Chloroform	0.012	0.0000030
Chloromethane	0.012	0.00010
Dichlorodifluoromethane	0.0040	0.0016
Dimethyl sulfide	0.018	0.00078
Ethane	0.010	0.089
Ethanol	0.0060	0.0027
Ethyl benzene	0.060	0.00046
Ethyl chloride	0.0040	0.00013
Ethylene dibromide	0.0060	0.00000010
Ethylene dichloride	0.030	0.000041
Fluorotrichloromethane	0.0040	0.000076
Hexane	0.0060	0.00066
Hydrogen sulfide	6.0	0.0036
Methane	0.024	N/A ^b
Methanol	0.0015	N/A
Methyl ethyl ketone	0.030	0.00071
Methyl isobutyl ketone	0.040	0.00019
Methyl mercaptan	0.060	0.00025
Methylene chloride	0.014	0.0014
Octane	0.0025	N/A
Pentane	0.0080	0.00033
Propane	0.0080	0.0011
Propylene dichloride	0.014	0.000018
Tetrachloroethene	0.0040	0.00037
Trichlorethylene	0.0040	0.00028
Vinyl chloride	0.010	0.00073
Vinylidene chloride	0.014	0.000020
Xylenes	0.030	0.0012

^a The AP-42 values represent an average concentration of different pollutants in the raw landfill gas. This is not comparable to the detection limits for the OP-FTIR which is an average value for a path length of 100 meters across the surface of the area source being evaluated. However, it does provide an indication of the types of pollutants and range of concentrations associated with landfill gas emissions in comparison to the detection limits of the OP-FTIR.

^b N/A = not available.

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calculated in the quantification software for all measurements taken. Minimum detection levels for each absorbance spectrum are determined by calculating the root mean square (RMS) absorbance noise in the spectral region of the target absorption feature. The minimum detection level is the absorbance signal (of the target compound) that is five times the RMS noise level, using a reference spectrum acquired for

a known concentration of the target compound.

1.4 Project Schedule

The field campaign was completed for this study during September 2003. Table 1-3 provides the schedule of ORS work that was performed.

Table 1-3. Schedule of Work Performed at the Site.

Day	Detail of Work Performed
Tuesday, September 9	Travel to site
Wednesday, September 10	AM—HRPM survey of NW quadrant
	PM—HRPM survey of SW quadrant
Thursday, September 11	AM—HRPM survey of NE quadrant
	PM—HRPM survey of SE quadrant
Friday, September 12	VRPM survey of site
Saturday, September 13	Travel from site

Chapter 2 Testing Procedures

The following subsections describe the testing procedures used at the site. The site was divided into quadrants designated as Northeast, Northwest, Southeast, and Southwest. HRPm was performed in each of the quadrants to produce surface concentration maps and to locate any emissions hot spots. VRPM was performed on the northern border of the site. The coordinates of the mirrors used in each configuration relative to the position of the OP-FTIR instrument are presented in Appendix A.

The site contained several passive vents located approximately 2 m above the surface. These vents were sealed during the HRPm surveys of the surface (see Figure 2-1). The rationale for sealing the vents was that they were suspected 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.

OP-FTIR data were collected as interferograms and archived to CD-ROMs. After archiving, the interferograms were transferred to ARCADIS. They were then transformed to absorbance spectra, and concentrations were calculated using Non-Lin (Spectrosoft) quantification software. This analysis was done after completion of the field campaign. Concentration data were then matched with the appropriate mirror locations, wind speed, and wind direction. The ARCADIS RPM software was used to process the data into horizontal plane concentration maps or vertical plane plume visualizations, as appropriate.

Meteorological data including wind direction, wind speed, temperature, relative humidity, and barometric pressure were continuously collected during the measurement campaign with a Climatronics model



Figure 2-1. Passive Vent Sealed During the HRPm Surveys.

101990-G1 instrument. The Climatronics instrument is automated. It collects real-time data from its sensors and records time-stamped one-minute averages to the data collection computer. Wind direction and speed sensing heads were used to collect data at the surface during the HRPm surveys and at heights of 2 and 10 m during the VRPM survey (the 10 m

sensor was placed on top of the scissors jack). The sensing heads for wind direction incorporate an auto-north function (automatically adjusts to magnetic north) that eliminates the errors associated with subjective field alignment to a compass heading. After collection, a linear interpolation between the two sets of data is done to estimate wind velocity as a function of height.

Once the concentrations maps and wind information were processed, the concentration values were integrated, incorporating the wind speed component normal to the plane at each height level to compute the flux through the vertical plane. In this stage, the concentration values were integrated from parts per million by volume to grams per cubic meter, considering the molecular weight of the target gas and ambient temperature. This enables the flux to be calculated directly in grams per second using wind speed data in meters per second.

The concordance correlation factor (CCF) is used to measure the reproducibility of a reference measurement to another measurement. In the RPM methodologies, it is used to represent the level of fit for the reconstruction in the path-integrated domain (predicted vs observed PIC). The CCF is similar to the Pearson correlation coefficient (r) but is adjusted to account for shifts in location and scale. Like the Pearson correlation, 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, and its slope equals 1. Its absolute value will be lower than the Pearson correlation when the above conditions are not met. For the purposes of this report, the closer the CCF value is to 1, the better the fit for the reconstruction in the path-integrated domain.

A moving average is used in the calculation of the average flux values to show temporal variability in the measurements. A moving average involves averaging flux values calculated from several consecutive cycles (a cycle is defined as data collected when

scanning one time through all the mirrors in the configuration). For example, a data set taken from 5 cycles may be reported using a moving average of 4, where values from cycles 1 to 4, and 2 to 5 are averaged together to show any variability in the flux values.

The shape of the plume maps generated by this method are used to give information on the homogeneity of the plume and do not affect the calculated flux values. The shape of the maps generated represents the best fit of the limited data to a symmetric Gaussian function, and this fit may drive the plume shape outside of the measurement configuration.

2.1 HRPM Measurements

The variation in terrain at the site resulted in a unique geometry and measurement configuration for each quadrant.

2.1.1 Northwest Quadrant

The Northwest quadrant was bounded on the north and west side by a slope, on the east by the Northeast quadrant, and on the south by the Southwest quadrant. Figure 2-2 is a schematic of the HRPM configuration used in the Northwest quadrant. The solid red lines represent the nine optical paths used in the configuration, each terminating at a mirror.

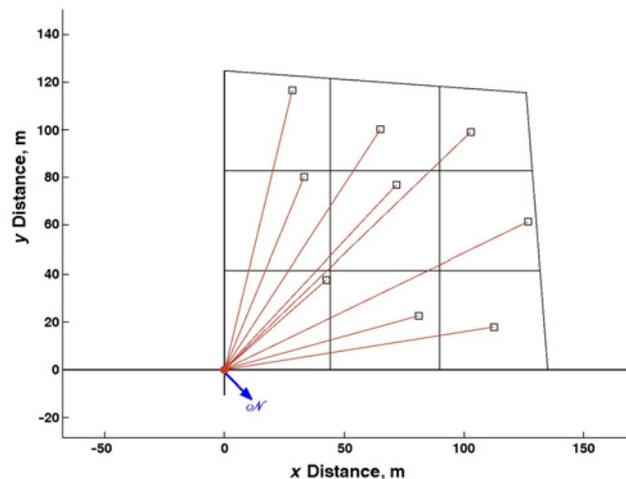


Figure 2-2. Schematic of the HRPM Configuration Used in the Northwest Quadrant.

Former Landfill in Colorado Springs, Colorado

2.1.2 Southwest Quadrant

The Southwest quadrant was bounded on the west and south sides by a slope, on the east by the Southeast quadrant, and on the north by the Northwest quadrant. Figure 2-3 is a schematic of the HRPM configuration used in the Southwest quadrant. Due to the shape of the quadrant, the configuration consisted of only seven optical paths.

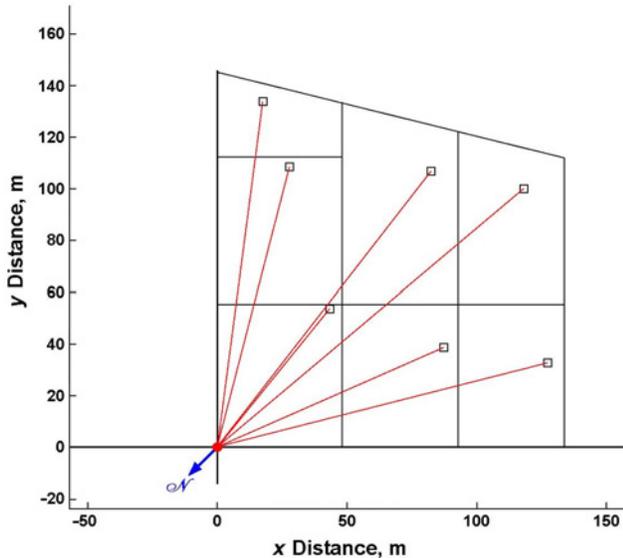


Figure 2-3. Schematic of the HRPM Configuration Used in the Southwest Quadrant.

2.1.3 Northeast Quadrant

Figure 2-4 presents a schematic of the HRPM configuration used in the Northeast quadrant. The Northeast

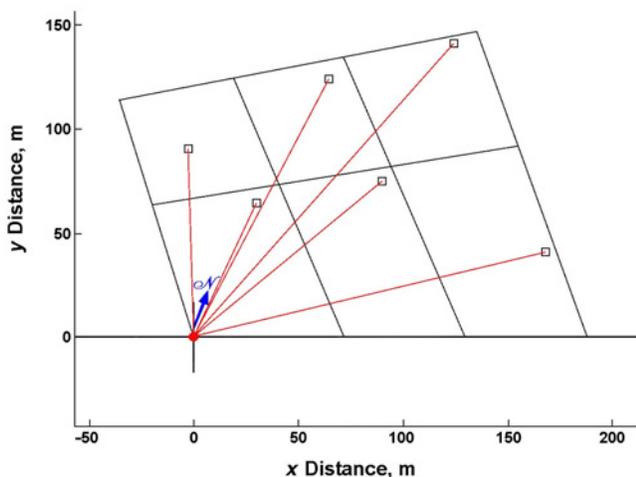


Figure 2-4. Schematic of the HRPM configuration used in the northeast quadrant.

quadrant was bounded on the east and north sides by a slope, on the south by the Southeast quadrant, and on the west by the Northwest quadrant. Due to the size and shape of the quadrant, the configuration consisted of only six optical paths.

2.1.4 Southeast Quadrant

The Southeast quadrant was bounded on the east and south sides by a slope, on the west by the Southwest quadrant, and on the north by the Northeast quadrant. Figure 2-5 presents a schematic of the HRPM configuration used in the Southeast quadrant. Due to the size and shape of the quadrant, the configuration consisted of only five optical paths.

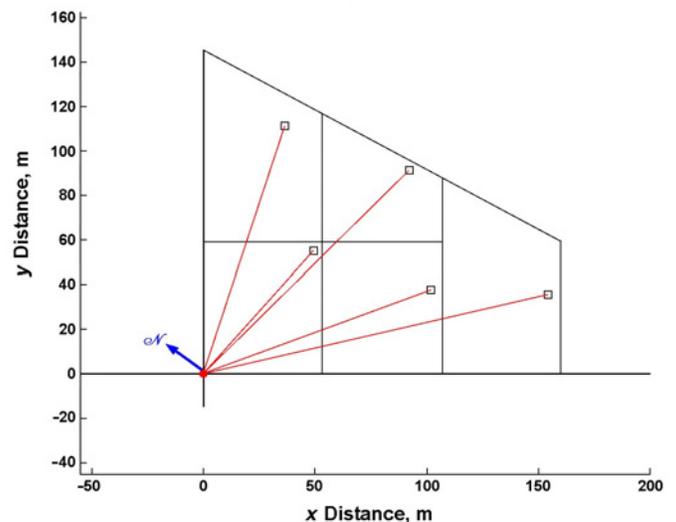


Figure 2-5. Schematic of the HRPM Configuration Used in the Southeast Quadrant.

2.2 VRPM Measurements

A VRPM survey was conducted along the northern border of the site (see Figure 1-3). The VRPM configuration consisted of one mirror placed on the ground between the OP-FTIR and the scissors jack, one mirror placed at the base of the scissors jack, two mirrors placed on the scissors jack, and one mirror placed on the ground beyond the scissors jack.

2.3 OP-TDLAS Measurements

The OP-TDLAS system was deployed for two days of the field campaign to provide additional informa-

tion on methane concentrations at the site. Figure 2-6 is a picture of the OP-TDLAS system. The OP-TDLAS collected data along the surface of the site on September 10. On September 11, the instrument was set up on a slope adjacent to the southern boundary of the site, where a large amount of erosion was observed. Figures 2-7 and 2-8 present a schematic of the OP-TDLAS configurations used on September 10 and 11, respectively. The distance of the path lengths used in each OP-TDLAS configuration are presented in Appendix B of this report.



Figure 2-6. OP-TDLAS System.

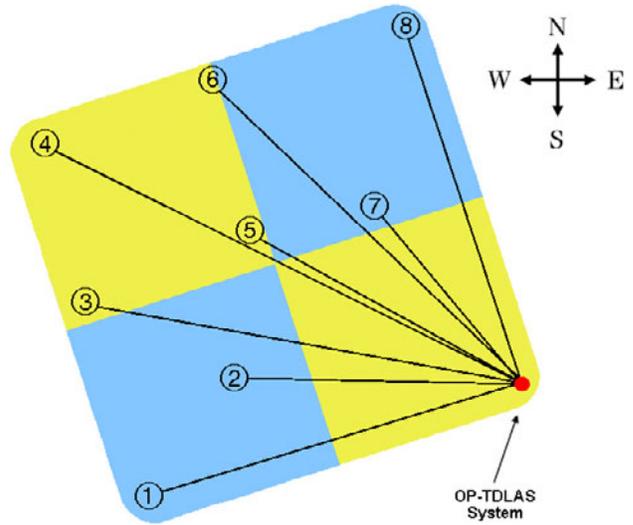


Figure 2-7. Schematic of the OP-TDLAS Configuration Used on September 10.

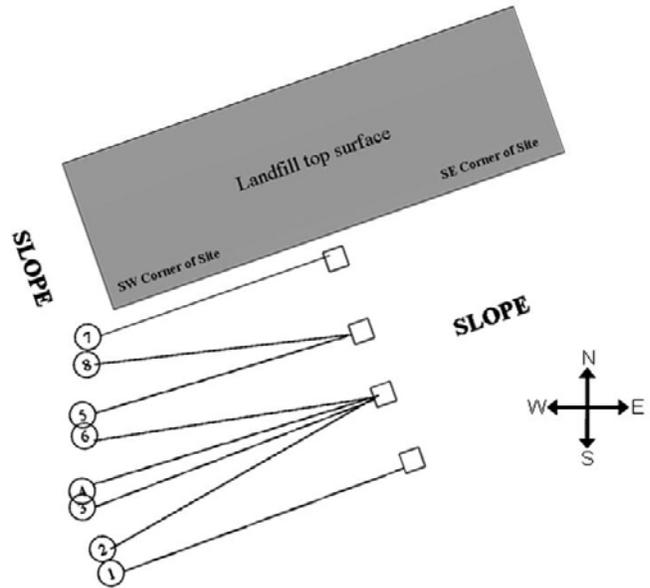


Figure 2-8. Schematic of OP-TDLAS Configuration Used on September 11.

Chapter 3 Results and Discussion

The results from the ORS data collected at the site are presented in the following subsections. It should be noted that the concentration values reported in the following sections have not been corrected to standard atmospheric conditions. The measured methane concentrations from the HRPM and VRPM surveys are presented in Appendix C.

3.1 The Horizontal RPM Results

Figure 3-1 presents the average surface methane

concentration contour map of the entire site. The contours give methane concentration values (in parts per million) above an ambient background concentration of 1.55 ppm, which was the lowest methane concentration measured during the field campaign. The determination of this map is based on the mean path-integrated methane concentration measurements collected with the Unisearch OP-FTIR instrument in the four quadrants, along 27 beam paths. The red X's show the location of the 27 mirrors used in the

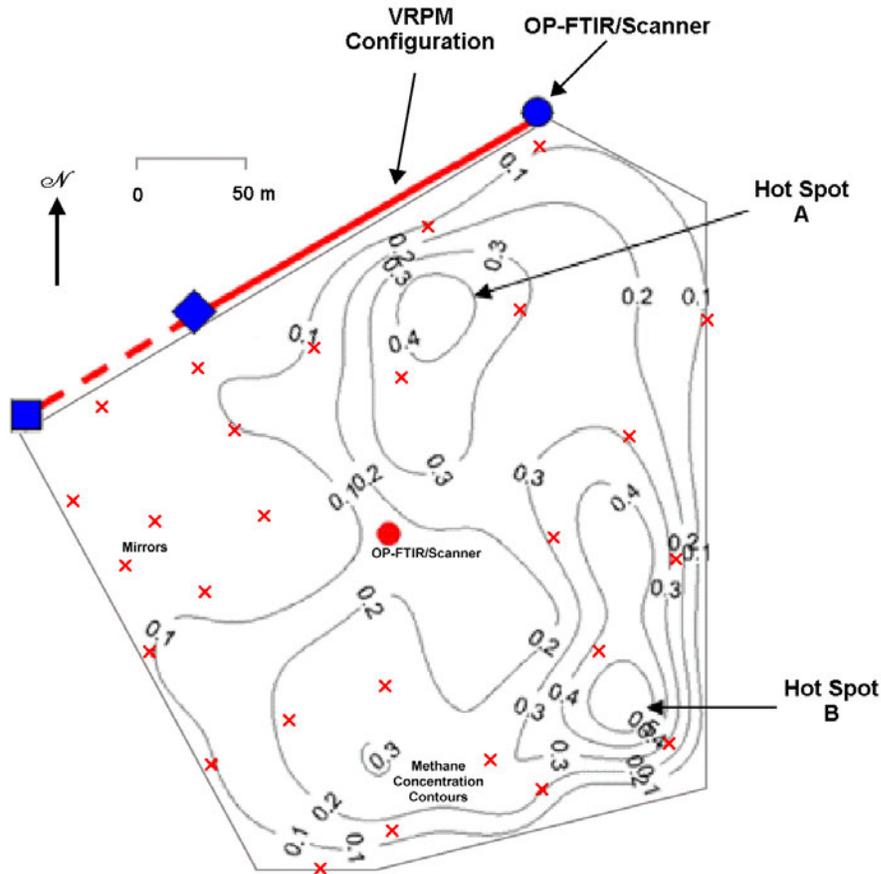


Figure 3-1. Average Surface Methane Concentration Contour Map of the Colorado Springs Landfill.

HRPM surveys, and the red dot shows the location of the OP-FTIR/scanner used in the HRPM surveys. The location of the VRPM survey is also shown in the figure. The blue dot indicates the location of the OP-FTIR/scanner used in the VRPM survey. The figure shows the presence of a hot spot in the North-east quadrant (denoted as hot spot “A” in Figure 3-1, with concentrations greater than 0.4 ppm above ambient background), and the Southeast quadrant (denoted as hot spot “B” in Figure 3-1, with concentrations greater than 0.5 ppm above ambient background).

3.2 The Vertical RPM Results

As mentioned previously, the VRPM configuration was located along the northern boundary of the site. Table 3-1 presents methane emission flux determinations from the downwind VRPM survey. Figure 3-2 presents the reconstructed methane plume from the VRPM survey of the site. Contour lines give methane concentrations (in ppm) above an ambient background concentration of 1.55 ppm. The average calculated methane flux from the site was 4.9 g/s. Even though the observed wind direction was nearly perpendicular to the VRPM configuration, this value may be an underestimation of the actual emission rate from the site.

Table 3-1. Moving Average of Calculated Methane Flux, CCF, Wind Speed, and Wind Direction from the VRPM Survey.

Cycles	CCF	Flux, g/s	Wind	
			Speed, m/s	Direction ^a , deg
1 to 4	0.959	5.7	4.9	15
2 to 5	0.960	5.8	4.9	14
3 to 6	0.930	5.3	4.7	17
4 to 7	0.932	4.3	4.9	17
5 to 8	0.930	4.3	4.8	20
6 to 9	0.914	3.9	5.0	19
7 to 10	0.893	5.0	4.9	14
8 to 11	0.934	6.1	4.5	12
9 to 12	0.926	5.4	4.4	5

Mean	0.931
Std. Dev.	0.0206

^a Wind direction is measured from a vector normal to the plane of the measurement configuration.

Figure 3-2 shows that the methane plume detected during the VRPM survey was centered near the location of the OP-FTIR/scanner (crosswind distance between 0 and 100 meters) indicating that most of the emissions originated from the eastern portion of the site. Based on an analysis of the HRPM data presented in Figure 3-1 and wind data collected during the VRPM survey, it is likely that the emissions from hot spot “A” were completely captured by the VRPM configuration. However, a portion of the emissions from hot spot “B” (the most intense hot spot detected during the HRPM survey) were probably not captured by the VRPM configuration. Consequently, the calculated methane flux may be underestimating the actual emission rate from the site by as much as a factor of two.

The methane concentrations measured during the VRPM survey (peak concentrations of greater than 2.25 ppm above ambient background) are higher than the surface methane concentrations measured during the HRPM surveys (peak concentration of greater than 0.5 ppm above ambient background). This is probably due to the fact that the passive vents at the site were sealed during the HRPM surveys, but were not sealed during the VRPM survey.

Figure 3-3 presents a time series of calculated methane fluxes and the observed wind direction (from normal to the configuration). The figure shows that the largest methane flux values occurred when the winds were close to perpendicular to the VRPM configuration.

3.3 VOC and Ammonia Results

All data sets from the HRPM and VRPM surveys were searched for the presence of VOCs and ammonia. The analysis detected the presence of gasoline (primarily octane) during the HRPM survey of the Northeast quadrant. However, this is attributed to emissions from the gasoline generators used in the

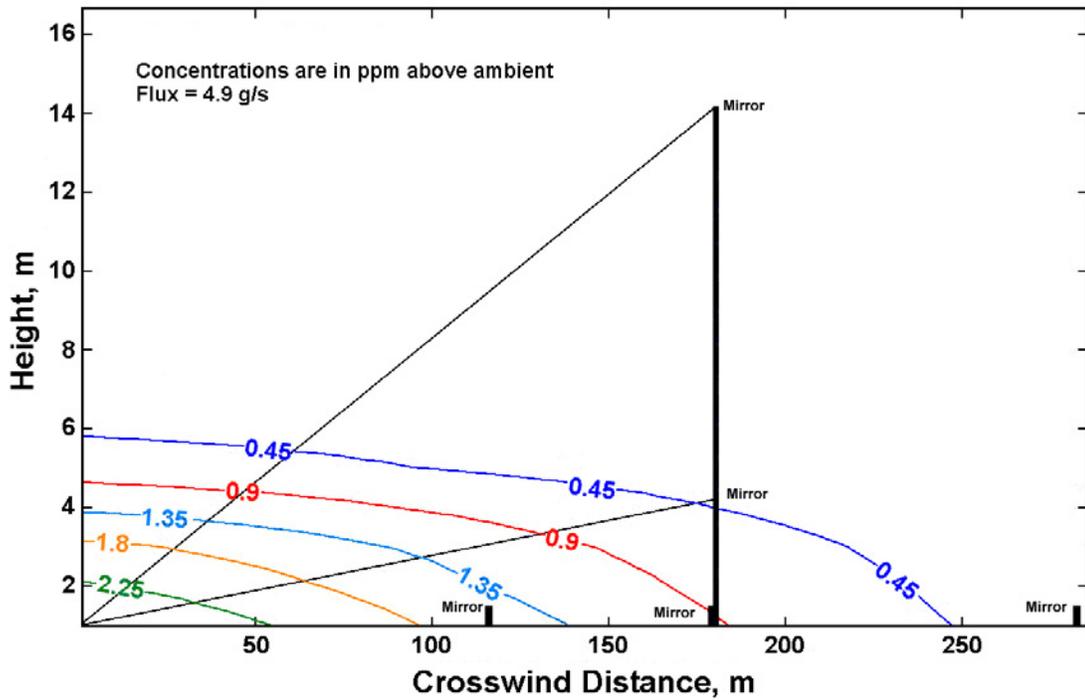


Figure 3-2. Average Reconstructed Methane Plume from the VRPM Survey.

field campaign, which were located upwind of the measurement configuration during the HRPm survey

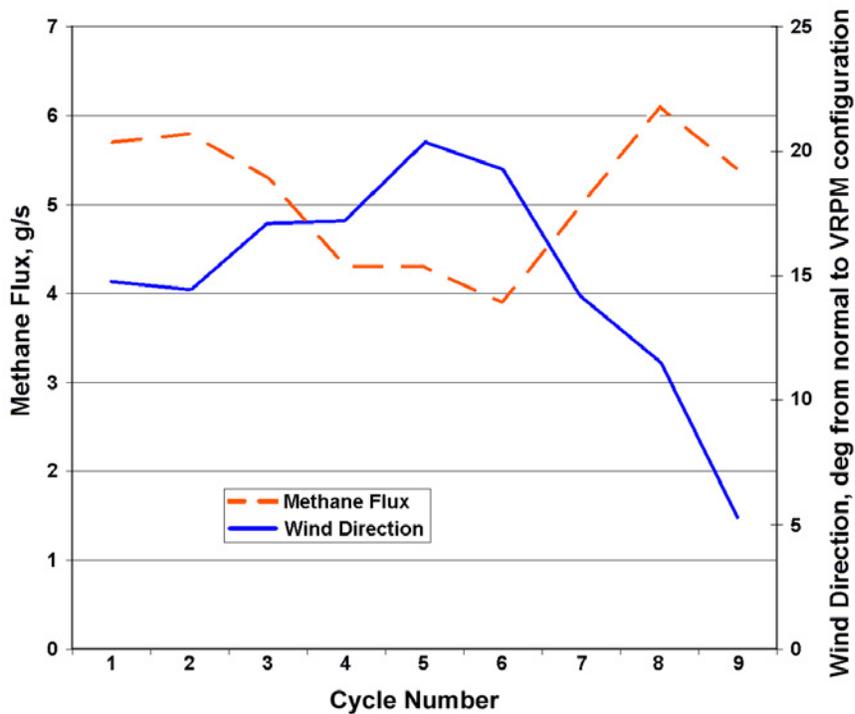


Figure 3-3. Methane Flux and Prevailing Wind Direction Measured During the VRPM Survey.

of the Northeast quadrant. The measured gasoline concentrations ranged from below detection level to 23 ppb.

Analysis of the other data sets did not reveal VOCs or ammonia at levels higher than the minimum detection level (MDL) of the OP-FTIR instruments. Table 3-2 presents the average MDL by compound of the OP-FTIR for this field campaign.

Table 3-2. Minimum Detection Levels by Compound for the OP-FTIR Instrument.

Compound	Average MDL, ppb	Range, ppb
Ammonia	8.4	3.6 to 20
Benzene	140	75 to 280
Ethanol	27	12 to 65
Gasoline	13	6.3 to 37
Methanol	17	7.2 to 41
Toluene	67	32 to 180
m-Xylene	45	22 to 120
o-Xylene	49	25 to 120
p-Xylene	59	28 to 160

3.4 OP-TDLAS Results

The OP-TDLAS system measured methane concentrations along the surface and on the slope adjacent to the southern boundary of the site. Table 3-3 presents the average methane concentrations (in parts per million above an ambient background level of 1.55 ppm) measured at the site by the OP-TDLAS system. Refer to Figures 2-7 and 2-8 for the location of the beam paths used in each survey.

The survey of the surface found average methane concentrations between 0.47 and 0.53 ppm above ambient background levels. The surface methane

concentrations measured with the OP-TDLAS system agree fairly well with the levels found in hot spots identified during the HRPMP surveys.

Table 3-3. Average Methane Concentrations above Ambient Background Levels Measured with the OP-TDLAS System.

Beam Path		Survey of Surface 9/10/03	Survey of Slope 9/11/03
1	Average	0.53	0.74
	Std. Dev.	0.05	0.13
2	Average	0.51	1.07
	Std. Dev.	0.05	0.16
3	Average	0.52	0.78
	Std. Dev.	0.03	0.15
4	Average	0.51	0.55
	Std. Dev.	0.01	0.12
5	Average	0.51	0.89
	Std. Dev.	0.05	0.27
6	Average	0.51	0.55
	Std. Dev.	0.02	0.20
7	Average	0.47	1.34
	Std. Dev.	0.02	0.33
8	Average	0.49	0.47
	Std. Dev.	0.02	0.22

The survey of the slope along the southern boundary of the site found relatively higher methane concentrations. The largest average methane concentrations were detected along beam path #2 (1.07 ppm above ambient background) and beam path #7 (1.34 ppm above ambient background). The relatively larger standard deviations found during the survey of the slope suggest that methane hot spots were present along the slope.

Chapter 4 Conclusion

This report presents the results from a field campaign conducted in September 2003 at a former landfill site in Colorado Springs, Colorado. The study used measurements from ground-based ORS instruments and the ORS-RPM method to characterize fugitive emissions of methane and VOCs from the site.

HRPM surveys of the site detected the presence of two methane hot spots located along the eastern side of 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 HRPM survey of the Northeast quadrant detected the presence of gasoline at concentrations ranging from below detection level to 23 ppb. This was attributed to the field operations based on analysis of the observed wind. The data sets from the HRPM and VRPM surveys were searched for the presence of VOCs and ammonia. Analysis did not detect VOCs or ammonia at levels higher than the minimum detection level (MDL) of the OP-FTIR instruments.

The VRPM configuration was set up along the northern boundary of the site. 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 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. The relatively larger standard deviations found during the slope survey suggest that methane hot spots were present along the slope.

The schedule of the field campaign allowed for only three days of data collection. HRPM data was collected during the first two days of the campaign, and VRPM data was collected during the last day. Due to a change in prevailing wind direction during the last day of the campaign, the VRPM configuration had to be relocated. Consequently, only about one hour worth of VRPM data was collected. For future campaigns, it is recommended that more time be allocated for VRPM data collection to ensure that a larger data set is obtained. This would provide more information on flux variations from the site due to differing weather conditions.

The site contained several passive vents located approximately 2 meters above the surface. These vents were sealed during the HRPM surveys because they were suspected 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. This may not have

been the best approach for characterizing the surface emissions from this site.

method with alternate configurations may be warranted in order to get a more definitive methane flux value, and to address the issues above.

Future monitoring of this site using the ORS-RPM

Chapter 5 Quality Assurance/Quality Control

5.1 Equipment 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 5-1 and further described in the text.

As part of the preparation for this project, a Category III Quality Assurance Project Plan (QAPP) was prepared and approved for each separate field campaign. In addition, standard operating procedures were in place during the field campaign.

5.2 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 5-2. More information on the procedures used to assess DQI goals can be found in Section 10 of the ECPD Optical Remote Sensing Facility Manual (U.S. EPA, 2004).

5.2.1 DQI Check for Analyte PIC Measurement

The precision and accuracy of the analyte path-integrated concentration (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. However, this value may fluctuate

Table 5-1. Instrumentation Calibration Frequency and Description.

Instrument	Measurement	Calibration Date	Calibration Detail
Climatronics Model 101990-G1 Meteorological Heads	Wind speed in miles per hour	22 April 2003	APPCD Metrology Lab cal. records on file
Climatronics Model 101990-G1 Meteorological Heads	Wind direction in degrees from north	22 April 2003	APPCD Metrology Lab cal. records on file
Topcon Model GTS-211D Theodolite	Distance	1 May 2003	Actual distance = 50 ft Measured distance = 50.6 and 50.5 ft
Topcon Model GTS-211D Theodolite	Angle	21 May 2003	Actual angle = 360° Measured angle = 359° 41' 18" and 359° 59' 55"

Table 5-2. DQI Goals for Instrumentation.

Measurement Parameter	Analysis Method	Accuracy	Precision	Detection Limit	Completeness
Analyte PIC	OP-FTIR: nitrous oxide concentrations	$\pm 25\%$, $\pm 15\%$, $\pm 10\%$ ^a	$\pm 10\%$	See Table 1-1	90%
Ambient Wind Speed	Climatronics met heads side-by-side comparison in the field	± 1 m/s	± 1 m/s	N/A	90%
Ambient Wind Direction	Climatronics met heads side-by-side comparison in the field	$\pm 10^\circ$	$\pm 10^\circ$	N/A	90%
Distance Measurement	Topcon Theodolite	± 1 m	± 1 m	0.1 m	100%

^a The accuracy acceptance criterion of $\pm 25\%$ is for pathlengths of less than 50 m, $\pm 15\%$ is for pathlengths between 50 and 100 m, and $\pm 10\%$ is for pathlengths greater than 100 m.

due to seasonal variations in nitrous oxide concentrations or elevation of the site. The elevation of the site surveyed in this field campaign is approximately 6,000 ft above sea level. At this elevation, the optical density of a nitrous oxide concentration of 315 ppb would be equivalent to a lower concentration of nitrous oxide at sea level, due to the decreased air density. To correct the background nitrous oxide level for the effects of elevation, the measured temperature and atmospheric pressure were ratioed to standard temperature and pressure values. The corrected background nitrous oxide concentration for this site is approximately 249 ppb.

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 corrected background concentration of 249 ppb. The number of calculated nitrous oxide concentrations

that failed to meet the DQI accuracy criterion in each data subset was recorded.

Overall, 39 data subsets were analyzed from this field campaign. Based on the DQI criterion set forth for precision of $\pm 10\%$, each of the 39 data subsets were found to be acceptable. The range of calculated relative standard deviations for the data subsets from this field campaign was 0.54 to 6.9 ppbm, which represents 0.22 to 2.8% RSD.

Each data point (calculated nitrous oxide concentration) in the 39 data subsets were analyzed to assess whether or not it met the DQI criterion for accuracy of $\pm 25\%$ (249 ± 62 ppb) for path lengths less than 50 meters, $\pm 15\%$ (249 ± 37 ppb) for path lengths between 50 and 100 meters, and $\pm 10\%$ (249 ± 25 ppb) for path lengths greater than 100 meters. A total of 646 data points were analyzed, and all met the DQI criteria for accuracy. Based on the DQI criterion set forth for accuracy and precision, all data points were found to be acceptable, for a total completeness of 100%.

5.2.2 DQI Checks for Ambient Wind Speed and Wind Direction Measurements

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Facility Manual (U.S. EPA, 2004) states that the DQI goals for precision and accuracy of the Climatronics meteorological heads are assessed by collecting meteorological data for 10 minutes with the two heads set up side-by-side. This was not done prior to the current field campaign because this DQI procedure had not been implemented at the time of the study. However, the Climatronics heads were calibrated in April 2003 by the APPCD Metrology Lab (see Table 5-1). Additionally, checks for agreement of the wind speed and wind direction measured from the two heads (2 m and 10 m) were done in the field during data collection. Although it is true that some variability in the parameters measured at both levels should be expected, this is a good first-step check for assessing the performance of the instruments. Another check is done in the field by comparing the measured wind direction to the forecasted wind direction for that particular day.

5.2.3 DQI Check for Precision and Accuracy of Theodolite Measurements

Although calibration of this instrument did not occur immediately prior to this field campaign, the theodolite was originally calibrated by the manufacturer prior to being received by the U.S. EPA. 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.

Prior to this field campaign, DQI checks were performed on the theodolite during May 2003 at a field site near Chapel Hill, NC. The calibration of distance measurement was done using a tape measure to compare the actual distance to the measured distance. This check was duplicated to test the precision of this measurement. The actual distance measured was 15.2 m. The measured distance during the first test was 15.4 m, and the measured distance during the second test was 15.4 m. The results indicate the accuracy (1.3% bias for test one and two) and precision (0% RSD) of the distance measurement fell well within the DQI goals.

The check to test the precision and accuracy of the angle measurement was done by placing two mirror targets approximately 180 degrees apart. The theodolite was placed in the middle of the imaginary circle formed by the two mirrors. Thus, the actual angle was 360°. The angle measured during the first test was 359° 41' 18", and the angle measured during the second test was 359° 59' 55". The results indicate the accuracy and precision of the angle measurement fall well within the DQI goals.

5.3 QC Checks of OP-FTIR Instrument Performance

Several checks should be performed on the OP-FTIR instrumentation prior to deployment to the field and during the duration of the field campaign. More information on these checks can be found in MOP 6802 and 6807 of the ECPD Optical Remote Sensing Facility Manual. At the time of the current field campaign, the procedures and schedule of QC checks were still being developed. Consequently, QC checks were performed only in the field on the Unisearch OP-FTIR.

On the first day of the field campaign (September 10), the single beam ratio, signal-to-noise, baseline stability, electronic noise, saturation, and random baseline noise tests were performed on the Unisearch OP-FTIR. The results of the tests indicated that the instrument was operating within the acceptable criteria range.

On September 11, the signal-to-noise, and single beam ratio tests were performed on the Unisearch OP-FTIR. The results of these tests indicated that the instrument was operating within the acceptable criteria range.

In addition to the QC checks performed on the OP-FTIR, the quality of the instrument signal (interferogram) was checked constantly during the field campaign. This was done by ensuring that the intensity of the signal is at least 5 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 constantly monitored the data collection computer to make sure these checks were completed.

5.4 Validation of Concentration Data Collected with the OP-FTIR

During the analysis of the OP-FTIR data, a validation procedure was performed to aid in identifying the presence of gasoline in the dataset. This validation procedure involves visually comparing an example of the measured spectra to a laboratory-measured reference spectrum.

Figure 3-4 shows an example of a validation done using a spectrum collected during the HRPM survey of the Northeast quadrant. Gasoline was detected in this particular spectrum. The gasoline features can be seen in the measured field spectrum (green trace). Classical Least Squares (CLS) analysis performed on

this spectrum resulted in determinations of 22.0 ± 6.5 ppb of gasoline. The uncertainty value is equal to three times the standard error in the regression fit of the measured spectrum to a calibrated reference spectrum.

5.5 Internal Audit of Data Input Files

An internal audit was performed by the ARCADIS Field Team Leader on a sample of approximately 10% of the data from the field campaign. The audit investigated the accuracy of the input files used in running the RPM programs. The input files contain analyzed concentration data, mirror path lengths, and wind data. The results of this audit found no problems with the accuracy of the input files created.

5.6 OP-TDLAS Instrument

At the time of the field campaign, the OP-TDLAS system had only recently been acquired by EPA. Consequently, standard operating and calibration procedures were still being developed. Many improvements have been made to the QA procedures for this instrument since this field campaign. Some of these improvements include the development of calibration cells, and the development of a standard operating procedure for collecting emissions measurements with the OP-TDLAS (see MOP 6811 of the ECPD Optical Remote Sensing Facility Manual).

The results of the current field campaign present methane concentrations measured with the OP-FTIR instrument and the OP-TDLAS system. In order to evaluate the comparability of measurements from the two instruments, an experiment was done in January 2004 to compare methane concentrations measured with the OP-TDLAS system and the IMACC OP-FTIR. Figure 3-5 shows the results of this experiment. The results show that methane concentrations measured with the OP-TDLAS were slightly higher (3%) than concentrations measured with the OP-FTIR instrument.

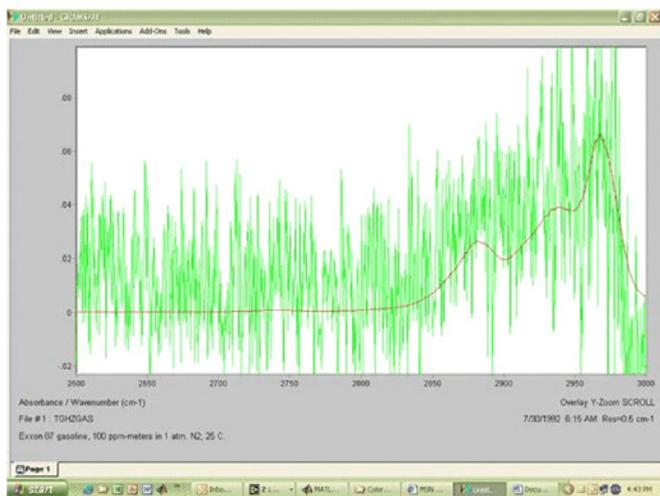


Figure 3-4. Comparison of a spectrum Measured at the Site (green trace) to Reference Spectra of Gasoline (red trace).

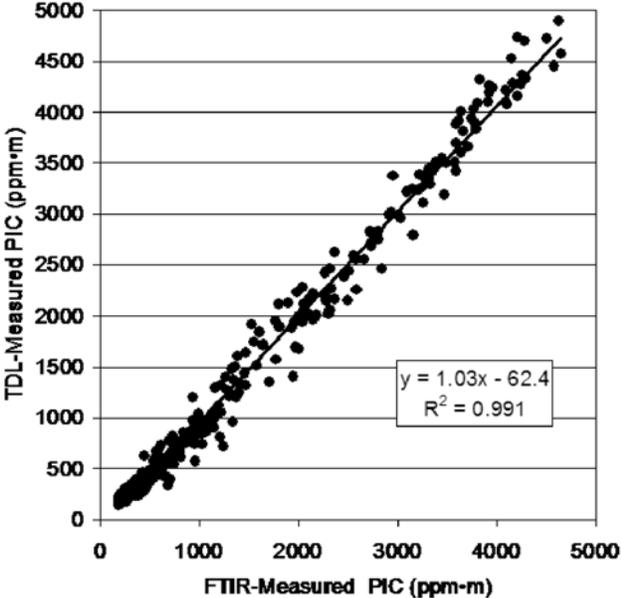


Figure 5-2. Post-Colorado Springs Comparison of Methane Concentrations Measured with the OP-TDLAS and OP-FTIR Instruments.

Chapter 6

List of References

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Appendix A OP-FTIR Mirror Coordinates

Table A-1. Standard Distance and Horizontal Coordinates of Mirrors Used in the HRPM Survey of Northwest Quadrant.

Mirror Number	Standard Distance (m)	Horizontal Angle from North (degrees)
1	120	244
2	87.1	253
3	120	263
4	106	273
5	143	276
6	56.7	279
7	141	293
8	83.3	305
9	114	311

Table A-2. Standard Distance and Horizontal Coordinates of Mirrors Used in the HRPM Survey of Southwest Quadrant.

Mirror Number	Standard Distance (m)	Horizontal Angle from North (degrees)
1	135	149
2	112	156
3	135	180
4	68.9	181
5	155	192
6	95.6	208
7	131	217

Table A-3. Standard Distance and Horizontal Coordinates of Mirrors Used in the HRPM Survey of Northeast Quadrant.

Mirror Number	Standard Distance (m)	Horizontal Angle from North (degrees)
1	115	327
2	90.5	338
3	70.8	5
4	140	7
5	188	21
6	117	30
7	173	56

Table A-4. Standard Distance and Horizontal Coordinates of Mirrors Used in the HRPM Survey of Southeast Quadrant.

Mirror Number	Standard Distance (m)	Horizontal Angle from North (degrees)
1	117	68
2	74.1	92
3	130	95
4	108	119
5	158	127

Table A-5. Standard Distance, and Horizontal and Vertical Coordinates of Mirrors Used in the VRPM Survey of the Northern Border.

Mirror Number	Standard Distance (m)	Horizontal Angle from North (degrees)	Vertical Angle^a (degrees)
1	116	235	0
2	179	233	0
3	282	234	0
4	180	233	2
5	179	233	5

^a Vertical angle shown is the angle from horizontal (positive values indicate elevation from the horizontal, negative values indicate descent from the horizontal).

Appendix B

OP-TDLAS Configuration Path Length Distances

Table B-1. Distance of Path Lengths Used in OP-TDLAS Configurations.

Mirror Number	Surface Survey on 9/10/03 (m)	Slope Adjacent to Southern Boundary Sur- veyed on 9/11/03 (m)
1	205	225
2	134	235
3	238	179
4	314	179
5	141	177
6	281	176
7	149	170
8	307	158

Appendix C Methane Concentrations

Table C-1. Methane Concentrations Found during the HRPM Survey of the Northeast Quadrant.

Cycle	Methane Concentration (ppm)						
	Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5	Mirror 6	Mirror 7
1	1.81	1.78	1.95	1.80	1.73	1.78	1.75
2	1.82	1.78	1.78	1.94	1.95	1.77	1.74
3	1.86	1.76	1.79	1.94	1.92	1.86	1.82
4	1.93	1.82	1.78	2.09	1.89	1.81	1.75
5	1.81	1.72	1.77	1.74	1.81	1.80	1.76
6	1.81	1.86	1.90	2.19	1.90	1.96	1.99
7	1.89	1.97	2.13	1.97	1.79	1.96	1.93
8	1.83	1.77	1.83	1.84	1.80	1.76	1.77
9	1.78	1.82	1.94	1.88	1.81	1.78	1.80
10	1.86	1.83	1.89	1.79	1.73	1.75	1.72
11	1.75	1.75	1.80	1.77	1.73	1.76	1.72
12	1.76	1.78	1.87	1.85	1.77	1.76	1.76
13	1.75	1.81	1.90	1.85	1.79	1.90	1.86
14	1.82	1.91	1.96	1.98	1.94	1.93	1.81
15	1.88	1.88	1.88	2.02	1.85	1.84	1.75
16	1.90	1.90	1.85	1.93	1.78	1.76	1.75
17	1.74	1.74	1.84	1.79	1.84	1.78	1.75
18	1.98	1.78	1.80	1.92	1.84	1.84	1.76

Table C-2. Methane Concentrations Found during the HRP Survey of the Northwest Quadrant.

Cycle	Methane Concentration (ppm)								
	Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5	Mirror 6	Mirror 7	Mirror 8	Mirror 9
1	1.63	1.65	1.60	1.62	1.60	1.66	1.61	1.60	1.57
2	1.61	1.65	1.59	1.61	1.59	1.64	1.60	1.60	1.59
3	1.64	1.64	1.59	1.62	1.60	1.66	1.60	1.62	1.59
4	1.61	1.65	1.61	1.61	1.58	1.64	1.59	1.60	1.58
5	1.64	1.65	1.59	1.60	1.59	1.63	1.60	1.60	1.55
6	1.61	1.63	1.60	1.59	1.60	1.65	1.61	1.60	1.58
7	1.63	1.64	1.60	1.61	1.58	1.63	1.60	1.60	1.60
8	1.60	1.63	1.58	1.58	1.58	1.65	1.59	1.62	1.60
9	1.63	1.66	1.61	1.61	1.58	1.65	1.63	1.63	1.60
10	1.62	1.67	1.62	1.60	1.62	1.67	1.63	1.63	1.61
11	1.63	1.66	1.62	1.61	1.61	1.66	1.63	1.63	1.61
12	1.64	1.67	1.63	1.64	1.62	1.68	1.64	1.64	1.61
13	1.64	1.67	1.63	1.64	1.63	1.69	1.65	1.66	1.62
14	1.65	1.66	1.62	1.63	1.63	1.66	1.61	1.64	1.62
15	1.66	1.67	1.63	1.66	1.62	1.67	1.62	1.63	1.61

Former Landfill in Colorado Springs, Colorado

Table C-3. Methane Concentrations Found during the HRP Survey of the Southeast Quadrant.

Cycle	Methane Concentration (ppm)				
	Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5
1	1.84	1.83	2.08	1.87	1.76
2	1.75	1.90	1.83	1.76	1.83
3	1.84	1.78	1.97	1.75	1.86
4	1.81	1.89	1.76	1.81	1.73
5	1.91	2.18	2.10	1.75	1.98
6	1.80	1.81	2.11	1.84	1.80
7	1.78	1.85	1.86	1.79	1.77
8	1.88	1.92	2.20	1.86	1.76
9	1.84	1.81	1.84	1.72	1.89
10	1.85	1.92	1.79	1.76	1.85
11	1.84	1.90	1.77	1.76	1.86
12	1.84	1.87	1.97	1.77	1.80
13	1.88	1.97	1.88	1.78	1.75
14	1.88	2.21	1.99	1.78	1.75
15	1.74	1.83	2.03	1.73	1.81
16	1.73	1.93	1.79	1.84	1.94
17	1.82	1.94	1.96	1.84	1.98
18	1.94	1.94	2.04	1.94	1.96
19	1.78	2.00	1.89	1.89	1.95
20	1.98	1.85	1.90	1.86	1.91
21	1.84	1.93	1.83	1.88	1.96
22	1.87	1.86	1.88	1.80	2.01
23	1.76	1.92	2.02	1.79	1.87
24	1.85	1.93	2.13	1.91	1.83
25	1.79	1.92	2.24	1.82	1.77

Table C-4. Methane Concentrations Found during the HRPM Survey of the Southwest Quadrant.

Cycle	Methane Concentration (ppm)						
	Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5	Mirror 6	Mirror 7
1	1.76	1.77	1.74	1.80	1.73	1.74	1.75
2	1.75	1.79	1.76	1.79	1.75	1.77	1.75
3	1.76	1.75	1.75	1.80	1.75	1.77	1.75
4	1.76	1.77	1.76	1.80	1.74	1.75	1.70
5	1.76	1.80	1.74	1.79	1.73	1.76	1.75
6	1.74	1.75	1.75	1.78	1.75	1.79	1.74
7	1.74	1.77	1.74	1.81	1.76	1.79	1.79
8	1.78	1.78	1.75	1.81	1.76	1.78	1.74
9	1.73	1.75	1.73	1.78	1.73	1.75	1.77
10	1.74	1.76	1.74	1.79	1.73	1.77	1.73
11	1.73	1.75	1.75	1.80	1.75	1.76	1.73
12	1.73	1.75	1.73	1.78	1.73	1.76	1.77
13	1.74	1.75	1.74	1.78	1.75	1.79	1.83
14	1.76	1.76	1.73	1.78	1.74	1.78	1.80
15	1.77	1.75	1.72	1.79	1.74	1.78	1.80
16	1.74	1.79	1.73	1.77	1.74	1.77	1.79
17	1.73	1.76	1.73	1.78	1.75	1.76	1.78
18	1.77	1.75	1.71	1.77	1.72	1.75	1.77
19	1.73	1.75	1.71	1.77	1.71	1.75	1.91
20	1.74	1.78	1.71	1.77	1.76	1.77	1.74

Former Landfill in Colorado Springs, Colorado

Table C-5. Methane Concentrations Found during the VRPM Survey.

Cycle	Methane Concentration (ppm)				
	Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5
1	4.03	3.86	3.28	3.06	2.59
2	4.42	3.61	3.17	2.79	2.36
3	3.55	3.68	3.36	2.81	2.42
4	3.69	3.89	3.28	2.97	2.54
5	4.32	4.15	3.58	3.16	2.71
6	3.75	3.49	2.79	2.39	2.34
7	4.73	3.14	2.84	2.72	2.69
8	3.82	3.25	3.12	3.11	2.60
9	3.96	3.74	3.12	2.76	2.41
10	3.77	3.52	2.77	2.79	2.79
11	3.80	3.64	3.21	3.00	2.46
12	3.60	3.41	3.02	2.85	2.23