

# ESTCP Cost and Performance Report

(SI-0214)



## Optical Remote Sensing Method to Determine Strength of Non-point Sources

September 2008



ENVIRONMENTAL SECURITY  
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

# COST & PERFORMANCE REPORT

## ESTCP Project: SI-0214

### TABLE OF CONTENTS

	<b>Page</b>
1.0 EXECUTIVE SUMMARY .....	1
1.1 BACKGROUND .....	1
1.2 OBJECTIVES OF THE DEMONSTRATION.....	2
1.3 REGULATORY DRIVERS .....	2
1.4 DEMONSTRATION RESULTS.....	2
1.5 STAKEHOLDER/END-USER ISSUES .....	2
2.0 TECHNOLOGY DESCRIPTION .....	3
2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION.....	3
2.2 PROCESS DESCRIPTION .....	4
2.2.1 HRPB Methodology for Hot Spot Source Location .....	4
2.2.2 VRPM Methodology—Estimation of Emission Rate.....	6
2.3 PREVIOUS TESTING OF THE TECHNOLOGY .....	7
2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY.....	8
3.0 DEMONSTRATION DESIGN .....	9
3.1 PERFORMANCE OBJECTIVES .....	9
3.2 SELECTION OF TEST SITES/FACILITIES .....	9
3.2.1 Duke Forest.....	9
3.2.2 Marine Corps Base Camp Lejeune .....	10
3.2.3 Marine Corps Air Station Cherry Point .....	10
3.2.4 Tinker Air Force Base.....	10
3.3 TEST FACILITY HISTORY/CHARACTERISTICS .....	11
3.3.1 Duke Forest.....	11
3.3.2 Marine Corps Base Camp Lejeune .....	11
3.3.3 Marine Corps Air Station Cherry Point .....	11
3.3.4 Tinker AFB .....	12
3.4 PHYSICAL SETUP AND OPERATION .....	13
3.4.1 Horizontal Radial Plume Mapping .....	13
3.4.2 Vertical Radial Plume Mapping (VRPM).....	15
3.4.3 1-D Radial Plume Mapping .....	16
3.5 SAMPLING/MONITORING PROCEDURES .....	16
3.6 ANALYTICAL PROCEDURES.....	16
4.0 PERFORMANCE ASSESSMENT .....	17
4.1 PERFORMANCE DATA.....	17
4.1.1 HRPB Validation at Duke Forest.....	17
4.1.2 HRPB Demonstration at MCBCL.....	17
4.1.3 HRPB Demonstration at Tinker AFB .....	18

## TABLE OF CONTENTS (continued)

	<b>Page</b>
4.1.4 VRPM Validation at Duke Forest.....	20
4.1.5 VRPM Demonstration at MCBCL.....	20
4.1.6 1-D RPM Demonstration at MCAS Cherry Point .....	21
4.2 PERFORMANCE CRITERIA .....	23
4.3 DATA ASSESSMENT .....	23
4.3.1 Performance .....	23
4.3.2 Regulatory Standards Attained .....	23
4.3.3 Health and Safety Requirements.....	23
4.4 TECHNOLOGY COMPARISON .....	24
5.0 COST ASSESSMENT .....	25
5.1 COST REPORTING.....	25
5.2 COST ANALYSIS.....	25
5.3 COST COMPARISON .....	25
5.3.1 Comparison to Point Monitoring and Inverse Dispersion Modeling.....	25
5.3.2 Comparison to DIAL .....	28
6.0 IMPLEMENTATION ISSUES .....	29
6.1 COST OBSERVATIONS.....	29
6.2 PERFORMANCE OBSERVATIONS.....	29
6.3 SCALE-UP .....	29
6.4 OTHER SIGNIFICANT OBSERVATIONS.....	29
6.5 LESSONS LEARNED.....	30
6.6 END-USER ISSUES .....	30
6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE.....	30
7.0 REFERENCES .....	31
APPENDIX A      POINTS OF CONTACT.....	A-1

## LIST OF FIGURES

	<b>Page</b>
Figure 1.	Overhead view of an example HRPM setup..... 5
Figure 2.	Example of a VRPM configuration setup..... 7
Figure 3.	Experimental setup for HRPM validation experiment..... 14
Figure 4.	VRPM measurement configuration at Duke Forest..... 15
Figure 5.	HRPM and VRPM configurations at MCBCL inactive landfill..... 18
Figure 6.	Composite HRPM results at the Old Landfill in MCBCL..... 19
Figure 7.	HRPM scanning configuration and result at Tinker AFB. .... 19
Figure 8.	VRPM vertical plume maps of methane plumes at the MCBCL inactive landfill..... 21
Figure 9.	1-D RPM at MCAS Cherry Point. .... 22

## LIST OF TABLES

	<b>Page</b>
Table 1.	Estimated minimum detection limit of OP-FTIR for selected compounds. .... 3
Table 2.	Flux measurement and hotspot location performance criteria. .... 9
Table 3.	List of sites at which HRPM was deployed. .... 14
Table 4.	List of sites at which VRPM was deployed. .... 16
Table 5.	Summary of results from Duke Forest HRPM. .... 17
Table 6.	Summary of results from Duke Forest VRPM. .... 20
Table 7.	Peak concentration of detected compounds from the MCAS Cherry Point survey. .... 22
Table 8.	Estimated costs for implementing a 5-day RPM measurement campaign. .... 26
Table 9.	Estimated costs for implementing a 1-week canister/modeling campaign. .... 27
Table 10.	Cost comparison between canisters/modeling and proposed approaches. .... 27

## ACRONYMS AND ABBREVIATIONS

---

AFB	Air Force Base
APPCD	Air Pollution Prevention and Control Division
CAAA	Clean Air Act Amendment
CAFO	concentrated animal feed operations
CAM	compliance assurance monitoring
DIAL	Differential Absorption LIDAR
DoD	Department of Defense
DOE	Department of Energy
ESTCP	Environmental Security Technology Certification Program
FFA	Federal Facilities Agreement
FID	flame ionization detector
GC	gas chromatograph
GWTP	Groundwater Treatment Plant
HAP	hazardous air pollutant
HRPM	horizontal radial plume mapping
IRP	Installation Restoration Program
IWTP	Industrial Wastewater Treatment Plant
MCAS	Marine Corps Air Station
MCBCL	Marine Corps Base Camp Lejeune
MDL	minimum detection limit
NADEP	Naval Air Depot
NNLS	non-negative least squares
NPL	National Priority List
NPS	non-point source
NRMRL	National Risk Management Research Laboratory
OC-ALC	Oklahoma City Air Logistics Center
1-D	one-dimensional
OP-FTIR	Open Path Fourier Transform Infrared
ORS	optical remote sensing
OTM	Other Test Method
OTM-10	Other Test Method-10
OU	Operable Unit

## ACRONYMS AND ABBREVIATIONS (continued)

---

PDC	path-determining component
PIC	path-integrated concentration
PID	photoionization detector
PI-ORS	path-integrated optical remote sensing
PM	particulate matter
QA	quality-assured
QC	quality control
RI/FS	Remedial Investigation/Feasibility Study
RPM	radial plume mapping
RTP	Research Triangle Park
SBFM	smooth basis function minimization
SRI	Southern Research Institute
TDL	tunable diode laser
2-D	two-dimensional
USEPA	U.S. Environmental Protection Agency
VOC	volatile organic compound
VRPM	vertical radial plume mapping
WWTP	Wastewater Treatment Plant

## ACKNOWLEDGEMENTS

We would like to thank the Environmental Security Technology Certification Program (ESTCP) for the financial assistance that enabled us to undertake this project. Appreciation for technical assistance is extended to Dr. Jeffrey Marqusee, ESTCP Director, and Drs. Robert Holst and John Hall, Sustainable Infrastructure Program Managers, former and present, and to the HydroGeoLogic, Inc., staff for their administrative assistance. We would also like to thank Dr. Patrick Sullivan of the Air Force Research Laboratory for overseeing this project and Robin Segall of USEPA Office of Air Quality Planning and Standards for supporting the publication of USEPA Other Test Method-10.

*Technical material contained in this report has been approved for public release.*

*This page left blank intentionally.*

## 1.0 EXECUTIVE SUMMARY

### 1.1 BACKGROUND

Due to the spatial extent and nonhomogenous nature of area sources, quantification of the total pollutant emission using traditional point sampling and dispersion modeling techniques can be problematic. Ground-based optical remote sensing (ORS) techniques provide several measurement advantages over point sampling methods with regard to assessment of inhomogeneous, extended area sources. The ORS radial plume mapping (RPM) methods that were tested and demonstrated under U.S. Environmental Protection Agency (USEPA) oversight were developed to meet the requirements of both USEPA and the Department of Defense (DoD) for an accurate and reliable method to characterize aerosol and gaseous non-point sources (NPS) to be used for current and future needs of an evolving regulatory environment. Area-source measurements have significant challenges because they must deal with extended measurement sizes and spatial inhomogeneities, making characterization with fixed point monitoring or single path ORS (coupled with inverse dispersion modeling) difficult (Bath et al., 1989; Börjesson and Svensson, 2000; Spokas et al., 2003; National Research Council, 2003). A direct and accurate ORS measurement approach, the Differential Absorption LIDAR (DIAL), has been utilized in Europe; however, the high cost of importing the technology to North America has hampered adoption of the technology in the United States (Walmsley and O'Connor, 1996; Gronland et al., 2005; Chambers et al., 2008). Because of these difficulties, there has been no accepted USEPA method for characterizing the emissions from area sources. USEPA endorsed the present ESTCP project to demonstrate RPM methods because of their promise to fill the void and become an USEPA accepted method for area sources. The ESTCP demonstration for RPM was successful, as evidenced by USEPA's published Other Test Method (OTM), *Optical Remote Sensing for Emission Characterization from Non-point Sources*, as a protocol for area-source emission measurements (USEPA, 2006).

The RPM method uses an open-path, path-integrated ORS (PI-ORS) system in multiple beam configurations to directly identify emission "hot spots" and measure emission fluxes. Surface fugitive emissions hot spots are located using the horizontal RPM (HRPM) method, which involves scanning the PI-ORS system in a horizontal plane. The downwind emission flux from the area is found by using the vertical RPM (VRPM) method. The VRPM method involves scanning in a vertical plane downwind of the area source and collecting wind data concurrently with the PI-ORS data. The downwind emission flux data can be used to determine a measurement-based emission rate from the source area. Used together, these tools provide for enhanced area-source assessment capability (Hashmonay et al., 1999; Hashmonay and Yost, 1999; Hashmonay et al., 2001; Thoma et al., 2005; Shores et al., 2005; Hashmonay et al., 2007; Hashmonay, 2008) and can be applied to measure gas emissions from sources such as gas leakage from underground dumps, leaking storage areas, as well as low-level above ground emission sources. Under ESTCP sponsorship, the RPM method has been well evaluated, demonstrated, and peer reviewed.

## **1.2 OBJECTIVES OF THE DEMONSTRATION**

The objective of the project was to utilize the RPM procedures for measuring emissions from area sources and demonstrate that the methods exhibit sufficient precision and accuracy to qualify as an USEPA-approved and prescribed method. Since there are no other methods for measuring area-source emissions, this objective was critical to both USEPA and DoD.

## **1.3 REGULATORY DRIVERS**

With enactment of the Clean Air Act Amendments (CAAA) 11 years ago, Congress directed USEPA to improve air emissions monitoring from all sources, including those located at federal facilities. Acting on that directive, USEPA now requires emission quantifications and improved monitoring from units subject to the air operating permits brought about by Title V of the CAAA. Many units previously grandfathered from regulations and the corresponding monitoring requirements are now required to have ongoing emissions monitoring and testing. Another monitoring component brought about by Title V is the compliance assurance monitoring (CAM) rule which focuses on large units with active control devices used to reduce particulate matter (PM) and volatile organic compound (VOC) emissions. Under the CAM rule, owners and operators (e.g., military bases and posts) obtain direct emissions data or parametric data to ensure that the active control device operation remains consistent with the operation recorded during a previous emissions test that demonstrated compliance with the emissions limits. Units not subject to Title V need to have data that continue to show emissions are below applicability thresholds. From a practical perspective, these units need monitoring data equivalent to that found in Title V permits in order to make such demonstrations.

## **1.4 DEMONSTRATION RESULTS**

The tests performed for this ESTCP demonstration were closely monitored by USEPA with a particular interest in the validation of the results. The validations successfully met USEPA's quality objectives for both HRPm and VRPM. For the HRPm validation, metered quantities of tracer gases (nitrous oxide, ethylene, acetylene, propylene, and propane) were released in a controlled manner, and the locations of the releases were recorded. By scanning the PI-ORS instrument in a radial fashion on a horizontal plane close to the ground, the location of the point releases were reconstructed. The distance of the reconstructed "hot spot" location from the actual release location was within 10% of the diagonal of the HRPm grid in all completed runs. For the VRPM validation, the average flux for all runs was within 25% of the actual release rate. These validations and demonstration efforts resulted in the drafting and approval of USEPA Other Test Method-10 (OTM-10) for area source emission monitoring.

## **1.5 STAKEHOLDER/END-USER ISSUES**

This demonstration project has led to the development of USEPA's OTM-10 method for measuring area-source emissions, which now allows the use of this technology by personnel at the field technician level. Because this technology is a stand-alone optical measurement method, there are no barriers to implementation related to integration into the manufacturing environment or for its use at any of the potential DoD sites.

## 2.0 TECHNOLOGY DESCRIPTION

### 2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The emission measurement technology demonstrated in this program uses multiple-beam PI-ORS instrumentation and mathematical optimization techniques to provide spatial information on the target emission plumes. These plume maps, used in conjunction with wind data collected concurrently, allow for the determination of emission fluxes. This method is applicable to any compound that can be measured by a PI-ORS instrument. The University of Washington and ARCADIS developed this technology with the support of the Department of Energy (DOE) and USEPA's Air Pollution Prevention and Control Division (APPCD). Reviewed reports of the algorithm and its application in a prepared environment are printed in a series of peer-reviewed publications (Hashmonay et al., 1999; Hashmonay and Yost, 1999; Hashmonay et al., 2001; Thoma et al., 2005; Shores et al., 2005; Hashmonay et al., 2007; Hashmonay, 2008).

Open Path Fourier Transform Infrared (OP-FTIR) instrumentation was chosen as the PI-ORS method for this study. OP-FTIR technology has been developed and evaluated for the past 20 years (Russwurm and Childers, 1999) by USEPA (compendium method for measurement of pollutant concentrations in ambient air was published in 1999: TO-16) (USEPA, 1999). The OP-FTIR instrument consists of an infrared light beam, modulated by a Michelson interferometer that is transmitted from a single telescope to a retro-reflecting mirror target, which is usually set up at a range of 100 to 500 m. 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. Table 1 presents the estimated minimum detection level of the OP-FTIR instrument for selected compounds that were measured in the current study.

**Table 1. Estimated minimum detection limit of OP-FTIR for selected compounds.**

Compound	Estimated Minimum Detection Limit (ppb)
Methane	10
Acetylene	3
Ethylene	10
Methanol	5
Chlorodifluoromethane	2
Bromotrifluoromethane	3
Dichloromethane	5

PI-ORS measurement technologies have been used for over 25 years in various environmental applications to determine the gas-phase content of plumes from chemical facilities (Kagann and Simpson, 1990); landfills (Modrak et al., 2004); concentrated animal feeding operations (CAFO) (Shores et al., 2005; Thoma et al., 2005); automobile traffic (Kagann et al., 2006); chemical threats and accidents (Kagann et al., 2005); and jet aircraft (Cheng et al., 2008).

The RPM method was derived from the much more labor-intensive ORS-tomographic methods and is an attempt to mimic the DIAL with cost-effective PI-ORS instruments (Hashmonay et al., 1999; Yost and Hashmonay, 2003). The RPM method for area-source applications was

developed in research and development programs funded by USEPA's National Risk Management Research Laboratory (NRMRL) with the goal to develop a reliable method for area-source monitoring of landfills. This goal was realized as a result of the validations achieved in the present ESTCP demonstrations.

Possible applications of the RPM method include wastewater treatment facilities, tank farms, and industrial complexes, as well as landfills. Typical compounds measured from these sources include methane, ammonia, VOCs, and hazardous air pollutants (HAP).

One of the important applications for RPM area-source monitoring is the measurement of landfill gas emissions. Landfill gases of concern include methane, VOCs, and air toxics. Landfill gas emissions are of concern to the environment, as well as human health, due to the explosive potential of the gas, emissions of HAPs and VOCs, emissions of methane that contribute to climate change, and odor nuisance associated with landfill gas. USEPA 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 Purdue University Department of Agronomy has undertaken a study to measure emissions from CAFOs. The study, which is funded by a consent agreement among USEPA, the U.S. Department of Agriculture and the major stakeholders within the industry, is using the new OTM-10 method to provide quality-assured (QA) air emission data from representative swine, egg layer, dairy, and meat-bird (broiler and turkey) farms. The study is currently ongoing, and data has not yet been made available.

## **2.2 PROCESS DESCRIPTION**

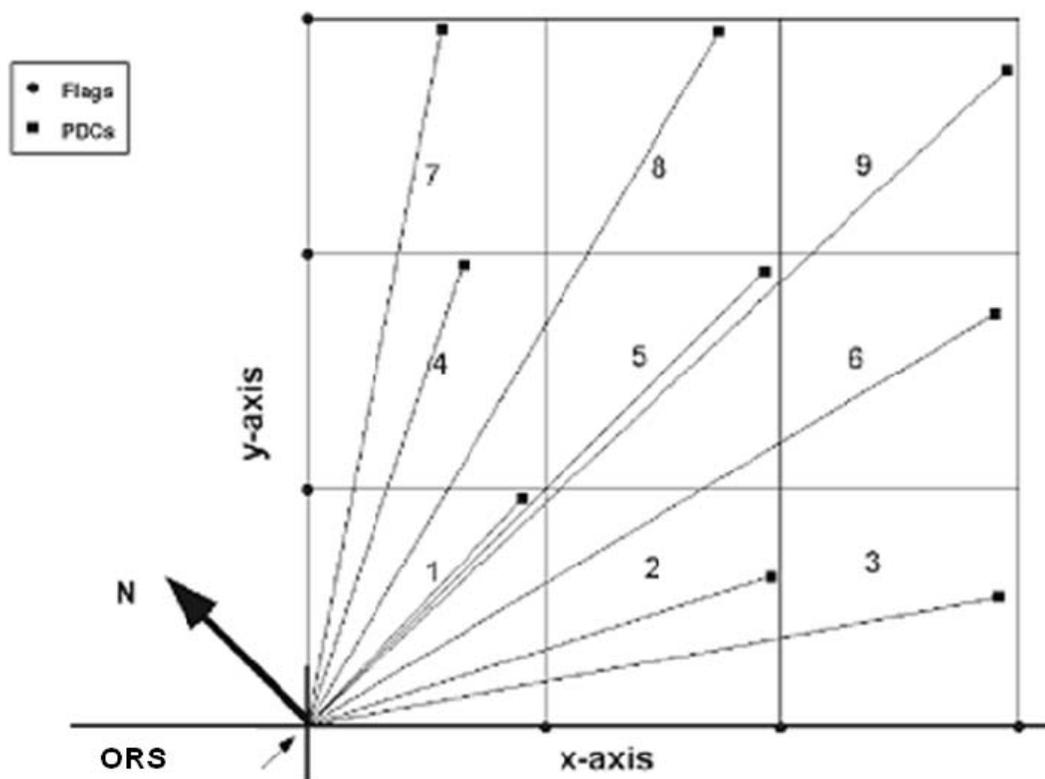
### **2.2.1 HRPM Methodology for Hot Spot Source Location**

The HRPM methodology is used to locate the source of relatively high fugitive emissions, or "hot spots". A rectangular area (which may be a square) is defined around the ground location where the suspected gaseous emissions are originating. Ideally, the HRPM configuration will cover the entire suspected source area; however, this may be prevented by equipment limitations or site conditions. Larger areas may need to be divided into smaller sections and studied separately.

The PI-ORS instrument is typically placed at the origin (in the first quadrant of the Cartesian convention) of the rectangular area to be measured. Once the HRPM measurement area and the number of path-determining components (PDC) have been determined, the area is divided into smaller rectangular areas called pixels. The total number of pixels required is smaller or equal to the total number of beam paths. The methodologies here are not instrument-specific. Any instrument capable of measuring path-integrated concentrations (PIC) of gases or particles can be used as the PI-ORS instrument. For ease of presentation, the PDC is used to denote the component on the other end of the optical path from the PI-ORS instrument. Depending on the instrument selected, this could be a source, detector, mirror, or other reflecting object.

As shown in Figure 1, the survey area is divided into nine pixels (boxes) of equal size. It should be noted that the survey area may be irregular in size, so that the resulting pixel grid is asymmetric (e.g.,  $2 \times 4$  pixels,  $3 \times 5$  pixels, etc.). Each pixel will have at least one optical beam path that terminates within its boundaries at a PDC (a retro-reflecting mirror for most ORS instruments). This geometry maximizes the spread of the optical beams inside the area of emissions by passing one optical beam through the center of each pixel.

It is recommended that a meteorological station is set up as part of the HRPm configuration. Although this data is not required for reconstructing the hot spot source location, wind speed and direction data may be helpful in interpreting the results. Dwelling time per PDC is determined by (1) the specific project goals and (2) the PI-ORS instrument-specific detection limits of the expected target gases. A range of 10 to 60 sec dwelling time per PDC is recommended.



**Figure 1. Overhead view of an example HRPm setup.**  
(dimensions of each pixel box are 40 m by 40 m)

Once the PICs for all beam paths are averaged with the predetermined grouping of cycles for the gas species of interest, the HRPm calculations make use of the information to reconstruct a plume map over the area of interest. Average concentrations for each pixel can be obtained by applying an iterative algebraic deconvolution algorithm described in Hashmonay et al. (2007).

The measured PIC, as a function of the field of concentration, is given by

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

Where

- $K$  = a kernel matrix that incorporates the specific beam geometry with the pixel dimensions
- $k$  = the number index for the beam paths
- $m$  = the number index for the pixels
- $c$  = the average concentration in the  $m^{\text{th}}$  pixel.

Each value in the kernel matrix  $K$  is the length of the  $k^{\text{th}}$  beam within the  $m^{\text{th}}$  pixel; therefore, the matrix is specific to the beam geometry. The HRPM procedure solves for the average concentrations (one for each pixel) by applying the non-negative least squares (NNLS) algorithm (Lawson et al., 1995). The HRPM procedure multiplies the resulting vertical vector of averaged concentration by the matrix  $K$  to yield the end vector of predicted PIC data.

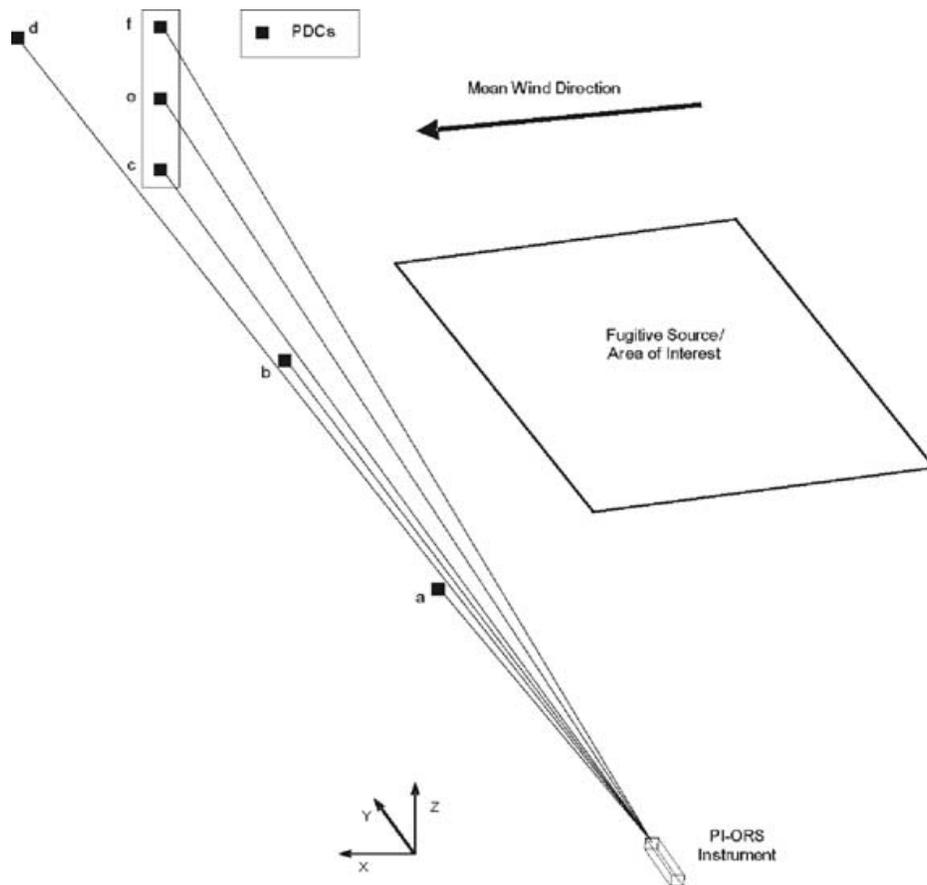
The second stage of the plume reconstruction involves interpolation among the reconstructed pixel's average concentration, providing a peak concentration not limited to the center of the pixels. A triangle-based cubic interpolation procedure (in Cartesian coordinates) is currently used in the HRPM procedure (Barber et al., 1996). The HRPM procedure provides a plume map and calculates the location of the peak concentrations. It is for the user to interpret this information and site constraints, such as obstructions or terrain complexities, for the determination of the actual location of the hot spot.

For the HRPM measurements, an OP-FTIR instrument (IMACC, Inc.) was mounted to a military-grade positional scanner (Orbit, Ltd.) to collect the path-integrated concentration data along multiple beam paths. The position of the OP-FTIR is adjusted by moving the scanner using a joystick control. Once the OP-FTIR beam has been aligned to the desired retro-reflecting mirror, the scanner coordinates are saved to the control module. The scanner control module is capable of storing multiple scanner locations so that the OP-FTIR can later be sequentially scanned to all locations in the configuration.

### 2.2.2 VRPM Methodology—Estimation of Emission Rate

The VRPM methodology is used to estimate the rate of gaseous emissions from an area fugitive source. A complete derivation of the VRPM algorithm can be found in Hashmonay et al. (2007). A vertical scanning plane, downwind of the source, is used to directly measure the gaseous flux. Two different beam configurations of the VRPM methodology are recommended: the five-beam (or more) and the three-beam configurations. Figure 2 illustrates the setup for these two VRPM beam configurations. In the five-beam (or more) configuration, the ORS instrument sequentially scans over five PDCs. Three PDCs are along the ground-level crosswind direction (beams a, b, and c in Figure 2), and the other two are elevated on a vertical structure (beams e and f in Figure 2). The additional beam (d) in Figure 2 is for the six-beam configuration, which provides better spatial definition of the plume in the crosswind direction. In the three-beam configuration, the ORS instrument sequentially scans over three PDCs. Only one beam is along the ground

level (beam c or d in Figure 2) and the other two are elevated on a vertical structure (beams e and f in Figure 2).



**Figure 2. Example of a VRPM configuration setup.**

A two-phase smooth basis function minimization (SBFM) approach is applied where there are three or more beams along the ground level (five-beam, or more, configuration). In the two-phase SBFM approach, a one-dimensional (1-D) SBFM reconstruction procedure is first applied in order to reconstruct the smoothed ground level and crosswind concentration profile. The reconstructed parameters are then substituted into the bivariate Gaussian function when applying a two-dimensional (2-D) SBFM procedure.

The VRPM measurements were collected using the IMACC, Inc. OP-FTIR instrument with the Orbit, Ltd. positional scanner.

### 2.3 PREVIOUS TESTING OF THE TECHNOLOGY

In previous years, two controlled validation studies were performed under USEPA funding (Hashmonay et al., 2001; Modrak et al., 2004). The first study, performed at a regional airport at Oxford, North Carolina, used the downwind vertical scanning plane perpendicular to the wind direction (as illustrated in Figure 2) to measure emission fluxes. The emission flux was successfully determined within 10 to 30% of actual release rates, depending on atmospheric

stability (Hashmonay et al., 2001). In the second study, the RPM measurement technology was tested by USEPA at a community park in Sommersworth, New Hampshire, that was previously a landfill (Measurement of Fugitive Emissions at USEPA Region 1 Landfill, Contract No. 68-C99-201, Work Assignment No. 4-3). A controlled Ethylene release was recovered very accurately (-4% of the known release rate) in very stable atmospheric conditions (Modrak et al., 2004).

## **2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY**

The advantages of the RPM methodology include a lower cost and the ability to determine NPS flux emissions in near real-time. Since the RPM determinations are based solely on measurements and require no plume-model assumptions, they are more accurate than other conventional methods. The fact that there is now an approved USEPA test method based on the RPM method is also an advantage of the technology. The RPM approach avoids inaccuracies introduced by assumptions required for the dispersion modeling. Also, data can be acquired at intervals of minutes instead of hours, giving information on temporal variations of emissions that simply is not available with a canister-based method. Using RPM with this time resolution can provide information on possible short-term events that could result in exposure to dangerous levels of the compound of interest.

When compared to canister sampling, one limitation of the technology may include higher detection limits than canister samples (not always) and a limited number of compounds that can be measured. However, most of the compounds of interest can be measured by PI-ORS instrumentation, and this limitation should not prevent the use of the RPM methodology for any of the anticipated sampling sites. For any analytes of interest that cannot be measured by the PI-ORS instrumentation, a limited number of canister samples may be deployed in conjunction with the RPM method to encompass a wider range of analytes. The overall time and cost savings associated with such an integrated effort will still be significant when compared to conventional point sampling approaches alone.

When compared to the DIAL, a vertical structure needs to be deployed for the PDCs. Therefore, the VRPM is less mobile than the DIAL, and vertical capture of the plume may be limited to the height of the structure. However, when long-term emission study is merited, the VRPM configuration may be installed at the site at appropriate elevation (USEPA, 2007) using onsite vertical structures (such as the water tower used in the elemental mercury study). This unattended and long-term application of the VRPM configuration is very cost effective (compared to the DIAL) and may provide information on seasonal effects and operational activity effects on site total emissions.

### 3.0 DEMONSTRATION DESIGN

#### 3.1 PERFORMANCE OBJECTIVES

The objectives of the project are summarized in Table 2. Detailed cost accounting was used to accurately quantify the end-user costs of implementing the technology. Complete technical success was considered to be tracer gas mass balances of  $100 \pm 10\%$  and within  $\pm 10\%$  of the area diagonal distance for the displacement of the artificial hot spot.

**Table 2. Flux measurement and hotspot location performance criteria.**

Type of Performance Objective	Primary Performance Criteria ( <i>examples</i> )	Expected Performance (Metric) ( <i>examples</i> )
Quantitative	<ol style="list-style-type: none"><li>1. Accurately measure tracer gases in stable atmospheric conditions</li><li>2. Accurately measure tracer gases in unstable atmospheric conditions</li><li>3. Displacement of an artificial hot spot relative to the area diagonal distance</li></ol>	<p>+/- 10%</p> <p>+/- 25%</p> <p>+/- 10%</p>
Qualitative	<ol style="list-style-type: none"><li>1. Reduced Cost</li><li>2. Increased data quality, convenience, and reliability</li><li>3. Real-time mapping and quantification of emissions (methane, ammonia, benzene, etc.)</li></ol>	<p>Achievable</p> <p>Achievable</p> <p>Results obtained within 1 hr of scanning</p>

The direct involvement of the regulatory community (in particular USEPA in providing an approved method) has ensured that the RPM methodology is considered an improvement over emission factor methods for source strength determinations.

#### 3.2 SELECTION OF TEST SITES/FACILITIES

The long-term project consisted of a validation study and three demonstration measurement campaigns — the former conducted at the Duke Forest Facility and the latter conducted at three military facilities (Marine Corps Base Camp Lejeune [MCBCL], Marine Corps Air Station [MCAS] Cherry Point, and Tinker Air Force Base [AFB]). The following sections provide details of the selection of the study sites.

##### 3.2.1 Duke Forest

For the validation portion of the long-term project, the Duke Forest facility of Duke University School of Environment, in Chapel Hill, North Carolina, was selected due to its convenience to both USEPA's Research Triangle Park (RTP) laboratories and to the ARCADIS Durham, North Carolina (ARCADIS-Durham), office. This location allowed USEPA to closely monitor the validation measurements. Other benefits to this location were that it contained on-site power, a sampling trailer, storage facilities, and a relatively flat and open terrain. Measurements of controlled releases of tracer gases were conducted using the RPM methodology. An open field was all that was required for the validation tests. Based on the past 8 years of meteorological data

from the National Weather Service observation site at the Raleigh-Durham airport, winds during the study were expected to be primarily from the southwest or northeast.

The 150 x 200+ m field was well-suited for addressing the demonstration/validation objectives of the project. The field had gentle terrain features with a uniform cover of fairly tall tufted grass that provided some roughness. Trees directly adjacent to the field were sufficiently short that they did not interfere appreciably with wind patterns within the site. Downwind distances of 200 m were available. In addition, the site had sufficient security to allow maintaining the measurement configurations overnight and on weekends if desired by the participants.

### **3.2.2 Marine Corps Base Camp Lejeune**

The MCBCL was chosen as one of the demonstration sites for the long-term project. The base is located in southeastern North Carolina, near the city of Jacksonville.

The main environmental concern at MCBCL is the possible contamination of the Castle Hayne aquifer. The test sites at MCBCL included a closed landfill, the wastewater treatment plant, and a gas station. These were chosen because of their possible impact on the quality of ground water. MCBCL was particularly favorable as a demonstration site due to its location, which is convenient to both USEPA's RTP campus and the ARCADIS-Durham office. The site also has appropriate NPSs to measure that are of interest to regulators.

### **3.2.3 Marine Corps Air Station Cherry Point**

MCAS Cherry Point was another site chosen as one of the demonstration sites for the long-term project. The facility was established in 1941 and is situated on 13,200 acres, about 90 miles west-southwest of Cape Hatteras at the foot of the great Outer Banks.

The Air Station has been entered on USEPA's National Priority List (NPL) due to groundwater contamination. The environmental problems at MCAS Cherry Point stem from past waste disposal and storage practices involving industrial chemicals, waste, and fuels, which resulted in several contaminated groundwater plumes and soil contamination from numerous smaller waste disposal units. The sites at MCAS Cherry Point where the RPM methods were tested include the Industrial Wastewater Treatment Plant (IWTP) and the Naval Air Depot (NADEP) industrial complex. The MCAS Cherry Point site was particularly favorable as a demonstration site due to its location, which is convenient to both USEPA's RTP campus and the ARCADIS-Durham office. The site also has appropriate NPSs to measure that are of interest to regulators.

### **3.2.4 Tinker Air Force Base**

Tinker AFB is located five miles east of downtown Oklahoma City, Oklahoma. The base is a heavily industrialized and urbanized facility comprising 5001 acres. The installation has 760 buildings with a building floor space of over 15.2 million sq ft. Tinker is one of the DoDs premier joint-service facilities.

The RPM tests were conducted in the area of the IWTP, 300 m east-northeast of Building 3001. In addition, a simple single-beam OP-FTIR survey was conducted on a narrow grassy area to the northeast of the Oklahoma City Air Logistics Center (OC-ALC), located on Tinker AFB.

### **3.3 TEST FACILITY HISTORY/CHARACTERISTICS**

#### **3.3.1 Duke Forest**

The Duke Forest site, a facility of the Duke University, has been used in the past to conduct wind flow and other environmental field-research projects, and was the site used by the Southern Research Institute (SRI) to conduct OP-FTIR validation studies in 1992 and 1993. The field tests of the RPM method with controlled gas releases took place at a 150-m<sup>2</sup> area at the southwest corner of the Blackwood division of Duke Forest.

#### **3.3.2 Marine Corps Base Camp Lejeune**

MCBCL was founded in 1942. World War II had started and military planners were posturing forces for America's eminent entry to the fight. The need for an East Coast amphibious training facility was answered as the War Department purchased an initial 11,000 acre tract of land. With close proximity to ports at Wilmington and Morehead City, Lejeune was a logistical gem. MCBCL has grown into a 246-square mile premier military training facility. Near the end of 1942, the base took on the name of MCBCL, named in honor of the 13th Commandant and Commanding General of the 2nd Army Division in World War I, Maj. Gen. John A. Lejeune.

Today, MCBCL boasts 14 miles of beach capable of supporting amphibious operations. There are 54 live-fire ranges, 89 maneuver areas, 33 gun positions, 25 tactical landing zones and a state-of-the-art Military Operations in Urban Terrain training facility. Military forces from around the world come to MCBCL on a regular basis for bilateral and NATO-sponsored exercises. These include Cooperative Osprey, a Partnership for Peace exercise that involved 13 countries last year. The base is home to an active duty, dependent, retiree, and civilian employee population of nearly 150,000 people. The base generates \$2 billion in commerce each year.

MCBCL treats and distributes its potable water using the Castle Hayne aquifer, which underlies the base and is its sole water supply source. There has been some concern about the possible contamination of this aquifer. A dry-cleaning facility on the base was placed on the USEPA NPL in 1989 after its operations were found to have impacted the quality of the groundwater. More recently, underground storage tanks holding industrial solvents were removed and replaced after they were found to be leaking. Presently, MCBCL has a strong and proactive environmental program and works closely with the state and federal regulators to ensure appropriate actions are taken to preserve public health and the environment.

#### **3.3.3 Marine Corps Air Station Cherry Point**

MCAS Cherry Point was added to the USEPA NPL on December 16, 1994. The Air Station's inclusion on the NPL was based on groundwater contamination. These environmental problems stem from past waste disposal and storage practices involving industrial chemicals, waste, and

fuels, which resulted in several contaminated groundwater plumes and soil contamination from numerous smaller waste disposal units.

Environmental investigations at MCAS Cherry Point are conducted under the IRP. Currently, 32 IRP sites are being investigated at the station, which is divided into 13 Operable Units. MCAS has taken numerous actions to clean up and control the areas of contamination.

### **3.3.4 Tinker AFB**

Tinker AFB was named in honor of Major General Clarence L. Tinker of Pawhuska, Oklahoma. General Tinker lost his life while leading a flight of LB-30 “Liberators” on a long-range strike against Japanese forces on Wake Island during the early months of World War II.

The present site in Oklahoma City was chosen in 1941 as a major aircraft maintenance and supply depot. During World War II, Tinker’s industrial plant repaired B-24 and B-17 bombers and fitted B-29s for combat. Throughout the Korean conflict, Tinker continued its output — keeping planes flying and funneling supplies to the Far East. The base also played an important role in the Berlin and Cuban crises. During the Vietnam War, Tinker provided logistics and communications support to Air Force units in Southeast Asia. Tinker AFB and OC-ALC began the 1990s providing frontline support to the forces engaged in Operation Desert Shield and Desert Storm. In 1999, Tinker AFB was awarded the largest engine repair contract in the history of the Air Force, valued at \$10.2 billion over 15 years. Today, with nearly 24,000 civilian and military assigned to the base, logistics work is just part of Tinker AFB’s mission. After the arrival of the Navy, Tinker AFB became one of DoD’s premiere inter-servicing facilities.

Tinker AFB’s 5,033 acres include two active runways and 254 acres of ramp space. The OC-ALC encompasses 138 acres of indoor maintenance facilities and 93 acres of covered warehouse space. Historic Building 3001, headquarters of the OC-ALC, covers 62 acres and stretches for 0.7 miles. Within its walls, workers perform a vast array of maintenance on aircraft, engines, components, and accessories and perform a multitude of necessary administrative tasks.

The base is comparable to a city with a population of 30,000, which includes Air Force and Navy active duty personnel, civilian employees, and military retirees.

From 1942 to 1979, industrial waste was disposed on the base. Groundwater contamination was caused by the disposal of solvents, cleaners, heavy metals, low-level radioactive materials, and a variety of oils, fuels, and lubricants used in the operational, maintenance, and repair activities at Tinker AFB. Since 1979, industrial waste has been disposed off-base. USEPA and the Air Force signed a Federal Facilities Agreement (FFA) in 1988. Two on-base operable units were entered in the NPL, Building 3001 and Soldier Creek Units. Remedial Investigation/Feasibility Study (RI/FS) activities were performed at Building 3001 from 1982 to 1986. Additional groundwater contamination was found during the RI/FS for the Soldier Creek Operable Unit. The Groundwater Treatment Plant (GWTP) for the Building 3001 Operable Unit began continuous operation in 1994. Long-term remedial action is ongoing.

## 3.4 PHYSICAL SETUP AND OPERATION

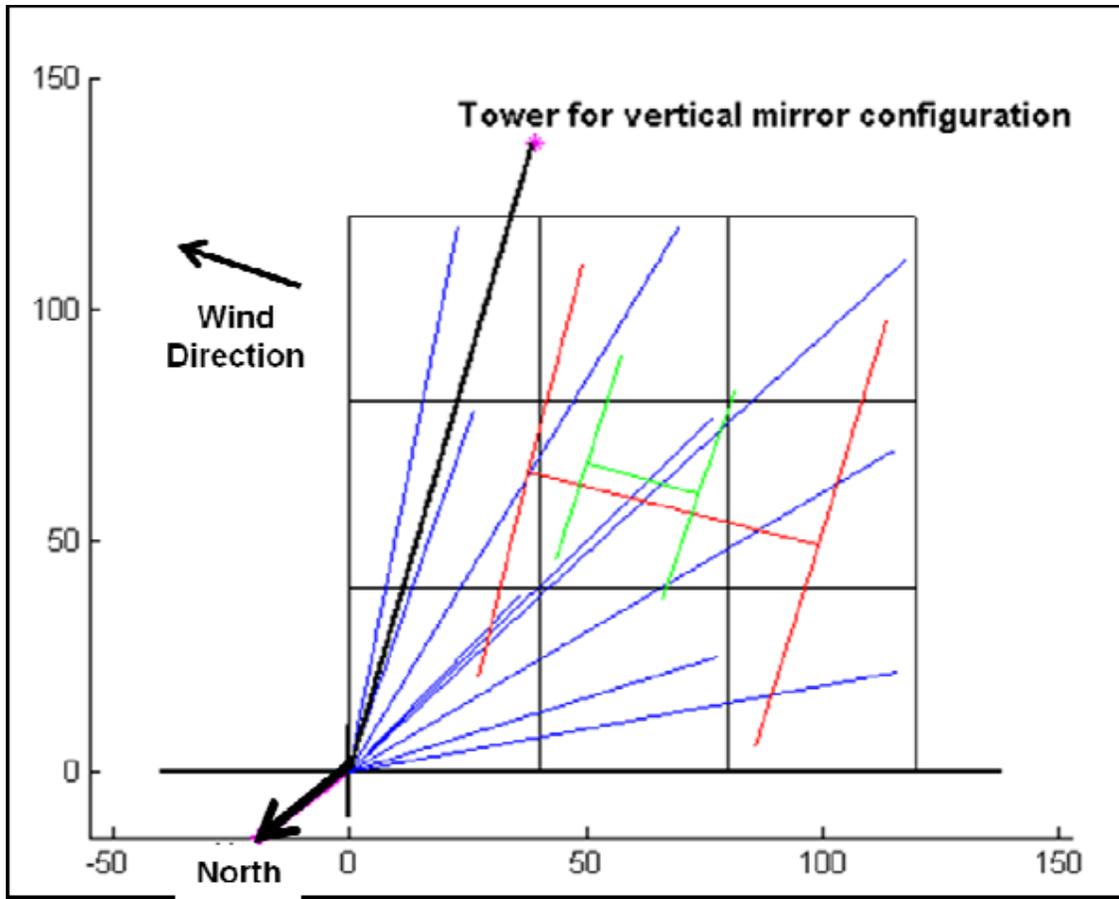
### 3.4.1 Horizontal Radial Plume Mapping

The HRPM configuration was deployed at a total of seven different sites within the four study facilities (including Duke Forest and the three different DoD facilities). To describe the physical setup and operation, we will use the Duke Forest validation as an example. The setup and operation at the other sites — MCBCL, MCAS Cherry Point, and Tinker AFB — were nearly identical to that at Duke Forest. The main difference between the Duke Forest and DoD sites is that at Duke Forest, the HRPM and VRPM methods were tested with ground-truth releases of metered quantities of gases, whereas the HRPM and VRPM methods at the DoD sites were used to perform real-world measurements.

The Duke Forest HRPM configuration setup required two field personnel, each working one 8-hour day. The first half of the day was spent loading and transporting the trailer to the site, then towing the tower (mounted on a trailer) to the site. The afternoon was spent surveying the site and determining the source locations and the placement of the intermediate mirrors on the vertical tower. Because Duke Forest was a secure site, the equipment could be left deployed over a long period of time. The weather conditions (prevailing wind direction and lack of rain) ultimately determined the days that sampling would occur.

Gasoline was used to power two generators — one for the trailer and the OP-FTIR, and a second for the meteorological instrumentation located at the tower. The tower was battery operated, and internal batteries supplied the power for the scales used to weigh the gas cylinders. No major maintenance issues occurred with any of the field-validation studies at the different sites.

The HRPM setup at Duke Forest is shown in Figure 3. The first step in performing the experiment was to divide the horizontal test area into nine cells of equal size. One retro-reflecting mirror was placed in each cell and was located so that the beam would pass through the center of the cell. After the nine mirrors were in place in their respective cells, a theodolite was used to measure the radial coordinates (radial distance, azimuth angle) for each mirror relative to the PI-ORS sensor. These coordinates are used to determine a kernel matrix containing information about beam length in each pixel, which is input to the HRPM algorithm for locating the hot spot sources. The OP-FTIR instrument was placed on a scanner at the origin of the study area (0,0). Soaker hoses were then deployed in an “H” pattern within the study area to release the tracer gases, simulating an area source. Data was collected during the releases, and HRPM surface plume maps were generated. The hot spot location determined by the HRPM plume maps was then compared to the actual location of the tracer gas releases. The blue lines in Figure 3 show the location of the optical beams used for the HRPM study. The red and green lines show the location of the tracer releases from two simulated area sources.



**Figure 3. Experimental setup for HRPM validation experiment.**  
Distances are shown in meters.

The HRPM method was also demonstrated by “real-world” measurements that were performed at five different sites within MCBCL and one site at Tinker AFB. Table 3 presents a summary of the sites where the HRPM method was deployed during the long-term study.

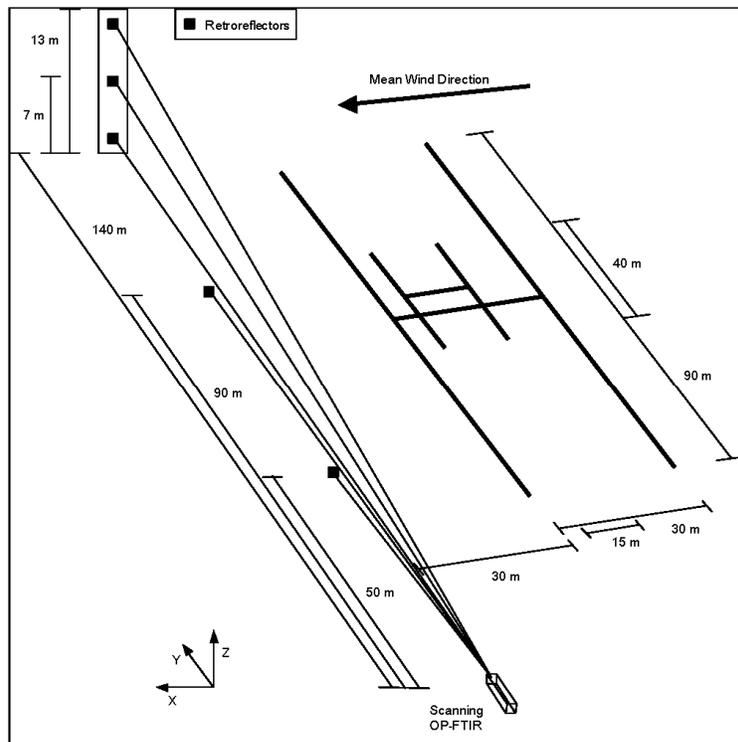
**Table 3. List of sites at which HRPM was deployed.**

Facility	Site	HRPM Cells
Duke Forest	Test field	3 × 3
MCBCL	Closed landfill – North Quad	3 × 3
	Closed landfill – East Quad	3 × 3
	Closed landfill – South Quad	3 × 3
	Closed landfill – West Quad	4 × 4
	Active landfill	3 × 3
Tinker AFB	IWTP*	Modified 3 × 4

\*Industrial Wastewater Treatment Plant

### 3.4.2 Vertical Radial Plume Mapping (VRPM)

The VRPM method was deployed when favorable wind conditions were observed (e.g., during conditions that the VRPM configuration was deployed downwind of the study area). In order to execute the VRPM validation study at Duke Forest, a 40-foot vertical structure was deployed, and the flux through the vertical plane was computed for controlled tracer gases released in small and large area source configurations (see Figure 3). Five mirrors were deployed along a horizontal line, with two of the mirrors at elevated positions on the tower. The resulting five beam paths completed a vertical plane 140 m wide by 13 m high (as illustrated in Figure 4), which was generally perpendicular to the wind direction. The results of the VRPM measurements are integrated to yield an area mass concentration, with units expressed in grams per meter, which is multiplied by the normal wind vector to yield a determination of the emission flux through the measured plane, with units expressed in grams per second. The tracer gases were released from two soaker-hose configurations deployed in an “H” pattern (shown as the solid black lines in Figure 4). The data collected from the PI-ORS instrument was then used with the VRPM software to yield a downwind plume map and flux determination. The flux rates determined with the VRPM method were then compared to the actual tracer gas release rates.



**Figure 4. VRPM measurement configuration at Duke Forest.**  
Distances are shown in meters.

The VRPM method was also demonstrated at three different sites within MCBCL and one site at Tinker AFB, as detailed in Table 4.

**Table 4. List of sites at which VRPM was deployed.**

<b>Facility</b>	<b>Site</b>	<b>Number of Paths</b>
Duke Forest	Test field	5
MCBCL	Closed landfill	6
	Active landfill – South Border active area	5
	Active landfill – West Border active area	6
	WWTP*	6
	Gas station	3
Tinker AFB	IWTP**	5

\*Wastewater Treatment Plant

\*\*Industrial Wastewater Treatment Plant

### **3.4.3 1-D Radial Plume Mapping**

The 1-D RPM configuration consists of deploying several mirrors along the surface and collecting path-integrated concentration data to develop concentration profiles of the target compounds (USEPA, 2006). Wind data collected concurrently with the ORS data is used to locate the source of the measured compounds within the facility. The 1-D RPM approach can be used to characterize emissions from a large industrial complex over varying periods of time. The 1-D RPM was demonstrated at the NADEP at MCAS Cherry Point.

### **3.5 SAMPLING/MONITORING PROCEDURES**

No sampling or monitoring of the sites took place other than those that were part of the RPM procedures described in Section 3.4.

### **3.6 ANALYTICAL PROCEDURES**

This project did not require analytical procedures, as no samples were collected.

## 4.0 PERFORMANCE ASSESSMENT

### 4.1 PERFORMANCE DATA

Both the HRPB and the VRPB methods were performed at seven sites, resulting in fourteen sets of performance data. The validations at Duke Forest were performed by measuring metered ground-truth releases of gases, whereas the demonstrations at the DoD sites were real-world measurements.

#### 4.1.1 HRPB Validation at Duke Forest

As part of the Duke Forest HRPB validation study, PI-ORS data was collected by dwelling on each retroreflector in the configuration for 10, 30, and 60 seconds (Varma et al., 2005). This was done to investigate the tradeoff between obtaining surface plume maps with better temporal resolution and the accuracy of the method in locating the emissions hot spot. The results of the HRPB validation experiments from the Duke Forest site are shown in Table 5. The table presents results for at least seven different arbitrary tracer release locations for each mirror dwell time. The distance column lists the average distance of the calculated plume location from the actual release (in meters), while the error column indicates the percentage error of this distance with reference to the diagonal distance of the HRPB configuration (170 m).

**Table 5. Summary of results from Duke Forest HRPB.**

Arbitrary Location	10 sec/mirror		30 sec/mirror		60 sec/mirror	
	Distance	Error	Distance	Error	Distance	Error
1	17.1	10.0%	21.1	12.4%	17.5	10.3%
2	8.4	4.9%	6.9	4.0%	15.7	9.3%
3	10.1	5.9%	4.1	2.4%	10.0	5.9%
4	5.4	3.2%	8.6	5.1%	32.7	19.2%
5	21.7	12.8%	5.4	3.2%	17.7	10.4%
6	5.1	3.0%	21.4	12.6%	4.6	2.7%
7	17.5	10.3%	4.9	2.9%	6.7	4.0%
8	7.3	4.3%	8.1	4.8%	N/A	N/A

Overall, the HRPB method performed favorably in locating the actual location of the hot spots generated by the tracer releases. The results of a majority of the release surveys met the expected performance matrix of the displacement of the determined hot spot location from the actual release location to be within 10% of the diagonal distance of the HRPB configuration, as presented in Table 2.

#### 4.1.2 HRPB Demonstration at MCBCL

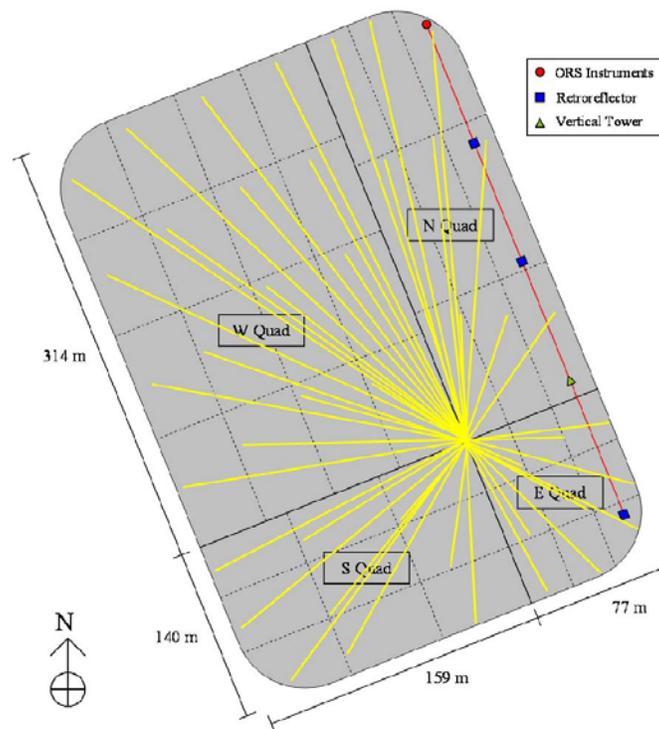
The next phase of the study involved a demonstration of the HRPB method at MCBCL in Jacksonville, North Carolina. The inactive landfill at MCBCL was a large, open rectangular field (approximately 240 m x 455 m), slightly graded downward in the SW direction, with over 30 methane vents within the area of interest. HRPB scanning over the entire area was not desirable partly due to the fact that the diagonal distances would have pushed the limits of the PI-ORS instrumentation used at the time, and also because the available number of mirrors would have resulted in large pixel divisions, yielding poor overall spatial resolution.

As a result, a location was identified from which the HRPm scans could be completed in four separate quadrants. The chosen scanning location was away from the geometric center of the area of interest, due to the asymmetrical inclines of the site, as well as some constraints caused by soft soil. The quadrants were named according to their orientation in reference to the scanning location. The exact boundaries of the quadrants are indicated by the solid black lines in Figure 5. The beam paths of the four HRPm surveys are shown by the solid yellow lines.

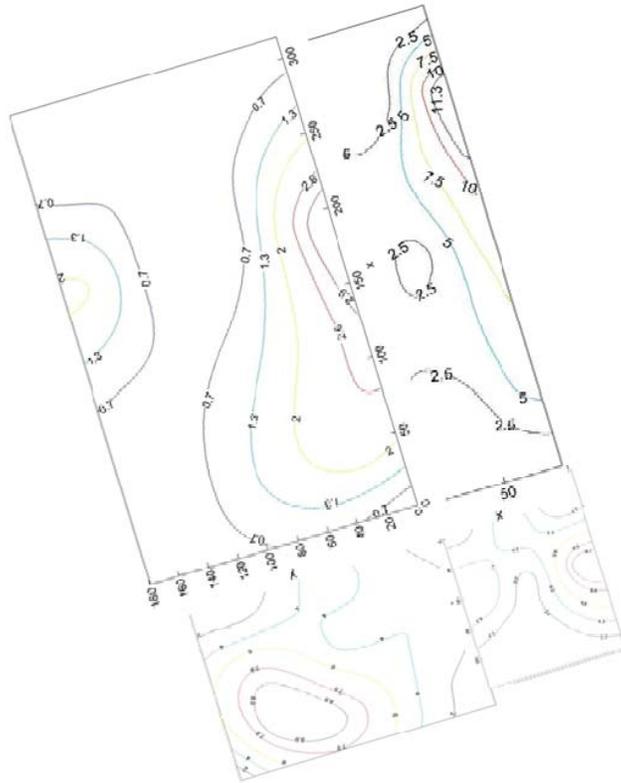
Figure 6 shows composite results of the four quadrants from the HRPm scanning. Three major hot spots were identified of about 10 ppm methane above background. The hot spot at the NE side was the strongest (11.3 ppm contour). The SW quadrant's hotspot was greater than 8.9 ppm in the SW corner, while the SE quadrant's hotspot was greater than 8.7 ppm on the east side. The VRPM configuration downwind from this hotspot primarily quantified the emission rate from this area of the landfill (see below section 4.1.5).

### 4.1.3 HRPm Demonstration at Tinker AFB

The HRPm beam geometry and overlaid plume map that was applied in Tinker AFB is shown in Figure 7. Methane was the target compound since other detected compounds such as dichloromethane were too close to instrument detection limits. The results of the survey found that surface methane emissions from the site were low, with one hot spot detected in the NW corner of the site with concentrations greater than 0.09 ppm above background levels, and another hot spot detected in the southern portion of the site with methane concentrations greater than 0.05 ppm above background levels.



**Figure 5. HRPm and VRPM configurations at MCBCL inactive landfill.**  
Distances are shown in meters.



**Figure 6. Composite HRPM results at the Old Landfill in MCBCL.**  
 Concentrations are shown in ppm above background values, distances in meters.



**Figure 7. HRPM scanning configuration and result at Tinker AFB.**  
 Concentrations are shown in ppm above background values, distances in meters. The wind direction is given by the arrow at the bottom of the figure.

#### 4.1.4 VRPM Validation at Duke Forest

As part of the Duke Forest VRPM validation study, PI-ORS data was collected using a two-dimensional VRPM plane approximately 140 m wide by 13 m high, as shown in Figure 4 (Varma et al., 2005). Tracer gases were released from a large and a small simulated area source. Two separate VRPM configurations were used for the validation. The first configuration consisted of three mirrors, with one mirror deployed at the base of the vertical tower, one deployed at a height in the middle of the tower, and one deployed at the top of the tower. The second configuration consisted of five mirrors, with three mirrors deployed at the tower, and two mirrors deployed along the surface of the plane, between the PI-ORS instrument and the tower. The two configurations were used to show the feasibility of using fewer mirrors in a VRPM measurement configuration when resources are limited. The use of fewer beams will also shorten the total measurement cycle time resulting in better temporal resolution, which may be valuable in cases of a highly variable source. The PI-ORS data was collected by dwelling on each retroreflector in the configuration for 10, 30, and 60 seconds.

The results from the Duke Forest VRPM validation experiments are summarized in Table 6. The actual tracer gas release rate (in g/s) is shown in fourth column from the left. The flux rates measured by the VRPM method are presented in the fifth column.

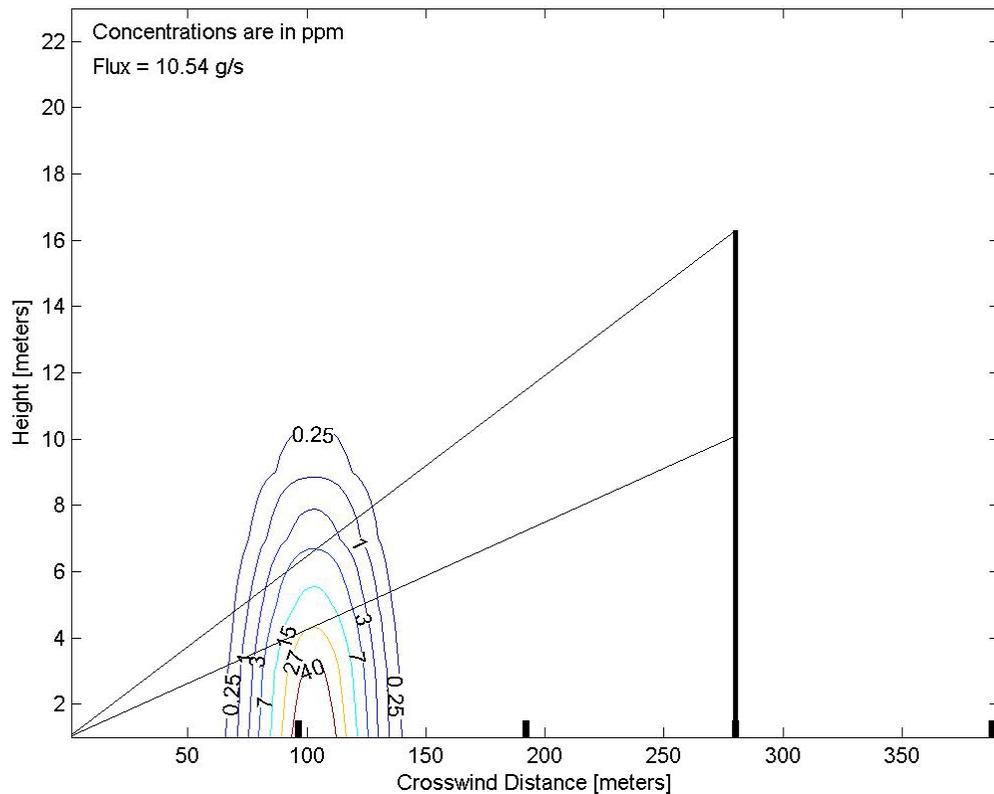
**Table 6. Summary of results from Duke Forest VRPM.**

Date	Number of Beams	Time Resolution [s]	Release Rate [g/s]	Emission Flux Measured [g/s]	Wind Direction from Normal [degrees]	Wind Speed [m/s]
11/25/02	5	60	0.11	0.11	+3	2.2
11/25/02	5	30	0.20	0.23	+7	1.6
12/23/02	5	10	0.21	0.091	+54	1.9
01/29/03	3	60	0.20	0.16	-10	2.2
01/29/03	3	30	0.15	0.13	-5	2.0
01/09/03	3	10	0.15	0.11	+30	3.3
05/06/03	3	10	0.24	0.22	+21	3.2
05/06/03	3	10	0.24	0.23	+21	3.2

The table shows that acceptable results were obtained from the 3- and 5-beam configurations using a dwell time of 10, 30, and 60 seconds per mirror, as the measured flux values were within the expected performance metric of  $\pm 25\%$  of the actual release rates for all of the test with average wind direction between  $-10^\circ$  and  $+30^\circ$  from normal to the VRPM plane.

#### 4.1.5 VRPM Demonstration at MCBCL

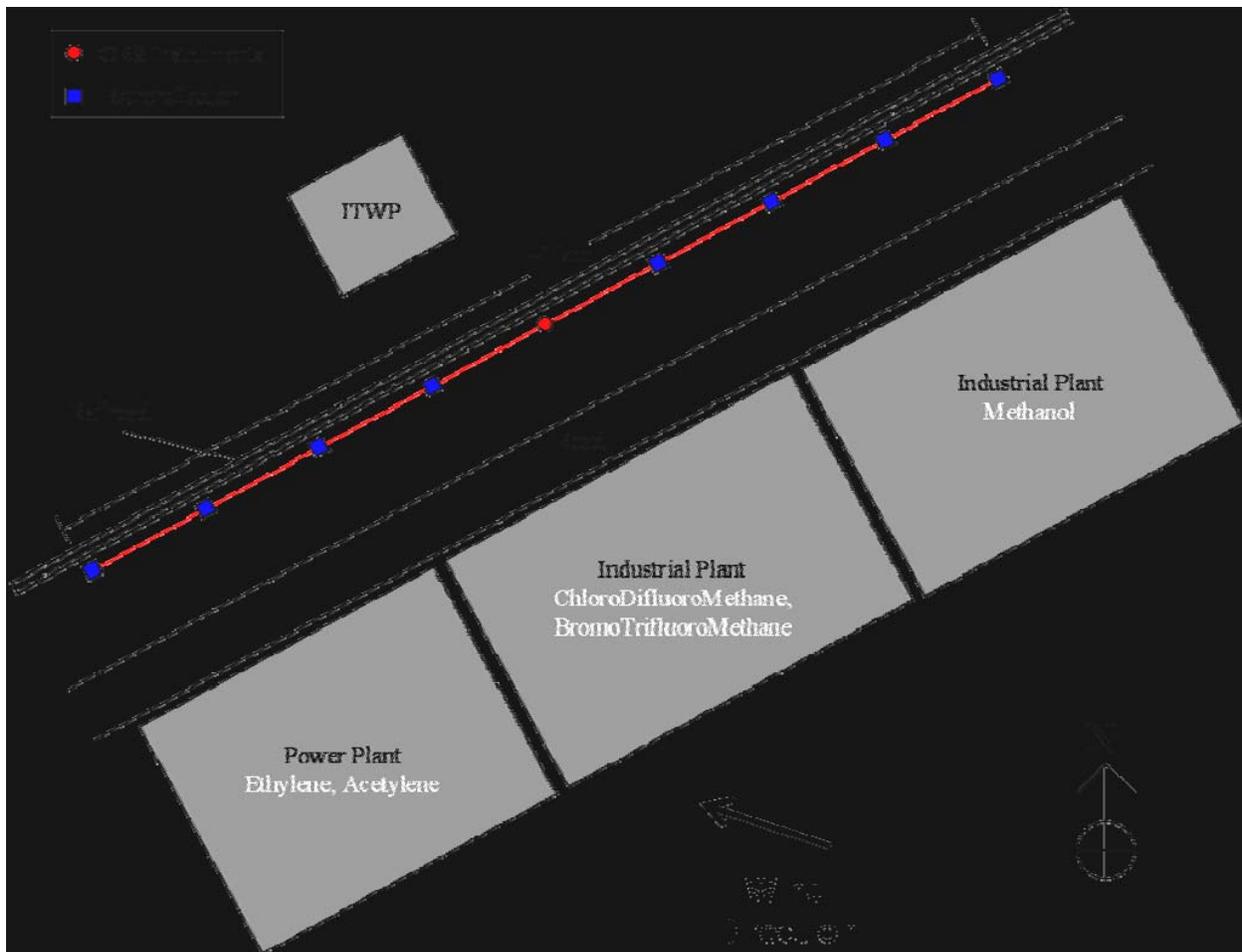
The VRPM method was demonstrated at the MCBCL inactive landfill. For this demonstration, the PI-ORS instrument was placed in the far northern corner of the survey area, and the mirrors were placed along the NE edge of the area of interest, with the vertical tower approximately 280 m from the PI-ORS instrument (see Figure 5). This configuration was preferred, as the prevailing wind direction was from the SW. Figure 8 presents the average VRPM methane plume map from the demonstration. The average methane flux value from the landfill was 10.5 grams per second.



**Figure 8. VRPM vertical plume maps of methane plumes at the MCBCL inactive landfill.**  
Concentrations are shown in ppm.

#### 4.1.6 1-D RPM Demonstration at MCAS Cherry Point

The MCAS Cherry Point demonstration utilized another RPM-based method known as 1-D RPM. The 1-D RPM configuration utilized at MCAS Cherry Point consisted of deploying several mirrors along the surface and collecting path-integrated concentration data to develop concentration profiles of the target compounds. Wind data was collected concurrently with the ORS data to assist in locating the source of the measured compounds within the facility. At the MCAS Cherry Point site, the 1-D RPM approach was used to characterize emissions from a large industrial complex at the NADEP. A 24-hour measurement campaign was conducted using a scanning OP-FTIR instrument. The instrument was deployed in the center of the configuration, and scanned to four surface mirrors aligned on either side, as shown in Figure 9. Sequential scanning was conducted, collecting data for 30 seconds on each mirror, and amassing a total of 213 eight-mirror cycles in 24 hours.



**Figure 9. 1-D RPM at MCAS Cherry Point.**

Five major compounds were detected in short events of several minutes during different times of the measurement period. The compounds detected were methanol, ethylene, acetylene, chlorodifluoromethane, and bromotrifluoromethane. Table 7 presents a table of the peak concentration of each compound measured during the survey.

**Table 7. Peak concentration of detected compounds from the MCAS Cherry Point survey.**

Compound	Peak Concentration (ppb)
Methanol	45
Ethylene	110
Acetylene	66
Chlorodifluoromethane	70
Bromotrifluoromethane	50

Correlating 1-D RPM concentration profiles with synchronized wind direction allowed for the determination of the source area within the complex (shown in Figure 9). These types of determinations can be performed along any type of industrial fence line, greatly supporting leak detection and repair programs by narrowing down significantly the area of search for leaks.

## **4.2 PERFORMANCE CRITERIA**

Performance criteria were shown previously in Table 2.

## **4.3 DATA ASSESSMENT**

### **4.3.1 Performance**

The method was validated in the Duke Forest tests, where gases were released and measured by the RPM method. The performance of the HRPM determinations was assessed by determining the distance between the location of the gas release and the location determination by the HRPM method. The performance of the VRPM method was assessed by comparing the measured emission rate of a gas release to the ground-truth value. The ground-truth emission rates were determined gravimetrically over a measured time period. In order to confirm the methodology, tracer gases were released in the field in two parts of the validation. For the HRPM validation, a point release was relocated between runs, and the displacement distance from the computed source location to the actual source location was measured. No alternate performance confirmation methods were required, as the performance criteria were computed from the mass of pollutant released and the measured distance from the release point. These mass and distance measurements were considered as primary standards.

The tests performed for this ESTCP demonstration were closely monitored by USEPA with a particular interest in the validation of the results. The validations successfully met USEPA's quality objectives for both HRPM and VRPM. For the HRPM validation, metered quantities of tracer gases (nitrous oxide, ethylene, acetylene, propylene, and propane) were released in a controlled manner, and the locations of the releases were recorded. By scanning the PI-ORS instrument in a radial fashion on a horizontal plane close to the ground, the location of the point releases were reconstructed. The distance of the reconstructed "hot spot" location from the actual release location was within 10% of the diagonal of the HRPM grid in all completed runs. For the VRPM validation, the average flux for all runs was within 25% of the actual release rate. These validations and demonstration efforts resulted in the drafting and approval of USEPA OTM-10 for area source emission monitoring.

### **4.3.2 Regulatory Standards Attained**

The HRPM and VRPM methods that were demonstrated in this project were adopted by USEPA and developed into its first and only area-source measurement protocol, the OTM-10 document.

### **4.3.3 Health and Safety Requirements**

The RPM method does not require the use of dangerous gases or materials. However, standard health and safety protocols for field work should be employed when conducting RPM measurements.

#### 4.4 TECHNOLOGY COMPARISON

The RPM method yields time-averaged concentration measurements across a plume of contaminant, from which the emission rate can be determined. 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 photoionization detectors (PID), PID/ flame ionization detectors (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 provide only concentration information from single points in the survey area, greatly increasing the chances of missing surface emissions hot spots or emissions plumes. Also, these approaches provide only instantaneous measurements, or measurements collected over a period of seconds or minutes. It would be necessary to collect multiple samples over a long period of time with the traditional point-sampling methods to provide time-averaged results equivalent to the RPM method. Even after collecting multiple data samples from multiple points in the survey area, the point sampling approaches lack the spatial data necessary to obtain a complete representative picture of the emissions from large area sources. Another disadvantage of using the point sampling approaches is that it is necessary to use dispersion modeling to obtain flux data from the site.

## **5.0 COST ASSESSMENT**

### **5.1 COST REPORTING**

The following parameters will be tracked for computing costs of the proposed measurement: equipment rental and field expenses, labor, and travel.

### **5.2 COST ANALYSIS**

Prior to the introduction of the RPM methods, no direct emission measurements of area and fugitive sources were performed in the United States. The common practice (and low cost) in the United States and around the world is to measure concentrations of the pollutant of interest downwind from the area source and apply inverse dispersion modeling to retrieve emission rates. Concentrations are typically measured with several point monitors in different locations and heights. Assumptions are made on atmospheric stability and on source location and size.

In Europe, on the other hand, it is much more acceptable to use the DIAL technology which directly maps the concentration profiles in a crosswind vertical plane similar to the VRPM method. This direct measurement approach is far more expensive and primarily applied in chemical industrial sites. The RPM methods described in this report can be applied as an alternative to both methods mentioned above. For this reason, we will perform a cost comparison with the two emission measurement methods: the indirect point monitoring approach coupled with some inverse dispersion modeling (typically a week-long campaign in landfills) and the DIAL (typically a month-long comparison at industrial complexes such refineries).

### **5.3 COST COMPARISON**

#### **5.3.1 Comparison to Point Monitoring and Inverse Dispersion Modeling**

The HRPM and VRPM methods, following OTM-10, were employed and tested in an USEPA fugitive emissions campaign during May 2005 at the Orange County Municipal Landfill located near Chapel Hill, North Carolina, and in close proximity to the ARCADIS Durham, North Carolina, office. The study consisted of 5 days of measurements in the field to characterize fugitive methane emissions from the site. HRPM and VRPM surveys were executed using two field technicians. This real-world application will be used to perform a cost comparison between the RPM method and traditional point monitoring methods.

Table 8 presents an estimate of the typical costs for performing a 5-day RPM-based field campaign using a tunable diode laser (TDL) instrument and crew consisting of two field technicians. If the actual field effort were less than a full week, the costs would be lower than the estimated \$35,000 and can be estimated by reducing the number of hours and adjusting the expenses in Table 8.

**Table 8. Estimated costs for implementing a 5-day RPM measurement campaign.**

<b>Equipment</b>	<b>Component</b>	<b>Rental Quantity</b>	<b>Unit Cost</b>	<b>Total Cost</b>
	TDL	1-unit-week	\$2,500	\$2,500
	Reflectors	5-unit-weeks	\$250	\$1,250
	Scissor jack	1-unit-week	\$600	\$600
	2.5 KW generator	1-unit-week	\$400	\$400
	<b>Total</b>			<b>\$4,750</b>
<b>Labor</b>	<b>Task</b>	<b>Man-Hours</b>	<b>Hourly Cost</b>	
	Planning & preparation	40	\$130	\$5,200
	Equipment setup	8	\$100	\$800
	Field measurements	72	\$100	\$7,200
	Analysis and report	80	\$130	\$10,400
	Travel	16	\$100	\$1,600
	<b>Total</b>			<b>\$25,200</b>
<b>Other</b>				
	Transportation for 2 people			\$2,000
	Shipping of all equipment			\$1,200
	Meals and lodging for 12 person-days			\$1,400
	<b>Total</b>			<b>\$4,600</b>
<b>Total Project Cost</b>				<b>\$34,550</b>

The total estimated cost is approximately \$35,000 but can vary from \$25,000 to \$50,000, depending on the desired length of the project, proximity of the project site to the office, requirement for equipment, costs of transportation, travel time, and the complexity of the project. As can be seen, most of the project costs are associated with labor.

The costs for attempting the same measurement goals using traditional monitoring techniques are highly variable and depend on the manpower and the required quantity of laboratory analysis.

Since the major component of the cost is labor, the costs will be in the same range as the RPM costs, \$25,000 to \$50,000 for a 1-week, two-man project.

Existing methodology for measuring NPSs is not directly comparable to the proposed PI-ORS method because the new method provides higher quality and quantity of data than is obtainable by current methods. The cost comparison will be for a 1-week, two-man measurement campaign for which the cost components for the RPM are listed in Table 9. The conventional methods for this cost comparison will be considered as applied to determination of the methane emissions from a landfill, similar to the USEPA RPM project at the Orange County landfill. One might expect that the traditional point-sampling approach of choice would involve the use of flux chambers, but because of the heterogeneous distribution of the ground emissions, a finite number of flux chambers cannot provide information that is representative of the 16-acre section. To provide a fair cost comparison, we chose to use a transect-sampling method. In this approach, horizontal and vertical arrays of samplers are used to measure concentrations of volatile species within the effective cross-section of the fugitive emission plume. The emission rate is obtained by spatial integration of the measured concentrations over the assumed plume area and multiplying the area integrated mass concentration by the wind component normal to the transect plane.

To cover the ~250-m downwind border to the survey area with sufficient number of samplers, we consider using a central mast with three Summa canisters, one at ground level (1-m height), and nine other ground-level Summa canisters along the downwind border for a total of 12 Summa Canisters. This configuration will result in a sampler spacing of 25 m.

The basis for the costs for implementing a 1-week measurement campaign is listed in Table 9 for a conventional sampling project, which would require two field hands. The cost of a 1-week, 2-man measurement campaign is \$47,000. It may be possible to reduce the cost by using a less expensive sampling medium, but the labor costs will be the same as the RPM measurements. Thus the estimated range of costs for a 1-week traditional measurement project would be from \$25,000 to \$60,000.

A direct comparison of the costs components for a 1-week, two-man RPM project versus a traditional monitoring project are listed in Table 10.

**Table 9. Estimated costs for implementing a 1-week canister/modeling campaign.**

Equipment	Component	Quantity per Week	Unit Cost	Total Cost
	Summa canisters (12)	1-unit	\$1,200	\$14,400
	Mast (4)	1-unit	\$250	\$1,000
			<b>Total</b>	<b>\$15,400</b>
Labor	Task	Man-Hours	Hourly Cost	
	Planning & preparation	40	\$130	\$5,200
	Equipment setup	8	\$100	\$800
	Field measurements	72	\$100	\$7,200
	Analysis and report	80	\$130	\$10,400
	Travel	16	\$100	\$1,600
			<b>Total</b>	<b>\$25,200</b>
Other				
	Canister analysis of 15 units at \$125 ea.			\$1,875
	Transportation for 2 people			\$2,000
	Shipping of all equipment			\$1,200
	Meals and lodging for 12 person-days			\$1,400
			<b>Total</b>	<b>\$6,475</b>
Total Project Cost				<b>\$47,075</b>

**Table 10. Cost comparison between canisters/modeling and proposed approaches.**

#	Task	Canisters	RPM
1	Preparation	\$5,200	\$5,200
2	Setup	800	800
3	Test	30,675	18,150
4	Analysis & report	10,400	10,400
	<b>Total</b>	<b>\$47,075</b>	<b>\$34,550</b>

Task 1 is preparation and planning of the project. This includes preparation of a QA/quality control (QC) plan and design of the measurement configuration, which is much more complex in the conventional approach. Use of the conventional approach also requires site-specific

preliminary dispersion modeling to optimize the measurement configuration and protocols. Further, the conventional method involves time-consuming preparation and calibration of a large number of point monitors and measurement equipment. The QA/QC plan is much simpler in the proposed approach (fewer instruments) and therefore less time-consuming. No preliminary dispersion modeling work is required in the new approach.

Task 2 is the field setup effort. The setup cost for the conventional approach is identical to the setup cost associated with the proposed approach.

Task 3 is the actual fieldwork priced for about one month in the field. As for the setup, labor and travel costs for the two methods are identical, but the equipment costs for the conventional approach are much higher than for the proposed approach. Task 4 is reporting the test results. The difference in cost is due to the difference in the complexity and length of the outcome reports. A major part of the reporting effort for the conventional approach is labor-intensive data analysis that includes inverse dispersion modeling to estimate sources' flux. Task 5 is the travel expenses, which will be more expensive for the conventional approach since more people are traveling to the measurement site. Task 6 is subcontractors' services, which mainly include lab analyses of the Summa canisters (90 units, VOCs TO-14 analysis at \$280/unit) and of the PUF/XAD (a sorbent) (110 units, PAHs TO-13 analysis at \$300/unit). We conservatively assume that we may reduce this effort to one-fourth of the total lab work when the ORS technique is included in the new approach. Task 7 is other expenses, which include instrument rentals, per diem, field supplies, sample shipping and handling, and vehicle rentals. The main difference is in the rental of the ORS instrument rental (\$20,000/mo), which makes this task more expensive for the new approach. The conventional approach includes rental of a PID (\$1,400/mo) and a real-time gas chromatograph (GC) (\$5,000/mo), which are not needed for the new approach. The other items in this task are similar in cost between the two approaches.

The PI-ORS methods require little or no maintenance. For smaller sites, this testing is foreseen as being provided through an environmental service contractor due to the infrequent nature of the testing and the cost of a PI-ORS instrument (\$100,000). The system contains no inherent hazardous chemicals and disposal of this system will require no unique methodology.

### **5.3.2 Comparison to DIAL**

A typical DIAL study at an industrial complex lasts 3-4 weeks, and the costs associated with bringing a DIAL system from Great Britain to North America and performing the study ranges between \$400,000 and \$600,000 (Chambers et al., 2008). A VRPM study for the same duration will cost approximately \$140,000 if we just multiply the 1-week effort by four (see Table 8). Realistically, there will be some cost savings in preparation, equipment rental, and reporting when one performs longer period studies. Therefore, a 1-month VRPM study will range between \$100,000 and \$150,000, which is one-fourth of the cost of a comparable DIAL study.

## **6.0 IMPLEMENTATION ISSUES**

### **6.1 COST OBSERVATIONS**

The resources required to have this method accepted by USEPA was the single biggest cost. Once the system is accepted and the technology continues to advance these systems, the capital cost of these systems should decrease. However, when implemented, the two biggest cost drivers will be the cost of the PI-ORS equipment rental and the cost of the technician labor required to operate it.

### **6.2 PERFORMANCE OBSERVATIONS**

Both VRPM and HRPm performed within the boundaries set in the test plan. For the VRPM method, gas mass recovery of  $100 \pm 25\%$  was achieved. For HRPm, the displacement of the artificial hot spot was to be within  $\pm 10\%$  of the diagonal distance of the HRPm survey area in most runs. These performance criteria validate the concept and deliver a revolutionary improvement in the technology. Direct involvement of the regulatory community virtually ensured the development and acceptance of OTM-10.

### **6.3 SCALE-UP**

The demonstrations described in this report are at full scale.

### **6.4 OTHER SIGNIFICANT OBSERVATIONS**

This validation was performed with a relatively small simulated area source compared to the VRPM length. When the source is larger than the VRPM plane (like in most landfills), new VRPM configurations should be considered. These VRPM configurations are currently being tested and demonstrated, and a new test method is being developed specifically for complex, large area sources such as landfills and industrial complexes.

This demonstration primarily used OP-FTIR but did not intend to demonstrate the OP-FTIR technology or any other ORS technology. Any PI-ORS technology can be used with the RPM methods that were demonstrated. It is recommended to use the RPM methods in scenarios where the typical levels of the target compounds are at least three times the instrument minimum detection limit (MDL). OP-FTIR technology can be acquired through several vendors. Information on the list of compounds and their typical MDL can be found at the websites of the vendors that supplied the OP-FTIR instruments for this demonstration (<http://www.kassay.com/NewKassayFSI/files/Download/RAM2000%20Brochure.pdf> and <http://www.imacc-ftir.com/limits.shtml>).

Not all compounds of interest need to satisfy this criterion. Relative concentrations of low-level compound can be measured with another (more sensitive) single-beam ORS technology or with more sensitive point monitoring (and time integrating) techniques.

## **6.5 LESSONS LEARNED**

The OTM-10 test method is generic with regard to ORS instruments and type of area source. In the future, each type of source will merit the development of more specifically tailored test methods. These test methods will specify the recommended ORS instruments and configurations for the type of area of fugitive source in question.

Emissions from area and fugitive sources are inhomogeneous in space and time. Demonstration of the RPM method significantly progressed the understanding of such spatial and temporal variability. However, for measurement-based emission-factor and annual total emissions, it is recommended that measurements occur for at least a month. Unattended fixed installation of the VRPM approach is possible and can be achieved with any ORS technologies (USEPA, 2007). This is the cost-effective way to accumulate long-term emission data. The unattended installation of the VRPM or the 1-D RPM systems for long-term continuous monitoring with remote access can be easily achieved with the placement of the RPM system near a telephone hookup or via a wireless system. Through this type of remote access system, continuous compliance monitoring may be achieved.

## **6.6 END-USER ISSUES**

The hardware associated with the technology is commercially available. The RPM-based methods totally depend on the accuracy and reliability of the ORS instrument used. In the course of developing and demonstrating the RPM method in this project, many vendors were examined and demonstrated their ORS technology. It is critical to carefully choose the type of instrument for the task at hand and also the appropriate vendor for the instrument rental or purchase. ARCADIS will share its experience upon request. ARCADIS algorithms are proprietary and will be available for separate purchase through contract.

## **6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE**

There will be no adverse environmental impact associated with the running of these monitoring systems. No environmental permits should be required for the running of these monitoring systems as no adverse materials are introduced into the environment during the employment of these systems.

## 7.0 REFERENCES

- Barber, C.B., D.P. Dobkin, and H.T. Huhdanpaa. 1996. "The Quickhull Algorithm for Convex Hulls," *ACM T. Math. Software*, 22(4), 469–483, December 1996.
- Bath, R.J., T.R. Minnich, and R.D. Spears. 1989. "Air Toxics Monitoring: A Comparison Between Remote Sensing and Point Monitoring Techniques," In *Proceedings of American Chemical Society*, Vol. 198, ENVR 160; 198th ACS National Meeting: Miami Beach, FL, September 10-15, 1989.
- Börjesson, G., Å. Danielsson, and B.H. Svensson. 2000. "Methane Fluxes from a Swedish Landfill Determined by Geostatistical Treatment of Static Chamber Measurements," *Environ. Sci. Technol.* 34, 4404-4050.
- Chambers, A.K., M. Strosher, T. Wootton, J. Moncrieff, and P. McCready. 2008. "Direct Measurement of Fugitive Emissions of Hydrocarbons from a Refinery," *J. Air & Waste Manage. Assoc.* 58:1047–1056.
- Cheng, M.D., E. Corporan, M.J. DeWitt, C.W. Spicer, M.W. Holdren, K.A. Cowen, A. Laskin, D.B. Harris, R.C. Shores, R. Kagann, and R.A. Hashmonay. 2008. "Probing Emissions of Military Cargo Aircraft: Description of a Joint Field Measurement. Strategic Environmental Research and Development Program," *J. Air & Waste Manage. Assoc.* 58:787–796.
- Gronlund, R., M. Sjöholm, P. Weibring, H. Edner, and S. Svanberg. 2005. "Elemental Mercury Emissions from Chlor-Alkali Plants Measured by LIDAR Techniques," *Atmos. Environ.* 39, 7474-7480.
- Hashmonay, R.A. 2008. "Theoretical Evaluation of a Method for Locating Gaseous Emission Hot Spots," *J. Air & Waste Manage. Assoc.* 58:1100–1106.
- Hashmonay, R.A. 2003. "Optical Remote Sensing Technologies in the United States," *A&WMA Environmental Manager*, Nov 2003, pp. 22 – 25.
- Hashmonay, R.A., D.F. Natschke, K. Wagoner, D.B. Harris, E.L. Thompson, and M.G. Yost. 2001. "Field Evaluation of a Method for Estimating Gaseous Fluxes from Area Sources Using Open-Path Fourier Transform Infrared," *Environ. Sci. Technol.*, 35, 2309–2313.
- Hashmonay, R.A. and M.G. Yost. 1999. "Innovative approach for estimating fugitive gaseous fluxes using computed tomography and remote optical sensing techniques," *J. Air Waste Manage. Assoc.*, 49, 966-972.
- Hashmonay, R.A., R. Varma, M.T. Modrak, R.H. Kagann, R.R. Segall, and P.D. Sullivan. 2007. "Radial Plume Mapping: A USEPA Test Method for Area and Fugitive Source Emission Monitoring Using Optical Remote Sensing," Y.J. Kim and U. Platt (eds.), *Advanced Environmental Monitoring*. Springer.

- Hashmonay, R.A., M.G. Yost, and C.F. Wu. 1999. "Computed Tomography of Air Pollutants Using Radial Scanning Path-Integrated Optical Remote Sensing," *Atmos. Environ.* 33 (2), 267-274.
- Kagann, R.H. and O.A. Simpson. 1990. "Open Path FTIR Measurements of Gaseous Emissions from a Chemical Plant Waste Water Treatment Basin," *Annual Conference of the Air & Waste Management*, Pittsburgh, Penn. (June 26-29, 1990).
- Kagann, R.H., R.A. Hashmonay, and D.B. Harris. 2005. "Investigation of Open-Path FTIR for Fast Deployment Emergency Response to Chemical Threats and Accidents," *Annual Meeting of the Air & Waste Management Association*, Minneapolis, MN (June 21 - 24, 2005).
- Kagann, R.H., R.A. Hashmonay, R. Shores, E. Thoma, and D.B. Harris. 2006. "Improving the Accuracy of OP-FTIR Measurements of Concentrations Close to Detection Limits," *Annual Meeting of the Air & Waste Management Association*, New Orleans, LA, (June 20 - 23, 2006).
- Lawson, C.L. and R.J. Janson. 1995. Solving Least Squares Problems, *In Soc. Ind. Appl. Math.*, Philadelphia, Chapter 23, pp. 158–165.
- Modrak, M. T., R.A. Hashmonay, and R. Kagann. 2004. "Measurement of Fugitive Emissions at a Region I Landfill," EPA-600/R-04-001; U.S. Environmental Protection Agency, Research and Development, Work Assignment No. 4-003, January 2004.
- National Research Council (NRC). 2003. *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. The National Academies Press, Washington, DC.
- Russwurm, G.M. and J.W. Childers. 1999. *FTIR Open-Path Monitoring Guidance Document*; 3rd Edition, TR-4423-99-03, Submitted by ManTech Environmental Technology, Inc., under contract 68-D5-0049 to the USEPA, Human Exposure and Atmospheric Sciences Division, National Exposure Research Laboratory: Research Triangle Park, NC.
- Shores, R.C., D.B. Harris, E.L. Thompson, Jr., C.A. Vogel, D. Natschke, R.A. Hashmonay, K.R. Wagoner, and M. Modrak. 2005. "Plane-integrated open-path Fourier transform infrared spectrometry methodology for anaerobic swine lagoon emission measurements." *Applied Engineering in Agriculture*, 2005 (Vol. 21) (No. 3) 487-492.
- Spokas, K., C. Graff, M. Morcet, and C. Aran. 2003. "Implications of the Spatial Variability of Landfill Emission Rates on Geospatial Analyses," *Waste Management*. 23 599-607.
- Thoma, E.D., R.C. Shores, E.L. Thompson, D.B. Harris, S.A. Thorneloe, R.M. Varma, R.A. Hashmonay, M.T. Modrak, D.F. Natschke, and H.A. Gamble. 2005. "Open Path Tunable Diode Laser Absorption Spectroscopy for Acquisition of Fugitive Emission Flux Data", *J. Air and Waste Manage. Assoc.* 55, 658-668.
- Thorneloe, S. 2007. "Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology." USEPA Report EPA/600/R-07/032. February 2007.

- U.S. Environmental Protection Agency (USEPA). 1999. *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Second Edition, Compendium Method TO-16, Long-Path Open-Path Fourier Transform Infrared Monitoring Of Atmospheric Gases*, Center for Environmental Research Information, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, January 1999, EPA/625/R-96/010b.
- U.S. Environmental Protection Agency (USEPA). 2006. *Optical Remote Sensing for Emission Characterization from Non-point Sources*, USEPA Other Test Method Protocol, OTM-10. <http://www.epa.gov/ttn/emc/prelim/otm10.pdf>.
- U.S. Environmental Protection Agency (USEPA). 2007. *Measurement of Total Site Mercury Emissions for a Chlor-alkali Plant Using Open-Path UV-DOAS – EPA/R-07/077 – July 2007* <http://www.epa.gov/nrmrl/pubs/600r07077/600r07077.pdf>.
- Varma, R., R.A. Hashmonay, R. Kagann, and M.A. Bolch. 2005. “Optical Remote Sensing to Determine Strength of Non-point Sources: Duke Forest Validation Study,” ESTCP Report #A528044, Contract No. CP-0214, 2005. November.
- Walmsley, H.L. and S.J. O’Connor. 1996. “The Use of Differential Absorption LIDAR to Measure Atmospheric Emission Rates at Industrial Facilities.” In *Proceedings of the A&WMA’s International Conference on Optical Sensing for Environmental and Process Monitoring*; A&WMA: Pittsburgh, PA, 1996, p. 127.
- Yost, M.G. and R.A. Hashmonay. 2003. “Mapping Air Contaminants Using Path-Integrated Optical Remote Sensing with a Non-overlapping Variable Path Length Beam Geometry,” U.S. Patent 6,542,242.

*This page left blank intentionally.*

## APPENDIX A

### POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role
Dr. Patrick D. Sullivan	AFRL/MLQF 104 Research Road Tyndall AFB, FL 32403	Phone : 850-283-0430 E-Mail : patrick.sullivan@tyndall.af.mil	
Dr. Ram Hashmonay	ARCADIS U.S., Inc. 4915 Prospectus Drive, Suite F Durham, NC 27713	Phone : 919-544-4535 E-Mail : rhashmonay@arcadis-us.com	
Robin Segall	Emission Measurement Center (MD-19) OAQPS, USEPA RTP, NC 27711	Phone : 919-541-0893 E-Mail : segall.robin@epa.gov	
Emily M. Sylvester	Environmental Management Division MCB Camp Lejeune, NC 28542	Phone : 910-451-9455 E-Mail : sylvesterem@lejeune.usmc.mil	
Ortahi Bulfer	Environmental Affairs Department MCAS Cherry Point Cherry Point, NC 28533-0006	Phone: 252-466-4826 E-Mail: BulferO@cherrypoint.usmc.mil	



## ESTCP Program Office

901 North Stuart Street  
Suite 303  
Arlington, Virginia 22203  
(703) 696-2117 (Phone)  
(703) 696-2114 (Fax)  
E-mail: [estcp@estcp.org](mailto:estcp@estcp.org)  
[www.estcp.org](http://www.estcp.org)