Development of Mobile Measurement Method Series OTM 33

Eben D. Thoma, Halley Brantley[1], and Bill Squier
U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory, 109 TW Alexander Drive, E343-02, Research Triangle Park , NC 27711, USA
[1] ORISE Fellow

Jason DeWees, Robin Segall, and Ray Merrill
U.S. EPA, Office of Air Quality Planning and Standards, 109 TW Alexander Drive, E143-02, Research Triangle Park, NC 27711, USA,

ABSTRACT

Starting in 2006, the United States Environmental Protection Agency has explored use of mobile instrumented vehicles for a variety of air quality assessment applications under its Geospatial Measurement of Air Pollution (GMAP) program. GMAP systems utilize next generation, fast-response instruments and precise global positioning systems (GPS) in mobile platforms to gain insight into source emissions, population impacts, and risk mitigation strategies in a variety of use scenarios. Other Test Method 33(OTM 33) describes a subset of GMAP approaches designed to quantify source emissions. OTM 33 techniques typically have two operational modes: (1) mobile mapping surveys to locate sources and (2) measurement and/or characterization procedures to assess near-source concentrations and mass emission rates. This presentation provides a general description of mobile source emission measurement approaches, including strengths and limitations, with a focus on sub-method OTM 33A, a technique for assessment of ground-level point sources such as may be encountered in oil and gas production fields. Other potential OTM 33 sub-methods, such as mobile tracer correlation and flux planes, serve to extend the range of application of OTM 33 to other sources and will be described briefly.

INTRODUCTION

Although area sources such as landfills, waste water, and agricultural operations, and fugitive sources in industrial facilities, refineries, and upstream energy production can have very different emission profiles, they share some common characteristics. Air pollutant emissions from these sources are usually heterogeneous, and of significant spatial extent or distributed over large areas. Emissions can be temporally variable and profoundly affected by environmental factors and operational conditions. The stochastic and site-specific nature of fugitive and area sources make them difficult to both measure and model. These factors have made development of standardized source assessment approaches more challenging than in the point source (stack) monitoring regime.[1] To help improve understanding of these non-point sources, the Office of Research and Development (ORD) of the United States Environmental Protection Agency (EPA) is working with EPA's Office of Air and Radiation (OAR) and external groups to facilitate development of new fugitive and area source measurement methods. An emerging class of approaches based on mobile monitoring is the focus of this conference paper and presentation.

Fixed-place optical remote sensing (ORS) is a well-known class of technical approaches to quantify emissions from fugitive and area sources. ORS systems employ open-path optical beams to spectroscopically speciate and quantify path-averaged pollutant concentrations in the

advected plume.[1] The long optical paths used (0.1 km to 1 km) aim to capture the spatially variable emissions from the source. When coupled with wind transport and/or micrometeorological analysis, ORS approaches can quantify source emission rates, usually with accuracy goals in the +/- 20% range. Multipath (flux plane) ORS techniques such as EPA OTM 10[2,3] have been demonstrated on waste water,[4] landfills,[5] and a variety of industrial-related sources.[6,7] Single optical path ORS approaches that use inverse modeling have also been widely used.[8-10] With fixed optical paths, these ORS approaches require some investment in on-site configuration and are limited to ground-level deployment or to elevated attachments to available site infrastructure. These ORS approaches are well-suited for longer-term assessment of emissions from temporally variable sources. A more spatially flexible ORS approach is atmospheric backscatter differential absorption (DIAL) LIDAR. Requiring no fixed retroreflectors, this powerful technique has been used to quantify emissions from refineries and other industrial sources.[11-13] As a class, optical remote sensing approaches are not very nimble, and are more suited for intensive or long-term studies.

Whereas ORS techniques address source spatial variability through use of extended optical paths, an emerging class of fugitive and area source measurement approaches meet these challenges by producing downwind mobile transect profiles of the advected plume using single point monitors or vertically extended flux planes. These mobile techniques are characterized by their ability to cover large areas, allowing discovery of unknown sources with emission rate quantification through a variety of approaches. Investigating these novel mobile source measurement concepts are part of EPA's Geospatial Measurement of Air Pollution (GMAP) research program which is one of several next generation air measurement (NGAM) initiatives that seeks to develop new sampling, sensor, and informetric techniques to improve knowledge of air quality, personal exposure, and source mitigation.[14-17] One goal of the GMAP effort is to improve understanding of different types of mobile source measurement approaches including their strengths and weaknesses for specific applications. This effort will develop standardized descriptions and classifications of mobile techniques and help communicate, as appropriate, engineering design, validation testing, and quality assurance information as part of an EPA draft method series called "other test method 33" (OTM 33). The OTM 33 series of mobile source measurement methods will be posted on EPA's technology transfer website for broader use and comment.[18] OTM 33 will be revised over time as information on GMAP-related measurement approaches and applications advances.

DEVELOPMENT OF MOBILE METHODS

Mobile Source measurements and OTM 33:

The U.S. EPA uses the term GMAP to refer to the full spectrum of research and practical applications of ground-based mobile measurements in use by many groups. GMAP approaches have in common the use of fast-response instruments and precise global positioning systems (GPS), configured in custom sampling vehicles, to investigate spatial and temporal air pollution patterns. There are many examples of GMAP used in research applications to study concentration gradients and near-source impacts of particulate matter and gas phase air pollutants.[18] OTM 33 focuses on a subset of GMAP applications that aim to improve understanding of fugitive and area source emissions and quantify emission rates. Air pollution sources in this category range from large area sources to fugitive point sources distributed over geographic regions. In a similar manner to ORS techniques, mobile source assessment

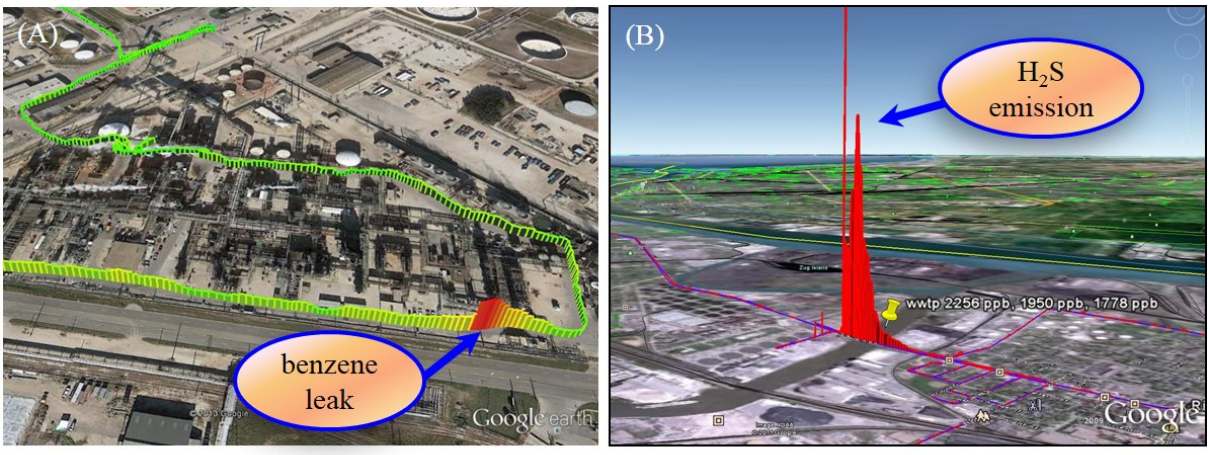
approaches come in several forms, each with specific performance and use parameters that should be matched with source type and measurement objectives. OTM 33 aims to provide a general prescription for mobile source measurements with specific technical approaches described in sub-methods to be developed over time. The sub-methods detail emissions quantification schemes, method equipment and analysis requirements, performance metrics, method quality indicators (MQIs) and typical application scenarios for the described approach. In general, OTM 33 sub-methods define the use of mobile platforms and auxiliary equipment for one or more source assessment functions:

- Concentration mapping (CM) - Find the location of unknown sources and/ assess the impact of source emissions on local air quality
- Source characterization (SC) - Improve understanding of known or discovered sources through acquisition of secondary measures (e.g. remote imaging or speciation)
- Emissions quantification (EQ) - Measure (or estimate) source emission rates

OTM 33A: Discovery/Characterization of Near-Field Fugitive Sources

OTM 33A is the first sub-method developed in the series and a draft including engineering designs is posted on EPA's Technology Transfer Network.[19] OTM 33A is applicable to near ground-level sources that are small in spatial extent and are located in close proximity (generally < 150 m) of the driving route. OTM 33A is designed to be a rapidly executed inspection approach that does not require deployment of fixed equipment or site-specific modeling. Figure 1 shows two examples of OTM 33A CM, detection of benzene emission in a refinery (1A) and discovery of a large hydrogen sulfide emission in an urban area (1B).[19] These surveys, performed by EPA GMAP vehicles, are but a few of numerous examples of mobile leak detection that are emerging including multiple research and commercial efforts to find methane leaks in natural gas distribution systems.[20-22]

Figure 1. Example of OTM 33A concentration mapping surveys (A) discovery of a benzene leak in a refinery and (B) identification of a an H_2S source.[19]

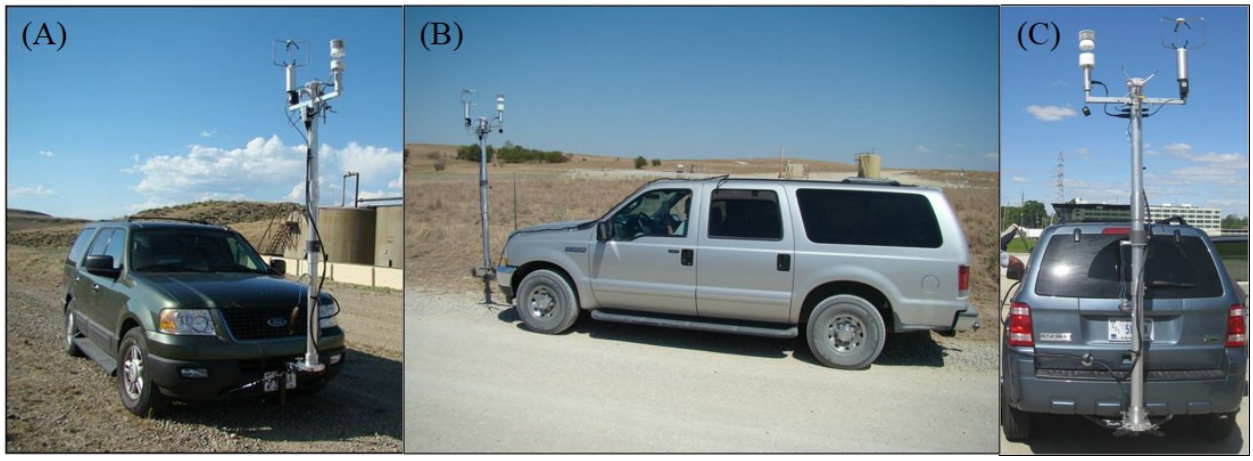


In addition to the sampling vehicle, the equipment required to execute OTM 33A or related CM surveys includes the pollutant concentration measurement instrument (CMI), a good quality global positioning systems (GPS), instrument power (invertor or battery system) and a data

acquisition system of some type (potentially part of the CMI function). Onboard wind measurement can also be helpful and some commercial mobile units allow in-motion ambient wind direction readings to facilitate leak location determination.[22] The CMI functions can range from single purpose (e.g. detection of methane) to very sophisticated speciated measurements with research survey vehicles.[23-27]

For execution of SC and EQ functions under draft OTM 33A, additional equipment is required. For example, OTM 33A currently describes an emission rate assessment approach that can be useful for near-field sources in open areas. The approach uses wind data from a 3-D sonic anemometer and requires the CMI probe and instruments to be located away from the body to avoid obstructed air flow, which could affect the measurement. Several examples of EPA-developed OTM 33A GMAP vehicles are shown in Figure 2. Instruments, mechanical designs, wiring diagrams, and control and analysis software are detailed in OTM 33A documentation.[19]

Figure 2. Examples of OTM 33A vehicles belonging to EPA (A) National Environmental Investigations Center, (B) Office of Research and Development, and (C) Region 5.



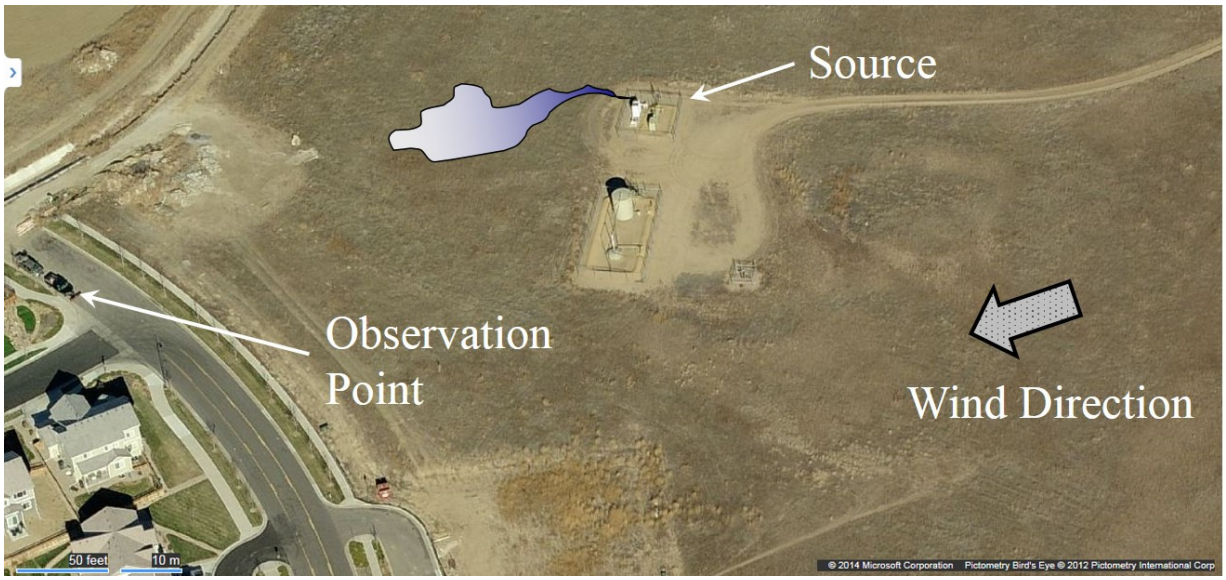
A well-suited application of OTM 33A is location and assessment of emissions from roadway-proximate oil and gas production pads in open areas. For oil and gas applications, the primary real-time measurement by the CMI is typically methane. After an emission has been located through CM, the operator positions the vehicle downwind in the emission plume at a safe and appropriate observing location using the real-time CMI readings. The GMAP vehicle is parked facing the source and the engine is turned off to prevent self-contamination of the measurement. After placement of traffic cones, and other safety precautions, the operator obtains site photos and infrared video information (if possible) and combines these SC observations with real-time wind direction and CMI data to help identify the primary source location(s). The sampling mast is then rotated to point in the direction of the source and a laser range finder is used to determine distance to the source. A series of 15 to 20 minute observations are acquired from the stationary observing location. Time-synchronized CMI and meteorological instrument data are acquired and potentially other SC functions, such as execution of a canister grab sample, are performed.[19,28,29] For OTM33A, all data can be acquired from off-site observing locations if required as there is no need to set up sampling equipment or release tracer gas from the site.

A large variety of sites can be inspected for elevated emissions using OTM 33A CM and some SC operations can almost always be performed. A smaller number of sites are suitable for emissions rate assessment, especially if limited to remote (off-site) observation. An example of a

site that could be investigated with OTM 33 EQ is shown in Figure 3. There are several key factors to consider when evaluating a site and sampling conditions for EQ using OTM 33A:

- Downwind roadway access to safe and appropriate measurement position
- Consistent wind conditions that can transport the emission plume to the observation point
- Lack of wind flow obstructions (open areas required)
- Sources that are near ground level
- Lack of nearby interfering sources along the direction of transport

Figure 3. Example of a site that could be investigated using OTM 33A CM, SC, and EQ source assessment modes.

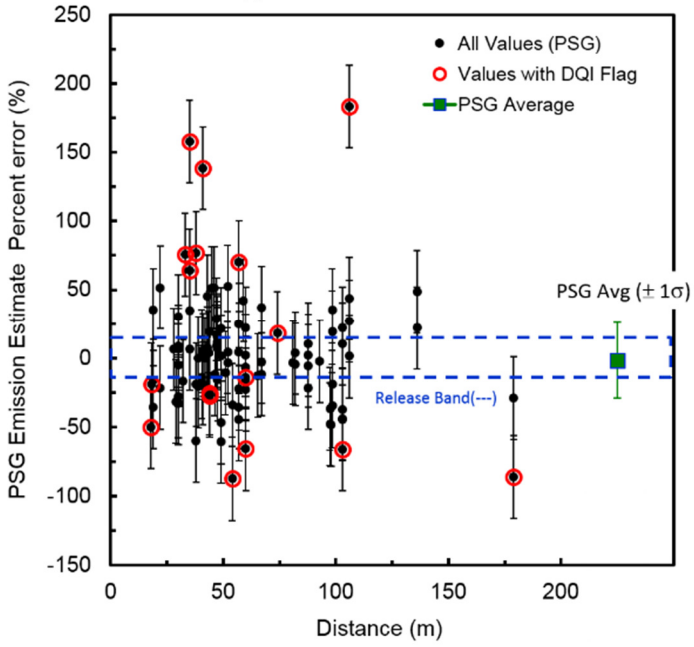


The determination of source emission rates using OTM 33A data can be accomplished using a number of inverse emission estimate approaches. Since the source and observation point are in close proximity, uncertainties in atmospheric dispersion are somewhat less important than for kilometer-scale inverse problems; however, because the plume is underdeveloped spatially, the probe-sample overlap statistics become more critical than in larger-scale work. The simplest inverse approach, called point source Gaussian (PSG), uses a look up table to determine dispersion parameters, whereas a more sophisticated approach, backwards Lagrangian stochastic (bLs) uses a model called WindTrax.[19,29,30] A conditionally-sampled Gaussian approach[31] has also been demonstrated and certainly other inverse schemes are possible with some comparisons discussed in presentation. It is thought that the accuracy of the OTM 33A EQ approach with any inverse estimation method is mostly determined by the validity of the base assumption for the specific observation. Any OTM 33A inverse approach assumes that the ensemble average of CMI and wind data is representative of the emission source. Representativeness implies stable source emissions, sufficient sampling time, and an adequate spatial overlap of the plume and the probe and the lack of significant symmetry breaking processes such as concentration enhancement by channeling effects. An example of a method interference where the OTM 33A approach would exhibit significant low bias is in the case of insufficient plume transport to the observing location. In this case, due to low wind speed and atmospheric instability, the centroid of the plume has too much vertical rise and essentially flows over the top of the distant sampling probe, producing an underrepresented concentration enhancement over background and therefore

a low emissions estimate. A significant overestimation could occur if the concentration from the source was enhanced by obstruction channeling or a downwash effect (if too close to the source) or other effects. Current knowledge of draft OTM 33A method interferences are discussed in the documentation, and MQIs that attempt to identify these conditions are under development.[19] In general, repeat measurements are recommended as this can help inform the presence of measurement issues as well as the temporal emissions profile of the source itself. An example will be provided in the presentation of repeat measurements at two oil and gas well pads.

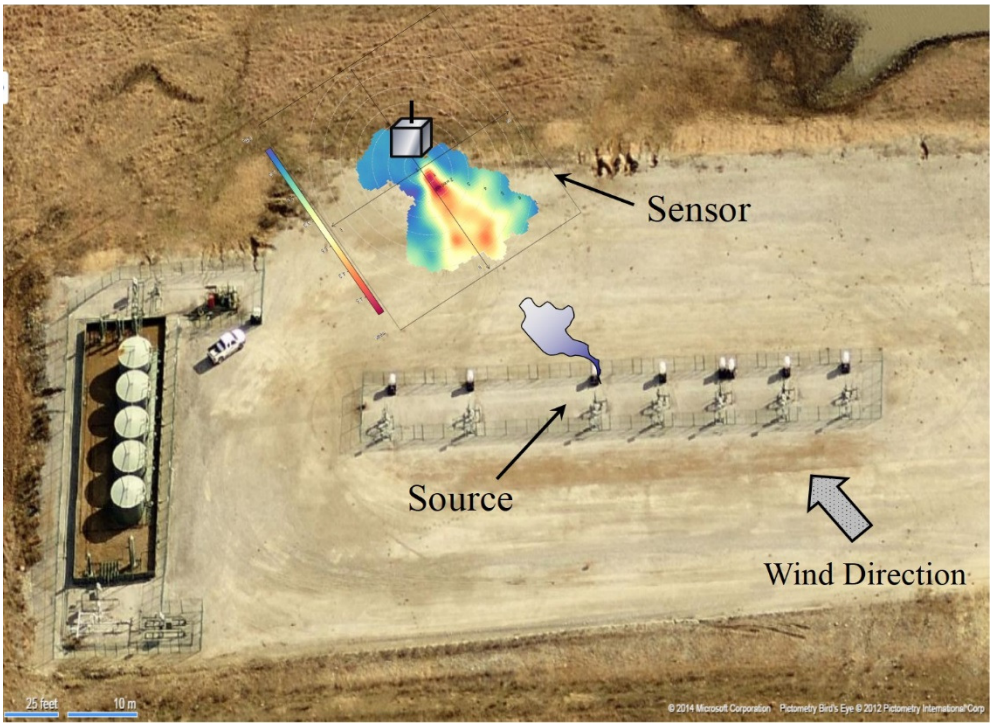
The performance of the OTM 33A approach was investigated in a variety of controlled methane release studies under a range atmospheric conditions using three different OTM 33A vehicles.[19] Results of 107, 20 minute observations, processed with the PSG inverse approach, are shown in Figure 4 (closed black data points), plotted as a function of distance between the simulated source and observation point. Release rates ranged from 0.19 g/s to 1.2 g/s with the majority of values at approximately 0.6 g/s. The accuracy of the controlled release rates were within +/- 10% (dashed lines). The error bars on the individual data points represent +/- one atmospheric stability indicator (ASI) class (used in the PSG calculation), and illustrate the degree to which uncertainty in atmospheric conditions can affect the emission estimate. Observations that depart from the nominal release band by more than the ASI error bars are likely affected by non-atmospheric factors, such as a non-representative concentration ensemble average. The red-encircled data points are values flagged by preliminary MQIs (also sometimes referred to as data quality indicators (DQIs).[19] The average of all measurements that pass MQIs is shown as the right-most green square data point (PSG Avg.), with error bars representing +/- 1 standard deviation in the data. As can be seen, even though individual data points error can vary, the overall average is relatively close to the nominal release value. With strict use protocols and favorable atmospheric transport and siting conditions, and using repeat (confirmatory) measurements, the PSG approach is believed to be able to deliver average EQ estimates with +/- 30 % of actual.

Figure 4. OTM 33A Controlled release trials using the PSG inverse estimate



As a related application, the PSG (or other) inverse emission estimation using nominal 20 minute stationary observations is also applicable to similarly-configured fixed-placed sensor systems designed to provide continuous observation of sites. Low-cost sensor prototypes in the class are described at this meeting.[32] An example of fixed-place application of the OTM 33A approach is shown in Figure 5, which additionally displays a bivariate polar plot of wind and CMI data that assists in locating the upwind emission point through simple back trajectory analysis. The sensor measurement point in this case would observe different parts of the site as the wind direction changed over time and could provide an alarm to the operator at onset of a malfunction.

Figure 5. Example of a fixed-place senor using OTM 33A inverse approach



OTM 33B: Mobile Tracer Correlation

Draft method OTM 33B (in development) differs from OTM 33A in the manner in which source emissions are quantified and in class of sources that can be measured. OTM 33B focuses on an EQ technique called mobile tracer correlation and aims to describe a relatively standardized version of this approach already in use by a number of research groups. The approach centers on controlled release of one or more atmospheric tracer gases with simultaneous downwind measurement of the emitted source plume and metered tracer with the source emissions rate determined through a simple ratio analysis. The technique has been demonstrated using a variety of tracer gases and CMIs to investigate emissions from landfills and other sources.[33-47]

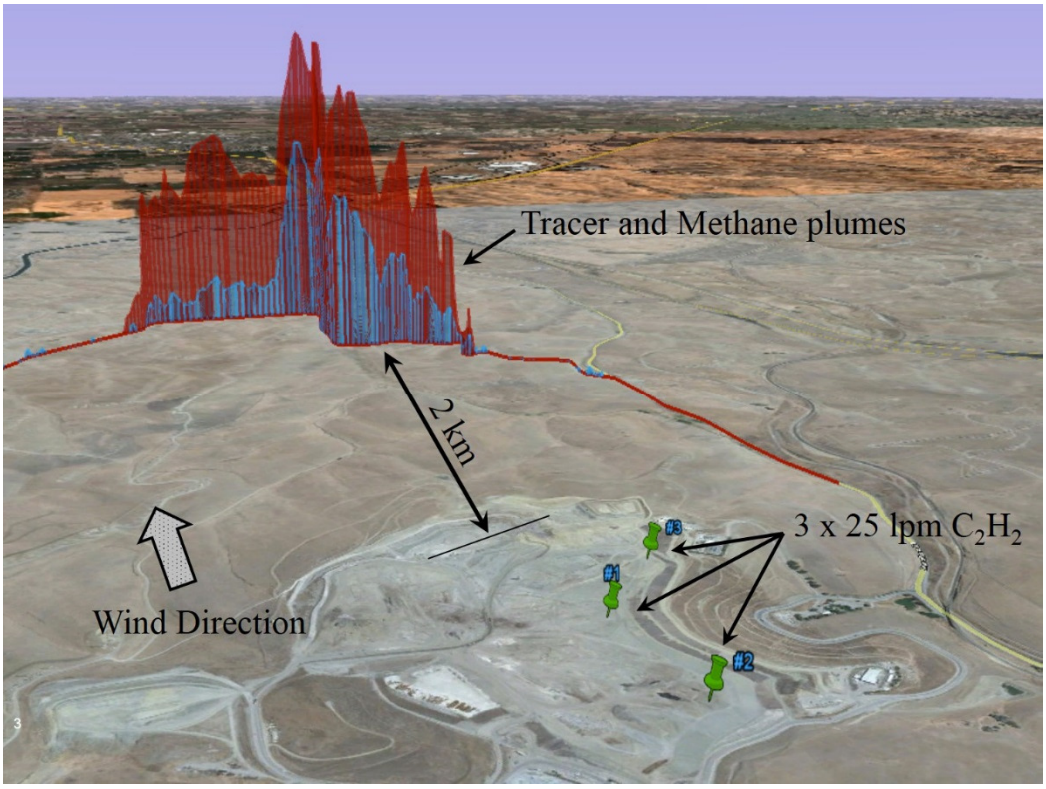
Whereas OTM 33A is designed to be a self-contained, rapidly executed inspection approach for point-like near-field sources, OTM 33B can be applied to both large and small sources. OTM 33B, is however more invasive with a higher execution burden, requiring site access and placement and operation of controlled tracer gas release gear. Whereas OTM 33A-use limitations are significant and EQ accuracy expectation is modest, OTM 33B employs the known release rate of the tracer to effectively eliminate atmospheric dispersion transport uncertainties and in principle, allowing high accuracy (< +/-15%) EQ to be obtained.

Figure 6 shows an example of mobile tracer correlation used to investigate emissions from a large area source, methane from a landfill in this case. Landfills are large in spatial extent with surfaces that allow placement of on-site tracer gas [here acetylene (C_2H_2)]. A simple multi-point tracer deployment strategy that is based on site geometry can result in well-mixed source and tracer plumes at far-field observing points. These "well-correlated" plumes help to provide confidence in calculation of the source rate emission (Qs), found to first order by:

$$Q_s = R_{s,t} * Q_t * M_{s,t} \qquad \text{(e.q. 1)}$$

where $R_{s,t}$ represents the ratio of the tracer to source analyte response (integrated area under the curve), Q_t is the known metered tracer release rate and $M_{s,t}$ is the ratio of molecular weights of source and tracer compuounds.[33,34,37,38,40] Details in the use of mobile tracer correlation for large area sources include the degree to which the tracer placement approximates the centroid of emissions, both along the mobile transect direction and perpendicular to it with the former presenting itself in the correlation analysis. Non-optimal tracer placement in the direction of plume transport will be not be detected in a correlation analysis and can result in positive or negative bias in the emission rate determination. Use of multiple transects under different wind directions (if roadways are available) can help elucidate tracer placement factors.

Figure 6. Example of OTM 33B mobile tracer correlation used for a landfill emission measurement. Red trace is methane and blue trace is acetylene



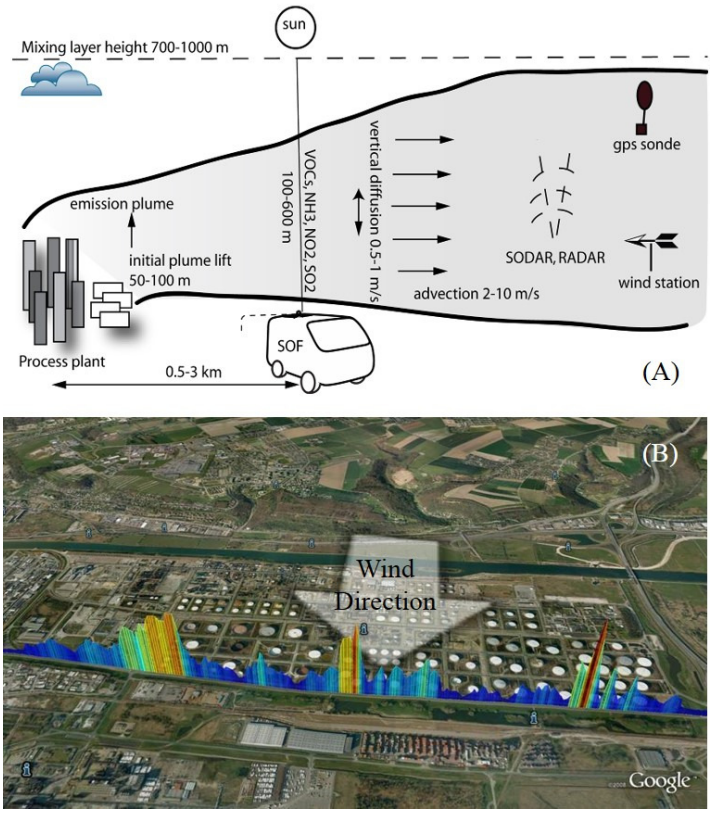
The development of a performance-based OTM 33B for large area source assessment centers on understanding baseline requirements, such as method detection limits, MQIs, and background subtraction procedures. These factors may depend on the tracer and CMI used and in some cases, on the specific application. A more challenging aspect for development OTM 33B is in the application of the method for near-field source assessment. A growing number of groups are using this mobile tracer correlation to understand emissions from a variety of small to mid-size facilities using measurement transects in the near- to mid-field. In this regime, the tracer-plume correlation MQI that is key for the large area source far-field case is not as useful here. Near-field applications involve placement of tracer gases somewhere near the source with mobile transects are sometimes executed in close proximity, usually delivering spatially separated plumes that may be difficult to correlate. Some groups are beginning to use multiple tracers at separated release points to help understand uncertainties associated with tracer placement in the

near-field case[47] or to investigate emissions from different areas of large sources.[40] A number of publications associated with emission assessment of upstream of oil and gas production facilities and natural gas distribution using near-field tracer release approaches are in process. These works will provide new information to assist in formulating OTM 33B for both the point-like sources (near-field) and large area source (far-field) applications. Additional information on OTM 33B will be provided in the presentation.

Mobile Solar Occultation Flux (FluxSense AB, Göteborg, Sweden)

There are a number of important emerging mobile measurement approaches that may be considered for OTM 33 sub-method development in the future (if appropriate). A few of these are briefly discussed here and in the presentation. The first is a powerful proprietary technique called mobile solar occultation flux (SOF) where a Fourier transform infrared spectrometer that uses the sun as a light source provides essentially an infinite flux plane capture of upwind source emissions.[48-53] This approach (Figure 7) relies on automated mobile tracking of light from the sun as the vehicle moves both upwind and downwind of the source under study (typically petrochemical facilities). Using analyte column concentrations retrieved from the background-corrected spectra and a knowledge of wind transport (at multiple heights), an EQ of the target source can be produced. As opposed to OTM 33A, there is essentially no chance for an elevated plume to be missed by this extended flux plane making even tall stack measurements possible. Limitations of the approach include vertical wind profile accuracy and that only compounds with little atmospheric background can be measured. For example, methane cannot currently be measured with mobile SOF due to the source signal's competition with the large integrated column background. The same research group is working a related mobile UV spectroscopy version based scattered light analysis that should allow additional compounds such as benzene to be measured. The mobile SOF techniques can only be operated in the daytime and works best on bright sunny days with few clouds and stable wind transport conditions. In principle, the SOF approach can be used on smaller point sources; however, the detection sensitivity of the approach would need to be evaluated and would be compound-specific. An excellent potential application for SOF may be assessment of ammonia (NH_3) emissions from large agricultural operations.

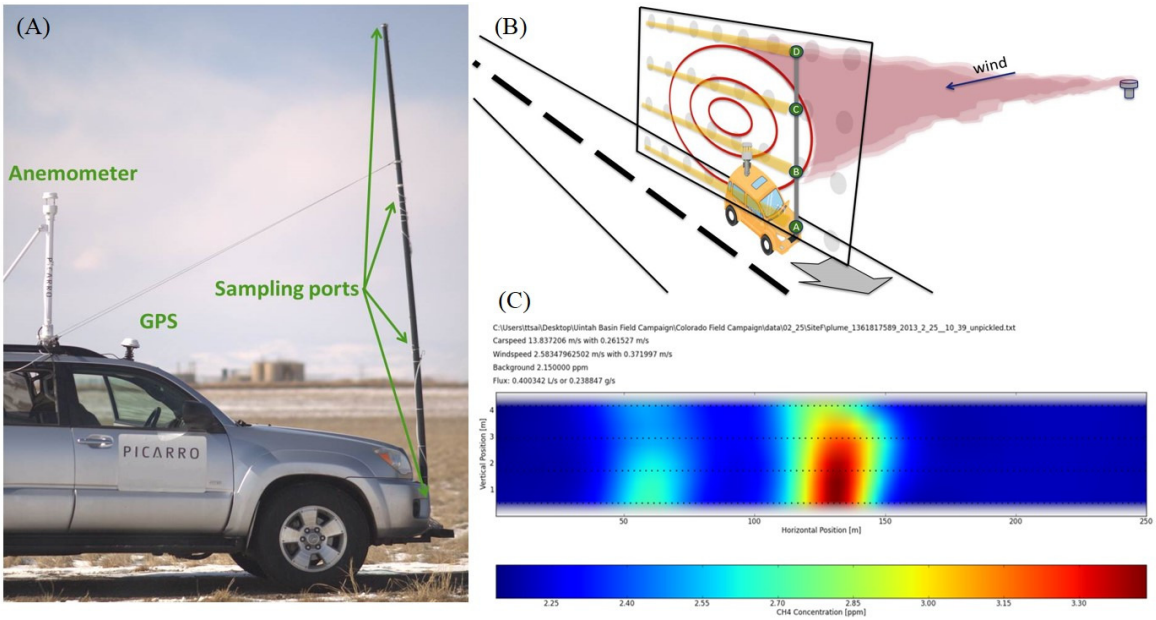
Figure 7. (A) Illustration of SOF, (B) example of column concentrations downwind of a tank farm. Courtesy of, adapted from J. Melquist[53]



Mobile Flux Plane (Picarro Inc. Santa Clara, CA USA)

As discussed, a primary application for OTM 33A EQ is near-field assessment of emissions from upstream oil and gas pads in open areas. Initial work on this topic was performed in collaboration with CMI manufacturer Picarro Inc. As EPA worked on OTM 33A approaches that would not be vendor-specific, Picarro continued to advance methane CM technology in the natural gas distribution space with their Surveyor™ technology.[20-22] Building off of these advancements, Picarro developed an EQ measurement called mobile flux plane (Figure 8) that was tested in part in collaboration with EPA and was used in key emerging research studies on methane emissions from oil and gas production.[54-56] The technique uses a single cavity ring down spectroscopy[57] CMI that samples multiple points on a vertically oriented mast (8A).

Figure 8. Picarro Mobile Flux Plane approach (A) vehicle with mast and multiple sampling points, (B) illustration of mobile flux plane, (C) Example of flux plane integration calculation to establish emission rate.



By driving through the emission plume, the vertical set of sampling points sweep out a plane. The emission calculation is based on a simple interpolated plane integration of the multipoint measurement (background subtracted) and the wind speed component perpendicular to the driving direction, determined while in motion by a properly oriented 2-D sonic anemometer.

The mobile flux plane approach has similar application requirements to OTM 33A (roadway proximate sources in open areas, wind transport). However, instead of producing an EQ estimate based on a 20 minute stationary observation, the mobile flux plane produces an instanteous picture of emissions as it drives through the advected plume. With this approach, some of the EQ inaccuracies seen in OTM 33A associated with the representativeness of the ensemble averages are eliminated. Both techniques share issues with underestimates due to lofted plumes and some biases caused by plume meandering effects. The drive-by measure is more easily executed and represents an instanteous picture of emissions capturing the state of a source at a particular point in time. This instantaneous measure can be a consideration for short term, non-sustained emissions such as flash emissions from condensate tanks.[58,59] To sample from multiple points with a single CMI, the technique uses a long sampling tube to "store and playback" the acquired

plume signal. The storage aspect of the measurement would limit application to compounds that can be handled robustly in that manner an currently only methane has been demonstrated.

Single Point Mobile - Towards Automated Work Truck Monitoring

With preliminary investigations associated with mobile tracer correlation studies, several research groups are considering tracer-free drive-by source measurement using single-point sampling coupled with inverse modeling, to estimate emissions for both near-field and large area sources applications.[31,33,34,60-63] Without benefit of time averaging or multi-point vertical sampling in the near-field or atmospheric dispersion information via tracers in the far field, the single-point drive-by measurements are likely to be of lower accuracy than previously described approaches. However, for what this approach class lacks in single measurement accuracy, it gains with regard to simplicity in implementation which could lead to statistical oversampling power. The lower cost, robust, and fully automated single-point sensors of the future, coupled with "data to the cloud" concepts, may facilitate applications such as instrumented work trucks. These future in-facility and in-field work truck sensors may help form the foundation of next-generation leak detection and repair concepts in multiple sectors; reducing emissions, making safer working environments, and saving companies money. Through advanced algorithms, data mined from routine work truck use may assist in reconciliation of emission inventories and verification of voluntary emissions reductions programs in the future.

SUMMARY

This conference paper and associated presentation provides an update on EPA's efforts to facilitate development of mobile source emissions measurement approaches though the OTM 33 method series. A general description of several approaches were provided with a focus on sub-method OTM 33A, a technique for assessment of ground-level point sources such as may be encountered in oil and gas production fields. Other techniques, such as mobile tracer correlation (potentially OTM 33B), Mobile SOF, flux plane, and single point drive-by approaches were briefly introduced with some strengths, weaknesses and applications discussed. Some aspects of these approaches are further summarized in Table 1. Periodic updates on progress in the development and revisions in the OTM 33 series are planned as part of future AWMA and other relevant conferences.

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authors and do not necessarily represent the views or policies of the U.S. EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Table 1. Summary mobile measurement approaches.

	OTM 33A	OTM 33B (Near-field)	OTM 33B (Far-field)	Mobile SOF	Mobile Flux Plane	Work Truck
CM, SC (various types)	✓	✓	✓	✓	✓	✓
EQ Approach	Stationary single point / inverse model	Tracer correlation	Tracer correlation	Extended flux plane / integration	Finite flux plane / integration	Mobile single point / inverse model
Primary Source Type	Point-like	Point-like	Large area / facility	Large area / facility	Point-like	Point / area
Distance to Source (m)*	20 - 150	50 - 300	300 - 4000	500 - 3000	20 - 150	20 - 500
Elevated Source	_	Possible	Possible	✓	_	_
EQ Observation Mode	20 min. stationary	Drive-by	Drive-by	Drive-by	Drive-by	Drive-by / stationary
Analyte Limitations	CMI-limited	CMI-limited	CMI-limited	Column background limited	CMI and storage tube-limited	CMI / sensor cost limited
Site Access Required	_	✓	✓	_	_	_
Key Use Limitation	Open areas / meteorological	Road access / meteorological	Road access / meteorological	Road access / sunny conditions	Open areas / meteorological	Meteorological
Anticipated Accuracy Goals*	< 30%	< 15%	< 15 %	< 20%	< 20%	< 50%
Application Cost	low	mid	mid	low/mid	low	very low
* approximate values based on current information						

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KEYWORDS

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