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# Atmospheric tomography: a bayesian inversion technique for determining the rate and location of fugitive emissions

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## **Abstract**

A Bayesian inversion technique to determine the location and strength of trace gas emissions from a point source in open air is presented. It was tested using atmospheric measurements of N<sub>2</sub>O and CO<sub>2</sub> released at known rates from a source located within an array of eight evenly spaced sampling points on a 20 m radius circle. The analysis requires knowledge of concentration enhancement downwind of the source and the normalized, three-dimensional distribution (shape) of concentration in the dispersion plume. The influence of varying background concentrations of ~1% for N<sub>2</sub>O and ~10% for CO<sub>2</sub> was removed by subtracting upwind concentrations from those downwind of the source to yield only concentration enhancements. Continuous measurements of turbulent wind and temperature statistics were used to model the dispersion plume. The analysis localized the source to within 0.8 m of the true position and the emission rates were determined to better than 3% accuracy. This technique will be useful in assurance monitoring for geological storage of CO<sub>2</sub> and for applications requiring knowledge of the location and rate of fugitive emissions

## **Keywords**

technique, determining, emissions, inversion, fugitive, tomography, location, rate, bayesian, atmospheric, GeoQUEST

## **Disciplines**

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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# Atmospheric Tomography: A Bayesian inversion technique for determining the rate and location of fugitive emissions.

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## Abstract

A Bayesian inversion technique to determine the location and strength of trace gas emissions from a point source in open air is presented. It was tested using atmospheric measurements of N<sub>2</sub>O and CO<sub>2</sub> released at known rates from a source located within an array of eight evenly spaced sampling points on a 20 m radius circle. The analysis requires knowledge of concentration enhancement downwind of the source and the normalized, three-dimensional distribution (shape) of concentration in the dispersion plume. The influence of varying background concentrations of ~1% for N<sub>2</sub>O and ~10% for CO<sub>2</sub> was removed by subtracting upwind concentrations from those downwind of the source to yield only concentration enhancements. Continuous measurements of turbulent wind and temperature statistics were used to model the dispersion plume. The analysis localized the source to within 0.8 m of the true position and the emission rates were determined to better than 3% accuracy. This technique will be useful in assurance monitoring for geological storage of CO<sub>2</sub> and for applications requiring knowledge of the location and rate of fugitive emissions.

## 1 Introduction

Carbon capture and storage (CCS) is an emerging technology for reducing CO<sub>2</sub> emissions to the atmosphere [1]. Because of the associated energy and carbon costs in CCS, even a small rate of leakage from geological storage over a prolonged period could result in more CO<sub>2</sub> being emitted in the long-term than would otherwise occur [1-3]. Reliable monitoring techniques must therefore be developed to locate and quantify leakages in order to fix leaks, confirm the long-term benefit of CCS to mitigating climate change and to underpin credits needed for carbon pricing schemes.

Many techniques are available for monitoring geologically stored CO<sub>2</sub> above and below ground [4] but direct atmospheric measurements of leakage have the advantage of focusing on the key purpose of CCS. A concise review of inversion analyses of concentration data to recover source strength and location is given by Shankar Rao [5]. Bayesian methods have been used extensively in large-scale atmospheric modeling, and have also been advocated and used for inversions on smaller scales with data captured over short periods in steady winds. A comprehensive summary of Bayesian inversion and its advantages is given by Yee and Flesch [6], with numerous other expansive studies undertaken [7-11]. Of particular importance are the abilities of Bayesian methods to incorporate prior information, to independently solve for the probability distribution of individual parameters, to quantify uncertainties from measurements and models, and to generalize to quite complex cases [8]. Bayesian inversion is conceptually quite distinct from parameter estimation of assumed source distributions (e.g. [12]), although in simple cases, can appear mathematically similar.

In the current paper, Bayesian model inversion techniques are combined with knowledge of the, three-dimensional distribution (shape) of concentration in the dispersion plume to provide both the position and strength of a source using concentrations measured at points surrounding a suspected source. Unlike previous studies which used tracers with minimally varying backgrounds [6, 7, 9, 10, 13], this study investigates small, hypothetical CCS leaks [3] which involve increases in CO<sub>2</sub> concentrations of only a few parts per million (ppm) above a typical diurnal range of 370 to 500 ppm [14, 15]. The influence of this background variability can be reduced considerably using an array of sensors that encircle the suspected leak location. Some sensors will then be upwind of the source irrespective of wind direction, thereby allowing the variable background concentration to be subtracted from the downwind measurement. Because such leaks are likely to be small and long-term [1], monitoring can be performed over long periods, allowing errors in background estimations to average away. Hence, perturbations which may be less than the variability of the background can be detected. Multiple wind directions are exploited to localize sources and determine their strength making the analysis analogous to tomographic imaging. The large data set associated with this long-term monitoring scheme also facilitates selection of favorable periods, such as day-time, when background concentrations are relatively steady.

Although Bayes' theorem can be applied to quite complex cases, this paper will describe the simplest and most accurate application where the leak is spatially small and temporally constant. The use of Bayes' theorem to determine the position and strength of emission sources is presented in detail elsewhere (e.g. [6, 7]) and only a brief outline is given here. The paper presents results of a small-scale field experiment designed to test the ability of this approach to determine both the position and source strengths of both CO<sub>2</sub> and a tracer (N<sub>2</sub>O), released at known rates over several months under a range of meteorological conditions. The potential utility of atmospheric tomography for monitoring emissions from CO<sub>2</sub> geological storage sites is also discussed.

## 2 Materials and Methods

### 2.1 Field Site

Measurements were made from 1 July to 30 October 2010 at the CSIRO Ginninderra Experiment Station near Canberra, Australia. The site, shown in Figure 1, was a flat, recently ploughed field surrounded by others used for sheep grazing and cropping. A 6 m high earth-fill dam wall was 150 m north-west of the release point. A caravan and shed housing the instrumentation were located ~35 m west-north-west of the release point. Average temperature during the four-month campaign was 8°C (range -3°C to 25°C). Mean rainfall was 72 mm month<sup>-1</sup> and north-west winds occurred > 60% of the time.

**Figure 1:** Schematic representation of the experimental site. The numbered yellow dots indicate air intake positions, Source 1 is the location of both the CO<sub>2</sub> and N<sub>2</sub>O release from the centre, and Source 2 is where the N<sub>2</sub>O was moved after some time for the blind test.

### 2.2 Emission Sources

Mass flow controllers controlled the simultaneous release of N<sub>2</sub>O and CO<sub>2</sub>, piped via Dekabon® tubing to a mixing chamber, 0.30 m above ground. N<sub>2</sub>O was released at 1.070 ± 0.04 g min<sup>-1</sup>, the rate required to get at least 10 % (~30 ppb) enhancement at downwind sampling points in most atmospheric conditions. CO<sub>2</sub> was released at 56.65 ± 0.8 g min<sup>-1</sup>, chosen to simulate a leak barely detectable above background variability in unstable, well-mixed conditions when background concentrations approximated a normal distribution with a standard deviation of 3.5 ppm. Figure 1 shows the two locations of the source during the campaign: Source 1 at the centre of the circle (known); and Source 2, which was unknown prior to the inverse analysis.

### 2.3 Concentration Measurements

Figure 1 shows the eight sampling points positioned every 45° on a 20 m radius. Air from intakes at 1.5 m above ground was pumped continuously through equal lengths of conjoined polyethylene and Dekabon® tubing (to minimize adsorption or migration of atmospheric constituents across tube walls) that was insulated and kept ~1 m above the ground to prevent condensation of water in the lines. An auxiliary switching manifold that allowed continuous flushing and autonomous switching of all 8 sampling lines was used to sample air into a Fourier Transform Infrared (FTIR) Spectrometer [16] for analysis of CO<sub>2</sub> and N<sub>2</sub>O mixing ratios. All sampling lines were filtered at sampling points and before lines entered instrumentation (AF20-02-C, SMC Pneumatics, Sydney, NSW, Australia) then dried using Nafion® membrane and magnesium perchlorate prior to entering the FTIR. All 8 lines were analyzed sequentially within a 30 minute period, allowing enough time for FTIR precision of 0.025 ppm for CO<sub>2</sub> and 0.1 ppb for N<sub>2</sub>O to be attained, but quick enough to

characterize changing atmospheric conditions. Air from radially-opposite intakes was analyzed sequentially to minimize the delay between upwind and downwind measurements.

## 2.4 Micrometeorology Measurements

Temperature and the  $x$ ,  $y$ , and  $z$  components of the wind vector were measured at 20 Hz using a three-dimensional sonic anemometer (Type HS, Gill Instruments Ltd., Lymington, UK) mounted at 1.42 m. These data provided the Monin-Obukhov stability parameter (MO length,  $L$ , [17]), friction velocity,  $u^*$ , mean horizontal wind speed,  $U$ , and wind direction,  $\theta$ . These quantities are required to model the shape and direction of the dispersion plume downwind of the source. The MO length provides a measure of atmospheric stability that controls horizontal and vertical mixing in the surface boundary layer, while friction velocity is a measure of the flux density of momentum to the surface. Using these turbulence statistics, the shape of the down-wind concentration plume can be calculated by a stochastic Lagrangian method [18, 19]. Because the MO theory for dispersion is unreliable under light wind conditions, both FTIR and micrometeorological data were removed when  $u^* \leq 0.15 \text{ m s}^{-1}$  [20].

## 2.5 Data Analysis: Bayesian Tomography

Estimating the position and strength of the source from a sensor network is an ill-posed inverse problem, which does not have a unique solution because of noise in the data and inadequacies in the dispersion model. As discussed in detail by Keats et al. [7] and by Yee and Flesch [6], the most probable solution may be determined using Bayes' Theorem to determine probability distributions for the locations and source strengths of fugitive emissions given experimental data,  $D$ , (background-subtracted concentrations, meteorological data and a dispersion model) and prior information (likely number of sources and their approximate location). The Bayesian method has the advantage of being able to handle a wide range of assumptions in its applications. In the current study, the simplest case is adopted.

For the simplest case of a single, continuous and steady source, Bayes' Theorem states [6, 7]

$$P(s, x_0, y_0 | D) = \frac{P(D | s, x_0, y_0)P(s, x_0, y_0)}{P(D)} \quad (1)$$

where  $P(s, x_0, y_0 | D)$  is the *posterior probability* of a source with strength  $s$  located at  $(x_0, y_0)$  given the data  $D$ ;  $P(D | s, x_0, y_0)$  is the *likelihood* of  $D$  given  $s$ ,  $x_0$  and  $y_0$ , and  $P(s, x_0, y_0)$  is the *prior probability* of  $s$ ,  $x_0$  and  $y_0$  that is assigned before data are obtained. The normalizing factor,  $P(D)$  is the *evidence*. It is not needed in our application but could be used to test the plausibility of competing models, e.g. a point vs. line source.

The likelihood can be calculated if the probability distribution of errors in the data is known. In this application, the prior captures the preexisting knowledge that the source is most likely located

within the sensor array. Both the prior and the likelihood can be expressed analytically and a function can be formed for the posterior probability,  $P(s, x_0, y_0 | D)$ .

### 2.5.1 Plume Functions

A Lagrangian stochastic (LS) model [18], as implemented in the WindTrax software (Thunder Beach Scientific, Nanaimo, Canada), was used to calculate plume shapes for the range of stability classes encountered during the field campaign. Run in forward mode,  $10^5$  ‘particles’ were released and their unique paths tracked to develop a plume shape for each stability class. Model concentrations were sampled at a height of 1.5 m, every 0.5 m over a 50 m x 50 m grid.

The computed plume shapes calculated using the LS model are noisy because of the finite number of particles released. They are also time-consuming to calculate and it was computationally more efficient to fit the following interpolation function, based on the theoretical cross-wind integrated function described by Hsieh *et al.* [21], to the 2-dimensional plume shapes at 1.5 m calculated using the LS model:

$$f(x, y, x_0, y_0, s) = f(x - x_0, y - y_0, s) = \frac{a s}{(x - x_0)^\alpha} e^{-\frac{d}{(x - x_0)^\zeta} - (y - y_0)^2 \frac{(b + (x - x_0)^\beta)^2}{c(x - x_0)^\gamma}} \quad (2)$$

where  $x$  and  $y$  are distances downwind and crosswind of the source at  $(x_0, y_0)$  respectively,  $s$  is the source strength, and the parameters  $a, b, c, d, \alpha, \beta, \gamma, \zeta$  were calculated separately for each defined stability class. Plume functions can be rotated to lie along the wind direction using a standard rotation matrix applied to the displacement vector of the argument of the plume equation. This enabled the measured wind direction for any particular period to be utilized in calculations.

### 2.5.2 Background Concentrations

A two-stage iteration was used to calculate background concentrations. The first iteration used measurements on the upwind air intake of the opposing member of the pair most closely aligned with the wind direction. This value was subtracted from measurements of concentration in the downwind intake and used with the inverse analysis to give the first estimate of the location and strength of the source. These results, combined with appropriate wind direction and modeled plumes, were used to identify those air intakes unaffected by the release. The identified unaffected air intake measurements were averaged to provide a second estimate of background concentration and an improved estimate of source position and strength. This second iteration enabled extraction of up to 7 perturbations within each 30 minute measurement period, dependent on stability conditions.

### 2.5.3 Calculating the Likelihood, $P(D|s, x_0, y_0)$

Suppose  $f(x, y, x_0, y_0, \theta, L)$  is a function (equation (2)) giving the mixing ratio, for a unit source strength, at position  $(x, y)$ , when the source is at  $(x_0, y_0)$ , the wind direction is  $\theta$  and the Monin-Obukhov length is  $L$ . This function can be used to predict the concentration at each sensor, given the

measured values of  $\theta$  and  $L$  and multiplying by the source strength,  $s$ . For the  $i^{\text{th}}$  measurement, if the error distribution is Gaussian with a standard deviation,  $\sigma_i$ , the probability,  $P_i$ , for measuring the observed concentration,  $c(x_i, y_i, \theta_i, L_i)$ , is [22]

$$P_i \propto e^{-\frac{(c(x_i, y_i, \theta_i, L_i) - s f(x_i, y_i, x_0, y_0, \theta_i, L_i))^2}{2\sigma_i^2}} \quad (3)$$

The probability of the  $N$  measurements is  $P = \prod P_i$ . If  $\sigma_i$  is constant, then we define

$$\chi^2 = \frac{1}{2\sigma^2} \sum_i^N (c(x_i, y_i, \theta_i, L_i) - s f(x_i, y_i, x_0, y_0, \theta_i, L_i))^2 \quad (4)$$

the likelihood becomes

$$P = \prod P_i \propto e^{-\chi^2} \quad (5)$$

#### 2.5.4 Estimating the Prior, $P(s, x_0, y_0)$

The prior expresses what is known before any experimental data are obtained. It decreases in importance as the number of experimental measurements increases. It is assumed that the source is located somewhere inside our array of sensors, and is spatially small and weak. If  $s$ ,  $x_0$ , and  $y_0$  are statistically independent of each other,

$$P(s, x_0, y_0) = P(s)P(x_0)P(y_0) \quad (6)$$

By assumption, the probability of finding the source in the area within the sensor array is finite, and drops quickly to zero outside this area.  $P(x_0)$  and  $P(y_0)$  can be taken to be Gaussian around  $(x_0, y_0)$  such that,

$$P(x_0) = \sum_i^8 e^{-\frac{(x_i - x_0)^2}{2w^2}} \quad (7)$$

where  $x_i$  is the  $x$  coordinate of sensor  $i$ , and  $w$  is a constant indicating the prior uncertainty in the location, set to 20 m for this experiment. A similar equation can be written for  $P(y_0)$ .

Since the probability of a scaled variable is being considered, the most agnostic prior that can be adopted is commonly known as Jeffreys' prior [23, 24]:

$$P(s) \propto \frac{1}{s} \quad (8)$$

This prior suits this problem well because it favours small leaks, the target of this technique. The model will produce a poor fit if the actual leak is large or variable, indicating the prior may have to be generalised. A complete Bayesian analysis would use several competing models for source and plume geometry to determine their posterior probability. Here the focus is on the simple situation of one plausible model.



### 2.5.5 Marginalization

Marginalization is an important step in the analysis which allows independent calculation of either location or source strength. Marginalization involves integrating the probability distribution over a subset of unknown variables in order to calculate a probability that is a function only of the remaining variable(s). The probability distribution for location is calculated by elimination of the source strength:

$$P(x_0, y_0 | D) = \int_{s_l}^{s_u} P(s, x_0, y_0 | D) ds \quad (9)$$

where  $s_u$  and  $s_l$  are upper and lower limits of the range of plausible values of source strength respectively. The source strength probability distribution is calculated similarly:

$$P(s | D) = \int_{x_{0l}}^{x_{0u}} \int_{y_{0l}}^{y_{0u}} P(s, x_0, y_0 | D) dy_0 dx_0 \quad (10)$$

where  $x_{0u}$ ,  $x_{0l}$ ,  $y_{0u}$  and  $y_{0l}$  are the upper and lower limits of the range of plausible values of the source location coordinates. The integrand of the above integrals has the form

$$P(s, x_0, y_0 | D) = \frac{1}{sP(D)} g(x_0, y_0) e^{-\chi^2} \quad (11)$$

where  $g(x_0, y_0)$  is a product of equation (7) for both  $x_0$  and  $y_0$ ,  $P(D)$  is the evidence, and  $\chi^2$  is a function of  $s$ ,  $x_0$  and  $y_0$  (equation (4)). This function contains  $N$  terms in  $\chi^2$  alone, each with exponential functions meaning that integrations had to be performed numerically. Determination of the most likely values and uncertainties of  $s$ ,  $x_0$  and  $y_0$  were done by inspection of the probability distributions of each variable, which were calculated and plotted over the integral domain using Wolfram Mathematica software (Wolfram Research, Inc., Champaign, USA).

## 3 Results

### 3.1 Background Characterization

Atmospheric N<sub>2</sub>O concentrations recorded for five weeks prior to N<sub>2</sub>O release showed that the FTIR analyzer (1 $\sigma$  repeatability ~0.1 ppb for N<sub>2</sub>O) could resolve the low background variability in N<sub>2</sub>O (2.2 ppb short-term, 8 ppb long-term). Variations in N<sub>2</sub>O concentrations seen in Figure 2 are caused by the changing activity of N<sub>2</sub>O emitting soil bacteria (longer term variation) and emitted N<sub>2</sub>O mixing into a surface boundary of variable depth during the diurnal cycle of atmospheric stability (shorter term variation). This same interaction between boundary layer depth with local sinks and sources (daytime photosynthesis and nighttime respiration for CO<sub>2</sub> respectively) causes background CO<sub>2</sub> concentrations to vary from 380 – 500 ppm (Figure 2).

Detection of small, short term increases in concentrations above background levels is required as the release plume passes over a sensor. Background concentrations of CO<sub>2</sub> vary on similar timescales to these perturbations making the Bayesian analysis for CO<sub>2</sub> more difficult than for N<sub>2</sub>O.

Examination of the no-release data obtained over several weeks showed that errors in the background-subtracted concentrations decrease as  $N^{1/2}$  as expected for uncorrelated fluctuations ( $N$  is the number of measurements). If drifts in the instrument calibration are small or can be measured, the combination of averaging and Bayesian model-fitting should allow the effective use of data where the concentration perturbations due to sources are well below the instantaneous noise level.

**Figure 2:** Background variability of N<sub>2</sub>O (top) and CO<sub>2</sub> (bottom). N<sub>2</sub>O is significantly more stable compared to CO<sub>2</sub>. This high relative stability is caused by weaker sources and sinks of N<sub>2</sub>O.

## 3.2 Atmospheric Tomography

### 3.2.1 Simulated Data

The analysis scheme was first tested using simulated data as input. An array of wind direction ( $\theta$ ) and stability conditions ( $L$ ) was generated at random within suitable ranges and the forward model was used to calculate concentrations at all sensor locations from sources at various positions. A noise component was added from a normal distribution with  $\mu = 0$  ppm and  $\sigma = 20$  ppm. This procedure generated realistic simulated data which were then used as input to the Bayesian inversion.

Analyses of the simulated datasets showed no systematic errors in the code. The source strength was estimated accurately with a precision determined solely by the number of data points used. The analyses located the sources to within 1 m, regardless of their position within the sensor array (data not shown). This corresponds to an uncertainty of 5% of the radius of the sensor array. Results were similar even when the source was placed outside the array (e.g. 30 m, -30 m).

### 3.2.2 N<sub>2</sub>O at Origin

N<sub>2</sub>O was released at a rate of  $1.070 \pm 0.04$  g min<sup>-1</sup> at the centre of the ring of sensors (referred to hereafter as the origin) between 12 August and 12 October 2010. This resulted in a ~30 ppb increase in mixing ratio at sensors 20 m downwind from the source under well-mixed daytime conditions and > 300 ppb under stable, nighttime conditions (Figure 2, [Supporting Information](#)).

Figure 3 shows that the logarithmic posterior probability distribution for the source location has a narrow ridge along the prominent north-westerly wind direction (78% of the 1569 measurement periods consisted of plumes directed over sensor 3). The peak is taken as the most likely source location at (0.0 m, 0.0 m) with peak shape represented by an ellipse with major and minor semi-axes of 0.9 m and 0.4 m ( $2\sigma$ ) respectively, rotated 60° east of north. Using a smaller dataset (65% of data removed) with a more even distribution of wind directions gave a more symmetrical probability distribution for the source location, with a narrower peak with major and minor semi-axes 0.1 m each, still rotated 60° east of north (Figure 3 in [Supporting Information](#)).

The accuracy and precision in calculating the source strength increases with more data, independent of wind direction. Using the full data set, the source strength was determined (Figure 3) to be  $1.103 \pm 0.06 \text{ g min}^{-1}$  ( $\mu \pm 2\sigma$ ), which was within 3.1% of the correct value.

**Figure 3:** Probability distributions calculated using the full set of experimental data collected while  $\text{N}_2\text{O}$  was being released at  $1.070 \pm 0.04 \text{ g min}^{-1}$  from the origin. The location probability distribution (log scale) shows the effect of sensor locations and the dominant wind direction on the distribution. The probability distribution for source strength, with a peak at  $1.103 \pm 0.06 \text{ g min}^{-1}$ , shows excellent accuracy and precision (red curve) comparable to the true release (purple bar).

### 3.2.3 $\text{N}_2\text{O}$ at Unknown Location

The  $\text{N}_2\text{O}$  source was repositioned to a location initially unknown to the analysis team from 12 - 30 October while the  $\text{N}_2\text{O}$  release rate remained unchanged. Filtering out ~50% of the data to give an even distribution of wind directions, the analysis placed the source at (6.2 m, 0.5 m), just 0.8 m from the actual location at (6.4 m, 1.3 m), with an uncertainty described by elliptical peak axes ( $2\sigma$ ): major 3.7 m; minor 1.0 m; rotated  $60^\circ$  east of north (Figure 4, [Supporting Information](#)). The error in source location is 4% when normalized by the radius of the instrument array. Source strength calculated using all available data was  $1.12 \pm 0.1 \text{ g min}^{-1}$ , within 4.7% of the correct value. Due to the much smaller data set (18 days, 438 measurement periods), results of this analysis were less accurate than for release at the origin (61 days, 1569 measurement periods).

### 3.2.4 $\text{CO}_2$ at Origin

Release of  $\text{CO}_2$  occurred between 10 September and 30 October 2010 at a rate of  $56.65 \pm 0.8 \text{ g min}^{-1}$ . Peaks in  $\text{CO}_2$  concentration during the release period are seen in Figure 4 to be clearly discernible, particularly when background concentrations were comparatively stable under well-mixed atmospheric conditions. These enhancements were just 1% of background concentrations. Atmospheric mixing was generally suppressed at night and resulted in high and variable concentrations and low  $u^*$  values. Much of the data for these periods were not used in the analysis.

**Figure 4:** Raw  $\text{CO}_2$  mixing ratios from all 8 sampling locations measured over two consecutive nights during  $\text{CO}_2$  release at  $56.65 \pm 0.8 \text{ g min}^{-1}$ . Perturbations in concentrations are discernible from background variations during well mixed conditions in the daytime and on the night of 18 September. Concentrations vary greatly during stable overnight conditions (e.g. on the night of 19 September), making it difficult to discern perturbations in the data due to the source. The inset shows the variation in  $\text{CO}_2$  mixing ratios measured sequentially at each of the 8 inlets (solid line) and the first iteration of background-subtracted values (connected dots). The latter are generally  $< 1\text{ppm}$  except for the sensor downwind of the source.

Good localization of the source was achieved using the 50 day (1000 measurement periods) data set, shown in Figure 5. The distribution in the logarithmic posterior probability plot is similar to

that for the N<sub>2</sub>O source. Using a dataset with ~45% of data removed for even weighting of wind directions, the peak of the probability distribution for the source at (-0.5 m, 0.5 m) was within 0.8 m (4%) of the true position (0 m, 0 m), with uncertainty described by elliptical peak axes (2 $\sigma$ ): major 1.1 m; minor 0.6 m; rotated 60° east of north. The estimated source strength was  $54.9 \pm 4 \text{ g min}^{-1}$  ( $\mu \pm 2\sigma$ ), statistically equal to the true value. Compared to results for N<sub>2</sub>O, the larger errors for CO<sub>2</sub> source location and strength were due to the smaller concentration perturbations relative to background (CO<sub>2</sub>  $\approx$  1%, N<sub>2</sub>O  $\approx$  36%), the smaller number of measurements, and the difference in wind direction data caused by different timing of respective releases.

**Figure 5:** Probability distributions for experimental data collected while CO<sub>2</sub> was being released at  $56.65 \pm 0.8 \text{ g min}^{-1}$  from the origin. The location distribution was calculated using a reduced, more evenly weighted data set, while the source strength distribution was calculated using the full data set available for analysis.

### 3.2.5 Determining the required number of measurements

The number of measurements necessary for accurate localization of the source depends strongly on having a variety of wind directions, while for source strength, the most important factor is having a large number of measurements under a range of stability conditions. The time required for convergence depends on the required accuracy of a particular application. Figure 5 in the [Supporting Information](#) shows convergence to within 5% of the correct source strength with ~1000 measurements (at a rate of up to 14 per hour when  $u^* > 0.15 \text{ m s}^{-1}$  in our field experiment).

### 3.2.6 Importance of characterizing dispersion

The effect of model errors was tested by creating simulated data with a range of stability conditions, but analyzing using only one plume. Results showed that localization remained just as accurate, although became less precise, while for source strength, both accuracy and precision were affected by up to 30%. This result suggests that errors in dispersion models will provide complications, however the method employed here is robust enough to deal with it, producing useful, albeit lower quality results.

## 4 Discussion

The tomographic technique used in this study has been shown to determine both source strength and location well on a small scale, using high-precision instrumentation to measure concentration perturbations. Pumps and tubing were used to sample air for analysis in this field experiment but this is unlikely to be practical for applications at larger scales. At these scales, a network of independent sensors will need to be deployed, likely lowering the resolution of the technique because of inherent inter-sensor variability.

Simple linear scaling of experimental results combined with Lagrangian stochastic modeling under various atmospheric stabilities suggests that for a sensor located 1 km downwind, a point source

emission of  $\sim 5 \text{ kg min}^{-1}$  would be required in all but the most turbulent conditions to increase  $\text{CO}_2$  concentrations by the required 1% above background (in the most unstable conditions, the required emission rate increases by a factor of  $\sim 3$ ). This equates to a detectable emission of  $2.6 \text{ kt CO}_2 \text{ yr}^{-1}$ . Enting et al. [3] calculate that for CCS to be beneficial in the long-term, a leak rate below 0.01% per year is required. This equates to a leak rate of  $1000 \text{ t yr}^{-1}$ , assuming a modestly-sized industrial storage site of 10 Gt. The required measurement time depends on required accuracy, the source strength, atmospheric stability, topography and the distances between sources and detectors.

More complex situations such as multiple sources, or the optimum location of extra detectors, can be handled in the Bayesian framework [8, 23]. Complex spatial sources, including multiple point, line and area sources [5-7] can be analyzed by the tomographic method by acquiring data from enough distinct wind directions for disambiguation. In the current analysis, temporally varying sources are not resolved but rather the average rate is calculated. Time resolved rates could be calculated by solving for source strengths within time sub-sets of data. More complex terrain will introduce more complex dispersion which, as discussed in Section 3.2.6, appears likely to increase the uncertainty in source strength, but may affect the determination of location less. Geological storage will probably mostly occur in sedimentary basins which often have low relief, so terrain may not be as much of a problem as it first seems. In real-world situations, background concentrations may also be more variable because of the greater heterogeneity of sources and sinks.

In addition to measurements of total  $\text{CO}_2$ , natural ( $^{13}\text{CO}_2$ ,  $^{14}\text{CO}_2$ ,  $\text{CH}_4$ ,) and man-made ( $\text{SF}_6$ ) tracers in the geologically stored  $\text{CO}_2$  will assist in the detection, attribution and quantification of any emissions [7, 25, 26]. Atmospheric measurements alone are unlikely to have to bear the entire burden of the proof of a leak though. With early knowledge of the approximate location of a leak, additional measurements such as soil  $\text{CO}_2$  flux and concentration measurements could be made to confirm predictions from atmospheric measurements.

Although qualitative short term ( $\sim 1$  week) localization is possible, high accuracy, quantitative localization is largely dependent on having data from a variety of wind directions, meaning that long term monitoring applications of this technique are ideal as they allow time for the variety of wind directions to be collected as well as the detection of perturbations of species in environments with highly variable backgrounds (e.g.  $\text{CO}_2$ ). Possible areas of application include industrial emission verification (see Table 1 in [Supporting Information](#)) investigation of GHG emissions from groundwater bores, air pollution monitoring, and localizing fugitive emissions from gas wells, coal mines, pipelines and other oil and gas operations [27].

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Supporting Information Available. This information is available free of charge via the Internet at <http://pubs/acs/org>.

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