Reviewer 2

Review of “Development of a Forced Advection Sampling Technique (FAST) for Quantification of Methane Emissions from Orphaned Wells”

December 24th 2024

Dubey et al. make measurements of methane emissions from orphaned wells using a new Forced Advection Sampling Technique (FAST). This technique places a fan upwind of a suspected point source, which blows the emissions toward a measurement location. Using measurements of the wind speed and some plume shape assumptions, they calculate an emissions rate. Their technique is compared with results from a SEMTECH HI-FLOW backpack in a controlled release experiment, and then used to determine emission rates from 4 real-world orphaned wells.

This paper investigated a new technique for determining natural gas emissions from orphaned wells. As such, it is worthy of publication. However, this reviewer would like to see some extra information in the discussion and results before I think it’s ready for publication.

Some discussion of the filter angle needs to be included in the methods section of the text. It is hinted at in Figure 5, but never really discussed. In Figure 4, the caption says data were filtered to remove points coming from the negative x direction (180 degrees). How many points were these relative to the total? Later, a filter of 300 degrees is used, but I don’t know what that means. If 180 degrees is the negative x direction, I am guessing a crosswind be either 90 or 270 degrees? In line 352, the authors state the crosswind is filtered as the filter angle approaches 360. Is that the same as saying it approaches 0? Or in line 356, when the authors state a filter angle of 300 filters out all crosswind interference, does this mean they are only looking at 60 to -60 degree wind directions? Or from 120 to -120? Since so much of the discussion (Fig. 16, Table 4, etc.) depends on understanding this filtering, I don’t think I can give a full final review of this manuscript.

Thank you for your very insightful comments and review. The lack of discussion of our filtering methods was a pretty glaring hole in the methodology and we have included an entire new section of the paper to address this, see below.

2.2.3 Data Filtering by Wind Direction

In order to optimize the FAST method under strong crosswind conditions, filtering was applied to improve data quality and estimate emissions more accurately. Despite the advection from the fan, strong crosswind interference (where $v > u$) introduces variability in both the concentration (C) and wind speed (u) measurements. Filtering addressed this issue by excluding data associated with wind directions unlikely to transport emissions directly to the sensors.

To filter the data, we first calculate the wind direction (Θ_i) from the x- and y-direction wind components (u and v) within a normalized range of [0, 360) degrees for each data point as follows:

1) $\Theta_i = ((arctan2(v, u) \, * \, \frac{180}{\pi}) \, + \, 360) \; mod \, 360$

The mean wind direction, Θ_{mean}, is then computed as the arithmetic average of the normalized wind directions:

2) $\Theta_{mean} = \frac{1}{N} \sum_{i=1}^{N} \Theta_i$

where N represents the total number of data points in a given measurement period.

We then apply a filter angle (ϕ) symmetrically around the mean wind direction to define the range of included data. The lower (Θ_{lower}) and upper (Θ_{upper}) bounds of the filtered range are defined as:

3) $\Theta_{lower} = (\Theta_{mean} - \frac{360 - \phi}{2}) \; mod \, 360$

$\Theta_{upper} = (\Theta_{mean} + \frac{360 - \phi}{2}) \; mod \, 360$

The wind and methane data are then filtered to include only directions within the specified range. If the bounds do not cross the 0°/360° discontinuity, the filtered data satisfies:

4) $\Theta_i > \Theta_{lower}$ and $\Theta_i < \Theta_{upper}$

and when the bounds span the discontinuity, data satisfying the following conditions are used:

5) $\Theta_i > \Theta_{lower}$ or $\Theta_i < \Theta_{upper}$

Figure 5 illustrates the impact of varying the filter angle on the time series of wind and methane concentration data, for a 1 g/hr release from the Richmond Field Station experiment (N = 300). As the filter angle decreases, more data from crosswind and background noise is excluded (shown in red) and the mean wind speed (u) and concentration (C) values change, resulting in different estimates from the FAST method. We found that a filter angle of 300° effectively aligns the analysis with wind directions closely aligned with the source when accounting for plume spread within x < 2 m.

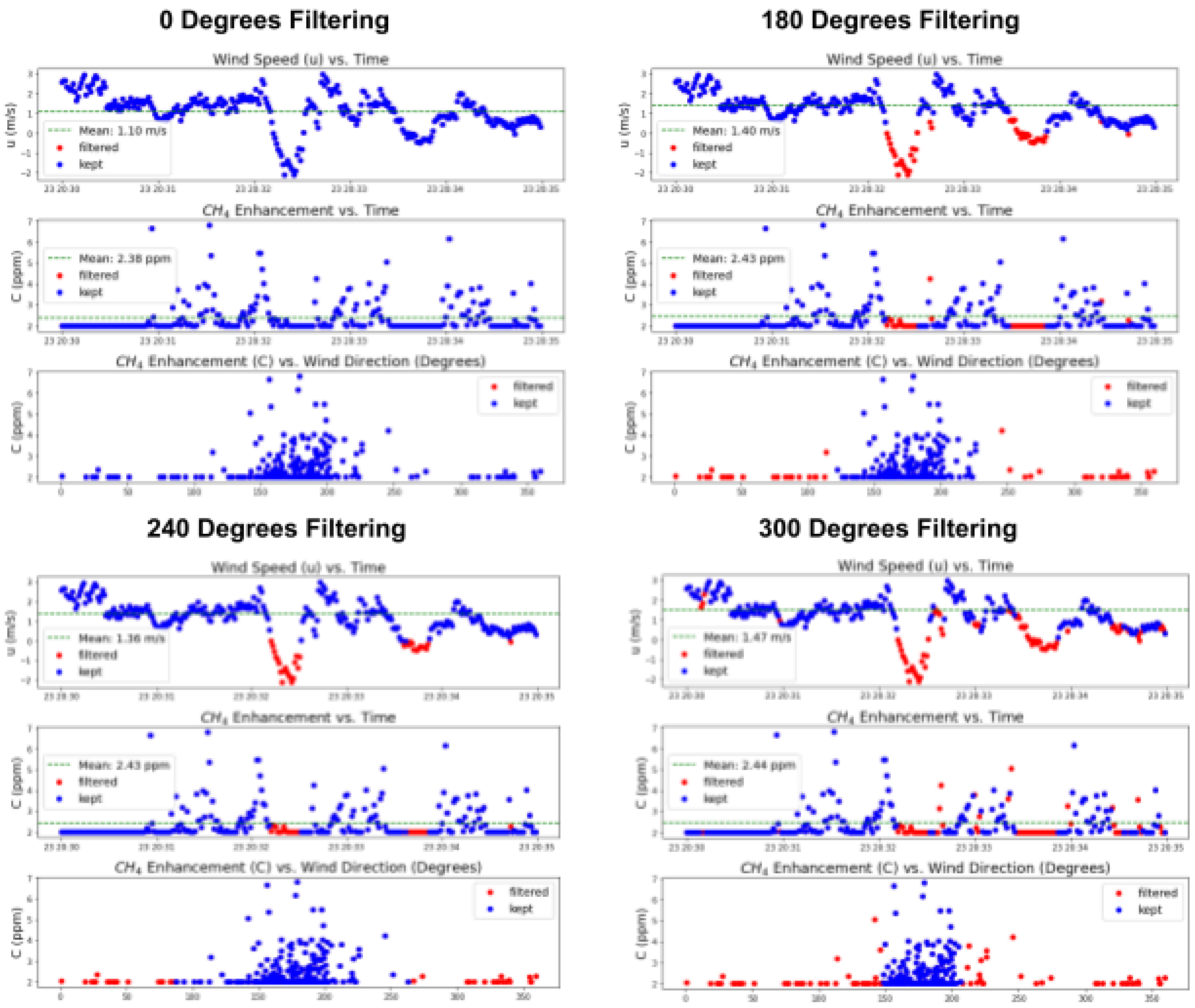


Figure 5: Time series of wind speed (u) and methane enhancement (C) as well as C vs. wind direction (in degrees) for various filtering angles from a ‘no fan’ release of 1 g/hr at the Richmond Field Station. Kept data are shown in blue while filtered data are shown in red. Mean u and C over the 5 minute measurement period are shown in green.

It seems like one of the bigger uncertainties is what Figure 6 would look like for concentration in the y-z plane, especially for cases like Hooper #41. In fact, concentration or mixing ratio data are missing throughout the manuscript. Could the authors show concentration data for the reader to get an idea of how much variability and plume enhancement are involved in these calculations?

This is a very good point. Unfortunately, we did not have the time or equipment to measure these vertical profiles, but would like to do this in future studies to verify this plume behavior. In addition to the above figure we are also including a similar figure showing the concentration data for a single well (Rayburn #7) with and without the fan on to address this. See below:

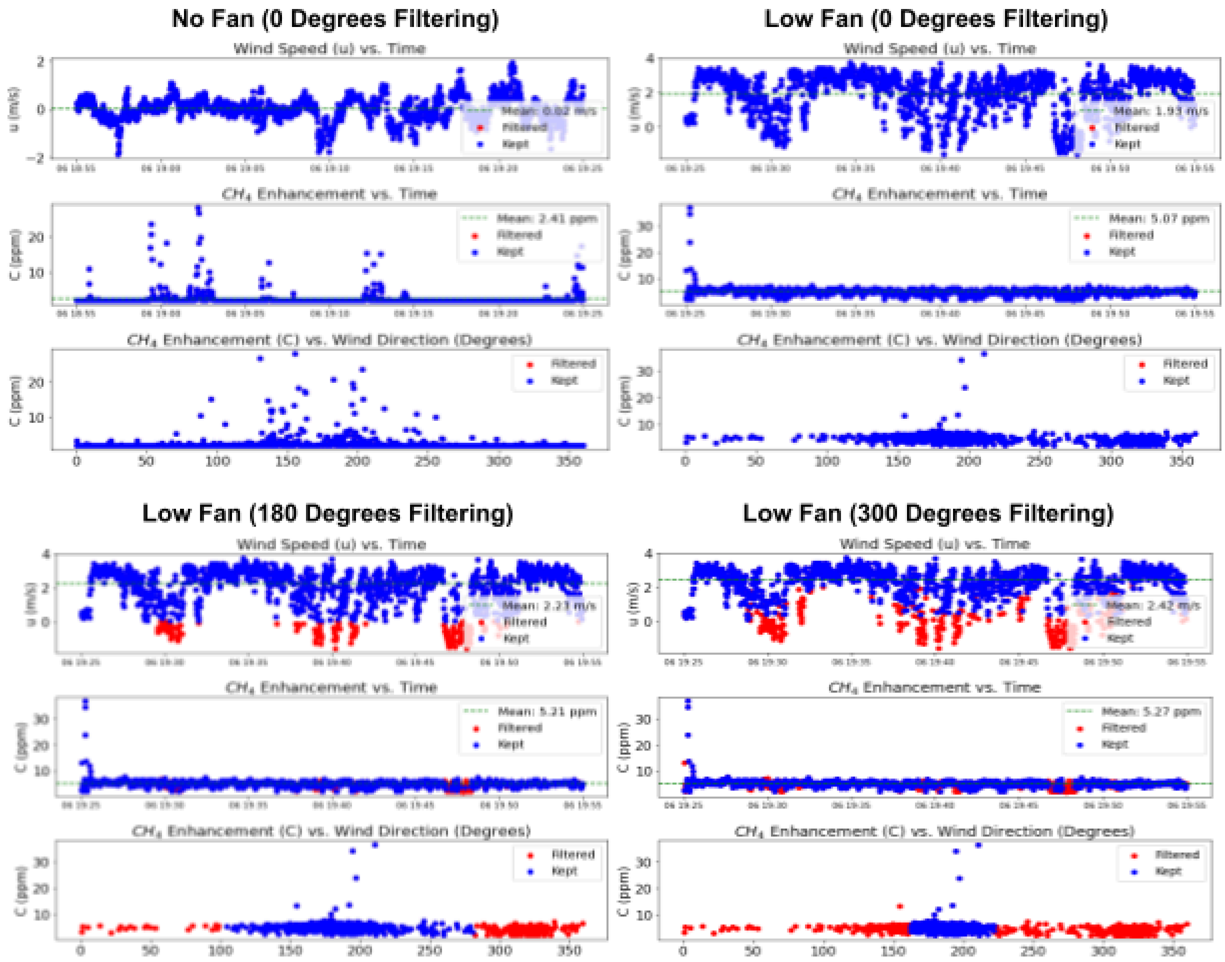


Figure XX: Time series of wind speed (u) and methane enhancement (C) as well as C vs. wind direction (in degrees) for 'no fan' setting and various filtering angles from a 'low fan' setting. Kept data are shown in blue while filtered data are shown in red. Mean u and C over the 30 minute measurement periods are shown in green.

Figure XX illustrates the effect of using the fan on the time series of concentration and wind speed measurements at Rayburn #7, providing insight into the variability of methane concentrations and plume enhancements. Without the fan (upper left), the average wind speed in the x-direction (u) over the 30-minute measuring period was approximately 0 m/s. However, infrequent gusts in the x-direction caused spikes in methane concentrations, ranging from about 10 to 20 ppm above background levels. These spikes were spread across a wide range of directions, between 100 and 250°, indicating variable plume dispersion under stagnant conditions. With the fan on at a low setting, the mean wind speed in the x-direction (u) increased to approximately 2 m/s, and the plume became more stable. The methane concentration spikes were more concentrated in direction, between 180 and 210°, corresponding to the airflow from the fan. While a large spike was observed at the start of the low fan measurement, likely due to the fan turning on, the concentration stabilized to around 5 ppm above background levels.

Other comments:

I'm suspicious that the Williams et al. (2021) conclusion that a 20% uncertainty in orphaned well emissions is most uncertain emission in the U.S. Alvarez et al. (2018) estimated a 60% under-reporting from oil and natural gas production, for example.

We are quoting directly from Williams et al. (2021) abstract where they say: "We find that annual methane emissions from abandoned wells are underestimated by 150% in Canada and by 20% in the U.S. Even with the inclusion of two to three times more measurement data than used in current inventory estimates, we find that abandoned wells remain the most uncertain methane source in the U.S. and become the most uncertain source in Canada."

However, I agree that this claim is suspicious and vague. We have updated the sentence to be more simple:
'Based on a database of leak measurements at 598 wells across the U.S. and Canada, it was found that "annual methane emissions from abandoned wells are underestimated by 150% in Canada and by 20% in the U.S." [Williams et al., 2021].'

Table 1, why is the safety so low for the SEMTECH compared to FAST? I assume this is partly due to FAST diluting the plume quicker.

Yes - we have fully updated Table 1 per another reviewer's suggestions and included more clarification on the meaning of "Safety". See below:

Method	**FLIR Camera**	**SEMTECH HI-Flow 2**	**Static Chamber**	**Dynamic Chamber**	**GPM**	**Vent**	**UAV**	**OTM**	**FAST**
Hardware Cost	>$50K	~$40K	>$400	>$400	>$5K	~$50K	>$50K	>$10K	$2K-50K*
Range (g/h)	>100	<1-30,000	>0.1	>0.1	>100	>100	>50	>50	>1
Uncertainty	High	Low	Low	Low	High	Low	High	Low	High
Size (L)	~0.3	~15	~20	~20	~50	N/A	~40	>1,000	~10-50**
Measuring Time (min.)	~2	~3	>30	>30	>10	>30	>30	>10	~3
Setup Time (min.)	~5	~5	>10	>10	>10	>10	>30	>30	~5-30**
Safety* **	High	Low	Low	Low	High	Low	High	High	High
Versatility****	High	Low	Low	Low	Low	High	Low	Low	High

Table 1: Comparative assessment of commercial (FLIR, SEMTECH, Vent) and research (Chamber, GPM, UAV, OTM) methods used to monitor fugitive methane leaks from orphaned wells. Hardware costs, detection range, accuracy, size, labor and safety are compared for each technology. *The FAST method costs are currently limited by the high cost of laser trace gas sensors (Picarro, Aeris, etc.) that can be reduced significantly by using cheaper non-laser sensors (i.e. Gas Rover) used in chambers. **The size and setup time of the FAST method can also be decreased by using a leaf-blower type fan and a more compact sensor setup. ***Safety reflects the likelihood of an operator not being exposed to unprocessed natural gas. ****Versatility reflects the ability of the method to work in complex aerodynamic environments (i.e. wooded areas, remote areas) and on a wide range of well types.

For Figures 2 and 3, is U defined in the x direction, or is it aligned to E-W?

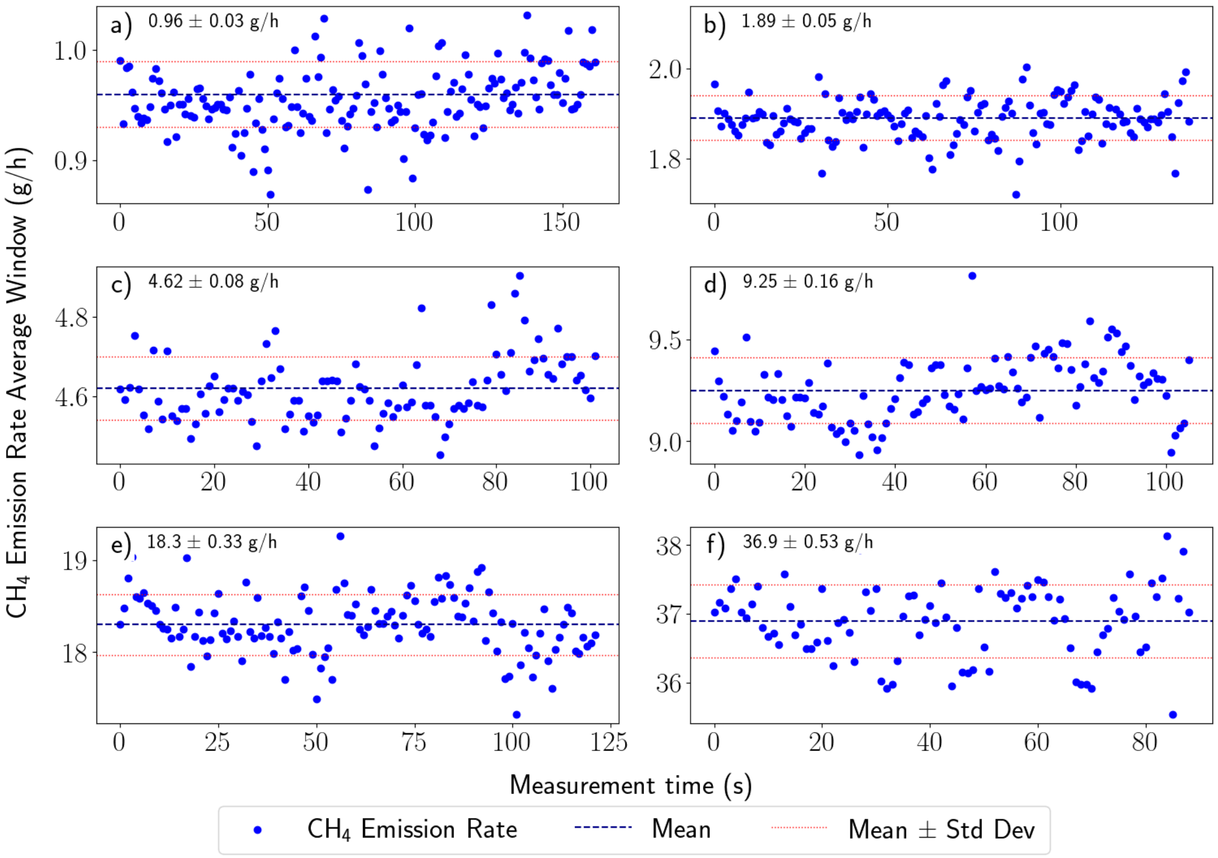
U is defined in the x direction, added text to clarify: “For these experiments, u is aligned to be in the x direction (upwind/downwind), v in the y direction (crosswind) and w in the z direction (vertical).”

Figure 3, why is w so high? Why wouldn’t one expect that to be 0? Add discussion

Added clarification: “Moreover, the vertical velocity (w) is higher than expected for two main reasons: the anemometer is mounted at a height of 1 meter and the experiment was conducted on a rooftop. While w should be ~0 m/s at ground level, we measured w on the order of ~1 m/s due to these factors.”

Figure 7, perhaps add the standard deviation of the emission rate to show “accuracy and precision … decrease” as stated in the caption.

The figure has been updated to include mean and standard deviation. This figure has also been moved to a new section in the appendix (Appendix B: SEMTECH Measurements) as they are not entirely relevant to the FAST method directly (per another reviewer’s suggestion).



Line 402, How do the authors account for changing upwind background in an oil field? Is there variability in the background? This is one instance where concentration data would be helpful to get a sense for what is being measured. For example, what is the signal to background variability? Can the authors show a time series of measurements?

Added this to clarify: “At each well, we measured background (upwind) methane concentrations using the Picarro for five minutes and this background value was subtracted from the methane concentrations collected during the FAST method to determine the enhancement.”

We now show time series of measurements in the new figure added to address filtering (Figure 5) and have added similar time series and filtering results for a well in Lufkin, TX (Rayburn #7), both shown above.

Fig. 15, would the SEMTECH estimate really be negative? Or is this a problem with an improper Gaussian distribution assumption?

Negative values would be non-physical, although the standard deviation reported by the SEMTECH does estimate this within the range of possible values. We have updated the figure to not allow negative values.

For Figure 1A, what is the blue dot? Also, this graph seems to be limited by the resolution of the plume tests of Figure 6. Wouldn't one still expect to have a Gaussian plume within the resolution of 0.3 meters?

The blue dot was unnecessary and has been removed. The point this figure is trying to convey is that while the Gaussian plume method (GPM) assumes a Gaussian plume shape, the FAST method collapses this Gaussian plume into an assumed average plume which is measured along the centerline and captures meaningful information out to some distance $\hat{\sigma}_0$.

Lines 58–59, please spell out all acronyms.

Updated to:
"... from expensive hand-held forward looking infrared cameras (FLIR) to more time-intensive mobile (OTM-33a) [U.S. EPA, 2014] and stationary systems (SEMTECH Hi-Flow 2 [SEMTECH], Chamber [Williams et al. 2023], Gaussian Plume Modeling (GPM) [Lushie and Stockie, 2010], Vent [Ventbusters, 2023]). Unmanned aerial vehicles (UAV, also known as "drones") have ..."

SEMTECH is the name of a company and not an acronym.