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Performance and sensitivity of column-wise and pixel-wise methane retrievals for imaging spectrometers

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S1: Controlled Release Quality Control Protocol

For the controlled release experiment, it was crucial that we only use high quality plume data. Therefore, we eliminated any plumes that were contaminated by clouds or cloud shadows, had an unstable plume morphology or seemed to have unstable wind conditions. We define unstable plume morphology as a non-contiguous plume, a plume that appears that has no definite shape or clear plume origin (e.g., a “blob”), or a plume that appears to be under challenging transport conditions (e.g., doubles back on itself). For example, in Figure S1 A the methane plume is non-contiguous, in this example we get drop out over dark (potentially wet) surfaces or a series of puffs due to unstable winds or an unstable emission. In addition, if the wind is too low or if the wind direction changes significantly during the plume formation, then methane is not transported down wind and therefore it can be a problematic for quantification. We can identify this by looking for a blobby plume morphology or a plume that doubles back on itself. An example of a blobby plume is in Figure S1 B and example of a plume doubling back in Figure S1 C. For reference Figure S4 D shows a good plume that we would include in our analysis. In order to determine the quality of the plume we had 7 analysts independently assess each plume. The analyst assessed each plume for stability, plume shape, wind direction/stability, clouds/cloud shadows, artifacts, and high background enhancements. The culmination of the assessment was a ranking for each plume (1-3). The plumes ranked 1 and 2 were included in the analysis and the plumes ranked 3 were not included in the final analysis. In addition, the 7 analysts discussed any disagreements in the assessment and ratings before assigning the plume a final rating.

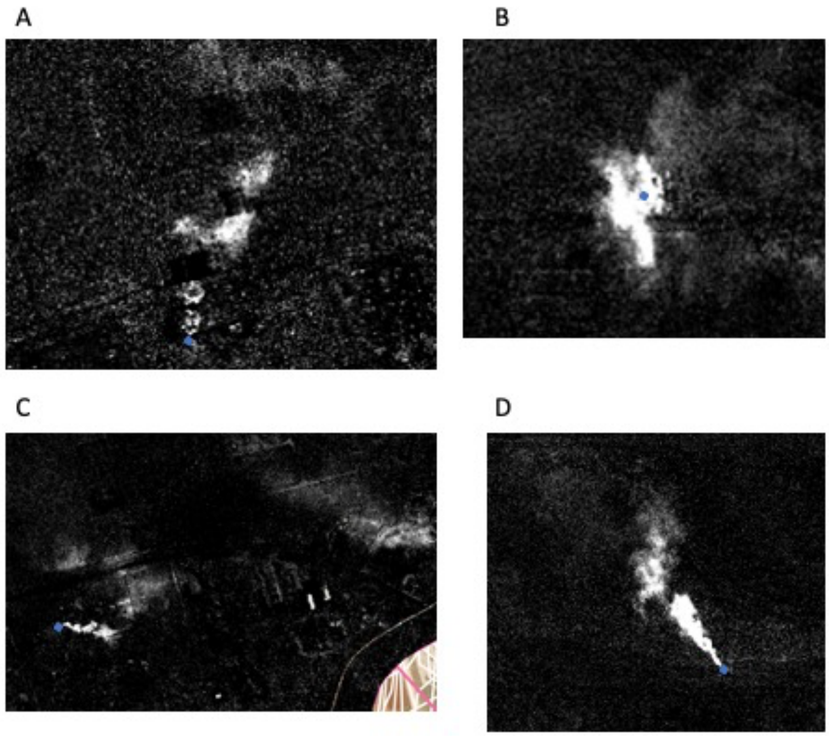

Figure S1: A) an example of a plume with gaps. B) An example of a blobby plume that does have good downwind transport. C) An example of a plume with unstable wind conditions. D) An example of a good plume. The blue dots represent the approximate plume origin for each plume.

S2: Concentric Circle IME Method and Results

In past publications Carbon Mapper has published data using a different implementation of the IME method. Past publication have used the following equation:

$$Q = \frac{IME}{L} * U_{10} \tag{1}$$

Where IME is the total mass in the plume, length is the max fetch and U10 is the wind speed at 10 meters. In addition, previous publications have used an iterative approach, called the concentric circle method, to estimate uncertainty. This means that the max fetch and IME associated with the fetch are iteratively expanded from the origin of the plume until the max fetch or 283 m is reached. The mean and standard deviation are calculated from the combination of iterations. In addition, we use HRRR wind estimates because most plumes do not have 10 m anemometer wind speed measurements available. These methods were used in Duren et al. 2019 and Cusworth et al. 2022. Here we show the results from the 2022 controlled release using these methods. The fit and bias, while not as good as using the methods presented in the main body of the article, are still good. This indicates that methods employed in previous studies also produce good results.

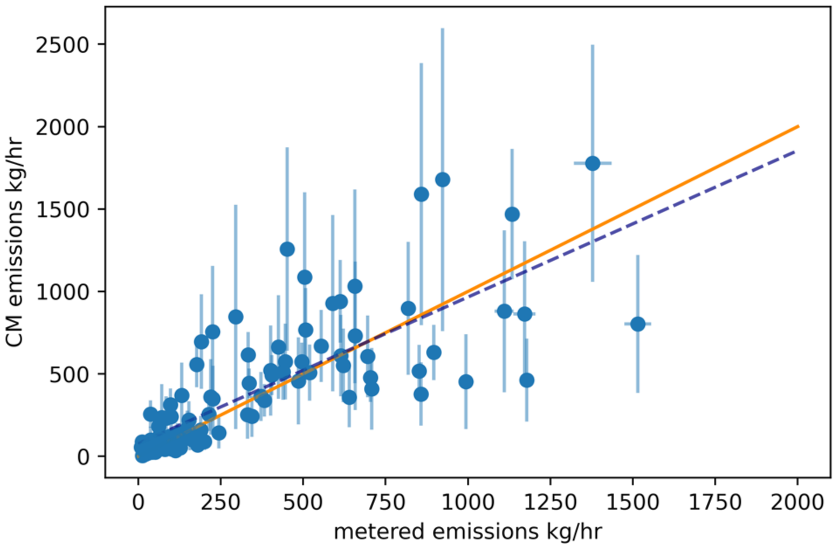

Figure S2: Metered emission rates versus the emission estimates for the 2022 controlled release using Duren et al. 2019 methods. An OLS fit to CMF results in $y = 0.89x + 77$ with $R^2 = 0.62$. The solid line represents the 1:1 line and the dashed line is the OLS fit.

S3: Line Length Analysis

For the analysis to determine the minimum line length for good quantification we first Identified 8 plumes that had at least three flyovers from GAO. This resulted in 24 individual scenes to analyze. These scenes ranged in pixel lengths from 25,000 to 5,720 pixels with a majority over 10,000 pixels. The plumes within each scene were previously determined to have emission rates between 70.67 and 3981.77 kg/hr. Scenes were acquired from various campaigns including The Permian 2021, DJ Summer 2021, North East 2021, Covid CA 2020, and Permian Fall 2021. Emissions sources ranged from coal vents to pipelines and landfills.

Each scene was cropped to 2000 pixels centered on the identified plume. This crop was then iteratively increased in 1000 pixel increments until the full scene length was reached. This produced between 6 and 24 cropped images per scene. Each scene crop was processed through the CMF. These cropped scene match filter outputs were then orthorectified and processed through the IME. The curves tended to level off at some point creating a “knee in the curve.” To determine the exact knee in the curve we used the KneeLocator function within the Python package kneed.

All 24 scenes were analyzed to determine optimal knee placements; however, only 19 produced usable results. The five scenes which were not included in final analysis failed to resolve an appropriate knee due to variations in their curves. For instance, the scenes below which observed plume G0011 were excluded as their shapes either produced no knees or set the knee at the 2000 pixel crop or maximum pixel crop, both of which indicate that no real knee is visible within the plotted data.

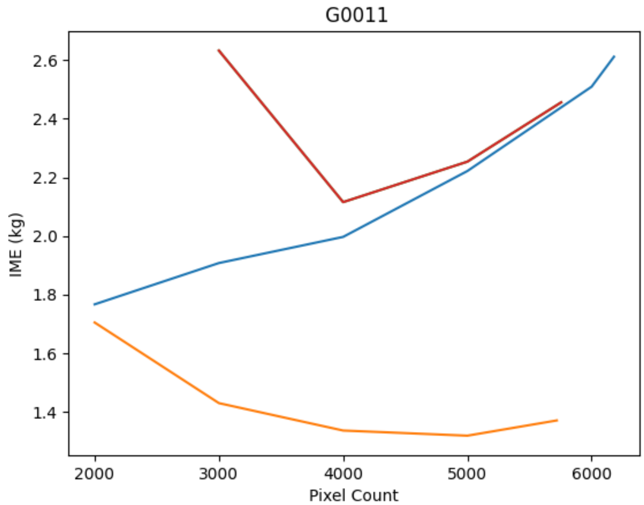

Figure S3: Pixel count versus the IME for plume G0011 (three images of the same plume on different days). The dynamic of this scene cause the IME to form a concave shape therefore these scenes were left out of the analysis.

The average knee value for the 19 scenes analyzed was of 8172, which was rounded to the nearest crop of 8,000 pixels, and the median knee value was 7000. Within the dataset multiple knees landed on 7,000-pixel crops however two outlier knees located beyond 15,000 pixels increased the average. This analysis led us to conclude that 7000 pixels should be sufficiently long for the controlled release experiment, hence the 20 km flight line in 2022.

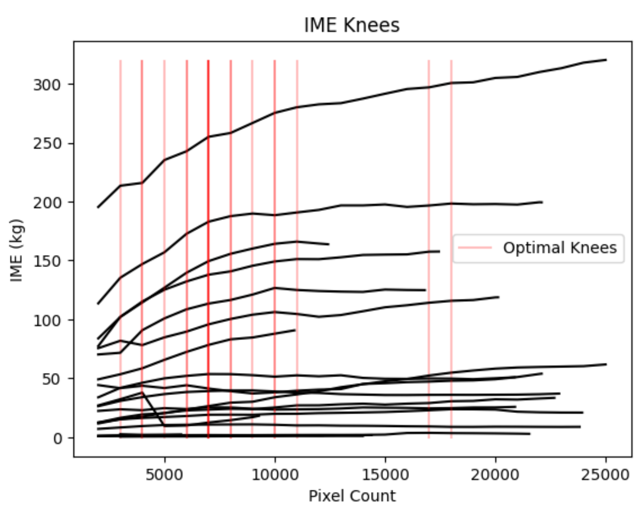

Figure S4: Pixel count versus the IME for all scenes used in the analysis as well as the optimal know for each scene (red).