MAY 13, 2019


# STATEWIDE AIRBORNE METHANE EMISSIONS MEASUREMENT SURVEY

## FINAL SUMMARY REPORT

AGREEMENT NO. 16RD018

*Prepared by:*

C. Thompson, C. Stockwell, M. Smith, S. Conley

SCIENTIFIC AVIATION, INC
3335 Airport Rd, Boulder, CO 80301

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## ACKNOWLEDGEMENT

This Report was submitted in fulfillment of agreement no. 16RD018 entitled “Statewide Airborne Methane Emissions Measurement Survey by Scientific Aviation” under the sponsorship of the California Air Resources Board. Work was completed as of May 9, 2019.



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# EXECUTIVE SUMMARY

Scientific Aviation was contracted by the California Air Resources Board to conduct airborne methane emissions quantifications at a variety of target sites representing known methane source sectors. Ninety-seven individual measurements were performed at sixty-six target sites between September 15, 2017 – May 9, 2019. Target sites included industrial, agricultural, natural, and waste sources. Several sites from each source type were sampled on more than one occasion to assess temporal variability.

The methodology used by Scientific Aviation is a modified mass balance approach based on Gauss's Law that has been extensively demonstrated to be accurate and robust, and has been published in the peer-reviewed literature. This method involves flying multiple closed-loop patterns around a site of interest at increasing altitudes to fully sample upwind and downwind of a source and the full vertical extent of a plume. An emission rate is determined by using on-board wind measurements and in situ chemical measurements of methane to calculate the mass flow of methane emanating from the target site.

Of the 97 measurements conducted, only emissions from 6 facilities were found to be below the detection limit of the method (i.e., < 10 kg $hr^{-1}$ $CH_4$). The landfill sites were found to be the largest methane emitters on a per site basis, with an average methane emission over all landfill measurements of 1580 ± 970 kg $hr^{-1}$ $CH_4$. The average emission from the gas storage facilities was 130 ± 210 kg $hr^{-1}$ $CH_4$, and emissions from three of these sites were below the detection limit.

The temporal variability of emissions between repeated samples at individual sites ranged between < 1% to > 100%, demonstrating the challenges associated with developing methane emissions inventories. The agricultural sites were generally found to be on the low end of the range in temporal variability, whereas the greatest variabilities were determined for landfill sites. The refineries fell within the middle of the range. It should be noted, however, that only 2 – 3 replicate measurements were made for each of these sites, and this is not sufficient for a robust statistical analysis of temporal variability.



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## I. Introduction

Methane is an important greenhouse gas, which is 84 times more potent than $CO_2$ over a 20-year time horizon[1]. After a prolonged period of nearly constant methane emissions and near-zero growth in the global atmospheric methane burden in the 1990's through early 2000's, the observation of a renewed methane increase beginning in 2007 has prompted the need to investigate and better quantify methane emissions sources. Several studies have identified weaknesses in the current national methane emissions inventory, particularly with respect to the oil and gas sector, where top-down measurements (via aircraft and satellite)[2] have found larger, and increasing, methane emissions relative to the traditional bottom-up inventory. Moreover, other methane sources (e.g., landfills, agriculture, wetlands) are known to be large contributors to total methane emissions, however there is significant uncertainty in the magnitude and the variability of those emissions.

The California Air Resources Board (CARB) estimates California annual methane emission as 40 MMT $CO_2e$ for year 2014, arising primarily from agriculture (59%), landfills (21%) and industrial sources (19%)[3]. Methane is responsible for 9% of California's total greenhouse gas emissions. Researchers have suggested the CARB inventory underestimates total methane emission by 30%[4]. An extensive understanding of methane sources, including locations, emission potential, distribution and contribution is complementary for CARB to improve the emission inventory and develop policy programs. Randomly sampling various sources from each of the primary emission sectors can help inform the emission inventory by comparing those measurements with the inventory estimations.

In 2015, the Governor approved Assembly Bill 1496 (AB 1496), which requires the CARB to monitor and measure high methane emission hotspots within the state using the best available scientific and technical methods. The CARB, in conjunction with California Energy Commission (CEC) and NASA Jet Propulsion Laboratory (JPL) has initiated a large-statewide aerial survey to identify methane "super emitters", whereby aircraft from JPL equipped with imaging spectrometers will map out 30,000 square kilometers to detect methane plumes and locate hot spots.

The current project complements the JPL survey and other CARB' efforts, to identify large area sources and provide a defensible source emissions estimate that can be used to improve the CARB inventory. Aerial measurements using in situ chemical analyzers has the unique advantage of quantifying emissions from both large area sources and point sources without the need to access the facilities. This approach utilizes an instrumented

[1] https://www.ipcc.ch/report/ar5/syr/

[2] Conley et al. (2017). Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases. Atmos. Meas. Tech. *10*, 3345-3358.

[3] https://www.CARB.ca.gov/cc/inventory/background/ch4.htm

[4] https://www.CARB.ca.gov/research/single-project.php?row_id=65091

aircraft and a modified mass balance methodology to quantify emissions from a variety of methane sources. The particular strength of this analytical approach was demonstrated, perhaps most notably, by Scientific Aviation during the 2015 Aliso Canyon Leak Incident (Conley et al., 2016).

In the present study, Scientific Aviation was contracted by CARB to perform airborne emissions quantification measurements from a variety of methane sources associated with industry, agriculture, and municipal waste, with several sites sampled repeatedly to assess temporal variability. This report presents the results of these survey measurements conducted from September 2017 through May 2019.

## II. Project Goals

The primary objectives of this project was to better understand methane emissions from California's major emission sectors, including:

- Measurement of important sources in the various primary methane sectors and sub-sectors with the ability to study whole facility emissions
- Obtain data for CARB Methane Research Program for systematic analysis of facility-level emissions in each sector by measuring different types of sources (geographic locations, size, operational characteristics, etc.) in different seasons
- Use a state-of-the-art measurement tool to complement the multi-tiered measurement and analysis research program.

## III. Methodology

This project utilized an instrumented Mooney aircraft owned and operated by Scientific Aviation to conduct emissions measurements from target sources. The aircraft is outfitted with a proprietary data system that measures and records aircraft speed, position, altitude, and horizontal winds (accurate to better than 0.5 m $s^{-1}$), as well as ambient temperature, pressure, and relative humidity. A Picarro G2210-m cavity ring down spectrometer interfaced with the on-board data system provides fast time response in situ measurements of methane, ethane, and $CO_2$. This analyzer measures methane with 1-s precision of 1 ppbv, and ethane with 1-s precision of 2.5 ppbv. All data collected by the aircraft is uploaded and stored in real time to a secure cloud-based server.

The measurement approach used a modified version of mass balance based on Gauss's Law as described in Conley et al. (2017). For each target site, the aircraft flew a closed loop pattern around the facility, beginning at the minimum safe altitude (typically 200 feet) and climbing progressively higher, until on-board measurements indicated that the aircraft was above the plume. Additional loops were flown above the plume to confirm the extent of the vertical mixing, as shown in Figure 1.

Mass-based emissions were calculated for the closed path at each transect altitude by integrating plume mixing ratio enhancements measured during transects, and then integrating through the vertical extent of the plume, as shown in Equation (1):

$$Q_c = \langle \frac{\partial m}{\partial t} \rangle + \int_0^{z_{max}} \oint c' u_h \cdot \hat{n} dl \, dz \qquad (1)$$

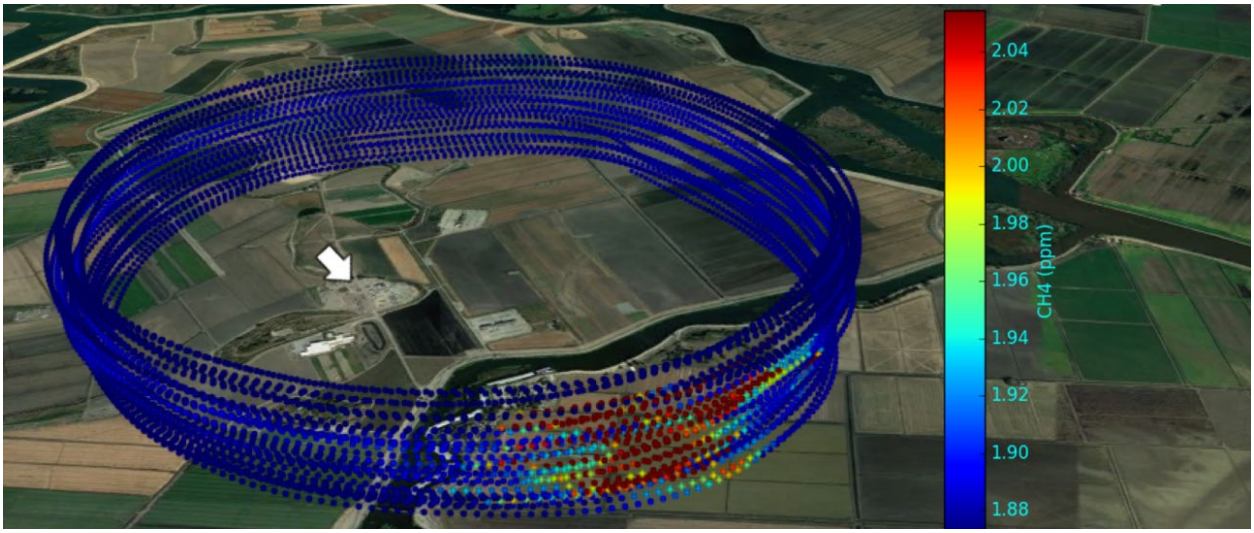

Figure 1. Flight path around McDonald Island from Conley et al. (2017).

In Eq. 1, $Q_c$ is the estimated surface mass emission rate, $\langle \frac{\partial m}{\partial t} \rangle$ is the observed rate of change of mass within the flight path, c' is the deviation from the mean of the density, $u_h$ is the horizontal wind vector, and $n$ is the unit normal to the flight path. A time-averaged atmospheric vertical profile was then reconstructed by averaging the horizontal mass flux divergence.[5] measured at each circle into equally-spaced bins spanning the vertical extent of the plume transects and extrapolating the value calculated for the lowest-altitude bin to the surface (Figure 2). Integrating the reconstructed vertical profile of the horizontal flux divergences gives the average emission for each site. Uncertainties on bin-averaged horizontal flux divergences were summed in quadrature to provide an estimated uncertainty on the average emission for each site.

The successful application of this method for quantifying emissions relies upon favorable wind conditions and sufficient vertical mixing. Ideal wind conditions are moderate and steady in both speed and direction. Completely calm conditions, very high speeds, or rapidly varying wind directions are not suitable for this method. Moreover, the highest degree of confidence in the results is contingent upon sampling the majority of the plume at and above the lowest flight altitude and below the top of the boundary layer to ensure complete sampling of the entire plume. Under ideal conditions, emissions uncertainties



[5] Conley et al. (2017). Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases. Atmos. Meas. Tech. *10*, 3345-3358.

≤10% can be achieved. Any conditions that are considered less than ideal will impose an increased level of uncertainty on the result.

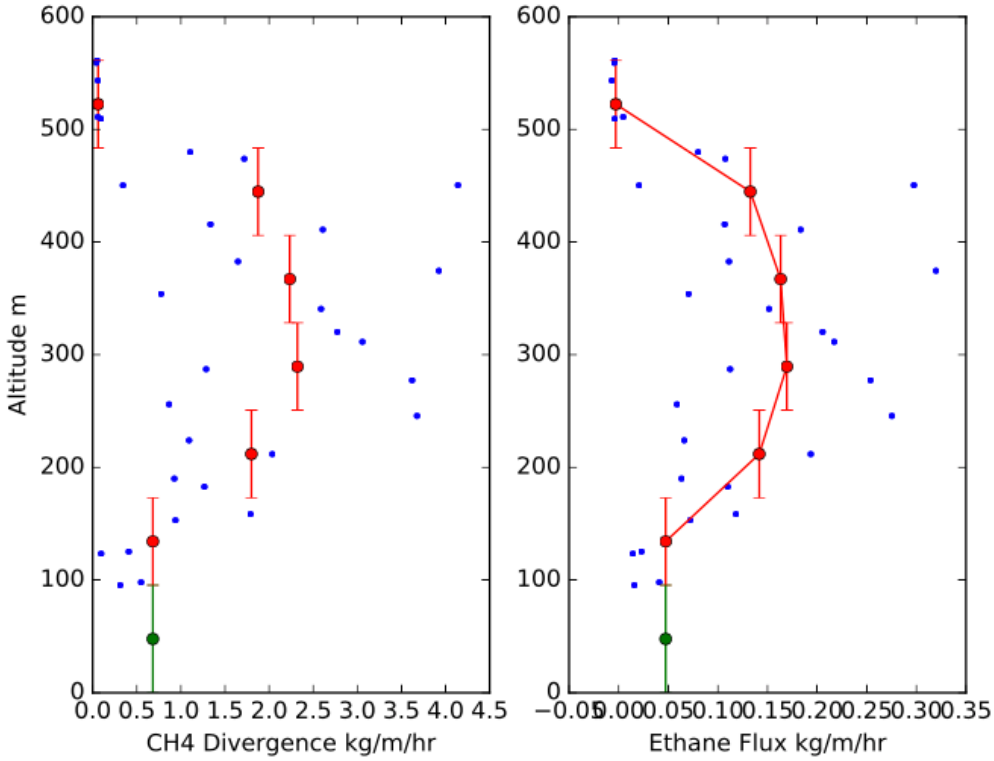


Figure 2. Flux divergence profile of methane and ethane from McDonald Island

Aside from meteorological conditions, there is also a relationship between measurement uncertainty and the number of transects (laps) around a site. In general, increasing the number of laps will reduce the uncertainty on the final emissions result (and vice versa). For the majority of sites, we have found that 15–25 laps is an appropriate range. Fewer laps may be performed if no methane enhancements above the instrument detection limit are observed, or if the studied region is larger than a few kilometers in radius; a greater number of laps may be done if wind/mixing conditions are less than ideal in an effort to increase the measurement confidence.

A further source of uncertainty for methane emissions estimated by this method, and any mass balance-based method, is the influence of emissions sources upwind of the target site. In theory, the method can account for emissions that enter and exit the volume defined by the flight path; however, in practice, if the upwind source is similar in magnitude or larger than the target source, the uncertainty associated with the upwind emissions transiting through the target volume can obscure emissions originating from the target source. Often an estimate of target emissions can still be made- but with larger associated uncertainty than in the absence of upwind sources.

Measurements to determine the height of the boundary layer are collected periodically during the day. Often during sampling of the larger perimeter sources, instances when mass balance boxes are employed, measurements are completed to near the top of the boundary layer. From the boundary layer height estimates it is determined whether the entire plume was completely sampled or whether emission rates need to be extrapolated to the boundary layer. These extrapolations result in a greater uncertainty. The vertical flux divergence gradient is less pronounced in larger mass balance boxes as compared to point sources, as sampling occurs at a greater distance from the source.

## IV. Summary of Measurement Results

Methane emissions quantifications were performed at 66 unique sites between September 15, 2017 – May 9, 2019. Of these sites, 18 were categorized as landfills, 20 as dairies, 4 as ranches, 6 as refineries, 6 as gas storage facilities, and 9 as oil fields or compressors. Three sites did not fall under one of these six categories and were categorized as “Other”.

Ninety-seven individual measurements were performed during the course of this project, with several sites sampled on more than one occasion. Table 1 presents a compilation of the methane and $CO_2$ emissions results for all 97 measurements. Table 2 presents the average and standard deviation of all measurements within each source category (excepting the oil fields because large differences in quantified source region sizes mean an average is not meaningful), as well as the average and standard deviation for the sites that were sampled on more than one occasion.

Table 1. Summary of individual results sorted by source type.

| Site | Date | Lat. | Lon. | Radius (m) | CH4 Em. (kg/hr) | Uncertainty (kg/hr) | CO2 Em. (kg/hr) | Uncertainty (kg/hr) | Lap # | Wind Dir. | Wind Spd. (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Landfills*** | | | | | | | | | | | |
| Forward | 12/9/2017 | 37.87 | -121.19 | 1,373 | 1,930 | 943 | 14,751 | 14,696 | 13 | 326 | 0.6 |
| Forward | 5/8/2018 | 37.87 | -121.19 | 1,528 | 2,683 | 418 | 16,659 | 10,531 | 21 | 293 | 3.7 |
| Keller Canyon | 10/6/2017 | 38.00 | -121.94 | 1,384 | 640 | 209 | -3,113 | 7,377 | 14 | 24 | 8.9 |
| Keller Canyon | 10/5/2018 | 38.00 | -121.94 | 1,080 | 1,361 | 209 | 5,029 | 6,699 | 18 | 289 | 3.2 |
| Kiefer | 12/9/2017 | 38.52 | -121.19 | 1,469 | 1,728 | 563 | -20,618 | 18,901 | 11 | 312 | 0.6 |
| Kiefer | 6/21/2018 | 38.52 | -121.19 | 1,554 | 2,756 | 383 | 8,741 | 4,751 | 21 | 272 | 1.5 |
| Kiefer | 8/24/2018 | 38.52 | -121.19 | 1,537 | 2,249 | 360 | 34,908 | 6,652 | 17 | 203 | 2.5 |
| Kiefer | 3/14/2019 | 38.52 | -121.19 | 1,509 | 2,024 | 457 | 21,824 | 9,399 | 20 | 207 | 2.2 |
| Kiefer | 5/7/2019 | 38.52 | -121.20 | 1,494 | 1,968 | 487 | 25,312 | 5,812 | 20 | 252 | 1.7 |
| Newby Island | 10/5/2017 | 37.46 | -121.94 | 1,109 | 2,075 | 586 | 22,945 | 19,172 | 17 | 333 | 3 |
| Newby Island | 10/5/2018 | 37.46 | -121.94 | 1,004 | 3,287 | 487 | 78,941 | 24,317 | 20 | 331 | 3 |
| Olinda Alpha | 11/9/2017 | 33.94 | -117.83 | 1,007 | 1,698 | 327 | 18,543 | 8,538 | 13 | 245 | 3.2 |
| Olinda Alpha | 11/19/2017 | 33.94 | -117.83 | 1,318 | 1,339 | 435 | 77,484 | 21,181 | 16 | 307 | 0.5 |
| Olinda Alpha | 5/15/2018 | 33.93 | -117.84 | 1,497 | 1,097 | 151 | 27,751 | 7,872 | 21 | 240 | 3 |
| Potrero Hills | 10/6/2017 | 38.21 | -121.98 | 977 | 2,292 | 385 | 11,291 | 6,707 | 13 | 15 | 5.7 |
| Potrero Hills | 10/5/2018 | 38.21 | -121.98 | 1,055 | 919 | 286 | -9,703 | 5,965 | 20 | 348 | 1.7 |
| Scholl Canyon | 11/9/2017 | 34.16 | -118.19 | 570 | 71 | 16 | 4,318 | 1,210 | 19 | 224 | 3.9 |
| Scholl Canyon | 11/19/2017 | 34.16 | -118.19 | 892 | 475 | 96 | -4,637 | 3,673 | 23 | 256 | 1.2 |
| Toland Road | 10/16/2017 | 34.40 | -118.99 | 1,305 | 3,200 | 767 | 1,096 | 11,485 | 18 | 217 | 2.8 |
| Toland Road | 5/14/2018 | 34.40 | -119.00 | 1,213 | 1,530 | 464 | 3,776 | 3,754 | 16 | 261 | 6.4 |
| Altamont | 10/6/2017 | 37.75 | -121.65 | 1,597 | 2,977 | 653 | 22,745 | 8,421 | 11 | 8 | 7.6 |
| BKK West Covina | 11/9/2017 | 34.04 | -117.90 | 934 | 93 | 10 | 22,168 | 4,259 | 17 | 277 | 2.9 |
| Chiquita Canyon | 10/17/2017 | 34.43 | -118.65 | 1,445 | 2,153 | 679 | 34,644 | 12,287 | 15 | 219 | 3.6 |
| Foothill | 11/18/2017 | 38.04 | -120.94 | 1,335 | 680 | 146 | 14,574 | 8,285 | 19 | 236 | 1.4 |
| Lopez Canyon | 11/19/2017 | 34.29 | -118.39 | 943 | 498 | 149 | 7,853 | 2,606 | 23 | 48 | 1 |
| Ostrom Road | 11/18/2017 | 39.07 | -121.39 | 1,044 | 504 | 318 | 5,395 | 3,963 | 15 | 145 | 1.1 |
| Ox Mountain | 10/6/2018 | 37.50 | -122.41 | 1,309 | 2,939 | 574 | -14,213 | 4,490 | 15 | 325 | 5.4 |
| Puente Hills | 11/9/2017 | 34.02 | -118.01 | 1,662 | 361 | 55 | 41,931 | 13,983 | 14 | 246 | 2.8 |
| Simi Valley | 10/17/2017 | 34.29 | -118.80 | 1,446 | 489 | 88 | 71,597 | 8,909 | 9 | 265 | 5.4 |
| Sunshine Canyon | 10/16/2017 | 34.33 | -118.51 | 3,950 | 1,435 | 283 | -- | -- | 24 | 350 | 5.8 |

Table 1 (Continue). Summary of individual results sorted by source type

***Dairies***

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dairy #1 | 9/15/2017 | 1,446 | 670 | 169 | 11,682 | 5,058 | 27 | 338 | 2.5 |
| Dairy #1 | 1/11/2018 | 1,294 | 428 | 150 | 1,727 | 5,067 | 12 | 136 | 0.6 |
| Dairy #1 | 5/17/2018 | 1,467 | 369 | 150 | -24,830 | 5,612 | 19 | 340 | 3.5 |
| Dairy #1 | 5/9/2019 | 1,810 | 830 | 114 | 1,797 | 3,901 | 16 | 305 | 8.3 |
| Dairy #7 | 1/10/2018 | 1,157 | 571 | 141 | 13,305 | 4,035 | 13 | 317 | 2.8 |
| Dairy #7 | 5/12/2018 | 1,495 | 727 | 106 | -440 | 3,034 | 17 | 289 | 3.9 |
| Dairy #7 | 5/7/2019 | 1,172 | 764 | 171 | -4,380 | 7,326 | 23 | 324 | 3.7 |
| Dairy #12 | 1/10/2018 | 1,014 | 541 | 95 | -4,292 | 2,198 | 18 | 326 | 4.3 |
| Dairy #12 | 5/12/2018 | 1,121 | 782 | 143 | 12,810 | 3,218 | 16 | 223 | 2.2 |
| Dairy #15 | 1/10/2018 | 1,232 | 669 | 191 | 25,026 | 5,123 | 20 | 326 | 4.8 |
| Dairy #15 | 5/7/2019 | 1,357 | 510 | 115 | 8,415 | 1,678 | 16 | 8 | 4.5 |
| Dairy #16 | 1/11/2018 | 985 | 560 | 374 | 3,363 | 9,374 | 21 | 218 | 0.8 |
| Dairy #16 | 5/12/2018 | 1,314 | 566 | 114 | 13,536 | 1,910 | 16 | 302 | 4 |
| Dairy #2 | 9/15/2017 | 1,150 | 298 | 153 | 1,511 | 5,737 | 41 | 310 | 2.6 |
| Dairy #3 | 11/18/2017 | 957 | 223 | 83 | -10,209 | 13,912 | 18 | 250 | 1.4 |
| Dairy #4 | 11/18/2017 | 1,045 | 121 | 52 | 1,465 | 2,346 | 18 | 358 | 0.6 |
| Dairy #5 | 11/18/2017 | 928 | 53 | 30 | 1,368 | 1,584 | 17 | 106 | 0.7 |
| Dairy #6 | 11/18/2017 | 779 | 69 | 30 | 1,983 | 1,526 | 18 | 39 | 0.6 |
| Dairy #8 | 1/10/2018 | 1,521 | 467 | 126 | 22,704 | 24,712 | 13 | 329 | 3 |
| Dairy #9 | 1/10/2018 | 1,501 | 475 | 72 | 3,894 | 2,869 | 12 | 325 | 5.2 |
| Dairy #10 | 1/10/2018 | 946 | 275 | 39 | -3,169 | 2,221 | 8 | 318 | 5 |
| Dairy #11 | 1/10/2018 | 796 | 167 | 50 | -640 | 1,481 | 9 | 322 | 6.2 |
| Dairy #13 | 1/10/2018 | 917 | 238 | 39 | 5,535 | 1,893 | 7 | 334 | 5.3 |
| Dairy #14 | 1/10/2018 | 1,217 | 403 | 75 | 4,723 | 1,866 | 10 | 333 | 4.4 |
| Dairy #17 | 1/11/2018 | 725 | 252 | 129 | 3,918 | 1,760 | 13 | 334 | 1.4 |
| Dairy #19 | 5/7/2019 | 1,071 | 317 | 79 | 11,115 | 1,791 | 21 | 322 | 2.4 |
| Dairy #20 | 5/7/2019 | 1,039 | 112 | 19 | -1,671 | 1,064 | 10 | 261 | 5.7 |
| Dairy #21 | 5/9/2019 | 1,610 | 1,199 | 243 | 24,460 | 9,837 | 19 | 335 | 3.7 |
| Dairy #18 | 1/11/2018 | 657 | 170 | 91 | 2,394 | 2,298 | 14 | 336 | 0.6 |

Table 1 (Continue). Summary of individual results sorted by source type

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Ranches*** | | | | | | | | | | | |
| Feedlot #1 | 1/11/2018 | 36.31 | -120.27 | 1,357 | 458 | 99 | 34,477 | 12,369 | 19 | 130 | 1.2 |
| Feedlot #1 | 5/12/2018 | 36.31 | -120.27 | 1,820 | 550 | 76 | 50,817 | 6,685 | 23 | 346 | 4.2 |
| Feedlot #2 | 5/15/2018 | 33.16 | -115.56 | 1,931 | 220 | 100 | 39,270 | 13,653 | 22 | 190 | 0.4 |
| Beef Company #1 | 1/11/2018 | 36.50 | -119.61 | 666 | 106 | 43 | 5,174 | 2,714 | 15 | 325 | 1.7 |
| Feedlot #3 | 5/15/2018 | 33.09 | -115.52 | 1,118 | 131 | 34 | 8,080 | 7,850 | 19 | 181 | 0.6 |
| ***Refineries*** | | | | | | | | | | | |
| Chevron Refinery | 10/5/2017 | 37.95 | -122.40 | 1,879 | 440 | 250 | 351,743 | 137,633 | 13 | 76 | 1.8 |
| Chevron Refinery | 10/5/2018 | 37.95 | -122.40 | 1,891 | 819 | 200 | 596,532 | 138,009 | 14 | 338 | 1.3 |
| Chevron Refinery | 10/6/2018 | 37.95 | -122.40 | 1,814 | 548 | 116 | 429,953 | 59,157 | 16 | 324 | 4.1 |
| Phillips 66 Refinery | 10/5/2017 | 38.04 | -122.26 | 1,530 | 156 | 83 | 208,256 | 120,456 | 16 | 68 | 1.6 |
| Phillips 66 Refinery | 11/19/2017 | 33.77 | -118.29 | 1,052 | 228 | 75 | 255,336 | 63,406 | 16 | 353 | 1.5 |
| Phillips 66 Refinery | 10/6/2018 | 38.05 | -122.26 | 1,619 | 439 | 66 | 301,174 | 40,438 | 22 | 350 | 2.8 |
| Exxon Refinery | 4/20/2018 | 33.85 | -118.33 | 1,314 | 126 | 21 | 287,745 | 51,528 | 18 | 280 | 3 |
| Shell Martinez Refinery | 10/7/2018 | 38.02 | -122.11 | 1,955 | 168 | 18 | 618,500 | 44,940 | 14 | 18 | 10 |
| Tesoro Refinery | 10/6/2017 | 38.02 | -122.07 | 1,317 | 546 | 184 | 497,760 | 87,407 | 11 | 40 | 4.6 |
| Valero Benecia Refinery | 10/6/2018 | 37.50 | -122.41 | 1,618 | 443 | 66 | 302,806 | 40,508 | 22 | 350 | 2.8 |

Table 1 (Continued). Summary of individual results sorted by source type

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Gas Storage Facilities*** | | | | | | | | | | | |
| Aliso Canyon | 10/16/2017 | 34.32 | -118.56 | 4,000 | 110 | 39 | | | 19 | | 4.1 |
| Aliso Canyon | 5/14/2018 | 34.31 | -118.57 | 2,098 | 80 | 34 | -13,291 | 11,941 | 14 | 186 | 5.5 |
| Honor Rancho | 10/16/2017 | 34.46 | -118.59 | 1,915 | 279 | 138 | 12,361 | 3,578 | 11 | 36 | 5 |
| Lodi GS | 12/9/2017 | 38.21 | -121.21 | 905 | bdl | bdl | 1,830 | 5,536 | 9 | 216 | 0.4 |
| McDonald Island | 10/6/2017 | 37.98 | -121.47 | 1,498 | 544 | 251 | -15,151 | 27,626 | 19 | 3 | 2.2 |
| McDonald Mini | 10/6/2017 | 38.00 | -121.48 | 802 | 265 | 116 | 2,257 | 12,684 | 20 | 331 | 1.7 |
| Princeton GS | 12/9/2017 | 39.38 | -122.03 | 687 | bdl | bdl | 3,803 | 1,463 | 8 | 348 | 3.3 |
| Wild Goose GS | 12/9/2017 | 39.32 | -121.88 | 607 | bdl | bdl | -2,757 | 2,506 | 6 | 278 | 0.7 |
| ***Oil Fields and Compressors*** | | | | | | | | | | | |
| Cymric McKittrick | 5/8/2019 | 35.36 | -119.71 | 7,213 | 3,051 | 557 | 229,492 | 70,216 | 6 | 345 | 2.6 |
| Elk Hills 4a | 5/8/2019 | 35.27 | -119.47 | 11,359 | 6,116 | 1,246 | 1,148,294 | 229,799 | 6 | 13 | 1.9 |
| Elk Hills 4b | 5/8/2019 | 35.26 | -119.58 | 1,714 | 413 | 95 | 31,936 | 6,863 | 14 | 49 | 2.2 |
| Elk Hills 4d | 5/8/2019 | 35.20 | -119.47 | 2,623 | 147 | 67 | -825 | 4,013 | 12 | 98 | 0.9 |
| Elk Hills Power LLC | 9/15/2017 | 35.28 | -119.47 | 1,507 | 284 | 65 | 138,442 | 38,463 | 26 | 325 | 1.5 |
| Midway Sunset Oil Field | 9/15/2017 | 35.26 | -119.59 | 1,297 | 103 | 75 | -3,096 | 40,000 | 18 | 0 | 0.9 |
| Mount Poso Oil Field | 4/18/2018 | 35.48 | -119.08 | 1,137 | bdl | bdl | 2,877 | 1,390 | 2 | 329 | 3.9 |
| Round Mountain Oil Field | 4/18/2018 | 35.49 | -118.90 | 940 | bdl | bdl | 19,622 | 6,626 | 5 | 345 | 4.3 |
| Wheeler Ridge Compressor | 4/18/2018 | 35.06 | -119.03 | 931 | bdl | bdl | 1,018 | 1,097 | 7 | 7 | 0.9 |
| ***Other*** | | | | | | | | | | | |
| La Brea Tar Pits | 12/4/2017 | 34.06 | -118.36 | 902 | 97 | 18 | 1,301 | 6,442 | 23 | 158 | 2.9 |
| La Brea Tar Pits | 4/18/2018 | 34.06 | -118.36 | 943 | 112 | 14 | 7,949 | 4,984 | 9 | 234 | 5.5 |
| La Brea Tar Pits | 5/14/2018 | 34.06 | -118.36 | 1,903 | 364 | 21 | 103,769 | 10,575 | 17 | 232 | 6.2 |
| San Jose Wastewater Treatment | 10/5/2017 | 37.43 | -121.95 | 1,001 | 631 | 139 | 60,817 | 18,925 | 15 | 319 | 3 |
| San Jose Wastewater Treatment | 10/5/2018 | 37.43 | -121.95 | 668 | 427 | 80 | 19,744 | 3,582 | 22 | 335 | 3.8 |
| Signal Hill Cluster Box | 5/16/2018 | 33.80 | -118.17 | 2,395 | 340 | 126 | 235,580 | 137,451 | 13 | 237 | 2.6 |

Table 2. Average methane emissions measured from all sites within each source category and for individual sites that were sampled on more than one occasion.

| Site | Number of measurements | Average CH4 Emission (kg/hr) | Standard Deviation | Relative Std. Deviation |
|---|---|---|---|---|
| ***Landfills*** | | | | |
| All Landfill Measurements | 30 | 1581.9 | 968.3 | 61.2% |
| *Sites with multiple measurements:* | | | | |
| Forward | 2 | 2308.3 | 530.7 | 23.0% |
| Keller Canyon | 2 | 1000.3 | 510.1 | 51.0% |
| Kiefer | 5 | 2145.1 | 388.6 | 18.1% |
| Newby Island | 2 | 2681.4 | 857.0 | 32.0% |
| Olinda Alpha | 3 | 1378.2 | 302.2 | 21.9% |
| Portrero Hills | 2 | 1605.4 | 971.4 | 60.5% |
| Scholl Canyon | 2 | 272.7 | 285.7 | 104.8% |
| Toland Road | 2 | 2364.9 | 1181.4 | 50.0% |
| ***Dairies*** | | | | |
| All Dairy Measurements | 29 | 442.3 | 269.8 | 61.0% |
| *Sites with multiple measurements:* | | | | |
| Dairy #1 | 3 | 489.0 | 159.4 | 32.6% |
| Dairy #7 | 2 | 649.2 | 110.2 | 17.0% |
| Dairy #12 | 2 | 661.5 | 169.8 | 25.7% |
| Dairy #15 | 2 | 589.8 | 112.3 | 19.0% |
| Dairy #16 | 2 | 563.3 | 4.2 | 0.8% |
| ***Ranches*** | | | | |
| All Ranch Measurements | 5 | 292.8 | 200.1 | 68.3% |
| *Sites with multiple measurements:* | | | | |
| Feedlot #1 | 2 | 504.1 | 64.6 | 12.8% |
| ***Refineries*** | | | | |
| All Refinery Measurements | 10 | 391.1 | 221.3 | 56.6% |
| *Sites with multiple measurements:* | | | | |
| Chevron Refinery | 3 | 601.9 | 195.2 | 32.4% |
| Phillips 66 Refinery | 3 | 274.5 | 147.1 | 53.6% |
| ***Gas Storage Facilities*** | | | | |
| All Gas Storage Facility Measurements | 7 | 256.0 | 184.0 | 71.9% |
| *Sites with multiple measurements:* | | | | |

| | | | | |
|---|---|---|---|---|
| Aliso Canyon | 2 | 95.2 | 21.0 | 22.0% |
| ***Oil Fields and Compressors*** | | | | |
| All Oil Field/Compressor Measurements | 10 | *NA - different site sizes means emissions not comparable* | | |
| ***Other*** | | | | |
| All Other Measurements | 6 | 328.3 | 201.5 | 61.4% |
| *Sites with multiple measurements:* | | | | |
| La Brea Tar Pits | 3 | 190.8 | 150.1 | 78.7% |
| San Jose Wastewater Treatment | 2 | 528.8 | 143.9 | 27.2% |

The largest methane emissions for an individual site were observed at the landfill sites, with 11 of 30 measurements in excess of 2000 kg $hr^{-1}$ $CH_4$. In total, all 28 landfill measurements averaged to 1581.9 kg $hr^{-1}$ $CH_4$, which is more than 3.5 times greater than the average dairy or oil and gas refinery emissions (on a per site basis). The Newby Island landfill had both the largest individual landfill measurement (3287.4 kg $hr^{-1}$) and the largest average emissions of the multiply-measured sites (2681.4 kg $hr^{-1}$). Scholl Canyon had the lowest individual landfill measurements (70.7 kg $hr^{-1}$), and the lowest average emissions of the multiply-measured sites (272.7 kg $hr^{-1}$). Both of these landfills are among some of the largest in the United States and are relatively similar in size (300-350 acres).

The agricultural sites and the refinery sites had comparable average methane emissions per site, with the dairies averaging 442.3 kg $hr^{-1}$, the ranches averaging 292.8 kg $hr^{-1}$, and the refineries averaging 391.1 kg $hr^{-1}$ of methane. Although the per site average for the agriculture and refinery sites are similar, total methane from the entire agricultural sector in California dominates that from petroleum refining simply due to the larger number of sites. California is currently in the top five US states in terms of total head of cattle, and is the top dairy producer in the US with 1750 dairy farms housing nearly 1.8 million dairy cows. In contrast, there are less than 20 petroleum refineries in the state. The refinery sites, as expected, do emit significantly more $CO_2$ than the agriculture or waste sites.

The gas storage facilities exhibited large site-to-site variability. Three of the target sites were below the measurement detection limit. The remaining measurements ranged from 80.4 kg $hr^{-1}$ to 543.8 kg $hr^{-1}$ $CH_4$. The Aliso Canyon facility, site of the 2015 leak incident, was sampled twice during this project. Emissions for this facility were determined to be 110.09 kg $hr^{-1}$ (on 10/16/2017) and 80.4 kg $hr^{-1}$ (on 5/14/2018), which is lower than the McDonald Island and McDonald Mini facilities. Two oil fields sampled during this project, Mount Poso and Round Mountain, were found to have methane emissions below the measurement detection limit.

Total methane emissions from Elk Hills/Cymric McKittrick oil field were quantified (sites named Cymric McKittrick and Elk Hills 4a, covering an area of ~500 $km^2$) and the combined emissions were 9167.3 kg $hr^{-1}$ methane. Emissions from these sites are not directly comparable to the other measurements of this study due to the large footprint region covered.

Other target sites for this survey included the La Brea Tar Pits, the San Jose Wastewater Treatment Facility, and a variety of industrial sites. The La Brea Tar Pits is a natural geologic seep of crude oil and bitumen that is known to release bacterial methane, and it is the only natural site sampled during this project. The three measurements of La Brea ranged from 96.5 to 363.9 kg $hr^{-1}$, with an average of 190.8 kg $hr^{-1}$ $CH_4$. These methane emissions are comparable to measurements made at the gas storage facilities and on the lower end of measurements made at the petroleum refineries. The San Jose Wastewater Treatment Facility was sampled twice, with an average measurement of 528.8 kg $hr^{-1}$ $CH_4$. This emission rate is comparable to that found from the petroleum refinery sites.

As stated previously, several sites in each source category were sampled on more than one occasion to get an initial idea of the temporal variability of methane emissions. The variability at these sites ranged from < 1% to > 100%. In a very general sense, the agricultural sites were found to be on the lower end of this range in variability. Although it is known that emissions from sites associated with oil and gas can vary greatly with time depending on specific operational activities, this project did not reveal any exceptional variability from the oil and gas sites relative to the other source types. Indeed, the oil and gas sites were in the middle of the range found for the landfill sites. The landfills and the La Brea Tar Pits exhibited some of the greatest variability between measurements. It should be noted, however, that the replicate measurements conducted for this project consisted of only 2 or 3 measurements, which is not sufficient to draw any statistically relevant conclusions on source variability. A larger set of regular measurements over time would be necessary to perform a reliable statistical assessment of variability.



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V. Individual Measurement Results, Sorted Alphabetically

*1. Aliso Canyon Gas Storage Facility, 10-16-2017*

The aircraft flew a total of 19 passes downwind of the Aliso Canyon Storage facility, as shown in Figure 3. Altitudes ranged from 122 mAGL to 981 mAGL. Winds were out of the north, averaging 4.1 m $s^{-1}$. Total methane emission is estimated at 110 ± 40 kg $hr^{-1}$.

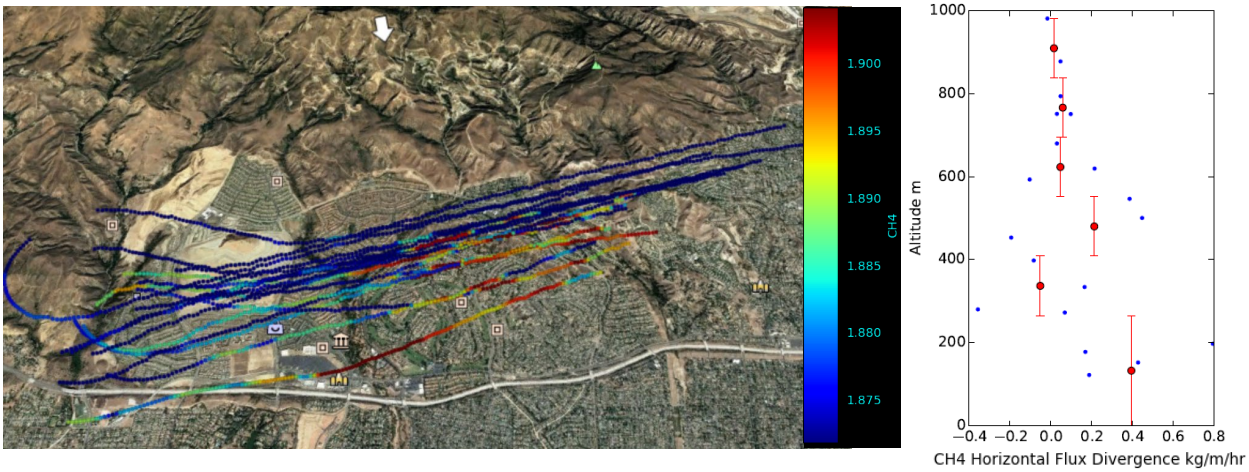


Figure 3. Flight path downwind of the Aliso Canyon Storage facility on October 16, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*2. Aliso Canyon Gas Storage Facility, 5-14-2018*

A total of 17 laps were flown around the Aliso Canyon, as shown in Figure 4. The aircraft completed circles from 182 meters AGL and 510 meters AGL. Winds were out of the south, averaging 5.5 m $s^{-1}$. Total methane emission is estimated at 80 ± 34 kg $hr^{-1}$.

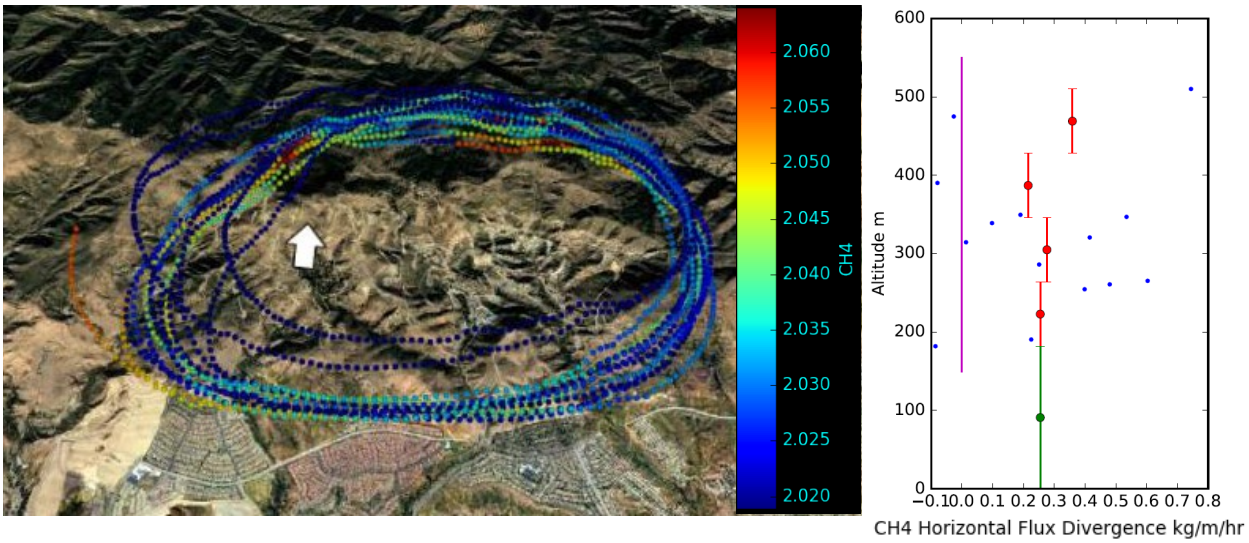


Figure 4. Flight path around Aliso Canyon on May 14, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *3. Altamont Landfill, 10/06/2017*

A total of 11 laps were flown around the Altamont Landfill, as shown in Figure 5. The aircraft completed circles between 80 meters AGL and 600 meters AGL. Winds were out of the north, averaging 7.6 m $s^{-1}$. Total methane emission is estimated at 2976 ± 700 kg $hr^{-1}$.

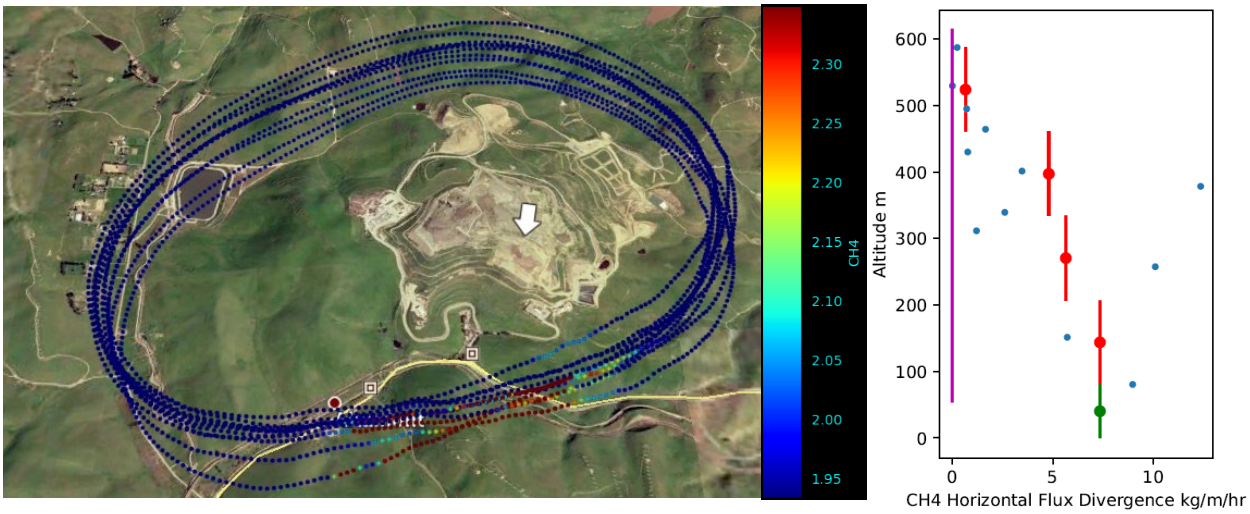


Figure 5. Flight track showing methane mixing ratios around Altamont Landfill on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *4. Beef Company #1, 1/11/2018*

A total of 17 laps (15 useable) were flown around Beef Company #1, as shown in Figure 6. The aircraft completed circles between 64 meters AGL and 450 meters AGL. Winds were out of the northwest, averaging 1.7 m $s^{-1}$. Total methane emission is estimated at 105 ± 42 kg $hr^{-1}$.

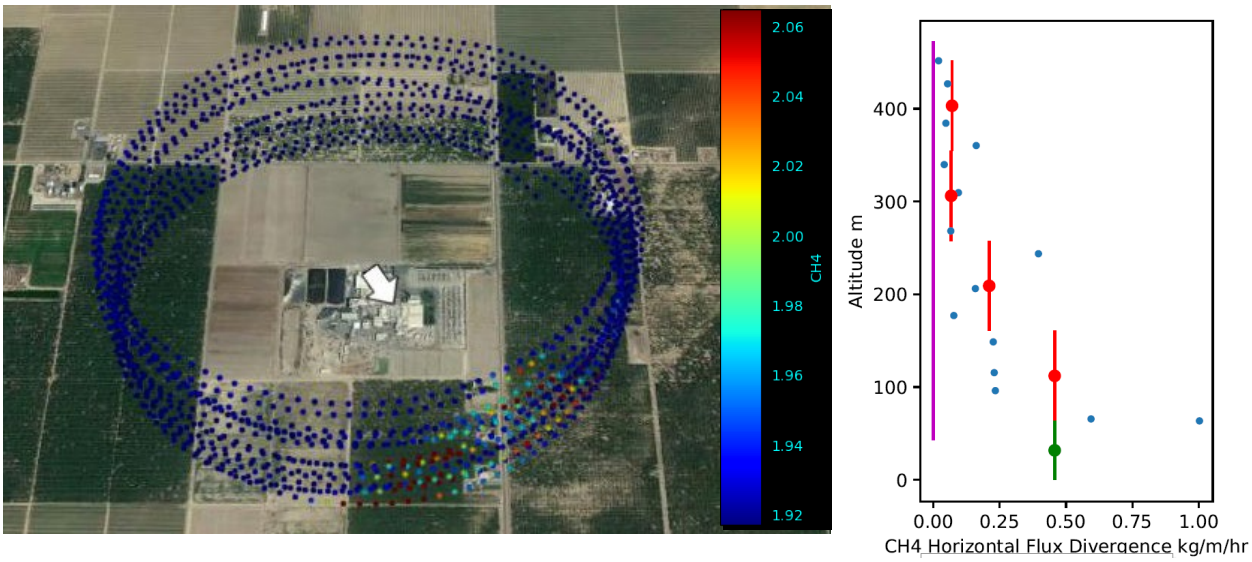


Figure 6. Flight path around Beef Company #1 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*5. BKK West Covina, 11-09-2017*

A total of 19 laps (17 useable) were flown around BKK West Covina Class I and III landfills, as shown in Figure 7. The aircraft completed circles between 168 meters AGL and 669 meters AGL. Winds were out of the west, averaging 2.9 m $s^{-1}$. Total methane emission is estimated at 93 ± 9 kg $hr^{-1}$.

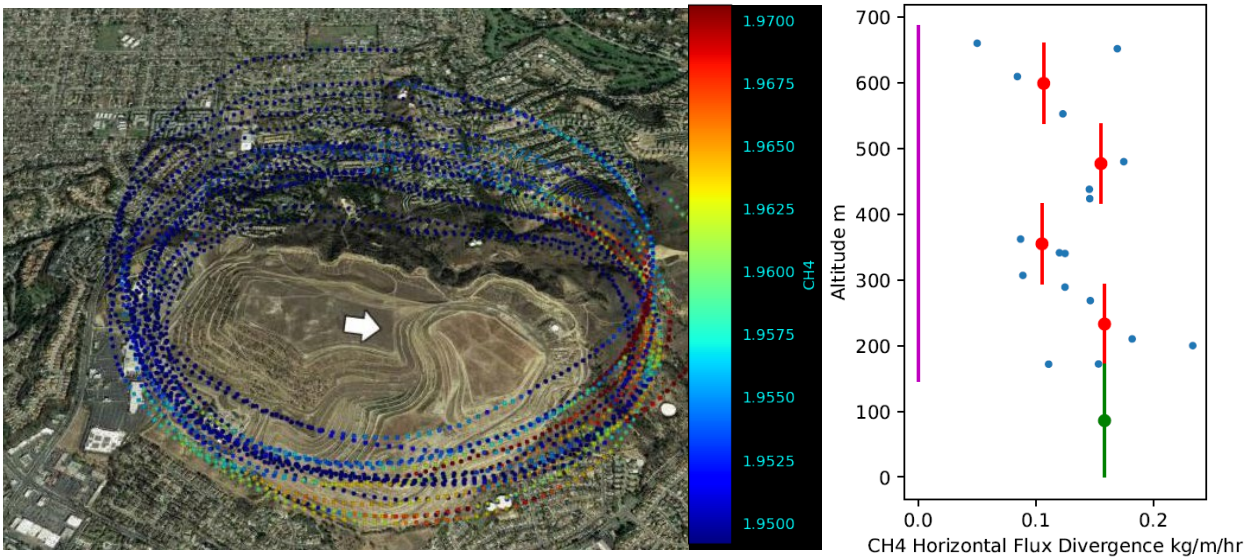


Figure 7. Flight path around BKK West Covina Landfill on November 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

## *6. Chevron Refinery, 10/05/2017*

A total of 13 laps were flown around the Chevron Refinery, as shown in Figure 8. Winds were light and variable near the surface, increasing to ~ 5 m $s^{-1}$ by 450 m AGL. The aircraft completed circles between 80 meters AGL and 450 meters AGL. Winds were out of the east, averaging 1.8 m $s^{-1}$. Total methane emission is estimated at 440 ± 250 kg $hr^{-1}$.

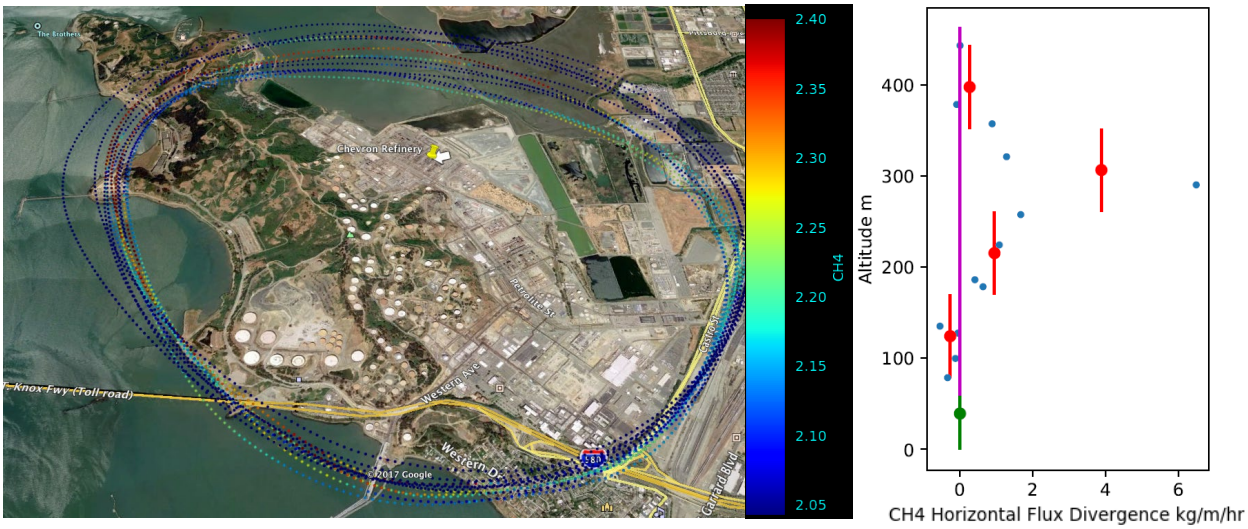


Figure 8. Flight track showing methane mixing ratios around the Chevron Refinery on October 5, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

## 7. *Chevron Refinery, 10/05/2018*

A total of 15 laps (14 useable) were flown around the Chevron Refinery, as shown in Figure 9. The aircraft completed circles from 120 meters AGL and 812 meters AGL. The winds were out of the north, averaging 1.3 m $s^{-1}$. Total methane emission is estimated at 819 ± 200 kg $hr^{-1}$.

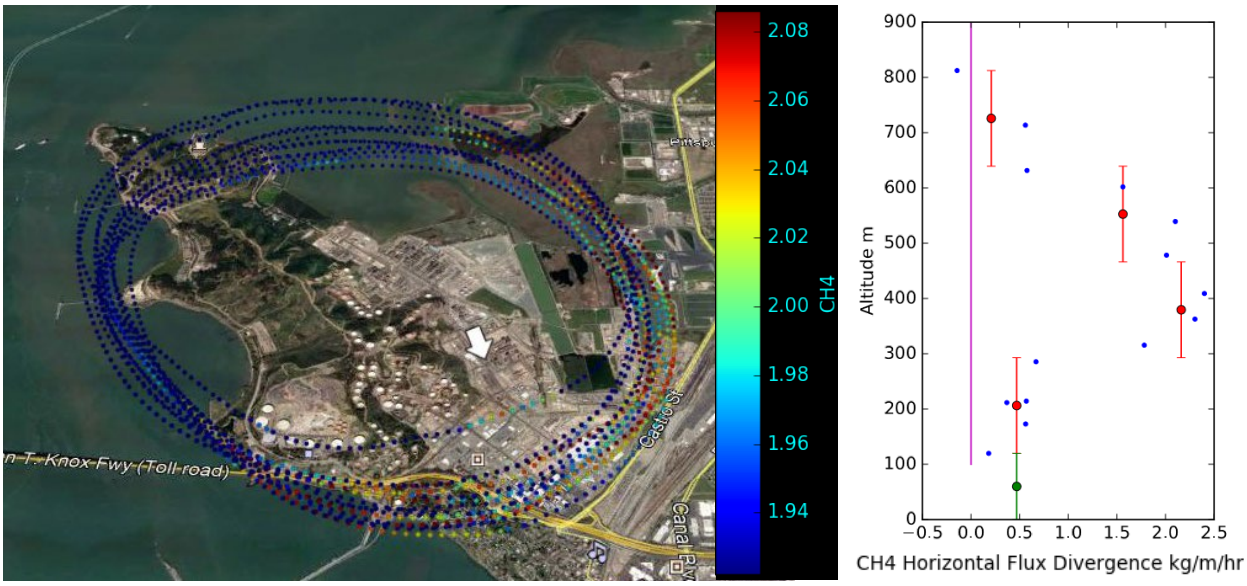


Figure 9. Flight path around the Chevron Refinery and the vertical flux divergence profile for methane on October 5, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

## 8. *Chevron Refinery, 10-06-2018*

A total of 20 laps (16 useable) were flown around the Chevron Refinery as shown in Figure 10. The aircraft completed circles from 290 meters AGL and 952 meters AGL. The winds were out of the north, averaging 4.1 m $s^{-1}$. Total methane emission is estimated at 548 ± 116 kg $hr^{-1}$.

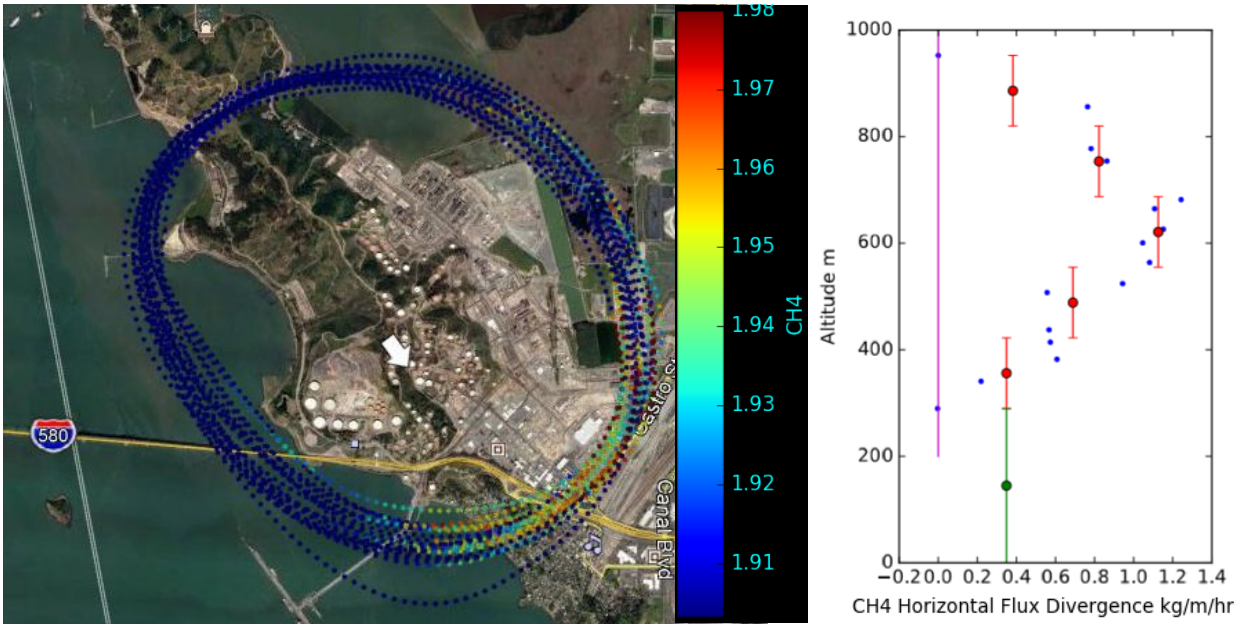


Figure 10. Flight path around the Chevron Refinery and the vertical flux divergence profile for methane on October 6, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *9. Chiquita Canyon, 10/17/2017*

A total of 20 laps (15 useable) were flown around Chiquita Canyon, as shown in Figure 11. The aircraft completed circles between 250 meters AGL and 710 meters AGL. Winds were out of the southwest, averaging 3.3 m $s^{-1}$. Total methane emission is estimated at 2153 ± 679 kg $hr^{-1}$.

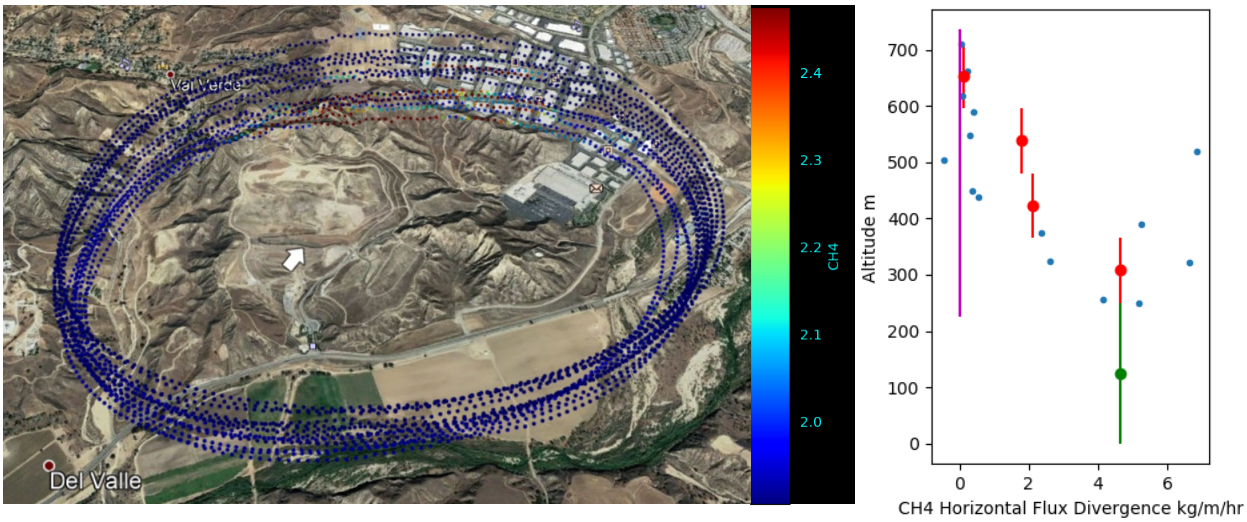

Figure 11. Flight track showing the flight path around Chiquita Canyon on October 17, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*10. Cymric McKittrick, 5/09/2019*

Six laps were flown around Cymric McKittrick at altitudes between 210 and 1223 m AGL. Winds were from the north/northwest and averaged 2.6 m $s^{-1}$. Total methane emission is estimated at 3051 ± 567 kg $hr^{-1}$.

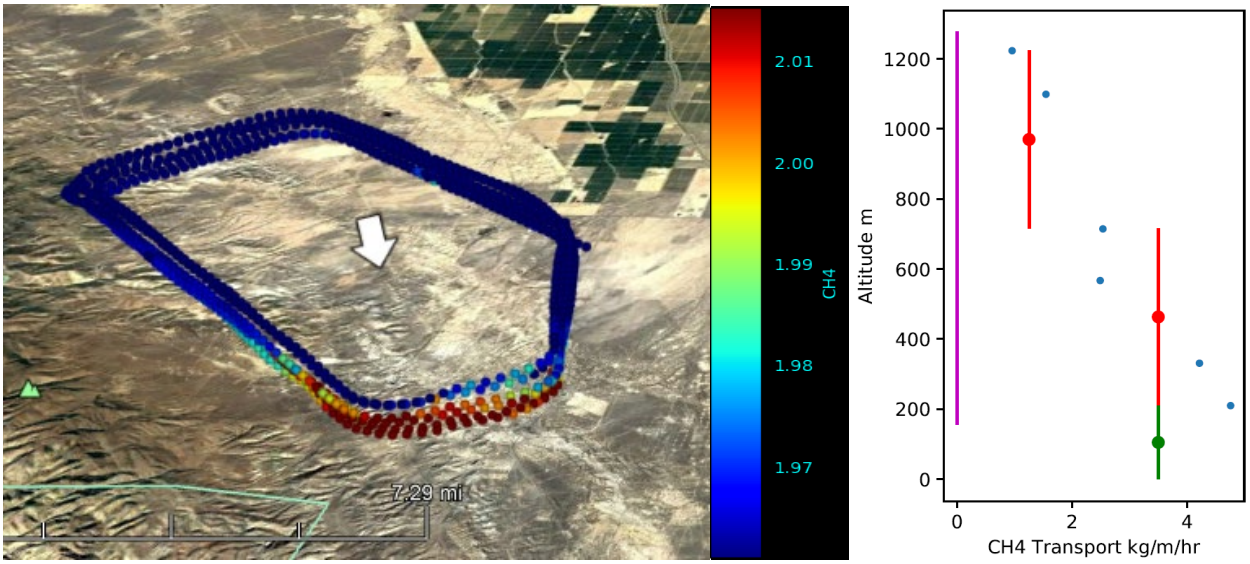


Figure 12. (Left) Flight path around Cymric on May 9, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*11. Dairy #1, 9/15/2017*

A total of 28 laps (27 useable) were flown around the Dairy #1, as shown in Figure 13. The aircraft completed circles between 35 meters AGL and 800 meters AGL. Winds were out of the northwest, averaging 2.5 m $s^{-1}$. Total methane emission is estimated at 670 ± 170 kg $hr^{-1}$.

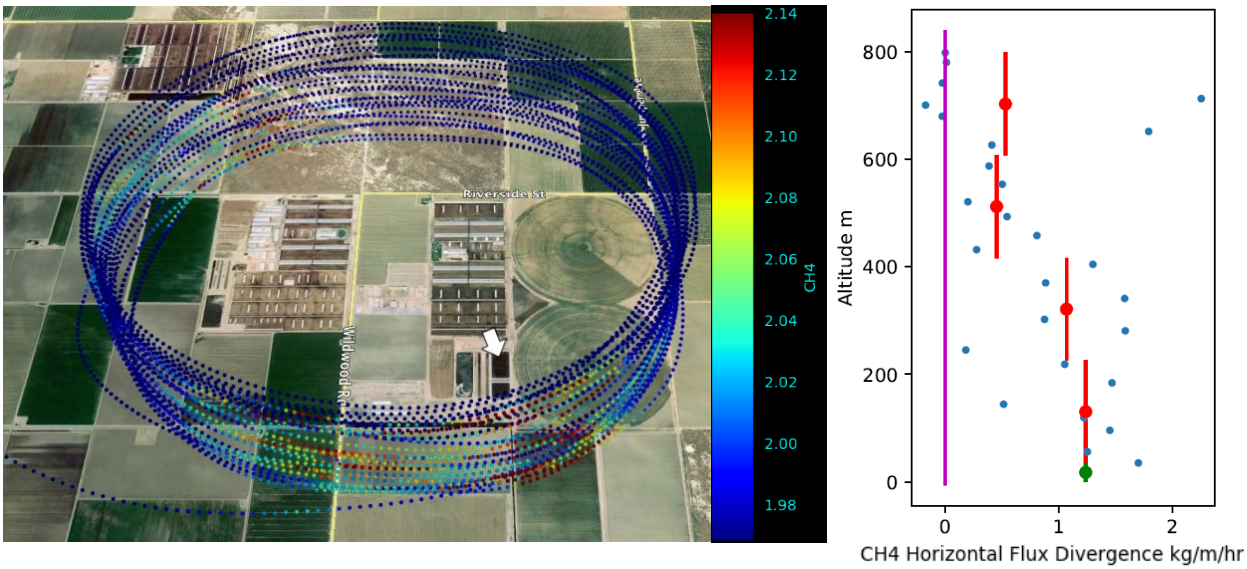


Figure 13. Flight path around Dairy #1 on September 15, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*12. Dairy #1, 1/11/2018*

A total of 12 useable laps were flown around the Dairy #1, as shown in Figure 14. The aircraft completed circles between 72 meters AGL and 752 meters AGL. Winds were out of the southeast, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 427 ± 150 kg $hr^{-1}$.

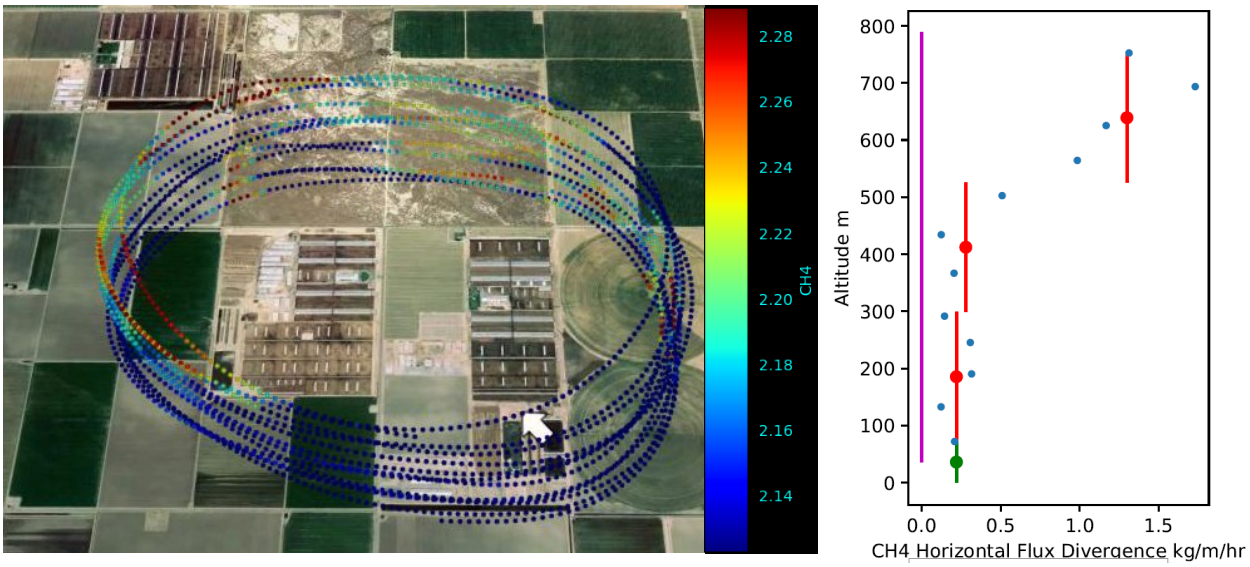


Figure 14. Flight path around Dairy #1 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*13. Dairy #1, 5/17/2018*

A total of 23 (19 useable) laps were flown around Dairy #1 as shown in Figure 15. The aircraft completed circles from 55 meters AGL to 1152 meters AGL. Winds were out of the northwest, averaging 3.5 m $s^{-1}$. Total methane emission is estimated at 369 ± 150 kg $hr^{-1}$. There was another dairy/ranch immediately northwest resulting in upwind methane enhancements, which added uncertainty to the measurement.

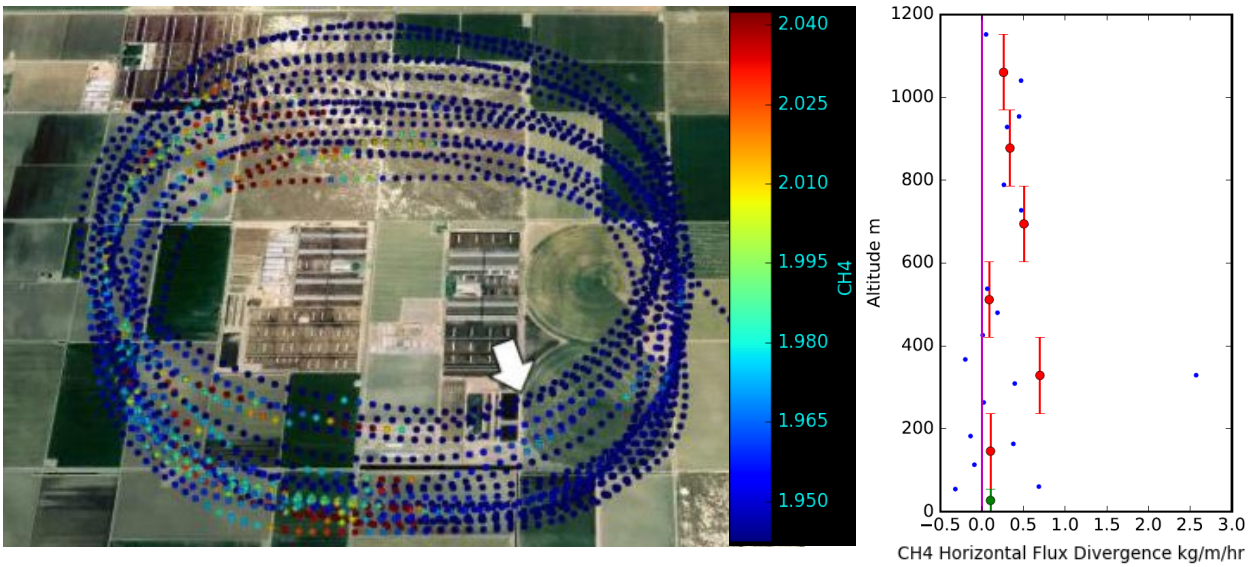


Figure 15. Flight path around Dairy #1 on May 17, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*14. Dairy #1, 5/09/2019*

A total of 16 laps were flown around Dairy 1 at altitudes between 98 and 709 m AGL. Winds were from the northwest and averaged 8.3 m $s^{-1}$. Total methane emission is estimated at 830 ± 114 kg $hr^{-1}$.

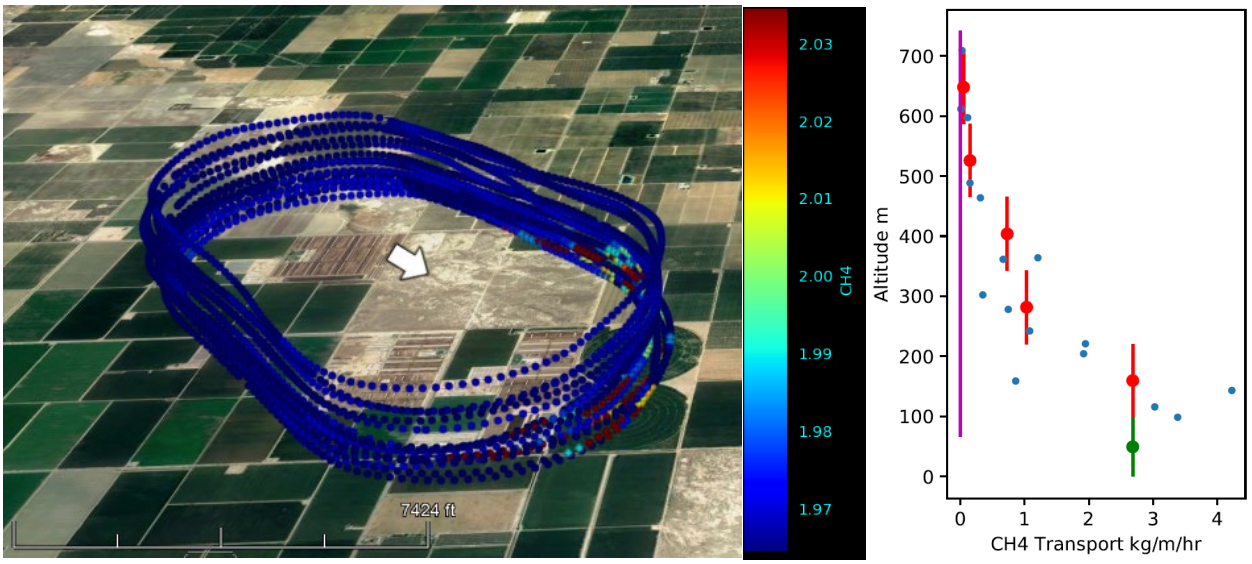


Figure 1. (Left) Flight path around the dairy on May 9, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*15. Dairy #2, 9/15/2017*

A total of 41 laps were flown around the Dairy #2, as shown in Figure 16. The aircraft completed circles between 40 meters AGL and 1550 meters AGL. There was a confounding source (another dairy) immediately upwind of Bidart, which increased the uncertainty in the measurement. Winds were out of the northwest, averaging 2.6 m $s^{-1}$. Total methane emission is estimated at 300 ± 150 kg $hr^{-1}$.

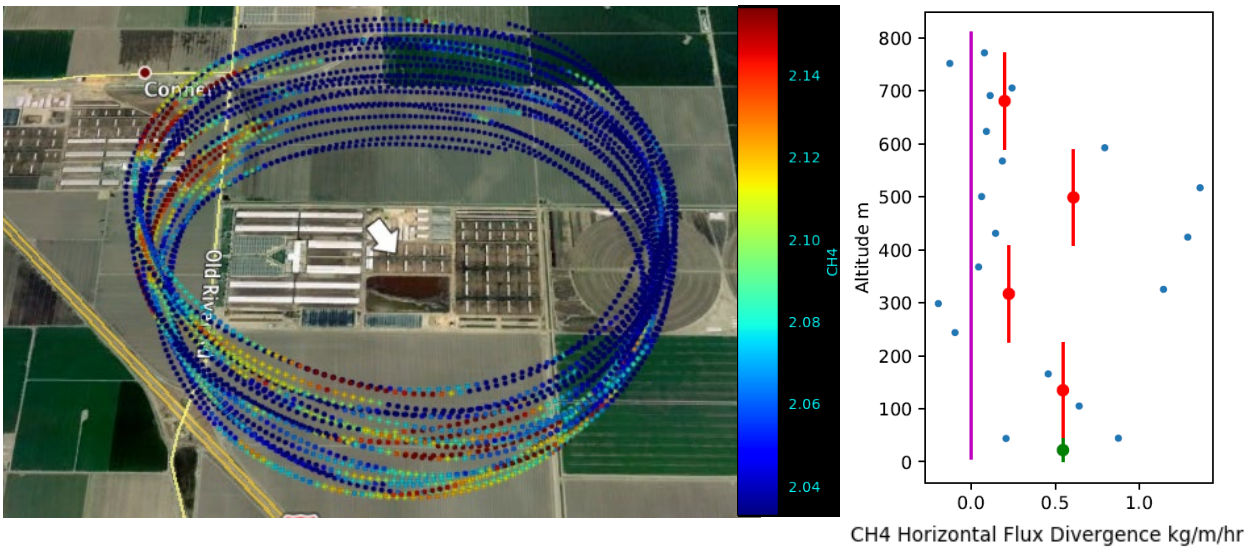


Figure 16. Flight track showing methane mixing ratios around the Dairy #2 on September 15, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*16. Dairy #3, 11/18/2017*

A total of 20 laps (18 useable) were flown around the Dairy #3, as shown in Figure 17. The aircraft completed circles between 77 meters AGL and 650 meters AGL. Winds were out of the southwest, averaging 1.4 m $s^{-1}$. Total methane emission is estimated at 223 ± 83 kg $hr^{-1}$.

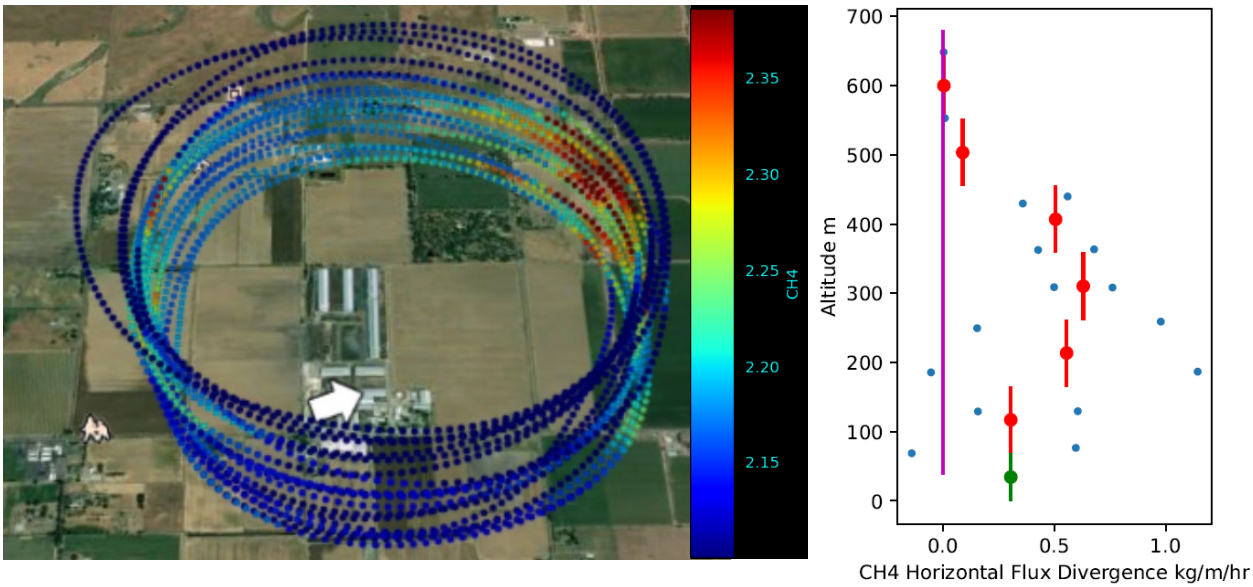


Figure 17. Flight path around Dairy #3 on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*17. Dairy #4, 11/18/2017*

A total of 18 were flown around the Dairy #4, as shown in Figure 18. The aircraft completed circles between 63 meters AGL and 586 meters AGL. The winds were out of the northwest, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 121±52 kg $hr^{-1}$.

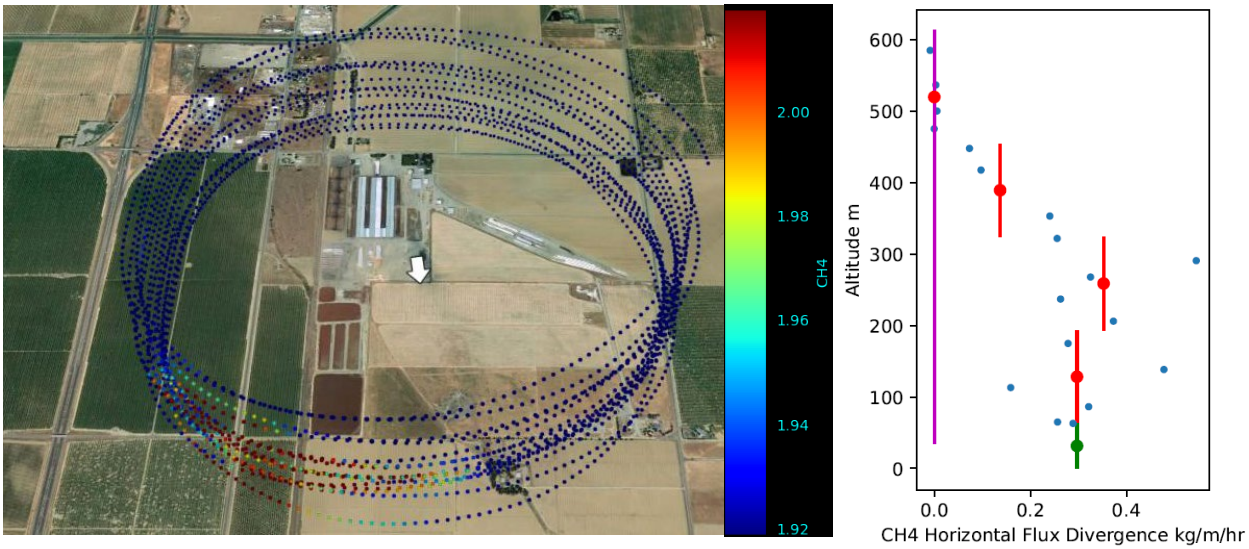


Figure 18. Flight path around Dairy #4 on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*18. Dairy #5, 11/18/2017*

A total 17 were flown around Dairy #5, as shown in Figure 19. The aircraft completed circles between 68 meters AGL and 541 meters AGL. The winds were out of the northeast, averaging 0.7 m $s^{-1}$. Total methane emission is estimated at 53 ± 30 kg $hr^{-1}$.

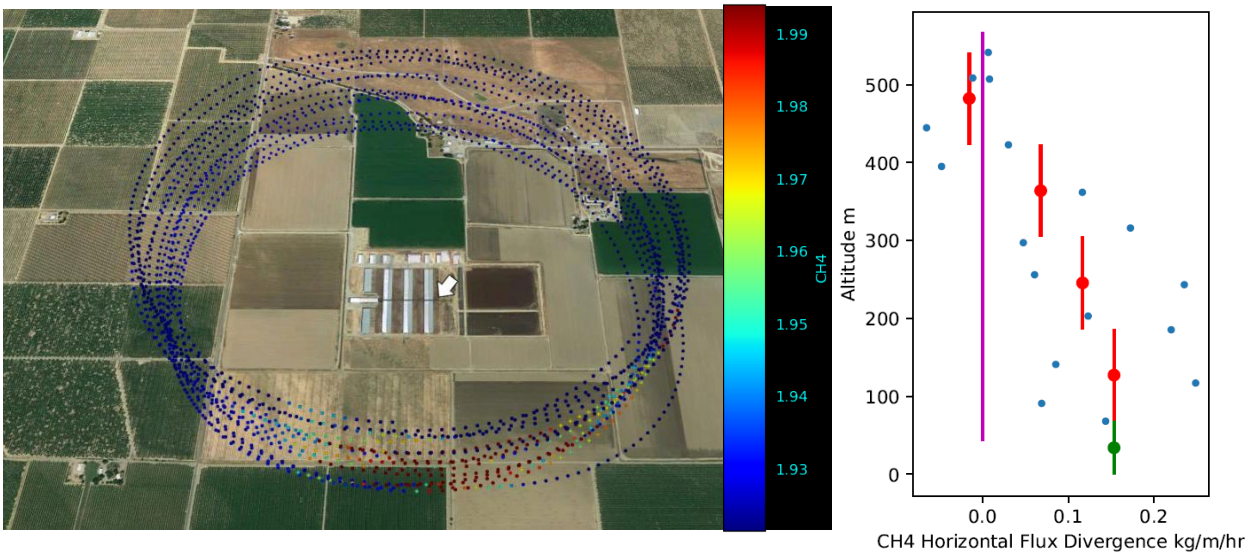


Figure 19. Flight path around Dairy #5 on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*19. Dairy #6, 11/18/2017*

A total of 21 laps (18 useable) were flown around Dairy #6, as shown in Figure 20. The aircraft completed circles between 69 meters AGL and 571 meters AGL. Winds were out of the northeast, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 70 ± 30 kg $hr^{-1}$.

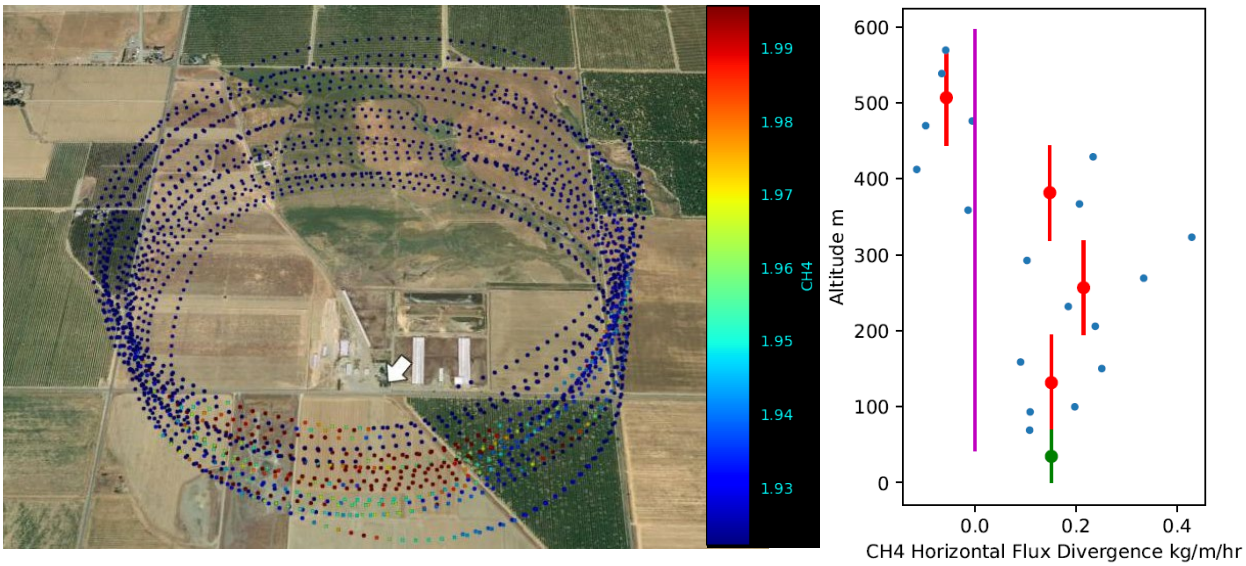


Figure 20. Flight path around Dairy #6 on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*20. Dairy #7 No. 2, 1/10/2018*

A total of 15 laps (13 useable) were flown around the Dairy #7, as shown in Figure 21. The aircraft completed circles from 26 meters AGL and 382 meters AGL. Winds were out of the northwest, averaging 2.8 m $s^{-1}$. Total methane emission is estimated at 570 ± 140 kg $hr^{-1}$.

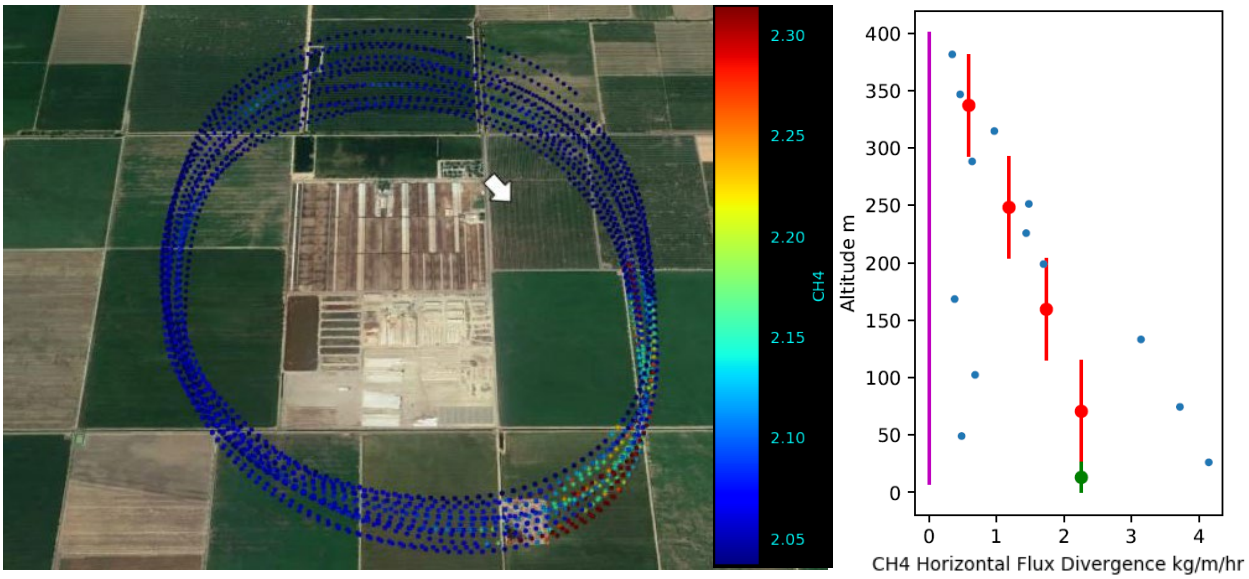


Figure 21. Flight path around Dairy #7 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*21. Dairy #7, 5/12/2018*

A total of 20 laps (17 useable) were flown around the Dairy #7 facility number 2, as shown in Figure 22. The aircraft completed circles between 33 meters AGL and 590 meters AGL. Winds were out of the west, averaging 3.9 m $s^{-1}$. The total methane emission is estimated at 727 ± 106 kg $hr^{-1}$.

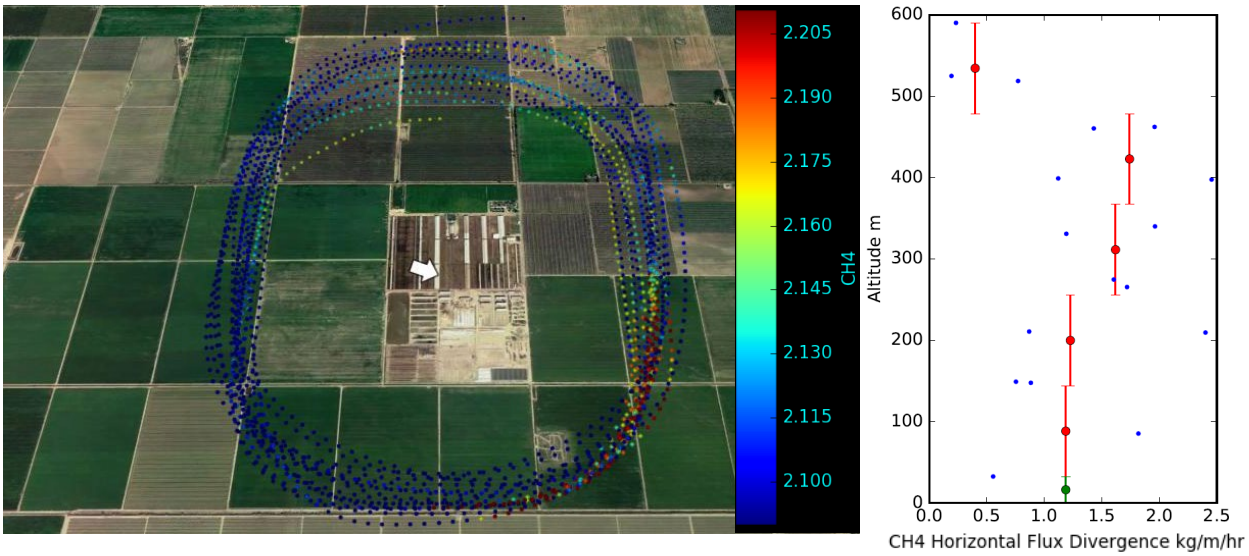


Figure 22. Flight path around Dairy #7 on May 12, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*22. Dairy #7, 5/07/2019*

A total of 23 laps were flown around the dairy (Fig. 23). The aircraft completed circles between 73 meters AGL and 954 meters AGL. The winds were out of the north, averaging 3.7 m $s^{-1}$. Total methane emission is estimated at 764 ± 171 kg $hr^{-1}$.

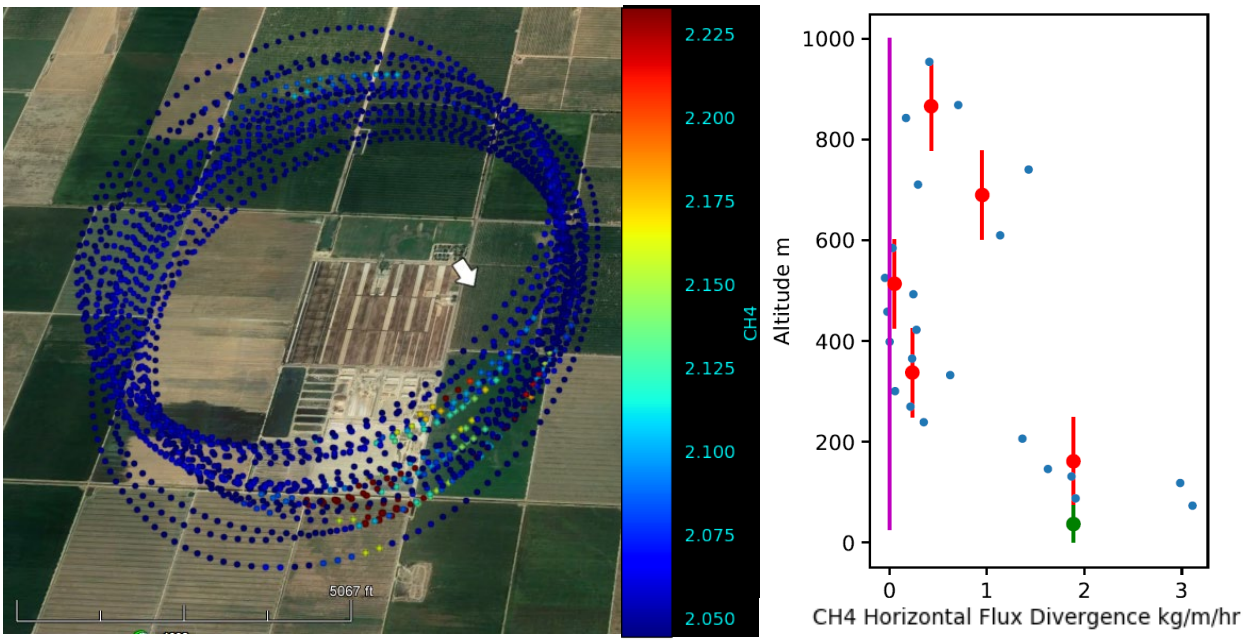


Figure 23. (Left) Flight path around the dairy on May 7, 2019, colored by methane concentration (blue = low, red = high). (Right) Vertical flux divergence profile of methane. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*23. Dairy #8, 1/10/2018*

A total of 14 laps (13 useable) were flown around Dairy #8, as shown in Figure 24. The aircraft completed circles between 49 meters AGL and 420 meters AGL. Winds were out of the northwest, averaging 3 m $s^{-1}$. Total methane emission is estimated at 466 ± 125 kg $hr^{-1}$.

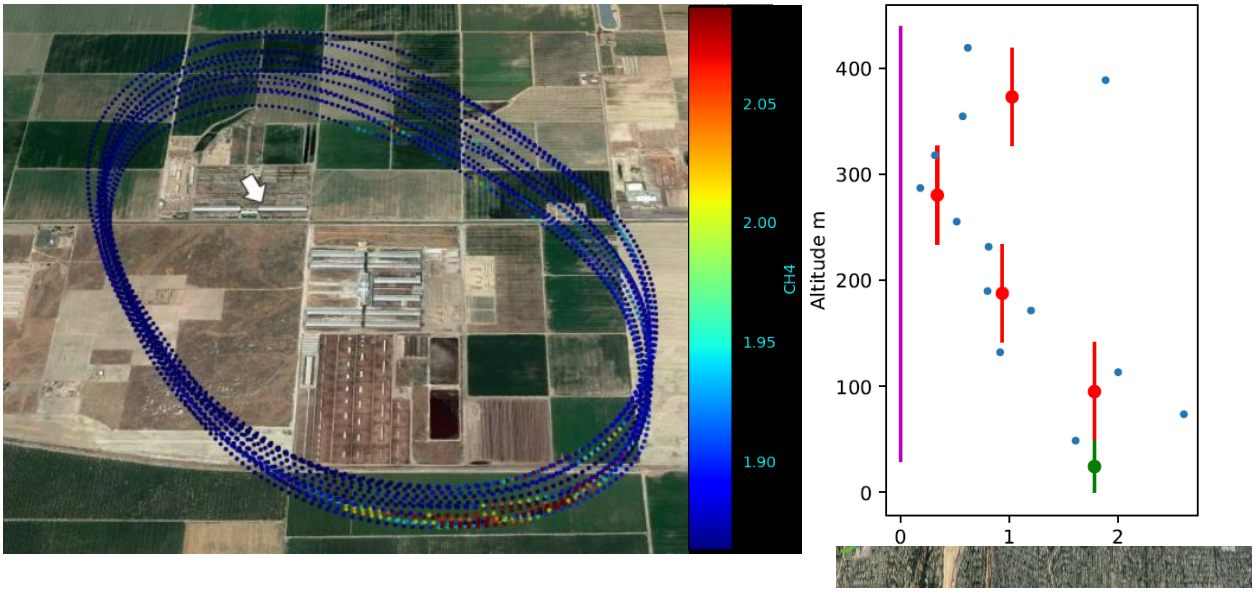


Figure 24. Flight path around Dairy #8 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*24. Dairy #9, 1/10/2018*

A total of 13 laps (12 useable) were flown around Dairy #9, as shown in Figure 25. The aircraft completed circles between 68 meters AGL and 361 meters AGL. Winds were out of the northwest, averaging 5.2 m $s^{-1}$. Total methane emission is estimated at 475 ± 70 kg $hr^{-1}$.

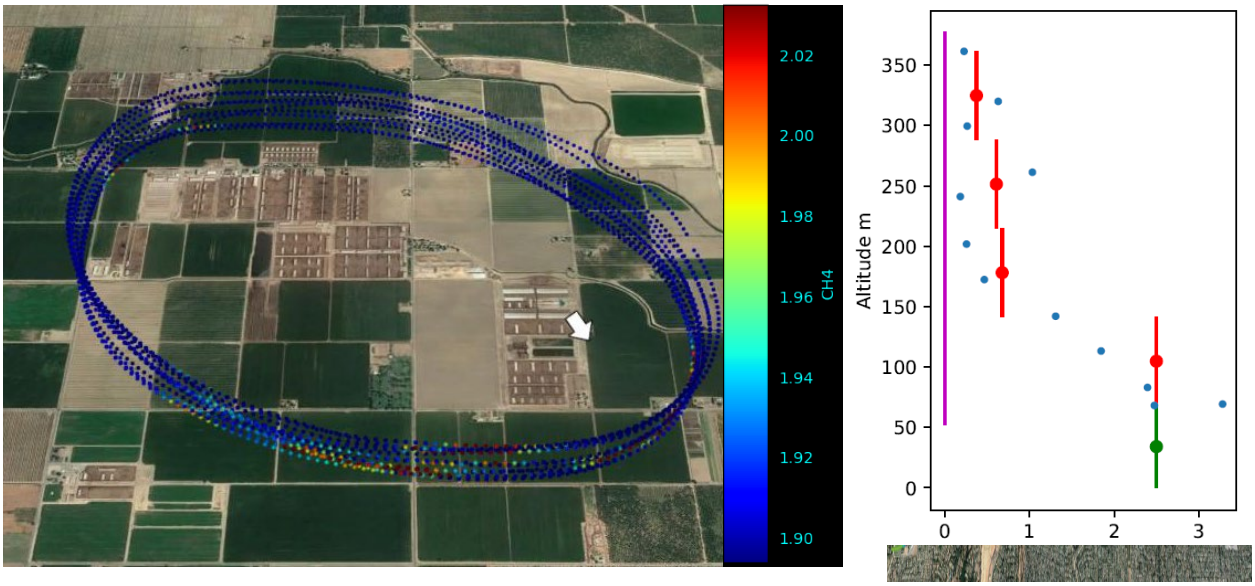

Figure 25. Flight path around Dairy #9 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*25. Dairy #10, 1/10/2018*

A total of 11 laps (8 useable) were flown around Dairy #10, as shown in Figure 27. The aircraft completed circles between 60 meters AGL and 273 meters AGL. Winds were out of the northwest, averaging 5 m $s^{-1}$. Total methane emission is estimated at 275 ± 40 kg $hr^{-1}$.

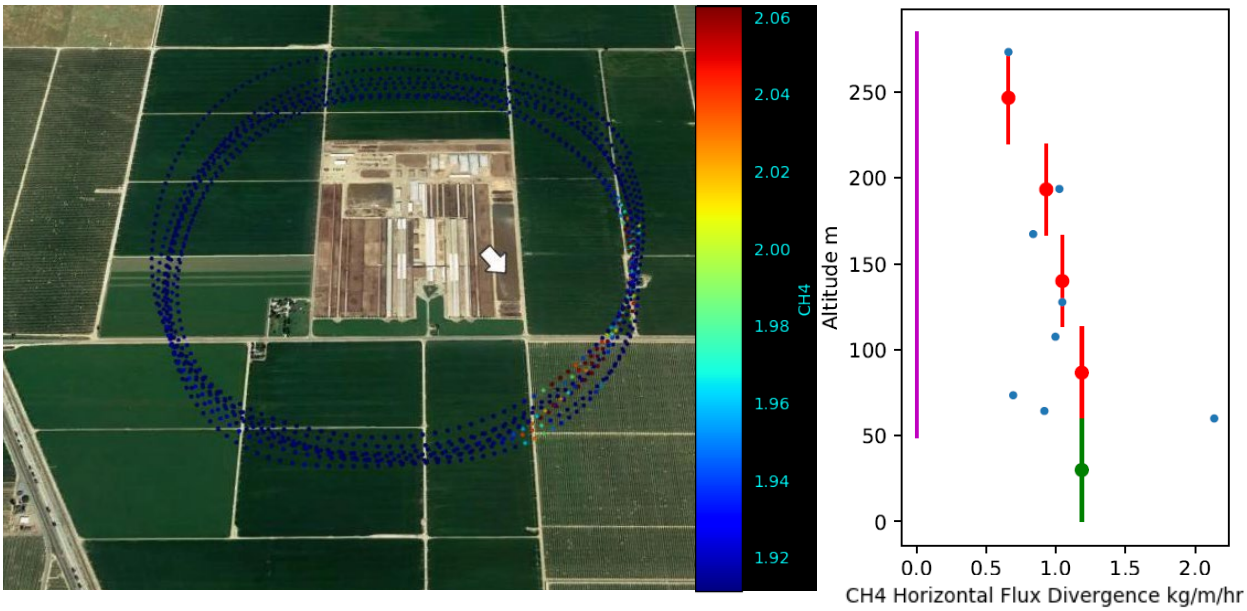


Figure 27. Flight path around Dairy #10 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*26. Dairy #11, 1/10/2018*

A total of 10 laps (9 useable) were flown around Dairy #11, as shown in Figure 28. The aircraft completed circles between 61 meters AGL and 291 meters AGL. Winds were out of the northwest, averaging 6.2 m $s^{-1}$. Total methane emission is estimated at 167 ± 50 kg $hr^{-1}$.

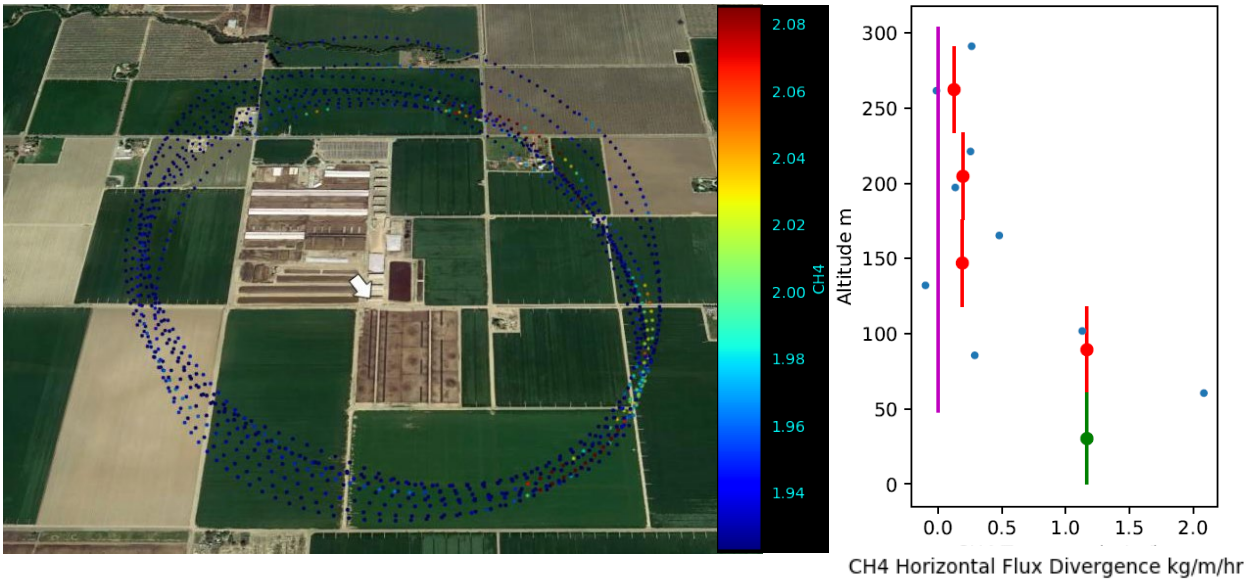


Figure 28. Flight path around Dairy #11 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*27. Dairy #12, 1/10/2018*

A total of 19 laps (18 useable) were flown around Dairy #12, as shown in Figure 29. The aircraft completed circles between 61 meters AGL and 547 meters AGL. Winds were out of the northwest, averaging 4.3 m $s^{-1}$. Total methane emission is estimated at 540 ± 95 kg $hr^{-1}$.

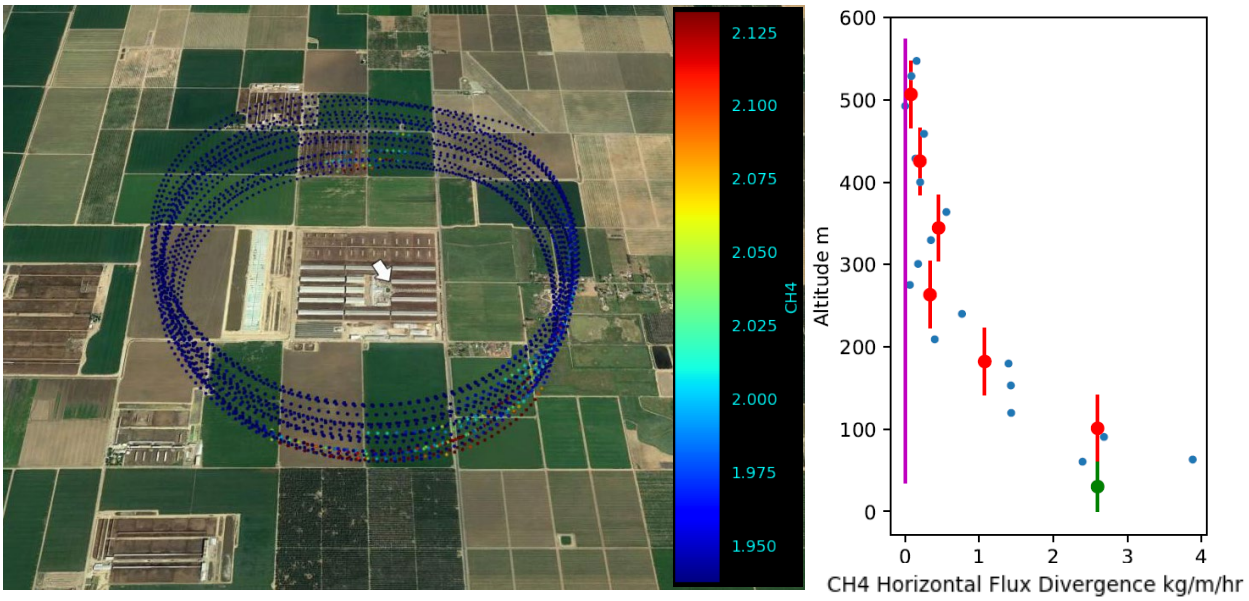

Figure 29. Flight path around Dairy #12 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*28. Dairy #12, 5/12/2018*

A total of 16 laps were flown around the Dairy #12, shown in Figure 30. The aircraft completed circles from 67 meters AGL and 1190 meters AGL. Winds were out of the northwest, averaging 2.2 m $s^{-1}$. Methane emission is estimated as 782 ± 143 kg $hr^{-1}$.

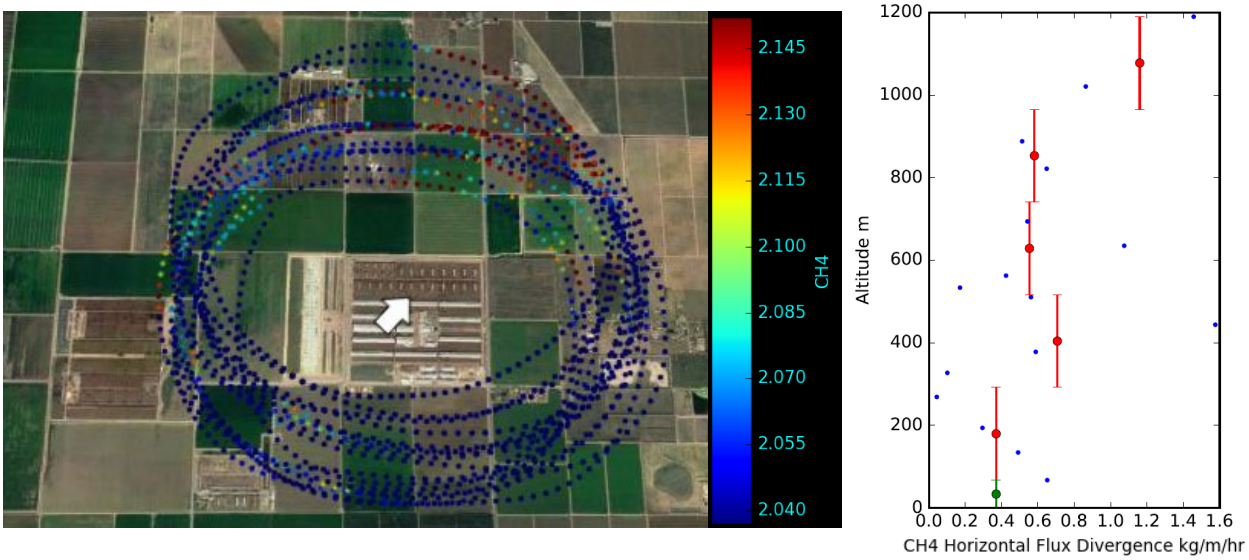


Figure 30. Flight path around Dairy #12 on May 12, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*29. Dairy #13, 1/10/2018*

A total of 8 laps (7 useable) were flown around the Dairy #13, as shown in Figure 31. The aircraft completed circles between 58 meters AGL and 215 meters AGL. Winds were out of the northwest, averaging 5.3 m $s^{-1}$. Total methane emission is estimated at 237 ± 40 kg $hr^{-1}$.

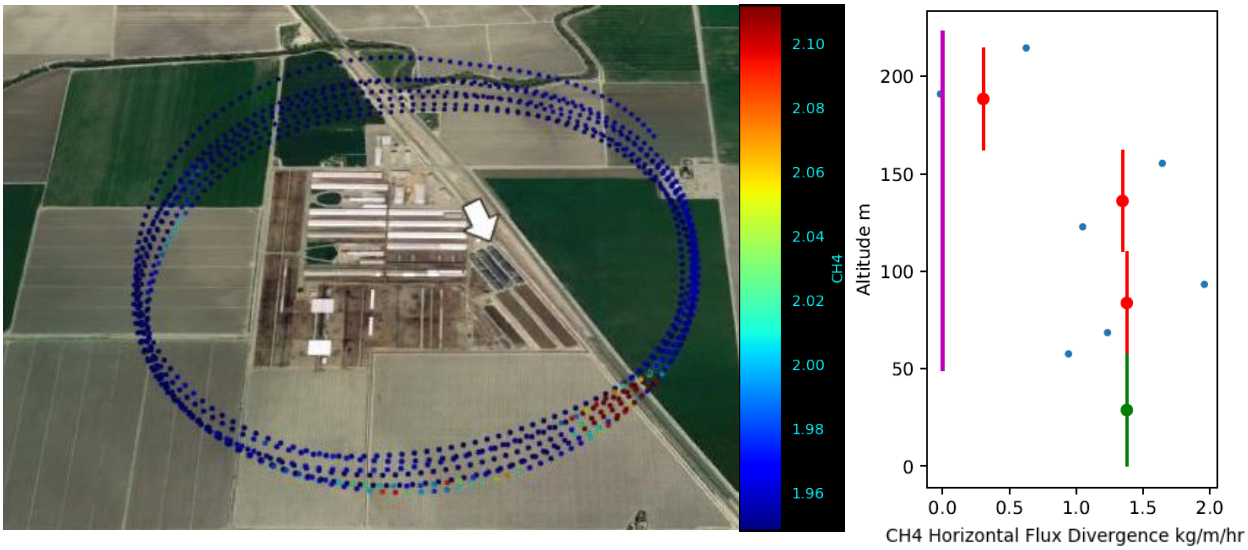


Figure 31. Flight path around Dairy #13 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*30. Dairy #14, 1-10-2017*

A total of 12 laps (10 useable) were flown around the Dairy #14, as shown in Figure 32. The aircraft completed circles between 67 meters AGL and 280 meters AGL. Winds were out of the northwest, averaging 4.4 m $s^{-1}$. Total methane emission is estimated at 403 ± 75 kg $hr^{-1}$.

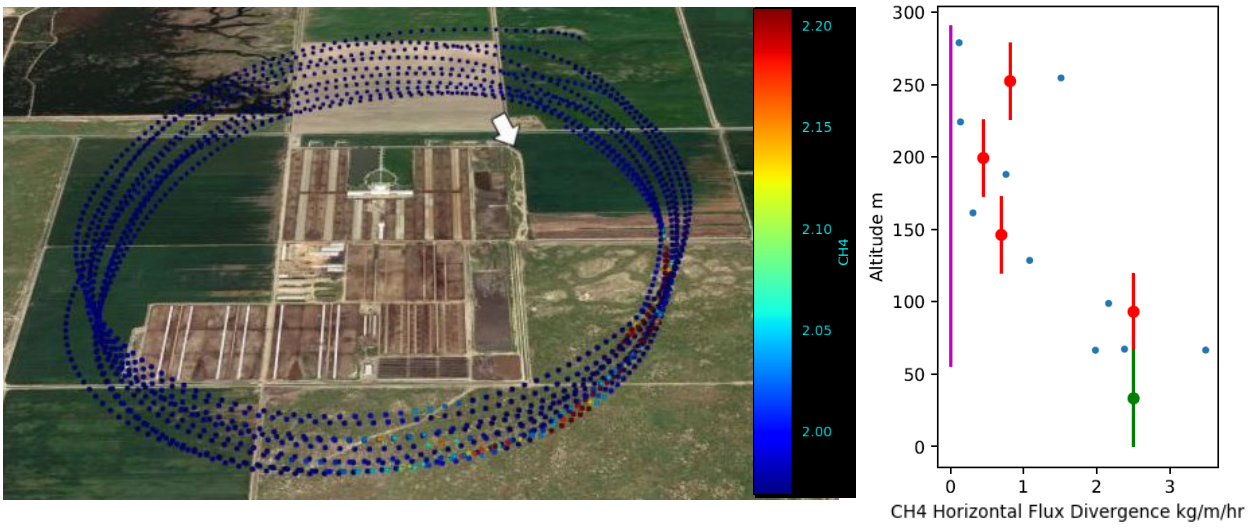


Figure 32. Flight path around Dairy #14 on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*31. Dairy #15, 1/10/2018*

A total of 21 laps (20 useable) were flown around the Dairy #15 Complex as shown in Figure 33. The aircraft completed circles between 46 meters AGL and 761 meters AGL. Winds were out of the northwest, averaging 4.8 m $s^{-1}$. Total methane emission is estimated at 670 ± 190 kg $hr^{-1}$. The uncertainty on this flight was high due to the close proximity of a feedlot to the northwest of the dairy.

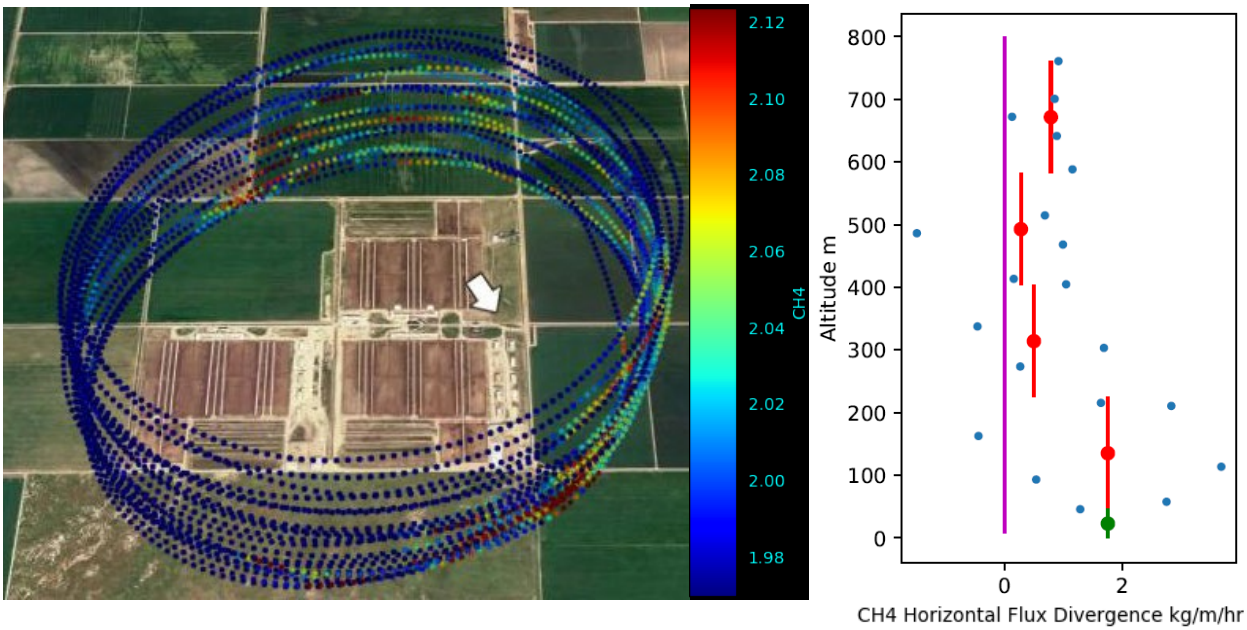


Figure 33. Flight path around Dairy #15 Complex on January 10, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*32. Dairy #15, 5/07/2019*

Eighteen laps (16 useable) were flown around the dairy (Fig. 34). Laps were completed at altitudes between 78 and 619 meters AGL. Winds were from the north averaging 4.5 m $s^{-1}$. Total methane emission is estimated at 510 ± 115 kg $hr^{-1}$.

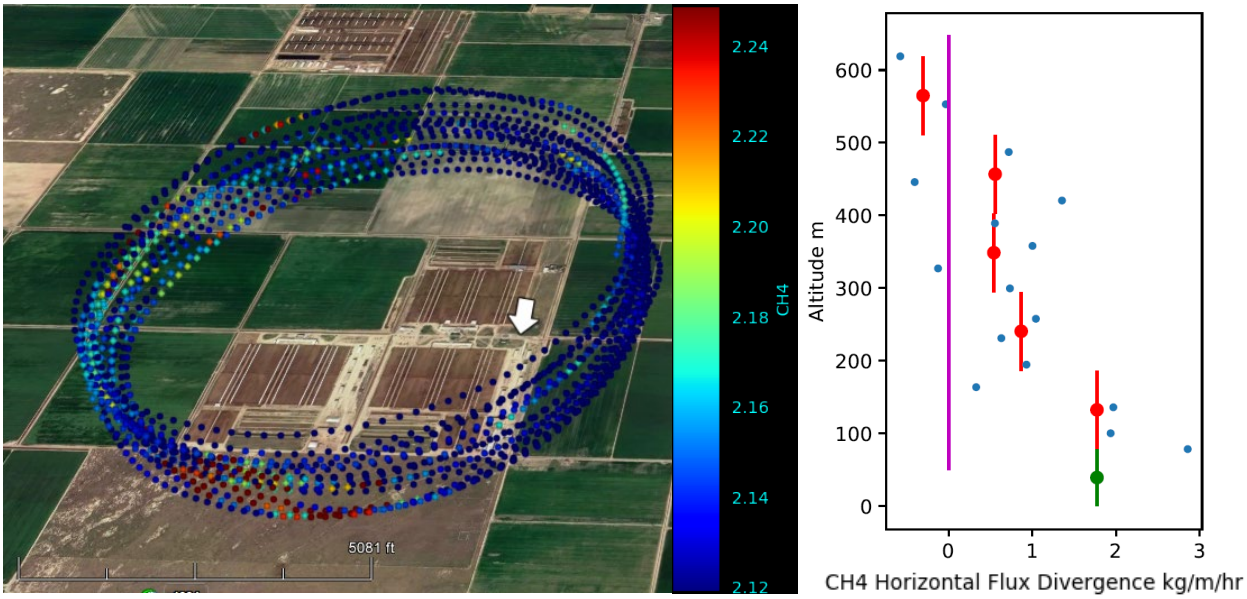


Figure 34. (Left) Flight path around the dairy on May 7, 2019, colored by methane concentration (blue = low, red = high). (Right) Vertical flux divergence profile of methane. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*33. Dairy #16, 1/11/2018*

A total of 22 laps (21 useable) were flown around Dairy #16, as shown in Figure 35. The aircraft completed circles between 52 meters AGL and 582 meters AGL. Winds were out of the southwest and averaged 0.8 m $s^{-1}$. Total methane emission is estimated at 560 ± 374 kg $hr^{-1}$. The uncertainty on this flight was high due a high variability in wind direction and low wind speed.

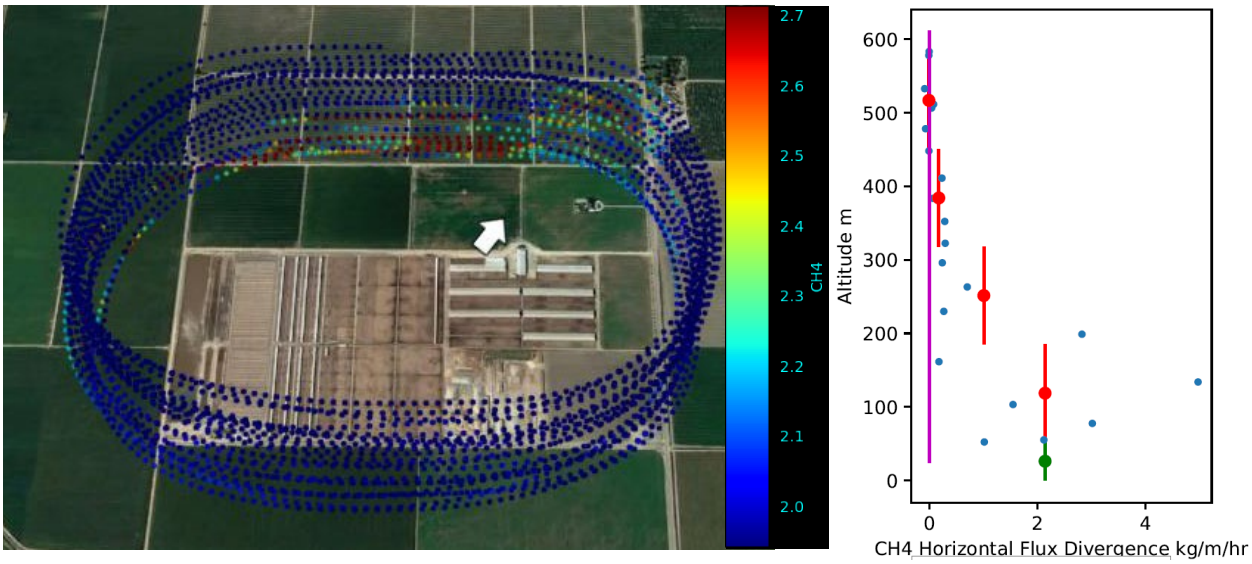

Figure 35. Flight path around Dairy #16 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*34. Dairy #16, 5/12/2018*

A total of 18 laps (16 useable) were flown around the Dairy #16, as shown n Figure 36. The aircraft completed circles between 39 meters AGL and 539 meters AGL. Winds were out of the northwest, averaging 4 m $s^{-1}$. The total methane emission is estimated at 566 ± 114 kg $hr^{-1}$.

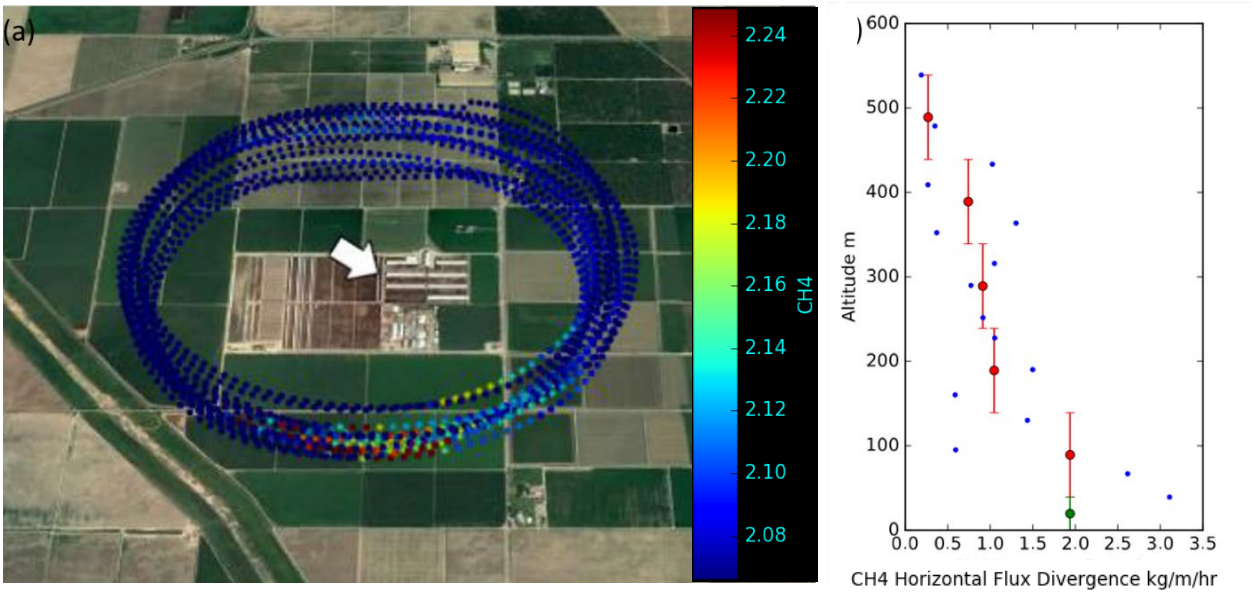


Figure 36. Flight track showing methane mixing ratios around Dairy #16 on May 12, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*35. Dairy #17, 1/11/2018*

A total of 20 laps (13 useable) were flown around the Dairy #17, as shown in Figure 37. The aircraft completed circles between 53 meters AGL and 475 meters AGL. Winds were out of the northwest, averaging 1.4 m $s^{-1}$. Total methane emission is estimated at 250 ± 130 kg $hr^{-1}$. The uncertainty on this flight was high due a high variability in wind direction and low wind speed.

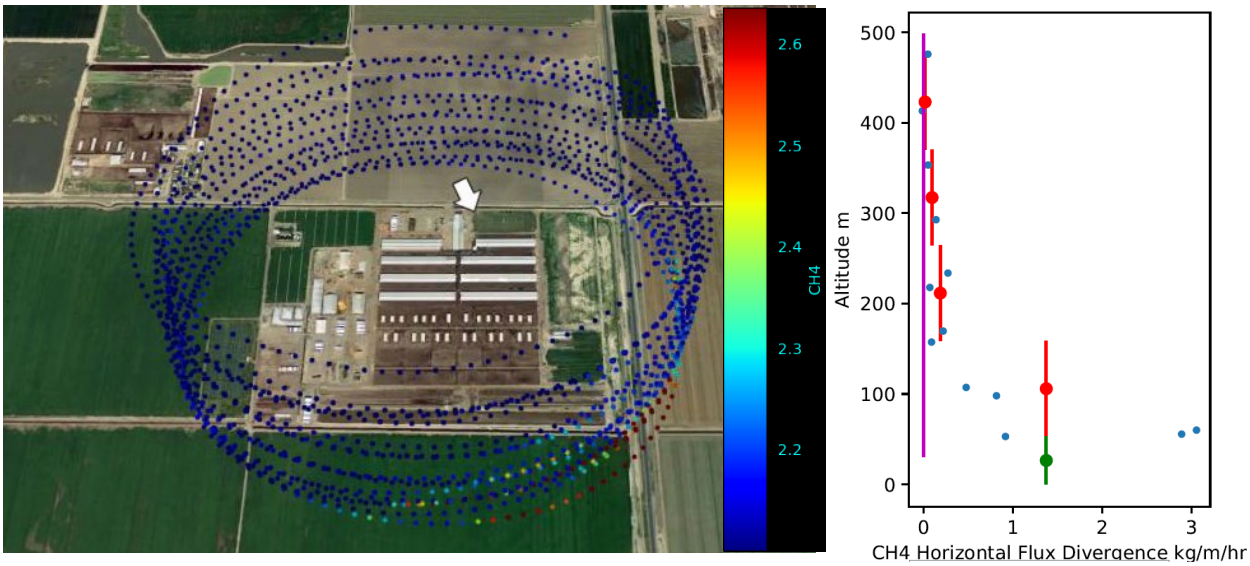


Figure 37. Flight path around Dairy #17 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*36. Dairy #18, 1/11/2018*

A total of 17 laps (14 useable) were flown around the Dairy #18, as shown in Figure 38. The aircraft completed circles between 47 meters AGL and 426 meters AGL. Winds were out of the northwest, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 170 ± 90 kg $hr^{-1}$.

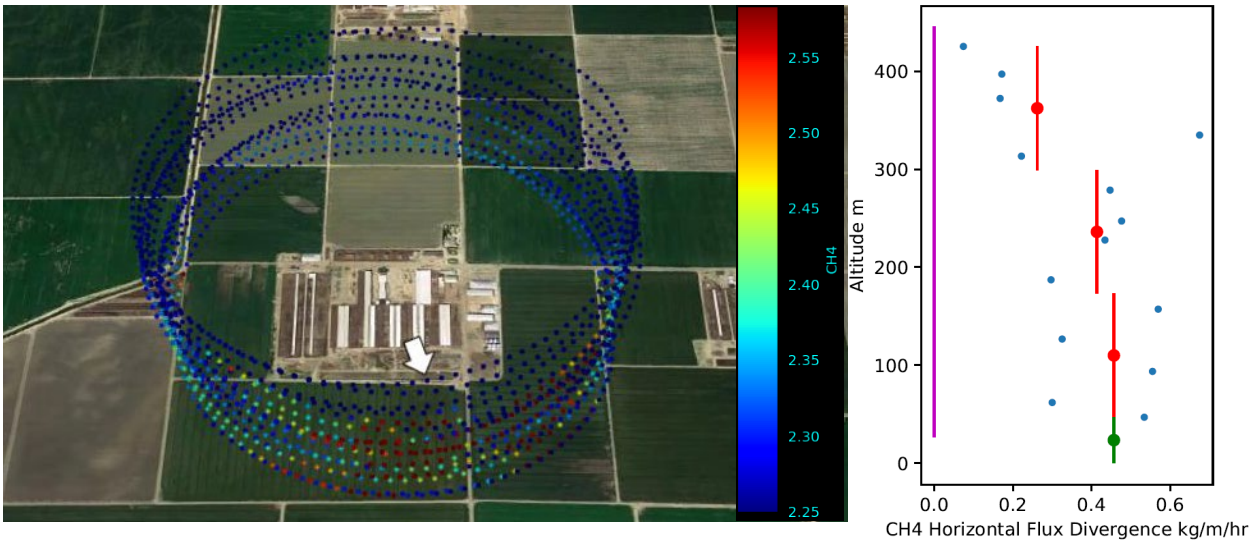


Figure 38. Flight path around Dairy #18 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*37. Dairy #19, 5/07/2019*

A total of 21 laps were flown around the dairy (Fig. 39). Laps were completed at altitudes between 75 and 737 meters AGL. Winds were from the northwest averaging 2.4 m $s^{-1}$. Total methane emission is estimated at 317 ± 79 kg $hr^{-1}$.

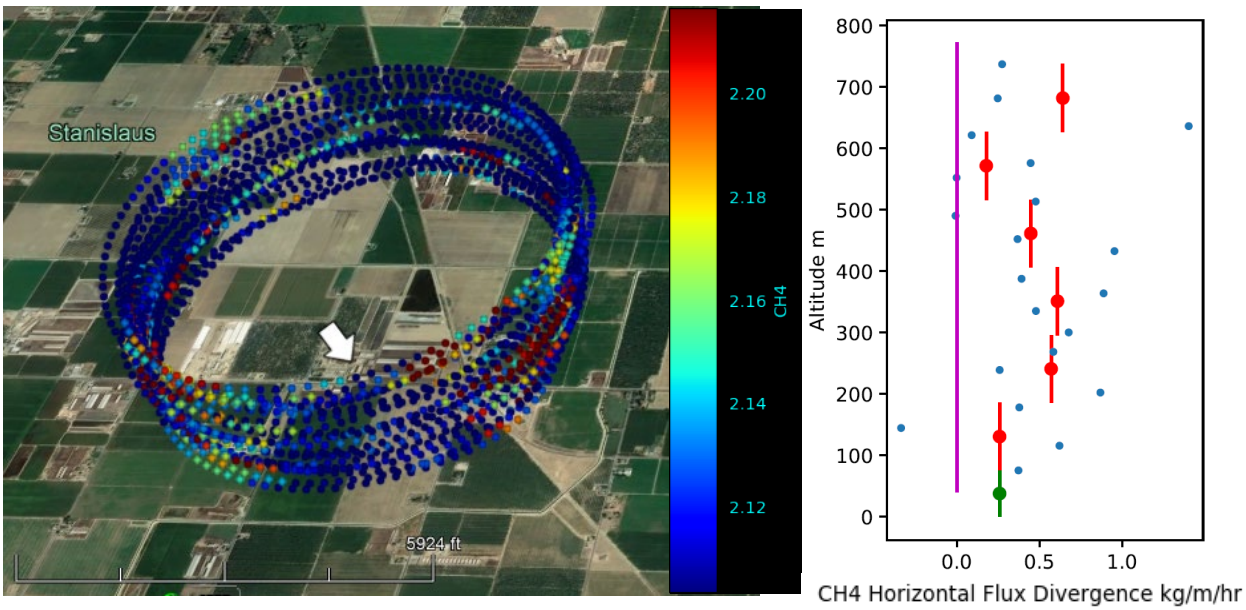


Figure 29. (Left) Flight path around the dairy on May 7, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*38. Dairy #20, 5/07/2019*

A total of 24 laps (10 useable) were flown around the dairy (Fig. 40). The aircraft completed circles between 81 meters AGL and 596 meters AGL. The winds were out of the west, averaging 5.7 m $s^{-1}$. Total methane emission is estimated at 112 ± 19 kg $hr^{-1}$.

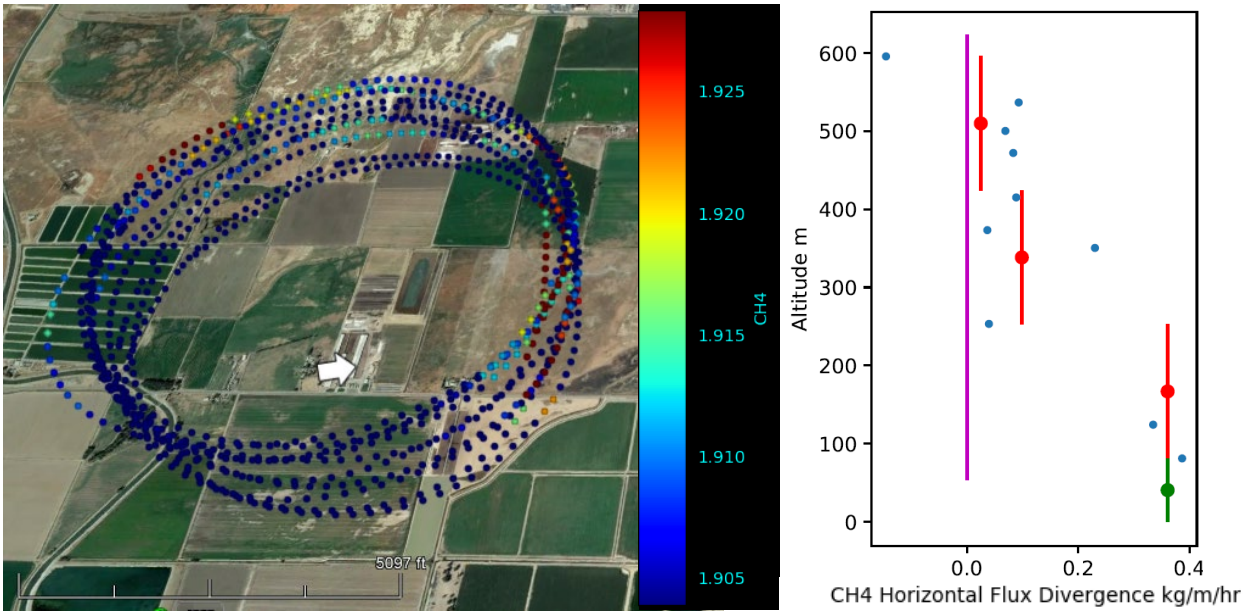


Figure 40. (Left) Flight path around the dairy on May 7, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*39. Dairy #21, 5/09/2019*

A total of 19 laps were flown around Dairy 9 at altitudes between 70 and 1647 m AGL. Winds were from the north/northwest and averaged 3.7 m $s^{-1}$. Total methane emission is estimated at 1199 ± 243 kg $hr^{-1}$.

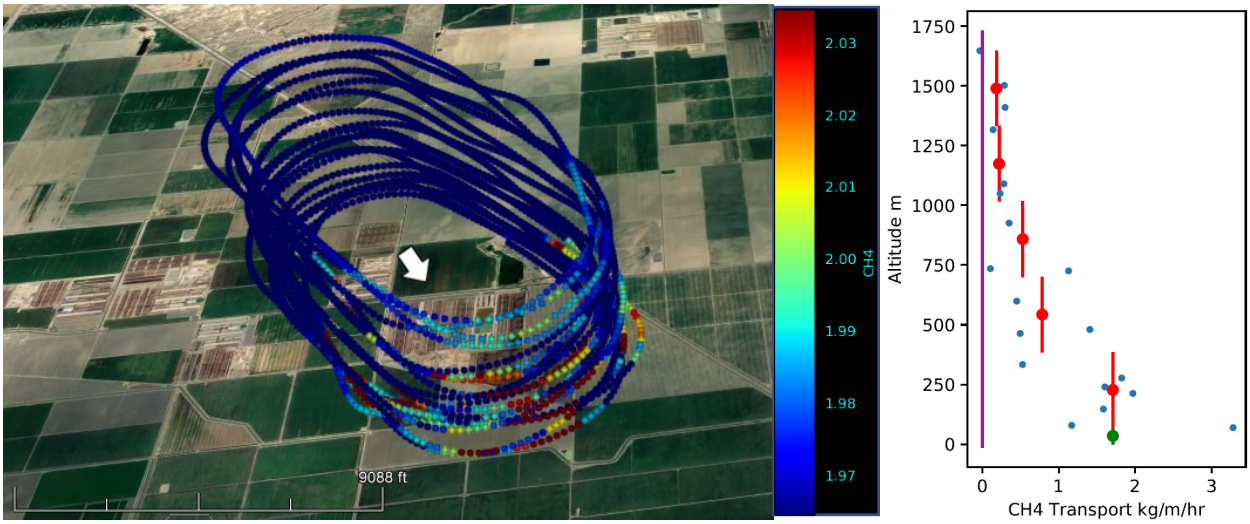


Figure 26. (Left) Flight path around the dairy on May 9, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*40. Elk Hills Power LLC, 9/15/2017*

A total of 26 laps were flown around the Elk Hills Power LLC, as shown in Figure 41. The aircraft completed circles between 77 meters AGL and 1000 meters AGL. Winds were out of the northwest, averaging 1.5 m $s^{-1}$. Total methane emission is estimated at 284 ± 65 kg $hr^{-1}$.

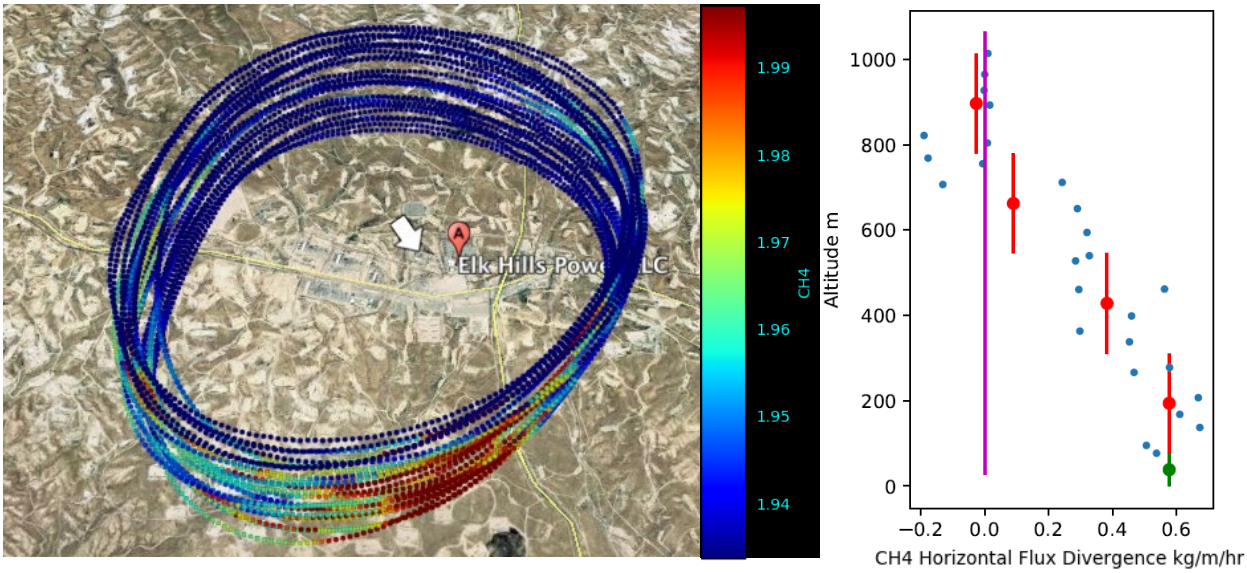


Figure 41. Flight track showing methane mixing ratios around the Elk Hills Power LLC on September 15, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*41. Elk Hills 4a, 5/08/2019*

Six laps were flown around Elk Hills 4a at altitudes between 184 and 1119 m AGL. Winds were from the north, averaging 1.9 m $s^{-1}$. Total methane emission is estimated at 6116 ± 1246 kg $hr^{-1}$.

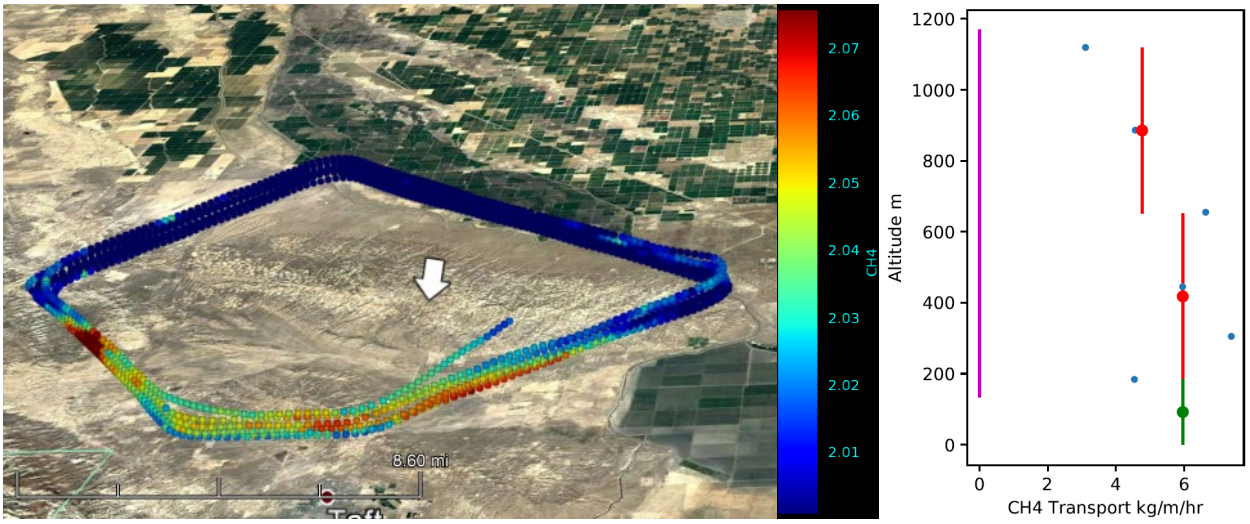


Figure 42. (Left) Flight path around Elk Hills 4a on May 8, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*42. Elk Hills 4b, 5/08/2019*

A total of 14 laps were flown around Elk Hills 4b at altitudes between 144 and 674 m AGL. Winds were from the northeast and averaged 2.2 m $s^{-1}$. Total methane emission is estimated at 413 ± 95 kg $hr^{-1}$.

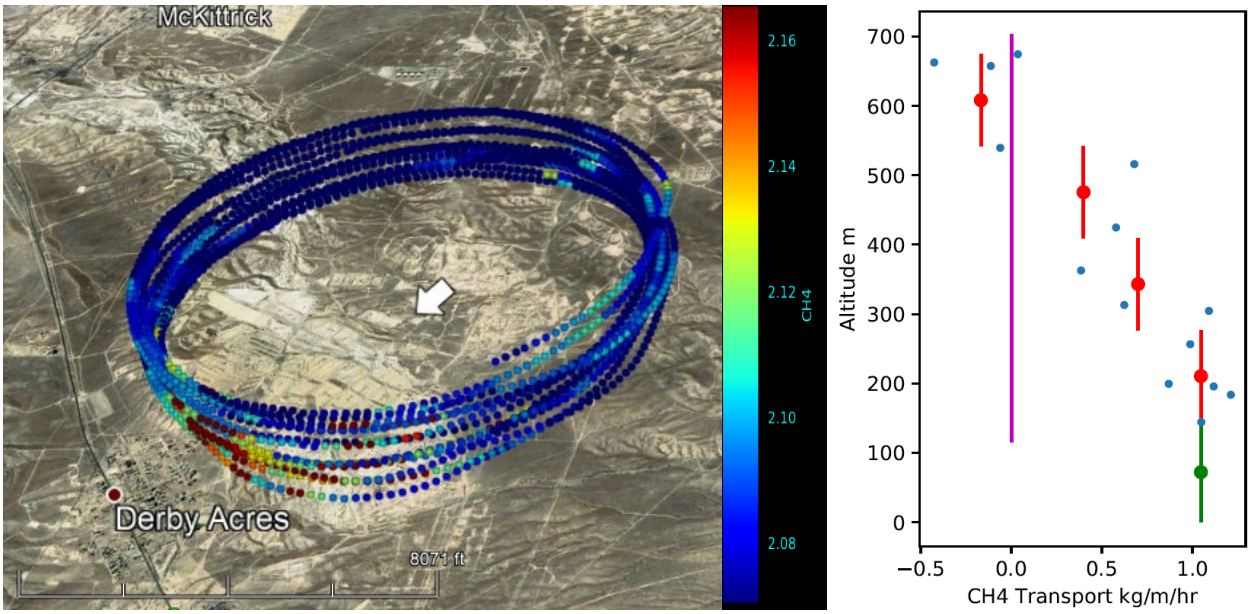


Figure 43. (Left) Flight path around Elk Hills 4b on May 8, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*43. Elk Hills 4d, 05/08/2019*

A total of 12 useable laps were flown around Elk Hills 4d at altitudes between 106 and 607 m AGL. Winds were from the east and averaged 0.9 m $s^{-1}$. Total methane emission is estimated at 147 ± 67 kg $hr^{-1}$.

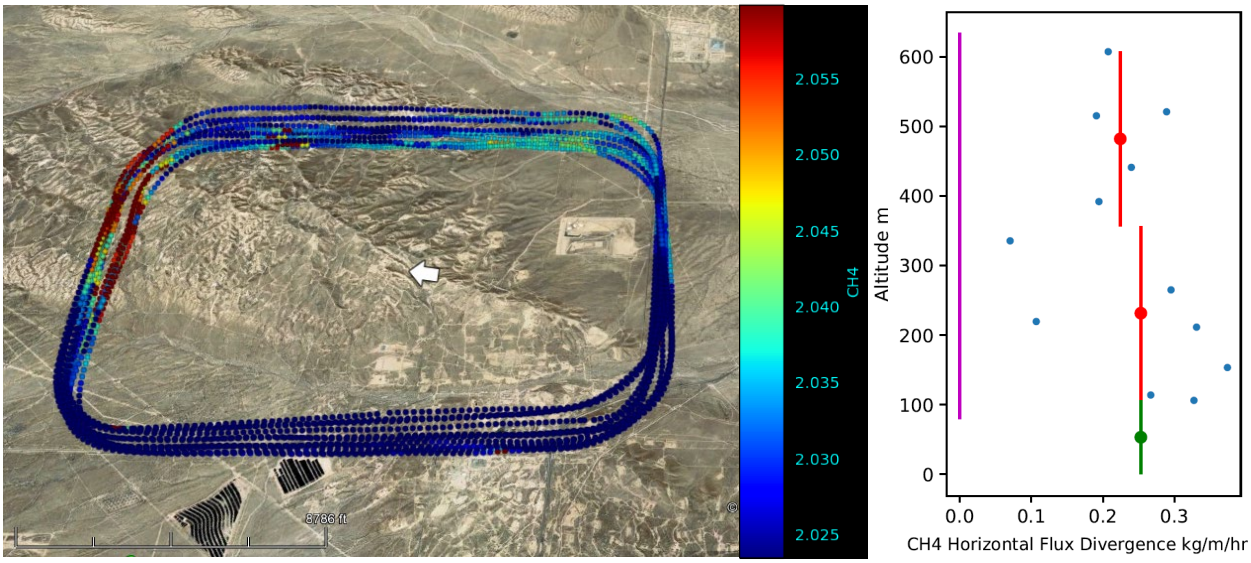


Figure 44. (Left) Flight path around Elk Hills 4d on May 8, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*44. Exxon Refinery, 4/20/2018*

A total of 21 laps (18 useable) were flown around the Exxon Oil Refinery, as shown in Figure 45. The aircraft completed circles from 59 meters AGL and 753 meters AGL. The winds were out of the west, averaging 3 m $s^{-1}$. Total methane emission is estimated at 126 ± 21 kg $hr^{-1}$.

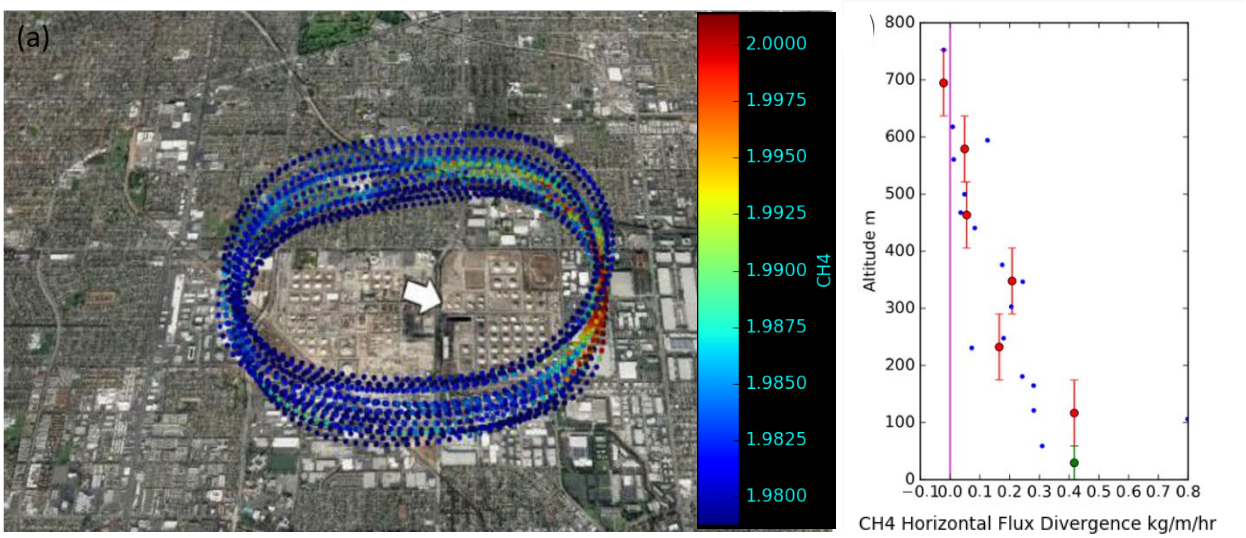


Figure 45. Flight path around the Exxon Refinery on April 20, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*45. Feedlot #1, 1/11/2018*

A total of 19 useable laps were flown around the Feedlot #1, as shown in Figure 46. The aircraft completed circles between 66 meters AGL and 615 meters AGL. Winds were out of the southeast, averaging 1.2 m $s^{-1}$. Total methane emission is estimated at 460 ± 100 kg $hr^{-1}$.

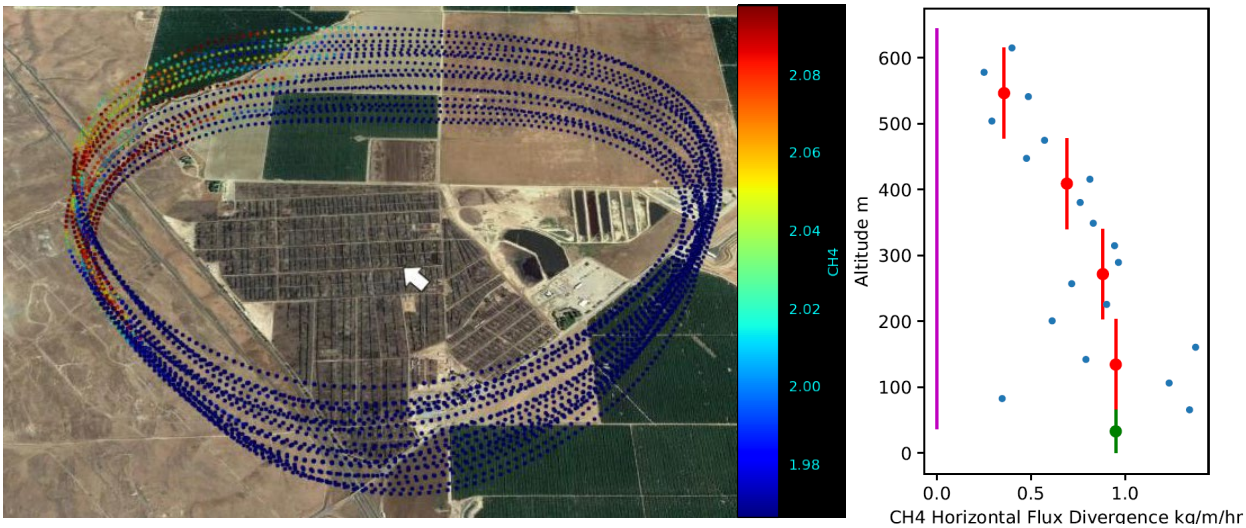


Figure 46. Flight path around Feedlot #1 on January 11, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*46. Feedlot #1, 5/12/2018*

A total of 23 laps were flown around Feedlot #1, as shown in Figure 47. The aircraft completed circles between 81 meters AGL and 1100 meters AGL. Winds were out of the north, averaging 4.2 m $s^{-1}$. The total methane emission is estimated at 550 ± 76 kg $hr^{-1}$.

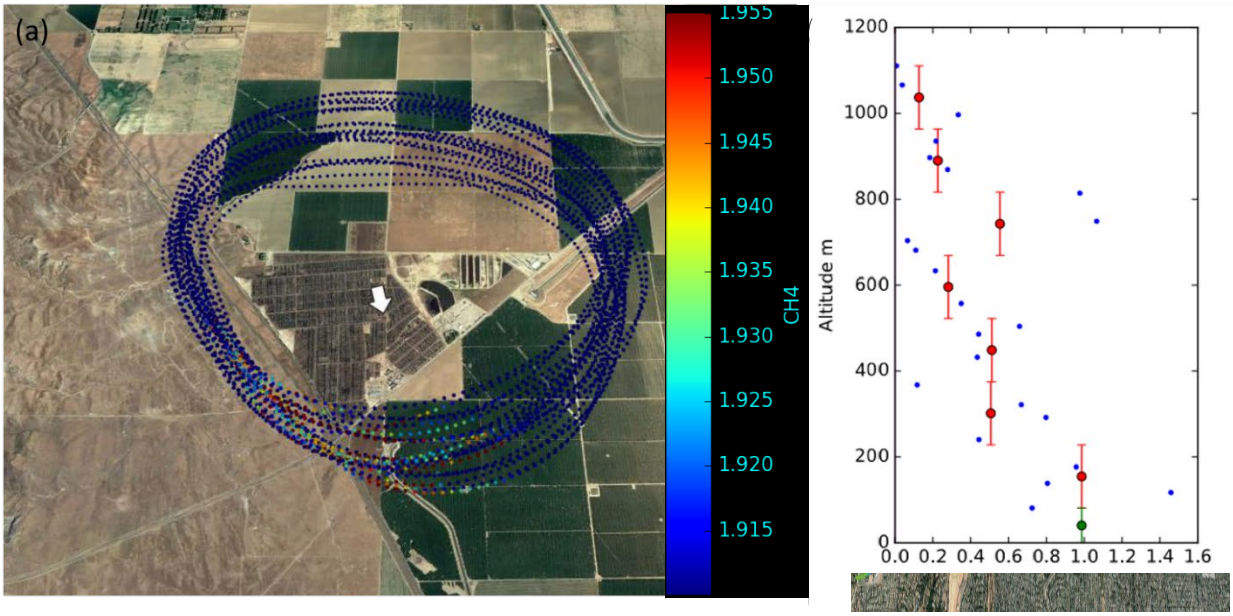


Figure 47. Flight track showing methane mixing ratios around the Feedlot #1 on May 12, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*47. Feedlot #2, 5-15-2018*

A total of 22 laps were flown around Feedlot #2., as shown in Figure 48. The aircraft completed circles from 67 meters AGL and 1135 meters AGL. Winds were out of the south, averaging 0.4 m $s^{-1}$. Total methane emission is estimated at 220 ± 100 kg $hr^{-1}$. The low wind speeds account for the greater uncertainty.

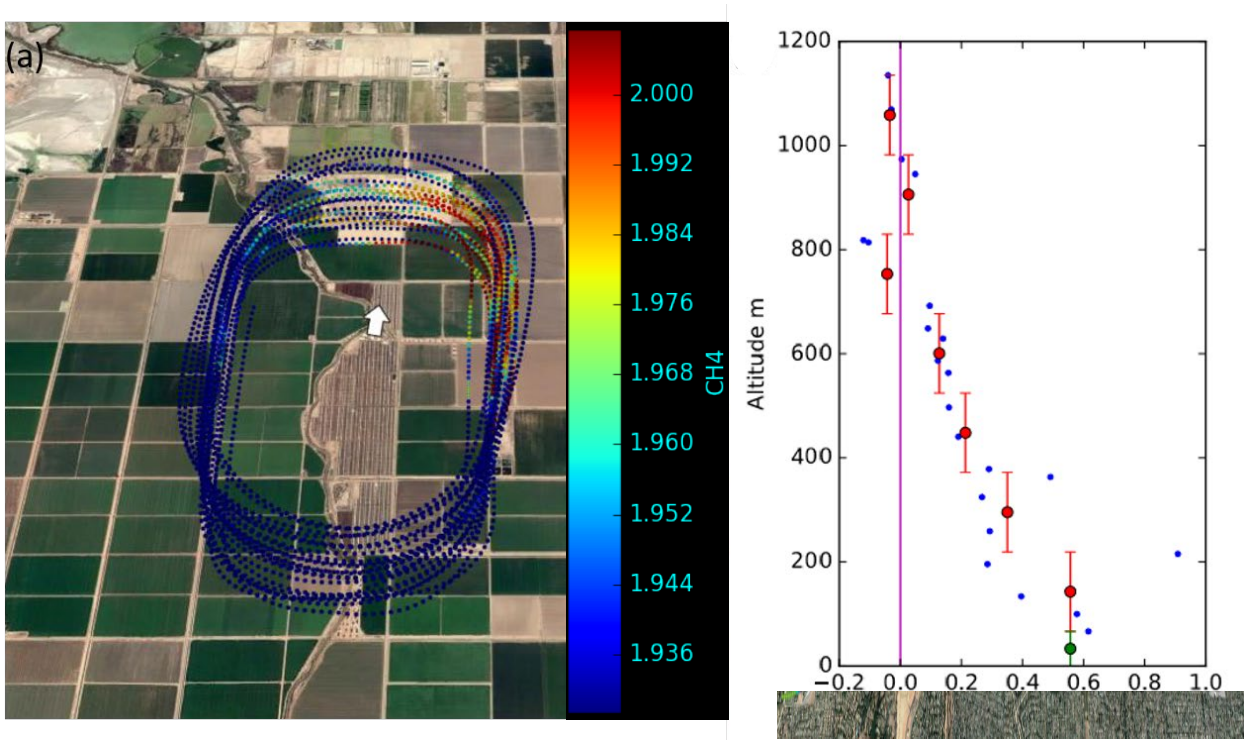


Figure 48. (a) Flight track showing methane mixing ratios around Feedlot #2 on May 15, 2018 Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*48. Feedlot #3, 5/15/2018*

A total of 19 laps were flown around the Feedlot #3, as shown in Figure 49. The aircraft completed circles from 106 meters AGL and 1094 meters AGL. Winds were out of the south, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 131 ± 35 kg $hr^{-1}$.

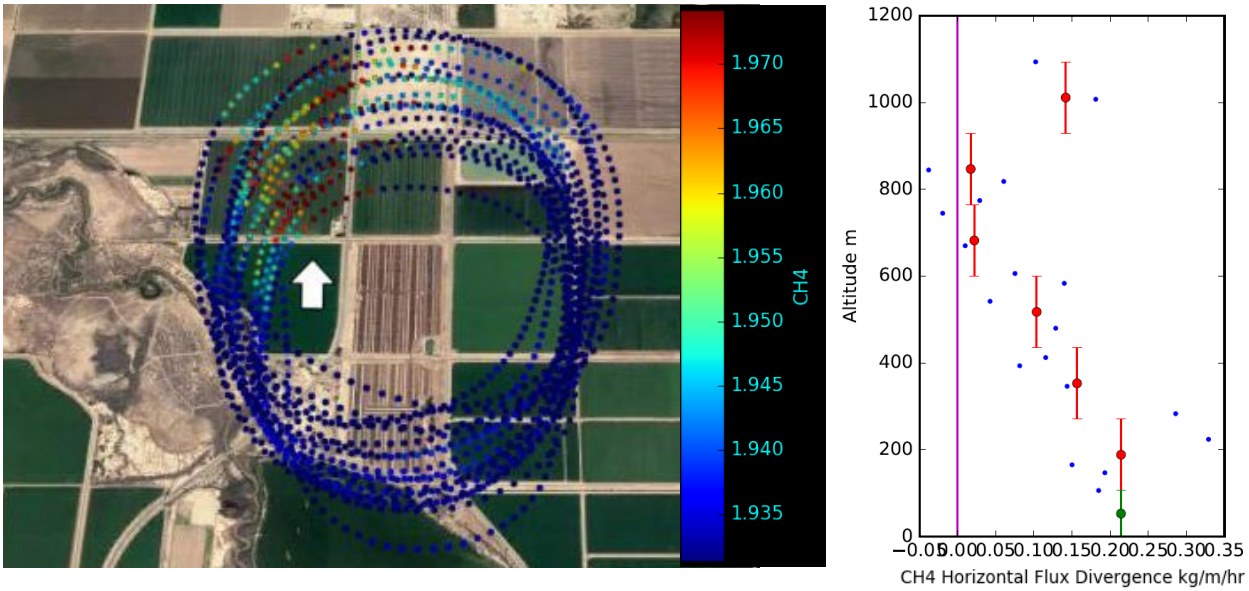


Figure 49. Flight path around Feedlot #3 on May 15, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*49. Foothill Landfill, 11/18/2017*

A total of 24 laps (19 useable) were flown around Foothills Landfill, as shown in Figure 50. The aircraft completed circles between 57 meters AGL and 613 meters AGL. Winds were out of the southwest, averaging 1.4 m $s^{-1}$. Total methane emission is estimated at 680 ± 146 kg $hr^{-1}$.

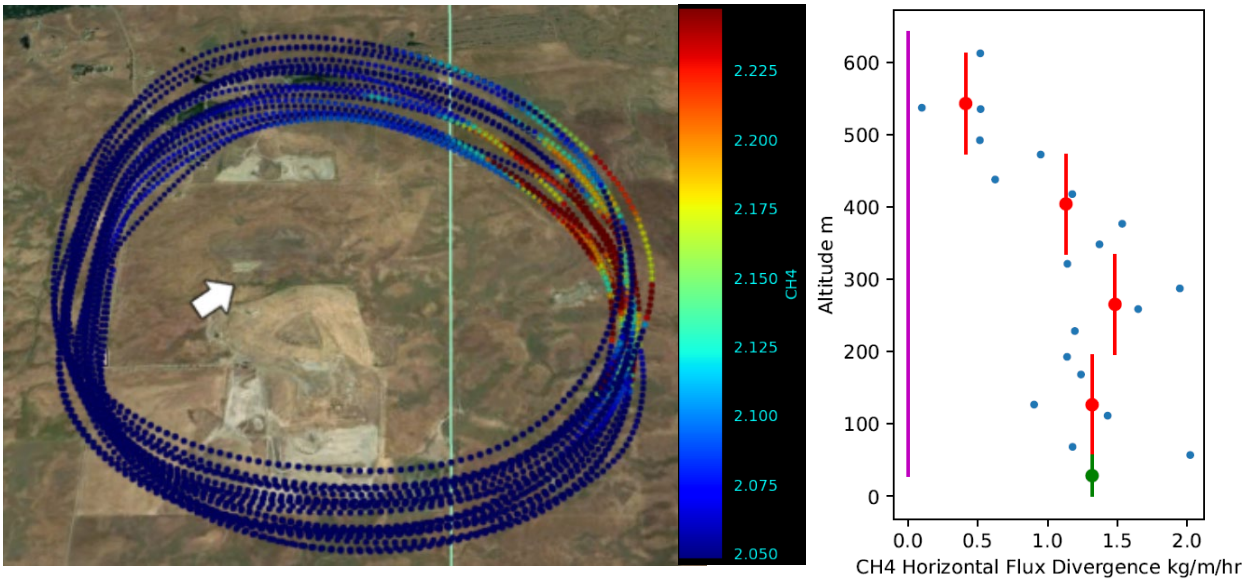

Figure 50. Flight path around Foothills Landfill on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*50. Forward Landfill, 12/09/2017*

A total of 18 laps (13 useable) were flown around the Forward Landfill, as shown in Figure 51. The aircraft completed circles between 20 meters AGL and 395 meters AGL. Winds were out of the northwest, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 1930 ± 940 kg $hr^{-1}$.

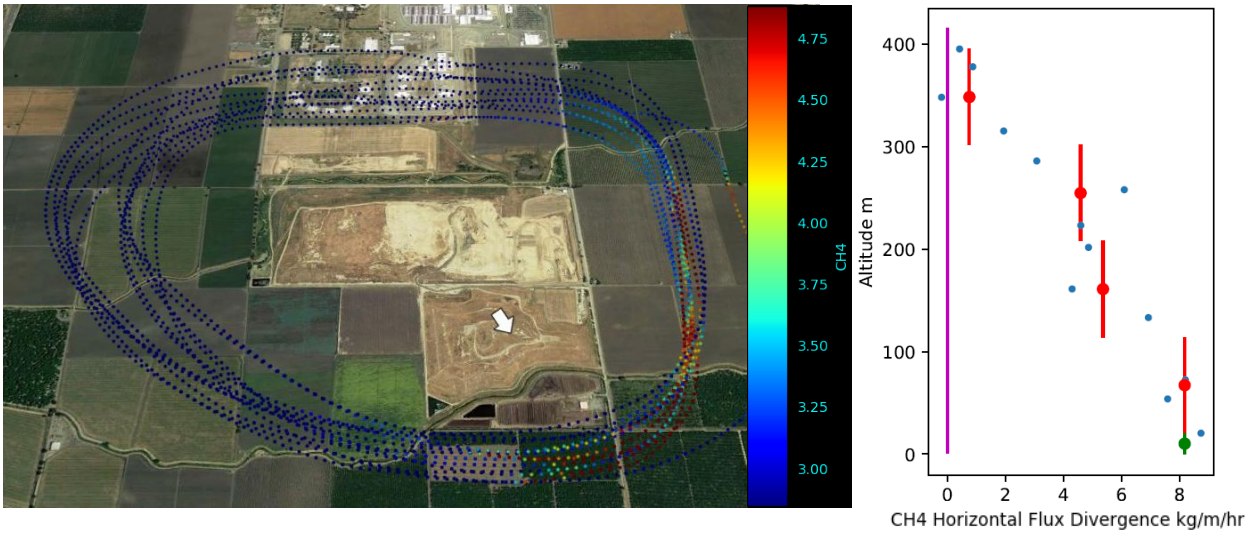


Figure 51. Flight path around Forward Landfill on December 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*51. Forward Landfill, 5/08/2018*

A total of 21 laps were flown around the Forward Landfill, as shown in Figure 52. The aircraft completed circles between 75 meters AGL and 765 meters AGL. Winds were out of the northwest, averaging 3.7 m $s^{-1}$. Total methane emission is estimated at 2684 ± 418 kg $hr^{-1}$.

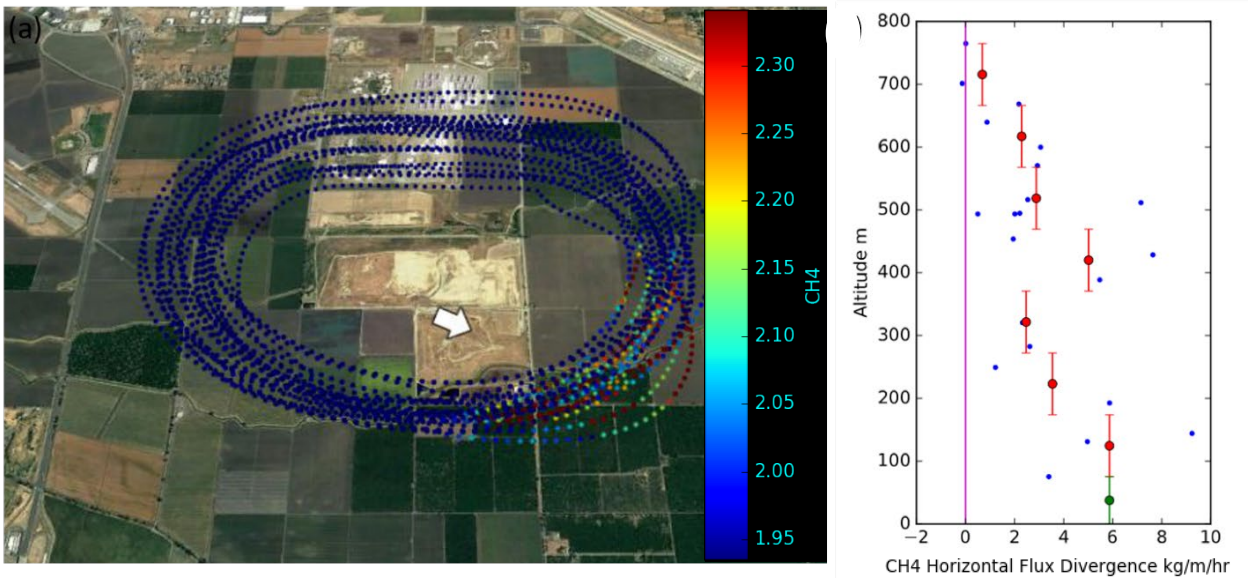


Figure 52. Flight track showing methane mixing ratios around the Forward landfill on May 08, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*52. Honor Rancho, 10/16/2017*

The aircraft flew a total of 18 laps (12 useable) around the Honor Rancho facility, as shown in Figure 53. Altitudes ranged from 214 mAGL to 600 mAGL. Winds were out of the northeast, averaging 5 m $s^{-1}$. Total methane emission is estimated at 279 ± 138 kg $hr^{-1}$.

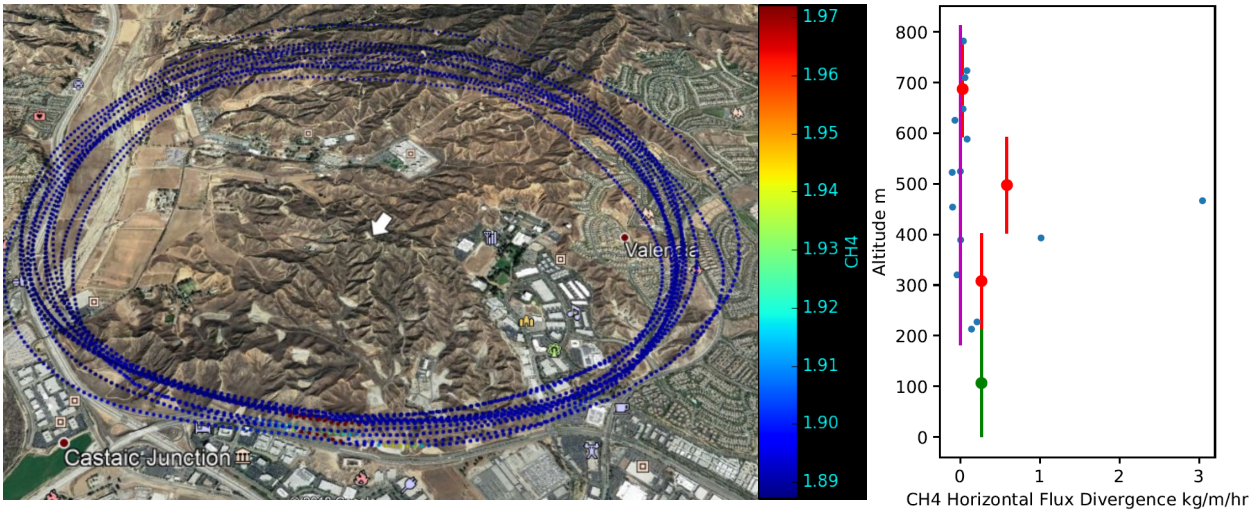


Figure 53. Flight path around Honor Rancho on November 16, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*53. Keller Canyon Landfill, 10/06/2017*

A total of 14 laps were flown around the Keller Canyon Landfill, as shown in Figure 54. The aircraft completed circles between 90 meters AGL and 400 meters AGL. Winds were out of the north northeast, averaging 8.9 m $s^{-1}$. Total methane emission is estimated at 633 ± 193 kg $hr^{-1}$. There is some uncertainty on this measurement due to the high value (10.8 kg $m^{-1}$ $hr^{-1}$) measured on the lowest leg (106 mAGL). The two closest legs were 1.5 kg $m^{-1}$ $hr^{-1}$ at 131 mAGL and 2.5 kg $m^{-1}$ $hr^{-1}$ at 138 Magl. We can not be sure if this was the result of the 30 m difference in altitude or an episodic event captured on the lowest leg. If that leg were removed from the calculation, the methane emission rate would be 384 ± 101 kg $hr^{-1}$.

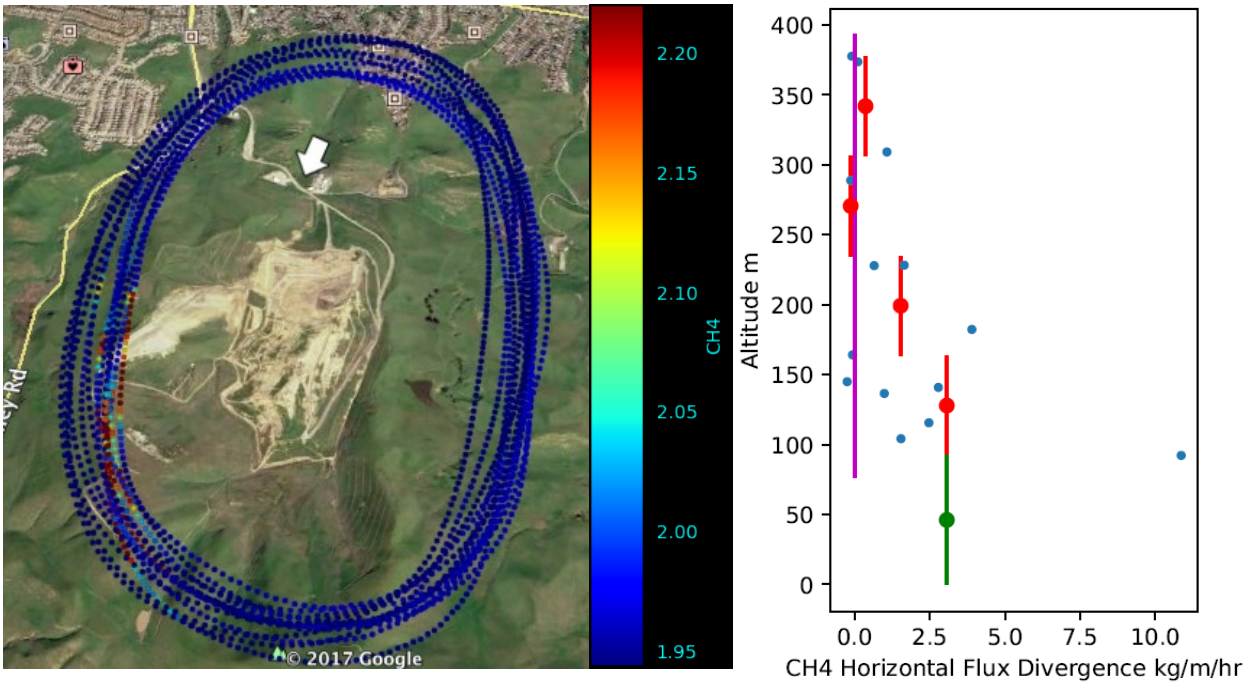


Figure 54. Flight track showing methane mixing ratios around Keller Canyon Landfill on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*54. Keller Canyon Landfill, 10/05/2018*

A total of 18 laps were flown around the Keller Canyon Landfill, as shown in Figure 55. The aircraft completed circles from 111 meters AGL and 573 meters AGL. The winds were out of the northwest, averaging 3.2 m $s^{-1}$. Total methane emission is estimated at 1361 ± 209 kg $hr^{-1}$.

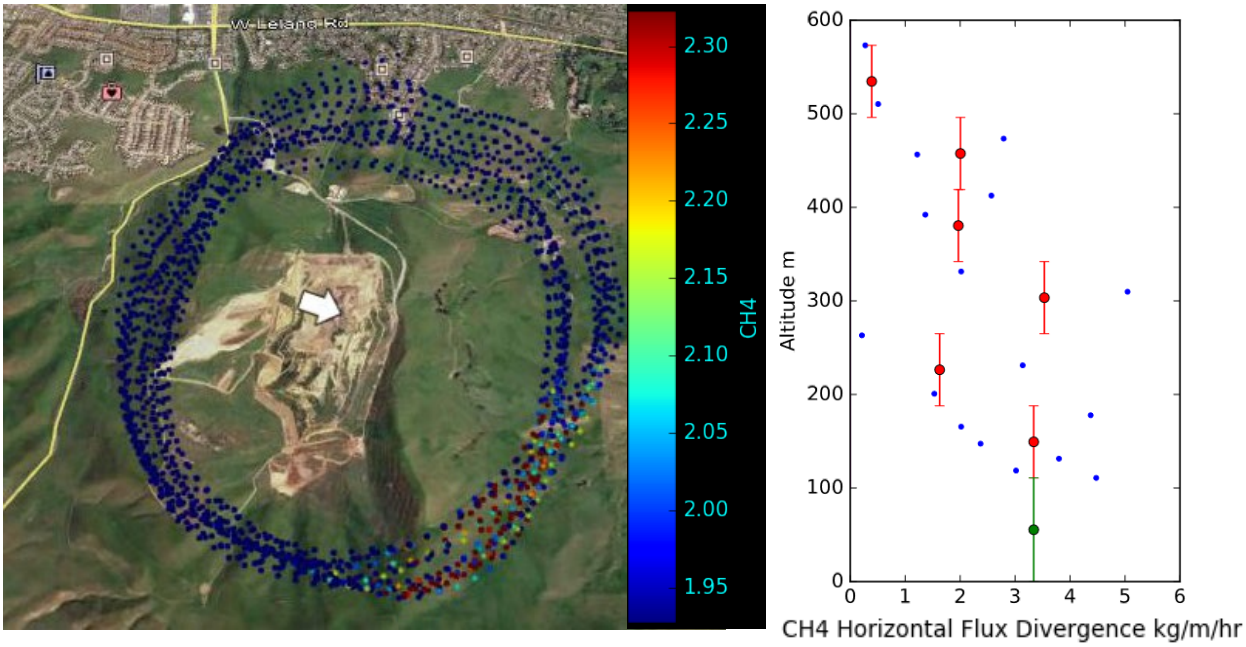


Figure 55. Flight path around the Keller Canyon landfill. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*55. Kiefer Landfill, 12/09/2017*

A total of 15 laps (11 useable) were flown around Kiefer Landfill, as shown in Figure 56. The aircraft completed circles from 32 meters AGL and 307 meters AGL. The winds were out of the northwest, averaging 0.6 m $s^{-1}$. Total methane emission is estimated at 1730 ± 560 kg $hr^{-1}$.

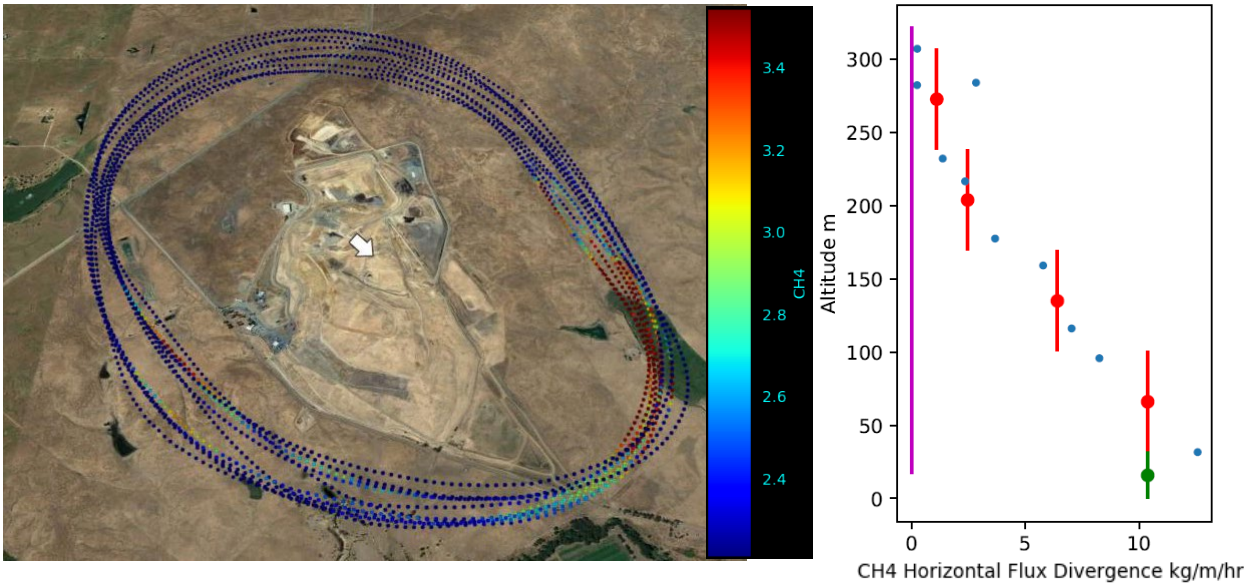


Figure 56. Flight path around Kiefer Landfill on December 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *56. Kiefer Landfill, 6/21/2018*

A total of 21 laps were flown around Kiefer Landfill as shown in Figure 57. The aircraft completed circles from 103 meters AGL to 871 meters AGL. Winds were out of the west, averaging 1.5 m $s^{-1}$. Total methane emission is estimated at 2756 ± 383 kg $hr^{-1}$.

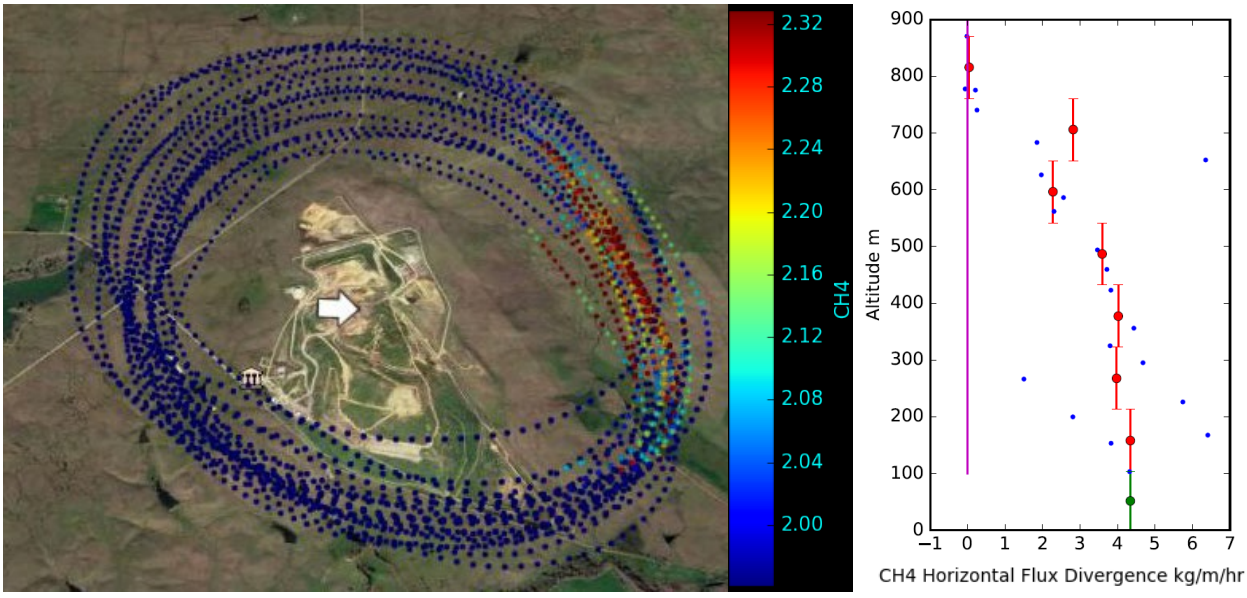


Figure 57. Flight path around Kiefer Landfill area on June 21, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*57. Kiefer Landfill, 8/24/2018*

A total of 17 laps were flown around the Kiefer Landfill, as shown in Figure 58. The aircraft completed circles between 44 meters AGL and 487 meters AGL. The winds were out of the southwest, averaging 2.5 m $s^{-1}$. Total methane emission is estimated at 2249.3 ± 360.4 kg $hr^{-1}$.

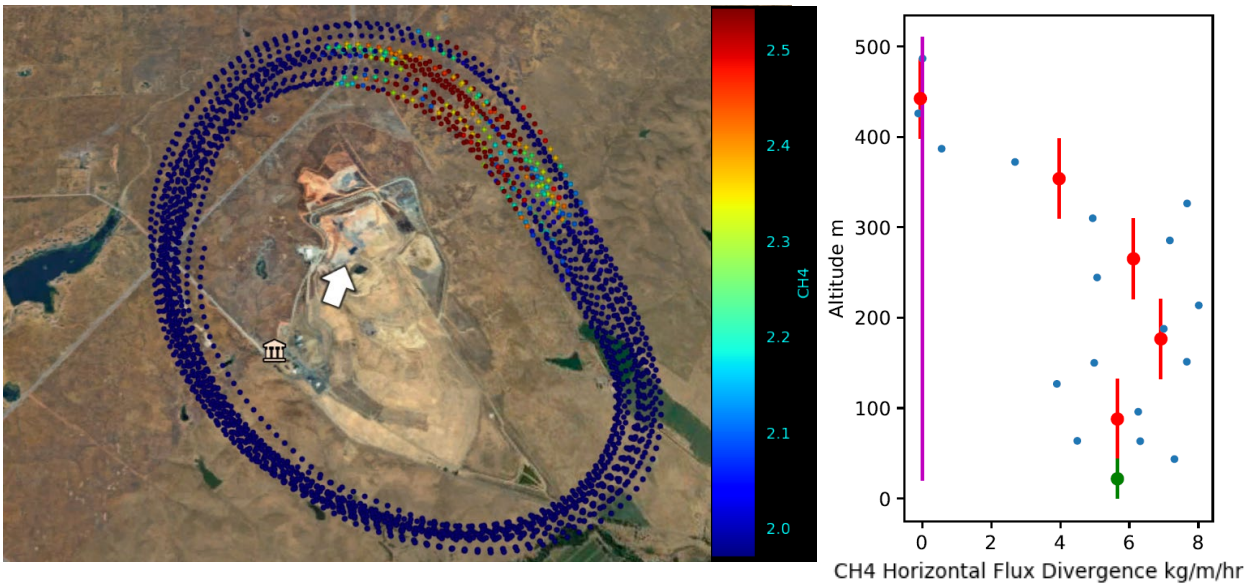


Figure 58. Flight track around the Kiefer Landfill on 8/24/2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*58. Kiefer Landfill, 3/14/2019*

A total of 20 laps were flown around the Kiefer Landfill (Fig. 59). The aircraft completed circles between 133 meters AGL and 830 meters AGL. The winds were out of the southwest, averaging 2.2 m $s^{-1}$. Total methane emission is estimated at 2024 ± 457 kg $hr^{-1}$.

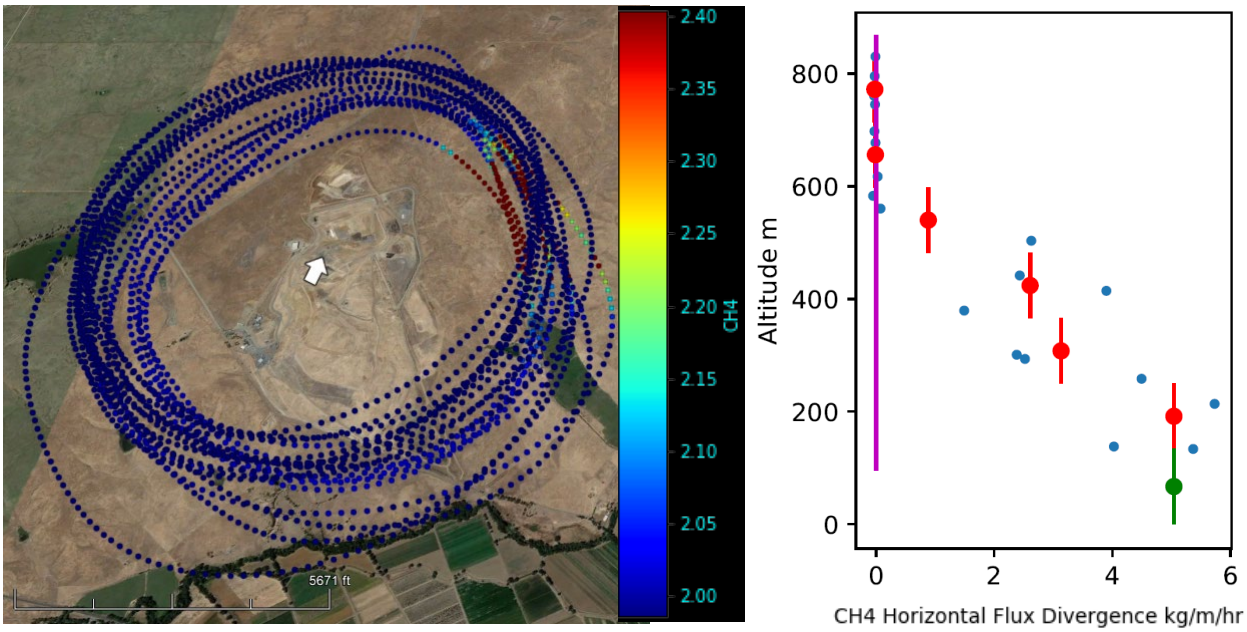


Figure 59. (Left) Flight path around Kiefer Landfill on May 7, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*59. Kiefer Landfill, 5/07/2019*

Twenty-five laps (20 useable) were flown around Kiefer Landfill (Fig. 60). Laps were completed at altitudes between 107 and 1122 meters AGL. Winds were from the west/southwest averaging 1.7 m $s^{-1}$. Total methane emission is estimated at 1968 ± 487 kg $hr^{-1}$.

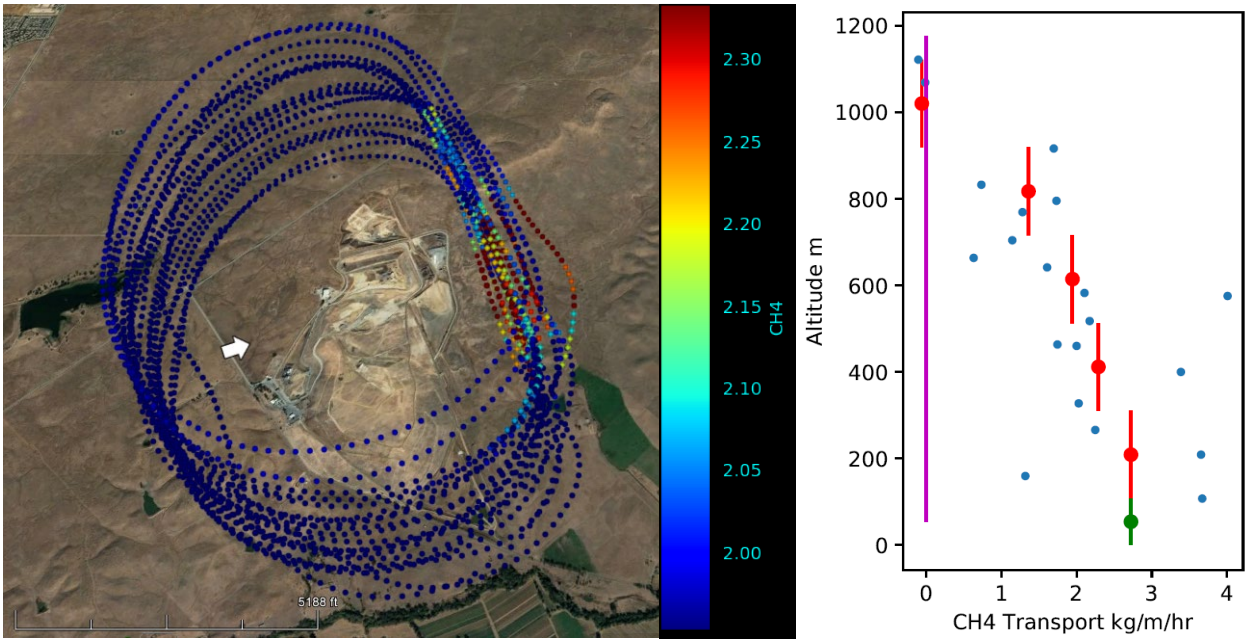


Figure 60. (Left) Flight path around Kiefer Landfill on May 7, 2019. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*60. La Brea Tar Pits, 12/04/2017*

A total of 23 laps were flown around the La Brea Tar Pits, as shown in Figure 61. The aircraft completed circles between 188 meters AGL and 623 meters AGL. The winds were out of the southeast, averaging 2.9 m $s^{-1}$. Total methane emission is estimated at 96 ± 19 kg $hr^{-1}$.

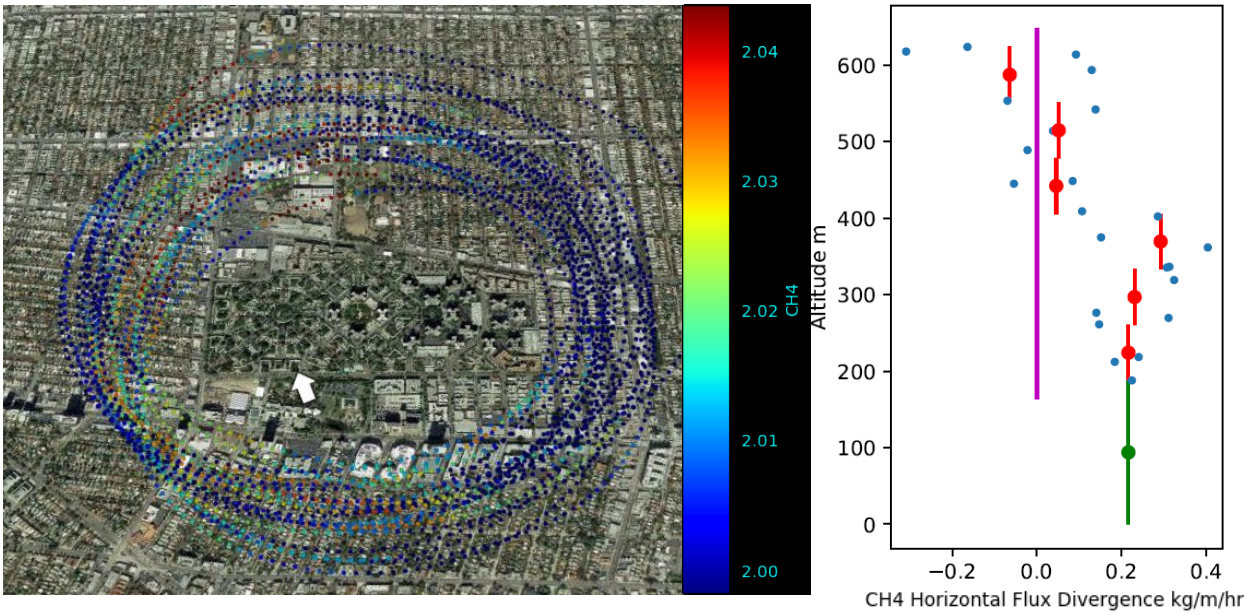


Figure 61. Flight path around La Brea Tar Pits on December 4, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*61. La Brea Tar Pits, 4/18/2018*

A total of 9 laps were flown around the La Brea Tar Pits. The aircraft completed circles between 83 meters AGL and 293 meters AGL. The winds were out of the southwest, averaging 5.5 m $s^{-1}$. Total methane emission is estimated at 112 ± 15 kg $hr^{-1}$.

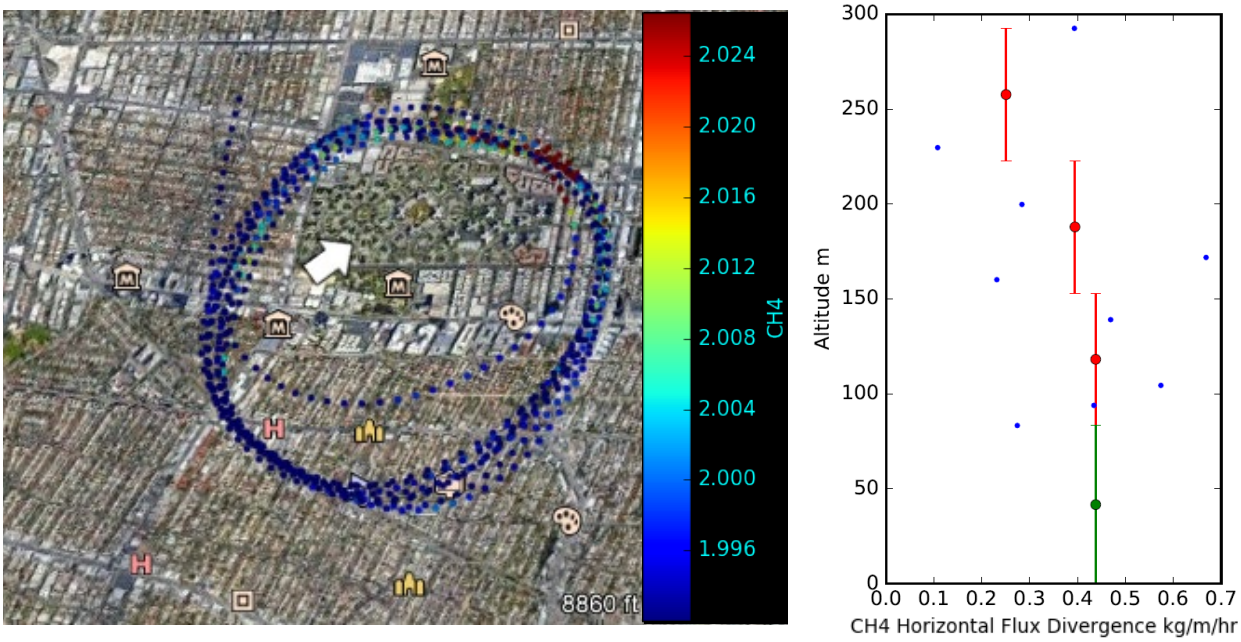

Figure 62. Flight path around La Brea Tar Pits on April 18 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).v

*62. La Brea Tar Pits, 5/14/2018*

A total of 17 laps were flown around the La Brea Tar Pits. The aircraft completed circles between 139 meters AGL and 612 meters AGL. The winds were out of the southwest, averaging 6.2 m $s^{-1}$. Total methane emission is estimated at 364 ± 23 kg $hr^{-1}$ and the methane mixing ratios for both deployment dates are shown in Figure 63.

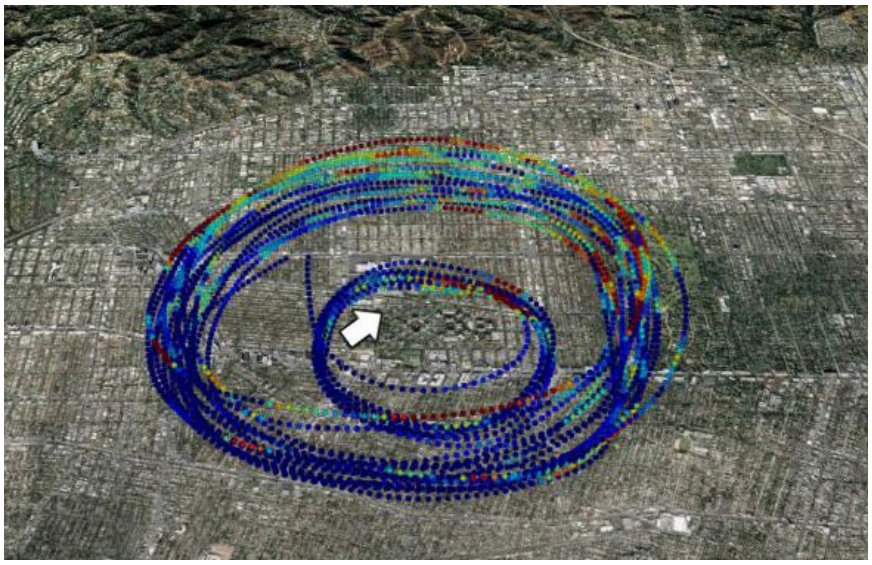

Figure 63. Flight path around La Brea Tar Pits on April 18 (inner circle) and May 14, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*63. Lodi Gas Storage Facility, 12/09/2017*

A total of 12 laps (9 useable) were flown around the Lodi GS facility, as shown in Figure 64. The aircraft completed circles between 39 meters AGL and 319 meters AGL. Winds were out of the southwest, averaging 0.4 m $s^{-1}$. The total methane emission was below our detection limit.

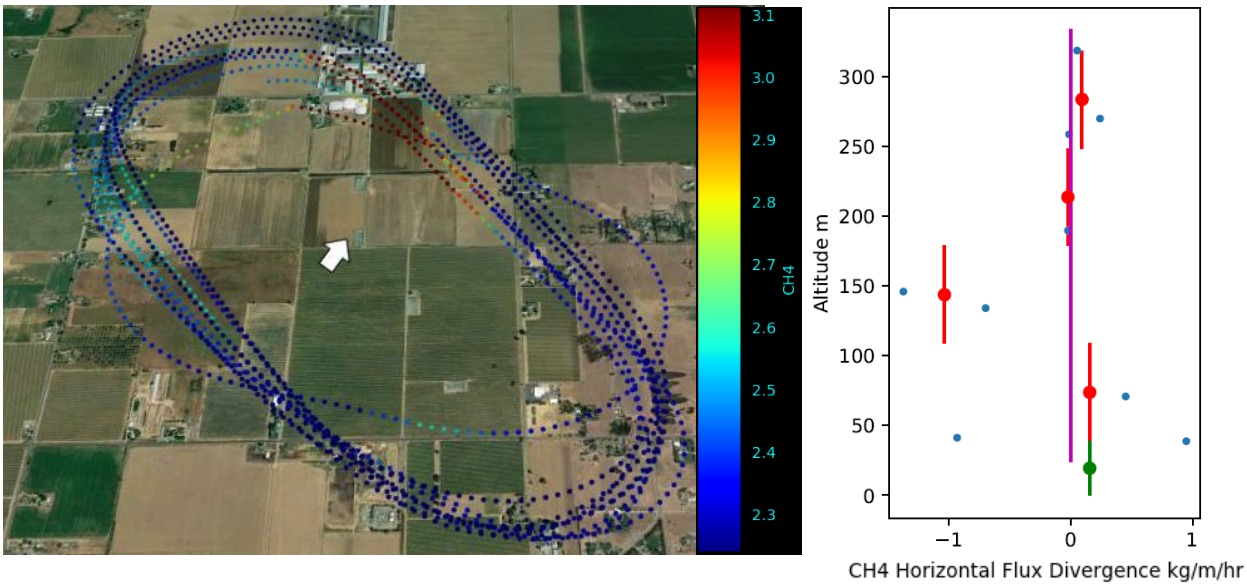


Figure 64. Flight path around Lodi GS on December 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *64. Lopez Canyon Landfill, 11/19/2017*

A total of 23 were flown around Lopez Canyon Landfill, as shown in Figure 65. The aircraft completed circles between 119 meters AGL and 827 meters AGL. Winds were out of the southeast, averaging 1.0 m $s^{-1}$. Total methane emission is estimated at 498±149 kg $hr^{-1}$.

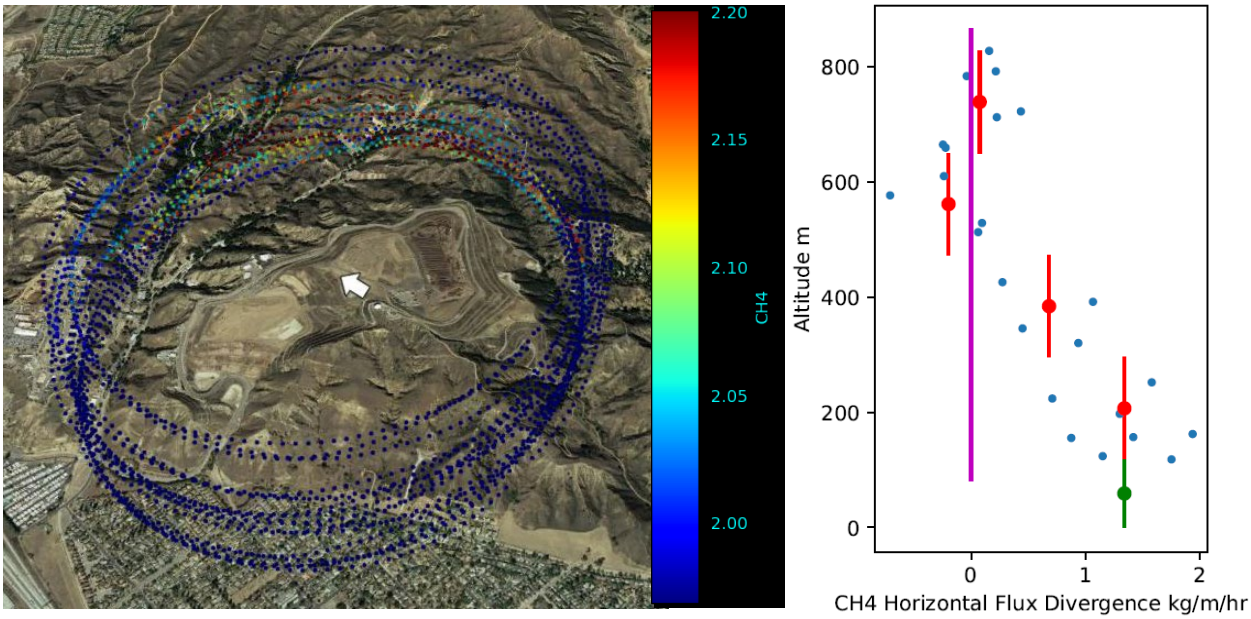

Figure 65. Flight path around Lopez Canyon Landfill on November 19, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*65. McDonald Island Gas Storage Facility, 10/06/2017*

A total of 19 laps were flown around the McDonald Island Gas Storage Facility, as shown in Figure 66. The aircraft completed circles between 70 meters AGL and 700 meters AGL. Winds were out of the north, averaging 2.2 m $s^{-1}$. Total methane emission is estimated at 544 ± 251 kg $hr^{-1}$.

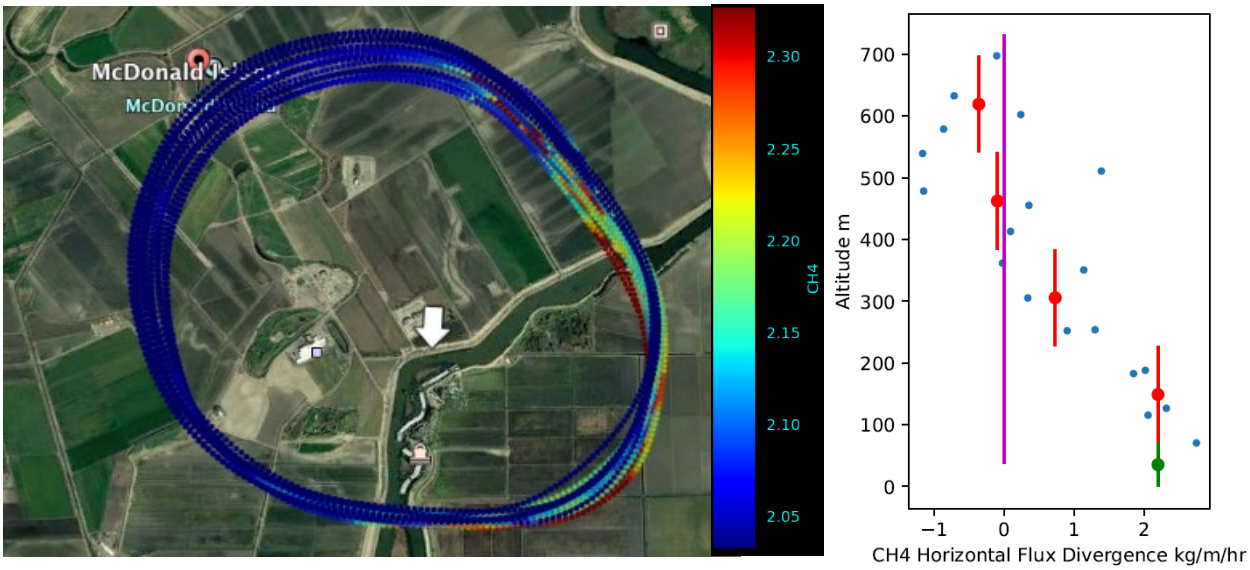


Figure 66. Flight track showing methane mixing ratios around McDonald Island on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*66. McDonald Mini Gas Storage Facility, 10/06/2017*

A total of 20 laps were flown around the McDonald Mini Gas Storage Facility, as shown in Figure 67. The aircraft completed circles between 72 meters AGL and 702 meters AGL. The winds were out of the northwest, averaging 1.7 m $s^{-1}$. Total methane emission is estimated at 265.4 ± 115.7 kg $hr^{-1}$.

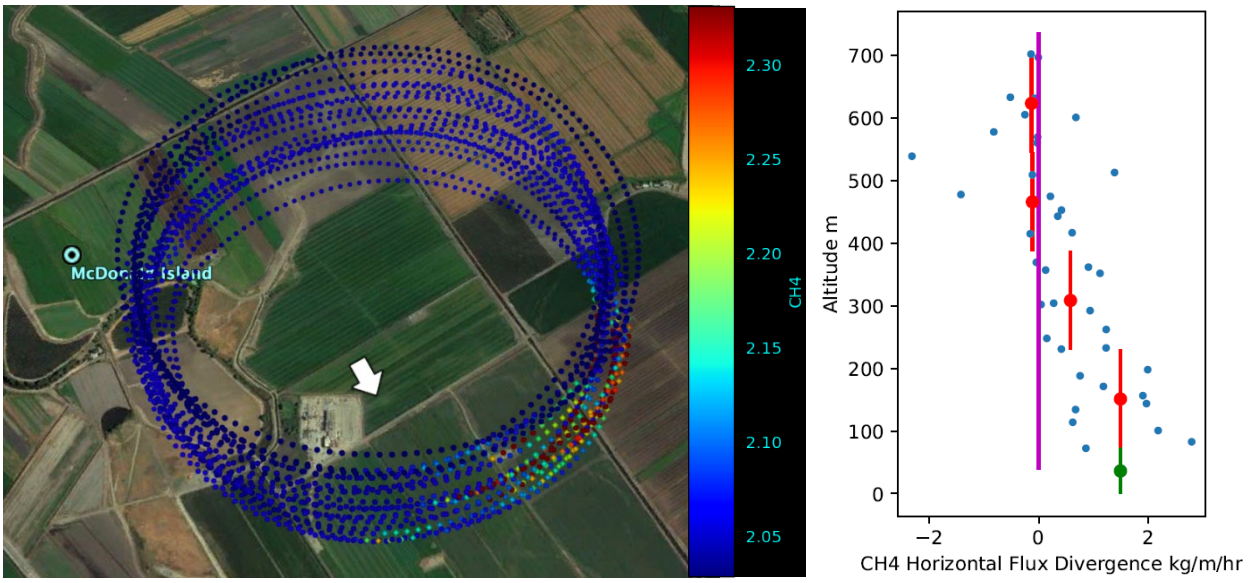


Figure 67. Flight track showing methane mixing ratios around McDonald Mini on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*67. Midway Sunset Oil Field, 9/15/2017*

A total of 37 laps (18 useable) were flown around the Midway Sunset Oil Field, as shown in Figure 68. The aircraft completed circles between 60 meters AGL and 777 meters AGL. Winds were out of the north, averaging 1.2 m $s^{-1}$. Total methane emission is estimated at 103 ± 76 kg $hr^{-1}$. The uncertainty was higher on this measurement because of light and variable winds plus complex terrain.

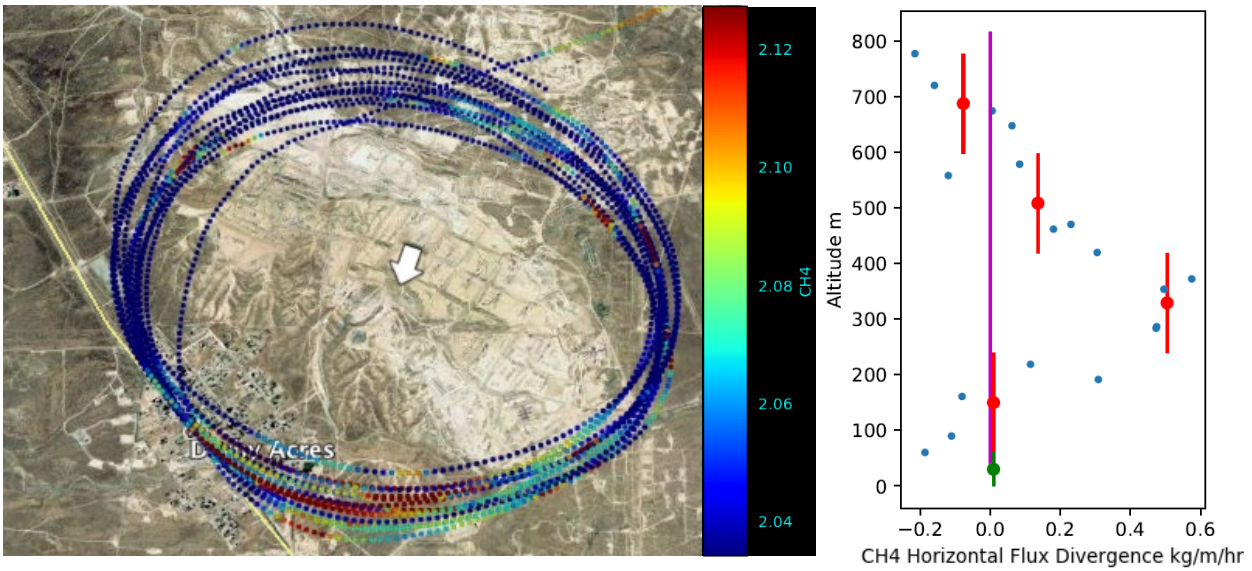

Figure 68. Flight track showing methane mixing ratios around the Midway Sunset Oil Field on September 15, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*68. Mount Poso Creek Oil and Gas Field, 4/18/2018*

A total of 2 laps were flown around Poso Creek field and the total methane emission was below our detection limit.

*69. Newby Island Landfill, 10/05/2017*

A total of 17 laps were flown around the Newbie Island Landfill, as shown in Figure 69. The aircraft completed circles between 80 meters AGL and 500 meters AGL. Winds were out of the northwest, averaging 3.0 m $s^{-1}$. Total methane emission is estimated at 2075 ± 600 kg $hr^{-1}$.

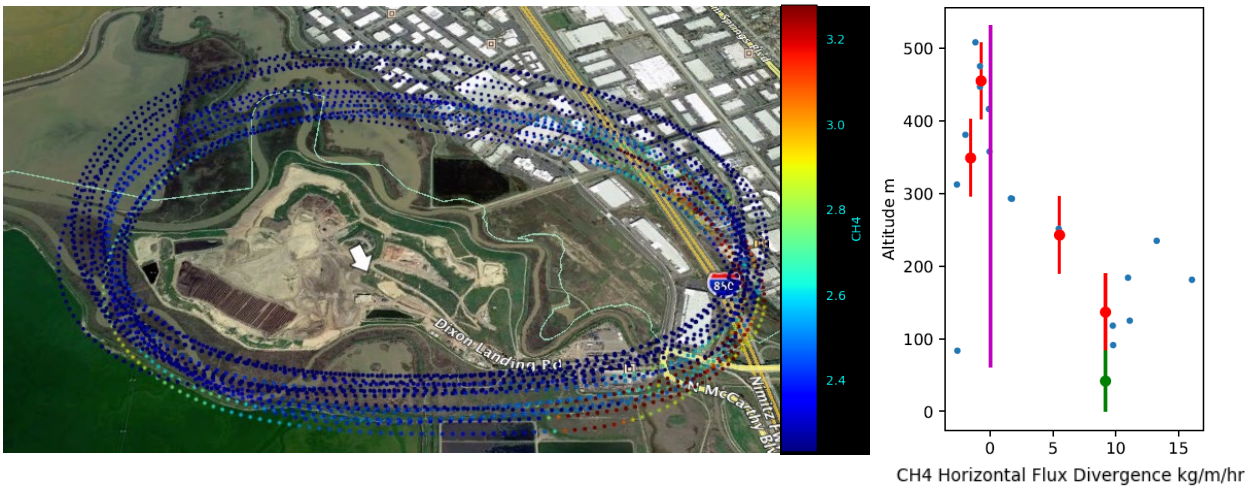


Figure 69. Flight track showing methane mixing ratios around Newby Island Landfill on October 5, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*70. Newby Island Landfill, 10/05/2018*

A total of 20 laps were flown around the Newby Island Landfill, as shown in Figure 70. The aircraft completed circles from 108 meters AGL and 715 meters AGL. The winds were out of the north, averaging 3 m $s^{-1}$. Total methane emission is estimated at 3287 ± 487 kg $hr^{-1}$.

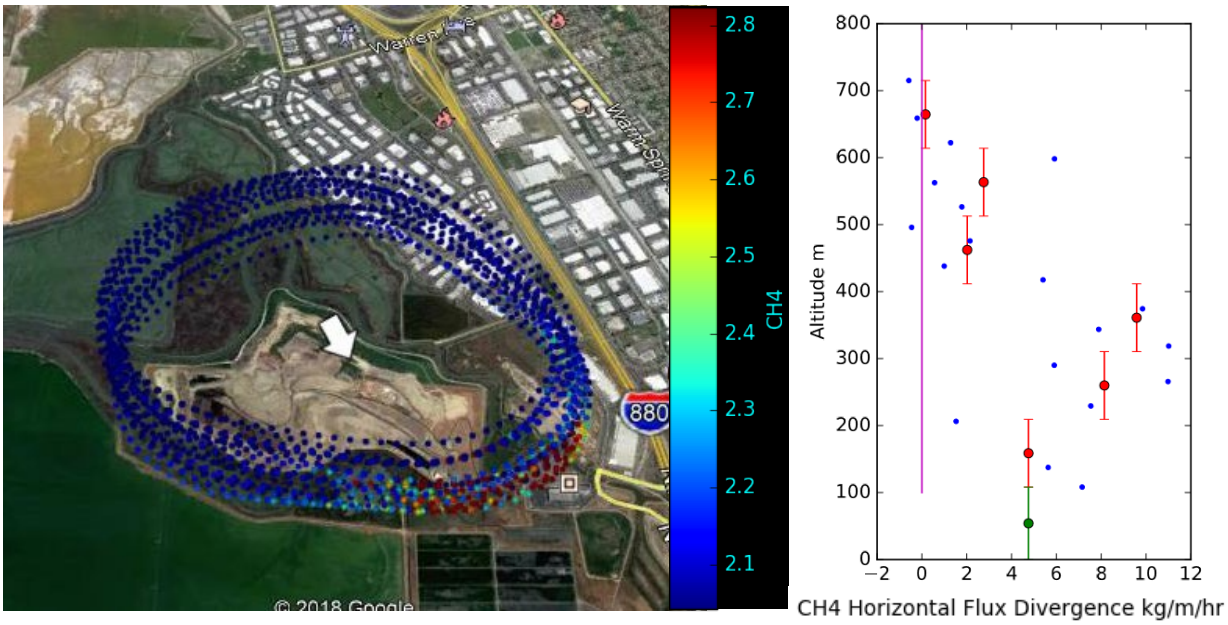


Figure 70. Flight path around the Newby Island Landfill and the vertical flux divergence profile for methane on October 5, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*71. Olinda Alpha Landfill, 11/09/2017*

A total of 14 laps (13 useable) were flown around the Olinda Alpha State Landfill, as shown in Figure 71. The aircraft completed circles between 114 meters AGL and 914 meters AGL. Winds were out of the southwest, averaging 3.2 m $s^{-1}$. Total methane emission is estimated at 1698 ± 327 kg $hr^{-1}$.

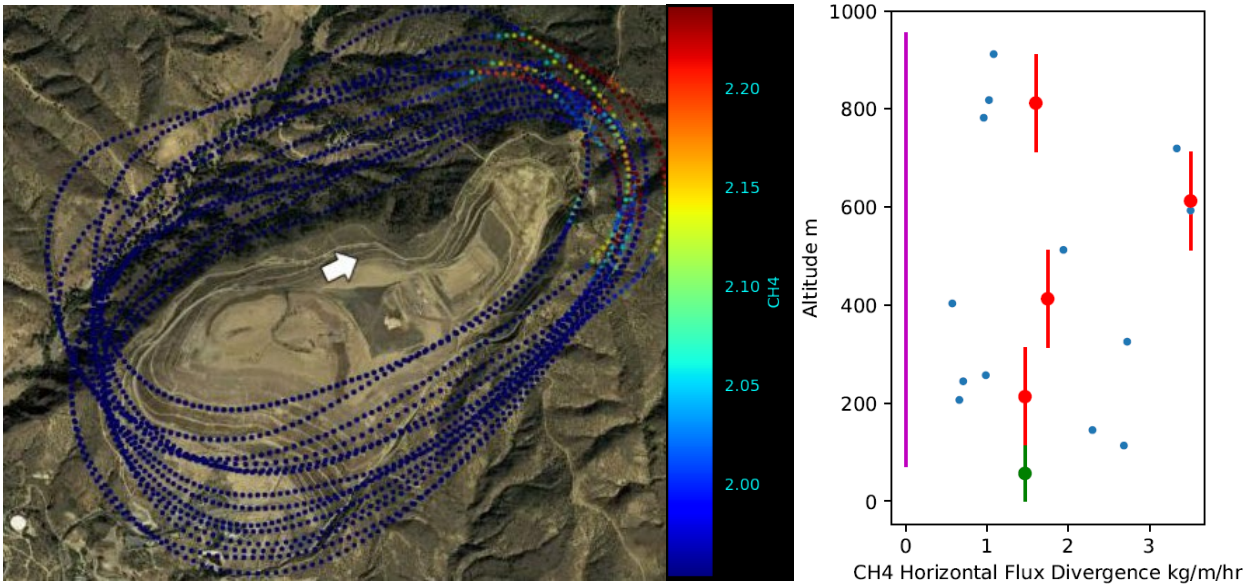


Figure 71. Flight path around Olinda Alpha State Landfill on November 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*72. Olinda Alpha Landfill, 11/19/2017*

A total of 16 laps were flown around the Olinda Alpha State Landfill, as shown in Figure 72. The aircraft completed circles between 114 meters AGL and 653 meters AGL. Winds were out of the west, averaging 1.1 m $s^{-1}$. Total methane emission is estimated at 1339 ± 435 kg $hr^{-1}$.

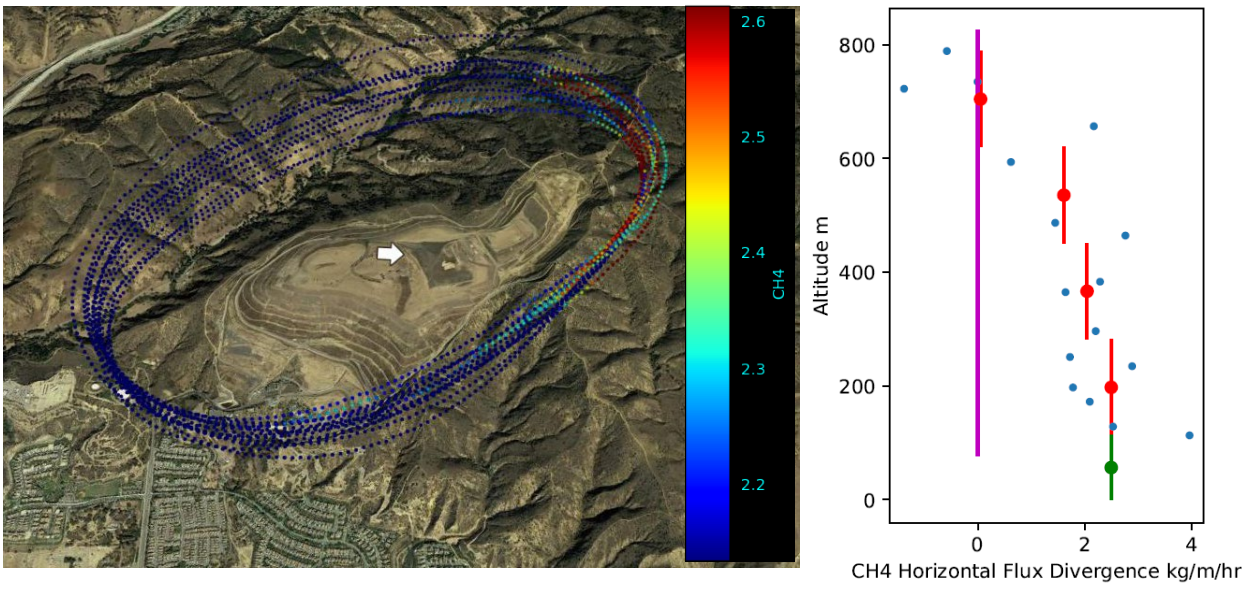

Figure 72. Flight path around Olinda Alpha Landfill on November 19, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*73. Olinda Alpha Landfill, 5/15/2018*

A total of 21 laps were flown around the Olinda Alpha Landfill, as shown in Figure 73. The aircraft completed circles from 158 meters AGL and 1001 meters AGL. Winds were out of the south, averaging 3.0 m $s^{-1}$. Total methane emission is estimated at 1097 ± 151 kg $hr^{-1}$.

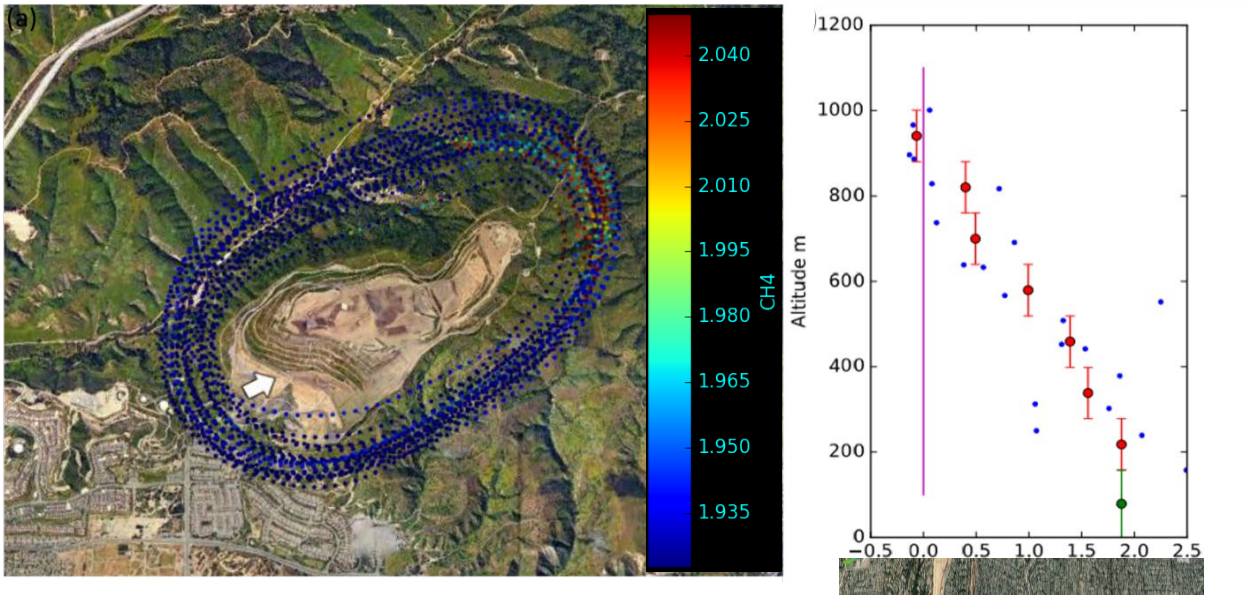


Figure 73. (a) Flight track showing methane mixing ratios around the Olinda Alpha Landfill on May 15, 2018 (b) Vertical flux divergence profile for methane on May 15, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*74. Ostrom Road Landfill, 11/18/2017*

A total of 15 laps were flown around Ostrom Road Landfill, as shown in Figure 74. The aircraft completed circles between 70 meters AGL and 412 meters AGL. Winds were out of the southwest, averaging 1.1 m $s^{-1}$. Total methane emission is estimated at 504 ± 317 kg $hr^{-1}$. The wind direction above 200 meters AGL was from the southeast.

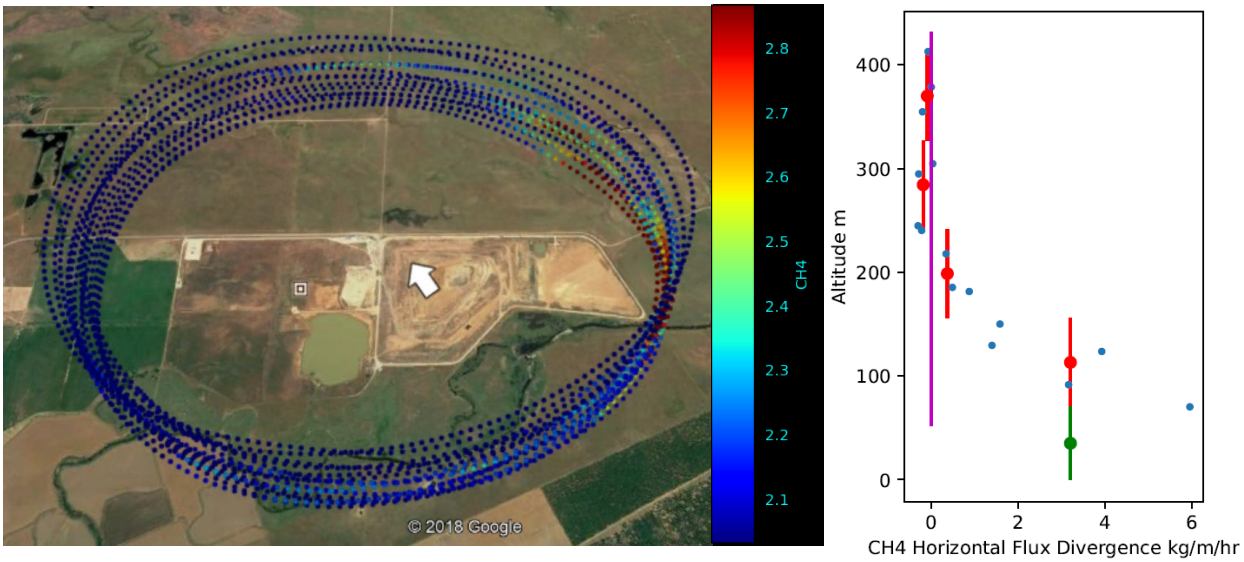


Figure 74. Flight path around Ostrom Road Landfill on November 18, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*75. Ox Mountain Landfill, 10/06/2018*

A total of 16 laps (15 useable) were flown around the Ox Mountain landfill, as shown in Figure 75. The aircraft completed circles from 401 meters AGL and 773 meters AGL. The winds were out of the northwest, averaging 5.4 m $s^{-1}$. The mountain terrain prevented any laps at lower altitudes, therefore a significant assumption was made for the emission rate from 400 m down to ground. Thus, the total methane emission is estimated at 2939 ± 574 kg $hr^{-1}$, though this value is likely an overestimate.

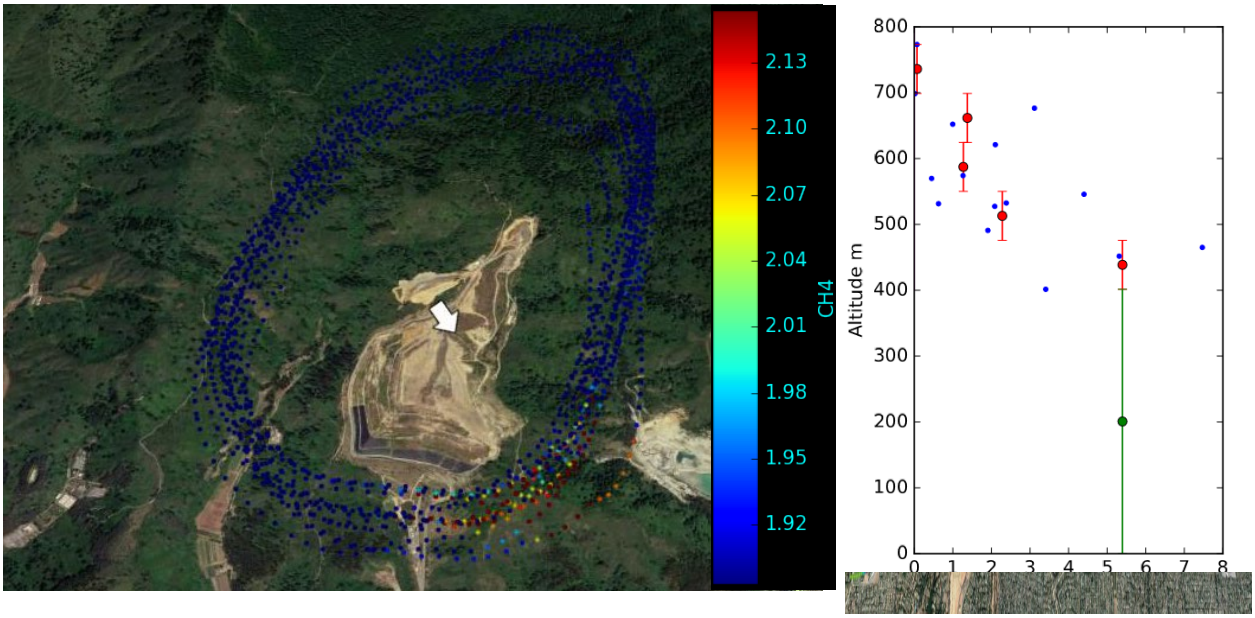


Figure 75. Flight path around the Ox Mountain Landfill and the vertical flux divergence profile for methane on October 6, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*76. Phillips 66 Refinery, 10/05/2017*

A total of 17 laps (16 useable) were flown around the Phillips 66 Refinery, as shown in Figure 76. The aircraft completed circles between 80 meters AGL and 500 meters AGL. Winds were out of the east, averaging 1.6 m $s^{-1}$. Total methane emission is estimated at 156 ± 83 kg $hr^{-1}$.

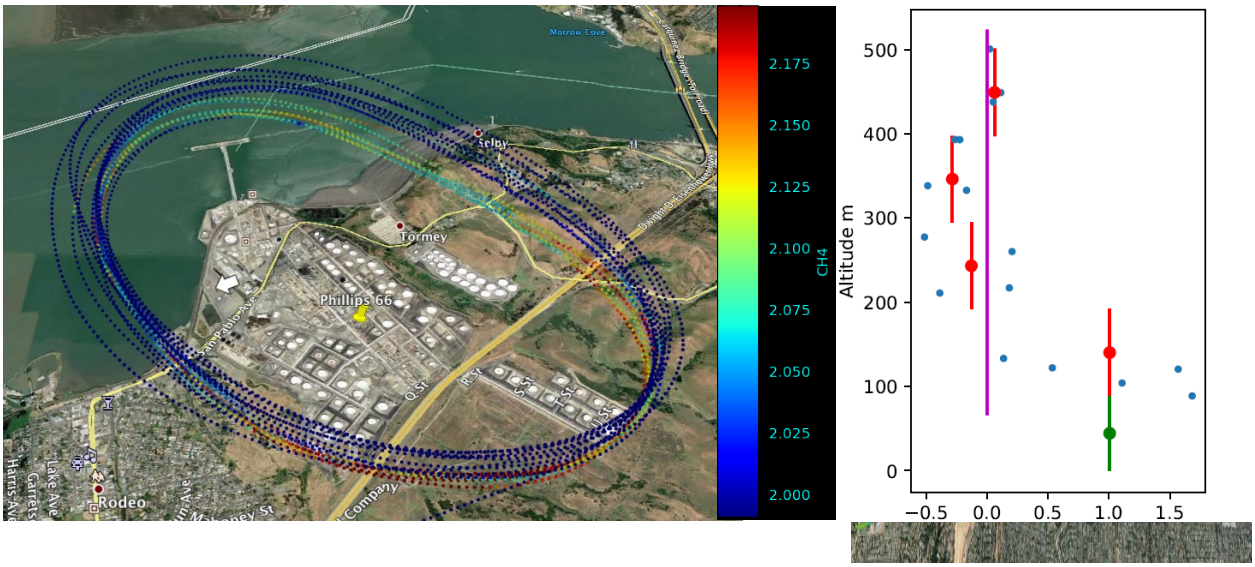

Figure 76. Flight track showing methane mixing ratios around the Phillips 66 refinery on October 5, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *77. Phillips 66 Refinery, 11/19/2017*

A total of 16 laps were flown around Phillips 66, as shown in Figure 77. The aircraft completed circles between 125 meters AGL and 642 meters AGL. Winds were out of the northwest, averaging 1.7 m $s^{-1}$. Total methane emission is estimated at 228 ± 75 kg $hr^{-1}$.

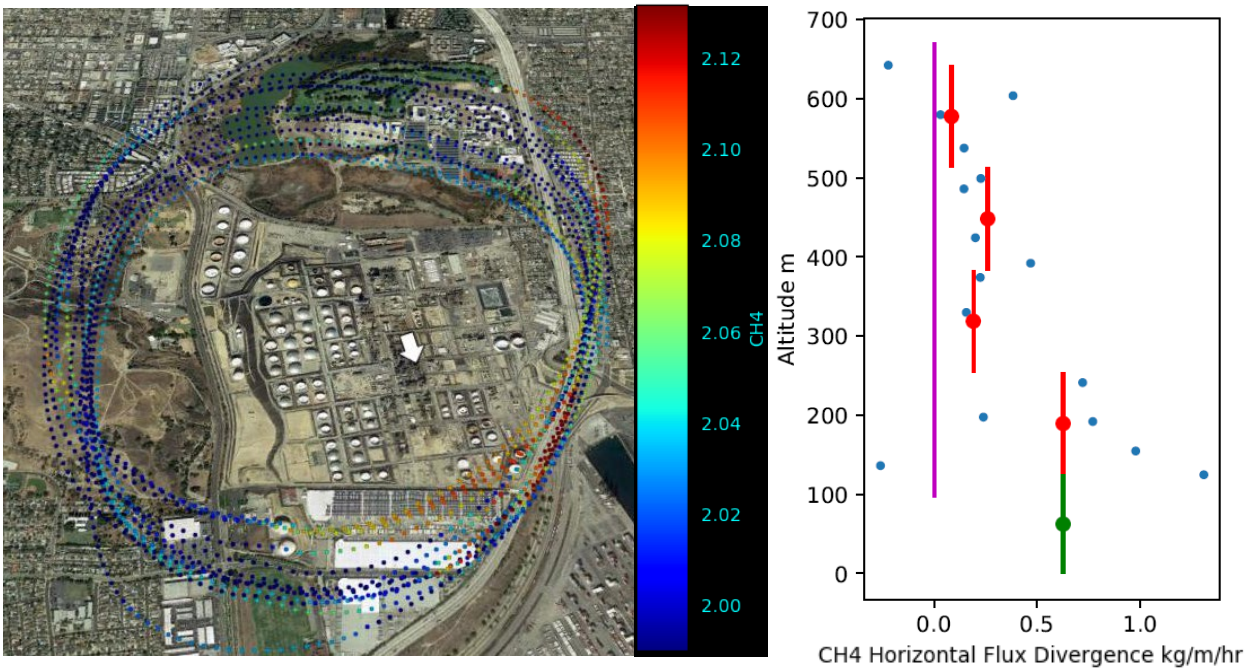


Figure 77. Flight path around Phillips 66 on November 19, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *78. Phillips 66 Refinery, 10/06/2018*

A total of 26 laps (22 useable) were flown around the Phillips 66-Rodeo refinery, as shown in Figure 78. The aircraft completed circles from 181 meters AGL and 1213 meters AGL. The winds were out of the north, averaging 2.8 m $s^{-1}$. Total methane emission is estimated at 439 ± 66 kg $hr^{-1}$.

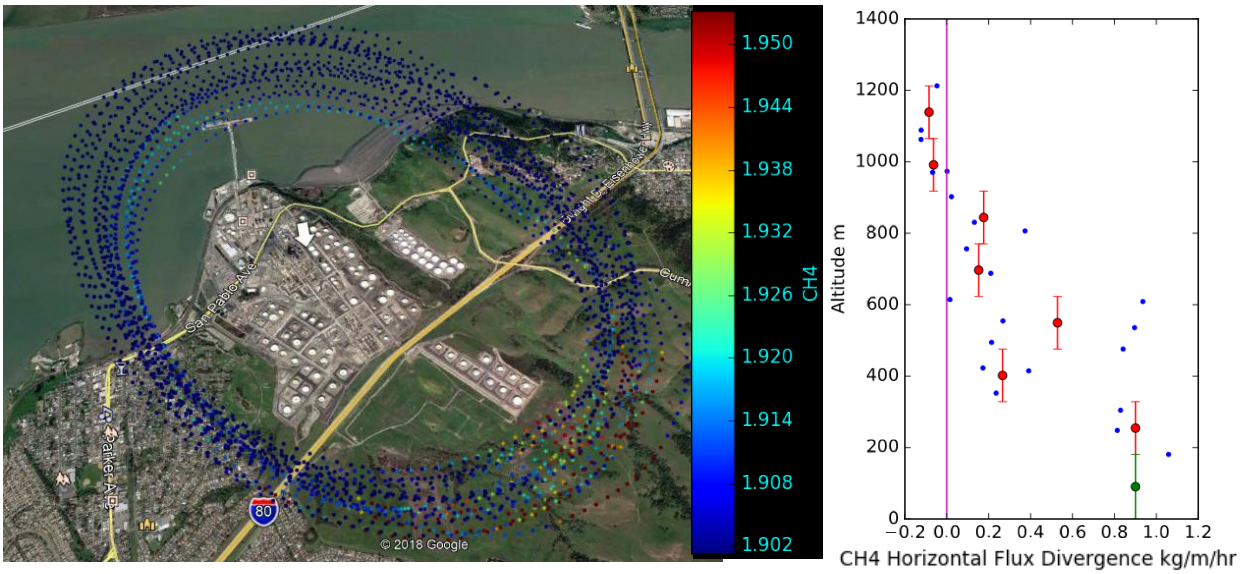


Figure 78. Flight path around the Phillips 66 refinery and the vertical flux divergence profile for methane on October 6, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*79. Potrero Hills Landfill, 10/06/2017*

A total of 13 laps were flown around the Potrero Hills Landfill, as shown in Figure 79. The aircraft completed circles between 80 meters AGL and 430 meters AGL. Winds were out of the north, averaging 5.7 m $s^{-1}$. Total methane emission is estimated at 2292 ± 400 kg $hr^{-1}$.

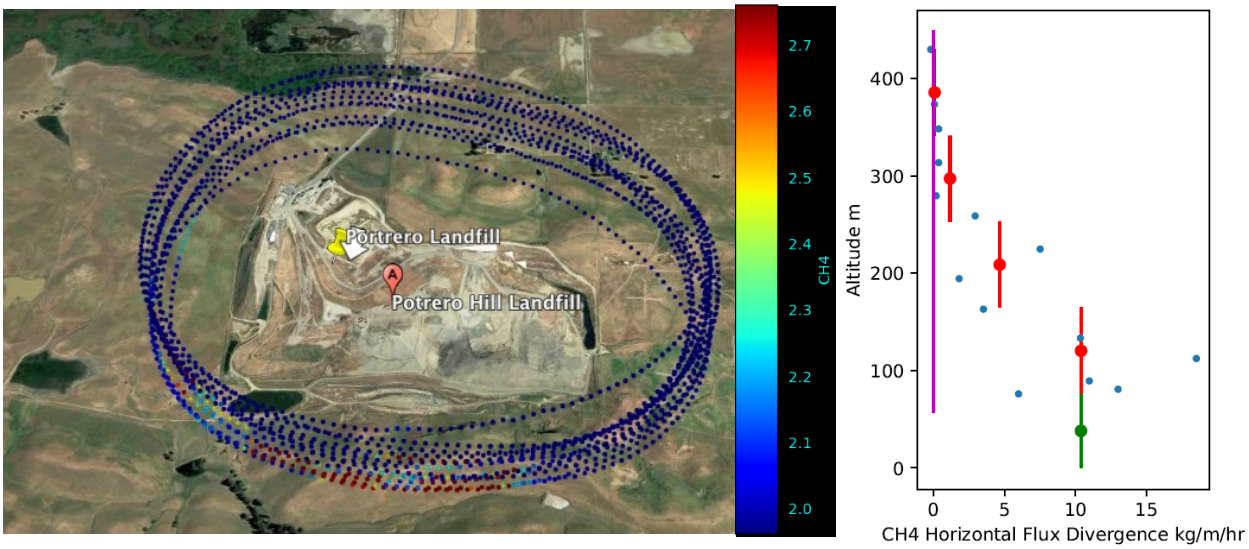


Figure 79. Flight track showing methane mixing ratios around Portrero Hills Landfill on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*80. Potrero Hills Landfill, 10/05/2018*

A total of 20 laps were flown around the Potrero Hills, as shown in Figure 80. The aircraft completed circles from 77 meters AGL and 613 meters AGL. The winds were out of the north, averaging 1.7 m $s^{-1}$. Total methane emission is estimated at 919 ± 286 kg $hr^{-1}$.

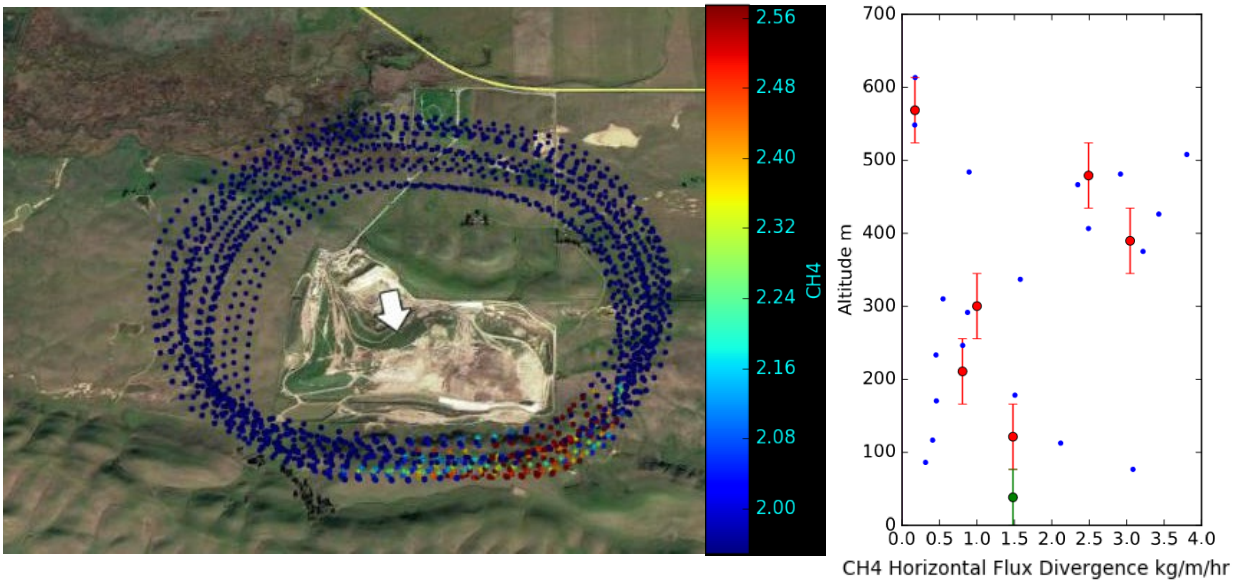


Figure 80. Flight path around the Potrero Hills Landfill and the vertical flux divergence profile for methane on October 5, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*81. Princeton Gas Storage Facility, 12/09/2017*

A total of 10 laps (8 useable) were flown around the Princeton GS facility, as shown in Figure 81. The aircraft completed circles between 23 meters AGL and 283 meters AGL. Winds were out of the northwest, averaging 3.3 m $s^{-1}$. The total methane emission was below our detection limit.

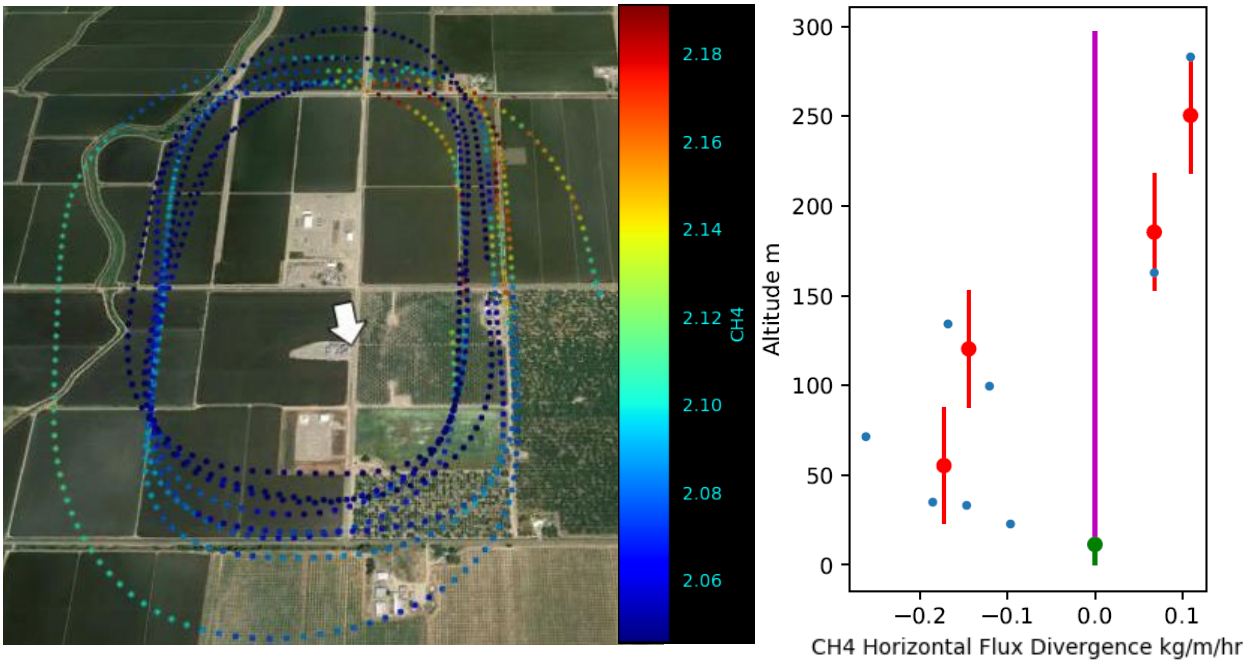


Figure 81. Flight path around Princeton GS on December 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*82. Puente Hills Landfill, 11/09/2017*

A total of 16 laps (14 useable) were flown around Puente Hills Landfill, as shown in Figure 82. The aircraft completed circles between 158 meters AGL and 841 meters AGL. Winds were out of the southwest, averaging 2.8 m $s^{-1}$. Total methane emission is estimated at 360 ± 55 kg $hr^{-1}$.

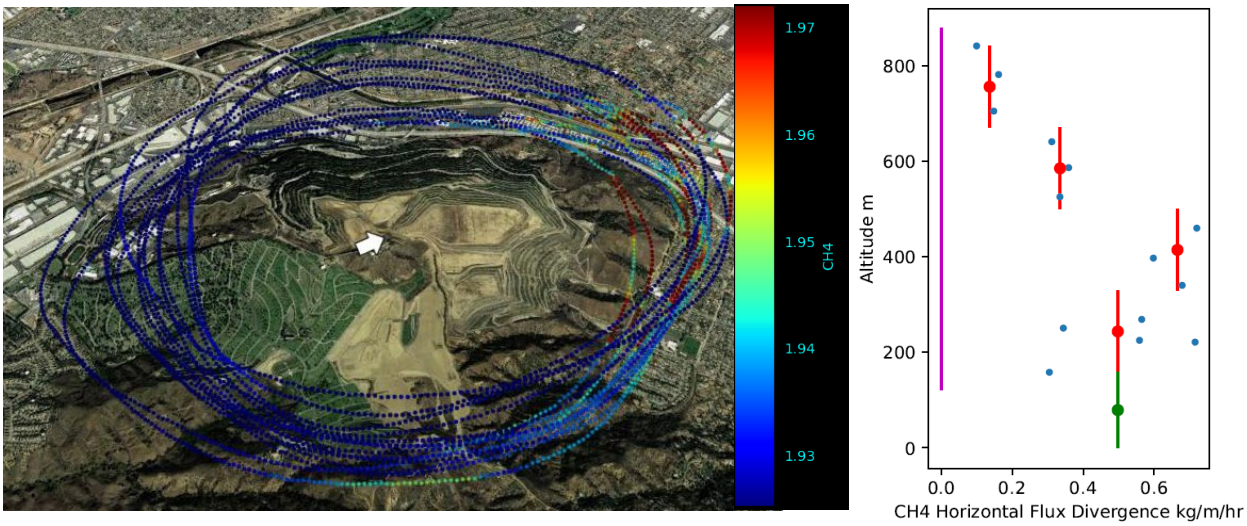

Figure 82. Flight path around Puente Hills Landfill on November 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*83. Round Mountain Oil and Gas Field, 4/18/2018*

A total of 6 laps (5 useable) laps were flown around Round Mountain field from 104 to 240 meters AGL. No statistically significant methane enhancements were observed, and the total methane emission was below our detection limit.

*84. San Jose Wastewater Treatment Facility, 10/05/2017*

A total of 15 laps were flown around the San Jose Wastewater treatment plant, as shown in Figure 83. The aircraft completed circles between 80 meters AGL and 450 meters AGL. Winds were out of the northwest, averaging 3.0 m $s^{-1}$. Total methane emission is estimated at 631 ± 140 kg $hr^{-1}$.

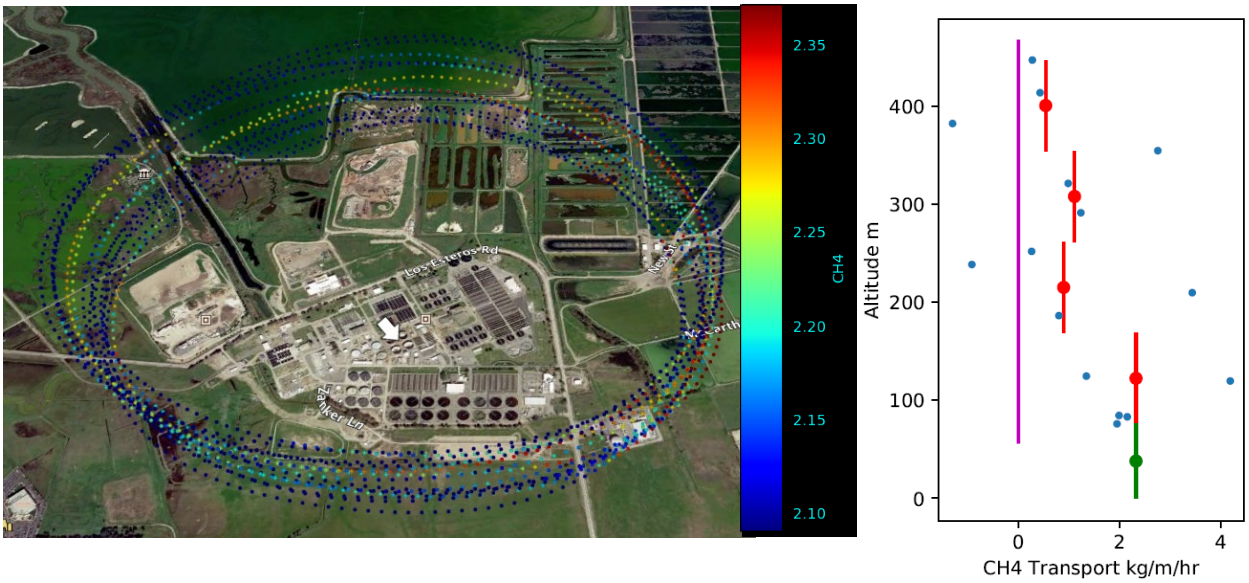


Figure 83. Flight track showing methane mixing ratios around San Jose Wastewater Treatment Plant on October 5, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*85. San Jose Wastewater Treatment Facility, 10/05/2018*

A total of 23 laps (22 useable) were flown around the San Jose Wastewater, as shown in Figure 84. The aircraft completed circles from 135 meters AGL and 633 meters AGL. The winds were out of the north, averaging 3.8 m $s^{-1}$. Total methane emission is estimated at 427 ± 80 kg $hr^{-1}$.

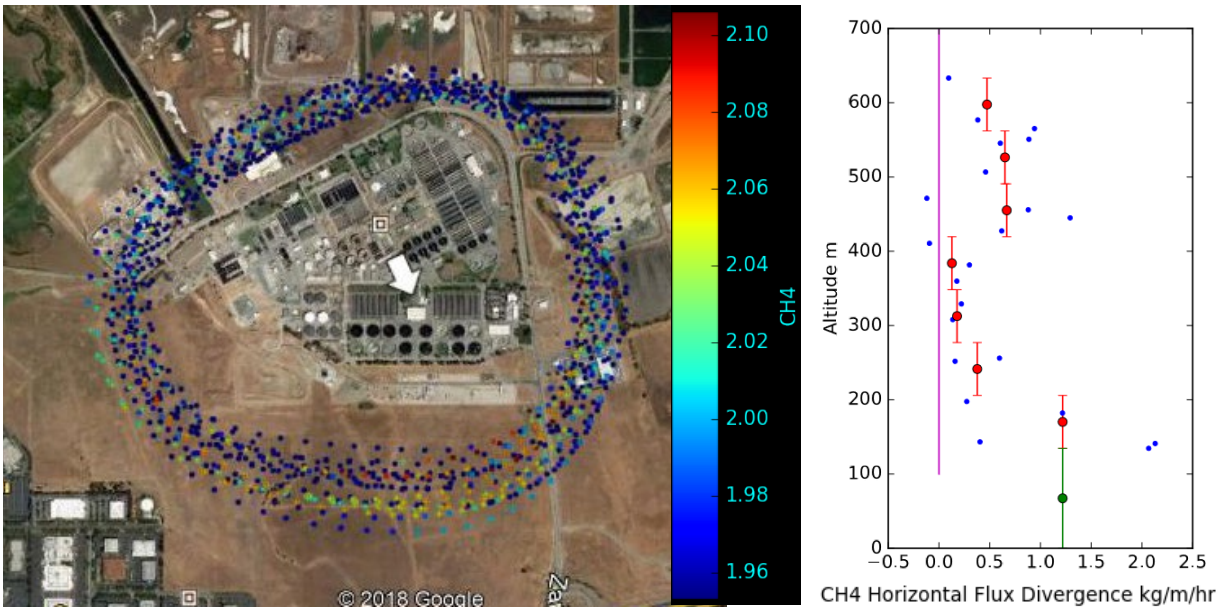


Figure 84. Flight path around the San Jose Wastewater and the vertical flux divergence profile for methane on October 5, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*86. Scholl Canyon Landfill, 11/09/2017*

A total of 21 laps (19 useable) were flown around Scholl Canyon Landfill, as shown in Figure 85. The aircraft completed circles between 121 meters AGL and 404 meters AGL. Winds were out of the southwest, averaging 3.9 m $s^{-1}$. Total methane emission is estimated at 70 ± 15 kg $hr^{-1}$.

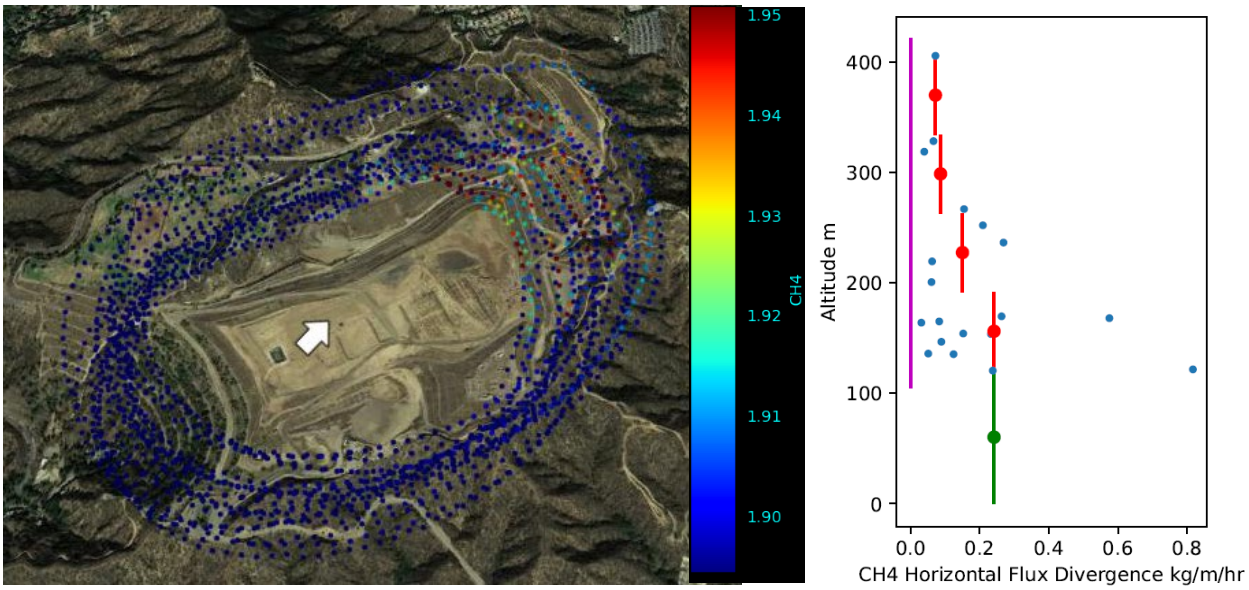


Figure 85. Flight path around Scholl Canyon Landfill on November 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*87. Scholl Canyon Landfill, 11/19/2017*

A total of 23 laps were flown around the Scholl Canyon Landfill, as shown in Figure 86. The aircraft completed circles between 166 meters AGL and 873 meters AGL. The winds were out of the southwest, averaging 1.2 m $s^{-1}$. Total methane emission is estimated at 475 ± 96 kg $hr^{-1}$.

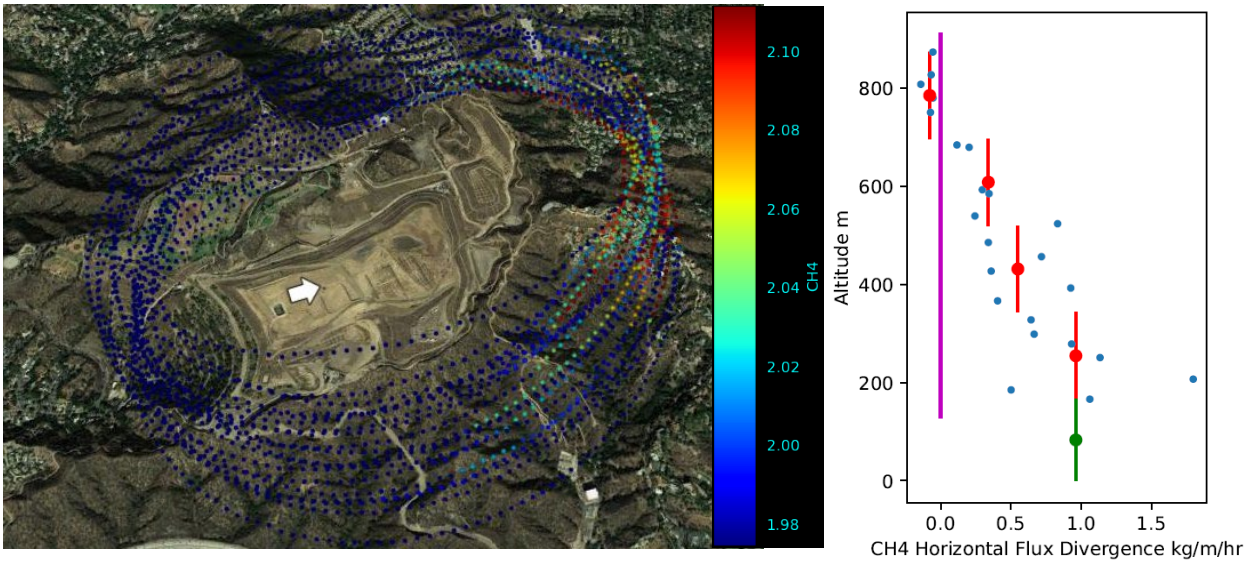


Figure 86. Flight path around Scholl Canyon Landfill on November 19, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*88. Shell Martinez Refinery, 10/07/2018*

A total of 14 laps were flown around the Shell Martinez Refinery, as shown in Figure 87. The aircraft completed circles from 137 meters AGL and 521 meters AGL. The winds were consistently out of the northeast, averaging 10 m $s^{-1}$. Total methane emission is estimated at 168 ± 18 kg $hr^{-1}$.

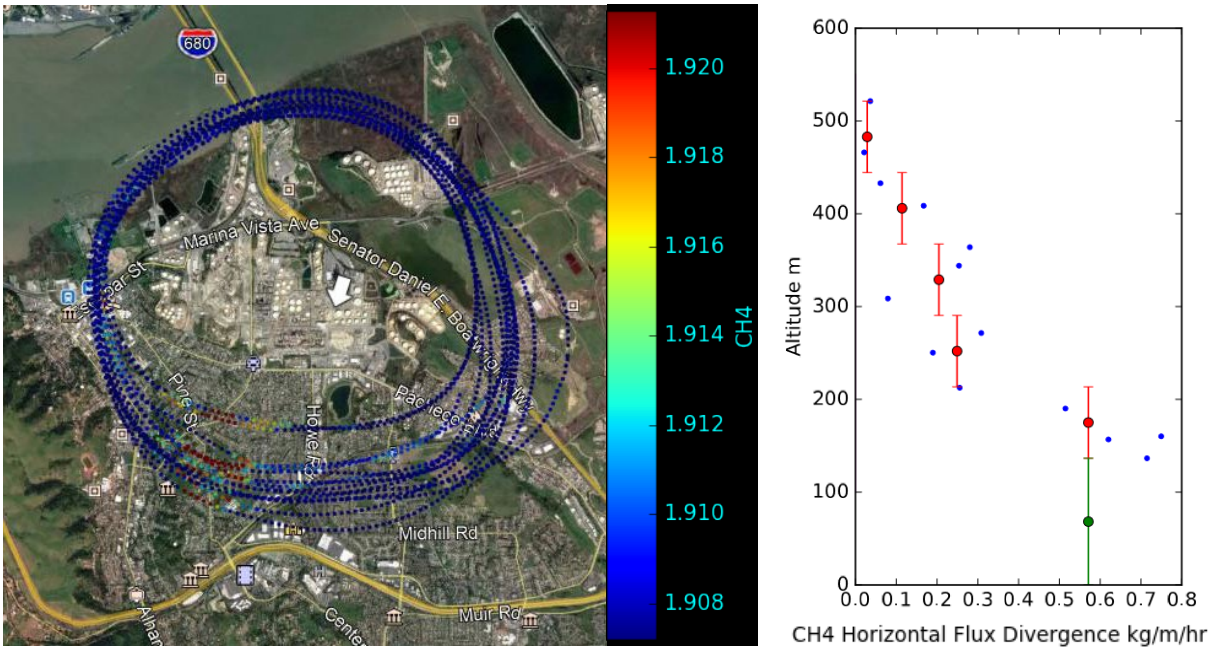


Figure 87. Flight path around the Shell Refinery and the vertical flux divergence profile for methane on October 7, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*89. Signal Hill Cluster, 5/16/2018*

A total of 16 (13 useable) laps were flown around the Signal Hill area, which contains several scattered small oil/gas facilities. The aircraft completed a mass balance box from 140 meters AGL to 973 meters AGL, as shown in Figure 88. Winds were out of the southwest, averaging 2.6 m $s^{-1}$. Total methane emission is estimated at 340 ± 126 kg $hr^{-1}$. The uncertainty was high because of the variability in the wind.

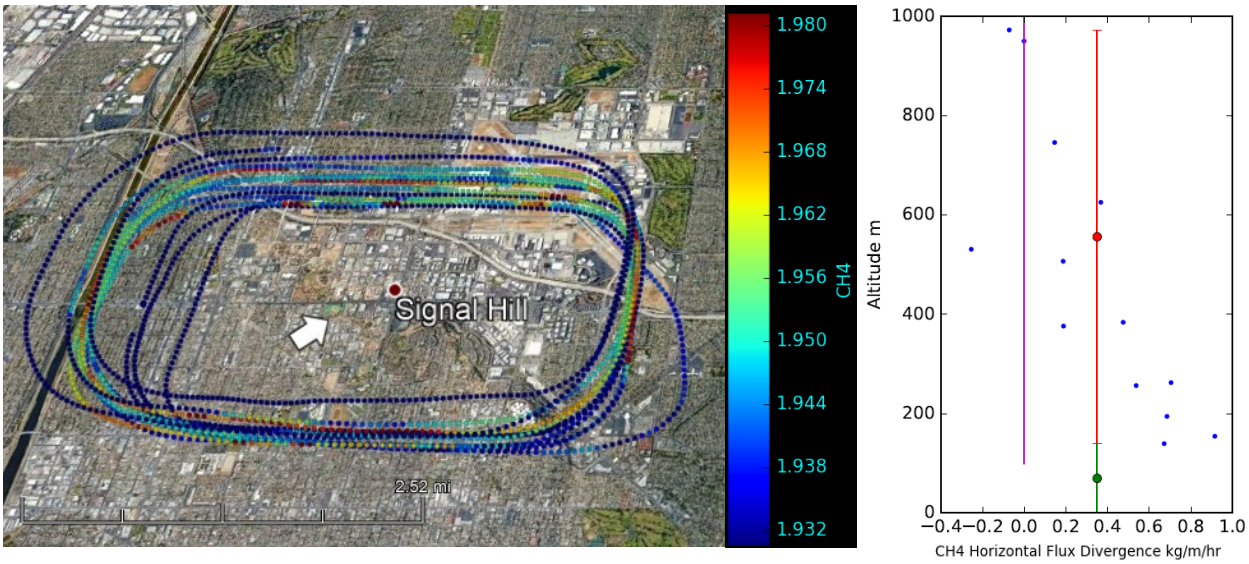


Figure 88. Flight path around Signal Hill area on May 16, 2018. The FluxSense small oil/gas sources are included on the map. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*90. Simi Valley Landfill, 10/17/2017*

A total of 12 laps (9 useable) were flown around Simi Valley Landfill, as shown in Figure 89. The aircraft completed circles between 184 meters AGL and 396 meters AGL. The winds were out of the west and averaging 5.4 m $s^{-1}$. Total methane emission is estimated at 490 ± 88 kg $hr^{-1}$.

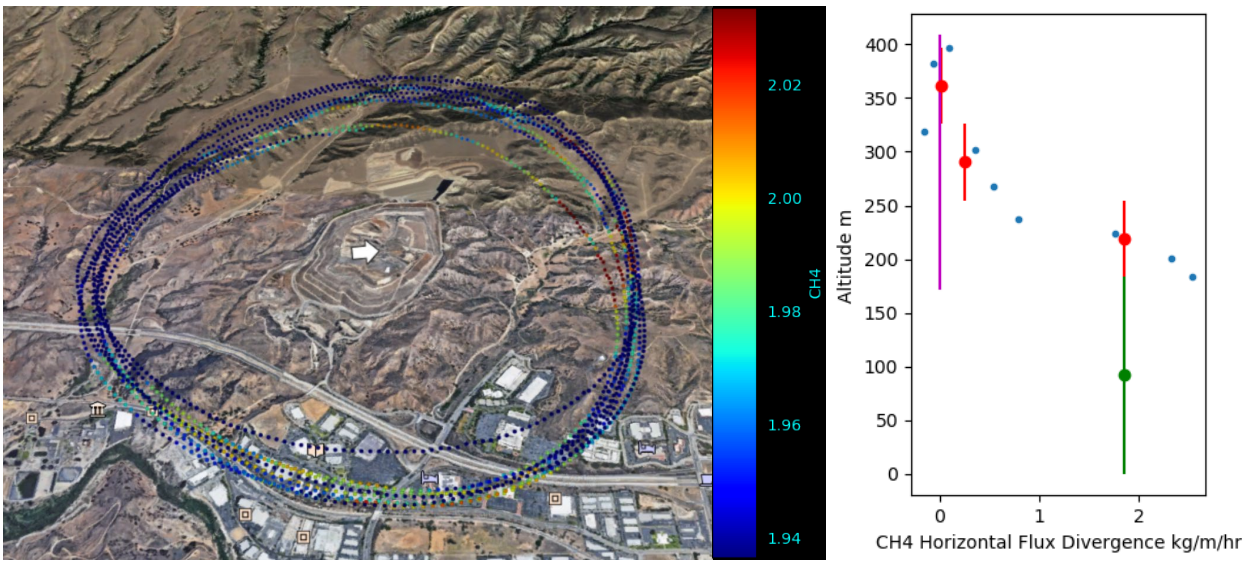

Figure 89. Flight path around Simi Valley Landfill on October 17, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*91. Sunshine Canyon Landfill, 10/16/2017*

The aircraft flew a total of 24 passes downwind of the Sunshine Canyon Landfill, as shown in Figure 90. Altitudes ranged from 113 mAGL to 910 mAGL. Winds were out of the north, averaging 5.8 m $s^{-1}$. Total methane emission is estimated at 1435 ± 283 kg $hr^{-1}$.

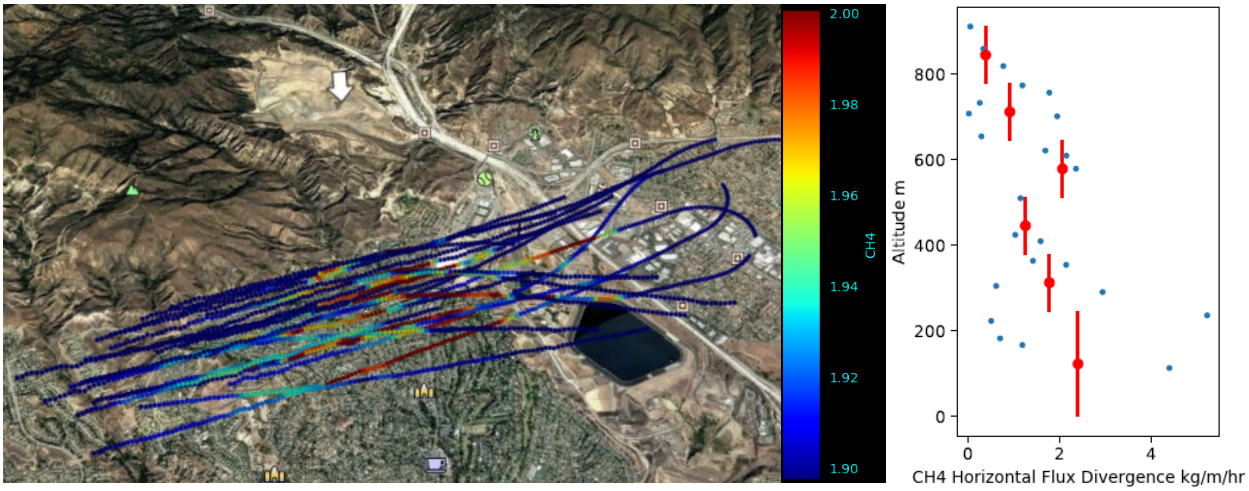


Figure 90. Flight path downwind of the Sunshine Canyon landfill on October 16, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*92. Tesoro Refinery, 10/06/2017*

A total of 11 laps were flown around the Tesoro Refinery, as shown in Figure 91. The aircraft completed circles between 130 meters AGL and 1150 meters AGL. Winds were out of the northeast, averaging 4.6 m $s^{-1}$. Total methane emission is estimated at 546 ± 184 kg $hr^{-1}$.

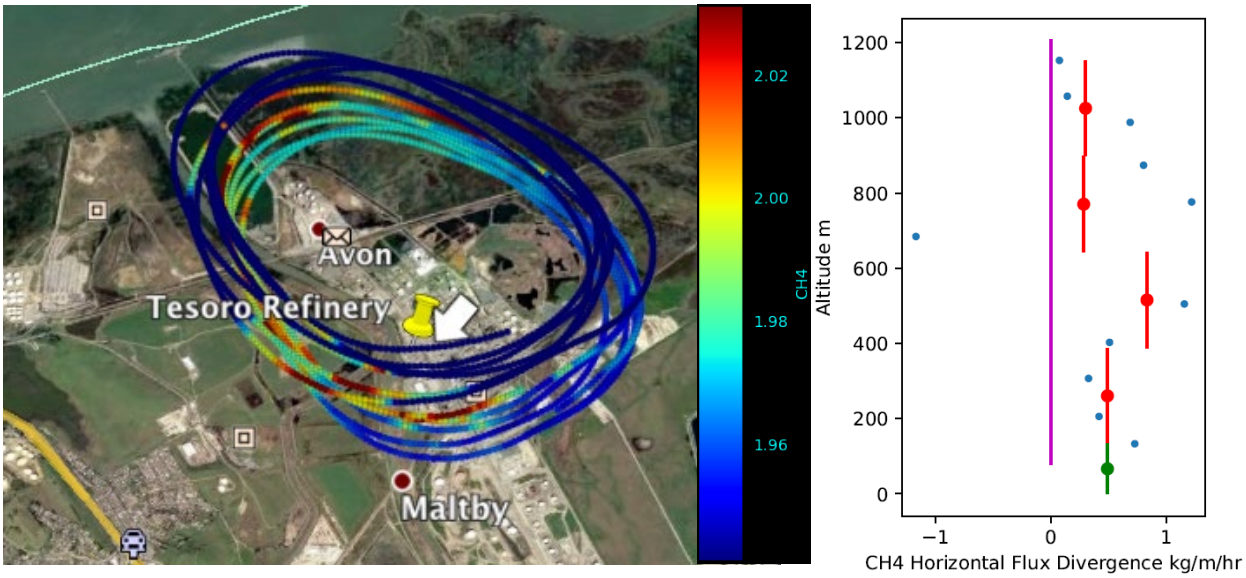


Figure 91. Flight track showing methane mixing ratios around the Tesoro Refinery on October 6, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*93. Toland Road Landfill, 10/16/2017*

The aircraft flew a total of 18 laps around the Toland Road Landfill, as shown in Figure 92. Altitudes ranged from 189 mAGL to 720 mAGL. Winds were out of the southwest, averaging 2.8 m s-1. Total methane emission is estimated at 3,200 ± 800 kg hr-1.

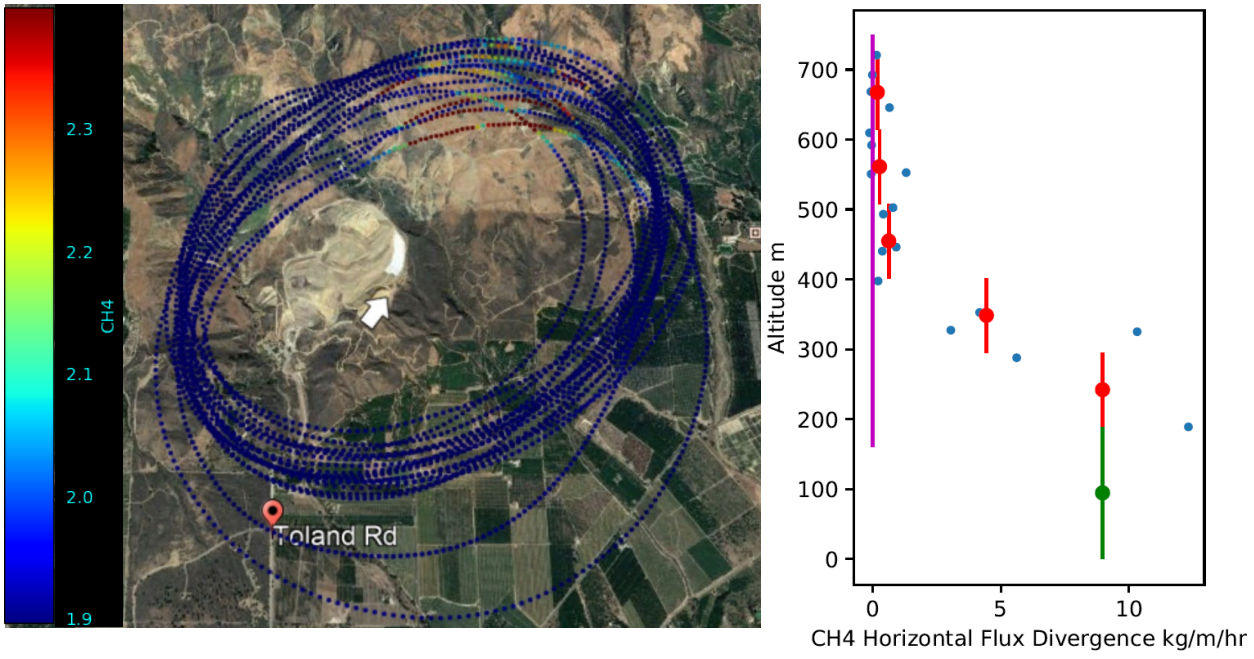

Figure 92. Flight path around Toland Road landfill on October 16, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *94. Toland Road Landfill, 5/14/2018*

A total of 16 laps were flown around the Toland Road Landfill, as shown in Figure 93. The aircraft completed circles from 238 meters AGL and 749 meters AGL. Winds were out of the west, averaging 6.4 m $s^{-1}$. Methane emission is estimated at 1530 ± 464 kg $hr^{-1}$.

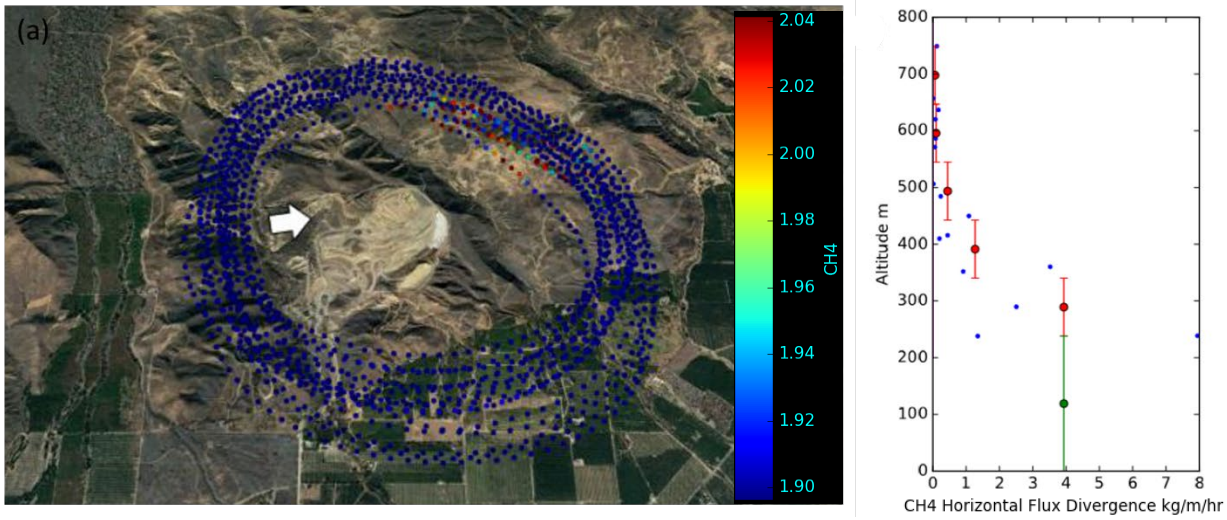


Figure 93. (a) Flight track showing methane mixing ratios around the Toland Landfill on May 14, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

### *95. Valero Benecia Refinery, 10/06/2018*

A total of 22 laps were flown around the Valero Refinery, as shown in Figure 94. The aircraft completed circles from 183 meters AGL and 1213 meters AGL. The winds were out of the north, averaging 2.8 m $s^{-1}$. Total methane emission is estimated at 443 ± 66 kg $hr^{-1}$.

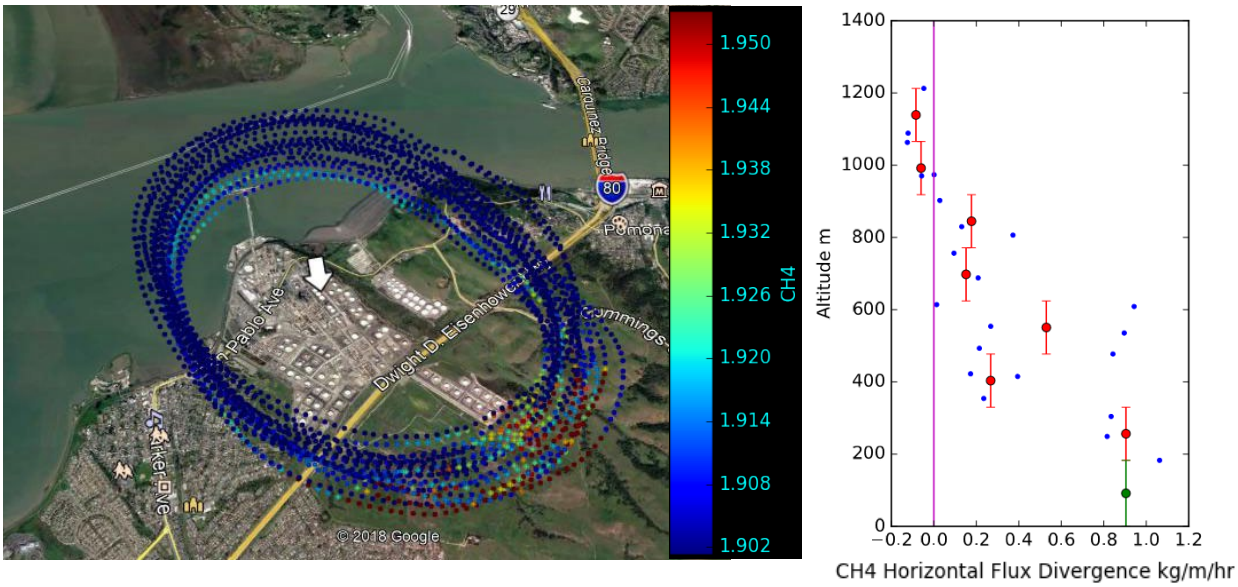


Figure 94. Flight path around the Valero Refinery and the vertical flux divergence profile for methane on October 6, 2018. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).

*96. Wheeler Ridge Compressor, 4/18/2018*

A total of 9 laps (7 useable) laps were flown around the Wheeler Ridge Compressor from 31 to 210 meters AGL. No statistically significant methane enhancements were observed, and the total methane emission was below our detection limit.

*97. Wild Goose Gas Storage Facility, 12/09/2017*

A total of 11 laps (6 useable) were flown around the Wild Goose GS facility, as shown in Figure 95. The aircraft completed circles between 45 meters AGL and 246 meters AGL. Winds were out of the west, averaging 0.7 m $s^{-1}$. The total methane emission was below our detection limit.

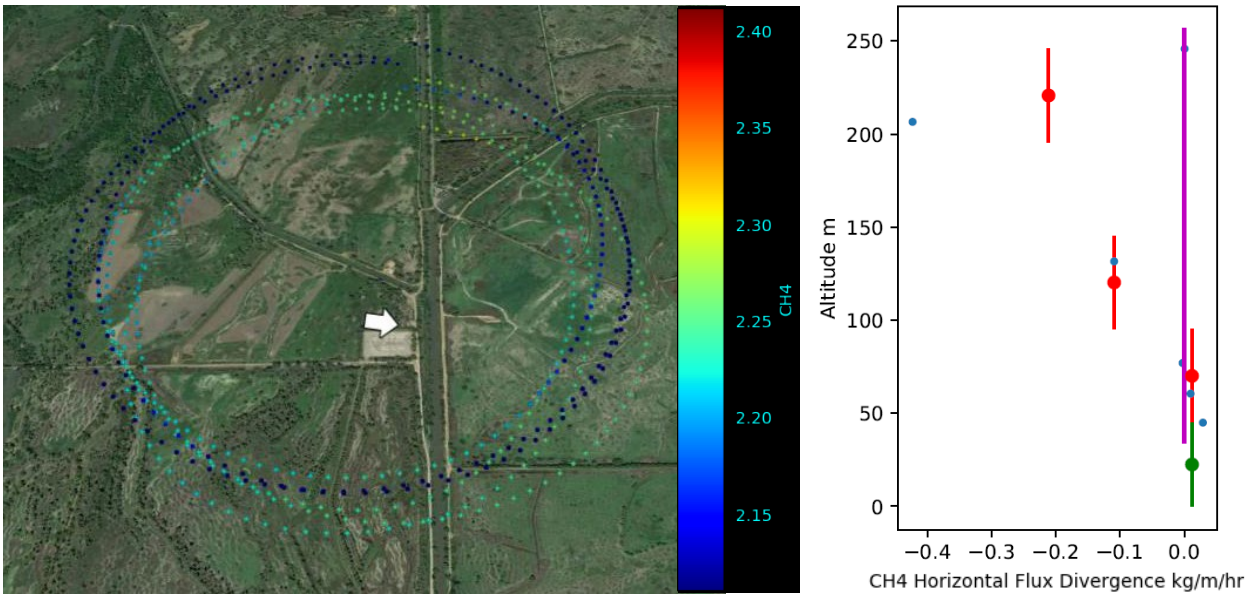


Figure 95. Flight path around Wild Goose GS on December 9, 2017. Flight path (left) colored by methane concentration (see color bar). Vertical profile of horizontal flux divergence (right) show individual laps (blue point), and altitude bins (vertical red bars).