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LETTER

Unmanned aerial vehicle observations of cold venting from exploratory hydraulic fracturing in the United Kingdom

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Abstract

Unmanned aerial vehicle (UAV) surveys allow for rapid-response near-field sampling, downwind of emission sources, such as gas extraction sites, without the need for site access. UAVs can be used in emission source identification alongside instantaneous flux estimation. A UAV was used to sample downwind of the UK’s first and only gas extraction site to use exploratory onshore horizontal hydraulic fracturing (fracking) of shale formations, in Little Plumpton, Lancashire. In-situ calibrated UAV methane mole fraction measurements were made from a neighbouring field on five sampling days between October 2018 and February 2019, during fracking, flow-back and flow testing. Methane emissions were identified on one of the five sampling days (14 January 2019), associated with known cold venting, following fluid unloading using a nitrogen lift. A near-field Gaussian plume inversion approach was used to calculate four instantaneous fluxes on this day (from four separate intermittent UAV flight surveys) with lower and upper uncertainty bounds of between 9–80 g s⁻¹, 23–106 g s⁻¹, 16–82 g s⁻¹ and 34–156 g s⁻¹, respectively. The cold venting emissions observed on this single day were at least an order of magnitude higher than UAV methane fluxes calculated for nearby dairy farm buildings, also presented here. Identifying and quantifying these methane emission sources are important to improve the national emissions inventory and to regulate this developing UK industry.

1. Introduction

In the UK, total methane emissions stood at 2.1 Tg yr⁻¹ in 2015 according to inventory (bottom-up) estimates (National Atmospheric Emissions Inventory 2017). This is in broad agreement with an atmospheric measurement based (top-down) estimate, ranging from 1.7 Tg yr⁻¹ to 2.7 Tg yr⁻¹ between 2012 and 2014 (Ganesan et al 2015). UK anthropogenic methane emissions are dominated by agriculture and waste (Ganesan et al 2015, National Atmospheric Emissions Inventory 2017, Brown et al 2019). Although the energy sector dominated UK methane emissions in the year 1990, these emissions decreased by 81% by 2016, due to reduced coal mining and gas distribution improvements (Brown et al 2019, p.95).

The Bowland shale formation, underneath a large area of the British Isles, may be a profitable gas reservoir (British Geological Survey 2013, US Energy Information Administration 2015) and potential methane emission source, if extracted. Between 800 and 2300 trillion cubic feet (tcf) of natural gas may lie within British carboniferous shale (British Geological Survey 2013), of which 25 tcf may be recoverable (US Energy Information Administration 2015). Horizontal hydraulic fracturing (fracking) may permit access to this reservoir (Field et al 2014). However commercial fracking has never taken place in the UK (US Energy
Information Administration 2015). Exploratory UK fracking emissions should be identified and quantified, for national inventory incorporation.

Fracking transformed natural gas production in the USA (Field et al 2014). However fugitive emissions can occur (Wigley 2011, Alvarez et al 2012), with potential for higher leakage than from conventional gas extraction (Howarth et al 2011). Leaks of over 2.4% can overwhelm the climate benefit (over a 20 year horizon) of the use of gas for fuel, over coal (Ren et al 2019). Fracking emissions occur during three major phases (Allen et al 2013): recovery of fracking fluid prior to gas retrieval (flow–back), fluid recovery from well clearing during production (unloading) and leaks from gas refinement and distribution. Net gas loss from shale regions in the USA varies, from zero up to the order of a 10% leak rate, depending on the prevalence of fracking and the presence of processing facilities (Schneising et al 2014, Omara et al 2016, Barkey et al 2019, Ren et al 2019). Omara et al (2016) observed higher average emissions from 13 unconventional than 18 conventional gas extraction sites in the Marcellus shale formation in the USA, though unconventional extraction had a lower leak rate due to better productivity.

In order to acquire rapid-response off-site sampling, downwind of natural gas infrastructure, an unmanned aerial vehicle (UAV) can be used. However UAV sampling may involve logistical challenges including availability of personnel, charging batteries and landowner permissions. Coordinating logistics may collectively require at least two days’ notice. Small lightweight UAV sampling is a relatively new and developing technology, with limited payload capacity (Fox et al 2019). Reliable source isolation (Barchyn et al 2019) and flux quantification (Shah et al 2019a) requires high spatiotemporal resolution. Flight endurance is temporally limited by battery life. Spatial limitations are often determined by legislation, for example The Air Navigation Order (2016, 2019) in the UK. Spatial limitations typically include UAV distance from the source (at least 50 m from buildings in the UK), distance from the pilot (within line of sight and no more than 250 m from the pilot in the UK) and maximum elevation (120 m in the UK). Meteorology is also a constraint (Fox et al 2019), for example, most off-the-shelf UAVs require no rain to protect electronic components (Oberle et al 2019), although this constraint is improving in new UAV designs. Downwind UAV sampling requires a suitable wind direction (Yang et al 2018) and low enough wind speeds for a UAV to safely maintain its position. Leak detection (Barchyn et al 2019) and flux quantification (Yang et al 2018) also require moderate wind speeds (above 2 m s$^{-2}$) for good results (i.e. uncertainties comparable to other methods), to allow emissions to flow towards the UAV.

Thus UAVs can be unsuitable for continuous and highly precise inventory-standard flux estimates. However a UAV is highly suitable for instantaneous (snap-shot) studies (Fox et al 2019), especially with restrictive site access. Whereas more precise (and often more expensive) techniques (using a tracer release, for example) require collaboration with the site operator, UAVs can operate independently by sampling from a neighbouring area. UAVs can provide three-dimensional sampling in the lowest portion of the boundary layer, otherwise inaccessible to manned aircraft (Fox et al 2019, Oberle et al 2019). A UAV can rapidly identify the presence of source emissions at low cost (Fox et al 2019, Oberle et al 2019). Furthermore, in conjunction with a flux technique such as the near-field Gaussian plume inversion (NGI) method (Shah et al 2019a), UAV sampling can be used to provide a rough flux estimate for the entire facility, bridging the gap between leak detection and precise inventory standard fluxes (Shah et al 2019b). The versatile nature of UAVs allows sampling to be dynamically adapted, to maximise in-plume downwind measurements, whereas stationary measurements depend highly on suitable wind conditions (Shaw et al 2019).

UAVs have been used in many studies to identify or quantify instantaneous natural gas leaks (or simulated leaks using controlled releases). For example, Ravikumar et al (2019) assessed the ability of six UAVs, employing different strategies, to identify and quantify leaks from a controlled release. Barchyn et al 2019 tested a leak detection algorithm, by flying in single transects downwind of a controlled release, measuring in situ methane mole fraction with ±0.05 ppm precision. Golston et al (2018) sampled at a fixed height above a controlled release, using remote sensing methane measurements in equally sized grid squares, to identify and quantify emissions using mass balance box modelling. Yang et al (2018) flew in circles around the rough location of a controlled release and used remote sensing measurements to identify the source location and quantify emissions, using mass balance box modelling. Nathan et al 2015 flew in concentric circles around a gas compressor station and used in situ ±0.05 ppm precision measurements to derive 22 mass balance box modelling fluxes, where geospatial kriging was used. Shah et al 2019b flew downwind of a controlled release and used in situ ±0.003 ppm precision measurements to test the capability of the NGI flux quantification method.

In this study, two UAVs sampled downwind of the UK’s first and only exploratory fracking operation managed by Cuadrilla Resources Ltd. Detectable emissions were identified on one of five sampling days. To our knowledge, this is the first use of UAV sampling downwind of fracking emissions. A different UAV was also used to quantify cattle emissions from nearby dairy farm buildings, for a contextual comparison with existing local methane sources. All fluxes were derived (where emissions were detectable) using the NGI method (Shah et al 2019a).
Table 1. A comparison of the three UAVs used during fracking and cattle surveys.

| Sampling source | UAV1                     | UAV2                     | UAV3                     |
|-----------------|--------------------------|--------------------------|--------------------------|
| Total flight surveys | 8                       | 7                        | 3                        |
| UAV platform    | DJI Spreading Wings S1000+ | DJI Spreading Wings S1000+ | DJI Spreading Wings S900 |
| UAV type        | Octocopter               | Octocopter               | Hexacopter               |
| Flights per survey | 2                       | 1                        | 2                        |
| Sampling strategy | Ascending diagonally with waypoints | Lateral transects in course lock | Random unbiased manual sampling |
| Required wind direction for downwind sampling | SW to NW | SW to NW | SE to SW |
| Height of plane of propellers above the ground | 0.540 m | 0.680 m | 0.520 m |
| Height of air inlet above the ground (with the UAV on the ground) | 0.845 m | 0.370 m | 0.550 m |
| Methane sensor | MGGA on the ground | pMGGA on-board | MGGA on the ground |
| Sampling lag time between the air inlet and the sensor cavity | 25 s | 2 s | 25 s |
| Average duration of [CH₄] sampling (in minutes) used per survey | 9 ± 1 | 6 ± 1 | 30 ± 6 |
| On-board wind sensor | Yes | No | No |

Figure 1. The operating site used for UAV sampling of fracking and cattle emissions. The background image is taken from Google Maps (imagery 2019): DigitalGlobe, GetMapping plc, Infoterra Ltd & Bluesky, The GeoInformation Group.

2. Experimental description

Two DJI Spreading Wings S1000 + UAV platforms (UAV1 and UAV2, see table 1 for details) flew downwind of the gas extraction site in Little Plumpton (near Wesham), Lancashire, UK (referred to hereafter as fracking surveys). Flights took place from the adjacent field belonging to an operational dairy farm (+53.78785° N, −2.94758° E, see figure 1). Eight UAV1 fracking flight surveys labelled F1.1—F1.8 (see table S1 for details and figure S1 for aerial flight tracks, which is available online at stacks.iop.org/ERC/2/021003/mmedia) and seven UAV2 fracking flight surveys labelled F2.1—F2.7 (see table S2 for details and figure S2 for aerial flight tracks) took place over five sampling days between October 2018 and February 2019. For further detail of the UAV sampling methodology, see Shah et al (2019b). The sampling window coincided with a combination of fracking, flow-back and flow testing activities. There were no cattle upwind of the UAVs during sampling. Baseline measurements conducted by Shaw et al (2019) over two years prior to fracking show that there are no significant upwind methane sources (in westerly winds), resulting in a flow of homogenous, well-mixed maritime background air.
A DIJ Spreading Wings S900 UAV platform (UAV3, see table 1 for details) flew downwind of nearby dairy farm buildings (referred to hereafter as cattle surveys). Flights took place from the adjacent field (see figure 1) during milking times. Three cattle UAV3 flight surveys labelled C3.1—C3.3 (see table S3 for details and figure S3 for aerial flight tracks) took place over two sampling days in September 2017. The farm buildings contained approximately 165 lactating cattle and 100 young cattle.

UAV1 and UAV3 were connected to an ABB Microportable Greenhouse Gas Analyzer (MGGA) on the ground using 150 m of perfluorooalkoxy alkane tubing (see Shah et al (2019b) for further details). UAV2 carried an on-board prototype MGGA (pMGGA) sensor. The MGGA and pMGGA measured atmospheric dry methane mole fraction \((\text{CH}_4)\), which was calibrated and water-corrected (see Shah et al (2019b) for details). Satellite time and geo-location was recorded on-board all three UAVs. \([\text{CH}_4]\) timestamp was corrected for time lag between air entering the inlet and sensor cavity (see Shah et al (2019b) for further details). Periods of \([\text{CH}_4]\) sampling in which the tubing attached to UAV1 and UAV3 kinked (blocking airflow) were omitted (see tables S1 and S3).

Wind speed measurements as a function of height above ground level \((z)\), from a two-dimensional sonic anemometer on-board UAV1, were combined with wind vector measurements made by a stationary sonic anemometer (see figure 1) to derive two-dimensional wind vector profiles (with corresponding uncertainty) as a function of \(z\) (see supplementary information (SI) for details). As UAV3 did not carry an on-board wind sensor during cattle surveys, two-dimensional wind vector profiles (with corresponding uncertainty) were inferred using a power law extrapolation of measurements from the stationary anemometer, following the method described by Justus and Mikhail (1976). The two-dimensional wind vector profiles were used to derive mean wind direction \((\theta)\) and average perpendicular wind speed profiles as a function of \(z\) \((\text{WS}(z))\), for the duration of \([\text{CH}_4]\) sampling for each fracking and cattle survey.

3. Source identification and flux estimation

Geospatially mapped UAV \([\text{CH}_4]\) measurements were first used to identify a measurable emission source. \([\text{CH}_4]\) was plotted on a vertical plane perpendicular to \(\theta\), to ascertain whether a well-defined background mole fraction could be derived from \([\text{CH}_4]\) measurements (see figure 2 for fracking surveys and figure S4 for cattle surveys). The vertical axis represents height of the air inlet above ground level and the horizontal axis represents distance along the plane perpendicular to \(\theta\) (see Shah et al (2019a) for a method to project longitude and latitude onto a perpendicular plane). It is clear from figure 2 that only four fracking surveys (F1.4, F2.5, F2.6 and F2.7) from a single sampling day resulted in \([\text{CH}_4]\) enhancements sufficient for use in flux calculation. This assumption was verified using a sensitivity test applied to \([\text{CH}_4]\) measurements for all surveys (see SI). There may have been minor on-site leaks on the other four sampling days, but the sensitivity test suggests it would be impossible for such a leak to exceed 3 g s\(^{-1}\). However all cattle surveys produced sufficient \([\text{CH}_4]\) enhancements for flux estimation.

To estimate fluxes (where detectable emissions were identified), \([\text{CH}_4]\) enhancements above a calculated representative background were combined with \(\text{WS}(z)\) profiles (as described in the previous section) to derive geospatially mapped methane flux density \((q)\) in kg s\(^{-1}\) m\(^{-2}\) (see Shah et al (2019a) for further details on \(q\); see figures S5 and S6 for \(q\) during fracking and cattle surveys, respectively). The NGI flux quantification method, described in Shah et al (2019a) and tested in Shah et al (2019b), was used to derive a range from the lower flux uncertainty bound \((F_\text{l})\) to the upper flux uncertainty bound \((F_\text{u})\). The NGI method is an adaptation of the traditional Gaussian plume model (see Turner (1994) for details). Briefly, geospatially mapped \(q\) measurements are inverted to derive an initial flux estimate \((F_\text{i})\), assuming Gaussian turbulent dispersion of a time-invariant plume, near to source. NGI time-invariant plume dispersion is characterised by variations in \(q\), rather than atmospheric stability. Furthermore, the NGI method takes into account offset between the orientation of the sampling plane and the plane perfectly perpendicular to \(\theta\). Uncertainties in \(q\) are propagated to derive total measured flux uncertainty \((\sigma_F)\). \(F_\text{a}, F_\text{m}, F_\text{u}\) and \(\sigma_F\) are given in table S5 for fracking surveys (from one sampling day) and table S6 for all cattle surveys.

4. Flux results and discussion

The flux range (within uncertainty) for each fracking and cattle UAV survey (where emissions were detectable, see section 3) is plotted in figure 3. The four fracking flux results suggest that over a 1.4-hour sampling window on 14 January 2019 (one of five sampling days), fugitive methane emissions of the order 10 g s\(^{-1}\) to 100 g s\(^{-1}\) were released from the shale gas extraction site. Flocking flux ranges are broadly similar for each survey. As we sampled directly downwind of the site and approximately 50 m away, it is unlikely that an emission plume was overlooked; we are therefore confident that there were no substantial emissions on the other four sampling days.
It was later made public that emissions on 14 January 2019 were due to cold venting following a nitrogen lift (Environment Agency 2019). A nitrogen lift is used during unloading (see section 1), where nitrogen is pumped into the well at high pressure to clear fluid and stimulate natural gas flow. As the emergent gas mixture may initially contain too much nitrogen to burn, it may be cold vented. The other sampling days did not demonstrate evidence of detectable cold venting. This suggests emissions were episodic and variable in the general window of on-site nitrogen lift processes. To fully capture total flux associated with such an event, continuous sampling
would be required (a challenge for UAVs). An analysis of this has been conducted by (Shaw et al 2020, submitted), from a monitoring station, co-located with the stationary anemometer (see figure 1), using a range of flux quantification approaches. They derived fluxes of a similar order of magnitude to the UAV NGI fluxes presented here. It may have been useful to compare results with operator records of site activity here; however these were unavailable at the time of writing.

To our knowledge, the UAV surveys on 14 January 2019 coincided with the only cold venting event between October 2018 and February 2019. This is consistent with the measurements made by continuous stationary monitoring (Shaw et al 2020, submitted). Shaw et al (2020, submitted) measured [CH₄] above the median baseline (in westerly winds, see Shaw et al (2019)) for 117 h, over a 6-day period (11–16 January 2019) which coincided with UAV emission observations. Meanwhile, the UAV sampled intermittently within a 1.4 hour window, demonstrating temporal limitations of UAV sampling compared to continuous stationary sampling. However Shaw et al (2020, submitted) may not have observed [CH₄] elevations during unfavourable winds as the sensor lacked mobility.

Emissions were undetectable during all other days in this 5-day UAV fracking study, albeit with limited sampling. This makes it impossible to draw statistically significant conclusions on the impact of a future scaled fracking industry on net UK methane emissions. Additional UAV sampling (or alternative monitoring) would be required to realise the statistical significance of the observed flux results, compared to emissions over the lifecycle of the well. However there are logistical, physical, legal and meteorological limitations to UAV sampling (see section 1), restricting our ability to acquire more measurements from this single UK site.

This UK study was the first assessment of methane emissions from a single exploratory fracking well. The nitrogen lift unloading fluxes presented here (observed on one sampling day) are of similar magnitude to the highest gas extraction emissions observed in the USA. Many of these previous studies found that a small number of facilities produced the lion’s share of emissions. For example, Omara et al (2016) derived emissions from 13 unconventional extraction facilities in the Marcellus shale region ranging from (0.2 ± 0.1) g s⁻¹ to (26 ± 13) g s⁻¹, with 3 sites accounting for 85% of total emissions. Rella et al (2015) measured mean emissions from 115 conventional and unconventional extraction facilities (from which emissions were detectable) of (6.3 ± 1.3) g s⁻¹ in the Barnett shale region, with maximum emissions of up to 170 g s⁻¹ and 6.6% of well pads responsible for 80% of total emissions. Yacovitch et al (2015) measured emissions from 49 conventional and unconventional extraction facilities in the Barnett shale region, with 42 fluxes of less than 20 g s⁻¹, but maximum observed emissions of 80 g s⁻¹. Caulton et al (2014) observed average emissions of 34 g s⁻¹ from 7 individual facilities in the Marcellus shale region, representing approximately 1% of all combined conventional and unconventional gas extraction sites from the studied area. Flow-back is often responsible for high (but transient) emissions, for example Goetz et al (2015) observed (90 ± 110) g s⁻¹ from a single flow-back site. Allen et al (2013) found a complete flow-back operation to produce an average of approximately 1.7 Mg, with maximum emissions of 17 Mg.

For a contextualised UK comparison of instantaneous emissions, the fracking fluxes (from one sampling day) in figure 3 dwarf the maximum cattle emission flux (within uncertainty) of 3 g s⁻¹. The cattle fluxes are in broad agreement with inventory predictions (0.0042 g s⁻¹ per animal) for enteric fermentation, from dairy cattle free to pasture in Western Europe (Wolf et al 2017). As the farm contained adult lactating cattle, young cattle and organic waste produced by the cattle, UAV sampling provides a unique opportunity to accurately quantify all methane emissions from the dairy farm, as a single facility.

Fracking emissions occurred as a short-term emission pulse compared to more continuous emissions expected from dairy agriculture. Although methane emissions from the farm buildings are expected to be substantially higher during milking times, individual cattle produce sustained and largely invariant emissions throughout the day (Blaxter and Clapperton 1965). Fugitive gas extraction emissions are only expected during cold venting events, which could occur at any time of day in principle. It should be noted that UAV sampling can only provide an instantaneous flux estimate at the time of sampling. Instantaneous fluxes may not be representative of time-integrated emissions over a prolonged period, making direct comparison in terms of net greenhouse gas emissions difficult, for example if compared annually. Therefore the fracking flux results of this study best serve as an indicator for further, more precise flux assessment as they lack statistical significance. Instantaneous fracking fluxes show that regardless of rigorous controls, UK shale gas emissions must be accurately quantified using precise and reliable methods such as a tracer release, for their incorporation into the UK’s national greenhouse gas inventory, in a potential future scaled industry.

5. Conclusion

Two UAVs were used to sample methane emissions from the UK’s first exploratory fracking operation. This was the first use of UAV sampling for methane flux quantification from fracking. Of the fifteen UAV flight surveys
carried out over five sampling days, methane emissions were observed on only one sampling day, over a 1.4-hour sampling window on 14 January 2019. The four UAV surveys from this period yielded instantaneous emission fluxes within a range of between 9 g s\(^{-1}\) and 156 g s\(^{-1}\) (within the full range of uncertainty over all surveys). However emission flux may vary over the 1.4-hour sampling window and between each flight survey, meaning that each survey should be interpreted as an independent snap-shot, which bears no statistical significance of long-term emissions over the life-cycle of the well. The instantaneous fracking emissions were due to cold venting of methane, following a nitrogen lift during unloading, used to initiate gas flow. Thus the first exploratory fracking operation in the UK resulted in substantial instantaneous methane emissions at the time of sampling. Fracking emissions from this single event were at least an order of magnitude greater than emissions from the nearby farm buildings (sampled with a different UAV, at a different time) housing lactating cattle.

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