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Optimized Inspection of Upstream Oil and Gas Methane Emissions Using Airborne LiDAR

Kashif Rashid, Andrew Speck, Timothy P. Osedach, Dominic V. Perroni, and Andrew E. Pomerantz*
Schlumberger-Doll Research
Cambridge, MA, USA
apomerantz@slb.com

Abstract— Methane is a short-lived climate pollutant responsible for approximately 20% of anthropogenic greenhouse gas emissions. Reducing methane emissions from the oil and gas (O&G) industry is considered among the most urgent and actionable measures to mitigate climate change. Recent reports suggest a large fraction of upstream O&G methane emissions result from a small number of super-emitter facilities, emphasizing the value of novel methods that inspect O&G facilities with greater frequency than is practical using existing techniques. Here we described an optimized method wherein O&G facilities are inspected for emissions at high frequency and high sensitivity using active laser (LiDAR) sensors mounted to aircraft. The method relies on a hierarchical clustering and routing procedure to establish optimal routes to be flown by aircraft departing from local airports and equipped with LiDAR methane sensors. Routes were optimized to inspect all well sites subject to emissions regulation in three O&G intensive regions: the Permian basin, the state of Colorado, and the state of Pennsylvania. While some cost estimates require additional field data, these modeling results suggest the optimized inspections can be performed with comparable effectiveness and up to a factor of six lower cost per inspection compared to current detection methods. This modeling exercise suggests that optimized routing may enable frequent inspection of upstream O&G facilities at large scale and potentially lead to a significant decrease in both anthropogenic methane emissions and compliance costs borne by industry.

Keywords—methane, oil, gas, LiDAR, routes, LDAR

I. INTRODUCTION

Methane is a short-lived climate pollutant responsible for approximately 20% of anthropogenic greenhouse gas emissions.[1] It is a potent greenhouse gas with global warming potential 84 times more potent than CO_2 over a 20 year period and 28 times more potent over a 100 year period.[2-5] Methane is the primary component of natural gas, and it is estimated that 2.3% of all produced gas in the US is lost to emissions, mostly from abnormal operating conditions in the upstream production sector.[6] Further, it is estimated the 20 year radiative forcing from this leaked gas is comparable to that from the CO_2 resulting from combustion of the remaining 97.7% of unleaked gas, such that including the impact of methane emissions doubles the footprint of natural gas that would be estimated from consideration of solely CO_2 emissions.[6] Reducing methane emissions from the O&G industry is considered among the most urgent and actionable measures to mitigate climate change[7-9] and an important complement to reducing CO_2 emissions.[10, 11]

The main technical challenge in reducing methane emissions in upstream O&G is locating emission sources, which typically arise from well pads in remote, unmanned locations.[12] Emission rates from well sites are widely distributed, with the highest-emitting 5% of sites ("super-emitters") causing 50% of emissions.[10, 13, 14] The extent of emissions reduction by leak detection and repair (LDAR) programs depends on the sensitivity of the detector used to identify emissions and the frequency with which inspections are performed. Improving detector sensitivity generally results in greater reduction because more leaks can be detected. However, there is a threshold at which detection sensitivity is sufficient to capture all significant leaks, and further improvements in sensitivity no longer result in meaningful emissions reductions. That threshold has been estimated at a detection limit of approximately 1 kg CH_4/hour emissions rate.[15] Increasing inspection frequency generally results in greater emissions reduction by decreasing the duration of emission events. Because facilities can become super-emitters unexpectedly, frequent inspection results in emissions reductions by allowing faster detection and repair of super-emitters.[10, 13, 16]

Today, upstream O&G methane emissions are detected via optical gas imaging (OGI) surveys in which a work crew drives to well sites and inspects for leaks using an infrared camera. Due to the sparse and remote locations of many well sites, emissions detection methods that involve a work crew driving to well sites are relatively inefficient. Novel approaches for detecting these emissions include mobile sensors (mounted on trucks, drones, helicopters, airplanes, and satellites), which are particularly well-suited to enable frequent inspection of O&G facilities.[10, 13, 16] These mobile sensors could be deployed as part of a comprehensive monitoring program[17] in which all regulated facilities would be screened by a mobile sensor, then OGI surveys would be performed only on facilities flagged during the screening as emitting abnormally. In this application, mobile sensors need identify only which facilities are emitting while the subsequent OGI surveys identify which particular component(s) on those facilities are leaking.[17]

One promising mobile technique involves active laser-based LiDAR sensors deployed on small aircraft.[18-23] These sensors involve a laser tuned to a wavelength of strong methane absorption, emitted from a low-flying aircraft, and then detected after reflecting off the ground. Airborne LiDAR sensors can have relatively high sensitivity, with limits of detection (determined by controlled released experiments) approaching the 1 kg CH4/hour emission rate threshold under favorable conditions (i.e. wind speeds below 15 miles per hour).[17-23] Additionally, with favorable environmental conditions, airborne LiDAR sensors can scan sites relatively quickly; i.e. in a single pass, without needing to fly laps. [18-23] Airborne LiDAR technology is used today to monitor emissions from pipelines. Deploying this technology to monitor pipelines is relatively straightforward because the aircraft can simply fly directly along the pipeline route. In contrast, deploying this technology in the upstream sector is more challenging because of the complex and sparse arrangement of well sites. The objective of this study is to develop an optimized deployment scheme and then to estimate the environmental benefits and implementation costs associated with using airborne LiDAR to inspect upstream O&G facilities for methane emissions.

II. METHODS

The LDAR strategy described here employs a comprehensive monitoring program in which all regulated wells in a region are investigated at facility level using airborne LiDAR, and then component level OGI inspections are performed only on sites where a facility level emission is detected. The deployment scheme is simulated in three O&G intensive regions: the Permian basin, where EPA regulation[24] requires inspection of wells drilled or modified after September 2015; Colorado, in which state regulation[25] requires inspection of all active wells; and Pennsylvania, which is considering modifying regulation to require inspection of all active wells.[26]

For all regions, maps[27] were created showing all airports[28] accessible by private aircraft (class C and D airspace) and all regulated O&G wells[29] (Figure 1). Specifications were compiled for four airborne LiDAR methane sensors that approach the 1 kg/hr sensitivity target and for three aircraft onto which the sensors could potentially be mounted (helicopter, drone, and fixed-wing aircraft). From this description of accessible airports, regulated target wells, LiDAR sensors, and aircraft, a vehicle routing procedure was developed to optimize the routes traveled by a given sensor/aircraft combination to scan all target wells. Each target site was assigned a scan radius of 100 m (typical of modern well pads and potentially larger than older well pads) and a hierarchical clustering procedure was employed to identify target groups with given scan coverage areas, resulting in optimized flight plans that inspect all target wells. The plan yields a scanned area that includes the full area of all regulated well pads. The optimization furnishes the number of flights required, with their respective routes, to scan all targets in the region. The analysis employs a fast target site-coverage solution that conforms to efficient flight operations for the given vehicle in scan mode. The set of target groups with given site scan costs are then conveyed to the higher-level vehicle routing problem (VRP) considering the sequence and length of each flight path subject to all constraints.[30, 31] The novelty of this approach is to decompose a given domain, comprising thousands of wells, into target cluster groups that serve as designated way-points in the VRP, and where the vehicle/sensor properties dictate the expected number and length of flights.

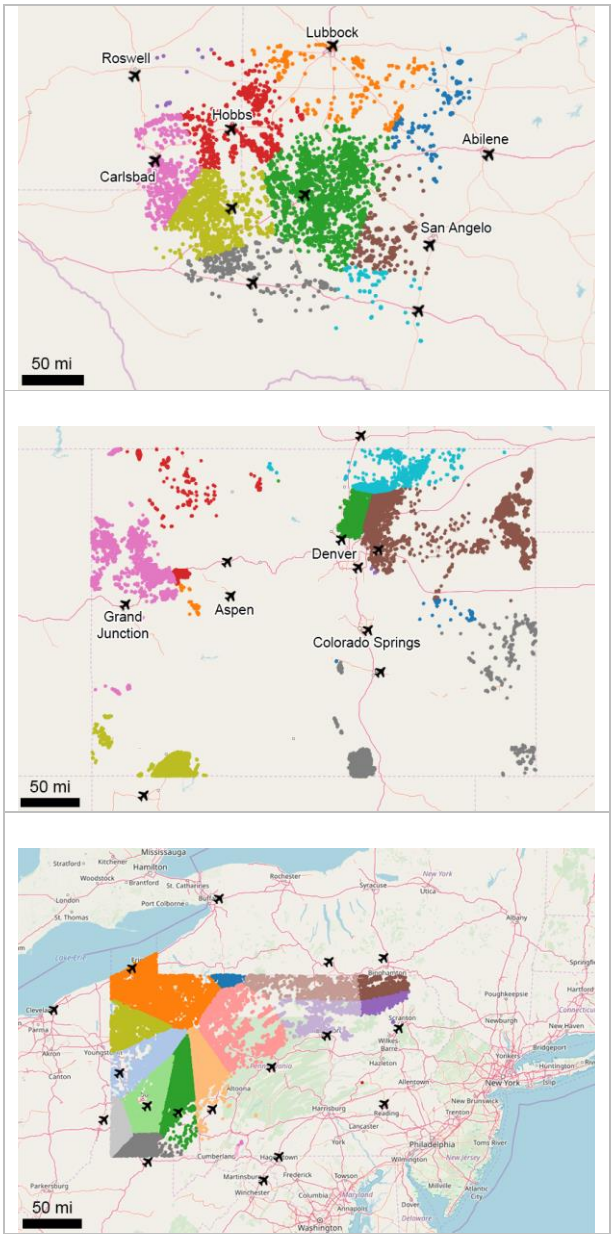

Figure 1. Well and airport locations for the Permian basin (top), state of Colorado (middle), and the state of Pennsylvania (bottom).[27] Colors represent wells optimally served by different airports.

III. RESULTS AND DISCUSSION

The optimization returns the flying distance to inspect all regulated facilities in the region, using the modeled sensor/aircraft combination, calculated using routes optimized for that specific combination. Optimizations were performed for all combinations of the four sensors and three aircraft. Specifications of the sensor and the aircraft are found to impact the results to a limited extent. Regarding sensors, the limit of detection of each sensor considered is similar, and the most important specification is the swath. Sensors with swaths wide enough to cover the full site in a single pass are more efficient than sensors needing multiple passes to scan a site completely. Regarding aircraft, the most important specification is the range. Drones have relatively short ranges and therefore require frequent returns to the bases to refuel, increasing costs. The helicopter and plane have similar ranges and, as a result, similar performances.

Figure 2 shows example optimized routes inspecting all regulated wells that are served most efficiently from a given airport flown by one sensor/aircraft combination. Note that as the VRP is NP-hard and global optimality is not guaranteed, some of the flight paths can cross-over undesirably.[31] However, this is due in part to the fixed parameterization used to batch run all cases, and more importantly, the fact that the travel time at faster cruising speed (edge cost) is strongly dominated by the scan time at slower scanning speed (vertex cost) in the overall objective.

In some cases, many well pads are located close together, such that performing a snake scan over a local area is more efficient than flying from the center of one pad to the center of the next, within that small area. Moreover, scanning the area provides additional methane concentration data which may help localize leak sources among nearby well pads. Using a preferred combination of sensor (large swath) and aircraft (long range), all regulated wells in the three regions are found to be within flying range of an airport. Therefore, the density of airports appears sufficient to allow optimized LiDAR inspection of the full area of all regulated wells in each region studied: the Permian comprising 10,471 wells; Colorado, 53,551; and Pennsylvania, 118,973 wells. Figure 2 indicates the complexity of optimal path planning.

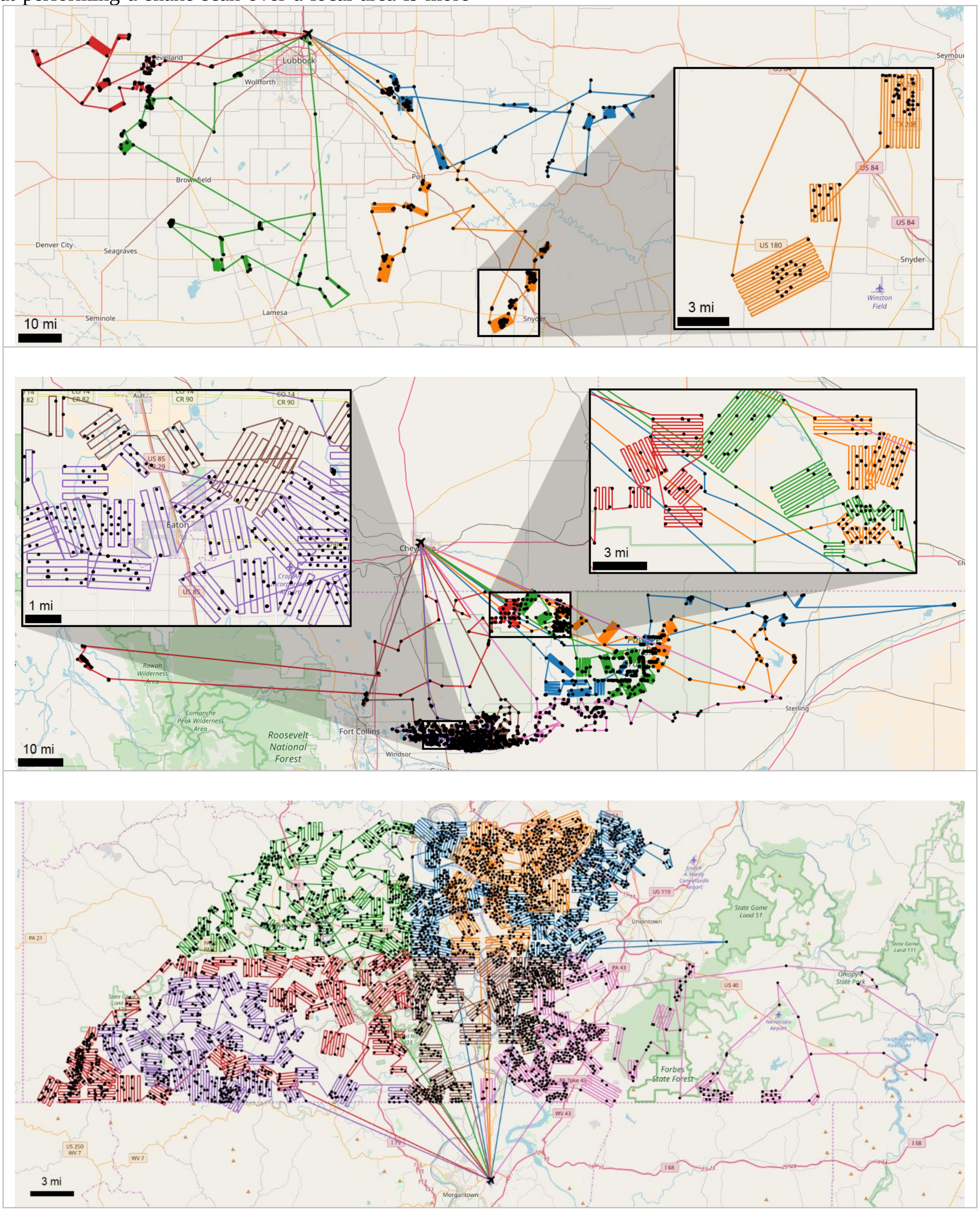

Figure 2. Representative sets of flight paths for airports in the Permian basin (top), Colorado (middle), and Pennsylvania (bottom).[27] Well locations are indicated by black dots. Colored lines represent different sorties.

Beyond investigating the feasibility of achieving comprehensive inspection, additional analyses were performed to evaluate the efficiency of airborne LiDAR inspection using optimized routes. Numerous O&G operating companies are active in the three regions studied, so coordinating inspections among these companies may improve efficiency through economies of scale. To explore potential efficiency gains from coordination, optimizations were performed using a preferred combination of sensor and aircraft for various subsets of well pads. These included individual subsets comprising well pads from each of the five largest operators individually (wherein a single sortie inspected only well pads operated by a single company), the subset of all remaining companies, and the set of all companies. In the latter two sets, a single optimized sortie could inspect different facilities operated by different companies. A miles/well metric was calculated for each optimized route by dividing the total flying distance by the number of wells inspected on that sortie. These calculations are represented as histograms in Figure 3.

Different results are obtained in the three regions studied. In the Permian basin and Pennsylvania, different operators drill wells interspersed with each other, so it is often the case that a flight between two wells operated by the same company will pass close to one or more wells operated by a different company. Inspecting those additional wells leads to gains from coordination because the additional inspections incur relatively little increase in flying distance. That gain is expressed as the miles/well required to inspect different operators independently typically being larger than that required to inspect all operators together. However, in Colorado the opposite result is observed. There, the wells of large operators are typically clustered together while the combined wells of smaller operators are more dispersed. Therefore, inspecting wells from the smaller operators requires an increase in flying miles compared to that obtained when inspecting wells from only the largest operators, so the miles/well required to inspect the largest operators independently is typically half that required to inspect all operators together. The arrangement of wells in Colorado can be observed in the histograms, where the distributions for the largest operators are relatively normal while the distribution for other operators is skewed towards higher miles/well. Additionally, the regulatory requirement to inspect both new and existing sources in Colorado and Pennsylvania leads to a higher density of regulated wells compared to the density found in the Permian basin where only new sources are regulated. That increase in well density results in a greater inspection efficiency in Colorado and Pennsylvania compared to the Permian basin.

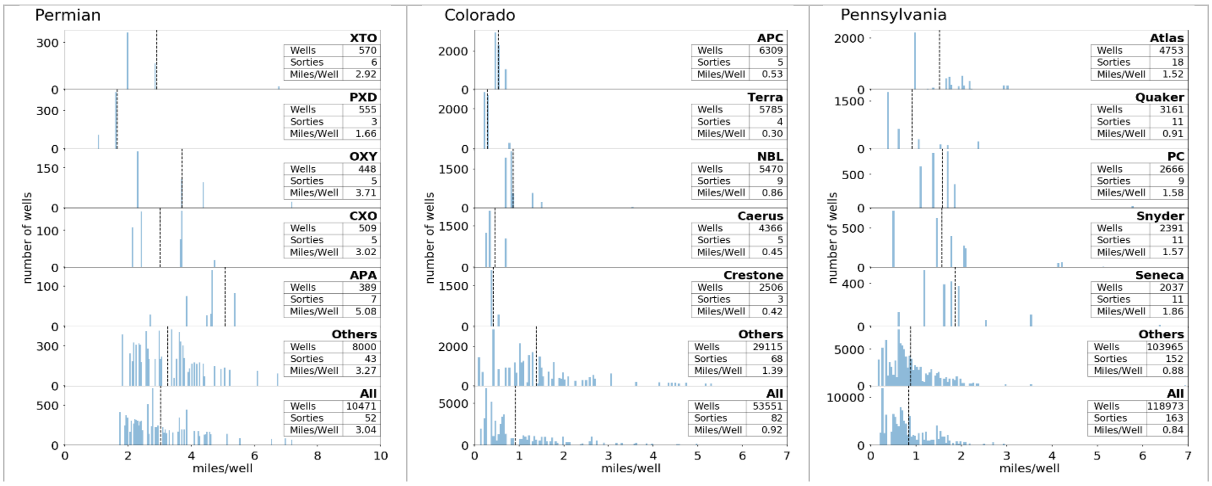

Figure 3. Histograms of the distribution of flying miles per well inspection in the Permian basin, Colorado, and Pennsylvania. The average miles/well is shown in the dashed line.

The insets in Figure 3 quantify these results in terms of the flying distance required for inspection, and these numbers address the feasibility of the proposed scheme. The proposed comprehensive monitoring program in which all facilities are screened by airborne LiDAR inspection flying optimized routes followed by component-level OGI inspection of only facilities flagged during screening is considered feasible if it can provide increased emissions reduction and/or reduced inspection cost compared to the traditional procedure in which all facilities are inspected by OGI. The amount of emissions reductions achieved by a LDAR program depends on both the sensitivity of the detector and the frequency with which inspections are performed.[15, 17] OGI inspection[15] is generally more sensitive than the 1 kg CH4/hour threshold while the sensitivity of airborne LiDAR[17-23] approaches that threshold under favorable conditions. Because FEAST models suggest that the reduction in methane emissions achieved by LDAR plateaus for sensitivity near or better than the 1 kg CH4/hour threshold, both airborne LiDAR and OGI are expected to achieve similar emissions reduction per inspection.[15, 32] In other words, the total volume of methane emissions arising from sources that can be detected by OGI but cannot be detected by airborne LiDAR is small, according to the FEAST model,[15] such that OGI and LiDAR achieve similar aggregate emissions reduction per inspection event. Therefore, the amount of emissions reduction that can be achieved with either OGI or LiDAR depends primarily on the inspection frequency.

Well pad inspections using OGI have costs near $600/inspection, which represents that the baseline cost against which the proposed program is compared.[33] Following the optimized routes described here, one well is inspected for approximately every mile flown. When flights are conducted only on days with favorable winds and other environmental conditions such that confident inspection can be performed with a single pass, rental costs for these aircraft and sensors (when deployed today for pipeline monitoring) are typically below $100/mile. Thus, it is estimated that facility scale methane inspection of O&G facilities using optimized airborne LiDAR can be performed at a cost of approximately $100 per inspection. However, $100 does not represent the full cost of this comprehensive LDAR program. As with every form of mobile inspection deployed as part of a comprehensive program,[17] two additional costs must be added. First, mobile inspection comprises only the first stage (facility inspection) of a comprehensive monitoring program. The second stage (component inspection and repair) presents an additional cost. This second inspection stage would be performed by traditional OGI inspection at a cost of approximately $600 per inspection—the cost of OGI inspection of a facility is assumed as independent of whether facilities are prescreened by airborne LiDAR (as described here) or whether all facilities were inspected without prescreening (as in the current approach). Due to the skewed distribution of emission sources, significant emissions reductions are achieved by repairing only a relatively small fraction of facilities, suggesting that airborne LiDAR screening would identify only a small number of facilities—namely, the super emitting facilities—for component level inspection and repair.[10, 13, 14] As a result, the additional cost of performing component level inspection of only the facilities identified as large emitters by airborne LiDAR inspection is expected to represent only a small incremental cost on top of the cost of airborne LiDAR inspection of all regulated facilities. Second, under currently regulation, some methane emissions are allowed equipment vents that do not require repair. Airborne LiDAR measures total methane emissions and may not distinguish allowed vents from fugitive emissions. An airborne LiDAR measurement that misclassified an allowed vent (that does not require repair) as a fugitive emission (that does require repair) would represent a false positive, and that false positive would increase costs either by directing OGI inspection to a facility where OGI inspection is not required or by necessitating a second airborne LiDAR inspection to confirm the classification. The frequency of these false positives, and therefore their associated costs, is not currently known and cannot be estimated by the route optimization described here. These additional costs may be significant, as some reports[34, 35] estimate that the total emissions from venting events, such as liquids unloading, may be comparable to or even exceed emissions from fugitives. However, multiple strategies are available to minimize these false positives. In some situations, the emission rate from continuous vents are below the limit of detection of airborne LiDAR so would not generate a positive response, or the wellsite activities that trigger intermittent vents are low enough in frequency and duration as to generate only a small number of false positives.[17] In other situations, allowed vents can be distinguished from fugitive emissions based on prior knowledge such as a facility's baseline emission rate from continuous allowed venting or when and where activities that result in intermittent allowed venting occur.

As with all comprehensive monitoring programs involving facility screening by mobile inspection, cost reductions (relative to the tradition approach in which all facilities are investigated at component scale by OGI) are achieved by reducing the number of facilities that are inspected by component level investigation, and emissions reductions are achieved by increasing inspection frequency and therefore reducing the duration of emissions. If many facilities screened by mobile inspection are identified as requiring component level inspection, there is no information provided from the mobile screening, and no comprehensive monitoring program will be able to reduce costs relative to performing component level inspection of all facilities without prescreening. Assuming the fraction of facilities screened by the mobile inspection and found to require component level inspection is small, then the benefits of low-cost mobile facility inspection may be realized.

IV. CONCLUSION

Reducing methane emissions from the O&G industry is considered among the most urgent and actionable measures to mitigate climate change, and the main technical challenge associated with reducing those emissions is efficiently locating emission sources on facilities that are often in remote, unmanned locations. Comprehensive monitoring programs represent one potential solution where costs are minimized by performing a facility level screening using a low-cost but low-precision detector and then performing component level inspection only on facilities identified as large emitters. Here we solve the VRP to optimize the routes flown by airborne LiDAR sensors to perform the facility level screening. This analysis assumes the availability of airborne sensors, such as airborne LiDAR sensors,[17-23] with sensitivity that under favorable conditions approaches the 1 kg CH4/hour threshold at which further improvements in sensitivity yield negligible further improvements in methane emissions reductions.[15] The methane emissions reduction per facility inspection using this approach is expected to be comparable to the reduction achieved by performing OGI inspection on every regulated facility, despite the greater sensitivity of OGI compared to airborne LiDAR, because FEAST modeling suggests that leaks observable by OGI but not by airborne LiDAR make only a minor contribution to aggregate emissions.[15] Using route optimization to minimize the cost of airborne LiDAR suggests that facility inspection can be performed by airborne LiDAR at a cost significantly lower than the cost of facility inspection by OGI. The total cost of a comprehensive monitoring program based on optimized airborne LiDAR is greater than just the cost of the facility inspection because component level OGI inspections and repair would have to be performed at facilities flagged during the airborne LiDAR inspection and because airborne LiDAR may falsely identify some allowed vents as fugitive emissions. While a precise determination of these costs requires additional field data, those additional costs are expected to be small relative to the cost of optimized airborne LiDAR inspection of all regulated facilities.

These results suggest that inspecting well pads using a comprehensive monitoring program based on active LiDAR inspection to screen all regulated facilities followed by OGI inspection of high emitting facilities can be achieved for up to a factor of six lower cost per inspection than occurs with traditional manual inspection of all regulated facilities. Such a cost reduction could allow inspection frequency to be increased while still reducing the total annual inspection cost, compared to what is typical today. That increased inspection frequency would result in further reduced methane emissions, primarily because super-emitting facilities would be identified and repaired more quickly. Therefore, this comprehensive monitoring program involving airborne LiDAR inspection following optimized routes appears to be a promising method of detecting O&G methane emissions with the potential to simultaneously reduce both methane emissions and inspection costs, compared to what can be achieved with conventional technology.

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