Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico

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Abstract
Offshore oil and natural gas platforms are responsible for about 30% of global oil and natural gas production. Despite the large share of global production there are few studies that have directly measured atmospheric methane emanating from these platforms. This study maps CH₄ emissions from shallow water offshore oil and gas platforms with an imaging spectrometer by employing a method to capture the sun glint reflection from the water directly surrounding the target areas. We show how remote sensing with imaging spectrometers and glint targeting can be used to efficiently observe offshore infrastructure, quantify methane emissions, and attribute those emissions to specific infrastructure types. In 2021, the Global Airborne Observatory platform, which is an aircraft equipped with a visible shortwave infrared imaging spectrometer, surveyed over 150 offshore platforms and surrounding infrastructure in US federal and state waters in the Gulf of Mexico representing ~8% of active shallow water infrastructure there. We find that CH₄ emissions from the measured platforms exhibit highly skewed super emitter behavior. We find that these emissions mostly come from tanks and vent booms or stacks. We also find that the persistence and the loss rate from shallow water offshore infrastructure tends to be much higher than for typical onshore production.

1. Introduction

CH₄ is a powerful greenhouse gas that significantly contributes to global climate change. Oil and gas emissions are estimated to make up at least 20% of the global anthropogenic methane budget (Saunois et al 2020). Offshore operations are responsible for about 30% of global oil and natural gas production (Gorchov Negron et al 2020, Yacovitch et al 2020). The majority of offshore O&G production is concentrated in a few key regions globally, including the Persian Gulf, the Tupi (Lula) oil field in Brazil, the North Sea, and the Gulf of Mexico (GOM). The remote location of offshore platforms has resulted in these sources being largely unmeasured by top-down CH₄ atmospheric methods. Therefore, there are currently few observational constraints on the methane emissions from offshore oil and gas operations compared to relatively well-studied onshore infrastructure. Remote sensing adapted for offshore conditions may provide an avenue to close this observational gap.

Current knowledge of CH₄ emissions from offshore O&G is limited to bottom-up inventories, self-reporting, and a handful of observational studies. Bottom-up inventories estimate emissions for offshore O&G production (and O&G more generally) by combining emission factors with activity data. While these bottom-up inventories are important
for national scale accounting, many field measurements of onshore oil and gas infrastructure indicate significant discrepancies when compared with inventories (Brandt et al. 2014, Zavala-Araiza et al. 2015, Alvarez et al. 2018). In some cases, emission factors from onshore oil and gas production are applied to offshore platforms or emissions factors from one type of offshore rig are applied uniformly to all offshore platforms. In either case, the lack of detail and specificity in the emission factors and inventories can contribute to inaccurate bottom-up inventories. Top-down methods using atmospheric observations can provide additional independent estimates that can help evaluate and improve inventories as well as provide mitigation guidance to operators and regulators. To date, there have only been a few studies that have directly measured a small number of platforms, so little is known about their emissions and whether they exhibit similar behavior as observed with onshore operations (Gorchov Negron et al. 2020, Zavala-Araiza et al. 2021). The few studies that have made atmospheric observations of offshore O&G platforms found that emissions from these platforms tend to be higher than previously reported. In the North Sea, Riddick et al. (2019) conducted boat surveys of offshore platforms and found the loss rate was higher than previously reported. In the GOM, Gorchov Negron et al. (2020) conducted an airborne study of offshore platforms and found the inventories underestimated emissions from many types of platforms. The same was found in a recent study of offshore platforms on the Norwegian continental shelf (Foulds et al. 2022). In China and Southeast Asia, boat surveys showed that offshore platforms are a significant source of CH₄ (Nara et al. 2015, Zang et al. 2020).

Underestimation of CH₄ emissions from offshore platforms could significantly impact the global anthropogenic CH₄ budget. Expanded atmospheric observations of large populations of offshore oil and gas infrastructure in multiple regions are needed to properly constrain emissions from these sources. Given the remote location of offshore platforms, observational studies can be logistically challenging. Boats may offer a cost-effective method to measure the platforms, however they cannot always get close enough to the platforms nor do they have sensors higher enough to accurately measure methane plumes from the elevated platforms and therefore may underestimate emissions (Riddick et al. 2019, Yacovitch et al. 2020). Aircraft with in-situ gas analyzers can estimate emissions through a mass-balance approach of flying circles around a small target area (Conley et al. 2017, France et al. 2021). While these approaches can accurately estimate the net methane emission rates from the target area and in some cases measure additional chemical species to further constrain emissions, they tend to lack the ability to directly attribute a plume to a specific piece of infrastructure or equipment within a site, and they are unable to map large areas efficiently.

Remote sensing of high emission CH₄ sources in the offshore environment is possible at high spatial resolution (∼3–30 m) with space- and aircraft-based imaging spectrometers (Frankenberg et al. 2016, Duren et al. 2019, Wunch et al. 2021). However, trace gas detection over water with spectroscopy is difficult given water is a very dark surface in the strong CH₄ absorption bands (2200–2400 nm) and typically does not provide enough reflected radiance to discern a CH₄ signal (Ayasse et al. 2018). However, a sufficiently large signal over water is possible when the spectrometer can be pointed at the sun glint reflection off the water surface. Glint is the specular reflection from the surface of water and occurs when the sun angle and view angle are equal and in the same principal plane. Previous studies have shown that imaging spectrometers can map CH₄ over natural oil seeps successfully when observing glint from the ocean surface (Roberts et al. 2010, Bradley et al. 2011, Thorpe et al. 2013, 2014, Tratt et al. 2014). The use of sun glint to characterize carbon dioxide fluxes over the ocean is used operationally by the GOSAT and OCO-2 satellite instruments (Shiomi et al. 2006, Zhou et al. 2016, Wunch et al. 2017). GOSAT is also capable of measuring methane but lacks the fine spatial resolution necessary to detect and pinpoint individual emission plume and attribute it to a specific facility.

In this study, we report on the first systematic application of imaging spectrometers and glint targeting to survey over 150 offshore oil and gas platforms in the GOM and to detect, quantify and attribute methane emissions to specific infrastructure. We revisited many of these platforms multiple times in Spring and Fall of 2021 which provided an initial characterization of source intermittency/ persistent and longer-term trends. We also assessed differences in methane emissions and loss rates by jurisdiction (i.e. federal versus state waters).

2. Methods

2.1. Sensor and flight strategy

Offshore platforms were mapped using the Global Airborne Observatory (GAO; Asner et al. 2012). GAO is a plane equipped with a 432 band visual and short-wave infrared imaging spectrometer with a 34° field of view and a bore-sighted high resolution context camera. The imaging spectrometer measures solar reflected radiance between 380 nm and 2510 nm with a 5 nm spectral sampling and ∼3 m pixels associated with the ∼3 km flight altitude.

To capture the maximum amount of glint, the view zenith angle of the sensor must equal to the solar zenith angle (SZA), and the sensor, sun, and target must be in the same principal plane. In order for the sensor to achieve these angles, special arc shaped flight paths were designed so that the aircraft could...
Figure 1. Panel (A) shows a cross section of the sun-target-plane arrangement for the glint collects. The VZA is the view zenith angle and the SZA is the solar zenith angle. Panel (B) shows a top-down view of the plane’s flight path, the projected collection area, and the actual collected image. The green line is where the plane enters the bank (note airplane not to scale), the red line is where the plane exits the bank, and the white outline is planned collection area. An example red–green–blue (RGB) image of the flight line collected by GAO is included under the planned collection area. The bright spot near the middle of the image is the glint spot. The small dot in the glint spot is the target platform. Although this method targets a single platform, the area surrounding the platform is also illuminated and any infrastructure within the glint spot is surveyed.

2.2. Types of offshore platforms and sampling strategies

GAO completed two surveys of offshore oil and gas platforms in the GOM, one in Spring and one in Fall. Given a limited number of flight days for this preliminary study and need for repeat measurements we were only able to target ~150 unique platforms and surrounding areas, however we estimate this to be about 7.8% of active shallow water infrastructure (section S3). Although this is 7.8% of shallow water infrastructure, we estimate in the Spring we sampled 33.74% of shallow water production and in the Fall 15.06% of shallow water production. The choice of target platforms was based on the following criteria. First, for the Spring campaign (27 April 2021 to 8 May 2021), we chose platforms that had been measured in a previous study as well as a few similar platforms that had not been previously measured (Gorchov Negron et al 2020). These platforms represented locations of higher probability for positive CH$_4$ detection and therefore could be used to test CH$_4$ glint mode retrievals. This also helped us to verify the emissions we observed by corroborating our observations with previous measurements. A comparison of the results from GAO and Gorchov Negron et al (2020) is included in section S3. For the Fall campaign (19 October 2021 to 19 November 2021) we expanded the sampling size and added previously unmeasured platforms based on production, reported emissions, infrastructure size, and water depth. Second, for both Spring and Fall we chose to focus on shallow water platforms (<200 ft of water) because shallow water platforms are predicted to vent more CH$_4$ compared to higher production, deep water platforms, which tend to flare (BSEE 2017, Gorchov Negron et al 2020). Within the shallow water we also chose to focus our efforts on larger hubs, offshore infrastructure that consist of more than just an individual well and are often a gathering point for many small ‘satellite’ wells. Despite the focus on central hubs, additional infrastructure, including satellite wells and pipelines, was also coincidently measured. Third, for Fall, we chose an even distribution of platforms in state and federal waters. In the GOM, platforms are divided into two different regulatory jurisdictions. The waters between 0 and 9 nautical miles off the coastline are considered state waters and are regulated by the state. In our study region most sources were in Louisiana state waters. Waters that are beyond the state boundary...
are considered federal waters. We selected platforms in both state and federal waters to sample different regulatory structures and to provide continuity with other studies that have divided platforms into state and federal categories (Gorchov Negron et al. 2020). Lastly, we chose to target a slightly smaller population of platforms and prioritize repeat measurement to get an understanding of persistence. In Spring 2021, GAO targeted 38 unique platforms and surrounding areas. In the Fall of 2021 GAO targeted 133 unique platforms and surrounding areas, 20 were the same targets from the Spring campaign and 113 were new targets. In total, 151 platforms and surrounding areas were surveyed. We successfully obtained three or more observations on 40 of the targets. A map of the locations of the target infrastructure sampled is shown in figure 2.

2.3. Methane retrieval method, flux method, wind
We retrieve column averaged methane concentrations from measured reflected radiance using a linearized and albedo corrected matched filter (Foote et al. 2020). The matched filter retrieves an estimate of CH$_4$ above a background concentration, also known as an enhancement. For this matched filter, we also used a CH$_4$ unit absorption spectrum that is optimized for the SZA of every scene (Foote et al. 2021). The resulting CH$_4$ enhancement image is measured in ppm-m, where ppm represents concentration and m represents the path length over which absorption occurs.

From the CH$_4$ enhancement image produced by the matched filter, we manually identified each plume then calculated an integrated mass enhancement (IME) and fetch. The IME is the sum of all the CH$_4$ enhancements in kg above the background concentration present in each plume. The fetch is the length of the plume or a distance in meters from the source location of origin of the plume to the outer edge of the plume. The IME and fetch were calculated using methods from Duren et al (2019). A flux estimate was calculated using the average IME divided by radius (fetch) and multiplied by the wind speed. For this study we used HRRRv3 10 m wind fields in forecast mode to estimate wind speeds for the location and time of each observed plume. The equation for the flux is as follows:

$$Q = \frac{\text{IME}}{r}U$$

where $Q$ is the flux, IME is the amount of CH$_4$ in kg, $r$ is the radius of the circle in meters used to estimate the IME, and $U$ is the wind speed m h$^{-1}$. The resulting flux in the units of kg h$^{-1}$. The uncertainties for the flux estimates result from uncertainties in the wind speeds, IME and plume length. Additional discussion on the winds and uncertainties can be found in section S1. More information on the flux calculation used in the study can be found in Duren et al (2019). We also use a persistence adjusted emission rate. The persistence adjusted emission rates are calculated on a source level. First the persistence is calculated by dividing the number of observed plumes by the number of overpasses for a source. If there were less than three overpasses the persistence was not calculated due to too few samples. The persistence is then multiplied by the average emissions rate for the source to get the persistence adjusted emissions rate.

The instrument, retrieval methods, and flux estimate methods are similar to the methods in other studies using the Airborne Visible/Infrared Imaging Spectrometer Next Generation (AVIRIS-NG) instrument. These methods have been validated in a controlled release experiment and used to characterize methane emissions from numerous onshore oil and gas basins (Frankenberg et al. 2016, Thorpe et al. 2016, Duren et al. 2019, Cusworth et al. 2021). While this is the first study to use these methods in an offshore environment, the difference between the
onshore and offshore environments are not significant enough to invalidate these methods. The main difference between the offshore and onshore methods are the angle of the sensor and the underlying surface. The underlying surface for the offshore study is sun glint and has been proven to be the ideal surface for CH₄ detection (Ayasse et al 2018). In addition, glint is not significantly different from onshore spectra in the shortwave infrared (SWIR) (figures S2.1 and S2.2). The angle of the sensor can affect the pixel size and shape as well as the view path length, but these methods are robust to variation in pixel size and path length. We also assume that the minimum detection limit for AVIRIS-NG, which is 10 kg hr⁻¹, applies to this study as well (Thorpe et al 2016, Duren et al 2019). However, no controlled release experiments have been performed specifically for the offshore environment.

3. Results

3.1. Methane plume detections

Of the 151 targeted platforms and surrounding areas surveyed between Spring and Fall, 62 pieces of infrastructure had an observable methane plume (over 10 kg h⁻¹). Some of these plumes were on the targeted infrastructure and some from infrastructure in the surrounding area. Examples of the retrieved plume images are shown in figure 3. The location of all the target platforms surveyed in the Spring and Fall and the average estimated emission rate for each source is shown in figure 4.

3.2. Persistence

Between Fall and Spring campaigns 40 platforms and surrounding areas were surveyed three or more times and 34 of the 40 platforms had a plume at least one time. Multiple revisits to these platforms allow for an estimate of persistence. Methane emissions are often intermittent or highly variable and a single observation can be misleading therefore multiple observations are needed to accurately characterize emissions. The persistence or frequency can be used to adjust observed emission rates to reflect a more probable average hourly emission rate. The persistence also provides insight into the emissions patterns for specific areas, sectors, or sources, which can help inform monitoring approaches. Persistence is the measure of how frequently a source emits or the number of observed plumes divided by the number of unique observations (unique observations are observations on different days). The persistence adjustment emission rate is the mean emission rate multiplied by the persistence for every source, the reported results are persistence adjusted emissions unless otherwise stated. For the persistence analysis we combine the Spring and Fall observations and filtered out any sources that did not have three or more unique observations. Three unique observations represents a minimum threshold needed to characterize persistence (Cusworth et al 2021).

The offshore sources measured in this study tend to be more persistent than their onshore counterparts. The average persistence or frequency of sources was 0.63 (table 1), meaning on average a source emitted 63% of the time. This is over twice as high as the average persistence of onshore oil and gas emission sources (0.25) reported in other studies (Duren et al 2019, Cusworth et al 2021). We also found that the persistence of emissions from the offshore platforms contributed to highly skewed super emitter behavior. One large observed emission event that occurs very infrequently may be less significant than a smaller emission event that is always present. By adjusting for persistence, we account for intermittency, or lack thereof, and get a better representation of the contribution from an individual source to the total emissions. For example, if we look at all sources with emission rates above 1000 kg hr⁻¹, 20% of the sampled sources (12 sources) had instantaneous plume emission rates above 1000 kg hr⁻¹, when we adjust for persistence 11% of sources (7 sources) had emission over 1000 kg hr⁻¹. In comparison, the onshore infrastructure had 14% of sources with instantaneous plume emissions over 1000 kg hr⁻¹ (188 sources) and when we adjust for persistent only 1.3% of onshore sources (18 sources) were over 1000 kg hr⁻¹. This illustrates how significant the high persistence values are in the shallow water GOM survey. In addition, the 7 sources over 1000 kg hr⁻¹ represent 50% of all the observed emissions. Figure 5 shows the persistence adjusted sources and non-adjusted plumes for offshore and onshore and illustrates the importance of persistence.

Lastly, the high persistence indicates that 2–3 samples a year may be sufficient to characterize and monitor emissions in this region, however a larger survey is needed to verify this. Our sampling, focused on shallow water and central hub facilities, does not capture all production across the GOM and is not representative of total basin emissions profile. These observations clearly highlight that these shallow water sources disproportionately contribute to the total emissions and provide an excellent target for mitigation efforts.

The persistence allows us to understand the frequency of emissions, however repeat measurements also allow us to track the duration of the sources. The duration of the sources is a measure of how long a source has been emitting. In this study 20 emitting sources were measured in both Spring and Fall. Out of these 20 sources, 8 sources had plumes in both seasons, 7 sources were only observed emitting in Spring, and 5 sources were only observed emitting in the Fall. From this we hypothesize that 8 sources had a duration of at least 6 months and the other 12 had shorter durations or are intermittent. An example of a source that we observed in both Spring and Fall is shown in section S4. This study has a small sample size and only has two periods of repeat observations so we
Figure 3. (A) A plume from a vent on 2 November 2021, with an emission rate of 3157 ± 650 kg hr$^{-1}$. (B) A plume from a tank on 25 October 2021, with an emission rate of 244 ± 67 kg hr$^{-1}$. (C) A plume from a satellite well on 2 November 2021, with an emissions rate of 96 ± 21 kg hr$^{-1}$. (D) A plume from a pipeline on 21 October 2021, the base imagery is from the co-incident DIMAC imagery. The small white dot at the plume origin is bubbling water, indicative of an emission source under the water, the emission rate is 1400 ± 424 kg h$^{-1}$.

Figure 4. Location of targeted platforms (sources) and average persistence adjusted emission rate for each source.
cannot generalize to any long-term trends. However, these trends in observations highlight the need for repeat observations over long time periods. A portion of emitting infrastructure will be missed if infrastructure is only observed once.

### 3.3. Attribution

GAO carries a visible context camera that is bore-sighted with the spectrometer and captures coincident high-resolution (\(\sim 70\) cm) images of the platforms over which our CH\(_4\) plume images can be overlaid. This, along with Google Earth images, allows for the plumes to be attributed to sub-platform infrastructure. Given that the attribution is limited to easily identifiable infrastructure from the platforms, our analysis was focused on several key equipment types: tanks, satellite wells, pipelines, and vents. We manually identified each source and to be conservative, only identified unambiguous infrastructure. In figure 6 we show an example of the four categories of infrastructure outside of ‘could not identify’. Vents, or what we believe to be unlit vent flare booms, were identified as large linear features pointing upward or outward from the platform and the plume was clearly emanating from said feature (figure 6(A)). Tanks were identified as a single or sets of round objects and were the easiest infrastructure to identify (figure 6(B)). Wells were identified as small platforms, often found in clusters, surrounding a larger hub (figure 6(C)). Pipelines were identified as areas where methane appeared to be coming out of the water and there was no other obvious infrastructure, for multiple pipelines we observed a small point of bubbling water co-located with the origin of the methane plume (figure 6(D)). The ‘could not identify’ category includes plumes from covered infrastructure, blurry infrastructure images, or general uncertainty from the reviewer. There are categories of infrastructure, like compressors, that are not included in this analysis because they were not easily identifiable. In total, we could not identify 59% of sub-facility infrastructure, but this represented only 19% of total emissions.

Tanks, satellite wells (henceforth referred to as wells), pipelines, and vents, where CH\(_4\) was detected were 41% of emitting infrastructure but represented about 81% of all observed emissions (table 1). This shows that a small number of easily observable emissions sources represents the majority of emissions. The exact number of tanks, wells, pipelines, and vents that we measured is hard to determine so the percent of observed infrastructure that was emitting is unknown. We also found that each infrastructure type had different persistence patterns (table 1), although it is important to note the sample size is too small to generalize to the entire GOM. Pipelines had a low persistence \((f = 0.33)\), tanks and well were \(\sim 50\%\) persistent \((f = 0.58)\), and vents were the most persistent \((f = 0.75)\). In this small survey we observed vents that were persistently emitting CH\(_4\) over many days and, in some cases, over months (section S4), again disproportionally contributing to the total emissions.

### 3.4. Jurisdiction and loss rates

This study measured shallow water platforms located in Louisiana state and US federais waters during the Spring and Fall of 2021. We compared emissions...
and loss rates between the state and federal waters for both seasons. We found that emissions in the measured areas were high relative to production. For this analysis we used persistence adjusted emissions and we needed to account for every plume observed, for the platforms that were sampled less than three times we multiplied the emissions rate by the mean persistence ($f = 0.63$). We also report loss rates as an aggregate of the observed areas, these loss rates do not apply to a single well or platform but rather the total observed area at a given time. We compared the total persistence adjusted emission rates for the observed state waters and the federal waters for both spring and fall to the total gas and oil produced per hour during May (Spring) and October (Fall) for all the infrastructure near the measured areas. Production was a large source of uncertainty, details on the methods to estimate production can be found in section S5. The Spring campaign was the smaller of the two campaigns, in the state waters during the Spring, four
sources were observed with a total emission rate of 3483 kg hr$^{-1}$ which translates to a 23.8 ± 9% natural gas loss rate and 3.9 ± 1.6% joules loss or total energy loss. For the federal waters in the Spring there were ten emissions sources that had a combined emission rate of 9941 kg hr$^{-1}$ which translates to a natural gas loss rate of 23.8 ± 8% and a joules loss rate of 6.7 ± 2.3%. In the Fall, the campaign was more extensive, and a larger amount of infrastructure was measured. In the state waters during the Fall, 38 sources were observed with a total emission rate of 21 660 kg hr$^{-1}$, this resulted in a natural gas loss rate of 66.2 ± 33.8% and a joules loss rate of 18.2 ± 9.4%.

In the federal waters 16 plumes were observed with a total emission rate of 9,893 kg hr$^{-1}$ this translates to a natural gas loss rate of 27.9 ± 12.2% and a joules loss rate of 10.4 ± 4.7%. The loss rates were consistent, except for the state waters in the Fall, here we see both the emissions and the loss rate more than double. The cause of the exceptionally high loss rate for this set of platforms at this time is unknown. In general, these loss rates are significantly higher than loss rates often observed at onshore oil and gas basins. For example, typical loss rates in the Permian Basin are 3.3%–3.7% (Zhang et al 2020, Lyon et al 2021). Recent studies of onshore wells have also shown that low production wells tend to have higher loss rates (Omara et al 2022). For our study the median production per well for the Fall was 18.89 boed in federal waters and 3.26 boed in state waters, for reference the median production per well for all GOM offshore production in the Fall was 50 boed. For the Spring the median production per well was 33.7 boed in federal waters and 4.6 boed in state waters, for reference the median production per well for all GOM offshore production in the Spring was 43 boed. For comparison, Omara et al (2022) defines low production as <15 boed. This high loss rates in the low production state waters are consistent with the trends in Omara et al (2022) but it does not explain the loss rates in the higher production federal waters. This study also does not strictly look at wells but rather all offshore infrastructure, which can include processing facilities on offshore hubs. Nevertheless, the high emissions and low production in this sub-region again highlights the mitigation potential in this sector.

4. Conclusion

In this study we successfully demonstrated the ability of an airborne imaging spectrometer to target ocean glint to detect and quantify CH$_4$ emissions. We measured 150+ shallow water platforms and surrounding infrastructure representing ~8% of shallow water infrastructure in US federal and state waters in the GOM. We found that CH$_4$ emissions from the measured platforms tend to be very persistent and exhibit highly skewed super emitter behavior. We used these data to directly attribute CH$_4$ plumes to specific infrastructure on the platforms and found that a few identifiable sources disproportionately contribute to the total observed emissions. We also found that the loss rates for the sampled shallow water platforms were higher than typical onshore basins. This study offers new insights and new methods to characterize CH$_4$ emissions from a previously understudied population of sources. It also underscores the high impact methane mitigation efforts could have in this sector.

Optimizing glint collects with airborne platforms remains challenging, complicating complete mapping of offshore basins. Satellites could be a pivotal next step towards constraining emissions. Planned missions such as the Carbon Mapper satellite mission (Duren et al 2021) will have the capability to do glint collects. Depending on spacecraft and instrument capabilities, other satellite and airborne imaging spectrometers may also be able to leverage these results to plan future glint collects. These satellites will be able use glint mode to conduct regular large area mapping of offshore O&G infrastructure, therefore providing improved understanding of the emissions from a critical and largely unmeasured methane sector.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://carbonmapperdata.org.

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