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Regional Methane Emissions in NSW CSG Basins

Final Report

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Copyright and disclaimer

Important disclaimer

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We acknowledge the assistance of Stephane Germaine of GHGSat in the planning and logistics involved in the acquisition of “Claire” for the Camden site and GHGSat’s ongoing support in processing the data and efforts in continuing acquisition to obtain an optimum dataset to showcase the capabilities of their sensor for the application of CSG emission monitoring.

Executive Summary

The purpose of this GISERA greenhouse gas project was to characterise methane emissions (both natural and anthropogenic) within the Pilliga region ahead of large scale gas development. This will provide important baseline information for the region. Identification and quantification of the main methane sources within the Pilliga/Narrabri region was conducted using ground based methods developed during earlier work undertaken in the Surat Basin in Queensland. A second component of the project was aimed at investigating a new satellite sensor specifically designed for measuring methane, which has the potential to be applied across Australia for ongoing monitoring of coal seam gas (CSG) sites. The project commenced in July 2016, and was concluded in August 2017. In this report we describe the work that was undertaken and present the results of the study. The implications of these findings and recommendations for further research are also discussed.

Methane, is a colourless, odourless, non-toxic gas, which originates from either decomposition of organic matter or from deeper beneath the Earth's surface by geochemical processes when temperature and pressure conditions are suitable. Mobile surveys using an instrumented motor vehicle were undertaken within the gas production regions of the Pilliga forest and elsewhere within the Narrabri region. These surveys, combined with earlier surveys acquired between 2014 and 2016, have shown ambient methane concentrations that are mostly similar to background concentrations observed in pristine areas with no sources of anthropogenic methane. However, there have been instances where transient elevated methane concentrations have been detected, which are largely attributed to nearby CSG production facilities. The source of this methane is likely to be from venting or the operation of gas-actuated pneumatic devices.

The mobile survey region contains a total of 3380 of boreholes including coal and mineral exploration holes and water bores. To date, surveys conducted in the near vicinity of a sample of boreholes have not indicated elevated methane concentrations, which suggests that these boreholes are not leaking methane. Surface flux measurement made at several borehole locations also yielded no indication of gas leakage with measured emission rates indistinguishable from natural surfaces. In addition, direct methane concentrations within some boreholes (mostly water bores) were made at locations where the casings were accessible from the surface. These measurements showed that methane levels within the bores were very low (near zero); in many cases below the detection limit of the methane analyser used. Overall, emissions from the boreholes examined to date in this study have been negligible suggesting that, unlike some areas in Queensland, boreholes do not represent a significant methane source. However, other researchers from the University of Adelaide have located some water bores that have been leaking methane. Consequently, further investigation of borehole emissions is warranted.

There are several large coal mines within the study region. The underground operation near Narrabri is estimated to have a methane emission rate of approximately 9,000 g min^{-1}, which is by far the largest source of methane so far identified within the region. This estimated figure from the mining company was further confirmed with actual measurements during the course of this study, where the emission rates were found to be 6,000-11,000 g min^{-1}. To provide context, this estimated figure of 9000 g min^{-1} is approximately the amount of methane

produced by approximately 150,000 cows[1] (twice the total herd in Narrabri or 2.7% of the total herd in NSW). This flux is also equivalent to 32 times the methane emissions from the medium-sized landfill near Narrabri, measured as part of this study (see below).

Three open-cut coal mines in the region had much lower emissions. The estimates obtained from the companies' annual reviews indicate that the emissions from these mines range from about 159 to 358 g min^{-1}. For comparison, we estimate that the emissions from the CSG wells within the gas fields (excluding all other gas infrastructure) is about 194 g min^{-1}. This estimate is based on an average emission rate of 2.7 g min^{-1} per well determined from a previous study conducted on CSG wells in the Pilliga region on behalf of the NSW EPA.

Methane emission rates from three other significant sources in the area have also been quantified using a ground based plume dispersion method. A landfill near Narrabri yielded 281 g min^{-1}, while a sewage treatment plant, also near Narrabri, was found during two surveys to have a methane emission rate of about 28 g min^{-1}. A smaller emission of about 2 g CH_4 min^{-1} was measured at the Wee Waa water treatment plant. The emissions from livestock for Narrabri was estimated to be 5083 g min^{-1} from 2010 herd population and the published emissions factors for the Narrabri region of 85 g day^{-1} per cattle and 10 g day^{-1} per sheep.

To date a large number of mobile methane surveys have been conducted throughout the study region over several years, both by CSIRO researchers and others from the University of Adelaide. In general these surveys have yielded ambient methane concentrations over a very large area that is consistent with baseline levels, except in the vicinity of the methane sources that have been identified. Hence it is considered reasonably likely that most of the large point source methane emitters in the region have already been identified. However, the distribution and magnitude of other more widely dispersed sources such as agriculture, boreholes and natural seeps are less well understood.

An initial trial of a new Canadian satellite-borne sensor ("Claire") operated by GHGSat was conducted during October and November 2016. This sensor was launched in June 2016 and is designed specifically to detect methane sources and quantify emission rates. For this trial, a target area within the Camden gas field south of Sydney was selected. The site, which is about 12 $\times$ 12 km in area, was selected as it contains a range of CSG production facilities as well as other methane sources including a vent from a large underground coal mine and a landfill site. The data for this trial acquired by the "Claire" sensor on-board the GHGSat satellite was collected on the 30th of October 2016. This was one of the first data acquired by "Claire" and consequently experienced some of the post launch issues related to the new sensors. Specifically, the data were partially overexposed and there were concerning levels of instrumental noise/artefacts associated with the data. Despite these issues, the data showed some interesting results.

A large region of high methane concentrations were detected in the Claire data and appears to coincide with an area where gas ventilation shafts, associated with underground coal mining, are located. This coincided with field data collected during the ground truthing survey close to this area, which also recorded some of the highest field values for methane. This indicates that "Claire" may be able to detect large emitters of methane levels from the underground coal vents. The estimated emission from the ventilation shaft calculated using the data from the mobile survey was 18,000 and 21,000 g min^{-1} which is within the detectable range in the specifications of GHGSat.

Overall, at this stage, there remains important uncertainties associated with the quantitative use of the methane concentration map derived from "Claire" as delivered from GHGSat. Specifically, the level of instrument noise/artefacts remains a concern and there appears to be influences of the local geology, landforms and/or compositional material that may require to be accounted for in the retrieval of the methane products. The methane concentration image

[1] Note that this figure is updated from the figure provided in the interim report using more specific figures for Narrabri.

can potentially be improved visually with noise removal techniques such as Fast Fourier Transform filtering. While the application of such techniques provide better definition and highlight other anomalous regions, i.e. improve the visual look of the methane concentration map, it will not improve the accuracy of the data.

1 Introduction

Greenhouse gas emissions from unconventional gas production have recently been the subject of considerable public and scientific interest. Over the last few years there have been numerous studies, especially in the United States of America (U.S.A.), that have estimated emissions from unconventional gas fields, some of which have reported methane emissions that are higher than accounted for in current national greenhouse inventories. For example, Caulton *et al.* (2014) estimated methane emissions from the Marcellus shale gas region in Pennsylvania, U.S.A. to be within the range of 2.8 to 17.3 % of production. The upper estimate of this study has been reported by Australian media suggesting that high levels of emissions are typical of Australian coal seam gas production (TAI, 2016). However, the wide range of emission estimates reported from these different publications actually serve to illustrate the complexity of the measuring methane emissions from the gas industry and the uncertainties associated with the reported estimates. Indeed, a more recent study that used identical methodology to measure emissions in the same region studied by Caulton *et al.* (2014) found much lower emission rates of between 0.18 and 0.41 % of production (Peischl *et al.*, 2015).

Despite the uncertainty that still surrounds fugitive emission estimates from unconventional gas production, there is now a consensus that total emissions are higher than previous inventory estimates (Schwietzke et al., 2016, Peischl et al., 2016). However, there is also mounting evidence to suggest that in the U.S.A. at least, emissions are not evenly distributed across the industry and that the bulk of emissions are associated with a relatively small proportion of large sources (Brandt *et al.*, 2014). Globally, it has been estimated that methane emissions from fossil fuel industries are between 20 and 60 % higher than inventory estimates, although emissions from natural gas production have apparently declined from about 8 % of production during the 1980s to about 2 % of production today, despite a large increase in the size of the industry over this period (Schwietzke *et al.*, 2016). The reduction in emissions is attributed to improvements in management practices and technology and replacement of older equipment.

While accurately determining methane emissions from gas production, processing and distribution infrastructure is critical to understanding and managing greenhouse gas emissions from the industry, there are other factors that must be considered when developing suitable monitoring approaches. Firstly, gas production regions are often co-located with other activities that produce methane and these must be properly accounted for when estimating emissions from gas production. For example, intensive agriculture and coal mining may produce significant quantities of methane during normal operations. Other anthropogenic sources include legacy boreholes or water bores that have in some cases been found to be sources of methane (Day *et al.,* 2015; Pinti *et al.,* 2016). A second consideration is the presence of natural sources of methane. These include wetlands and also gas seeps, which are frequently associated with oil and gas production areas. Reliable detection and quantification of landscape methane sources, both natural and anthropogenic, is required for proper greenhouse accounting.

To address this, research is currently underway in the Surat Basin in Queensland through GISERA to develop a suitable methodology to characterise regional fluxes of methane across the region (Day *et al.,* 2015). During that study, various techniques were investigated to detect and quantify methane emissions. These include remote sensing methods using satellite and airborne systems, ground surveys and various atmospheric methods. As a result of that work, a top-down method utilising a network of fixed monitoring stations for accurately monitoring emissions is now under development. This work will continue until at least the end of 2017 and will provide regional-scale monitoring of methane fluxes across one of the main CSG production areas of the Surat Basin.

Although the work in Queensland is essential for assessing and quantifying changes in emissions as production increases to supply the export liquid natural gas (LNG) market, the study only commenced at a comparatively late stage of gas field development and thus there are no 'greenfield' monitoring data available. In NSW, on the other hand, the gas industry is at an earlier stage of development and hence there is a unique opportunity to establish a programme to establish baseline conditions ahead of large scale gas development.

The Queensland GISERA methane project also demonstrated the value of remote sensing technology for methane detection (Day, et al. 2015). While the results were promising, it was clear that there were certain limitations with the systems available at the time. Satellite sensors, in particular, have the advantage of providing rapid regional coverage with ongoing monitoring that potentially can detect temporal changes in emission patterns. However, until recently, the spatial resolution provided by satellites capable of detecting methane emissions is usually very coarse (in the kilometres scale) and hence was useful mainly to determine broad scale variations. This tends to limit their applicability for detecting low level natural emissions or even emissions from CSG infrastructure. A Canadian company (GHGSat) has recently deployed a sensor on a new satellite ("Claire") that is claimed to be capable of monitoring surface methane emissions to 50 x 50 m. With this finer spatial resolution the sensor has a potential to be widely applied in the gas industry. The opportunity existed to acquire data over gas producing regions in Australia, which allowed the detailed evaluation of the sensor's capability and to determine if it was applicable to the Australian gas industry.

The aim of the part of this NSW GISERA project described in this report was to investigate potential land seeps of methane across the proposed CGS production areas in the Pillaga and surrounding areas. This included legacy boreholes and other natural and anthropogenic methane sources in the Pilliga region, which may see significant development over the next few years. Attempts were made to measure or estimate methane emissions from these sources (which include coal mining, landfills, wastewater treatment, agriculture) using some of the techniques developed during the Queensland GISERA project or by other appropriate methods. These data are necessary for developing a detailed emissions inventory which will provide a baseline against which to compare emissions should large scale gas extraction commences.

A second but important objective of the project is to evaluate the new GHGSat "Claire" sensor for the purpose of monitoring methane emissions from a range of sources including CSG infrastructure.

2 Experimental Method

2.1 Ground Measurements

Work towards developing a methane inventory for the Pilliga region of NSW was focussed on the use of mobile ground-based vehicle surveys that were trialled extensively during the Queensland GISERA Project (Day et al., 2015). The advantage of this method, which relies on driving an instrumented vehicle on roads to measure ambient methane concentrations, is that large areas can be covered to detect methane sources. This approach can be used to detect unknown methane sources upwind of the vehicle (e.g. leaking boreholes). The method is also suitable for detecting plumes from other sources that are more obvious such as landfills or CSG facilities.

While mobile surveys are well suited to detecting emission sources, on its own, conducting a mobile survey only provides ambient methane concentration data, not emission rate. To estimate emission rates from sources other methods were used as appropriate to the site. The methods used throughout the project are described in the following sections.

2.1.1 MOBILE SURVEYS

Mobile ground-based surveys were performed using a Picarro G2301 CO_2/CH_4/H_2O analyser or Los Gatos Research (LGR) Ultraportable C_2H_2/CH_4/H_2O Methane/Acetylene Gas Analyzer mounted in a four-wheel drive vehicle. The performances of these insturments are similar with resolutions of approximately 1 part per billion (ppb), which enables very small sources to be reliably detected. In some situations if access to methane plumes from these sources are available and meteorological conditions are favourable, it is possible to estimate the emission rate from the sources. However, ground surveys are restricted to navigable roads and tracks which limits access in many areas. Prevailing winds also affect the ability to detect sources.

Positional data were obtained simultaneously using GPS receivers (Hemisphere R100 DGPS, Gill Maximet GMX200). The positional data were combined with the gas concentration data to produce maps of methane concentration across the study region. This approach has been used previously in the region and elsewhere to locate the presence of methane emission sources (Day *et al.,* 2015). The survey vehicle is shown in **Figure 1**.

Sampling lines are located on the upper edge of the frontal collision bar while the GPS, anemometers and weather station were located above the vehicle, as shown in **Figure 1**.

Figure 1. Survey vehicle showing the location of sampling lines and anemometer/weather stations.

During surveying air is drawn from the front of the vehicle to the Picarro Analyser, which is located in the canopy located at the rear for the vehicle.

Meteorological data were acquired by a weather station attached to the LGR Ultraportable Analyser. The measurements collected included temperature, barometric pressure and dewpoint.

While the method of mobile surveys is versatile and rapid, it is acknowledged that because surveys are generally restricted to trafficable roads and tracks, it is not practical to completely assess very large areas. Moreover, emission sources must be upwind of the survey vehicle so prevailing wind conditions affect the ability to detect sources.

2.1.2 GROUND SURFACE EMISSIONS

Emissions from ground surfaces were measured at numerous locations such as natural surfaces and areas in the immediate vicinity of boreholes. Ground surface emission measurements were made using a plastic cylindrical chamber 375 mm in diameter and 400 mm high with a total volume, *V*, of about 45 L and an area of coverage, *A*, of 0.11 m^2. The chamber was placed on the ground and the CH_4 concentration within the chamber, *C*, was measured over a period, *t*, of several minutes. A small fan inside the chamber ensured that the sample was well mixed during the measurement period. Emission flux, *F*, was calculated according to Equation 1.

$$F = \frac{dC}{dt} \times \frac{V}{A} \qquad \text{Equation 1}$$

In most cases, the concentrations of methane and carbon dioxide in the chamber were measured using the vehicle mounted Picarro Analyser, which was connected to the chamber via a length of 6 mm diameter nylon tubing. For occasions when vehicle access was not practical, analyses are performed using a battery powered LGR Ultraportable $C_2H_2/CH_4/H_2O$ Methane/Acetylene Analyser, which could be carried to the measurement site.

2.1.3 BOREHOLE MEASUREMENTS

A total of 69 boreholes were examined during this project. Many of the sites visited showed no surface manifestations of the hole; the casing had been removed and covered over, often many years previously. In some instances, however, where the casing of the core hole or water bore was found to be intact, the casing was covered with plastic film and sealed with adhesive tape while sampling with the Picarro Analyser as shown on Figure 2(a). This method of measurement was used for the core holes sampled during July 2017. When the casing ended close to the ground, the flux chamber was placed over the casing opening as shown on Figure 2(b).

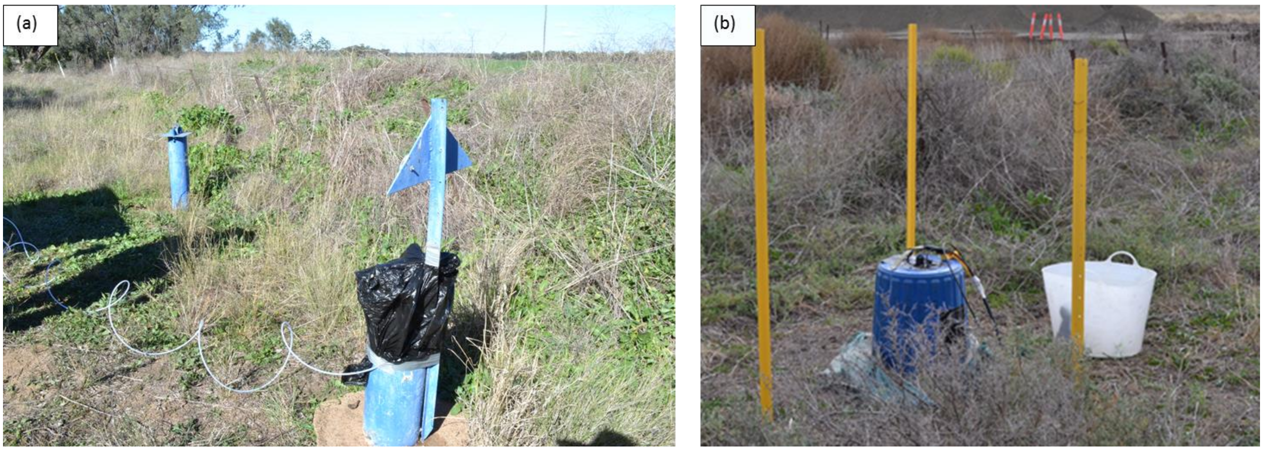


Figure 2. (a) Photo showing sampling for intake casing where the hole was covered with plastic film and sealed with adhesive tape. (b) Photo showing a borehole which ended at ground level where the casing was covered with a flux chamber.

2.1.4 PLUME TRAVERSES

Although mobile surveys usually only yield concentration data, in some circumstances the emission rate from a source may be estimated by traversing across the methane plume and applying plume modelling methods. Accordingly, for some methane sources, under conditions when the methane plume was sufficiently well developed, a Gaussian dispersion analyses was used to predict the release rate from the source. These analyses used the Gaussian "Point" Source Plume model but with zero stack height and zero thermal rise of the plume, that is, the plume release is at ground level and at ambient temperature. The assumption of the plume reflection arising from the ground release was included in these calculations.

The Gaussian "Point" source model for stack release can described simply by Equation 2;

$$C_{(x,y,z)} = \frac{Q}{U}\frac{1}{2\pi\sigma_y\sigma_z} e^{\left(\frac{-y^2}{2{\sigma_y}^2}\right)} e^{\left(\frac{-z^2}{2{\sigma_z}^2}\right)} \qquad \text{Equation 2}$$

where $C_{(x,y,z)}$ is the local concentration at coordinates x, y, z (kg m^{-3}), Q is the release rate (kg s^{-1}), U is the wind speed (m s^{-1}) blowing continuously in the direction x (measured in metres from the source), σ_y and σ_z are the wind standard deviations of the Gaussian distributions that indicate the spread of the plume in the y and z direction respectively at distance x and y and z are the lateral distances relative to the vertical and horizontal planes orthogonal to the x direction (Hanna *et.al.,* 1982).

It is important to note that for this method we were only able to measure the methane concentration at ground level; the vertical extent of the plume was estimated using the Gaussian model. Consequently, there is a significant level of uncertainty associated with emission estimates derived from this approach. Previous work using known release rates of methane under controlled conditions has indicated that uncertainties of about 30 % may be achieved under ideal conditions although significantly higher uncertainty may occur in some circumstances (Day et al., 2014). Despite the high uncertainty, the method in many cases provides the only practical opportunity to estimate emission rate.

2.2 Satellite Acquisitions

Satellite imagery from GHGsat were acquired across the Camden area in NSW, to determine its feasibility for the detection and measurements of the sources of methane. This satellite was trialled as it was the first to be launched with sufficient spatial resolution to potentially measure the source of methane surrounding CSG fields.

2.2.1 CLAIRE INSTRUMENT/SENSOR

The “Claire” is the first of a series of satellite-borne remote sensing instruments launched into space by GHGSat Inc. It was successfully launched on 21 June 2016. “Claire” was designed specifically to measure greenhouse gas (GHG). More specifically, it was tuned to capture spectral features in the electromagnetic spectrum specific to carbon dioxide and methane using passive optical remote sensing.

The “Claire” consist of two sensors, namely (1) a Wide-Angle Fabry-Perot (“WAF-P”) imaging spectrometer, and (2) a Clouds & Aerosols (“C&A”) sensor. The WAF-P measures vertical column densities of CO_2 and CH_4 with a spatial resolution of 50 m. Specifically for CH_4 the sensor focuses on the 1690 nm spectral absorption feature at 0.12 nm spectral resolution. The C&A measuring in the 400-1000 nm spectral range across 325 spectral bands at 1.9 nm spectral resolution and 150 m spatial resolution. The C&A data are mainly used for determining clouds and aerosols in the field of view of the WAF-P, as clouds and aerosols can affect the measurement of CH_4 and hence must be corrected to appropriately account for them.

The total area captured by a “Claire” acquisition is approximately 12 km x 12 km. The acquisition area for this project was designed to target industrial facilities and reference measurement sites where the target audience includes the oil and gas, power generation, mining, cement, and agricultural industries. The instrument was designed to have a detection limit of greater than 50 kt CO_2 equivalent per year or approximately 2.4 kt CH_4 equivalent per year at a precision of 1% of atmospheric background level for CO_2 and CH_4 mixing ratios in the atmospheric column. With this design target, the instrument has the potential to detect emissions from a mid-level emitting coal mine (10kt is considered low while 2Mt is considered to be a high emitting coal mine).

2.2.2 TEST SITE

The test site selected for this experiment was centred around an underground coal mine (Appin Colliery) in the Camden area of NSW, centred at approximately 34° 7'48.47"S, 150°43'35.76"E as shown on Figure 3 by the pink polygon. This mine was selected because it was a large source of methane (estimated to be 5.35 million tonnes (Mt) of carbon dioxide-equivalent (CO2-e) per year (Illawara Coal, 2009)) and surrounding the mine there were other potential sources of methane including a landfill, dairy industry and gas processing plant. The different sources of methane would provide a range of different sources at different levels for us to determine the capabilities and limitations of the “Claire” sensor.

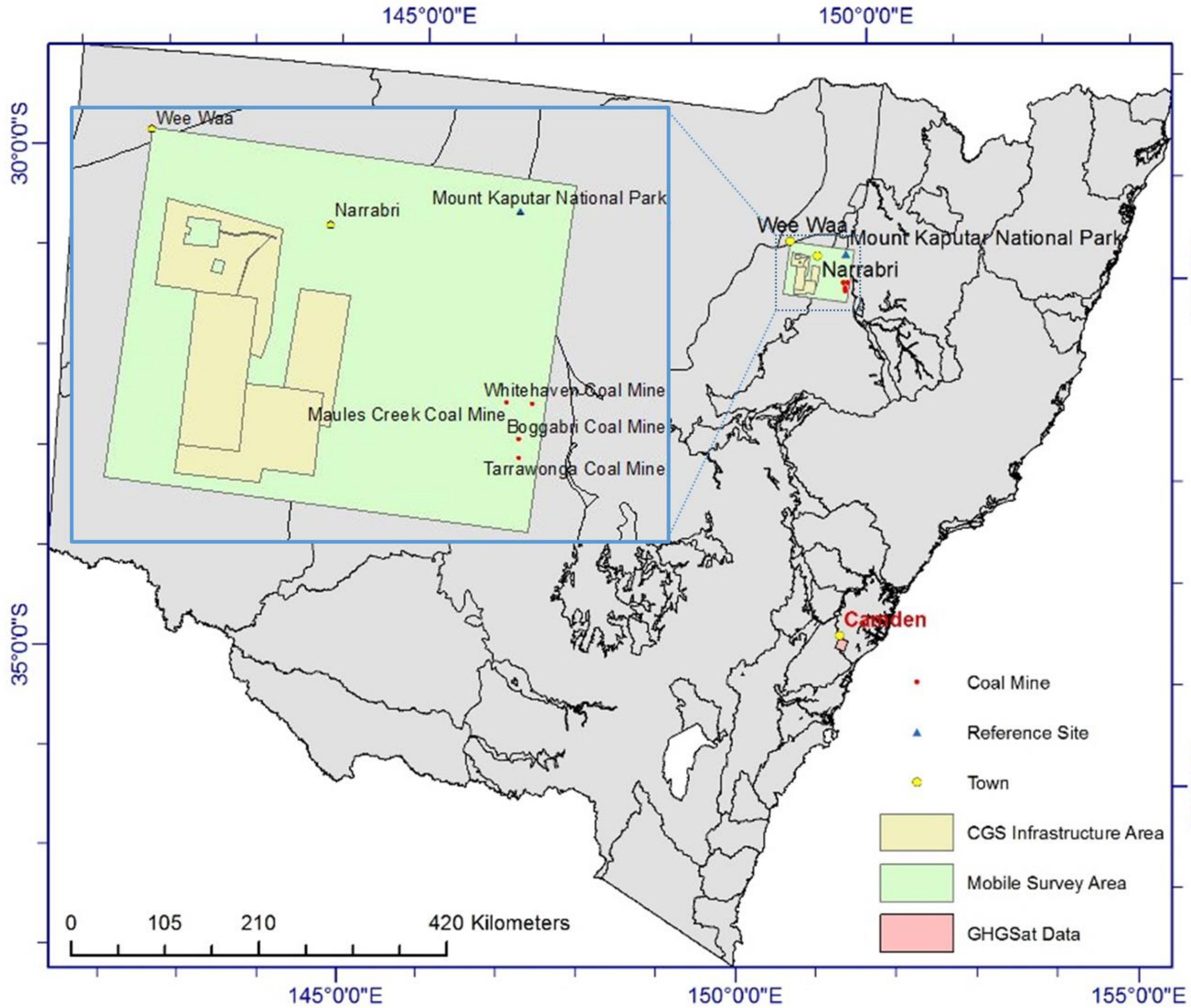


Figure 3. Map of NSW showing the "Claire" satellite acquisition area in the pink polygon. The surrounding towns are marked by the yellow circles. Also shown in the insert is the mobile survey area (light green) and the CSG infrastructure area (beige). The insert show the surrounding coal mines in the mobile survey area and Mt Kaputar which was used as a reference site with little anthropogenic impact.

3 Results and Discussion

3.1 Methane Inventory

Mobile surveys were conducted in the Pilliga and Narrabri regions to locate and identify sources of methane. The first series of surveys were conducted in September 2016 followed by a second series in July 2017. The general area of the mobile survey is shown the insert in

Figure 3 (light green polygon). Also shown on Figure 3 are the locations of several large coal mines within the region, and, the CSG infrastructure area (beige polygons). The study region also contains a number of waste water treatment facilities, landfill sites as well as a large number of water bores and abandoned exploration core holes which were included in the surveys.

Figure 4 shows and an enlargement of the study where the locations of CSG wells within the region (note that these include both production and abandoned well sites) are shown by the red circles and the other bore holes and water bores are marked by green and blue circles.

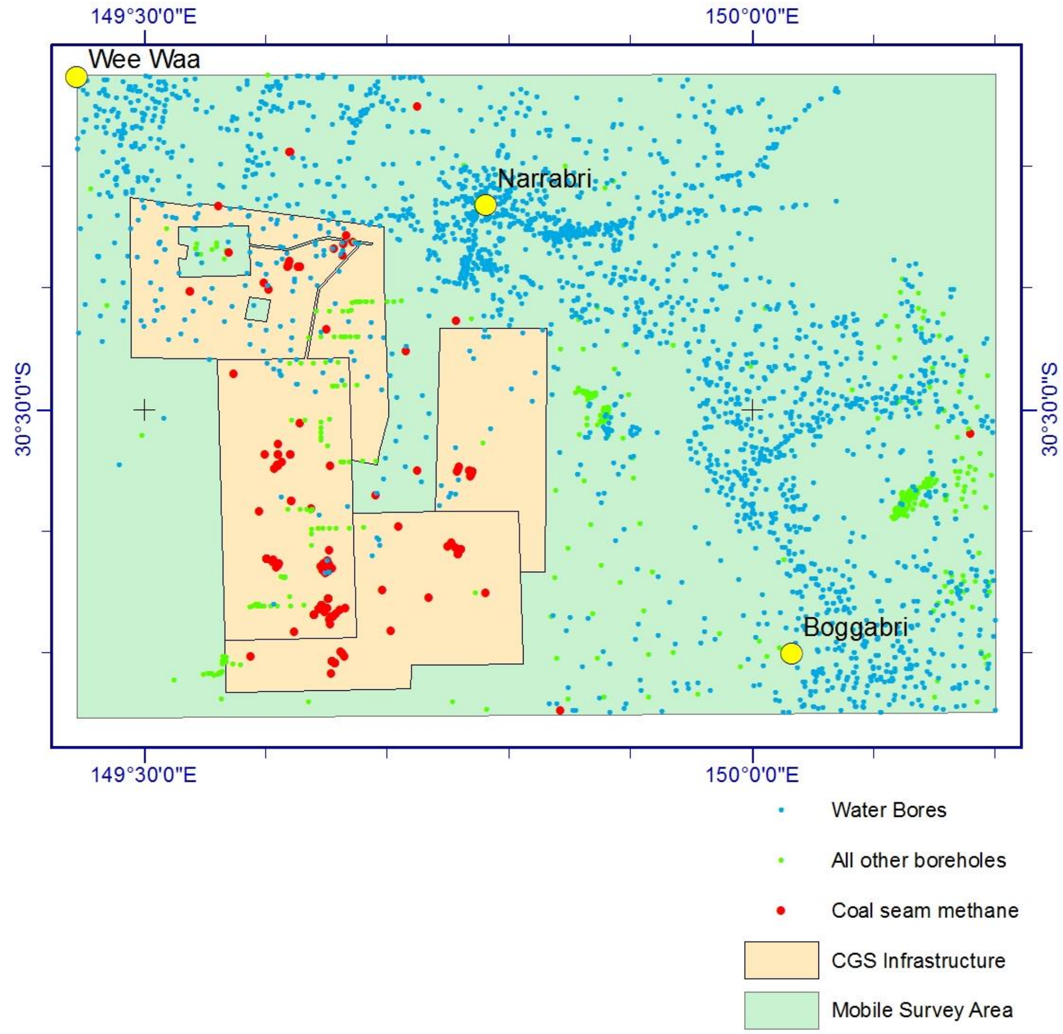


Figure 4. Mobile survey area. The CGS infrastructure area is shown in beige while light green indicates the mobile survey area. Bore holes are marked by the circles. The red circles indicate CSG wells while the other drill holes related to minerals, coal and other petroleum bores, and, water bores in the areas are marked in green and blue respectively.

Surveys were made through the Pilliga and Bibblewindi forests to measure ambient methane concentrations during September 2016. The surveys found generally low levels of ambient methane that were consistent with background levels in the region. Slightly elevated concentrations (up to approximately 2.0 ppm) were found in and around Narrabri during the early morning but higher ambient concentrations are common in urban areas especially during cool still conditions (Blake et *al.,* 1984; Lowry *et al.,* 2011; Phillips *et al.,* 2013: Day *et al.*, 2016). Within the forest areas near the CSG wells, the ambient methane concentration was virtually constant with no peaks that usually indicate the presence of nearby methane sources observed.

For comparison, a similar survey was made within the Mount Kaputar National Park (see location on Figure 3) which is approximately 50 km east of Narrabri. This area has no significant anthropogenic methane sources such as agriculture in close proximity. Moreover, the geology of the park is volcanic in origin and has not been subject to coal and gas exploration, as has the Pilliga, and as a consequence there are no potentially leaking boreholes. Ambient methane concentrations were at normal background levels and no evidence of any local sources were found within the national park. The average methane concentration measured over several hours was approximately 1.83 ppm (dry basis) which was identical (within the instrumentation error) to the 1.84 ppm measured within the Pilliga forest survey.

Generally, low methane levels were also found during a previous study of the region where surveys were made periodically throughout the gas production areas of the Pilliga between July 2014 and February 2016 (Day *et al.*, 2016). That study, which was partially funded by the NSW Environmental Protection Agency (NSWEPA), found similar ambient levels during each survey, although there were some instances were very localised perturbations of elevated methane concentrations of more than 10 ppm were observed. These methane peaks were attributed to emissions from CSG wells that were within approximately 50 m of the survey route.

Apart from CSG wells, other potential methane sources within the survey area include:

- CSG production facilities and infrastructure;
- Gas-fired power station;
- Coal mining activities;
- Abandoned boreholes (coal and mineral exploration boreholes; CSG plugged and abandoned wells);
- Water bores;
- Agricultural activities;
- Landfills; and,
- Sewage treatment facilities.

During this study, we attempted to locate these sources and estimate their methane emission rates, where possible, for the purposes of developing an emissions inventory for the region. In the case of CSG production most of the current operations are within the Pilliga and Bibblewindi State Forests with some wells (Tintsfield) and water treatment facilities (Leewood) located to the north outside the forest reserves Figure 4 and Figure 5.

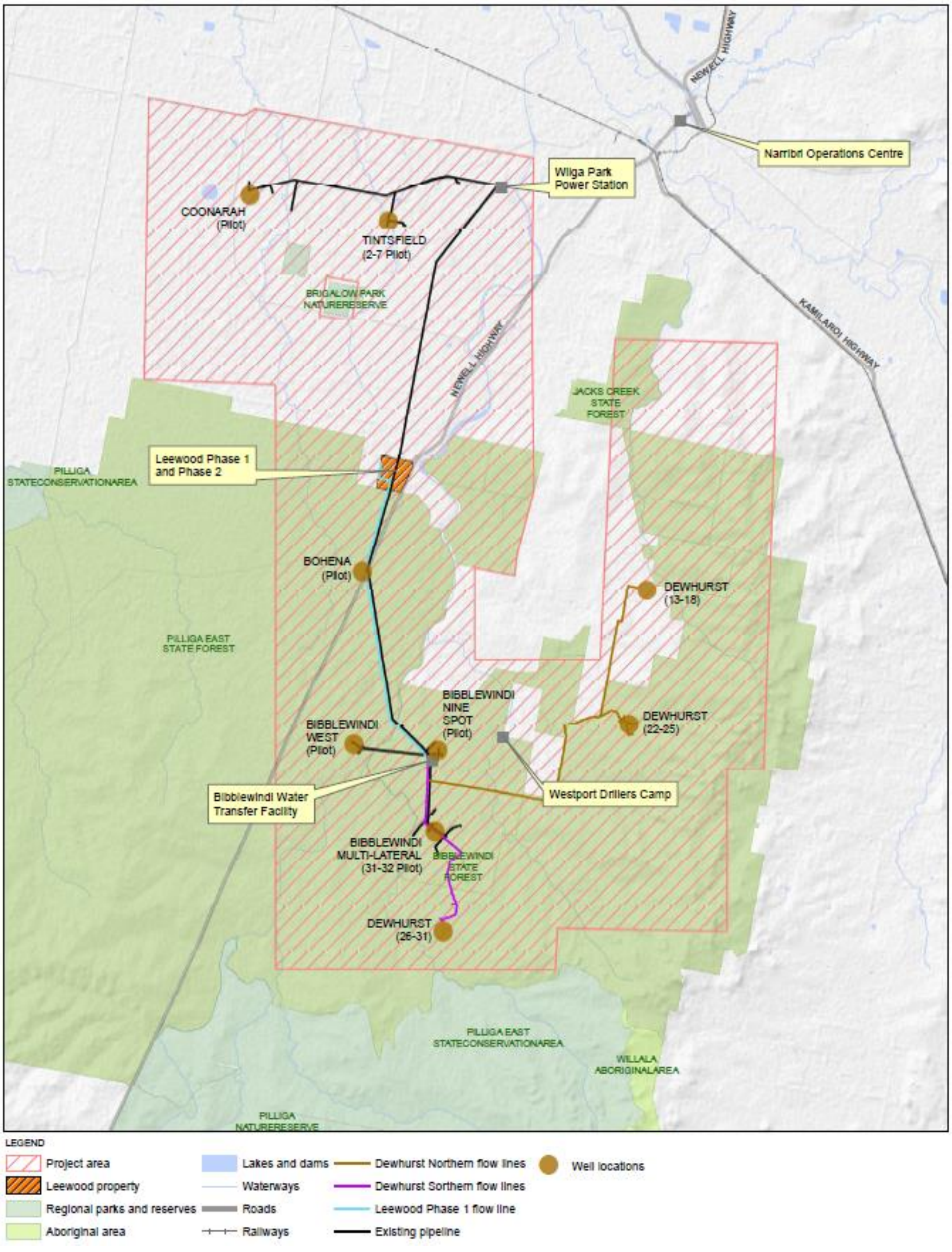


Figure 5. Location of current CSG infrastructure (from Narrabri Gas Project Preliminary Environmental Assessment; GHD, 2014)

Within this GISERA project we have generally not measured emission rates from CSG infrastructure (although as discussed in the section on boreholes, emissions from a selection of non-producing well pads were assessed). However, the previous NSWEPA project included flux measurements at six well pads within the Pilliga gas field and at the Leewood water facility. The results of that work showed that the methane emissions rates from the wells examined ranged from zero to approximately 23 g min^{-1} methane, which is consistent with previous emission rates measured at CSG wells at other Australian locations (Day *et al.*, 2014). The mean of 21 measurements made at these six wells between May 2015 and February 2016 was 2.7 g min^{-1}.

The most recent database provided by the NSW Trade & Investment, Resources & Energy[2] show that there are currently approximately 72 wells in the mobile survey area that are producing gas. If it is assumed that each well is emitting methane at the average determined from the periodic on-site measurements, the total well related emissions from the field would be approximately 194 g min^{-1}. It should be noted that this is at best a rough approximation with very high uncertainty. Moreover, emissions from other infrastructure such as gas processing plants and water treatment facilities are not included. For example, the total methane emissions from the Leewood water treatment site estimated between September 2015 and February 2016 ranged from 12.6 g min^{-1} to 22.3 g min^{-1} (Day *et al.*, 2016). However, this estimate is likely to be lower than the actual emissions from the facility since the measurements were made on water that had been in the holding ponds for an extended period during which time most of the seam gas originally present would have been lost to the atmosphere. Therefore, further work is therefore necessary to more reliably define the level of emissions from the gas facilities.

To place these emissions estimates into context, emission rates for other potential sources in the region have been determined. One of the largest sources of methane is coal mining and there are several large coal mines to the east of the Pilliga gas field (see Figure 3). The four main mines are the:

- Narrabri underground mine;
- Maules Creek open-cut mine;
- Boggabri open-cut mine, and;
- Tarrawonga open-cut mine (which is adjacent to the Boggabri mine).

To assess the methane emissions from these sites ground traverses were made downwind of each mine.

The Narrabri mine is a large underground operation that produced 6.9 Mt of run of mine (ROM) coal during 2016, although it currently has approval to produce up to 12 Mt per annum (Whitehaven Coal, 2017). During previous surveys in the Narrabri region, we have detected elevated methane levels along the Kamilaroi Highway to the east of the mine. However, the wind conditions had not been suitable to estimate the emission rate from the mine. A detailed survey of the mine was made in September 2016, although in this case we did not observe elevated methane levels along the highway due to the wind direction at the time. Accordingly ground traverses were made on publicly accessible roads elsewhere around the mine site.

Methane levels up to approximately 3.8 ppm were measured at about 2 km from the ventilation fan outlets (Figure 6) but most of the plume was formed over private land that was not accessible for crosswind traverses. Consequently we were unable to determine the mine's methane emissions from these traverses. Another attempt was made to obtain emission rate measurements from the Narrabri mine in July 2017. On this occasion 6 traverses were acquired around the mine when local wind conditions were favourable for estimating the emission rate for the mine. The emission rates estimated for these traverses ranged from 6,000 to 11,000 g CH_4 min^{-1}.

[2] http://dwh.minerals.nsw.gov.au/CI/warehouse

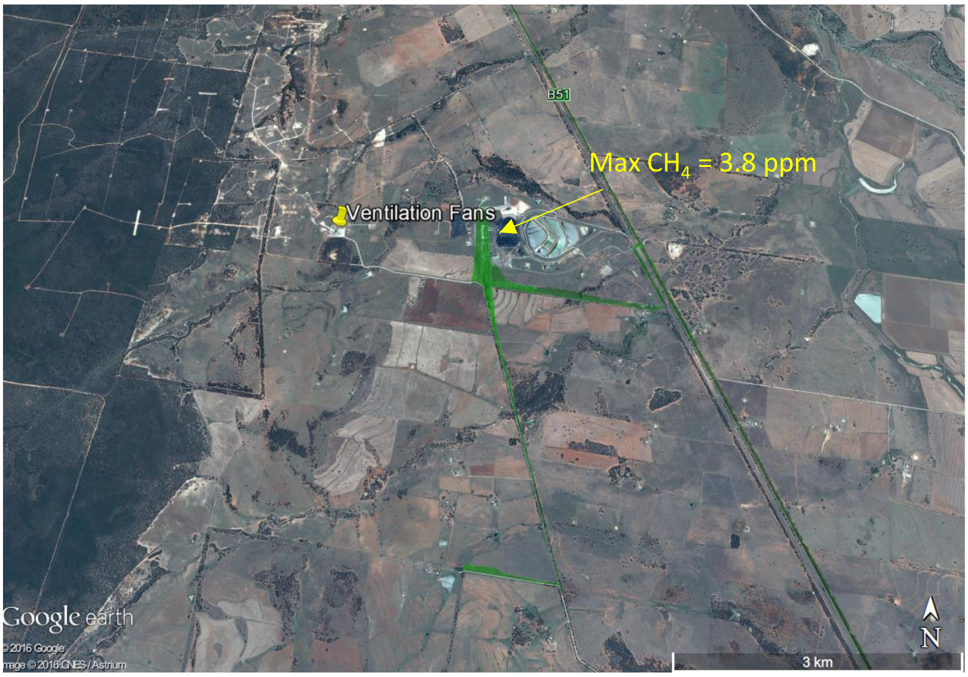


Figure 6. Methane concentration measured near the Narrabri underground coal mine.

For comparison, we compared the emission rate derived from the plume traverses with the estimate published for this mine by the mine owners. The mining company estimates their greenhouse gas emissions, which are publicly reported in the Annual Environmental Management Report and Review as required under the NSW Environmental and Planning Assessment Act. During the 2013-2014 reporting year, fugitive emissions of methane from the Narrabri mine were estimated to be 4.1×10^6 m^3 in the ventilation exhaust air with a further 3.1×10^6 m^3 from the gas drainage system giving a total yearly volumetric emission rate of 7.2×10^6 m^3 of methane (Whitehaven Coal, 2014). This is equivalent to approximately 9,000 g min^{-1}, which agrees reasonably well with the ground level plume traverses.

Like the underground mine, the three open-cut mines in the survey region also report fugitive emissions in their annual reviews which are also in the public domain. The Boggabri mine, which produced about 7.7 Mt ROM coal during 2015 (Boggabri Coal, 2016), reported fugitive emissions from the mine as 4,696 t CO_2-equivalent for 2014 (Boggabri Coal, 2016). This is equivalent to 188 t CH_4 (with a GWP factor of 25[3]) or 358 g min^{-1}. The Maules Creek mine, despite being adjacent to the low emissions Boggabri mine, reported much higher fugitive emissions during 2015 at 117,618 t CO_2-e, which is equivalent to 4,705 t CH_4 (Whitehaven Coal, 2016). However, it is noted that this estimate was made using a generic state-based emission factor for NSW open-cut coal mines. This factor is known to have high uncertainty and open-cut mines now mostly estimate fugitive emissions based on measured *in situ* gas content. This latter approach was used during the initial environmental assessment for the Maules Creek mine which resulted in an emissions estimate of 3,688 t CO_2-e (148 t methane; 276 g min^{-1}) for the 2015 reporting year (Whitehaven Coal 2011), which is probably a closer estimate of the mine's emissions than that determined by the generic emission factor approach. It should be noted that the Maules Creek mine is quite new with mining only commencing during 2015 with just over 2 Mt of coal produced during that year. It is anticipated that production will increase significantly in subsequent years which may also increase methane emissions from the mine.

[3] Note that recent IPCC report revised this figure to 28

Fugitive emissions from the Tarrawonga mine (approximate ROM coal production during 2014-2015 was 2.4 Mt) were also estimated using *in situ* gas content data and yielded 2,084 t CO_2-e during the reporting year of 2014-2015 (Whitehaven Coal, 2015). This is equivalent to a methane emission rate of 159 g min^{-1}.

During September 2016, traverses were made downwind of both the Boggabri and Maules Creek mines along the Manilla Road, about 4 km to the south of the mines. On this occasion a moderate wind of around 5 m s^{-1} was blowing directly from the north which gave ideal conditions to intercept any methane from these mines. However, during several passes along the road, the recorded methane concentrations were at background levels. This confirms that both mines are likely to be low gas operations as their own emissions reporting data would suggest.

Other methane sources investigated include a landfill site near Narrabri and, the Narrabri and the Wee Waa wastewater treatment facilities. All of these sites were subject to ground level downwind traverses under wind conditions that allowed quantification of the methane emission rate.

Figure 7 shows a plot of the ambient methane concentration as a function of the distance across the plume at about 1000 m downwind of the active tipping area of the landfill. The plume is clearly visible with the concentration varying from background of approximately 1.79 ppm (dry basis) to a maximum of about 1.95 ppm. The plume in this example was 500-600 m wide at the transect.

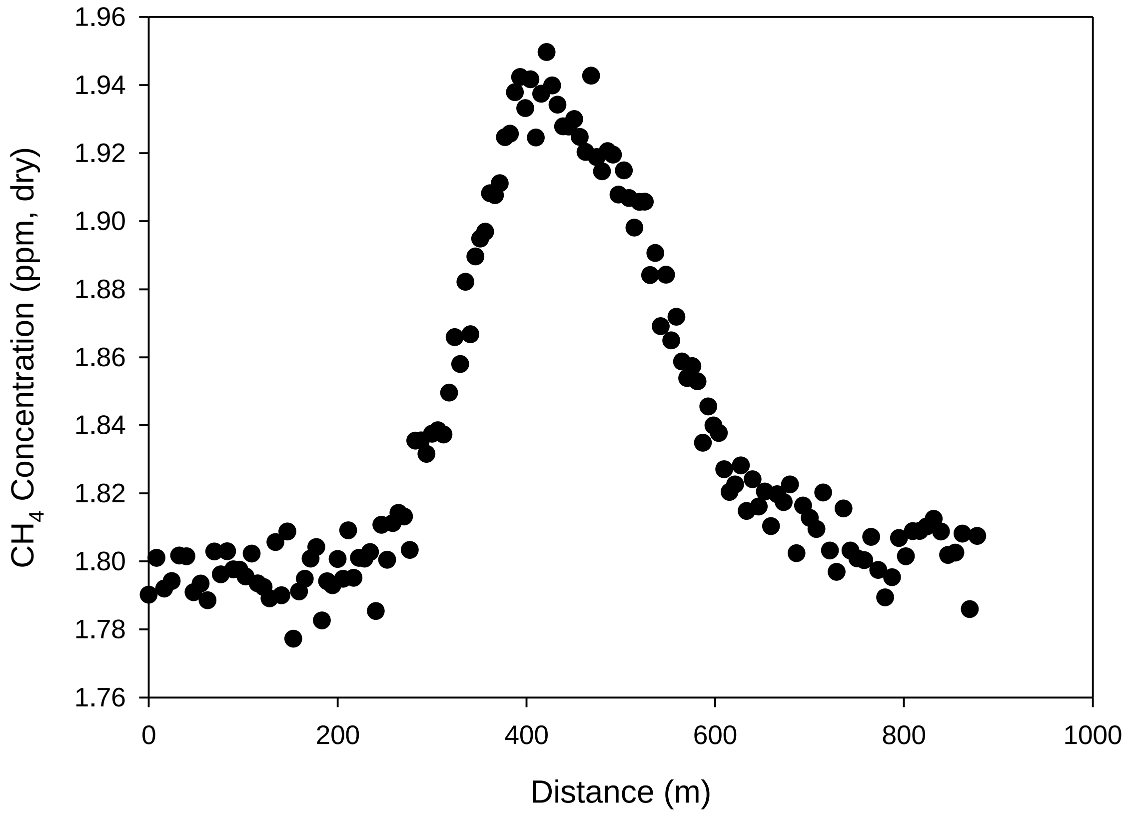


Figure 7. Methane concentration as a function of distance across the methane plume from a landfill site near Narrabri.

Six traverses were made at this location yielding an average methane emission rate of 281 g min^{-1} (standard deviation of 30.1 g min^{-1}).

Similar traverses made at the Narrabri wastewater plant yielded good emission data during the September 2016 campaign. The average methane emission rate estimated from the facility was 28 g min^{-1} (standard deviation of 11.8 g min^{-1}). These results are supported by additional traverses in July 2017. In the later survey, a total of 8 additional traverses were completed with the estimated methane emission rate ranging from 3 g min^{-1} to 27 g min^{-1}. This result is broadly in agreement with the earlier findings of 28 g min^{-1} within the uncertainty associated with the estimation method. The large range in emission values found during the July 2017 survey is due largely to the low and variable wind speed prevailing at the time of the measurement.

Additional flux estimates were made during July 2017 at the Wee Waa sewage treatment facility, which is approximately 35 km west of Narrabri. The average methane emission rate measured on this occasion was approximately 2 g min^{-1}.

Agricultural activities (especially enteric fermentation from livestock) is also another source of methane. In the course of the study and during the surveys, there were no operating cattle feedlots (which can represent large localised methane sources) observed that could be measured to provide an estimate of emission for this source. As an alternative, the herd population of livestock at Narrabri were used to estimate the methane emissions related to agricultural activities. In 2010, published statistics indicated that there were 73,000 heads of beef cattle, 35 heads of dairy cattle and 104,040 heads of sheep (Navarro, et al., 2016, Eady, et al., 2016). Using emission factors of 85 g day^{-1} (0.06 g min^{-1}) per cattle and 11 g day^{-1} (0.008 g min^{-1}) per sheep determined by Navarro, et al., 2016 and Eady, et al., 2016 for the NSW North West Slopes and Plains, the estimated total emission for the herd population in Narrabri in 1990 was calculated to be approximately 5083 g min^{-1} CH_4 equivalent.

A summary of the methane emission rates estimated from the main sources investigated is provided in Table 1.

Table 1. Summary of methane source locations and emissions rates.

Methane Source	Estimated Average Emission Rate (g min^{-1})	Location	Notes
Narrabri Underground Coal Mine	9,000 6,000-11,000	-30.52°, 149.88°	Obtained from mining company's own estimate published in 2014 AEMR and verified as part of this study. Estimate from July 2017 survey
Boggabri Open-Cut Coal Mine	358	-30.61°, 150.16°	Obtained from mining company's own estimate published in 2015 AEMR
Maules Creek Open-Cut Coal Mine	276	-30.56°, 150.13°	From an estimate based on in situ gas content provided in the Maules Creek Mine Environmental Assessment from 2011.
Tarrawonga Open-Cut Coal Mine	159	-30.64°, 150.17°	Obtained from mining company's own estimate published in 2014/2015 AEMR and Annual Review.
Narrabri Landfill	281	-30.33°, 149.72°	Estimated from downwind traverses.
Narrabri Wastewater Treatment Facility	28 3-28	-30.30°, 149.78°	Estimated from downwind traverses in September 2016. Estimated from downwind traverses in July 2017.

Methane Source	Estimated Average Emission Rate (g min^{-1})	Location	Notes
Wee Waa Wastewater Treatment Facility	2	-30.23°, 149.44°	Estimated from downwind traverses in July 2017.
CSG Wells	194	Various	Estimated using average emission rate measured on six CSG wells between May 2015 and Feb 2016 during a previous investigation in the area.
Livestock	5083	Narrabri	Estimated from herd population in 2010 and emission factors obtained from Navarro Garcia, et al., 2016 and Eady, et al., 2016.

Based on this dataset, the underground mine is seen to be the largest source of methane emissions within the region. Somewhat surprisingly, emissions from the three open-cut mines are relatively small and are comparable in size to those from the landfill site. It is important to note, however, that these results are not a complete inventory for the region so it is not yet possible to conclusively rank regional emission sources. For example, the Wilga Park power station and CSG infrastructure (apart from the well pads), which are likely to emit some levels of methane, have not been included. Moreover, most of these estimates presented here are based on limited measurements and do not consider any seasonal or other variability that may affect emissions.

Although it is acknowledged that the inventory of methane sources identified in this study is not necessarily complete, detailed surveys made during two intensive field campaigns during this project and at other times over several years have not indicated the presence of any other large methane sources. Indeed, ambient methane levels are essentially indistinguishable from normal background concentrations except in close proximity to the sources identified in Table 1. As well as the CSIRO work, teams from the University of Adelaide conducted detailed methane surveys across NSW and elsewhere between 2013 and 2015 and their results also show generally low background levels of methane (Hatch and Hamilton, 2017). This suggests it is relatively unlikely that there are many large point emission sources within the region apart from those already identified. However, further investigation is required to confirm this, especially in relation to abandoned boreholes, which are discussed in the following section.

3.1.1 EMISSIONS FROM WATER BORES AND EXPLORATION BOREHOLES

Previous research has shown that in some cases, abandoned boreholes, especially oil and gas wells, may be a significant source of methane (Kang *et al.*, 2014; Vielstadte *et al.*, 2015). In the United States, for example, Kang *et al.* (2014) estimate that between 4 and 7 % of methane emissions in Pennsylvania may be from this source (although this is based on a small sample of wells). In Australia, Day *et al.* (2015) found significant methane emissions from some legacy abandoned coal exploration boreholes in the Surat Basin in Queensland. Other unpublished work conducted by CSIRO since then has identified various water bores in the same region where up to 100 g CH_4 min^{-1} was emitted from a single bore. In the Narrabri region, researchers from the University of Adelaide have previously found water bores on farmland with elevated methane concentrations (Hatch and Hamilton, 2017). Hence, to assess the potential for borehole emissions in the Narrabri region the current study included an examination of a small selection of abandoned exploration boreholes and water bores.

Exploration boreholes in the survey area were located using the NSW Department of Resources and Energy database MinView (http://www.resourcesandenergy.nsw.gov.au/miners-andexplorers/geoscience-information/services/online-services/minview) to locate boreholes within the study region. These data are shown on

Figure 4 displaying various borehole locations. The CSG wells are marked by red circles and the other bore holes by green circles. The current figures extracted from the database show that within the mobile survey area, there are a total of 667 mineral, coal and petroleum bore holes. Of these 170 are related to CSG. Additionally, details of registered water bores are maintained in the National Groundwater Information System administered by the Bureau of Meteorology (http://www.bom.gov.au/water/groundwater/ngis/); water bores of various types within the study region are also shown in

Figure 4 and marked by blue circles. The most recent database show that there are a total of 2713 water bores in the CSG infrastructure area.

A summary of the total number of the various bores in the mobile survey area are shown in Table 2. It is obvious from this table that there is a large number of bores (total of 3380) of different types distributed over a wide area within the mobile survey area. Where possible, mobile surveys have been made along public roads near many of these boreholes during the September 2016 and July 2017 surveys. During previous work in Queensland, this method was found to be effective for locating leaking coal exploration boreholes (Day *et al.,* 2015).

Table 2. Summary of bore holes related to minerals, coal, petroleum and water bores in the CSG infrastructure area.

Area	Number of Minerals, Coal & Petroleum Bore Holes	Number of CSG Bore Holes	Number of Operating CSG Bore Holes	Number of Water Bores
Mobile Survey Area	667	170 of the total Minerals, Coal & Petroleum Bore Holes	72 of the total CSG Bore Holes	2713
CSG Infrastructure Area	258	159 of the total Minerals, Coal & Petroleum Bore Holes	71 of the total CSG Bore Holes	146

For the measurements collected in September 2016 from four exploration bore holes within the Pilliga forest, we used surface flux chambers to measure methane emissions at the bore locations indicated by the NSW Department of Resources and Energy database, although, usually, there is no longer any surface indication of presence of the bore. At the time the surface flux measurements were made the area was still very wet from recent rain, which restricted access to many of the known borehole locations, hence the limited number of measurements at the time. At each borehole location up to six individual flux measurements were made; the average of these measurements at each location is shown in Table 3.

Table 3. Summary of surface methane flux measurements made at four borehole locations within the Pilliga Forest acquired in September 2016.

	Location	Average CH_4 Emission Rate (g m^{-2} day^{-1})
Hole No A	-30.43°, 149.77°	-0.0022

	Location	Average CH_4 Emission Rate (g m^{-2} day^{-1})
Hole No B	-30.49°, 149.84°	-0.0007
Hole No C	-30.53°, 149.78°	0.0002
Hole No D	-30.86°, 149.45°	-0.0005

The methane fluxes measured at these sites were very low, and, three of the sites yielded negative methane fluxes, which, is indicative of microbial uptake of atmospheric methane by the soil. These results are consistent with the results of similar measurements made on undisturbed surfaces (Day *et al.*, 2015; Day *et al.*, 2016).

A total of 32 sites consisting mainly of water bores around the mobile survey area were measured in July 2017 when the conditions for measurements and access to sites were better. For these sites, where the borehole casings were at ground level, the emission measurements were collected using a flux chamber and where the casing was intact and above the ground, measurements were collected by sealing the casing with a plastic film as described in section 2.1.

In addition to exploration and water bores, some CSG well sites in the Pilliga and Bibblewindi forests were examined in August 2017. This included a total of 33 sites which comprised of a combination of exploration boreholes, CSG wells and abandoned CSG wells within rehabilitation sites. At these sites, the well head gear had been either completely or partially removed (i.e. only the well head remained in place; the separator and associated equipment and pipework was not present). Most of these well sites were fenced so it was not possible to measure surface emissions at the well. Instead, downwind ambient concentration measurements were made approximately 50 m from the well. The sensitivity of the methane analysers has been previously shown to be sufficient to detect even very small leak rates from this distance (Day et al., 2014).

The average of these measurement for each of the site visited in the Pilliga forest is presented in Appendix A in Table A- 1 and the emission rates for the water bores around Narrabri are presented in Table A- 2. These additional measurements acquired in July and August 2017, agreed with the data acquired in September 2016. Specifically, both the data from September 2016 and July and August 2017 indicate that the methane fluxes for the abandoned exploration holes (Table A- 1) and water bores (Table A- 2) were very low and are consistent with the results of flux measurements made on undisturbed surfaces (Day et al., 2015; Day et al., 2016).

In summary the results of the exploration and water bore surveys do not indicated the presence of any leaking bores; however, we have only examined a total of 69 bore holes a very small fraction of the total number. Many of the boreholes are also on private land which complicates access in many cases. Despite the small sample of bores examined during the study, the negligible flux emissions measured over a wide area, combined with low ambient methane concentrations measured throughout the survey region suggest that methane emissions from boreholes is not a major contributor to the region's overall methane budget. Nevertheless it acknowledged that a substantial amount of further work is required to confirm this, especially given that other water bores in the general survey region have been found to have significant methane emissions (Hatch and Hamilton, 2017). Moreover, the effect of water extraction for irrigation or gas production on the emissions from boreholes or land seeps has not been determined for the region.

It is beyond the scope of this project to assess all of the known bores within the study region but this is an area that does warrant further investigation. The use of suitable remote sensing systems is likely to be particularly useful in identifying boreholes with significant emission levels. Investigation of suitable remote sensing platforms was pursued as part of this project (see Section 2.2 of this report).

3.2 Remote Sensing Trial

Satellite data from "Claire" onboard GHGSat were first acquired across the target site on 30th October 2016 at 23:10:42 UTC (10:10:42 local time in Camden, NSW). Field validation data were acquired with the Picarro G2301 $CO/CO_2/CH_4/H_2O$ analyser and LGR Ultraportable $CH_4/C_2H_2/H_2O$ Methane/Acetylene Gas Analyzer mounted in two vehicles (as used for the surveys described in Section 2.1) concurrent with the "Claire" acquisition. A plume from the underground coal mine ventilation fans was detected during the ground surveys. However, the direction of the wind was not suited to allow full access to the plume on public roads, hence we were unable to conduct the necessary transects across the plume to estimate the emission rate from the fans. Figure 8 shows the methane concentration profile near the ventilation fans measured during the ground survey.

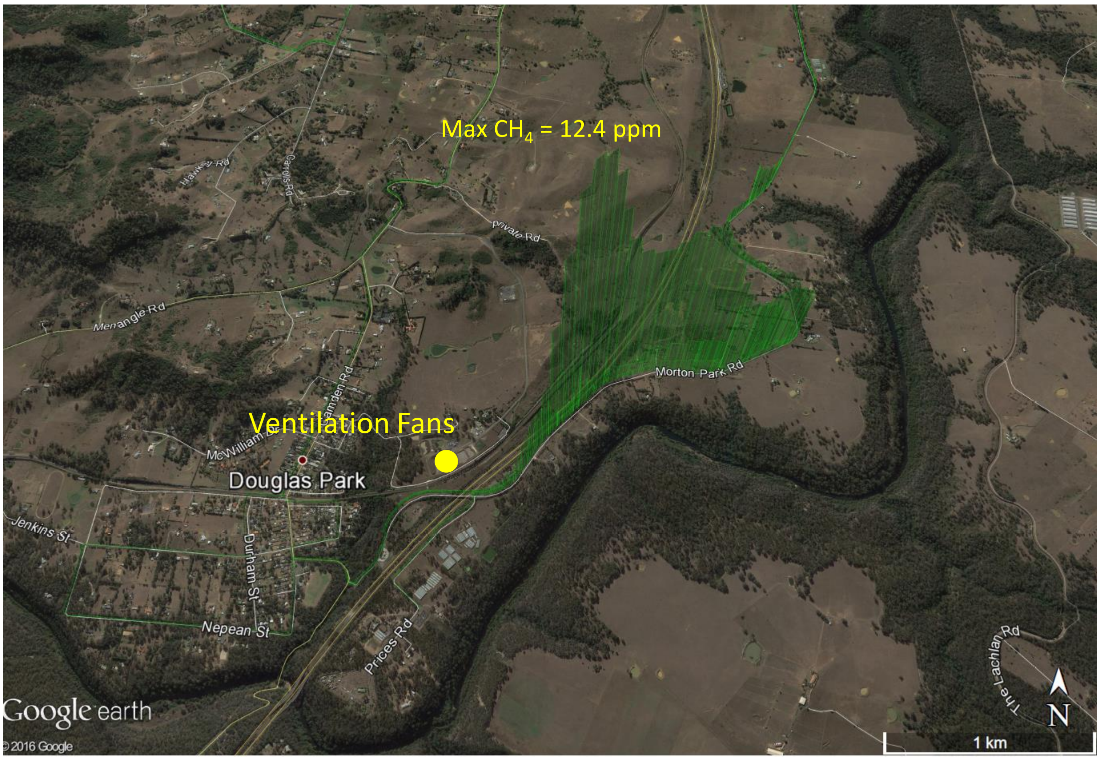


Figure 8. Methane concentration as a function of position measured near the outlet of the underground mine ventilation fans on 31st October. The methane concentration is shown by the green trace which is linear line in 3D with higher values having taller bars. The maximum methane concentration measured during the survey was approximately 12.4 ppm.

Although we do not have actual emissions from the mine we have used published data to estimate the approximate methane emission rate. According to the environmental impact assessment for the construction of the fans, the expected ventilation flow rate from the fans is of the order of 550-650 $m^3\ s^{-1}$ with an average methane concentration in the air stream of 0.8 % (Cardno, 2010). On this basis the methane emission rate from the fans would be between about 3 and 3.5 kg s^{-1} (18,000 and 21,000 g min^{-1}).

The data from "Claire" was one of the first datasets acquired and consequently experienced some post launch issues related to new sensors. One of these issues caused the image captured on 30th October to be partially exposed. Initially, GHGSat choose to ignore this non ideal dataset for further processing opting to continue to acquire further data.

However, at a later date GHGSat revisited the dataset and found that the information content were sufficient for further processing. A retrieval of column CH_4 concentration was performed by GHGSat using their in-house latest toolchain (in June 2017). Processed "Claire" data, as shown on Figure 9 consisting of an albedo map (left), derived methane (middle and right) and carbon dioxide (not shown) column concentration maps produced from "Claire" data, were delivered to CSIRO for evaluation.

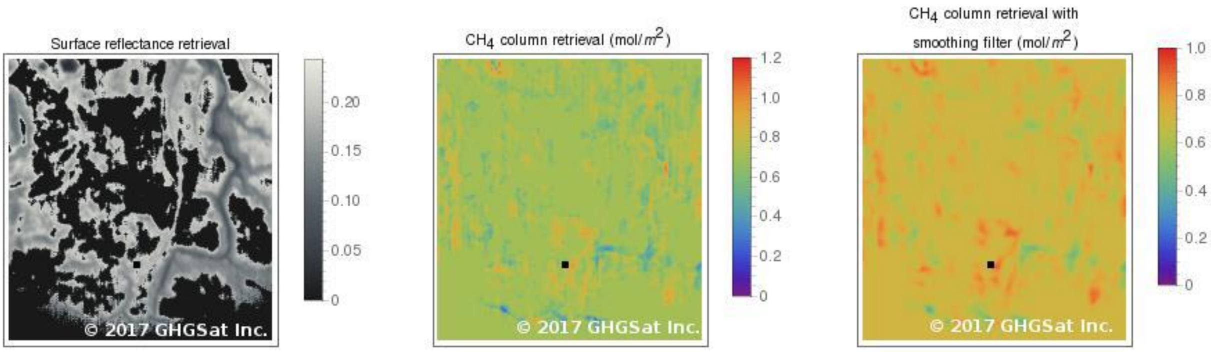


Figure 9. Retrieved information products from the "Claire" sensor acquired over the Camden area. On the left is the albedo image. In the middle is the methane column product and on the right is the same image as the middle after smoothing. Note that there is a scale difference between the middle and right image. Black dot shows the area of elevated methane concentration detected by "Claire".

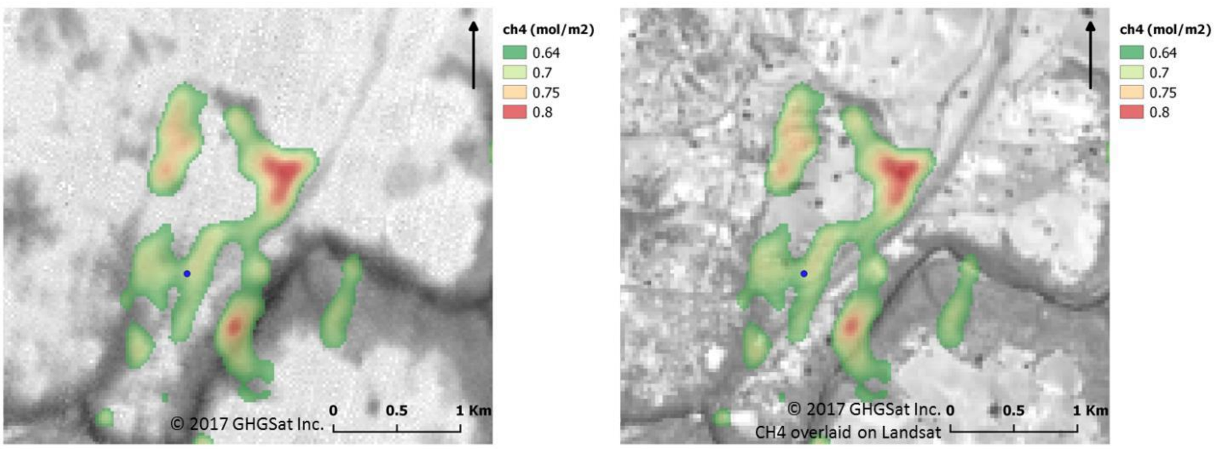


Figure 10. Enlarged figure of the area of elevated methane concentrations. On the left, the methane concentration has been overlaid over the albedo image produced from "Claire". On the right, the methane concentration has been overlaid over a Landsat TM imagery to allow better visualisation of the location.

A large region of elevated methane concentrations (around the black dot on Figure 9 and shown enlarged on Figure 10) was detected. This area of elevated methane levels appear to coincide with an area near the location of the gas ventilation fans associated with underground coal mining operation. Further, the data collected from the ground truthing survey (as shown on Figure 11) close to this area also recorded high values. Note that the estimated emission rate from the vent of 18,000-21,000 g min^{-1} is within the measureable limit of "Claire" as specified in the objectives of GHGSat. These objectives are to be able to measure land-based sources of greater than 50kt CO_2 equivalent per year (approximately 4500 g equivalent CH_4 min^{-1}). This indicates that "Claire" may be able to detect large emitters such as underground coal vents.

Although this result is encouraging, GHGSat highlighted some issues to consider with the results provided from "Claire". Specifically,

- The retrieved methane column density array contains significant variations relative to the methane background levels across the imagery. As expected with the non-ideal dataset which was partially overexposed across some parts of the imagery, the noise level is higher than typically observed by GHGSat's other datasets using their latest toolchain. These variations remain significant and a concern although simulations performed by them suggest that plumes could still be visible with this higher noise level;
- The excess methane appears to be in approximately the right locations, but there is no clear plume shape, potentially because the wind at the time of the observation was strong and gusty; and,
- The local topography may play a role in the dispersion of the gas and consequently the impacts on the ability to detect the plume. The coal mine ventilation fans noted in the retrieval are in a small valley, affecting the dispersion of methane, and in this case perhaps aiding detection of the source.

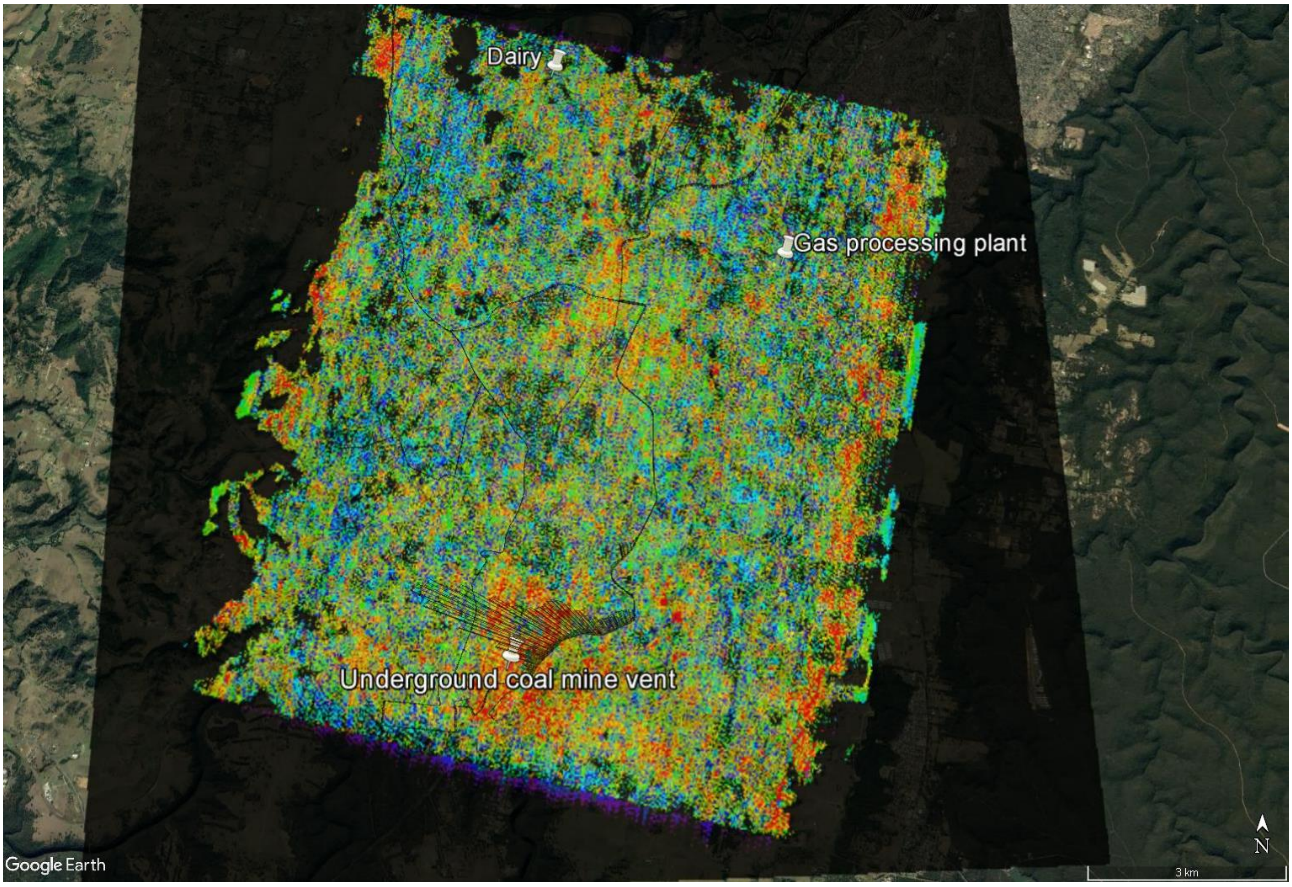


Figure 11: Ground truthing trace (black vertical bars) overlaid on methane concentration map derived from the "Claire" sensor. The locations of the underground ventilation shafts and other potential sources of methane are also shown.

We undertook further evaluation of the digital products that were delivered and post-processed the data, as the level of instrument noise/artefacts as indicated by diagonal stripping (red wide strip on the left and right edge as well as thinner blue strips) across the imagery on Figure 12(a) is a concern and hampers the ability to define features or anomalies in the image. It is difficult to post-process already processed data, however, an attempt was made to reduce the noise using a classical noise removal technique called Fast Fourier Transform (FFT) filtering.

This was done to determine if it would provide better enhancement and/or delineation of any potential anomalies detected and the attributes of those anomalies.

The visual appearance of the image was improved by reducing the noise with the FFT filtering and the result better delineated the anomalous features. The large patch of elevated methane at the bottom of the image, as shown by the red patch towards the bottom image of the original image on Figure 12(a), was better defined on the post-processed Figure 12(b). However, even with the additional noise-removal, as indicated by GHGSat, the red elevated values did not have a plume-like structure. Additionally, there were other areas of similarly elevated values that were better defined, such as the red smaller patches towards the right of the middle large patch on Figure 12(b). However, these 'highs' in the satellite-derived methane column concentration maps did not coincide with elevated values measured by the ground-based survey or known sources of elevated methane values. There may be several reasons for elevated values not to have been measured during the ground survey. This includes the fact that elevated values may not be actually present during the data collection or the wind directions did not permit the interception of the plume by the ground sensor for them to be measured.

The noise-removed Figure 12(b), also enhances the intermediate and lower values better than the unenhanced Figure 12(a). Some of the features on Figure 12(b) appear to align with the local geology, topography and/or compositional material. For example, the low values (blue, representing low amounts of methane) towards the right of the large and smaller red patches appear to coincide with the creek line. Therefore, there appears to be an influence of the geology, landform and/or compositional material on the signal and retrieved data.

Although better definition of the features were achieved, it must be emphasised that while the application of noise removal techniques such as FFT provide better definition and highlight other anomalous regions, it will not improve the accuracy of the data and as indicated previously, application of noise removal on data that has already been processed is not ideal. The ideal situation would be to evaluate the raw data to better understand the contributions of the noise and remove or reduce them with appropriate methods at an early stage in the process before any retrieval of higher level products are made. However, the raw data were not made available to us.

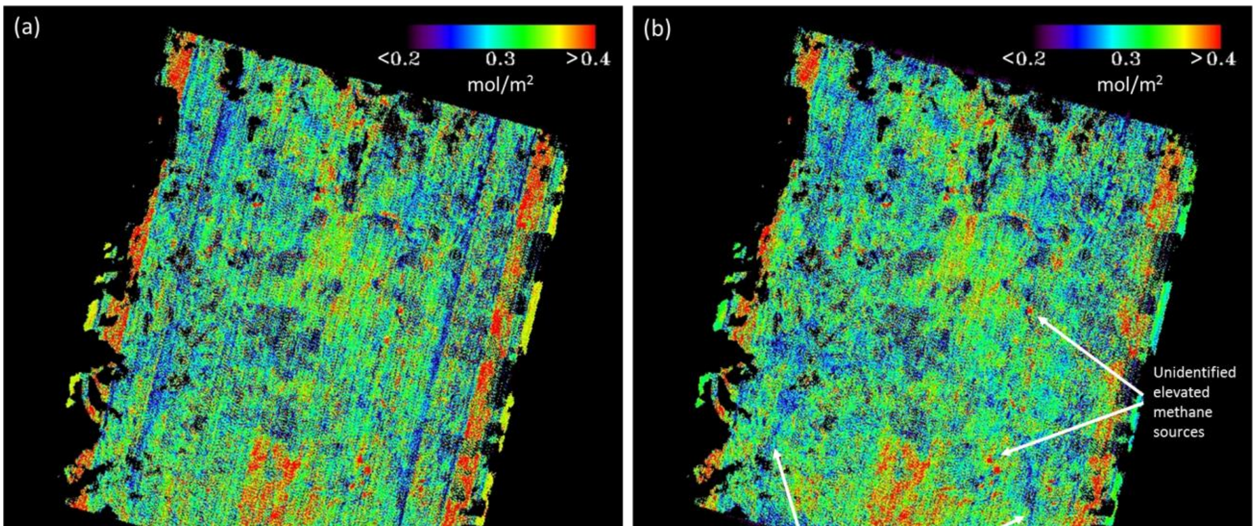
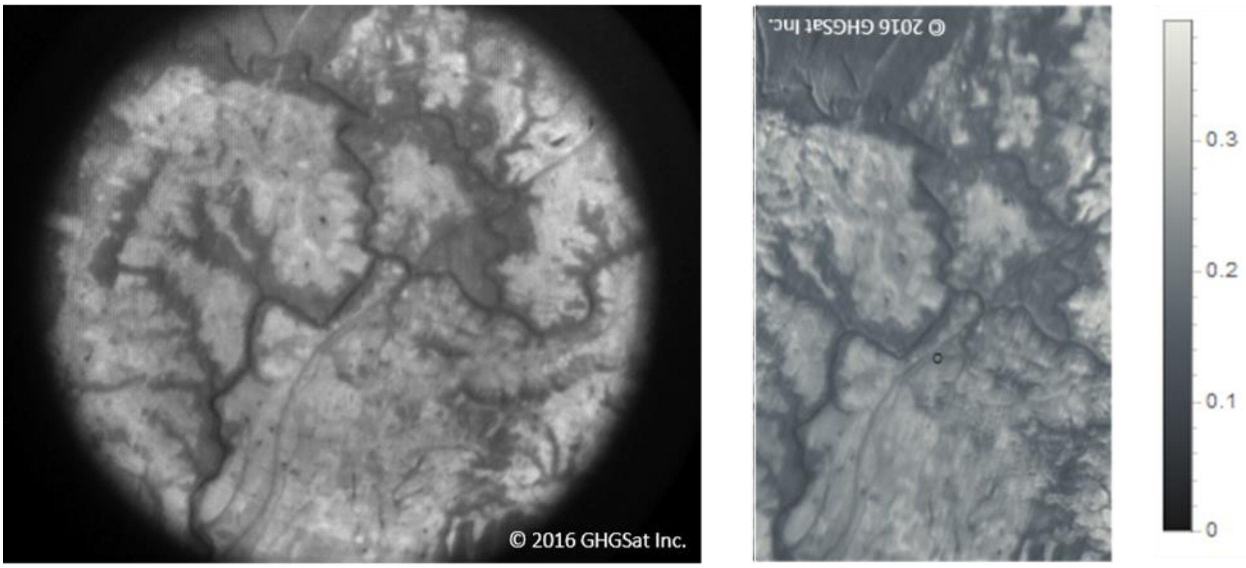


Figure 12. (a) Original retrieved methane column concentration product as delivered to CSIRO. (b) Methane column concentration data that were post-processed using the Fast Fourier Transform filtering technique to reduce the noise.

In summary, at this stage there remains important uncertainties associated with the quantitative use of the delivered methane concentration map. Specifically, the level of instrument noise/artefacts remains a concern and there appears to be an influences of the local geology, landform and/or compositional material that may require to be accounted for in the retrieval of the methane products.

GHGSat collected four more observations of this area from November 2016 to May 2017, again with inconclusive results. For example, a further acquisition was rescheduled for the week starting 4th November 2016 following the first acquisition. Data from this acquisition are shown in the black and white imageries of a single band of the raw and processed to surface reflectance products in Figure 13. The subsequent datasets acquired were processed by GHGSat with inconclusive results. Their report (Appendix C indicated that some of the data showed evidence of plumes, but some also contained patterns and spurious variations in the retrievals which GHGSat believes are primarily due to modelling errors, image alignment errors and the effect of uncorrected instrument imperfections.



Level 0: Raw Image

Level 2: Surface Reflectance Retrieval (geo-referenced)

Figure 13. Left: Raw data acquired from "Claire" on 4th November 2016. Right: Georeferenced surface reflectance derived from "Claire" data acquired on 4th November 2016. Note that the acquisition area was shifted to centre on the underground coal mine vent (black circle in right hand image) and therefore missing some of the other sources of methane. South is up in these images.

4 Conclusion and Recommendations for Further Work

Mobile surveys have been made through the Pilliga forest region where most of the CSG development is located and these combined with previous field surveys indicate generally low levels of methane within this area. Although this suggests that emissions from CSG activities are low, only a small number of wells have been examined in detail (during a previous project) and emissions from the bulk of the infrastructure have not been measured. To gain a better understanding of the emissions from CSG development, in the longer term (i.e. beyond the current project) it would be important to measure emission rates from other parts of the gas production facilities, especially the gas processing plant and water treatment facilities.

One of the largest sources of methane in the study area is coal mining and there are several large coal mines to the east of the Pilliga gas field. The main mines are the Narrabri underground mine, Maules Creek open-cut mine, Boggabri open-cut mine and Tarrawonga open-cut mine (which is adjacent to the Boggabri mine). Estimation of the emission rates from these mines were obtained from the companies' published annual environmental report. The underground operation near Narrabri is estimated to have a methane emission rate of approximately 9,000 g min^{-1}, which is by far the largest source of methane identified within the region. This estimate from the mining company was further confirmed with actual measurements where the emission rates were found to be 6,000-11,000 g min^{-1}. The other coal mines were estimated to produce emission rates ranging between 159-358 g min^{-1} based on published data and therefore are considered to be low methane emitters. Data from field measurements captured from the Boggabri and Maules Creek mines in conditions ideal to intercept any methane from these mines concurred with the fact that these three mines were low methane emitters. Maules Creek mine however, is a new mine and production rate may increase with time and hence future amendments to the actual emission rates may be required.

Agricultural activities (especially enteric fermentation from livestock) is a known source of methane. In the course of the study and during the surveys, there were no operating cattle feedlots (which can represent large localised methane sources) observed that could be measured to provide an estimate of emission for this source. As an alternative, the herd population of livestock at Narrabri were used to estimate the methane emissions related to agricultural activities. The emissions from livestock for Narrabri was estimated to be 5083 g min^{-1} from 2010 herd population and the published emissions factors for the Narrabri region of 85 g day^{-1} per cattle and 10 g day^{-1} per sheep.

Methane emission rates from two other significant sources in the area were quantified using a ground based plume dispersion method. A landfill site near Narrabri yielded 281 g min^{-1}, while a sewage treatment plant, also near Narrabri, was found to have a methane emission rate of about 28 g min^{-1}. The Narrabri water treatment plant was measured on two occasions and the measurements concurred with each other. Another water treatment plant at Wee Waa was found to have low methane emissions during July 2017 equivalent to about 2 g CH_4 min^{-1}.

At the current time, according to published databases, there are a total of 3380 boreholes of various types throughout the study region. Within this study we have measured 69 boreholes. Four were exploration bores, 32 were water bores and 33 sites contained exploration bores, abandoned CSG wells in rehabilitation areas and a CSG well. The measurement collected at these sites indicated that no methane emissions were present from these wells. The emissions from these boreholes were found to be very small and within the levels measured previously for natural surfaces. Although this is a small sample of the total number of boreholes in the Narrabri area, the data we have collected indicates that the levels of methane from boreholes were negligible. Nevertheless, a handful of water bores in the study region have been found by other researchers from the University of Adelaide to be leaking methane so further investigation of borehole emissions is a priority.

Notwithstanding the uncertainty of the results, indications are that most of the largest point source methane emitters have been identified in the region. This is based on the large number of mobile surveys conducted throughout the region over several years, both by the CSIRO and researchers from the University of Adelaide. Estimating methane contributions from sources spread over wide areas such as agriculture (cattle grazing), boreholes and natural methane seeps is less well defined at this stage and is an area where remote sensing has an important role.

With the large number of boreholes distributed across the landscape, including those that are in private land and inaccessible by road, to undertake a complete inventory of all these boreholes is a significant activity. A more viable and efficient method would be the use of a remote sensing technique. However, it is important to note that an appropriate remote sensing sensor, with high enough sensitivity to detect low levels of methane, would be required. Additionally, while remote sensing will measure the concentration, the one-time measurement is insufficient to quantify the emission rates. A potential strategy would be to use remote sensing techniques to provide a broad area comprehensive survey. This survey will then allow identification of "hot spots" of elevated concentration of methane where further targeted ground investigations with a mobile survey and flux chamber can be undertaken.

The GHGSat series of remote sensing satellites pose a promising proposition of being able to obtain broad area coverage with spatially-comprehensive medium spatial resolution. With 50 m pixels, these satellite sensors have the potential to close some of the gaps in being able to identify more of the typically-small spatially sized sources of methane than other greenhouse and trace gas sensors that are currently in orbit, which provide global scale measurements at spatial resolutions in the 100s of metres. Additionally, GHGSat's objective was to detect land-based sources of the order of 4500 g min^{-1} which would be in the range of medium gas operators.

Data were acquired from the "Claire" sensor onboard the GHGSat microsatellite in October 2016. Although these data appear to be able to detect methane from vents related to the Narrabri underground mine, the results together with further acquisitions across the Camden area were inconclusive, GHGSat attributed this uncertainty primarily to modelling errors, image alignment errors and the effect of uncorrected instrument imperfections. The measurement of methane from space is a highly demanding task because the sources are usually small, compounded by the large vertical column from space to earth (>500 km), and, the spectral features are very narrow and the spectral region where these features occur overlap with other atmospheric features (water vapour) and other surface features (minerals and dry plants). In addition, passive sensors such as "Claire", rely on sunlight to provide the illumination/energy, which is generally quite low in those spectral regions. The signal received would also be small because it is integrating over a small area unlike other GHG/trace gas sensors which are integrating over much larger areas to obtain higher signals. Therefore, a very high signal to noise ratio would be required and any instrumental "noise" would pose a challenge and compromise the ability to detect and characterise methane.

During the course of this study, several studies related to the use of remote sensing for methane quantification in USA have been published. This included a study on the use of the airborne NASA AVIRIS-NG across the Four Corners region of Utah, Colorado, Arizona and New Mexico USA (Frankenberg *et al.* 2016) and the NASA EO-1 Hyperion satellite sensor across the Aliso Canyon Porter Ranch accidental methane release in California USA (Thompson *et al.* 2016).

Hyperion sensor data on board the EO-1 satellite were acquired opportunistically across the Camden test site. However, after evaluation of the data in the spectral regions which may yield methane information and thorough review of the results shown in Thompson *et al.* (2016), the results indicated that quantification of methane across the Camden area would be problematic. Specifically, although the Hyperion sensor was the first civilian imaging spectroscopy sensor and demonstrated the technology across a range of useful applications, the shortwave-infrared (SWIR) region where methane spectral features reside has a fairly low signal-to-noise (SNR) ratio of 20:1[4], and, the methane concentration mapped with the Hyperion in Thompson *et al.* (2016) showed significant confounding issues that appear to be related to surface composition. Although the methane plume appeared to have been mapped at the source, further away from the source where the methane level would be lower, the plume appears to be significantly confounded by surface composition. This is further verified when compared to the accompanying methane concentration produced by the AVRIS-NG which does not have a similar feature. Since AVIRIS-NG has a much better signal to noise ratio, it is likely that the measurements were better and hence the additional features mapped in the Hyperion imagery but not in the AVIRIS-NG imagery may be interpreted as commission issues related to the background surface composition. Additionally, note that the emission rate estimated for the Aliso Canyon area was measured to be 20,000 kg h^{-1} (333,300 g min^{-1}), 37 times larger than the most significant source in Camden. It is likely that the analogous areas on the Aliso Canyon study to Camden would be the edge of the plume where there appears to be significant commission issues.

The Frankenberg *et al.* (2016) study across the Four Corners regions show a more promising result. In this study they estimated that the detection limit of the AVIRIS-NG is 2-5 kg h^{-1} (33-83 g min^{-1}). These figures indicate that sources of emissions of the size of a sewerage treatment plant, landfill site, low emitting coal mines and above can be detected. However, it is unlikely that CSG wells will be detectable. Although the NASA operated AVIRIS-NG is not easily accessible in Australia, if the opportunity arose, it may be worth investigating. Ultimately, as recommended previously in Day *et al.* (2013), active systems such as differential absorption light detection and ranging (DIAL) (Riris, et al., 2012) and laser systems which use an active light source tuned to the absorption lines of a particular atmospheric gas (methane) to augment the signal, may be the best option to provide the sensitivity to detect the low levels of methane sources across potential gas producing areas such as the Pilliga Narrabri area. During the course of this study and other similar studies, both the location and detection of the sources of emission were challenging. Therefore, in addition to active systems, systems that have the capability of collecting spatial data rather than the ones which only collects single profiles (traditionally used for pipeline monitoring). Systems that use line profiling such as the Methane Monitor[5], which can acquire a swath of 40-200 metres wide, are now becoming commercially available in USA. When such systems become available in Australia, it would be useful to conduct a trial with these systems.

[4] Note that satellite sensors specifically for measuring GHG or trace gas such as SCIAMACHY report SNRs in the order of 300:1 (https://www.wmo-sat.info/oscar/instruments/view/478).

[5] http://www.ball.com/aerospace/Aerospace/media/Aerospace/Downloads/D3242-Methane-Monitor_0916.pdf?ext=.pdf

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Appendix A

Table A- 1. Summary of surface methane flux measurements made at thirty three sites consisting of exploration bores, CSG wells and abandoned wells at rehabilitation locations within the Pilliga Forest acquired in August 2017.

	Location	Average CH_4 Emission Rate ($g\ m^{-2}\ day^{-1}$)	Comment
Hole No PIL1	-30.53°, 149.61°	<0*	Rehabilitation Site -CSG
Hole No PIL2	-30.12°, 149.14°	~0	Sealed steel cased borehole – CSG – ~250mm ø
Hole No PIL3	-30.53°, 149.61°	<0*	Sealed steel cased borehole – CSG – ~600mm ø
Hole No PIL4	-30.53°, 149.60°	0^+	Sealed steel cased borehole – CSG – ~600mm ø
Hole No PIL5	-30.54°, 149.61°	0^+	NSW Water monitoring bore under construction
Hole No PIL6	-30.55°, 149.61°	0^+	Fenced rehabilitated CSG well pad
Hole No PIL7	-30.55°, 149.61°	0^+	Fenced rehabilitated CSG well pad
Hole No PIL8	-30.63°, 149.61°	0^+	“Bibblewindi” CSG well Pad
Hole No PIL9	-30.63°, 149.61°	0^+	“Bibblewindi” CSG well Pad
Hole No PIL10	-30.63°, 149.61°	0^+	“Bibblewindi” CSG well Pad
Hole No PIL11	-30.63°, 149.61°	0^+	“Bibblewindi” CSG well Pad
Hole No PIL12	-30.63°, 149.61°	0^+	“Bibblewindi” CSG well Pad
Hole No PIL13	-30.62°, 149.60°	0^+	“Bibblewindi” area
Hole No PIL14	-30.67°, 149.65°	**	CSG well
Hole No PIL15	-30.55°, 149.65°	0^+	“Bohena 13C” rehabilitated
Hole No PIL16	-30.57°, 149.69°	0^+	“Burrawarna 1” rehabilitated
Hole No PIL17	-30.60°, 149.71°	0^+	“Dewhurst 7” rehabilitated
Hole No PIL18	-30.55°, 149.73°	0^+	“Dewhurst 11” rehabilitated
Hole No PIL19	-30.55°, 149.76°	0^+	“Dewhurst 14”
Hole No PIL20	-30.55°, 149.76°	0^+	“Dewhurst 15”
Hole No PIL21	-30.55°, 149.76°	0^+	“Dewhurst 13”

	Location	Average CH_4 Emission Rate ($g\ m^{-2}\ day^{-1}$)	Comment
Hole No PIL22	-30.55°, 149.76°	0+	"Dewhurst 8 & *A"
Hole No PIL23	-30.55°, 149.77°	0+	"Dewhurst 18H"
Hole No PIL24	-30.55°, 149.77°	0+	"Dewhurst 17H"
Hole No PIL25	-30.54°, 149.77°	0+	"Dewhurst 16H"
Hole No PIL26	-30.61°, 149.75°	0+	"Dewhurst 24"
Hole No PIL27	-30.62°, 149.75°	0+	"Dewhurst 22"
Hole No PIL28	-30.62°, 149.75°	0+	"Dewhurst 6"
Hole No PIL29	-30.61°, 149.76°	0+	"Dewhurst 25"
Hole No PIL30	-30.61°, 149.76°	0+	"Dewhurst 23"
Hole No PIL31	-30.65°, 149.78°	0+	"Dewhurst 5"
Hole No PIL32	-30.65°, 149.73°	0+	"Dewhurst 3"
Hole No PIL33	-30.65°, 149.69°	0+	"Dewhurst 2"

*NB: * Flux chamber measurements showed a negative slope indicating biogenic consumption of methane.*

+ access to the borehole /well was fenced and or restricted. However, Picarro detected no above background methane in the down wind plume.

*** gated CSG well – inaccessible.*

Table A- 2. Summary of methane flux measurements made at thirty two water borehole locations within the Narrabri area.

	Location	Depth	Average CH_4 Emission Rate ($g\ day^{-1}$)*
Hole No 1	- 30.31°, 149.71°	190-205	<0
Hole No 2,3	- 30.31°, 149.71°	220	<0
Hole No 3	-30.31°, 149.68°	-	<0
Hole No 4, 5, 6	-30.29°, 149.58°	82	0
Hole No 7, 8,	-30.30°, 149.58°	100.6	0
Hole No 9, 10, 11	-30.25°, 149.54°	80	0
Hole No 12, 13	-30.23°, 149.58°	56	0
Hole No 14, 15, 16	-30.21°, 149.44°	-	0

	Location	Depth	Average CH_4 Emission Rate (g day^{-1})*
Hole No 17, 18, 19, 20	-30.20°, 149.54°	75	0
Hole No 21,	-30.20°, 149.68°	51	0.2
Hole No 22,	-30.22°, 149.41°	30	<0
Hole No 23,	-30.21°, 149.41°	67	0
Hole No 24, 25	-30.18°, 149.30°	67	<0
Hole No 26, 27	-30.12°, 149.14°	67	0
Hole No 28	-	300	0
Hole No 29	-	100	0
Hole No 30	-	300	0
Hole No 31	-	30	<0.1
Hole No 32	-	326	0

NB: Values of emissions <0 indicates that the emission concentration within the sealed water bore casing was reducing with time while 0 indicated that the concentration was constant over the sampling period.

Appendix B

GHGSat-D

CSIRO INTERIM INFORMATION

Document No. GHG-1145-6001 23 January 2017

GHGSAT PRODUCT/DOCUMENT APPROVAL

Title: **GHGSat-D**

4CSIRO Interim Information

Document No.: **GHG-1145-6001-a**

Submission Date: **23 January 2017**

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Product/Document Originator: Stephane Germain	Signature and Date 23 January 2017
Product/Document Review: Richard Giroux	Signature and Date 23 January 2017

Change History

Version	Release Date	Notes
a	2016-12-15	Initial Release

1 INTRODUCTION

GHGSat successfully launched its first satellite named "GHGSat-D", or "Claire", on 21 June 2016.

Since early July 2016, GHGSat has measured emissions for several industries including oil and gas, power generation, mining, cement, and agriculture. GHGSat Inc. is collaborating with the Commonwealth Scientific and Industrial Research Organisation ("CSIRO") on measurements being performed in a test area near Camden, for verification and validation of satellite measurements of greenhouse gas emissions in Australia.

This report provides a first look at satellite measurements from GHGSat-D.

5 1.1 Contents

1.1.1 Acronyms

AQG	Air quality gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FOV	Field of View
GHG	Greenhouse gas

Note that all units in this report are metric. For example, abbreviations such as “Mt/yr” refer to millions of tonnes per year.

2 DOCUMENTS

2.1 Applicable Documents

The following documents are useful for understanding the content of this document.

Ref	Title	Doc No.	Author	Publisher

2.2 Normative Documents

These documents should be considered as part of this document.

Ref	Title	Doc No.	Author	Publisher

3 SATELLITE MEASUREMENTS

3.1 Measurement Process

3.1.1 Business Process Overview

The measurement process begins with an understanding of customer needs, and ends with delivery of products and services that fulfill those needs. This process as applied to satellite measurements is illustrated in Figure 1, and summarized below:

- Customer: GHGSat reviews product / service requirements (measurement type, measurement frequency, detection thresholds, source characteristics, weather constraints, etc.) with the customer to ensure that the customer's needs can be appropriately addressed with current GHGSat resources available (e.g. one or more satellites).

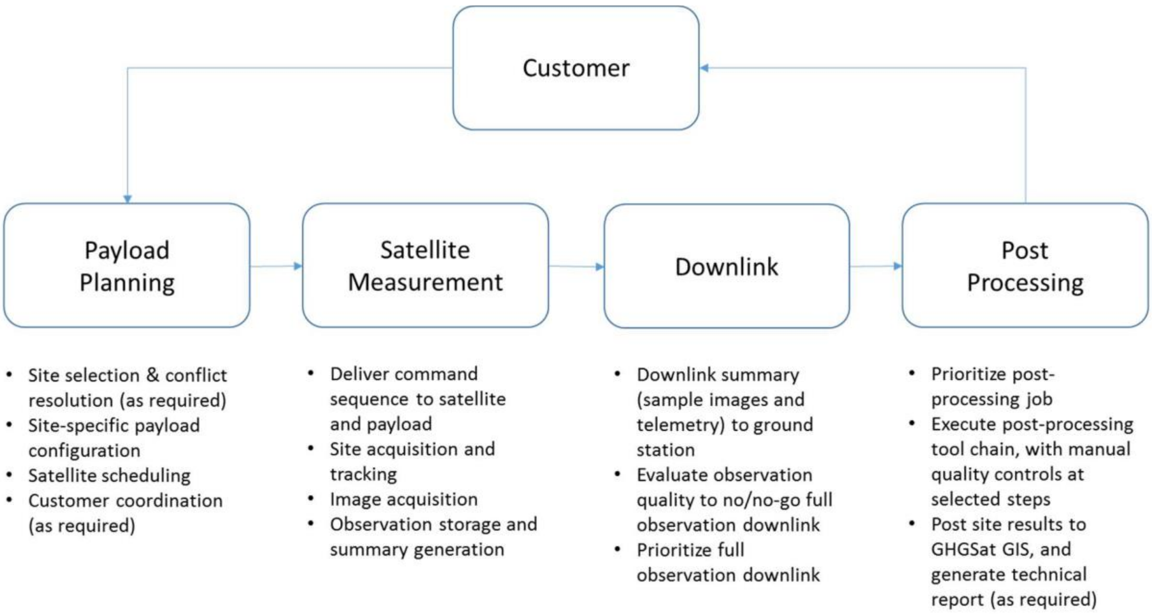


Figure 1: Operations Sequence

- Payload planning: Customer sites are selected (using GPS coordinates defining either a polygon or a center point for the site) and verified for scheduling conflicts with other customer sites. Satellite and payload parameters are determined for each site measurement. Coordination with customers is handled as required for scheduling coincident satellite & ground measurements.
- Satellite measurement: Satellite and payload parameters are converted into a command sequence which is transmitted to the satellite. When the satellite arrives in proximity of the customer site, it begins to track the site for measurement. At the appropriate time within this satellite tracking manoeuvre, the payload acquires images of the customer site (the full set of images and associated telemetry is referred to as an "observation"). Observation data is then transferred to on-board storage, and a summary is generated (a "summary" is a sample of images / telemetry for the site).
- Downlink: The downlink is currently the system bottleneck; the satellite can generate data at a faster rate than it can be downlinked to the ground. The summary is therefore downlinked for evaluation on the ground before the satellite downlinks the full observation (which is typically 20x more data than the summary). Once ground operators decide that the full observation should be downlinked, it is prioritized in the downlink queue.

- Post-Processing: Once the full observation is downlinked, it is prioritized in the post-processing queue. Post-processing involves multiple steps which are further described in the following sections. Results are posted in GHGSat's Geographic Information System ("GIS") (these can also be shipped manually to customers upon request), and any additional analysis is then performed and delivered as a technical report.

A typical customer order will include multiple measurements of the same site over a period of time. In these cases, the measurement process is iterated until the full set of measurements is collected, and technical reports are generated using the full set of measurements.

3.1.2 Technical Process Overview

The technology described in this Section 3.1.2 is protected under U.S. Patent 9,228,897 - FABRY-PEROT INTERFEROMETER BASED SATELLITE DETECTION OF ATMOSPHERIC TRACE GASES. Note that this technology is also patent-pending in Canada, Europe, India and Japan.

3.1.2.1 Image Correction

For each observation, raw files collected by the primary instrument on GHGSat-D are digital numbers. The image correction process converts these files of digital numbers into images with radiometrically calibrated light intensities.

Corrections include field flattening (correction for dark current and gain non-uniformity) and instrument spectral response adjustments (optical transmittance, quantum efficiency and instrument-specific corrections).

GHGSat selects the ground surface area within each acquisition sequence of images where post-processing provides the greatest spectral content (typically centered around the targeted site), substitutes bad pixels and removes spectroscopic information, leaving an image of surface reflectance in the short-wave infrared which GHGSat refers to as a "radiance image".

3.1.2.2 Column Density Retrievals

The GHGSat-D satellite measures the emissions rates of CO_2 and CH_4 from individual industrial sites via spatially resolved spectroscopy over a relatively small ground field of view ("FOV", 12 km diameter at 500 km altitude).

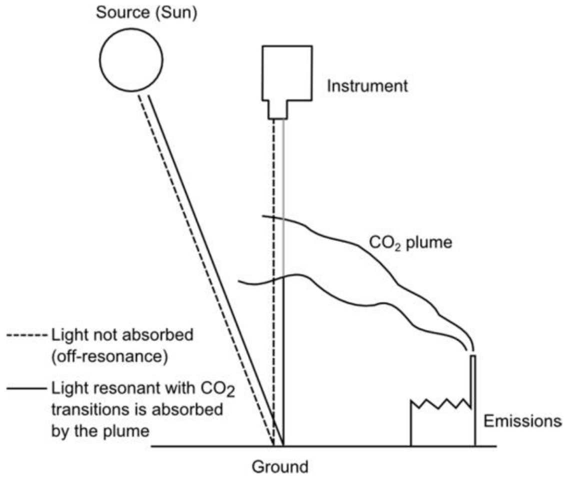


Figure 2: Simplified diagram showing the spectrally specific absorption of reflected sunlight by a CO_2 emissions plume, and subsequent detection by GHGSat-D.

A series of algorithms perform column density retrievals which result in an array of quantities for each ground pixel in an observation, including surface reflectance, carbon dioxide, methane and water vapour. This array is referred to as an "abundance dataset".

A "concentration map" combines the column densities from an abundance dataset and surface reflectance of a radiance image into a high readability pseudocolor map for a given observation. A simulated concentration map of an underground coal mine is provided in Figure 8 below to illustrate the result.

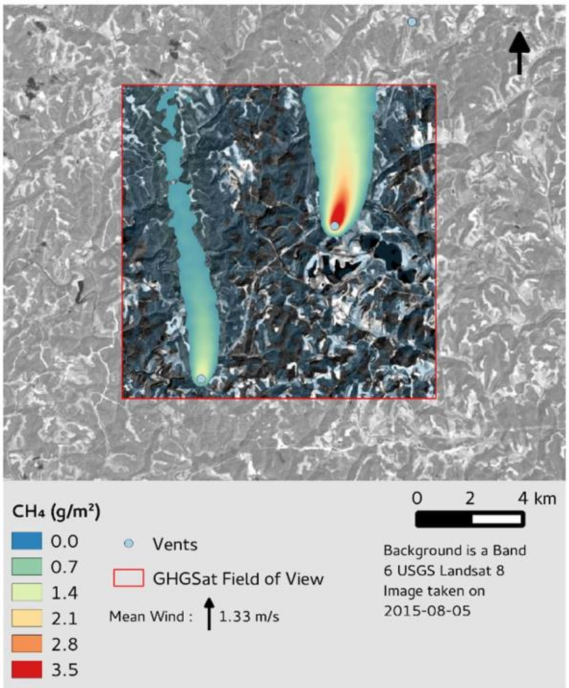


Figure 3: Simulated concentration map of underground coal mine.

3.1.2.3 Emissions Retrievals

The extraction of the emissions rate of CO_2 and/or CH_4 from a target measurement is referred to as emissions retrievals. The GHGSat approach is based on the fact that inverting the emissions from sources present within the FOV can be performed from column density maps having good relative accuracy without necessarily having high absolute accuracy. In other words, the variation of column density within the FOV is critical, whereas the background concentration level is less important because it is independent of the source.

The background columns of CO_2 and CH_4, while quite variable regionally, are expected to be fairly constant over the small 12 km x 12 km FOV of the instrument. Thus the column densities retrieved over a given site can be understood (modulo a small additive constant due to the slowly varying background column) and still permit the use of dispersion models to retrieve the emission rates, depending on the quality of the weather and terrain data.

Emissions retrievals take as input the abundance maps produced by the column density retrievals described above. These maps are then iteratively compared with a dispersion model that takes in meteorological conditions, terrain data and knowledge of source positions and simulates the dispersion and propagation of the plume for a given emissions rate. The dispersion model output is then converted to column densities for comparison with the satellite data. The estimated emissions rate and its uncertainty given the satellite observations and auxiliary data are obtained via convergence.

3.1.2.4 Post-Processing

The technical concepts described in the previous section are implemented in a series of algorithms which are collectively described as a "toolchain". The processing steps can be described using definitions consistent with the NASA Earth Observing System Data and Information System (EOSDIS), as summarized in Table 1 below. GHGSat products and services are outputs of certain levels.

Table 1: GHGSat Processing Levels, Products & Services

Processing Level	**EOSDIS Definition**	**GHGSat Products & Services**	**Description**
Level 0	Reconstructed, unprocessed instrument data at full resolution	n/a	Raw imagery is not offered as a product by GHGSat
Level 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information	n/a	Raw imagery is not offered as a product by GHGSat.
Level 1B	Level 1A data that has been processed to sensor units	Radiance Image	Imagery acquired in the SWIR band providing, per pixel, calibrated top-of-the-atmosphere radiance, in a 1600-1700 nm band
Level 1C	Level 1 data that has been processed to derive geophysical variables	n/a	Per-pixel column-density arrays for a single species (mol/m2)
Level 2	Derived geophysical variables at the same resolution and location as the Level 1 source data.	Abundance Dataset	Georeferenced set of (a) per-pixel column density (mol/m2) for a single species, and (b) per-pixel measurement error expressed as a standard deviation.
Level 3	Variables mapped on uniform space-time grids, usually with some completeness and consistency.	Concentration Maps	Map, sampled on a geodetic grid, providing: (a) surface reflectance (b) column density for a single species (c) estimated excess foreground density and (d) plume visualization layer combining the column density and surface reflectance in a high readability pseudocolor map.
Level 4	Model output or results from analyses of lower level data (ie. variables derived from multiple measurements)	Monitoring & Emission Rates	Monitoring: 6-month or full-year monitoring for detection of instantaneous emissions exceeding a predetermined threshold; Emissions Rates: Emission rate from targeted source estimated using abundance dataset(s) and applying dispersion modelling techniques

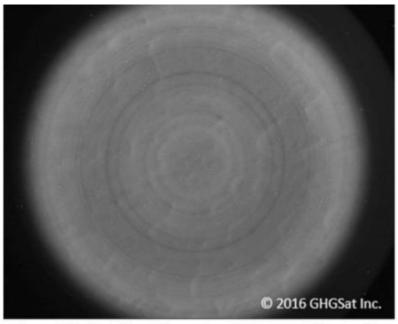
Other products and value-added services are also available from GHGSat on a case-by-case basis. Examples include (a) augmented analysis of emissions, using additional operator-provided facility data, and (b) trending analysis of emissions from individual sites, or grouped sites in a region.

4 INTERIM SATELLITE MEASUREMENTS

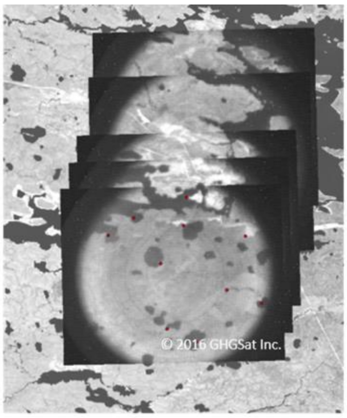
On 09 December 2016, Claire performed her 500th measurement – this time of a cement plant in South Africa. All satellite systems continue to operate normally, and GHGSat plans to double Claire's measurement rate as of early 2017.

The first set of images below is from summer 2016, during Claire's commissioning.

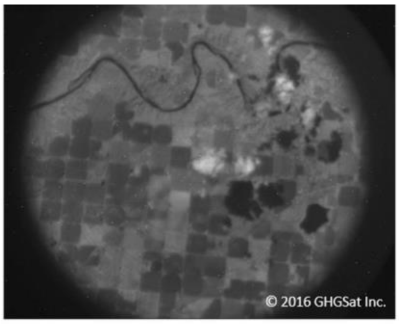
- Level 0, or "raw" images from Claire are two-dimensional surface images overlaid with circular absorption lines corresponding to carbon dioxide and methane in the atmosphere in the field of view of the image. One of the first such images was taken over the Arabian desert (left panel), and clearly confirmed that Claire's primary instrument had survived launch and was performing as expected.
- GHGSat must be able to geo-reference measurements with sufficient precision to identify facilities of interest. One of GHGSat's first efforts is shown below for a hydroelectric reservoir in Canada (middle panel). Again, this test confirmed GHGSat's ability to meet specifications.
- A successful measurement of emissions from any site requires tracking of the site for an extended period of time. An early tracking test over an animal feedlot (right panel) verified that Claire's attitude determination and control system exceeded specifications.



Level 0: Arabian Desert – Uniform Albedo & Thermal Stabilization Test



Level 0: Hydro Reservoir – Customer & Georeferencing Test (overlaid on Landsat-8)

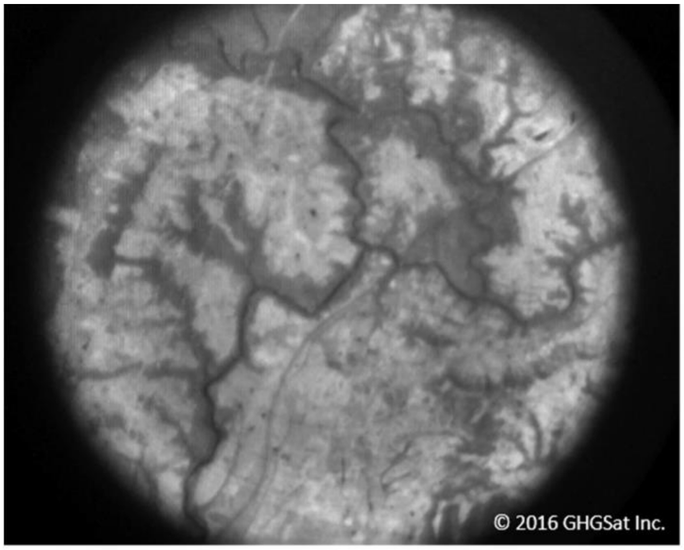


Level 0: Animal Feedlot –Tracking Test

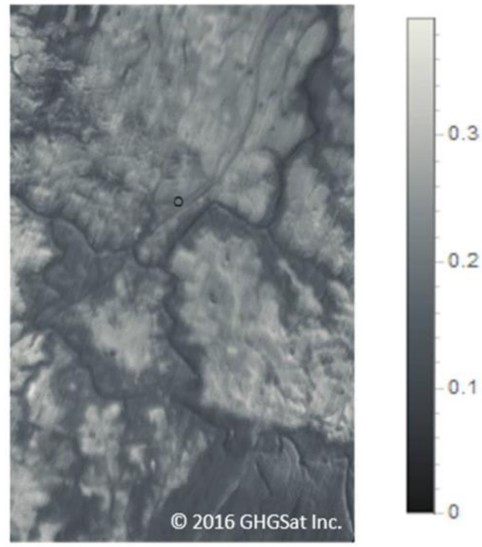
The second set of images below illustrates several steps of GHGSat post-processing. These images are from a measurement of the Camden site requested by CSIRO, as observed on 05 November 2016.

- The left panel is the raw image from Claire. Note that the raw image in the left panel is approximately inverted compared to the right-hand panel.
- GHGSat's retrieval algorithms produce several outputs, including geo-referenced surface reflectance as shown in the right-hand image.

One of the significant insights from these images is that the same features are readily recognizable in both images – demonstrating successful performance of GHGSat retrieval algorithms.



Level 0: Raw Image



Level 2: Surface Reflectance Retrieval (geo-referenced)

The same retrieval algorithms that generate the surface reflectance image such as the one shown above also generate carbon dioxide and methane data. GHGSat plans to release these data in early 2017.

Appendix C

GHGSat-D

CAMDEN CH4 ABUNDANCE DATASET

Document No. GHG-1145-6002

26 April 2017

GHGSAT PRODUCT / DOCUMENT APPROVAL

Title:	**GHGSat-D**
	Camden CH4 abundance dataset
Document No.:	**GHG-1145-6002-a**
Submission Date:	**26 April 2017**
Contact Information:	GHGSat Inc. 3981 boul. St-Laurent, Suite 500 Montréal, QC H2W 1Y5 email: stephane.germain@ghgsat.com Tel: 514-847-9474 Fax: 514-847-9474

Product/Document Originator:	Signature and Date
Stephane Germain	26 April 2017
Product/Document Review:	Signature and Date
Richard Giroux	26 April 2017

CHANGE HISTORY

Version	Release Date	Notes
a	26 April 2017	Initial Release

1 INTRODUCTION

GHGSat successfully launched its first satellite named "GHGSat-D", or "Claire", on 21 June 2016.

Since early July 2016, GHGSat has measured emissions for several industries including oil and gas, power generation, mining, cement, and agriculture. GHGSat Inc. is collaborating with the Commonwealth Scientific and Industrial Research Organisation ("CSIRO") on measurements being performed in a test area near Camden, for verification and validation of satellite measurements of greenhouse gas emissions in Australia.

This report describes abundance dataset results from one observation (GHGSat ref: 14hWJVo).

6 1.1Contents

2 DOCUMENTS

2.1 Applicable Documents

The following documents are useful for understanding the content of this document.

Ref	Title	Doc No.	Author	Publisher

2.2 Normative Documents

These documents should be considered as part of this document.

Ref	Title	Doc No.	Author	Publisher

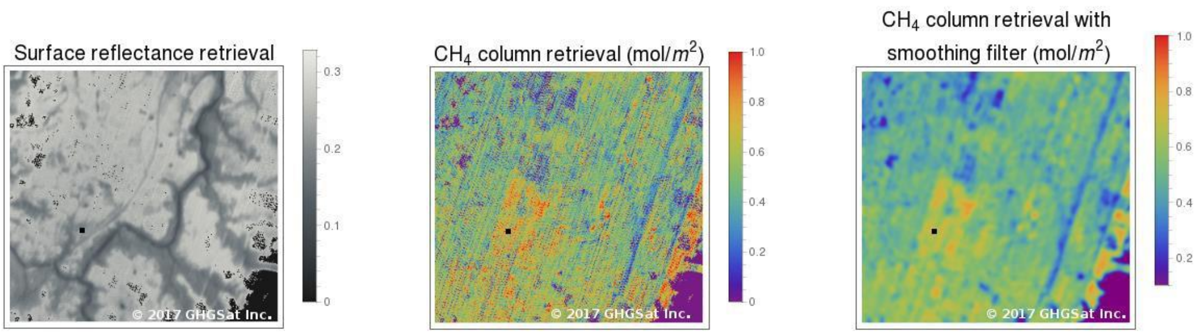
3 CAMDEN 14hWJVo OBSERVATION

The satellite observation was performed on 2016-10-30 23:10:42Z (2016-10-31 10:10:42 local time in Camden). The observation was centered at the following coordinates: -34.1285603, 150.7300895.

This observation was partially overexposed, and was therefore initially ignored for post processing. Upon further review, GHGSat determined that there would likely be sufficient information available to attempt a retrieval.

A retrieval was performed, and a selection of retrieval outputs is provided in Figure 1. The figure shows the retrieved surface reflectance and methane column density arrays (with and without smoothing). Areas in black (in the surface reflectance) and purple (in the CH4 column retrieval) are overexposed and therefore masked from the retrieval.

Visual inspection of the retrieval outputs suggests the presence of an emissions plume in these data. A concentration map is therefore produced in Figure 2, showing a zoomed version of the retrieved methane column density overlaid on a Landsat image (right image) and overlaid on GHGSat's retrieved surface reflectance (left image).



7 Figure 1: Camden Observation 14hWJvO Retrieval Output. Retrieval results for the Camden observation. For ease of visualization in this document we have cropped these data down to a 7.1 km x 7.6 km area. The black square indicates the location of coal mine ventilation fans. Note that the orientation of these images deviates slightly from North-South.

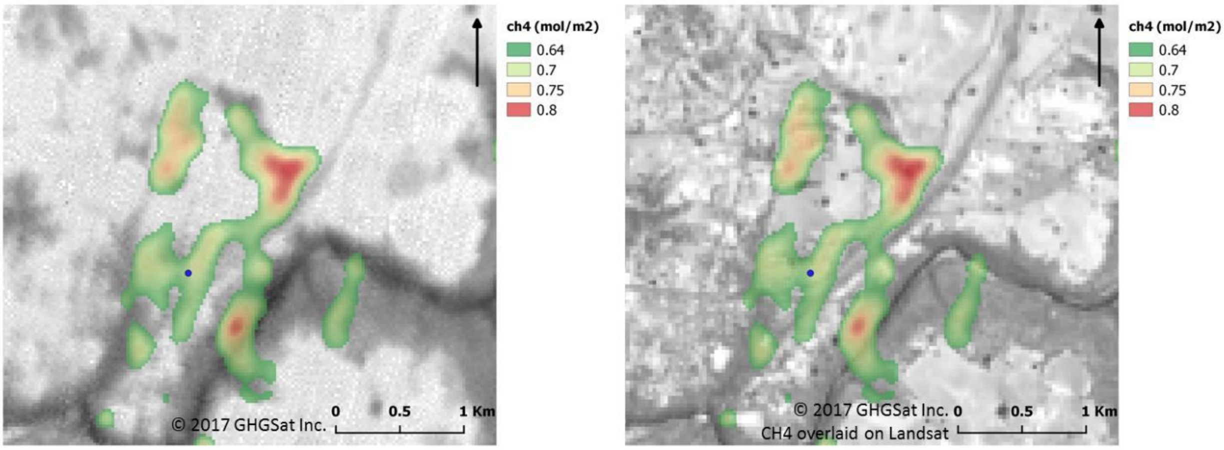


Figure 2: Concentration Maps

Figure 2 suggests that the location of the excess methane is generally consistent with simulated plumes evaluated separately from this report. Further, excess methane is generally consistent with CSIRO data collected near this site on the day of the satellite observation, providing indirect ground truth for the satellite observation. However, some issues must be considered in this retrieval:

- The retrieved methane column density array contains significant variations relative to methane background for the observation. The noise level is higher than typically observed with GHGSat's latest toolchain, although this is to be expected since the observation was degraded because some parts were overexposed. Simulations suggest that plumes could still be visible with this higher noise level, but these variations remain significant.
- Wind at the time of the observation was strong and gusty. The excess methane appears to be in approximately the right locations, but there is no clear plume shape – perhaps because of the wind.
- The local topography may play a role in the dispersion of the gas in this retrieval. The coal mine ventilation fans noted in the retrieval are in a small valley, affecting the dispersion of methane, and in this case perhaps aiding detection of the source.

In general, the evidence of plumes in this observation is very encouraging (particularly with the available ground truth), but these data are not yet conclusive. GHGSat has and will continue to repeat post-processing as updated toolchains become available to reduce noise, and repeat measurements of Camden under more favourable wind conditions to provide other examples of plumes from this site.

Note that there are some patterns to the variations (e.g. diagonal stripes, albedo crosstalk), which are unlikely to be the result of emissions sources. GHGSat believes these patterns and spurious variations are primarily due to modelling errors, image alignment errors and the effect of uncorrected instrument imperfections, all of which are currently being addressed by ongoing retrieval toolchain development efforts.

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