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Regional Methane Emissions in NSW CSG Basins

Interim Report

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Copyright and disclaimer

Important disclaimer

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Acknowledgements

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We acknowledge the assistance of Stephane Germaine of GHGSat in planning and logistics in the acquisition of "Claire" for the Camden site and their ongoing support in processing the data and efforts in continuing acquisition to obtain an optimum dataset to showcase the capabilities of the sensor for the application.

Executive Summary

The purpose of the current GISERA greenhouse gas project is 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 is being conducted using ground based methods developed during the earlier work undertaken in the Surat Basin in Queensland. A second component of the project is aimed at investigating a new satellite sensor specifically designed for measuring methane, which has the potential to be applied across Australian CSG sites for ongoing monitoring. The project commenced in July 2016, and in this report we describe the work that has been undertaken to date and present some preliminary findings. The plan for the remainder of the project is also briefly discussed.

Mobile surveys using an instrumented vehicle have been 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 operation of gas actuated pneumatic devices.

The survey region contains a large number of boreholes including coal and mineral exploration holes and water bores. To date, surveys in the near vicinity of some 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. However, we have so far examined only a very small proportion of the total number of boreholes present.

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 identify within the region. To provide context, this figure is approximately the amount of methane produced by 90,000 cows (1.6% 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 mines have much lower emissions, ranging 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 120 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 two 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 to have a methane emission rate of about 28 g min^{-1}.

An initial trial of a new Canadian satellite borne sensor (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. This site, which was about 12 $\times$ 12 km in area, was selected to contain a range of CSG production facilities as well as other methane sources including a large underground coal mine vent and a landfill site. Analysis of the data from the acquisitions is currently being undertaken by the satellite operator.

1 Introduction

Greenhouse gas emissions from unconventional gas production have been the subject of considerable public and scientific interest recently. Over the last few years there have been numerous studies, especially in the United States, 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 emissions from the Marcellus shale gas region in Pennsylvania to be within the range of 2.8 to 17.3 % of production. The upper estimate of this study has been reported in Australian media to suggest that high levels of emissions are typical of Australian coal seam gas production (TAI, 2016). However, the wide range of emission estimates reported 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. However, there is also mounting evidence to suggest that in the U.S. 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 but also 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 suitable methodology to characterise regional fluxes of methane across the region (Day et al., 2015). During this study, various techniques have been 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 this work is essential for assessing and quantifying changes in emissions as production increases to supply the export LNG market, the study only commenced at a comparatively late stage of gas field development; 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. 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. This tends to limit their applicability to detecting low level natural emissions or even emission for CSG infrastructure but a Canadian company has recently deployed a new satellite (GHGSat) that is claimed to be capable of monitoring surface methane emissions to 50 x 50 m. This fine resolution potentially has wide application in the gas industry. The opportunity now exists to acquire data over a gas producing region in Australia, which will allow detailed evaluation of the sensor's capability and to determine if it has application to the Australian industry.

The aim of the current GISERA project described in this interim report is to investigate potential land seeps of methane, including legacy boreholes such as those that have been discovered in the Surat Basin in Queensland, and other natural and anthropogenic methane sources in the Pilliga region, which is likely to see significant development over the next few years. Emissions from these sources (which include coal mining, landfills, wastewater treatment, agriculture) will be estimated using some of the techniques developed during the Queensland GISERA project or by other appropriate methods to build a detailed methane emissions inventory for the region. This inventory will provide a baseline against which to compare emissions once large scale gas extraction commences.

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

Since commencing the project, we have started to develop a detailed methane emissions inventory for the Pilliga and surrounding region. In addition, a trial of the new GHGSat satellite methane sensor was undertaken during November and December 2016. The results obtained to date are briefly described in the following sections. A detailed final report of the project is due to be provided at the conclusion of the project scheduled for later in 2017.

2 Progress

2.1 Methane Inventory

Work towards developing a methane inventory for the Pilliga region has been focussed on the use of mobile vehicle surveys that were trialled extensively during the Queensland GISERA Project. A detailed description of the method is provided in 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. The performance of the methane analysers used in this and similar studies (either a Picarro 2301 cavity ringdown spectrometer or a Los Gatos Research Ultraportable $CH_4/C_2H_2/H_2O$ Analyser) are such that often even very small sources can 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 and prevailing winds also affect the ability to detect sources.

Surveys have been made in the Pilliga and Narrabri regions to locate and identify sources of methane. The general survey area is shown in Figure 1, which shows the locations of CSG wells within the region (note that these include both production and abandoned well sites. Also shown are the locations of several large coal mines within the region.

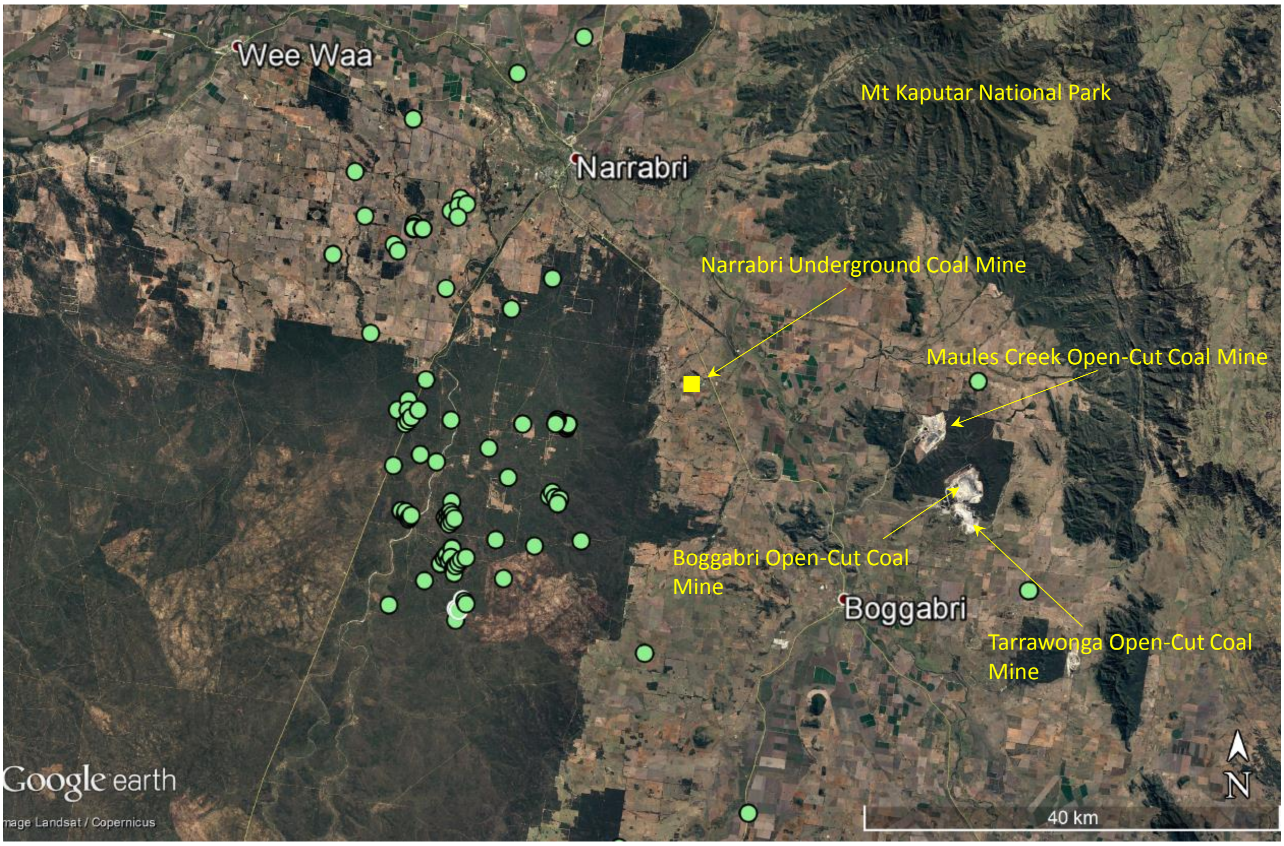


Figure 1. Survey region - the green markers indicate CSG wells. The main coal mines within the region are also marked.

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 (Day et al., 2016; Blake et al., 1984; Lowry et al., 2011; Phillips et al., 2013). Within the forest areas near CSG wells, the ambient methane concentration was virtually constant with none of the peaks that usually indicate the presence of nearby methane sources observed.

For comparison, a similar survey was made within the Mount Kaputar National Park, 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. As expected, 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 essentially identical 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 NSWEPA, found similar ambient levels during each survey although there were some instances where 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 about 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
- Sewage treatment facilities

Where possible, we have attempted to locate these sources and estimate their methane emission rates 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 2).

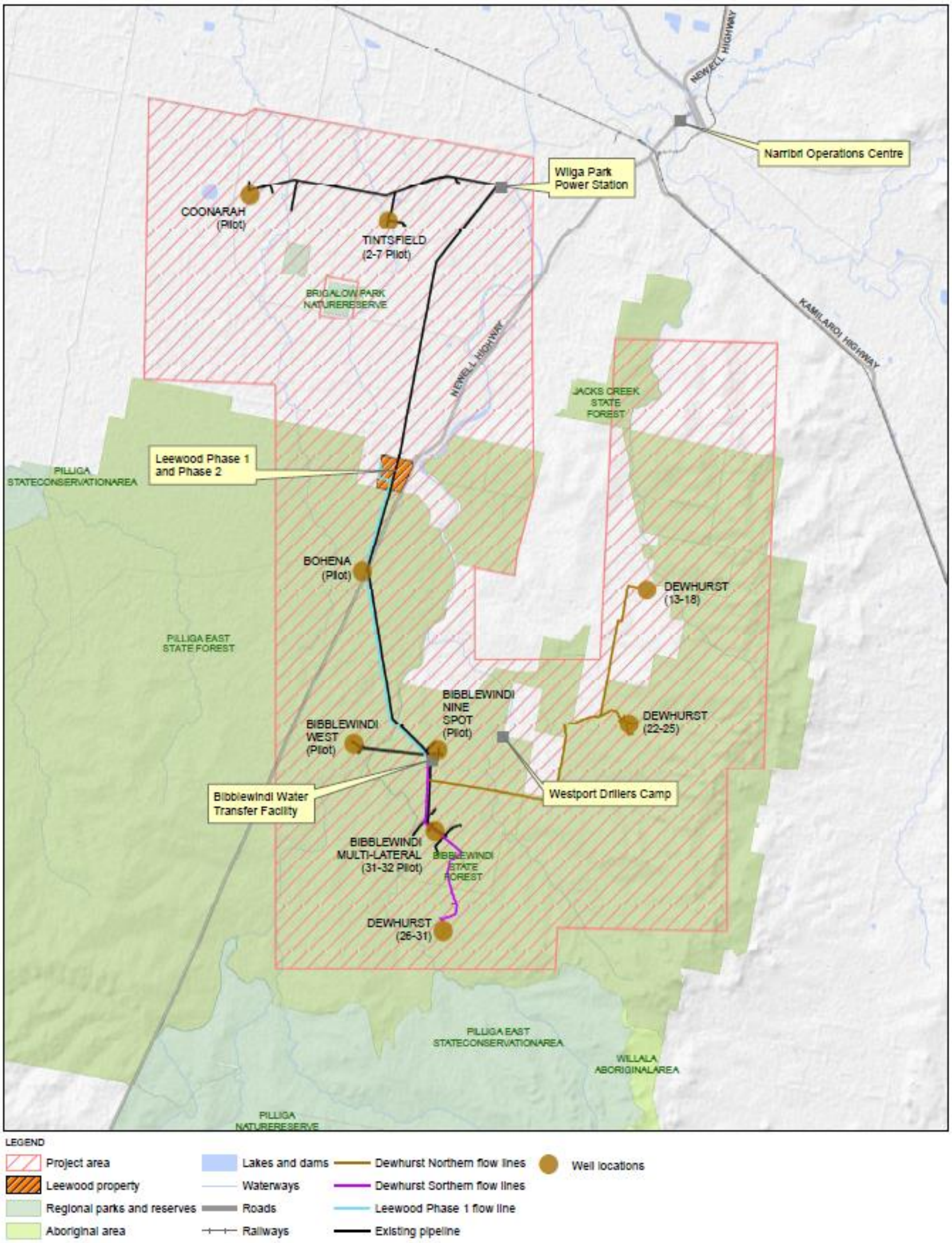


Figure 2. Location of current CSG infrastructure (from Narrabri Gas Project Preliminary Environmental Assessment; GHD, 2014)

So far within the current GISERA project we have not measured emission rates from CSG infrastructure. 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 Australian CSG wells (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}.

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.

There are approximately 45 wells in the Pilliga gas field 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 120 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. Further work is therefore necessary to more reliably define the level of emissions from the gas facilities.

To place this albeit approximate emission estimate 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 (Figure 2.1). The three 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 have 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 3) 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.

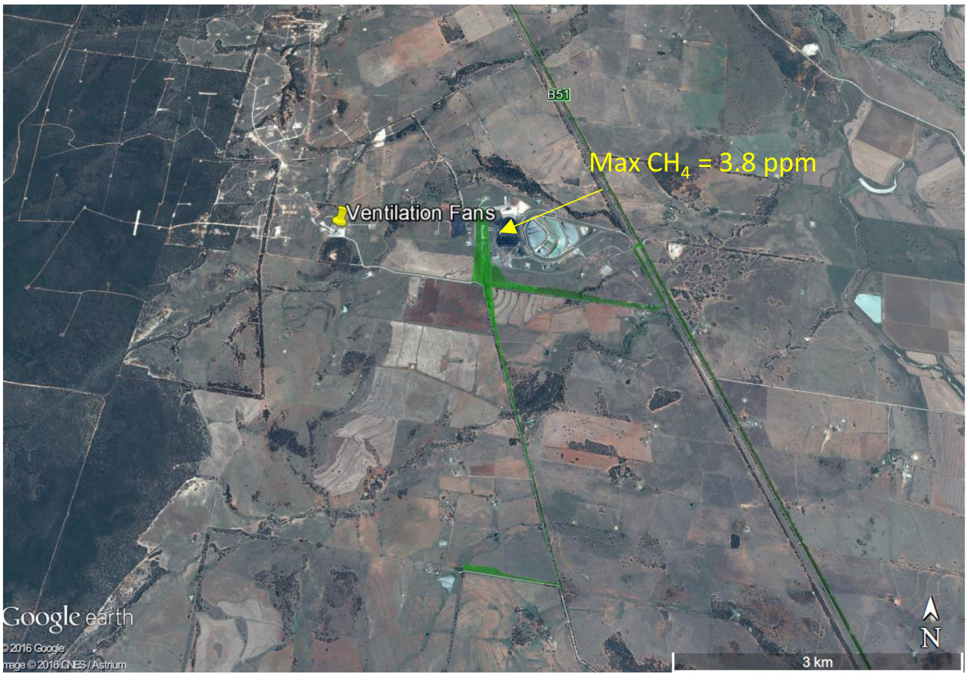


Figure 3. Methane concentration measured near the Narrabri underground coal mine.

Despite this, 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 methane (Whitehaven Coal, 2014). This is equivalent to approximately 9,000 g CH_4 min^{-1}.

Similarly, the three open-cut mines also report emissions in their Annual Reviews. 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-e for 2014 (Boggabri Coal, 2016). This is equivalent to 188 t CH_4 (with a GWP factor of 25) 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 CO2-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 (147 t methane; 281 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.

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, after several passes along the road, methane concentrations remained 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 near Narrabri and the Narrabri wastewater treatment plant. Both of these sites were subject to ground level downwind traverses under wind conditions that allowed quantification of the methane emission rate.

Figure 4 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.

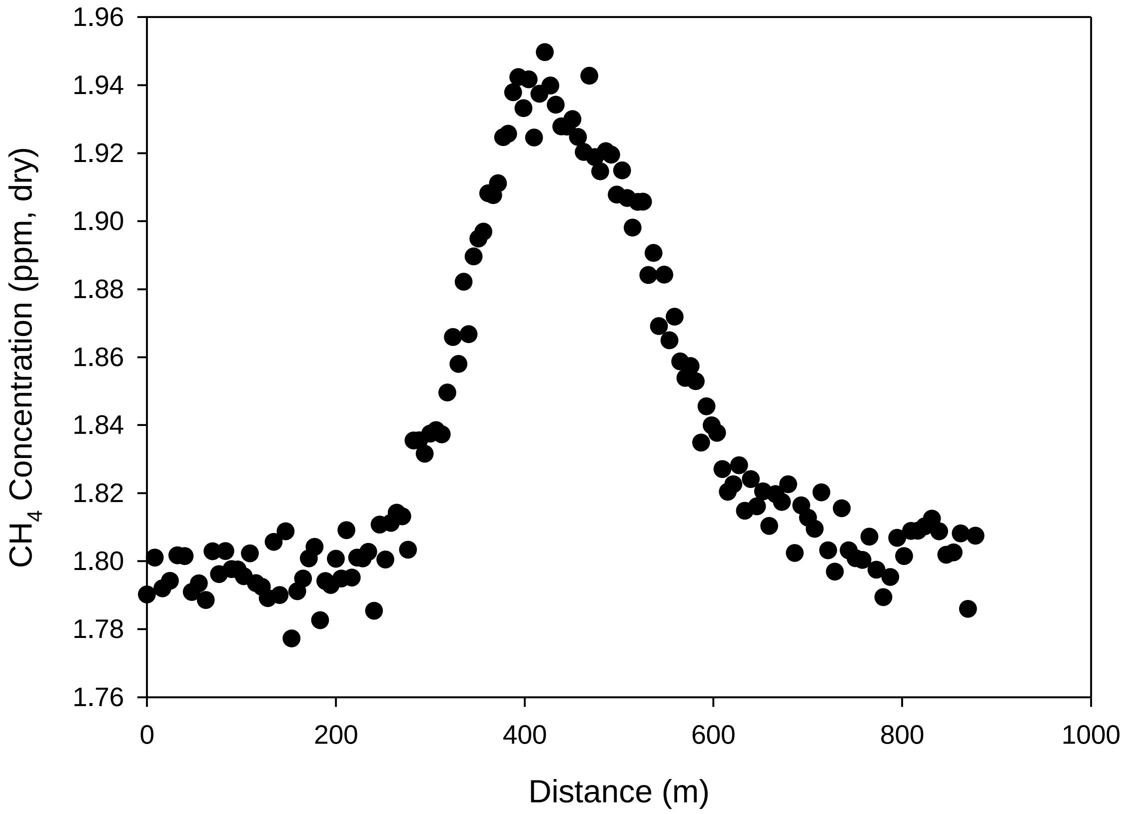


Figure 4. Methane concentration as a function of distance across the methane plume from a landfill site near Narrabri.

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. In this case the average methane emission rate estimated from the facility was 28 g min^{-1} (standard deviation of 11.8 g min^{-1}). A summary of the emission rates estimated from the main sources investigated to date is provided in Table 1

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

Methane Source	Estimated Emission Rate (g min^{-1})	Location	Notes
Narrabri Underground Coal Mine	9,000	-30.52°, 149.88°	Obtained from mining company's own estimate published in 2014 AEMR
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	281	-30.56°, 150.13°	From an estimate based on in situ gas content provided in the Maules Creek Mine Environmental Assessment from 2011.

Methane Source	Estimated Emission Rate ($g\ min^{-1}$)	Location	Notes
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
Landfill	281	-30.33°, 149.72°	Estimated from downwind traverses
Wastewater Treatment Facility	28	-30.30°, 149.78°	Estimated from downwind traverses
CSG Wells	120	Various	Estimated using average emission rate measured on six CSG wells between May 2015 and Feb 2016 during a previous investigation in the area.

Based on this limited 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 preliminary and incomplete so it is not yet possible to accurately rank regional emission sources. For example, the Wilga Park power station and CSG infrastructure (apart from the well pads) have not been included. Moreover, most of these estimates are based on single measurements and do not consider any seasonal or other variability that may affect emissions.

Two other sources that are not listed in Table 1 but may be significant are agricultural activities (especially enteric fermentation from cattle production) and potential leaks from boreholes. Methane emissions from cattle has been studied extensively and reliable emission factors are available so total emissions from the sector can be estimated using herd populations. Work in this area is continuing for this project.

With regard to leaking boreholes, previous investigations in Queensland found a number of legacy coal exploration boreholes were leaking varying amounts of methane (Day et al., 2015). Other unpublished work conducted within our group has identified various water bores in the same region where up to 100 g CH_4 min^{-1} was emitted from a single bore. To assess the extent of methane leakage from borehole, we used the NSW Department of Resources and Energy database MinView (http://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/services/online-services/minview) to locate boreholes within the study region. Figure 5 shows a map produced from MinView showing various borehole locations.

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 shown in Figure 6.

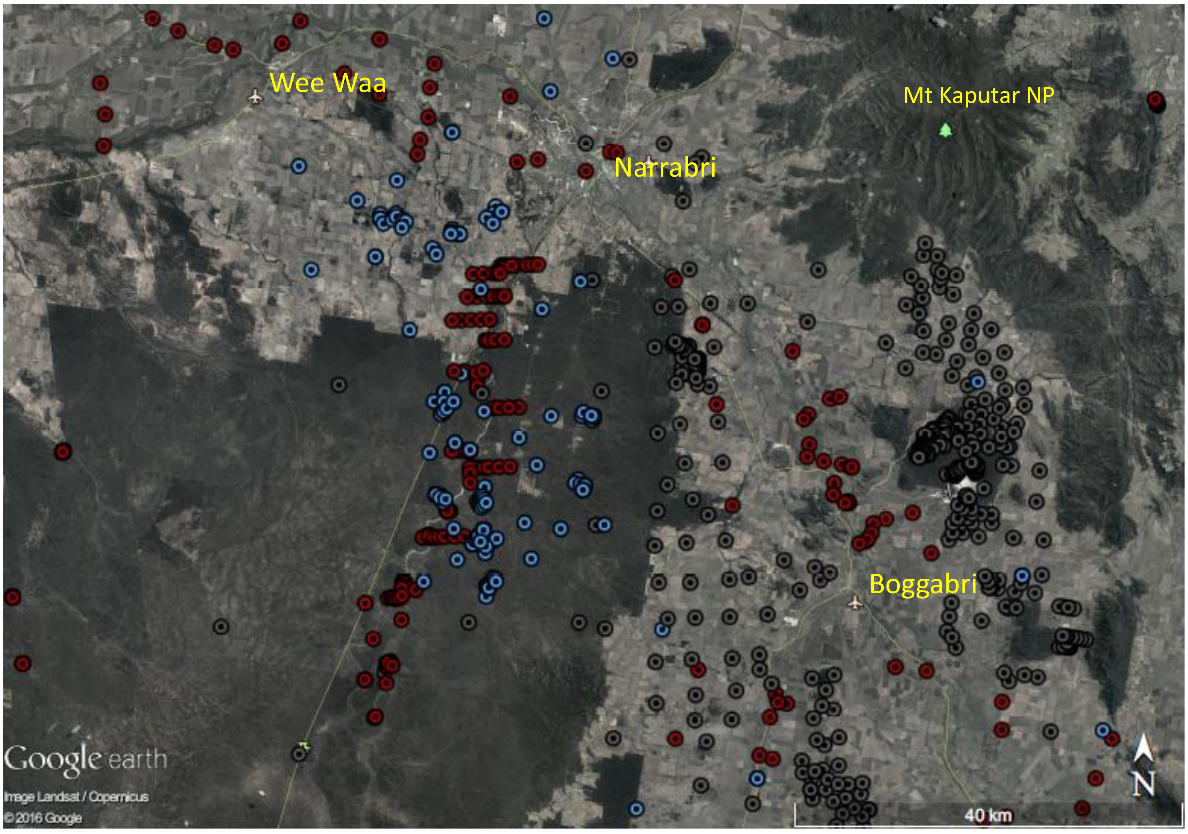


Figure 5. Location of registered petroleum boreholes (blue markers), mineral boreholes (red markers) and coal boreholes (brown markers).

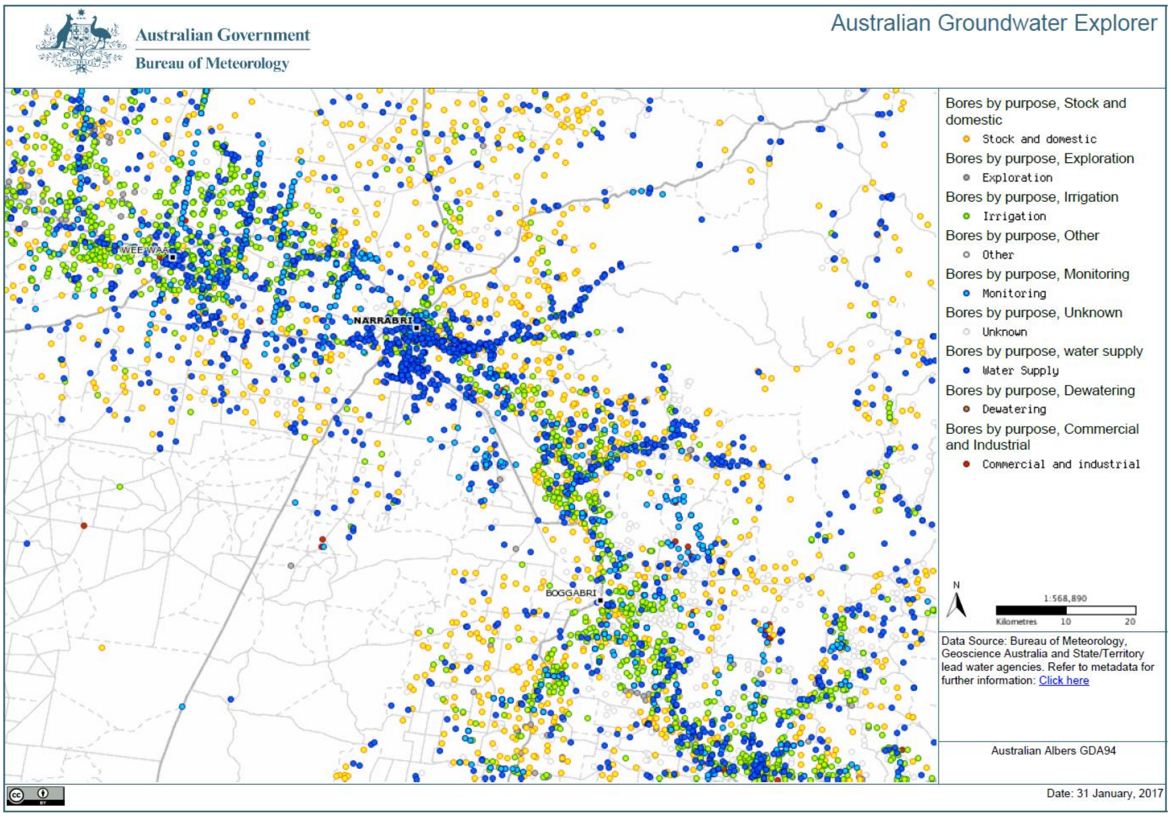


Figure 6. Locations of water bores within the survey region (from Australian Groundwater Explorer, Bureau of Meteorology)

It is obvious from Figures 5 and 6 that there is a large number of bores of different types distributed over a wide area within the survey area. Where possible, mobile surveys have been made along public roads near many of these boreholes. During previous work in Queensland, this method was found to be effective for locating leaking coal exploration boreholes (Day et al., 2015).

The results of the surveys have not so far not indicated the presence of any leaking bores; however, we have only examined a very small fraction of the total number. Many of the boreholes are also on private land which complicates access in many cases.

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 this regard. Investigation of suitable remote sensing platforms is being actively pursued as part of this project (see Section 2.2 of this report).

In four cases, we have used surface flux chambers to measure methane emissions at the indicated bore locations within the Pilliga forest, although, usually, there is no longer any surface indication of presence of the bore. Details of the experimental method used for measuring surface flux is provided in Day et al. (2015). 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 each borehole location up to six individual flux measurements were made; the average of these measurements at each location is shown in Table 2.

Table 2. Summary of surface methane flux measurements made at four borehole locations within the Pilliga Forest.

	Location	Average CH_4 Emission Rate (g m^{-2} day^{-1})
Hole No 1	-30.43, 149.77	-0.0022
Hole No 2	-30.49, 149.84	-0.0007
Hole No 3	-30.53, 149.78	0.0002
Hole No 4	-30.86, 149.45	-0.0005

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

2.2 Remote Sensing Trial

2.1.1 GHGSAT-D INSTRUMENT/SENSOR

The "GHGSat-D", or "Claire" is the first of a series of satellite-borne remote sensing instrument launched into space by GHGSat Inc. It was successfully launched on 21 June 2016. This instrument 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 (CO_2) and methane (CH_4) using passive optical remote sensing.

The GHG Sat-D 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 will be exploiting the 1690 nm spectral absorption feature at 120 pico nm spectral resolution. The C&A measuring in the 400-1000 nm spectral range at 0.12 nm spectral resolution and 150 m spatial resolution, is mainly 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 for.

The total area captured by an acquisition is approximately 12 km x 12 km. This acquisition area 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 gas underground coal mine.

2.1.2 TEST SITE

The test site selected for this experiment was an underground coal mine in the Camden area centred at approximately 34° 7'48.47"S, 150°43'35.76"E as shown on Figure 7. This mine was selected because it was a large source of CH_4 and surrounding the mine there were other sources of methane including a landfill, dairy industry and gas processing plant. The different sources of CH_4 would provide a range of different sources at different levels for us to determine the capabilities and limitations of the instrument.

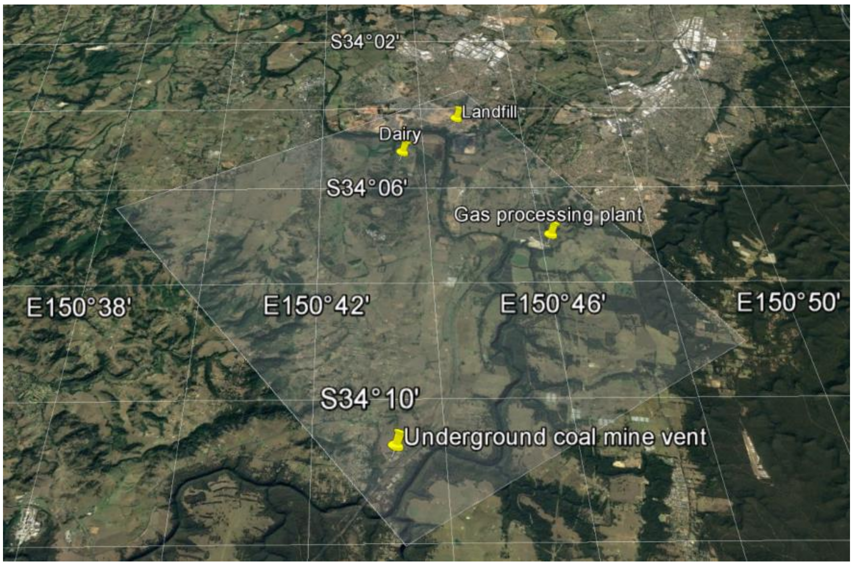


Figure 7: Google Earth image showing the acquisition area and the sources of CH_4 covered by the imagery.

2.1.3 INTERIM RESULTS

Field validation data were acquired with the Picarro and Los Gatos Research instruments mounted in two vehicles (as used for the surveys described in Section 2.1 on 31st October 2016) scheduled to be concurrent with a "Claire" satellite 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.

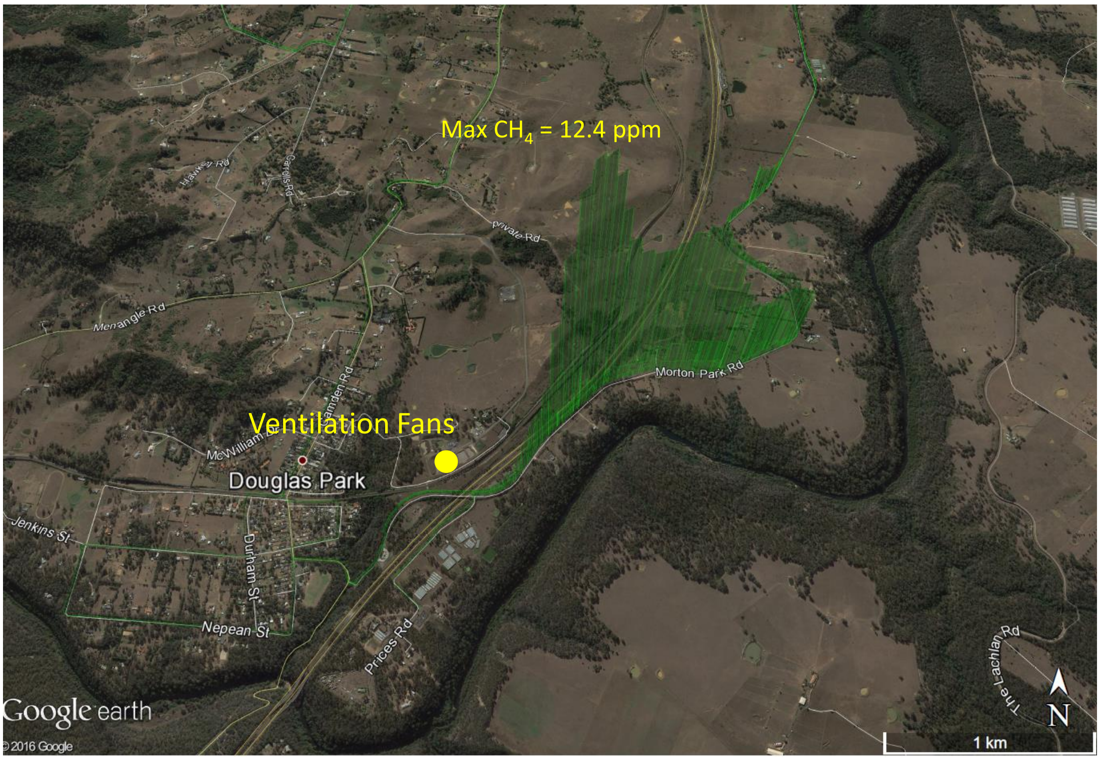


Figure 8. Methane concentration as a function of position measured near the outlet of the underground mine ventilation fans on 31st October. The green trace represents the methane concentration. The maximum methane concentration measured during the survey was approximately 12.4 ppm.

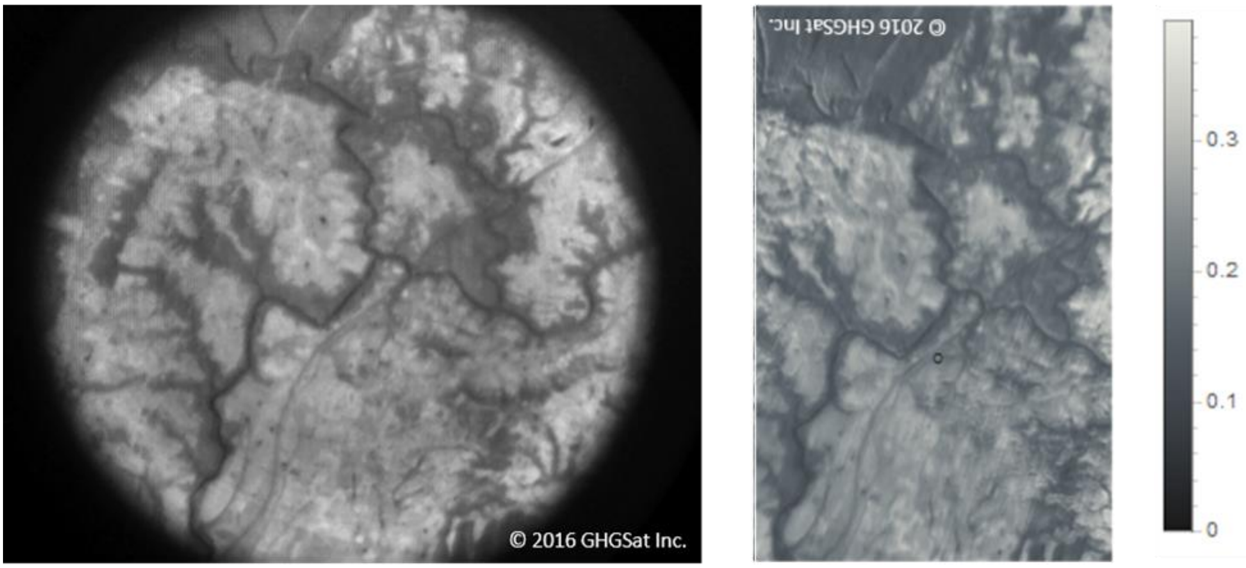
Although we do not have actual emissions from the mine we have used published data to estimate the approximate methane emission rate. According to the environmental impact assessment for the construction of the fans, the expected ventilation flow rate from the fans is of the order of 550-650 $m^3 s^{-1}$ 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}.

The satellite acquired data over the target site at approximately 10:30 am, local time which coincided with the ground measurements. Unfortunately, the satellite data yielded an overexposed image that was not suitable for further analysis.

A further acquisition was rescheduled for the following week. Data were successfully acquired for the test site on 4th November 2016. However, the acquisition area was shifted to centre on the underground coal mine missing some of the other sources of CH_4.

At this stage, the information delivered is an interim report (Appendix A) documenting the processing that was conducted for this imagery. Black and white imageries of a single band of the raw and processed to surface reflectance products (shown in Figure 2.7) were provided to confirm the area of acquisition and the accuracy of the geo-positioning. GHGSat is currently undertaking further post-processing of the data to account for spurious variations from various sources of error. It is anticipated that we will received further processed data including Level 1B (surface reflectance data) in early 2017.

In addition to the data acquired on 4th November, “Claire” is expected to acquire more data across the Camden test site.



Level 0: Raw Image

Level 2: Surface Reflectance Retrieval (geo-referenced)

Figure 9. Left: Raw data acquired from "Claire" on 5th November 2016. Right: Georeferenced surface reflectance derived from "Claire" data acquired on 5th November 2016.

2.1.4 HYPERION EO-1 SENSOR

Hyperion is the first imaging spectroscopy (or hyperspectral) sensor mounted on an Earth orbiting satellite (EO-1). Launched by NASA in November 2000 as a civilian science mission, it is still in operation today, albeit beyond its projected mission life. Hyperspectral sensors, such as Hyperion, are highly calibrated instruments that collect imagery containing many (more than 100) spectral bands representing a range of wavelength ranges from the ultraviolet to the infrared (400-2500 nm). The instrument acquires a 7.5 km by 100 km land area per image, and provide detailed spectral mapping across all 220 channels at approximately 10 nm spectral resolution. In comparison, traditional satellite imagery of multispectral sensors, that were operationally available since 1980 and are more commonly used, only collect information across several to 20 spectral bands.

Recently, Thompson, et al. (2016) reported on the use of Hyperion data to detect an accidental CH_4 release. Hyperion data were requested across the same test area at Camden to test the feasibility of the use of Hyperion data. At this stage, there are 8 acquisitions of the Camden area ranging in dates from January 2003 to January 2017. The cloud free images from these set will be evaluated to determine their use for mapping methane for the Camden test site.

3 Further Work

Preliminary surveys have been made through the Pilliga forest region where most of the CSG development is located and these combined with previous surveys indicate generally low levels of methane within this area. Although this suggests that emissions from CSG activities are low only a handful of wells have been examined in detail (during a previous project) and emissions from the bulk of the infrastructure have not been measured. We plan to conduct further surveys through the gas field during the remainder of the project but in the longer term (i.e. beyond the current project) it would be worth attempting to measure emissions from other parts of the gas production facilities, especially the gas processing plant and water treatment facilities.

There are a large number of various types of boreholes throughout the study region and so far only a small number of these have been examined to determine if they are leaking methane. We intend to continue investigating this potential source as part of the project, although it is acknowledged that time limitations and land access will limit the scope of these investigations.

Work will continue on identifying the main methane sources within the Narrabri/Pilliga region to further develop the emission inventory for the region.

Currently, the complete datasets and results have not been delivered from GHGSat. It is expected that the complete set of “best available” set of data will be available from GHG Sat in early 2017. After receipt of these data, evaluation will be undertaken of these datasets to determine their suitability for regional scale characterisation of methane sources.

A temporal dataset is available from the Hyperion sensor. The datasets that are least affected by cloud acquired by the Hyperion sensor will be processed and analysed. Evaluation of this sensor to understand the uses and limitations of this sensor to undertake regional scale baseline surveys of methane. Although this sensor’s capabilities is lower than imaging spectroscopy sensor expected to be launched in the future, it may provide an insight into their capabilities for methane mapping.

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Appendix A

GHGSat-D

CSIRO INTERIM INFORMATION

Document No. GHG-1145-6001

16 Dec 2016

GHGSat Product / Document Approval

Title:	**GHGSat-D**
	CSIRO Interim Information
Document No.:	**GHG-1145-6001-a**
Submission Date:	**16 Dec 2016**
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: Stephane Germain	Signature and Date
Product/Document Review: Richard Giroux	Signature and Date

CHANGE HISTORY

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

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.

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.

Documents

Applicable Documents

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

Ref	Title	Doc No.	Author	Publisher

Normative Documents

These documents should be considered as part of this document.

Ref	Title	Doc No.	Author	Publisher

Satellite Measurements

Measurement Process

1.1.2 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 10, 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).

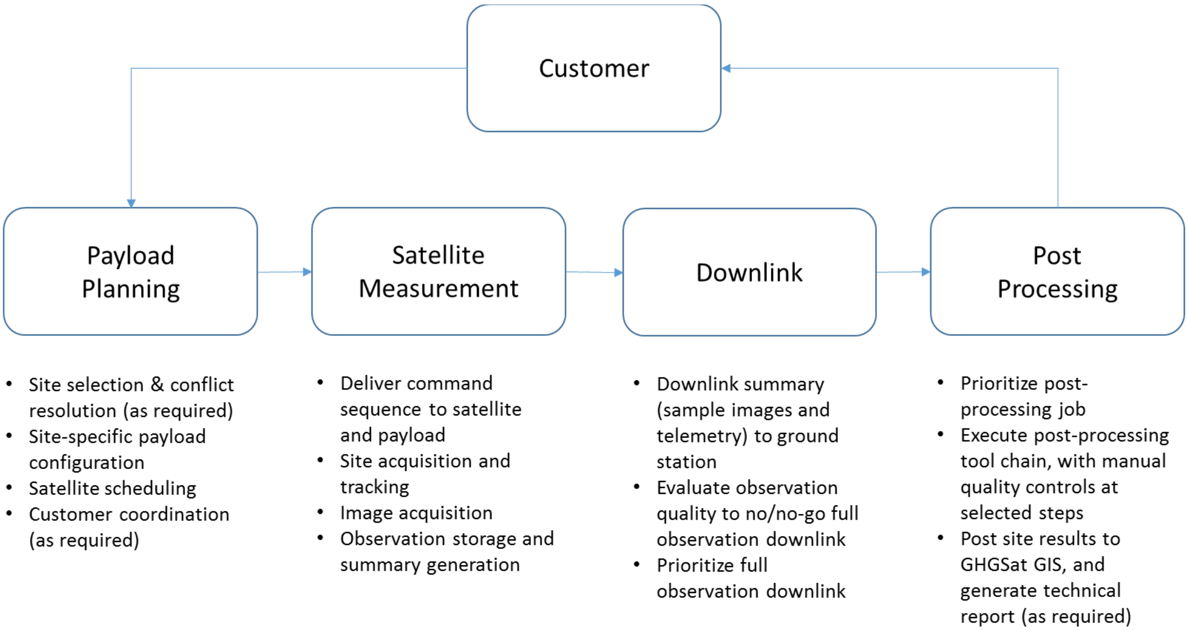


Figure 10: Operations Sequence

- 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.

1.1.3 TECHNICAL PROCESS OVERVIEW

The technology described in this Section 1.1.3 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.

1.1.3.1 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".

1.1.3.2 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).

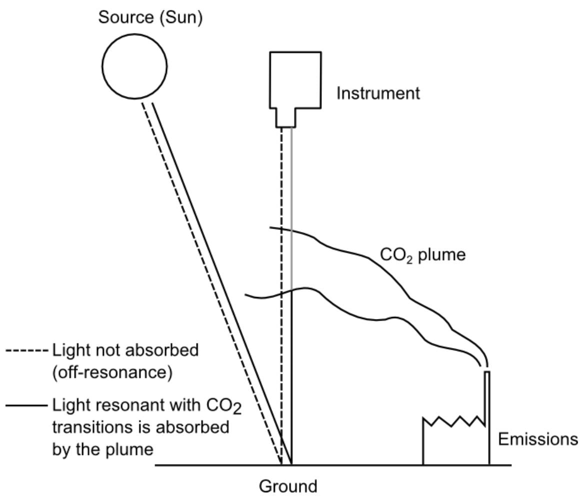


Figure 11: Simplified diagram showing the spectrally specific absorption of reflected sunlight by a CO_2 emissions plume, and subsequent detection by GHGSat-D.

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.

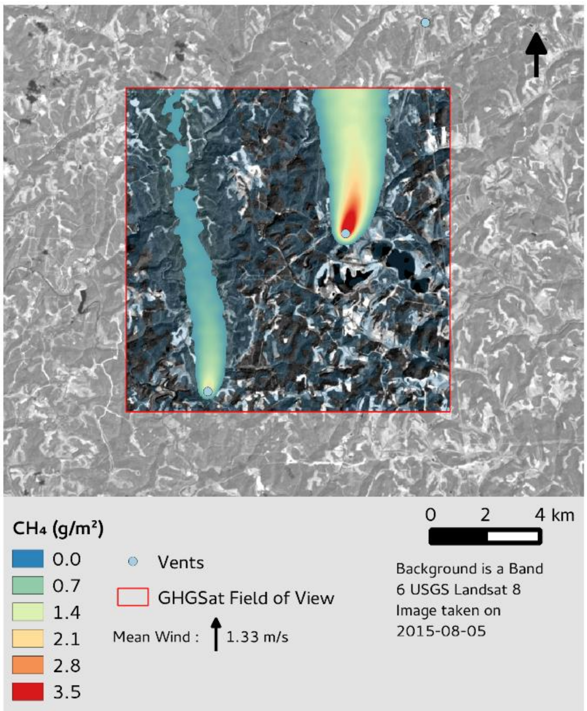


Figure 12: Simulated concentration map of underground coal mine.

1.1.3.3 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.

1.1.3.4 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 3 below. GHGSat products and services are outputs of certain levels.

Table 3: 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

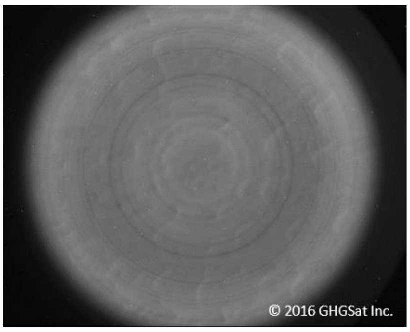
Other products and value-added services are also available from GHGSat on a case-by-case basis. Examples include (a) augmented analysis of emissions, using additional operator-provided facility data, and (b) trending analysis of emissions from individual sites, or grouped sites in a region.

Interim Satellite Measurements

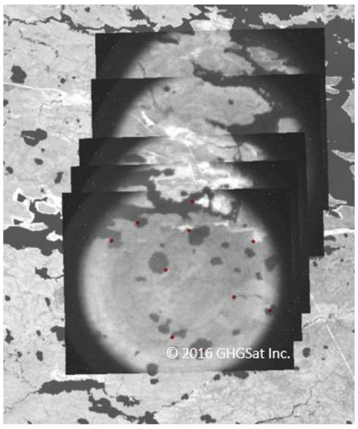
On 09 December 2016, Claire performed her 500th measurement – this time of a cement plant in South Africa. All satellite systems continue to operate normally, and GHGSat plans to double Claire's measurement rate as of early 2017.

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

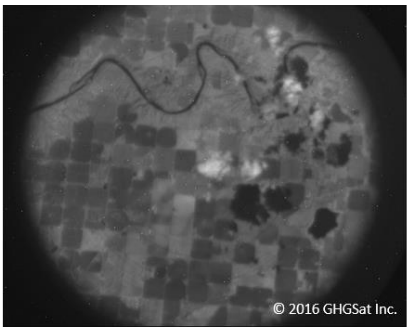
- Level 0, or "raw" images from Claire are two-dimensional surface images overlaid with circular absorption lines corresponding to carbon dioxide and methane in the atmosphere in the field of view of the image. One of the first such images was taken over the Arabian desert (left panel), and clearly confirmed 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)

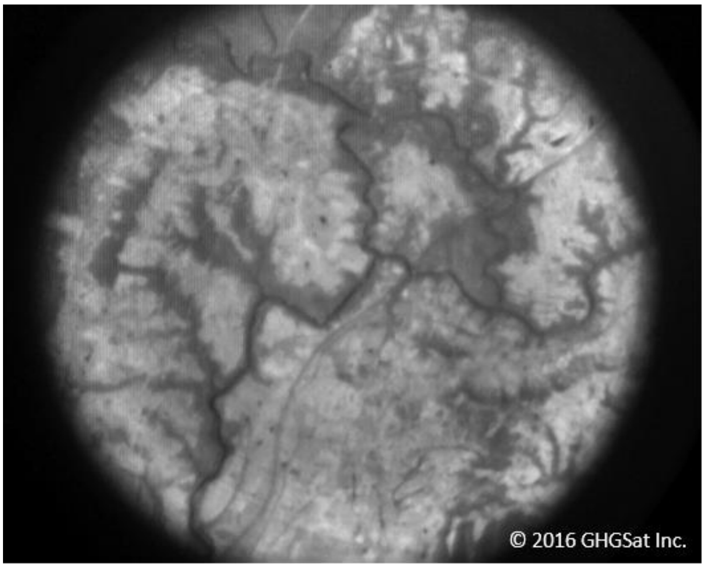


Level 0: Animal Feedlot –Tracking Test

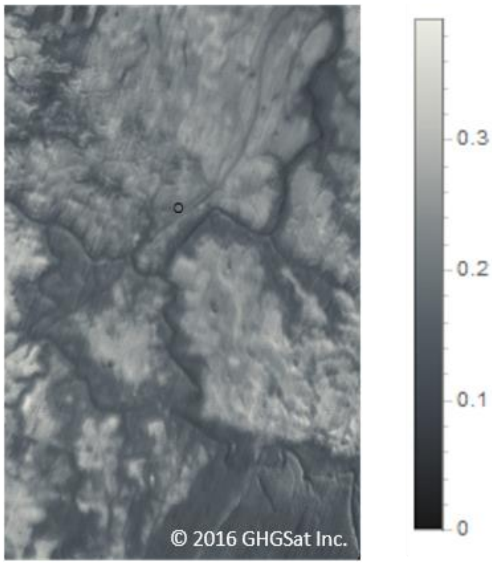
The second set of images below illustrates several steps of GHGSat post-processing. These images are from a measurement of the Camden site requested by CSIRO, as observed on 05 November 2016.

- 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.

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