The use of high-resolution satellite imagery to identify methane emissions from underground mines: A CMM case study of a mine within the Karaganda Coal Basin

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Introduction

The concept of coal mine methane (CMM) encompasses the methane released during and after mining operations. Thus, the CMM constantly presents health, safety, and environmental (HSE) challenges (1). Therefore, the implementation of efficient ventilation systems in underground coal mines is critical in the operational safety of the mines. As opposed to surface mining operations where surface mine methane (SMM) is emitted directly as an area source, ventilation systems are typically designed to exhaust an air stream with a concentration of methane that does not exceed one percent by volume, increasing the diffusivity of methane when released to the atmosphere (2). However, these ventilation air methane (VAM) emissions may account for 60-70% of the total methane emissions emitted by the industry (3).

Coalbed methane (CBM), of which CMM is a subset, is the methane that is generated prior to mining. CBM is also known as coal seam methane (CSM), coal seam natural gas (CSNG), and coal seam gas (CSG). In the last twenty years, the production of CBM has taken notoriety as an alternative to coal-based electricity production. Recent research has indicated that its extraction could be less expensive than shale gas due to the shallowness of CBM coal fields (4). A recent study indicates that the CBM production has expanded from coalfields dominated by thermogenic methane to coalfields with significant biogenic contributions (5). Nonetheless, studies on coal extracts indicate that the composition of CBM in the San Juan basin (the largest CBM producing area in the world) is a mixture of thermogenic (25-35%), migrated thermogenic (12-60%) and secondary biogenic (15-30%) (6). A study in the Bowen basin, concluded that microbial gas generation is responsible for zones of higher gas saturation and production, enriching the CBM content through the reduction of longer hydrocarbons (7).

The differentiation in the origin of CBM is associated with the quality of the methane gas generated. Biogenic CBM is the result of bacterial conversion of coal into acetate or carbon dioxide, which is then converted into methane by methanogenic archaebacteria (8). In turn, thermogenic CBM originates when the chemical devolatilization occurs during the coalification process. A study suggested that, within a single coal basin, the shallow coal beds may be of biogenic origin whereas the deeper coals may be thermogenic (9). Nonetheless, biogenic components can also be found in deeper strata, as their generation and retention are a function of hydrodynamics, varying the depth in each play. It is relevant to note that transition from biogenic and thermogenic is not instantaneous, therefore composition of the gas in a particular play will have a mix of both biogenic and thermogenic origin.

The closed or abandoned mine methane (AMM) emitted is mostly of the biogenic origin (8). However, in CBM reservoirs, uncertainties on the biogenic/thermogenic CBM proportion still exists. A study done in the eastern Illinois Basin in the United States suggests that thermogenic gas contribution amounts to almost a fifth (19.2%) of the total composition (10).

The nature of methane as a global warming pollutant encourages the need for methane emissions monitoring, reporting, and verification (MRV) initiatives. An MRV program is established with the end goal of mitigating the release of methane, which can rely on the best practice guidance of CMM published by the United Nations Economic Commission for Europe (UNECE) and the Global Methane Initiative (GMI) (11). Therefore, behaviors and trends can be identified when a periodic monitoring program is established, which in turn allows to enhance the verification of any individual emissions minimization efforts.

The purpose of this case study is to present an example of the use of remote sensing practices utilizing satellites to demonstrate the feasibility of the technology as part of an MRV program for coal mines. Hence, the premise of the study is to demonstrate, by means of an example, how the coal industry can benefit from performing remote sensing monitoring of individual facilities.

Satellite Platform

The use of satellite technology is intended to remotely sense to understand and complement other information sources (12). The satellite platform utilized in this study belongs to GHGSat Inc, a Canadian company headquartered in Montreal. GHGSat was established in 2011 and deployed its first demonstrator satellite in 2016 (13) (14). Currently, the company has five commercial satellites dedicated to measure methane from different sectors, including the mining sector (15) (16). The launch of three additional methane satellites will occur in April 2023, and three more, two methane and the first carbon dioxide satellite, in December 2023 (17).

Throughout this time, GHGSat has not only being able to identify emissions from point sources such as vents of underground coal mines (18), but also from area sources such as those found in open pit mines (19).

GHGSat frequently conducts internal and external third-party validation of results. In a recent third-party study (currently under peer review process) comparing multiple satellite platforms and data processing teams, GHGSat's measurements not only showed the lowest detection threshold of all the systems, but also depicted the greatest accuracy and precision in these blind tests study (20).

Initial conditions

This study focuses in a production area in Kazakhstan. The coalfields in the Karaganda Coal Basin are structurally and geologically complex. Minable coal seams, characteristically have low coal permeability and high methane content (21). The basin contains strata that range in age from Upper Devonian through Cenozoic, exceeding 3,000 square kilometers in area. The area of interest (AOI) in this case study is a section of the Shakhtinskaya coal mine, belonging to the Karaganda coal basin in Kazakhstan (Figure 1). The mine started operations in 1973, situated about 35 km to the west of Karaganda City. Due to the ongoing mining activities, deformation in the underworked territories is occurring. A recent study shows a methodology for tracking deformation via radar images from the ENVISAT satellite (22). This 50-year-old underground coal mine continues to produce using the Longwall mining method (23). The mine employs Z-type ventilation system, utilized to minimize the methane concentration near the production face (24). Karaganda basin is considered a high gas content basin, where seams have a high gas content that increases from the first encounter with methane in the coal bearing strata down to a depth of 400 to 500 meters. The mine has proven and probable coal reserves of approximately 24 million metric tons remaining (23).

Figure 1. The green border delimits the area of interest (AOI) for this study in the Karaganda Coal basin close to the Shakhtinskaya coal mine, Kazakhstan. Image: Google Earth.

Objective

The objective of this study was to remotely observe the AOI (depicted in Figure 1) aiming to identify methane emissions utilizing GHGSat's targeted satellites. The period of the study was for the months of June, July, and August 2022, effectively monitoring during the summer season in the Karaganda region. The idea of these observations was to identify and quantify individual sources of methane emissions from the Shakhtinskaya underground coal mine. By understanding these observations, additional insights can be obtained when applying assumptions of intermittent or continuous emissions behavior**.**

Challenge

The coal mining activities inherently produce methane emissions. In underground coal mines, gas drainage and ventilation systems are the main conduits for atmospheric emissions of methane. Therefore, developing an understanding of these emissions is the first step towards mitigation efforts. Currently, efforts to monitor emissions from multiple vents within a coal mine are limited. This leads to a misunderstanding of the current behaviors and trends of the methane emissions. Understanding the origins and evolution of CBM is relevant for exploration and development purposes. For instance, understanding the biogenic pathway, structure, and coal rank of biogenic methane is relevant in creating new technologies and approaches in the exploitation of coal reserves (25). Although current in situ and remote sensing capabilities present the challenge of differentiating the CBM emissions between biogenic or thermogenic origins, the total CMM emissions (which directly affect the atmosphere) can be identified and measured.

Solution

The use of targeted satellites that monitor methane emissions enables the periodic monitoring of facilities within a coal mine basin. A 2020 study shows the feasibility and effectiveness of monitoring coal mine vents for a period of two years (2016-2018) with GHGSat's demonstrator satellite (18). Also, high-resolution satellites can also function as a tool for verification (11). In this study, the proposed solution was to utilize the GHGSat's commercial satellite constellation to monitor the AOI, which is capable of providing the location within a 25-30-meter resolution of each emitting source that exceeds background concentration at a rate of 100 $kg \cdot hr^{-1}$. Currently, GHGSat constellation is composed of five satellites, effectively able to revisit every 2-3 days. By the end of 2023, the constellation will grow to ten satellites, having the capacity to revisit daily.

Results

The different satellites within the GHGSat constellation observed emissions in three days in June (4th, 22nd, and 24th), one day in July (19th), and two in August (2nd and 25th). In each of these days, multiple plumes were detected in a single standard field of view (FOV), which can cover 144 km^2 (12 km by 12 km). Figure 2 shows a map of all the detections found in this study. Table 1 depicts the simple descriptive statistics by month accounting for all the detected emissions.

Table 1. Summary of emissions detected within the Shakhtinskaya underground coal mine of, with GHGSat satellites for the period of June through August 2022.

Month	Total ($kg \cdot hr^{-1}$)	Average ($kg \cdot hr^{-1}$)	Min ($kg \cdot hr^{-1}$)	Max ($kg \cdot hr^{-1}$)	Number of Plumes
June	6980	698	283	1378	10
July	1239	619.5	462	777	2
August	2575	643.75	478	901	4
Total	**10794**	**653.75**	**283**	**1378**	**16**

It is relevant to note that GHGSat's satellites operate in target mode, meaning that a decision to observe a particular site is determined previously. In this study, every time a satellite was tasked to observe the AOI, emissions were found. The exception was during the month of July, in which two attempts were unsuccessful due to AOI's weather conditions. Frequency of measurements can provide a basis to determine persistency of emissions.

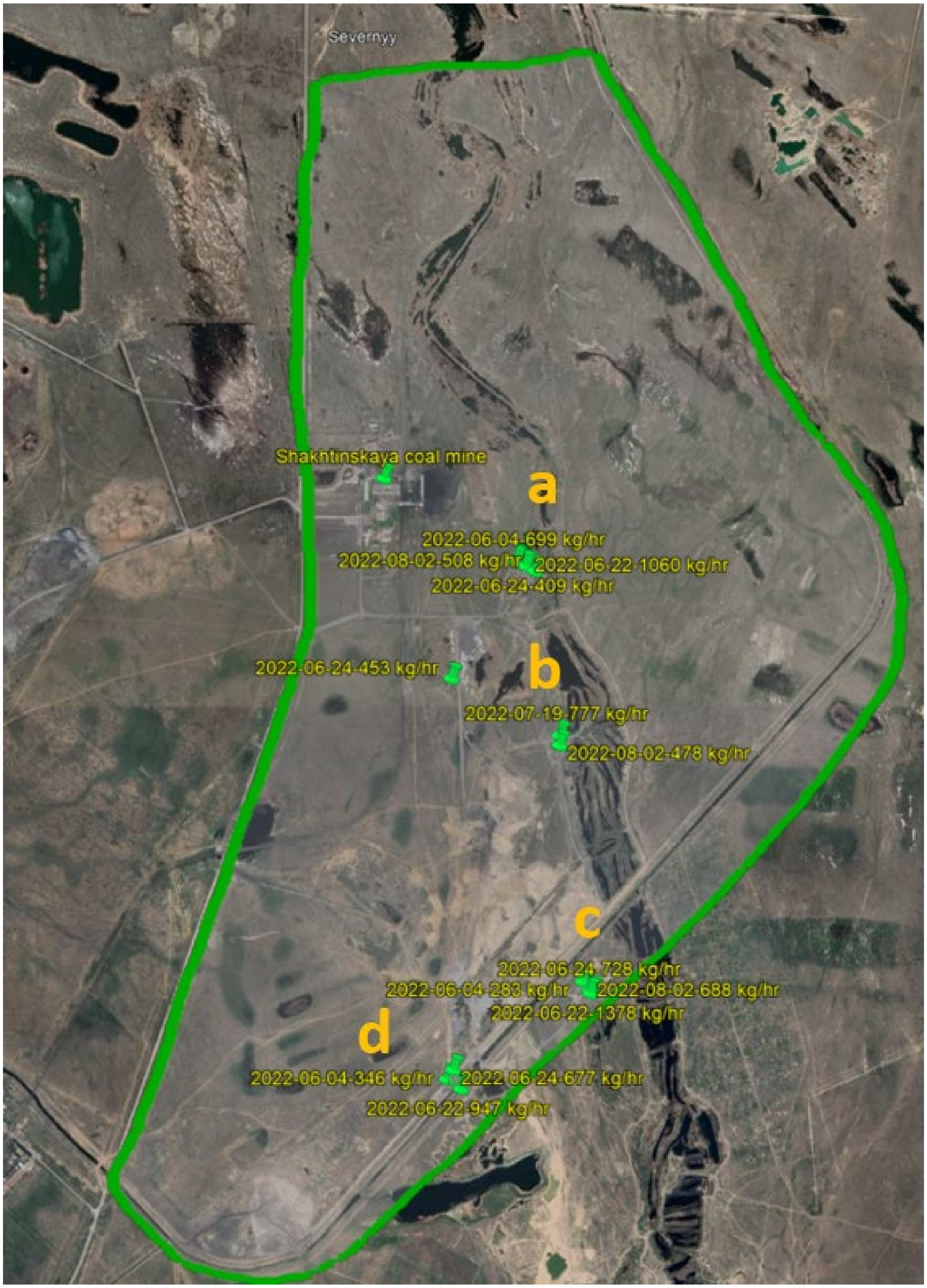

Figure 2. Emissions detected in the AOI in the Karaganda Coal basin close to the Shakhtinskaya coal mine, Kazakhstan, for the period of June through August 2022. Close up images of denoted areas a through d are shown in Figure 3. Image: Google Earth.

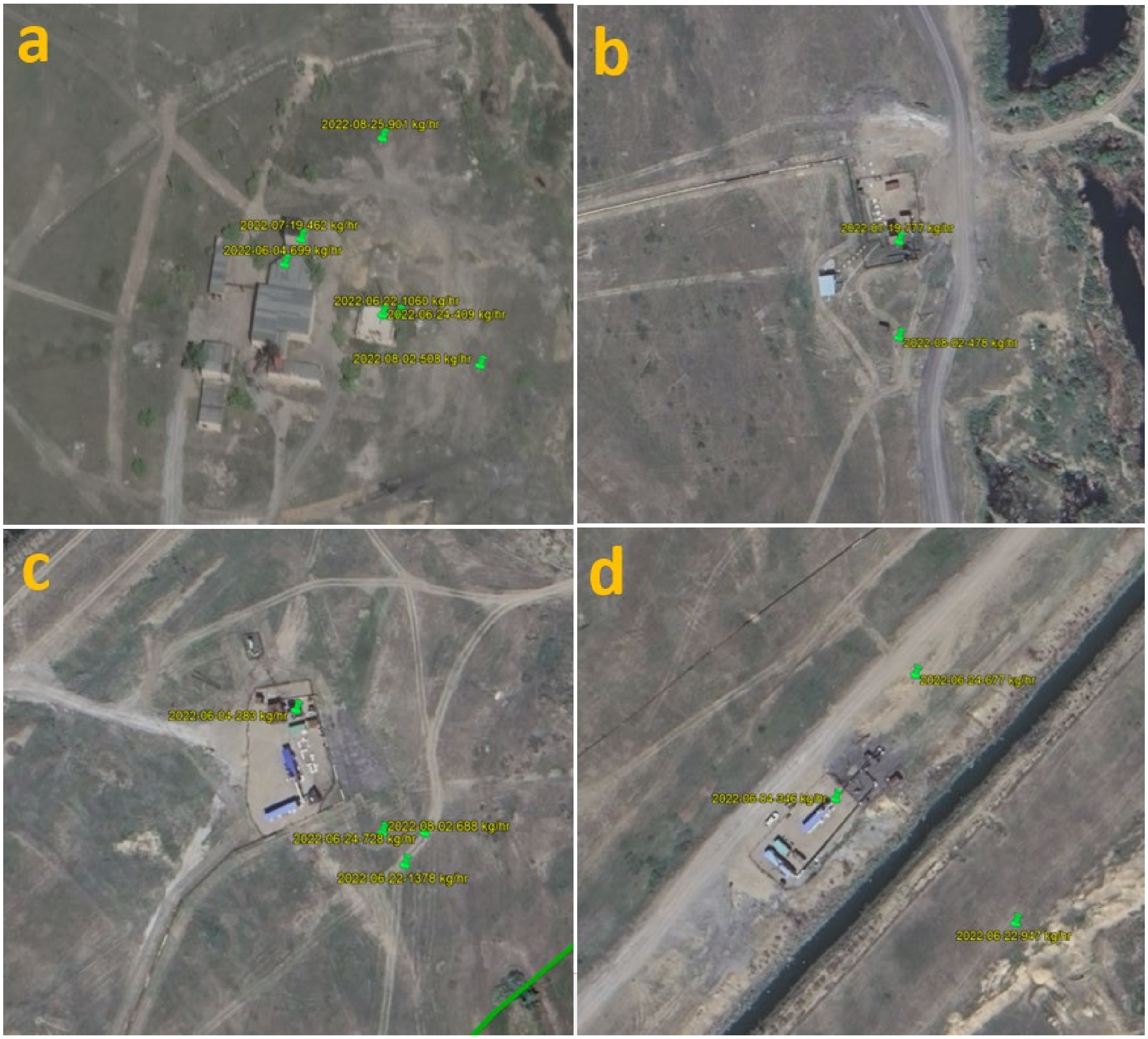

Figure 3. Close up on areas where emissions were detected in the AOI in the Karaganda Coal basin close to the Shakhtinskaya coal mine, Kazakhstan, for the period of June through August 2022. Image: Google Earth.

June 2022

During the month of June 2022, a total of ten plumes were identified. On June 4, 2022, three plumes were detected, with the lowest being detected at 283 kg·hr^{-1} ± 61%. This detection was the lowest of all the 16 detected in the study. Figure 4 illustrates GHGSat's concentration map of this plume. The other two detected plumes within the FOV were 346 and 699 kg·hr^{-1} ± 61%.

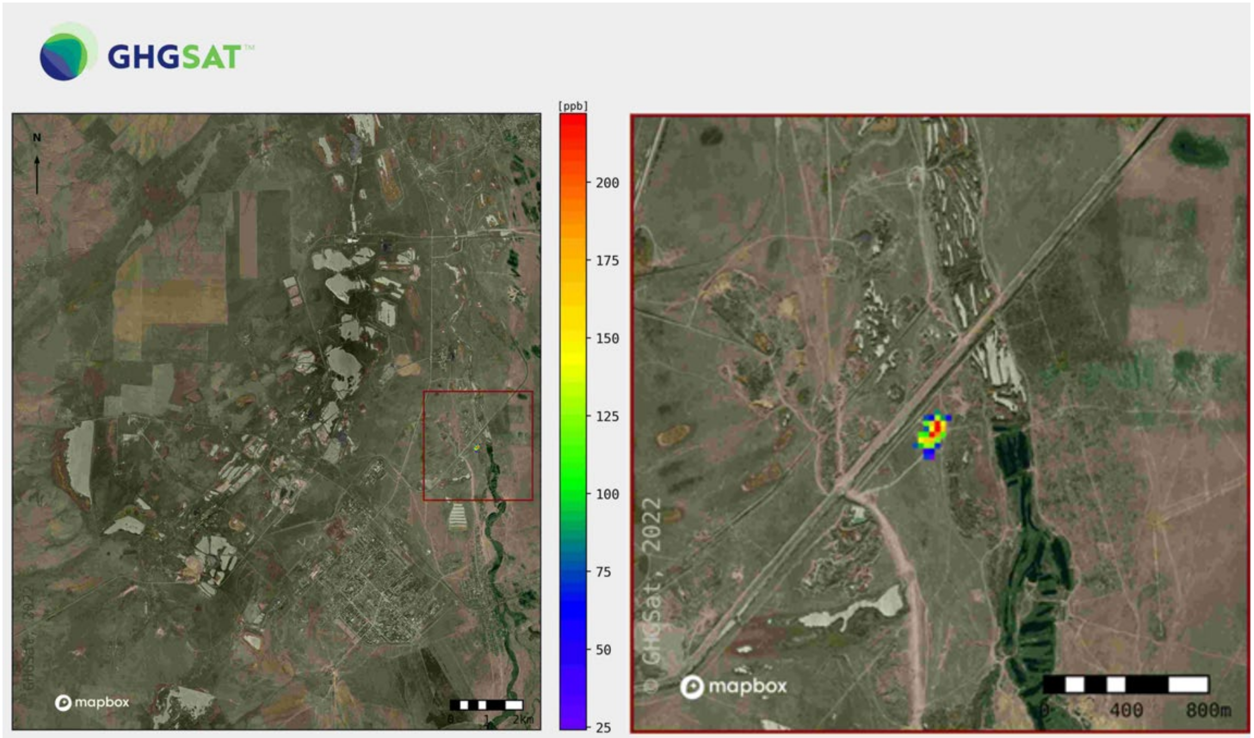

Figure 4. Concentration map of emission detected on June 4, 2022, at the Shakhtinskaya coal mine. Image: GHGSat Inc. overlaid on a Mapbox imagery.

Therefore, the summation of the emissions rates on that observation from that area was equal to 1328 $kg{\cdot}hr^{-1}$. If a uniform persistence is assumed, this rate would lead to almost 32 metric tons of methane per day. On June 22, 2022, three plumes were also observed, in which the highest emission rate of all the 16 detections was detected, representing a value of 1378 $kg{\cdot}hr^{-1} \pm 28\%$. In comparison, if this single emission is assumed to be persistently uniform, it will amount to about 33 metric tons of methane per day, more than the three combined on June 4, 2022. Figure 5 depicts the concentration map for this emission.

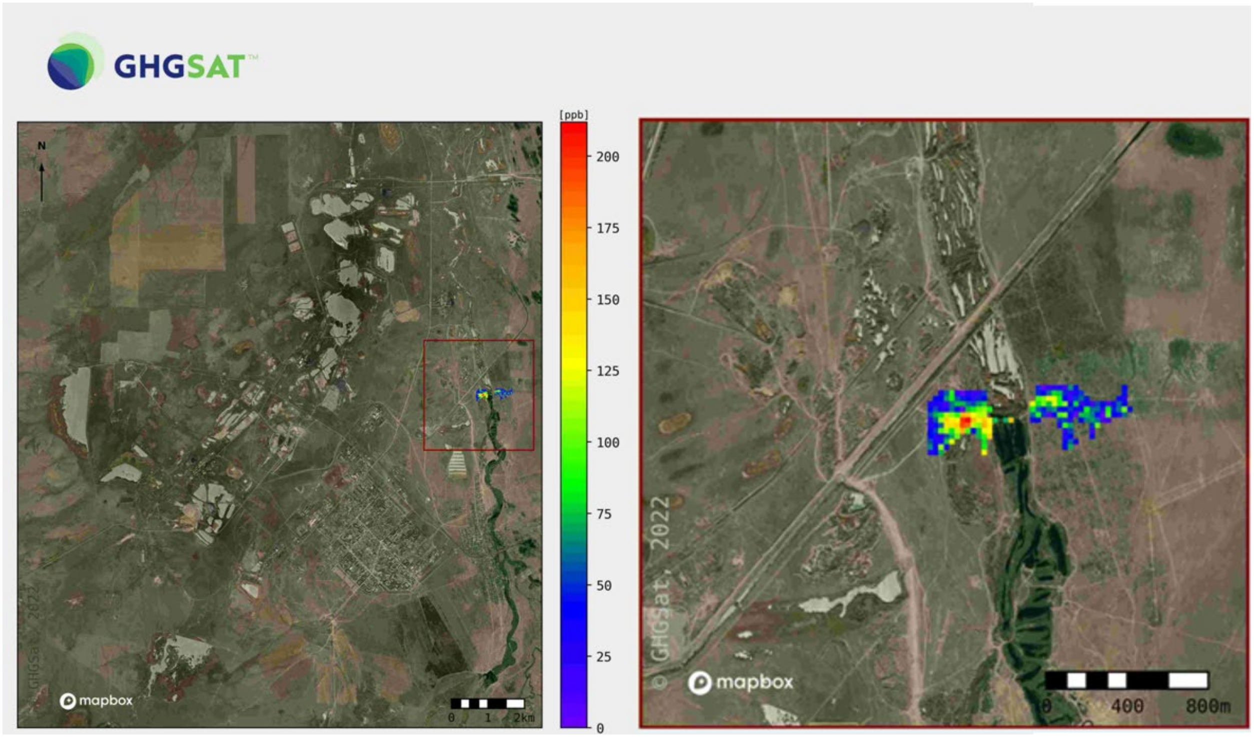

Figure 5. Concentration map of emission detected on June 22, 2022, at the Shakhtinskaya coal mine. Image: GHGSat Inc. overlaid on a Mapbox imagery.

The total emissions on that day amounted to 3385 kg·hr^{-1}, since the other two detections were 947 and 1060 kg·hr^{-1}. Assuming uniform persistence, these emissions represent about 81 metric tons of methane per day. On June 24, 2022, four emissions were detected. These emissions were 409, 453, 677, and 728 kg·hr^{-1}± 46%. The aggregate amount was 2267 kg·hr^{-1}, or about 54 metric tons of methane per day if persistence is assumed.

During the month of June, it can be inferred that three sources were persistent, each with varying emission rates. In aggregate, the total emissions in the month of June amounted to 6980 kg·hr^{-1}, or about 167 metric tons of methane per day, assuming 24 hours of persistent emissions.

July 2022

In the month of July 2022, a total of two plumes in a single standard FOV taken on July 19 were identified. The largest plume in the FOV was calculated to be emitting at 777 kg·hr^{-1}± 39%. Figure 6 depicts this detection. The emission rate of the other plume was calculated at a rate of 462 kg·hr^{-1}± 40%, which came from the same location of the largest emission observed on June 2. Hence, the total observed emissions on this day were 1239 kg·hr^{-1}, which can represent almost 30 metric tons of methane per day, if emitted constantly. It is important to note that during this month, there were a couple of unsuccessful data retrievals due to weather conditions, hence the reason for obtaining a single observation in the entire month.

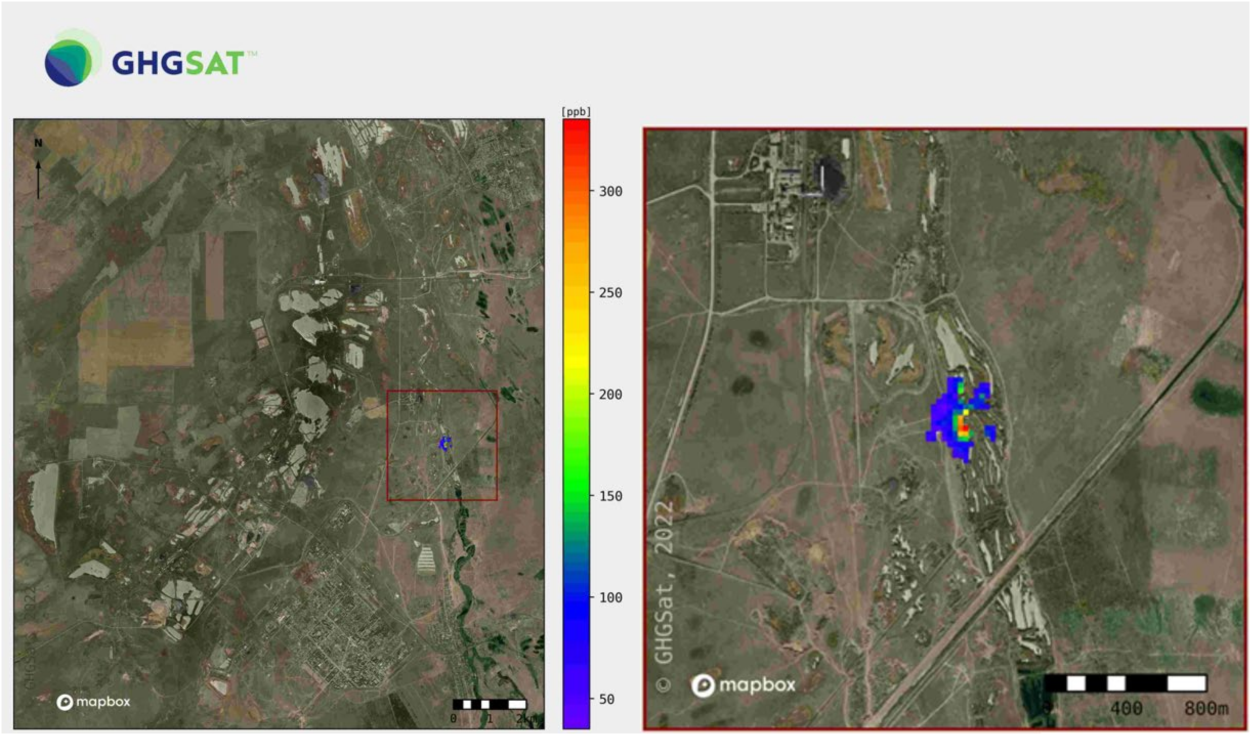

Figure 6. Concentration map of emission detected on July 19, 2022, at the Shakhtinskaya coal mine. Image: GHGSat Inc. overlaid on a Mapbox imagery.

August 2022

For the month of August 2022, emissions retrievals for two different days were achieved. On August 2, two emissions of 508 and 688 kg·hr^{-1} ± 46%, respectively, were detected in a single FOV. The latter came from the same source that was identified on June 22 and June 24. On August 25, one emission of 901 kg·hr^{-1} was detected. Figure 7 shows the concentration map of this detection. In aggregate, the total emissions in the month of August amounted to 2575 kg·hr^{-1}, which can represent almost 62 metric tons of methane per day, if persistence is assumed.

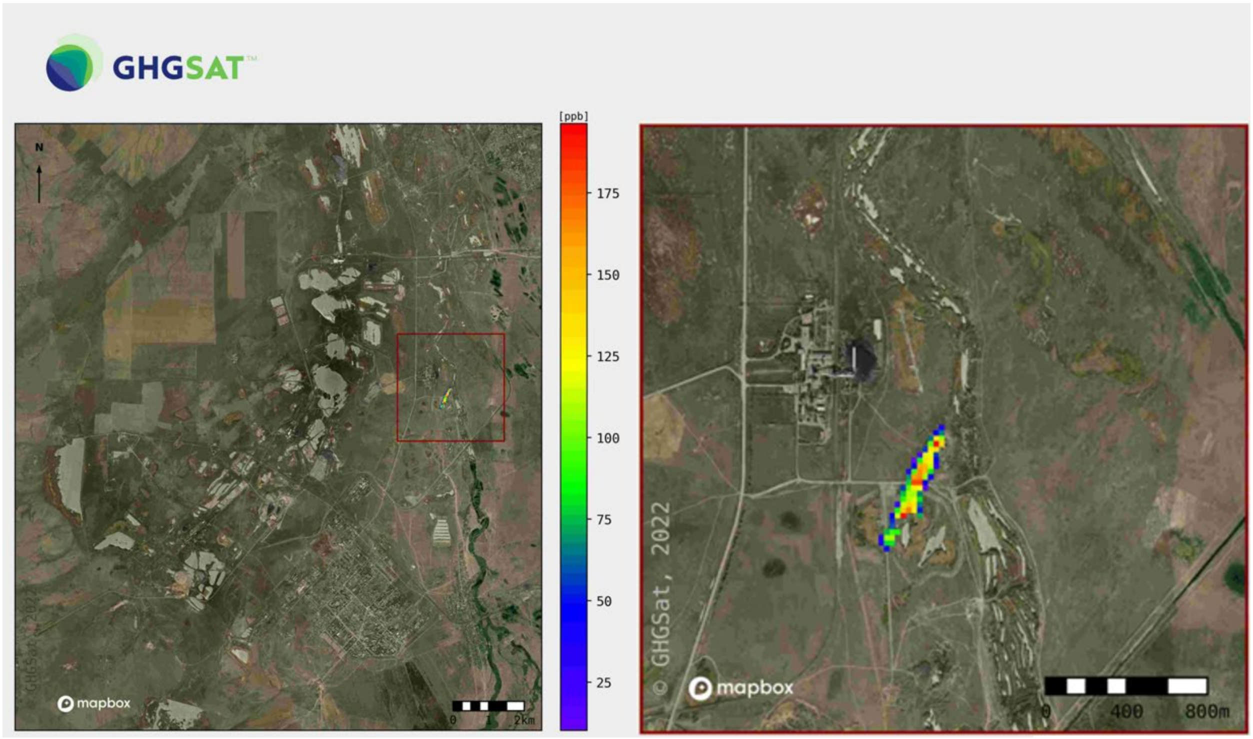

Figure 7. Concentration map of emission detected on August 25, 2022, at the Shakhtinskaya coal mine. Image: GHGSat Inc. overlaid on a Mapbox imagery.

Conditions to consider

CMM emissions often show large temporal variability. This is largely in part due to production rates but can also be affected by multiple factors ranging from geological characteristics to changes in atmospheric pressure. Also, the methane concentration in a stream varies, particularly when mine vents are monitored, as the presence of methane molecules is diluted by the constituents of air (nitrogen, oxygen, and argon plus other gases including carbon dioxide). This in turn, may impact the detection threshold of an instrument due to the diffusivity effect.

Also, the satellite platform experiences detection and quantification uncertainties. Methane detection depends on the absorption of solar radiation. Therefore, having clear sky is the optimal condition for a successful retrieval. Also, the detection limit depends on wind speed, where high wind speed leads to increased dilution in the plume. Quantification uncertainty is associated with the quality of data used in the calculation of solar radiation reflection and methane absorption into an emission rate. GHGSat uses the integrated mass enhancement (IME) method (18) (26). This method associates the mass of the entire detected plume to the source rate, which can infer source rates with an error of 5-12% (depending on instrument's precision 1-5%), in addition to errors associated with wind data (27). Varon et al., observe that low winds are favorable for source detection but impact source quantification. In addition, the sensor is sensitive to methane molecules but currently is not capable of distinguishing between methane's biogenic and thermogenic origins.

Conclusion and Lessons

Coal continues to be an important supply of energy for the world, since it is the largest source of electricity generation (over one-third of total generation) despite being the largest source of carbon dioxide emissions (28). However, the mining and production of coal liberates methane, described as CMM.

The impacts of methane as a global warming agent have been widely documented. Efforts to minimize its emissions from methane-intense industries are current and of relevance in the global stage. Methane emissions arising from the coal mining industry have taken notoriety and efforts to minimize them are undergoing. An important step towards that goal is to first identify where the emissions occur. For this, the use of remote sensing technologies can provide an effective tool in monitoring and identifying methane emissions periodically.

This study presented the use of a constellation of satellites to monitor a coal mine in the Karaganda basin. Six observations occurred during the 2022 summer season (June, July, and August), in which 16 plumes were detected. From these observations, it was noticed that four different sites showed persistent emissions of varying emission rates during the study. The highest plume detected had a calculated rate of 1378 $kg \cdot hr^{-1}$ ± 28% (Figure 4) and the lowest detected was 283 $kg \cdot hr^{-1}$ ± 61% (Figure 3).

Additional and more in-depth analysis can be performed if supplementary information about the operations is known. First-hand knowledge of each specific facility under monitoring can be leveraged to provide further meaning and understanding of the data provided by the monitoring platform.

Takeaways

- In 2021, coal accounted for over one-third of total electricity generation (28).
- Controlling and minimizing CMM continues to be an imperative goal.
- Variability in the emission rates depends on production and mining activities.
- Remote sensing technologies, like the ones employed by satellites, can assist in the monitoring and verification of CMM emissions.
- The methane sensor does not distinguish between biogenic and thermogenic origins.
- The minimum detection threshold of each satellite in the constellation is 100 $kg \cdot hr^{-1}$.
- The lowest detected methane emission rate in this study was 283 $kg \cdot hr^{-1}$± 61%.
- The highest detected methane emission rate in this study was 1378 $kg \cdot hr^{-1}$± 28%

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