Observations from Space: Exploring the Landscape of Current and Emerging Technologies to Identify and Quantify Methane Emissions Using Satellites

Introduction

Satellite observations of atmospheric methane emissions are gaining attention due to their ability to quickly and frequently monitor large areas with global coverage. Uniquely positioned to provide near real-time information on rapid changes in emissions, satellites can help to improve global capabilities in quantifying country- or regional-level emissions by sector, inform national methane reduction goals, and monitor emission patterns over time. Most importantly, satellites can be used to identify large emission sources dubbed "super-emitters"[1] or "ultra-emitters"[2] so those sources can be targeted for repair, resulting in real reductions in overall methane emissions to the atmosphere.

The Collaboratory to Advance Methane Science (CAMS) is an industry-led research collaboration administered by GTI Energy and dedicated to improving the scientific understanding of methane emissions. In 2021, CAMS launched a new study to explore current and future capabilities of satellite-based methane detection technologies, methods and data analytics and current limitations. To lead this research project, Geosapient teamed up with Harvard University's Dr. Daniel Jacob, a recognized international expert in satellite observations of methane, and Innovative Imaging and Research (I2R), which specializes in remote sensing, geospatial, and optics-based products and services. The academic review was performed over a four-month period by Dr. Jacob and his research team. The full results of the analysis have been peer reviewed and are available in the journal *Atmospheric Chemistry and Physics*.[3] The purpose of this white paper is to provide the primary findings of the Jacob et al. 2022 review at a high level that may be insightful for industry members, regulators, technology providers and other researchers.

> *This study highlights the emerging capabilities for satellite observations to anchor a global methane monitoring system that can deliver information worldwide in near real time, from the global scale down to point sources.*

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Current and Future Methane Satellites

Satellites that detect and quantify methane emissions measure shortwave infrared radiation (SWIR) with wavelengths between 1,100 and 3,000 nm (1.1 to 3.0 µm). The radiation originates from the sun in most cases or via a laser emitted from the satellite itself that is reflected off the earth's surface back to the satellite, called backscatter. The area of the Earth's surface from which the backscattered radiation is detected is referred to as a pixel. Satellites image the earth's surface, and like normal digital cameras, combine many pixels together to create each image. The number and size of the pixels dictate the type of data that can be collected with each satellite. The two primary types of satellite-based methane detection and quantification discussed in the paper are area flux mappers and point source imagers.

Area flux mappers cover wide areas using a large pixel size—anywhere from 100 meters to 10 kilometers—coupled with high precision instruments to quantify methane emissions (see Box 1). These satellites have an essential role to play because of their dense and global coverage, which allows them to identify the regions that drive the global trends.[3, 10] Global and regional observation via satellite area flux mappers primarily focuses on the causes of increasing atmospheric methane concentrations since pre-industrial times and the contributions of individual countries or regions to total methane emissions.[3] *See Box 1 for more on how area flux mappers work.*

Point source imagers use a finer-scale pixel size, with each pixel covering an area of less than 60 meters to focus in and quantify the plumes emitted from individual point sources. Determining the location and size of large and unknown point sources (super- or ultra-emitters) can have a direct impact on methane emissions reductions when corrective action and/or abatement of the source happens. However, detecting point sources from satellites can present some important obstacles. Since plumes are often narrower than one kilometer,[3, 12] detection requires the use of satellite pixels finer than 60 meters.[13] *See Box 2 for more on why scientists are using point source imagers.*

Figure 1. Satellite instruments for observation of methane in the shortwave infrared (SWIR). Satellite icons were obtained from https://www.gosat.nies.go.jp for GOSAT; Wikipedia Commons for TROPOMI, EMIT (International Space Station), and Sentinel-2; https://space.skyrocket.de for GOSAT-GW, MERLIN, CO2M, and Carbon Mapper; https://www.methanesat.org for MethaneSAT; ESA (2020) for Sentinel-5; https://www.ou.edu/geocarb/mission for GeoCarb; https://www.planetek.it/ for PRISMA; https://www.ghgsat.com/ for GHGSat; https://www.enmap.org/mission for EnMAP; https://directory.eoportal.org for WorldView-3; and https://www.usgs.gov/landsat-missions for Landsat. (Jacob et al. 2022)

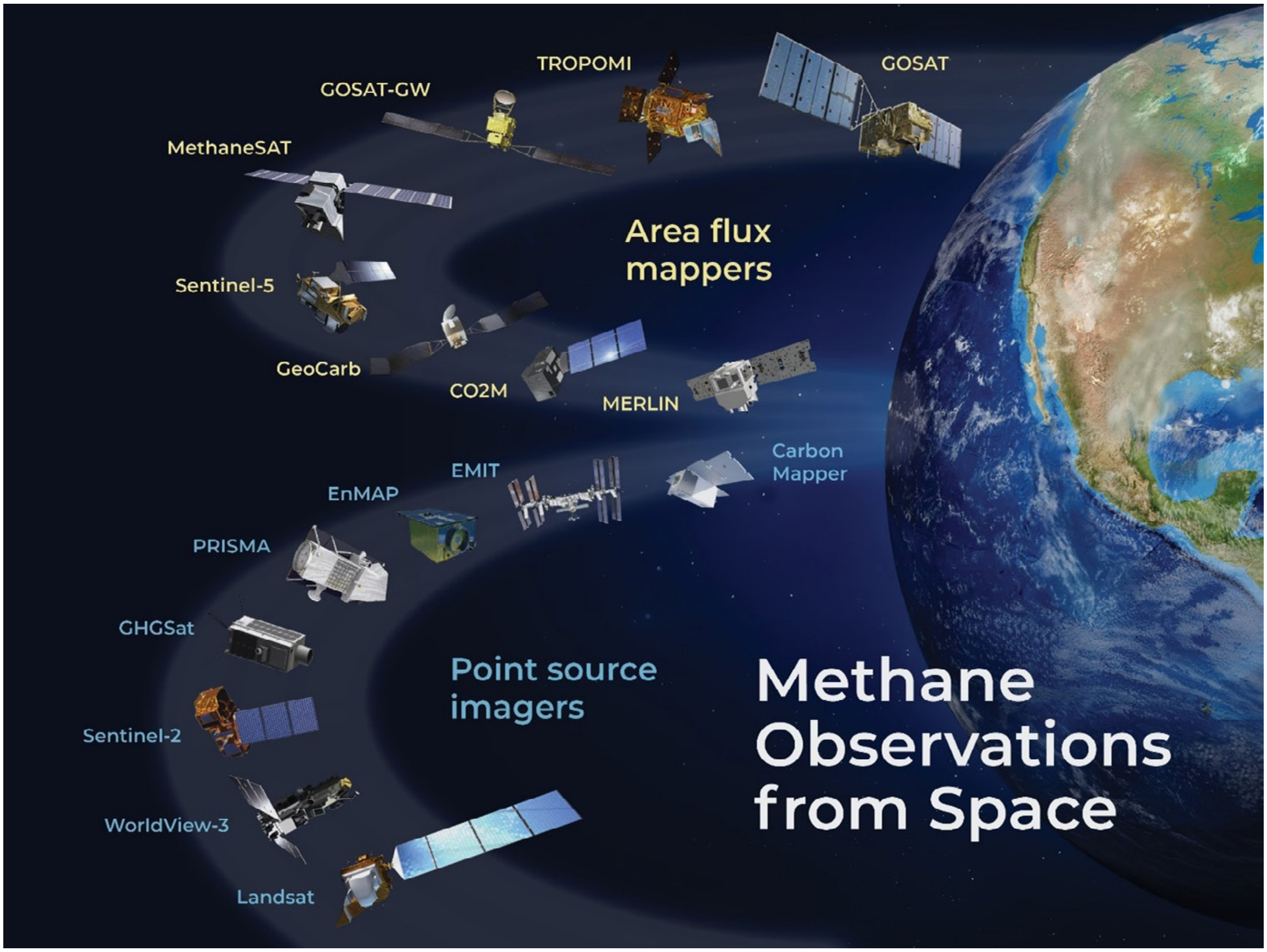
Box 1. How Do Area Flux Mappers Work?

Area flux mappers produce two-dimensional (2-D) fields of methane observations to generate and optimize 2-D fields of gridded emission fluxes. The optimization takes advantage of an atmospheric transport model (forward model) to relate emissions to observed concentrations.

Optimal emissions can be obtained using Bayesian inference, fitting the observations to the forward model and including prior estimates of emissions to correct the solution where the observations provide insufficient information.[3, 11]

Box 2. Why Use Point-Source Imagers?

Point emissions often vary over time, requiring observational instruments to frequently re-scan a particular site. This type of investigation can be achieved most effectively using a constellation of instruments3. Point sources that are detectable from satellites usually consist of super- or ultra-emitters. The very large emission sources drive atmospheric concentrations far above ambient levels and therefore require less precise instrumentation than would be needed for regional or global observations.[3]



WorldView-3; and https://www.usgs.gov/landsat-missions for Landsat. (Jacob et al. 2022)

Currently, at least 16 satellite systems that provide publicly accessible data and document methane-observing capabilities have been deployed already or are slated for deployment by 2030.[4] As detailed in Jacob et al. 2022[3] and summarized in Figure 1, there are currently:

- seven operational point source imagers;
- two operational satellites capable of area flux mapping;
- one point source imager scheduled to come online through 2023; and
- six satellites capable of area flux mapping that are scheduled to come online by 2027.

With the exception of EMIT and GeoCarb, all instruments shown in Figure 1 operate in polar sun-synchronous low Earth orbit (see Box 3).[3] **EMIT**, a satellite instrument designed to observe dust surfaces, will sit aboard the International Space Station, prioritizing observations over arid regions and with variable local overpass times. **GeoCarb** will be in geostationary orbit, moving west to east at the same speed as Earth's rotation and remaining "stationary" above a single fixed location. In this case, the satellite will remain continuously over the Americas, providing twice daily observations from 45oS to 55oN.[3]

Box 3. What is Polar Sun-Synchronous Orbit?

Satellites in polar sun-synchronous orbit travel north to south rather than west to east. They orbit roughly over the poles and are always in the same "fixed" position relative to the sun.[5] This means that the satellites will pass over the same spot at the same local time each day—usually in morning or early afternoon.[5]

Passes in the morning have a greater likelihood of clear sky, while passes in early afternoon generally have steadier boundary layer winds for interpreting methane enhancements.[3]

Methane Satellite Quantification Methods

A 2022 review by Cooper et al6 discusses the methods that are used to detect and measure methane from satellites. Briefly, satellite detection works by determining the atmospheric concentration of methane, typically what is called the *column-averaged dry mole fraction*.[6] This average concentration between the surface and the satellite can be converted into a flux through **atmospheric inversion modeling** that ultimately enables emission source detection.

To reiterate, the measurement is achieved by measuring the backscattering of sunlight or laser light emitted from the satellite when the light is reflected from the Earth's surface into a spectrometer onboard a satellite. As the light travels through the atmosphere, it is absorbed by any gases it encounters. The spectrometer analyzes the incoming light for the relevant wavelengths—in this case, those wavelengths pertaining to methane.

The measurement is only possible in clear sky. Any cloud occurring over a fraction of the observing pixel will contribute disproportionately to the radiation detected by the satellite. Quantitative interpretation of the observation in terms of methane abundance is then impossible, and the data must be discarded. Cloud detection is performed either by the satellite instrument itself or by a complementary instrument operating in tandem.

Jacob et al. 2022[3] expands on this discussion by including details of three methods for retrieving methane from the satellite observations:

- The **full-physics method** is used to determine methane concentrations from satellite SWIR spectra focused on two wavelength "bands": (i) the 1.65 μm band encompassing wavelengths between 1.63 – 1.70 μm, and (ii) the 2.3 μm band encompassing wavelengths between 2.2 – 2.4 μm. This method solves simultaneously for the vertical profile of methane concentration, the vertical profile of aerosol extinction, and the surface reflectivity by inversion of the radiance spectrum using a radiative transfer model. Susceptibility to atmospheric haziness, surface heterogeneity, and surface darkness means that the full-physics method has only roughly a 3% global success rate over land.
- The **CO_2 proxy retrieval method** uses simultaneous measurements of both methane and carbon dioxide (CO_2). The CO_2 concentration is then determined independently and subtracted out, leaving only the methane concentration.[3] This method is much faster than the full-physics method and takes advantage of the lower variability in CO_2 compared to methane. However, this method is susceptible to biases in the independent quantification of CO_2.
- The **matched-filter method** is used for mapping methane point sources. The matched-filter method has been used extensively for airborne hyperspectral campaigns and is useful for individual plume imaging, but not for determining regional emissions.

Retrievals of satellite column-averaged methane dry mole fraction can be affected by random error (precision) and systematic error (bias or accuracy).[3] A uniform or consistent bias is straightforward to handle, as it can be subtracted from the data; random error can be controlled with temporal averaging. The most difficult systematic error to process is **spatially variable bias** (see Box 4). To attempt to reduce bias, area flux mapper instruments used to generate global or regional estimates are often validated by reference to the highly accurate dry mole fraction measurements from the worldwide Total Carbon Column Observing Network (TCCON) that consists of ground-based sun-staring spectrometers.[3, 8]

Box 4. What Is Spatially Variable Bias?

Spatially variable bias is usually caused by aliasing of surface reflectivity spectral features into the methane retrieval. This type of bias is often referred to as relative bias.

Variable bias corrupts the retrieved concentration gradients and produces artifact features that may be wrongly attributed to methane. Variable bias is also a concern for point source imagers where it can generate artifact features that can be mistaken for methane plumes.[3, 7, 9]

Big Picture Observations on Methane Sensing from Satellites

Jacob et al. 2022[3] make several key observations pertaining to the current and future direction for methane sensing from satellites.

Some methane sources are intrinsically difficult to observe from space, including observations over water, the wet tropics, and the Arctic. Nevertheless, satellite observations of atmospheric methane in the shortwave infrared (SWIR) provide an **increasingly powerful system for continuous monitoring of emissions** from the global scale down to point sources.

As technologies, regulations, and operating practices continue to advance, finding solutions to challenges such as **connecting top-down methane emission information to the improvement of bottom-up emission inventories** will grow increasingly important. Critical pathways that can **combine different satellite-based instruments or pair satellite measurements with ground-based and airborne detection platforms** will offer multi-tiered observing strategies that maximize detection abilities and long-term effectiveness of satellite-based detection platforms.

This study highlights the emerging capabilities for satellite observations to anchor a global methane monitoring system that can deliver information worldwide in near real time, from the global scale down to point sources. These capabilities will become increasingly pivotal in verification and in supporting proliferating climate policies, regulations, and rules for corrective action.

Areas for Future Research

Most importantly, the reviews of Cooper et al. 2022[6] and Jacob et al. 2022[3] reveal several key high-level areas for future research that can significantly advance satellite-based methane detection. In particular, Cooper et al. 2022[6] suggest that in the future, modeling advancements and analytics platforms will be needed to determine the impact that wind speed and turbulence have on our ability to estimate methane emission rates (e.g., flux) and the impact of gas mixing in the atmosphere between the surface and satellite (e.g., column). Important synergies can be realized by **combining and comparing data between multiple satellites and aircraft or ground-based measurements** to enhance detection capabilities and reconcile differences between measurement techniques and emissions estimates.[3, 6] Moreover, potential uses of “tipping and cueing,” wherein information from an area flux mapper satellite can be used to inform a point source imager satellite to focus on a point source emissions (see Box 5), are already being explored.

Briefly, current gaps and future needs that have been identified but are not covered in this study include:

- the absence of a km-resolution, hourly observing geostationary satellite over oil and gas basins in the U.S. that have shown high levels of emissions (e.g., the Permian Basin);
- an understanding of methane sources that are intrinsically difficult to observe from space, including observations over water, the wet tropics, and the Arctic; and
- a detailed study of the steps needed for oil and gas operators to integrate satellite detection into existing leak detection and repair programs, and on a more granular level, to detail how operators operationalize the information collected via satellite.

Box 5. Tipping and Cueing

Did you know that “tipping and cueing” was a concept developed by the intelligence community?

The advantage of employing a tipping and cueing strategy for methane detection is that it allows an area or region of interest to be monitored with low resolution and low cost (or free) satellite imagery, and when an anomaly is identified that needs to be further investigated a higher resolution and more costly satellite is tasked for imagery collection and follow up analysis and exploitation. Although the tip and cue process could work in theory for a small satellite constellation and other commercial assets, significant hurdles—including the range of commercial agreements that would need to be in place—exist in practice.

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